From Challenges to Rewards with HDR SWIR Imaging in Metal AM

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Recent advances in Metal Additive Manufacturing have led to greater application of the technology in new markets and at new scales. This has driven an increased requirement for real-time in-situ process monitoring solutions. Researchers have made significant progress in modeling, simulation and applied techniques, with innovations in vision systems enabling some key advances.

The novel approach of combining high dynamic range vision technology with SWIR sensors overcomes several hurdles related to defect detection in DED and WAAM processes. Harsh, high temperature environments with high contrast scenes, high-speed processes, and changing emissivity is challenging with even the best of sensors. As build and part sizes grow, so do the cost of failure. Only constant and reliable monitoring and control can help lessen an expensive, and possibly catastrophic, failure.

Specific benefits that HDR SWIR imaging offer include a human-like vision experience – even when brightness levels far exceed the range we normally can discern; real-time 2D thermography of the process with higher temperature measurement accuracy than other non-contact sensors; and an ability to view clearly through particulates and glass, without expensive and problematic secondary lighting requirements.

Fabricating High Performance-Lightweight-Low-cost Batteries

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Development of additive-free electrodes with low cost and in an environmentally friendly way represents a sustainable and ecologically friendly energy expansion. Most conventional electrode preparation process is currently facing serious obstacles. The underlying problem with the conventional procedure for the preparation of battery electrodes is time consuming involving unhealthy multiple steps, including materials synthesis with toxic reagents, slurry formation, coating onto current collectors, and drying in a vacuum oven. Furthermore, various additives such as carbon black, polymeric binders, and organic solvents are commonly included during slurry preparation for electrical conduction and better physical contacts between particles and current collector, respectively. The addition of various additives to the electrodes generates several problems such as increase battery weight, environmental hazard, production cost, and decrease overall energy and power density of the battery. To solve some of these problems with existing battery technology, the fabrication of thin film electrodes by adopting modern thin film technique such as magnetron sputtering system is highly recommended. The demonstrated technique is faster, easier, and most importantly one-step process which opens a new way to develop high performance-lightweight-low-cost batteries, and this is to be demonstrated in this presentation.

Laser surface modification of Ti40Zr25Nb25Ta10O0.5 high entropy alloy

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Abstract

As-cast Ti40Zr25Nb25Ta10O0.5 high entropy alloy (HEA) provides an excellent combination of tensile strength (yield strength: about 980 MPa) and uniform elongation (about 10%) and is biocompatible. However, this HEA does not possess high surface hardness. In this study, the as-cast Ti40Zr25Nb25Ta10O0.5 HEA was laser surface remelted to modify its microstructure for improved tribological and corrosion resistance properties. Both the as-cast precursor HEA and laser surface remelted HEA exhibited a single body-centred cubic phase. However, the laser surface modification reduced its grain size from about 106 µm to 12 µm, and the grain morphology became much more equiaxed than the as-cast grain morphology. This fine equiaxed grain structure increased the hardness of the HEA from the 4.42 ± 0.02 GPa in the as-cast condition to 7.40 ± 0.13 GPa. As a result, the wear resistance of the surface modified Ti4025ZrNb25Ta10O0.5 HEA showed a clear improvement under different applied loads versus the as-cast HEA. Furthermore, the corrosion current density of the modified HEA (0.007 ± 0.06 µA/cm^2) in Hank's solution was reduced compared with the as-cast microstructure (0.02 ± 0.08 µA/cm^2) due to the markedly reduced grain size and microsegregation. Laser surface modification proved to be a highly effective approach for modifying Ti4025ZrNb25Ta10O0.5 HEA.

Polyaryl ether ketone (PAEK) matrix composites for material extrusion additive manufacturing

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Abstract

Despite widespread use of Fused Filament Fabrication (FFF) to manufacture end use parts for various industry sectors, limited materials are available for this process, particularly those suitable for structural applications in extreme environments like space. Currently available high-performance polymers need to be improved by incorporating additives within the polymer matrix to improve performance and deliver functional properties. Additives such as Graphene, Graphene Oxide, Carbon Nanotubes and Boron Carbide are known to improve mechanical and thermal properties and assist with radiation shielding. This study aims to understand if such additives can be successfully incorporated into a high performance polyaryl ether ketone matrix to produce filaments suitable for FFF. Graphene, Graphene Oxide (GO), and Boron Carbide (B_4C) were melt compounded in PAEK matrix and their mechanical, thermal, and rheological properties were analysed and compared with commercially available Carbon Fibre and Carbon Nanotube reinforced PAEK where appropriate. As rheological properties of the formulations confirmed that they were printable, filaments for FFF were then manufactured. TEM images of filament cross-section showed good dispersion of Graphene and Graphene Oxide while Boron Carbide formed agglomerates. Dispersion of the additives was also confirmed by studying their X-ray diffraction (XRD) patterns and chemical structures were assessed using FT-IR spectroscopy. Finally, parts were printed using selected composite filaments and their porosity and surface roughness were compared with neat PAEK and commercial CNT-reinforced PAEK to develop an understanding of metrology and bulk material properties of the printed composites.

Keywords: Fused deposition modelling (FDM); nanocomposites; rheology; chemical properties; X-ray Diffraction Spectroscopy; Porosity

Alpha-phase variant selections in additively manufactured titanium alloys

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The transformation from the body-centered-cubic (BCC) β-phase to the hexagonal-close-packed (HCP) α-phase in α or α-β titanium alloys normally follows the Burgers orientation relationship (BOR), $(1\bar{1}0)_{\beta}//(0001)_{\alpha}$ and $[111]_{\beta}//[11\bar{2}0]_{\alpha}$. In principle, this could result in 12 α-phase variants with equivalent frequency and six types of inter-α-variant boundary. The dynamic heating and cooling cycles during additive manufacturing (AM) provide a unique environment to study the α-phase variant selection/multiplication. This study reports the experimental results of the α-phase variant selection and cluster formation (Category I or Category II triple-α-variant clusters), and the configuration of inter-α-variant boundary in AM Ti-6Al-4V and Ti-4Al-2V alloys through detailed microstructural characterisation. The underlying mechanisms for α-phase variant selection and its influence on mechanical properties are discussed.

Understanding the superior mechanical properties of hollow-strut metal lattice materials

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Intricate hollow-strut metal lattice materials are an emerging class of novel metallic cellular materials enabled by additive manufacturing. This work shows that hollow-strut Ti-6Al-4V lattice materials are consistently stronger and stiffer (up to 60% better) than their solid-strut counterparts of the same relative density, both experimentally and through finite element analysis (FEA). The underlying reasons are investigated using analytical models derived from the Timoshenko-beam theory, which considers deformation by concurrent stretching, bending and shear, rather than the single-mode deformation mechanism assumed by the Gibson-Ashby model. Hollow-strut lattices exhibit higher resistance to bending than solid-strut lattices at the same strut length and relative density, thereby leading to increased strength and stiffness. Hollow-strut metal lattices offer an unusual option for lightweight designs, with better mechanical properties at the same or lower density than solid-strut metal lattices.

The Gibson-Ashby model for additively manufactured metal lattice materials: Its theoretical basis, limitations and new insights from remedies

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The Gibson-Ashby (G-A) model has been instrumental in the design of additively manufactured (AM-ed) metal lattice materials or mechanical metamaterials. The first part of this work reviews the proposition and formulation of the G-A model and emphasizes that the G-A model is only applicable to low-density lattice materials with strut length-to-diameter ratios greater than 5. The second part evaluates the applicability of the G-A model to AM-ed metal lattice materials and reveals the fundamental disconnections between them. The third part assesses the deformation mechanisms of AM-ed metal lattices in relation to their strut length-to-diameter ratios and identifies that AM-ed metal lattices deform by concurrent bending, stretching, and shear, rather than just stretching or bending considered by the G-A model. Consequently, mechanical property models coupling stretching, bending and shear deformation mechanisms are developed for various lattice materials, which show high congruence with experimental data. The last part discusses new insights obtained from these remedies into the design of strong and stiff metal lattices. In particular, the use of inclined struts should be avoided.

Reuse of waste resources in concrete 3D printing

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Concrete 3D printing is a emerging technology in the manufacturing industry that can construct complex architectures rapidly and at a low cost without the use of formwork, minimize labor involvement, and reduce wastage. Any geometry can be produced by modifying the digital 3D model and controlling the rheological properties of the concrete mix. Due to its versatility, the merging of 3D printing technology and the use of industrial waste materials can play a crucial role in reducing the problems associated with waste recycling and minimizing CO_2 emissions related to cement production process.

In this study, two industrial wastes are employed to develop a cement paste with printable rheological and hardened properties: fly ash (FA) and ground waste glass (GWG). Waste materials were added as pozzolans as substitute for ordinary Portland Cement (PC). The chemical composition, particle size distribution, rheological, and flexural strength were measured.

The results demonstrate that the waste-containing printed specimens could attain strength comparable to the ones without waste replacements, without sacrificing mechanical strength. The reference control mixture had the most substantial reduction in the average flexural strength of casted versus the corresponding 3D printed (66%), compared to those with waste materials incorporated in the following descending order; FA20 (35%), FA10-GWG10 (35%), GWG10 (32%), FA10 (11%), and GWG20 (4%). Hence, the incorporation of waste materials is recommended for cement 3D printing, with the added benefit of helping tackle problems related to recycling industrial waste and to upcycle waste products.

Luminescent 3D printed PLA nanocomposites with enhanced mechanical properties

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Abstract

3D printing has gained tremendous academic and industrial interest owing to its outstanding ability to create complex geometries with reduced material consumption. Several techniques such as Stereolithography (SLA), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Fused Filament Fabrication (FFF), etc. are used to create 3D objects. Despite being a simple process, FFF based 3D printing process has certain limitations. Warping and lack of strength of final 3D printed products are some of the most common challenges in FFF, which restrict the range of polymers suitable for 3D printing. Among the various biopolymers, PLA has been widely explored for FFF-3D printing. PLA is a renewable, biodegradable, thermoplastic biopolymer. 3D printing of functional PLA nanocomposites has garnered a lot of interest. However, the mechanical properties of such 3D-printed functional nanocomposites are often inferior compared to that of conventional melt-processed nanocomposites. Herein we demonstrate an approach to obtain luminescent 3D printed nanocomposites with better mechanical properties. We also describe the thermal, rheological, morphological, fluorescent, and mechanical characteristics of these 3D printed nanocomposites.

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Isolated influence of upward and downward facing surface roughness on fatigue life of laser powder bed fusion Ti-6Al-4V

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Surface roughness is known to be detrimental the fatigue performance of LB-PBF components with as-manufactured surfaces. Surface roughness is linked to the primary processing parameters, feedstock and inclination angle relative to the build plate. It is also understood that downwards facing surfaces (facing towards the build plate) will have higher surface roughness than upwards facing surfaces (facing away from the build plate). This research uses experimental testing to highlight the benefits associated with removing downwards facing surface roughness for fatigue performance. Furthermore, the surface roughness is linked to fatigue performance using the equivalent defect area, thus determining the stress intensity factor. The stress intensity factor derived from surface roughness provided a better prediction for the fatigue life than using applied stress, thus reinforcing the importance of surface roughness to fatigue performance.

Wire Arc Additive Manufacturing of Titanium Alloy

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Robot-assisted wire arc additive manufacturing (WAAM) is a high deposition process, which creates large-scale near-net-shape metallic components. This work investigates the effects of the deposition orientation and the loading rate on the tensile properties of titanium alloy specimens fabricated with WAAM. The specimens were cut from a WAAM-fabricated bulk plate in the longitudinal and transversal orientations and loaded in tension with the loading rates of 0.1–0.5 mm/min. The test results indicates that the tensile strength of 770–829 MPa, the Young's moduli of 80–98 GPa, the fracture strength of 720–803 MPa, the ductility of 14–18%, and the resilience of 26–40 kJ/m^3 were obtained. All these properties were not significantly affected by the deposition orientation and the loading rate (ANOVA, $p > 0.05$). Although the yield strength values of 635–680 MPa were significantly independent from the deposition orientation (ANOVA, $p < 0.05$), they were significantly affected by the loading rate (ANOVA, $p > 0.05$). Fracture mechanism observed in all tested specimens had predominantly brittle appearance. The future efforts will be focused on the understanding of the fatigue behavior and developing post processes to improve the mechanical properties of titanium alloy components fabricated with WAAM process.

Node-reinforced hollow-strut metal lattice materials for higher strength

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Intricate hollow-strut metal lattices are novel cellular materials or metamaterials. However, their hollow nodal regions often lead to premature failure under stress. This study reports a design strategy to substantially improve the strength of hollow-strut metal lattices by applying nodal reinforcement. The proposed nodal reinforcement designs increased the yield strength of hollow-strut cubic Ti-6Al-4V lattices by up to 144% and elastic modulus by up to 113% with a modest 21% increase in density compared to the unreinforced lattices. In addition, a 42% increase in peak strength was observed when compared to solid-strut cubic Ti-6Al-4V lattices of similar density. These properties exceeded the empirical upper limits in the Gibson-Ashby model for cellular metallic materials, thus extending the property envelope. Distinct failure modes were observed for the proposed nodal reinforcement designs. Numerical analysis clarified their role in determining the deformation response.

Directional Recrystallization of Additively Manufactured Ni-base Superalloys

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Metal additive manufacturing processes can create intricate components that are difficult to form with conventional processing methods; however, the as-printed materials often have fine grain structures that result in poor high-temperature creep properties, especially compared to directionally solidified materials. Here, we address this limitation in an exemplary additively manufactured Ni-base superalloy by converting the fine as-printed grain structure to a coarse columnar one via directional recrystallization. The present results demonstrate how directional recrystallization of additively manufactured Ni-base superalloys can achieve large columnar grains, manipulate crystallographic texture to minimize thermal stresses expected in service, and functionally grade the grain structure to selectively enhance fatigue or creep performance in complex net-shaped components.

Strengthening and densification of cold sprayed titanium structures using cost-effective open-to-air Electro-Plastic thermomechanical treatment.

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Porosity and brittleness are the two main challenging drawbacks of the as-Cold Sprayed Additive Manufactured (CSAM) structures. These two inevitable weaknesses become more profound in CSAM high-strength and low-formability alloys such as titanium, nickel and steel. Titanium poses more challenges due to its excessive susceptibility to oxygen beyond ~550ºC, which demands the use of costly inert gases or vacuum post-treatments. In addition, the higher strength and hardness of titanium feedstock powder usually requires higher CSAM particles' velocities i.e. through utilisation of expensive Helium to improve particles adhesion/cohesion and to reduce porosity. Therefore, titanium alloys exhibit higher technological and cost challenges during the CSAM process and the necessary post-treatment. CSIRO patented Cold Spray ZAP™ (CS-ZAP) with in-Situ Electro-Plastic treatment (ISEPT) capability was deployed in post-treating two most commonly used titanium alloys, Commercial Purity (CP) grade 2 and Ti-6Al-4V grade 5. The CS-ZAP constitutes a specially designed rolling process to simultaneously apply electric resistive heating and load at a carefully designed strain rate and current density on the CSAM structures. The CS-ZAP process allowed for Ti to be treated in air. Dynamic recrystallization rapidly transformed cold spray splat structure and at a lower temperature that was estimated to be ~200ºC lower than the reported titanium recrystallization temperature in literature. Significant porosity reduction and improvement in tensile properties were achieved after a few successive ISEPT passes.

The results revealed that two ISEPT passes reduced porosity of as-CSAM CP-Ti from 8% to as low as 0.05% for CP-Ti. The tensile properties significantly improved, and elongation increased from 0.5% in the as-CSAM condition to 18% after ISEPT. Similarly, the ultimate tensile strength (UTS) of CP-Ti increased from 307 MPa to a maximum of 509 MPa. The final CP-Ti microstructure had a refined grain size of 16 µm, with slight 0.06% rise in oxygen content after ISEPT treatments. The CS-ZAP process on the as-CSAM Ti-6Al-4V samples using six ISEPT passes reduced the porosity from 12% to 0.03%. Grade 5 Ti elongation increased from 1.2% to 7.3% with increased UTS from 220 MPa to 1050 MPa. The final Ti-6Al-4V microstructure showed near ultra-fine grains of 1~4 µm, and that oxygen pickup rose from 0.2% in as-CSAM up to 0.35% after the six ISEPT passes. A unique characteristic in the CS-ZAP process was the simultaneous application of electric current and load with generation of electron wind that assists the dislocation motion in material microstructure. The electric resistive heating and its electrons' flow are expected to generate the "Hot-Spots mechanism" and the "Electro-Plastic Effect" (EPF) that cause localized heating effects at the crystallographic imperfections, including dislocations. Dynamically recrystallized CSAM structure of titanium will be discussed.

Innovative zirconia-based material shaped by SLA 3D printing

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Introduction

Today a strong need for high-performance ceramic materials combined with new shaping techniques appears on the market. 3D printing technology of ceramic objects is in strong development as it opens new perspectives.
While ceramic materials are brittle and subject to catastrophic failure that is difficult to predict, ceria-stabilized zirconia-based composites can provide new ceramic materials with a plastic deformation domain before rupture, excellent resistance to processing flaws and a Weibull modulus approaching that of a steel.
In this study, we explored the influence of SLA stereolithography shaping on this new ceria-stabilized zirconia-based material with unique mechanical behavior.

Experimental

Firstly, a slurry compatible with the CERAMAKER process was developed. Then, the specific object of the study was to evolve the influence of the shaping parameters (layer thickness, lasing power, etc.) on the green part quality. Finally, the effect of the sintering temperature on the microstructure and mechanical properties of optimized SLA-printed material was also studied.

Conclusion

Through this study, 3DCERAM has been able to prove that this new material could be shaped by 3D SLA. Different sintering parameters have been studied to optimize densification and material properties. SEM observations show original layer structures and microstructure development attributable to the shaping process.

Increasing electrical anisotropy and current waveform response of soft, flexible 3D printed sensors through material formulation

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Rising interest from the smart electronics industry in 3D printable sensors has been driven by the limitless choice of geometries and rapid prototyping options enabled by the printing process. Moreover, bespoke feedstock materials can be imbued with a variety of specific properties desired in the final product. Specifically, piezoelectric and conductive fillers can be incorporated within a polymer matrix to obtain flexible sensor. However, piezoelectricity must be activated by poling, which consists in applying a potentially dangerous high voltage electrical field. To reduce this risk, we present a polymer-based material that can be printed into soft and flexible sensors that are conductive and contain piezoelectric elements. We investigate several non-poling techniques to understand their effect on the electrical characteristics of the 3D printed parts. It was found that a combination of these techniques leads to significantly higher sensor responses with respect to the untreated parts. In addition, electrical anisotropy was governed through the orientation of 'sea-island' structures induced by the composite formulation and the shear forces generated by the printing process. The results discussed within this study highlight the importance of tuning the composite formulation and applying appropriate non-poling treatments before any piezoelectric sensor is activated under an electric field.

ADDITIVELY MANUFACTURING FROM AL-MG-TI(-SC-ZR) ALLOY WIRES

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Additive manufacturing using Al-5Mg-0.1Ti and Al-5Mg-0.1Ti-0.2Sc-0.1Zr (wt.%) alloy wires and cold metal transfer and electron beam additive manufacturing is studied in this work. It is found that the Sc and Zr addition improves the processability of Al-Mg-Ti alloys by eliminating cracks in the microstructures of additively manufactured products. The Sc and Zr addition also promotes formation of much finer and equiaxed grains in the as-deposited alloys. The grain refinement in the as-deposited Al-Mg-Ti-Sc-Zr alloy samples is attributable to the inoculation effect of primary $Al_3(Sc,Zr,Ti)$ phase, grain growth restriction effect from solute elements, and Zener pinning effect of solid-state, nano-sized precipitates of Al_3Sc. The refined grain size and the presence of nano-sized precipitates lead to higher yield strength of the Al-Mg-Ti-Sc-Ti alloys.

The effect of geometric design and materials on section properties of additively manufactured lattice elements

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Additive manufacturing (AM) technologies such as laser-based powder bed fusion (LB-PBF) facilitate the fabrication of complex lattice structures. However, these structures consistently display dimensional variation between the idealised and as-manufactured specimens. This research proposes a method to characterise the impact of common LB-PBF powders (aluminium and titanium alloys) and geometric design parameters (polygon order, effective diameter and inclination angle) on section properties relevant to stiffness and strength of as-manufactured strut elements. Micro-computed tomography (μCT) will be applied to algorithmically characterise the as-manufactured variation and identify a scale threshold below which additional geometric resolution does not influence the section properties of as-manufactured parts. This methodology provides a robust and algorithmic, design for additive manufacturing (DFAM) tool to characterise the effects of manufacturing and design parameters on the functional response of AM strut elements, as is required for certification and optimisation.

Keywords: Laser-based powder bed fusion, Additive manufacturing, Geometric analysis, Micro-computed tomography, Additive manufacturing defects, Design for additive manufacturing

Synchrotron X-ray Hierarchical Imaging of Phase Transformations during Laser Additive Manufacturing

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Laser Additive Manufacturing (LAM) has the potential to revolutionize traditional manufacturing processes. The pinnacle of LAM is not just to produce complex geometries but also to manipulate microstructures to create functionally graded mechanical properties. Metastable austenitic steels, specifically designed for LAM processes, shines new light on this pathway. Upon manipulating the thermal history (hatches, layer thickness, etc) during the build process, the material shows different phases and grain sizes. Furthermore, the volumetric changes during the layer-wise phase transformation mitigate the high residual stress issue associated with the rapid solidification of LAM. To accurately control the process, an in-depth understanding of the phase-transformation is necessary. Here, a hierarchical and correlative Synchrotron X-ray imaging approach is adopted to establish a well-rounded picture of the material behaviour *in situ*. The approach starts with high-speed synchrotron radiography (40 kHz) using an *in situ* LAM rig. Fast X-ray imaging enables both real and reciprocal space quantification of the laser-matter interaction, including phase evolution during the build process. Post build Diffraction Contrast Tomography (DCT) was implemented to directly visualise the resulting microstructural morphology. Finally, high angular resolution Dark Field X-ray Microscopy (DFXM) was adopted to focus on the grain and sub-grain level structures, spatially resolving strain distribution, lattice misorientation and Geometrically Necessary Dislocations (GNDs) within a single grain in 3D during the phase transformation using *in situ* thermal cycling, revealing the key kinetics for phase transformation control. The results presented here provide new insights into the LAM process with relevance to microstructure control in AM fabricated components, envisioning the pathway to industrialise LAM for wider applications.

Formation of the 1st layer 0° overhang of IN718 by Laser Powder Bed Fusion

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One of the most revolutionary aspects of Laser Powder Bed Fusion (LPBF) is to be able to lift the design constraints from conventional manufacturing. However, as a rule of thumb, any surfaces lower than 45° would need to be redesigned for LPBF or require sacrificial supports in order to complete the build. Moreover, it has been unclear whether it is even possible to print 1st layer 0° overhang and how to optimise the parameters. This research demonstrates that large 1st layer 0° overhangs can be printed with sufficient coverage, which is then proven to be vital to accelerate the transition to the quasi-steady state. With our experimental design, for the first time, the parameter space of laser power, scan speed and hatch spacing for the 1st layer overhang has been simultaneously explored efficiently. Also, some important descriptors concerning the parameter selection are discussed. A high speed thermal camera data is utilised to statistically quantify the parameters selected and the transition to the quasi-steady state.

3D Printing Hierarchical Porous Ceramics

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Multiscale porous ceramics are produced by Direct Ink Writing ceramic pastes. Millimeter scale porosity is created by the printed filaments. 20 micron scale porosity is produced within filaments by adding oil to aqueous suspensions to create pores by particle stabilized emulsions or capillary suspensions. Micron scale porosity is developed by partial sintering. The storage modulus and yield stress of the pastes must be controlled to produce inks suitable for printing by extrusion through the nozzle. Control of the internal filament microstructure (particle stabilised emulsions or capillary suspensions) is possible by controlling the amount of oil, surfactant and dispersant concentration. The objects become strengthened by sintering at high temperature. Formulations have been developed for alumina, ultra-high temperature ceramics and bio-ceramic materials. Complex shaped objects can be printed and sintered into crack free components, but distortion during drying and sintering lead to poor shape and tolerance control. X-ray tomography is used to characterise the internal structure of the printed components. 4-point bend strength measurements demonstrate high strength to density ratio. The filament diameter and spacing influences the bending strength. Many small fracture events within individual filaments give rise to composite like fracture with larger strain to failure than monolithic dense ceramics.

New insights into the melt pool dynamics in the cladding process by an in-situ monitoring approach

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We report a series of deposition experiments with in-situ monitoring to investigate the melt pool formation during laser cladding of Stellite 6. An XIRIS XVC-1000 welding camera with a narrow bandpass filter for 1030 nm laser radiation was used to image the laser spot and the irradiated powder stream during deposition with a shutter speed of 55 frames per second. The experiments investigated the melt pool formation on mild steel and 300M high strength steel substrate materials at processing speeds from 1 to 20 m/min with and without powder deposition. The in-situ melt pool observations reveal a discernible distance between the identified laser spot and melt pool boundary, termed melt pool lag, during laser-substrate interaction. The melt pool lag increases as the processing speed increases at a given incident laser power level. The analysis of results indicates that the melt pool lag is influenced by both deposition conditions and material properties. An analytical calculation was performed to predict the melt pool lag. The identification of the melt pool lag feature enhances the understanding of the fundamental physics of laser cladding and in particular at high speed. The melt pool lag measurements can be used as an indicator of several high speed deposit characteristics. It also provides an insight into improving the powder deposition efficiency during the deposition.

A Comprehensive Study on Meltpool Depth in Laser-Based Powder Bed Fusion of Inconel 718

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One problematic task in the Laser-Based Powder Bed Fusion (LB-PBF) process is the estimation of meltpool depth, which is a function of the process parameters and thermophysical properties of the materials. In this research, the effective factors that drive the meltpool depth such as optical penetration depth, angle of incidence, the ratio of laser power to scan speed, surface properties, and plasma formation are discussed. The model is useful to estimate the meltpool depth for various manufacturing conditions. A proposed methodology is based on the simulation of a set of process parameters to obtain the variation of meltpool depth and temperature, followed by validation with reference to experimental test data. Numerical simulation of the LB-PBF process was performed using the computational scientific tool "Flow3D Version 11.2" to obtain the meltpool features. The simulation data was then developed into a predictive analytical model for meltpool depth and temperature based on the thermophysical powder properties and associated parameters. The novelty and contribution of this research are characterising the fundamental governing factors on meltpool depth and developing an analytical model based on process parameters and powder properties. The predictor model helps to accurately estimate the meltpool depth which is important and has to be sufficient to effectively fuse the powder to the build plate or the previously solidified layers ensuring proper bonding quality. Results showed that the developed analytical model has a high accuracy to predict the meltpool depth. The model is useful to rapidly estimate the optimal process window before setting up the manufacturing tasks and can therefore save on lead-time and cost. This methodology is generally applied to Inconel 718 processing and is generalisable for any powder of interest. The discussions identified how the effective physical factors govern the induced heat versus meltpool depth which can affect the bonding and the quality of the components.

A pilot study on temperature monitoring and morphology of the meltpool in EB-PBF of copper using numerical and analytical models

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In this research, a pilot study on temperature monitoring of Electron Beam Powder Bed Fusion (EB-PBF) of pure copper has been carried out. Two different methods including an analytical model and a numerical simulation tool were tested to estimate the temperature and morphology of the meltpool such as the transition from conduction to keyhole mode for this process. The analytical model was developed based on process parameters (beam power and speed) and thermophysical properties of the material. The heat transfer of copper is substantially higher than for most metals and introduces faster heating and cooling response in the AM process, the analytical heat transfer model was developed for copper and the results were compared well with numerical results. Experimental tests were used to verify both the analytical model and numerical simulations. Results demonstrated that the developed analytical model containing the conduction of the material has great accuracy. Statistical analysis showed both beam power and speed have a significant effect on the width, depth and meltpool temperature for EB-PBF of copper. The proposed model and simulation can be useful to predict the meltpool morphology (conduction and keyhole modes) which drives the bonding quality of the subsequent layer and the overall quality of the printed parts.

Keywords
Additive manufacturing, Electron beam powder bed fusion, Meltpool temperature,
Simulation,
Analytical model

A characteristic time-based heat input model and a thermal simulation strategy for selective laser melting

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Abstract

Goldak heat input model has been commonly used to model the heat source in a selective laser melting (SLM) process. However, it incurs an unpractically high computational cost when simulating building a part with dimensions in centimetres due to the huge scale gap between the component size and the laser spot size. We developed a characteristic time-based heat input (CTI) model and implemented in a finite-element thermal-mechanical model to significantly reduce the process simulation time while satisfactorily predicting the temperature and residual stress state of SLMed parts. This characteristic time-based heat input model speeds up the computation by applying the integrated energy along the scan path over a characteristic heating time, which is defined as the ratio of the axis of the ellipsoidal heat source in the laser scanning direction to the scanning speed. To extend the developed CTI model for simulating larger parts efficiently, we developed a macroscale finite element thermal simulation strategy with a track-scale resolution by combining the CTI model with a currently proposed adaptive mesh re-mapping method. Due to the uniformly distributed power density along the scan direction in the CTI model, the optimized mesh strategy allows one element to capture the temperature solutions over the majority of a scan track except at the two ends. The adaptive mesh re-mapping method is used to map simulated results from a previous scan track model to a current scan track model with a new mesh configuration. This strategy has been implemented for a Ti-6Al-4V part with the dimensions of 20 × 40 × 3 mm^3. The predicted temperature histories agree well with the in-situ measurements at the points in both the printed part and powder bed. Three case studies demonstrate that our strategy can improve computational efficiency between 6 to 30 times.

Additively manufactured hierarchical multiple-principal element alloys with superior properties

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Multiple-principal element (MPE) alloys, also well known as high-entropy alloys (HEA), are a novel class of metallic materials with three or more principal elements having approximately equiatomic concentrations, which open up a new avenue for the design of materials with optimized properties. The severe lattice distortion and sluggish diffusion that are induced by the mixture of multiple elements endow MEA alloys with exceptional structure stability and outstanding mechanical properties. However, the current preparations of MEA alloys rely mainly on the conventional melting or casting methods, imposing enormous limitations to produce samples with complex geometry in terms of cost and efficiency for practical applications. The additive manufacturing (AM) techniques have been recognized as a transformative technology across multiple industries. Based on their advantages of net-shape manufacturing capability and design freedom, it is feasible to harvest parts with complex geometries directly from computer-aided design (CAD) models. In this study, we applied selective laser melting (SLM) technique, which is one of the most popular AM techniques, to prepare near-fully dense MEA alloys. The as-built samples exhibit a hierarchical nanostructure, including melt pools, columnar grains, dislocations, and sub-micron cellular structures. An outstanding combination of high strength and excellent ductility compared to those fabricated by conventional methods was achieved in the as-built samples. The detailed deformation behaviour, strengthening mechanism, thermal stability, and tunable hydrogen resistance will be discussed in this talk.

The characterisation of a novel irregularly shaped Ta and spherical Ti powder blend on the powder spreading process in powder bed fusion systems

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Assessing the quality of the powder spreading process is essential to ensure that homogeneous, highly packed, and defect-free layers can be produced in powder bed fusion systems. Current flowability techniques like the Hall and Carney flowmeter are inadequate to determine whether powders like irregularly shaped, very fine, and cohesive powders can flow and spread well in powder bed systems. This study presents a novel tool called the Universal Powder Bed (UPB) designed to mimic the powder spreading process of an electron beam melting machine. A novel bimodal powder blend comprised of Ti and Ta with two contrasting shapes, sizes and densities is employed with the UPB. In this work, the effects of layer thickness and rake speed against three spreadability measures namely, the area fraction of powders, the surface roughness and the composition of the powder bed are examined. The metrics revealed that by manipulating the spreading parameters (increasing layer thickness and decreasing rake speed), acceptable levels of spreadability can be achieved. However, the segregation of Ta towards the bottom of the plate was still prevalent at all rake speeds.

Ceramic 3D Printing:
Technology and Applications Presented by a Market Leader

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Thanks to its unique properties, ceramics have always been considered a powerful material that play a decisive role in many innovative technological solutions. The process of 3D printing ceramic parts begins, when other materials reach their limits. From industry to medicine and beyond, the outstanding material properties of high-performance ceramics open up entirely new possibilities for applications with extreme demands.

With its ultra-precise Lithography-based Ceramic Manufacturing technology (LCM), Lithoz truly changed the game by being the first company to 3D print advanced ceramic parts with equal properties to those produced via traditional methods. This technology made it possible to combine the excellent properties of ceramics with the most complex geometries and miniaturized structures with absolute accuracy. This allows the creation of 3D printed solutions that were previously considered unattainable.

At the end of this presentation, attendees will gain exclusive insight from a market leader into the latest advances in the world of ceramic 3D printing, discover the unique and powerful benefits of this technology, and learn about new applications and ideas for innovation in manufacturing.

Effect of annealing treatment on mechanical behaviour and microstructural evolution of additively manufactured, titanium modified Al 2024 alloy

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The current study elucidates the effect of annealing temperature on mechanical properties such as strength, hardness, and microstructural evolution of laser powder bed fabricated, Ti modified Al 2024 alloy. Al 2024 is a precipitation hardened Cu, and Mg based aluminum alloy that finds widespread applications in various industries. The titanium acts as a grain refining agent for the aluminum alloys and reduces the solidification cracking in aluminum alloys. The addition of titanium in additively manufactured Al 2024 alloy can lead to the formation of ultrafine grained (UFG) structure with average grain size of 0.4 µm. The formation of UFG structure also improves the mechanical properties of the Al 2024 alloy. The Al 2024 alloy has Al_2Cu, and Al_2CuMg as its main strengthening precipitates. These precipitates are evolved during heat treatment process and are responsible for the high strength observed in the Al 2024 alloy. Hence, optimal evolution of these precipitate is very essential for producing high strength, additively manufactured Al 2024 alloy. The mechanical properties were evaluated using compression, and hardness test. The microstructural behavior and phase evolution were analyzed using a variety of techniques such as x-ray diffraction, scanning electron microscopy, and tunneling electron microscopy.

Latest Developments in the Use of HIP for Additive Manufacturing

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Abstract

Hot Isostatic Pressing (HIP) has been used to remove shrinkage porosity and internal defects in cast products for many years, predominantly to improve mechanical properties and fatigue resistance. Recently, there is increasing focus on the Additive Manufacturing (AM) process for demanding applications where internal defects and porosity are a concern.

Post processing using HIP is now being used to shorten process times using a combination of HIP, Solution Heat Treatment (SHT) and Aging to automate and make processes leaner, leading to cost reductions and productivity increases whilst reducing scatter in material properties.

This paper will present solutions to many issues with quality assurance seen by OEMs for critical components, along with cost savings realised though speeding up of production lines.

Keywords: Additive Manufacturing, AM Market, Heat Treatment, Aging, HIP, Hot Isostatic Pressing, Mechanical Properties, Reduced Cycle Time, Combined HIP and Heat Treatment, Post processing, Lean Manufacturing

Challenges in powder production for Additive Manufacturing

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In recent years an upsurge in interest for fine, spherical, metallic powders can be observed. This is mainly driven by an increased demand in powders for Additive Manufacturing and coating processes including selective laser melting and laser metal deposition, cold spraying and other thermal spray techniques. Properties of a powder feedstock material are a major influencing factor for the quality and deposition efficiency of the produced part.

In this overview presentation the different production methods for metallic powders with a focus on the atomizing processes, will be discussed. It will be explained how the atomizing technique, the atomizing medium (e.g. water vs. gas), the alloy and its inherent material properties influence the achievable particle size and morphology of the resultant powder. Another aspect will lie on the economy of powder production and how the costs of powder feedstock can be reduced by changing the powder specification without sacrificing the quality of the final product.

Stabilised mechanical properties in Ni-based Hastelloy C276 alloy by wire arc additive manufacturing through interlayer control

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Abstract

In this study, a Ni-based Hastelloy C276 alloy was prepared using cold metal transfer (CMT)-based wire arc additive manufacturing (WAAM) under different heat inputs with a zig-zag deposition path, integrated with active cooling and interlayer temperature control. Analogous mechanical properties were obtained for the fabricated alloys under different heat inputs (276, 368 and 553 J/mm) through effective interlayer temperature control. Nevertheless, the lower heat input appears to slightly refine the microstructure and decrease the mechanical anisotropy of manufactured alloys, which is ascribed to combined effects of the manipulated bulk texture, refined dendrite arm spacing and reduced chemical segregation under lower heat input. Despite the variations of geometrically necessary dislocation (GND) densities with heat inputs, no significant change in the average total dislocation density (TDD) in the microstructure in all samples as suggested by the peak profile analysis of Synchrotron X-ray diffraction data. Moreover, all as-fabricated alloys present a typical strong fibre-type (200) crystallographic bulk texture from Neutron diffraction, while such texture was relatively weaker in the lowest heat input condition. This work provides a reliable approach with a large operation window for stable additive manufacturing of Hastelloy C276 alloy, and innovatively presents rationales of stabilised properties based on the obtained insights into microstructure and bulk texture developments in a wide observation range by various techniques.

Keywords: Hastelloy C276, Neutron and Synchrotron X-ray diffraction, interlayer temperature control, heat inputs

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Defect Categories, Assessment and Mitigation in Metal Additive Manufacturing

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Presence of process-induced defects are most detrimental to the fatigue life of additively manufactured (AM) metallic materials, and is one of the main causes of the wide scatter of the mechanical properties, and poor repeatability. It is essential to appropriately categorize processed-induced defects based on the formation mechanisms to provide a better understanding of the defect influence. This presentation elaborates a sophisticate approach to quantify a defect, including size and location, both having significant effects to the fatigue life under a given stress level. It also introduces strategies and measures for a better mitigation of process-induced defects to ensure structural integrity of AM components.

In-situ Microstructure Engineering During Additive Manufacturing

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Targeted control of the microstructural constituents, i.e., ‘microstructure engineering’ is a key approach to enhance the properties of metallic materials. This can be done during fabrication (in-situ) or upon a post-process treatment (ex-situ). Strain and heat are the two major tools used for microstructure control in metals to create desirable microstructures and properties in most conventional processing routes. During additive manufacturing (AM), metallic materials go through multiple cycles of heating/cooling and thermo-plastic straining. This means AM cycles can be engineered to induce a synergistic combination of strain and heat. In this regard, the current study reveals that how one can induce desired interfaces, precipitates, and clustering of alloying elements of interest, in-situ, during printing through harnessing the thermal hysteresis in AM. This includes grain boundary engineering in 316L stainless steel through introducing Σ3 boundaries, copper cluster hardening in 17-4 precipitation hardening steel, and precipitation of fine γ’ in Inc738 nickel-based superalloy. Such ‘dynamic’ microstructural refinements eliminate the need for time-consuming and expensive post-process treatments, leading to advanced mechanical and corrosion properties in the as-built state.

Tailored heat treatment of additively manufactured metals

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Metal additive manufacturing (MAM) has in the last decade undergone a transition from being a rapid prototyping technology to full-scale industrial implementation. Among the available MAM technologies, laser powder-bed fusion (L-PBF) is one of the most widely used. The rapid movement and high energy density of the laser during L-PBF results in a rapidly moving, very small pool of molten metal. This in turn creates steep thermal gradients and rapid solidification rates and the layer-by-layer nature of the process entails that a cycling thermal profile arise. This unique thermal history of the L-PBF process leads to unconventional microstructures in otherwise conventional alloy systems such as martensite in Ti-6Al-4V or a cellular microstructure in austenitic stainless steel. These unconventional microstructures also result in unconventional properties.
The present contribution explores these unconventional properties in a range of alloy systems and investigates how heat treatments influence the microstructural features and resulting properties. The heat treatments need to be tailored to the unconventional microstructure of LPBF materials. To this end understanding how the LPBF features evolve as a function of thermal exposure is pivotal. Herein, advanced microscopy techniques (LOM, SEM and TEM) as well as mechanical testing are applied.

Heat-tolerant and crack-free additively manufactured Ce modified Al6061 with exceptional ductility

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Abstract

A characteristic of laser powder bed fusion (LPBF) is rapid solidification, which presents both challenges (e.g., solidification cracking for alloys such as Al6061) and opportunities (e.g., new avenues for microstructure design to achieve attractive mechanical properties) for researchers. With that in mind, this research overcomes the challenge of solidification cracking and creates an opportunity for highly ductile and crack-free Al6061 *in-situ* alloyed with 1-4 wt.% Ce.

Alloying Al6061 with 3 wt.% Ce achieves crack-free fabrication due to solidification pathway reaching 0.9 solid mass fraction 14 °C below solidification onset. Moreover, alloys containing 3 or 4 wt.% Ce develop continuous τ_1-CeAlSi grain boundary eutectic, further inhibiting solidification cracking. Hot isostatic pressing converts τ_1-CeAlSi eutectic to nanoscale discrete particles resulting in a ductility and tensile strength of 18.3% and 153±6 MPa at room temperature and 32.5% and 89±6 MPa at 200 °C, respectively. Such room temperature ductility is much higher than cast Al-Ce-Si alloys and is attributed to the dispersion of nanoscale τ_1-CeAlSi precipitates within grains and presence of large columnar α-Al grains. Thus, a simple and effective pathway for LPBF fabrication of heat-tolerant and ductile Al-alloys suitable for room temperature and high temperature applications is uncovered.

Functional Grading of Strut Elements in Additively Manufactured Lattice Structures

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Additive manufacturing enables fabrication of intricate geometries such as lattice structures. These typically indeterminate structures behave as meta-materials and can be designed to elicit specific mechanical properties, by controlling a number of geometric and topological variables. Traditionally, as an expedient design strategy these structures are comprised of constant cross-section strut elements leading to sub-optimal structural efficiency. To functionally grade strut elements requires an understanding of the structural optimisation methods for a systematic variable cross-section optimisation. This research overcomes the uncertainty in functional strut cross-section optimisation by creation of a hybrid numerical model. This provides a systematic, procedural method for mass minimisation of lattices, by continuously varying the strut element cross-section along their length in response to an arbitrary load condition. This presentation discusses the method developed for functional grading of strut elements and presents the results of destructive testing of AlSi10Mg graded strut lattices produced by laser-based powder bed fusion.

Keywords: Additive manufacturing, laser-based powder bed fusion, Graded strut lattice structures, hybrid numerical model, optimisation of indeterminate structures

Laser additively manufacturing of steels

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Heating and cooling dramatically change the microstructure and then properties of steels. This make difficulty for the quality control of steel additive manufacturing (AM) due to the complicated thermal history of AM. Even in the simplest case, AM of 316 stainless steel only involves precipitation of δ-ferrite from liquid and δ to γ transition, the coarse columnar structure causes anisotropic properties. AM of H13 tool steel leads to the formation of elongated, high-carbon retained γ films between the laths of martensite resulted from the rapid solidification and solute segregation. Such γ-film is responsible for the high brittleness of as AM-built H13 steel. To overcome this problem, we have identified TiN as an effective inoculant for steel AM based on crystallographic calculation. 0.5wt.% addition of TiN nanoparticles can not only lead to elimination of the property anisotropy, but also simultaneously increase strength (tensile strength of 2051 ± 48 MPa) and ductility (elongation of 7.4 ± 0.7%) of the SLM-fabricated H13 steel. However, AM of 4340 steel produces equiaxed grains with isotropic properties, which is even compatible with forged steel.

Interpretable prediction approach for exploring process window of additive manufacturing

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Forecasting the build quality of additively manufactured (AM) parts is important to optimization of the complicated manufacturing process. Because the build quality is strongly influenced by a large number of process parameters/variables, exhaustive trial and error searches for the optimum settings are time and cost intensive. In this work, we propose a new paradigm of data-driven prediction approach based on Gaussian process regression (GPR) for laser powder bed fusion (LPBF), using AlSi10Mg as example, to enable the optimization of the process window. Our results reveal that the approach can identify a new and much larger optimized LPBF processing window for fabricating fully dense AlSi10Mg samples than was reported before, with superior mechanical properties. Meanwhile, the hyperparameters in the GPR kernel enable the prediction model can be interpreted to help establish the process-structure-property relationship of LPBF AlSi10Mg and provide guidance for tailoring the mechanical properties. The optimization and prediction process approach established in this study can be applied to other AM techniques and materials to gain a better understanding of the influence of process parameters and intrinsic structure on mechanical performance and to uncover even larger process windows with previously unattainable mechanical properties.

Keywords: Additive manufacturing, Interpretable process optimization, Gaussian process regression

Tungsten doping enhances the mechanical properties of $FeCr_2V$-based medium entropy alloy revealed by experiments and calculations

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The medium entropy alloys (MEAs) composed of high-melting-point, low-activation elements often demonstrate favorable mechanical properties and reduced activation required for nuclear applications. In this work, novel low activation MEAs of $FeCr_2V$ and $FeCr_2VW_{0.1}$ as potential nuclear structural materials have been developed. Thermodynamic calculation was used to guide the MEA design. The materials were fabricated using arc melting and their microstructure and mechanical properties were investigated. The results show that the developed MEAs are characterized by a dual-phase microstructure consisting of both body-centred-cubic (BCC) phases. The as-fabricated $FeCr_2VW_{0.1}$ exhibits improved hardness (average nano-hardness 9.6 GPa) compared with $FeCr_2V$ (7.4 GPa), owing to the enhanced solid solution strengthening (SSS) and precipitation strengthening (PS). Meanwhile, after doping with W, the compressive ultimate strength and yield strength of MEAs increased by about 11% and 10.5%, respectively. Being quantitatively consistent with the experimental results, the first-principles calculations based on the density functional theory (DFT) and the theoretical strengthening calculations confirmed that the W doping into $FeCr_2V$ based MEA significantly enhanced the SSS and PS in the studied alloy. The results provide insights that are useful for future development and microstructural engineering of these novel MEAs.

Keywords: Medium entropy alloys (MEAs); Synchrotron XRD; Microstructure; Mechanical properties; Strengthening mechanisms.

Fabrication of bulk-wall Inconel 625 alloy components using wire arc additive manufacturing

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In this study, Inconel 625 bulk-wall structures were fabricated by wire arc additive manufacturing (WAMM) with three heat inputs (276 J/mm, 552 J/mm, and 828 J/mm) and active interpass cooling. The macrostructure, microstructure, and mechanical properties of the produced components by CMT were investigated. The results showed that the lowest heat input of 276 J/mm in this work induced a better surface finish, which, in turn, resulted in fewer voids in overlapping areas of the bulk-wall structure. Moreover, dendrite arm spacing was decreased and precipitates appeared to be lessened, which contributed to the enhanced mechanical properties. In comparison, with increasing heat input, more voids and precipitation occurred, in particular, adjacent to the overlaps, resulting in the dedicated mechanical properties. This work provides an insight into understanding the microstructure evolution and mechanical properties under different heat inputs in the fabrication of bulk-wall structures for Inconel 625 Ni alloy by WAAM.

3D Printing of Electron/Ion Fluxes Dual-Gradient Anode for Dendrite-free Zinc Batteries

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Three-dimensional (3D) porous Zn metal anodes have aroused widespread interest in Zn ion batteries (ZIBs). Nevertheless, the notorious “top-growth” dendrite caused by the intrinsic top-concentrated ions and randomly-distributed electrons may ultimately trigger a cell failure. Herein, for the first time, an electron/ion fluxes dual-gradient 3D porous Zn anode is elaborated for dendrite-free ZIBs by adopting 3D printing technology. The 3D-printed Zn anode with layer-by-layer bottom-up attenuating Ag nanoparticles (3DP-BU@Zn) establishes dual-gradient electron/ion fluxes, i.e., an internal bottom-up gradient electron flux created by bottom-rich conductive Ag nanoparticles, and a gradient ion flux resulting from zincophilic Ag nanoparticles which pump ions toward the bottom. Meanwhile, the 3D printing technology enabled hierarchical porous structure and continuously conducting network endow unimpeded electron transfer and ion diffusion among the electrode, dominating a bottompreferential Zn deposition behavior. As a result, the 3DP-BU@Zn symmetrical cell affords highly reversible Zn plating/stripping with an extremely small voltage hysteresis of 17.7 mV and a superior lifespan over 630 hours at 1 mA cm^{-2} and 1 mAh cm^{-2}. Meanwhile, the 3DP-BU@Zn//VO2 full cell exhibits remarkable cyclic stability over 500 cycles. This unique dual-gradient strategy sheds light on the roadmap for the next-generation safe and durable Zn metal batteries.

Titanium Cold Spray of WAAM Components for Corrosion Protection in Naval Applications

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The high deposition rate (+10 kg/hour) of Wire Arc Additive Manufacturing (WAAM) and cold spray process has made these technologies highly promising for large scale commercial production of corrosion resistant naval products. In this study, commercial purity (CP) Ti was cold spray deposited on low cost WAAM mild steel substrate for corrosion protection. Microstructure and mechanical properties of the substrate and coating were investigated. Successful deposition of CP Ti on WAAM substrate was achieved via a developed digital twin for cold spray process considerably reducing laboratory experimentation. Results revealed that vacuum heat treatment of the CP Ti coated WAAM led to full protection of substrate through elimination of open pores in cold spray Ti coating. The optimised conditions developed in this study are highly promising for corrosion protection of large naval components manufactured from steel.

Real-time autonomous control of Additive Manufacturing processes in the Industry 4.0 era

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The high-value nature of parts made using additive manufacturing (AM) makes it prohibitive to scrap these parts on the basis of manufacturing defects. Such costs may be avoided, however, if the defects are prevented by allowing the AM process to drive itself along an optimal path in much the same way some road vehicles negotiate their way autonomously. Advances in technologies such as machine learning and artificial intelligence are now bringing such possibilities closer. They can assist with selecting the optimal process routine for a given part on a given machine and diagnostically control the build process in real-time or near-real-time. Such technologies that are capable of handling a relatively broad bandwidth of likelihoods are indispensable for the control of AM. This is because of the extensive diversity in AM parts resulting from its customisation value proposition and the numerous ways in which a process may deviate from its optimal path. These technologies would depend on Industry 4.0 concepts - such as connected sensors and actuators via the digital twin mechanism for effective analytical control. In this talk, we consider the status quo of the various technical elements that must be combined to implement autonomous AM successfully and highlight the associated opportunities and challenges.

Hybrid modelling of the
Wire Arc Additive Manufacturing Process

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Numerical modelling of wire arc additive manufacturing (WAAM) is applied, for example, to investigate complex physical phenomena that are difficult to observe experimentally. The multiscale nature of WAAM, with millimetre-scale arc and melt pool and part dimensions up to metres, requires the adoption of hybrid approaches for a comprehensive picture of the process to be obtained.

We have developed a hybrid numerical model to simulate interactions between the arc, metal droplets, melt pool and substrate. The model links two distinct fluid modelling approaches: magneto-hydrodynamics (MHD) based on the finite volume method and smoothed particle hydrodynamics (SPH). MHD simulation of the arc and its interactions with the substrate predicts the steady-state heat flux from the arc and droplets, which provides input data for the SPH domain. SPH is then used to simulate the time-dependent multilayer deposition along various welding paths, including heat transfer and flow in the melt pool.

The model has been validated by comparing the predicted melt-pool profile with measurements of WAAM based on metal–inert-gas welding. The hybrid approach provides a detailed picture of the heat and mass transfer in the arc plasma, melt pool and substrate, and can be applied to the multilayer deposition of complex parts.

Bioprinting of Soft tissues using bioinks derived from Ecologically-destructive tunicates

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Urochordates are the closest invertebrate relative to humans and commonly referred to as tunicates, a name ascribed to their leathery outer “tunic”. The tunic is the outer covering of the organism which functions as the exoskeleton and is rich in carbohydrates and proteins. Invasive or fouling tunicates pose a great threat to the indigenous marine ecosystem and governments spend several hundred thousand dollars for tunicate management, considering the huge adverse economic impact it has on the shipping and fishing industries. In this work, the environmentally destructive colonizing tunicate species of Polyclinum constellatum and Substantia nigra were successfully identified in the coast of Abu Dhabi and methods of sustainably using it as wound-dressing materials, decellularized extra-cellular matrix (dECM) scaffolds for tissue engineering applications and bioinks for bioprinting of tissue constructs for regenerative medicine are demonstrated. Both dECM scaffolds and bioprinted dECM-based tissue constructs show enhanced metabolic activity and cell proliferation over time. Several bioinks were then prepared and optimized for bioprinting of human Mesenchymal Stem Cells (hMSCs) and human Neural Stem Cells (hNSCs). Successful post-bioprinting differentiation of hMSCs into chondrogenic and osteogenic tissues and hNSCs to peripheral neural tissue were achieved.

Beyond global energy density for additive manufacturing: machine learning for modelling and optimizing process parameters

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Direct energy deposition (DED) additive manufacturing (AM) has numerous process parameters that lead to significant variation in the success and quality of the manufactured product. The input parameter of ‘global energy distribution’ (GED) is used throughout the literature to describe the input energy onto the surface of a build due to the combination of laser power, laser scanning speed and laser spot size. This paper identifies more accurate modelling using machine learning for the GED constituent process parameters and their influence on the responses of manufacturing layer height, relative density and grain size on the build. An experimentally efficient method is described to measure the responses and produce accurate models. These models show why reproducibility is difficult when considering GED singularly, as each of the constituent parameters influence these individual responses to varying magnitudes. The methodology presented should aid industrial uses with resource efficient process parameter response modelling with application in optimization and should be expandable to further parameters and responses.

A Hybrid Multiscale Model of Wire-Arc Additive Manufacturing and Steps toward a Digital Twin

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Computational modelling of metal additive manufacturing (AM) plays a vital role in process development, for example, by assisting in selecting process parameters and reducing defects. Moreover, reliable computational models can play an important role in process certification and part qualification and serve as critical elements of digital twins.

After providing an overview of metal AM processes, including the rationale for modelling, I will focus on the modelling of wire-arc AM. As with all metal AM variants, wire-arc AM is a multiscale process, with dimensions ranging from hundreds of micrometres (metal microstructure) to millimetres (the arc and melt pool) up to metres (the part size). To address this challenge, we are developing hybrid multiscale models. For example, we are using a magnetohydrodynamic (combined computational fluid dynamic and electromagnetic) model of the arc and wire to provide the heat flux to the substrate and a finite element model to predict the temperature and residual stress distribution in the build.

Finally, I will consider the steps to develop a digital twin that supervises the wire-AM process based on such computational models. These include developing surrogate models that can run in real-time and integrating the models with sensors and control systems.

Polymer/metal composite filaments for fused filament fabrication (FFF)

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Fused filament fabrication (FFF) is a widely used additive manufacturing (AM) technique capable of printing a variety of materials, including polymers, ceramics, and metals. In this study, we investigated the viability of FFF for printing titanium-based particle-reinforced polylactic acid (PLA) composites. Polymer-metal composite filaments were made by melt extrusion of commercially available PLA and recycled Ti alloy powder from powder bed fusion processes, mainly electron beam melting (EBM). The composite filament was then printed using a prosumer FFF equipment. The analysis of the composite filaments, conducted by scanning electron microscopy (SEM) and X-ray energy dispersive spectroscopy (EDS), showed a uniform distribution of the metal powder in PLA. The printing parameters were optimised for the composite filaments containing 20 wt% of metal. The mechanical properties of the 3D printed samples were improved by the addition of metal particles, specifically in terms of stiffness and microhardness. These results suggest that FFF can be used to create high-performance PLA composite parts for various applications, with the potential for tailoring product properties depending on consumer needs. Furthermore, a new perspective has been proposed to promote the effective use of recycled metal powders from other AM processes in FFF to valorize waste powders and reduce the environmental impact of 3D printing.

Process design and refinement of high-speed laser directed energy deposition through fluid dynamics and statistical modelling.

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Recently developed laser additive manufacturing (AM) technologies, such as high-speed processes with large deposition rates (e.g. EHLA, HSLC), overcome some problems inherent in earlier AM technologies. Despite the increasing application of high-speed processes in industrial settings, the understanding of the interplay of physical phenomena that enable their capabilities is lacking. Developing a deep understanding of this interplay will guide design of new ultra-efficient processes. To develop our understanding of the physical processes involved, multi-scale-multi-physics modelling approaches must be developed to elucidate the interactions of different phenomena and to map theory to carefully controlled, matched experimental conditions via numerical modelling. To this end, we present an analysis of the high-speed directed energy deposition (HS-DED) processes using a combination of fluid dynamics and statistical modelling to understand these processes from a numerical-theoretical viewpoint and begin to map out the importance of certain features of the physical processes and design of the components that lead to their peculiar advantages. The example of a HS-DED process with conical powder source and coaxial heat source, a common process design, when operated around the substrate melting threshold is explored. We focus on observable correlates of melting through high-framerate process monitoring using the incident laser light as illumination. This monitoring setup enables us to view the relationship between the laser spot and the molten pool features over time. We observe a lag of the molten pool leading edge that increases non-linearly with the speed of the process. Fluid dynamics simulations shed light on the sensitivity of this melting delay to various features of the material and process. The melting delay is sensitive to both the dynamics of the process, i.e. the substrate temperature distribution and heat accumulation, as well as material parameters, i.e. the laser absorptance of the solid phase and ability of the material to dissipate heat via the thermal conductivity. The implications of this phenomenon for process design and recommendations for parameter optimization are discussed.

Defect detection by multi-axis infrared process monitoring of Laser Directed Energy Deposition

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The proliferation of metal-based additive manufacturing technologies in recent years has provided for an increase in applications to high-value industry. In particular, Laser beam Directed Energy Deposition (DED-LB) is growing in prevalence due to its capacity for cladding, repair, and three-dimensional fabrication. However, the viability of manufactured parts is difficult to assess prior to completion, and parts must be extensively inspected post-production to ensure conformance. In-situ monitoring provides an avenue to assess the quality of printed parts throughout manufacture, enabling early detections of defects and abnormalities.

We report a new monitoring system combining three infrared cameras along different optical axes, capable of monitoring melt pool geometry and vertical displacement throughout deposition. An intersecting, thin-walled geometry is used to demonstrate the capability of the system to identify the formation of structural features and defects from in-situ monitoring data at early stages of the build. The detection of porosity in narrow-angle samples is confirmed via micro-CT, and it is shown that filleted tool paths can create depletion zones at wall junctions, leading to extensive porosity. The presented methodology demonstrates the value of multi-axis monitoring for identifying both defects and structural features, providing an advancement towards automated detection and alert systems in DED-LB.

Prediction of Mechanical Properties from the Microstructures of Additively Manufactured Parts

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The mechanical properties of additively manufactured (AM) parts are of critical importance in determining their suitability for their intended application. Due to the spatial variation in the microstructure of AM parts caused by local cooling rates, AM parts can have anisotropic, location-specific mechanical properties, which cannot be measured efficiently with physical testing. This motivates the need for the prediction of mechanical properties using computational homogenization (CH). CH is a mathematical technique that allows for the calculation of mechanical properties and associated quantities. We implement this technique for laser powder bed fusion (LBPF) AlSi10Mg parts and show that the predictions agree with the stress-strain curves obtained via mechanical testing. These results demonstrate the accuracy and efficiency of CH for AM parts allowing for: a reduction in the amount of destructive and expensive physical testing required for qualification and certification; the completion of a missing link in the process-structure-property-performance relationship in the Integrated Computational Materials Engineering (ICME) paradigm; and faster and more efficient builds.

An oxygen-stabilized face-centred cubic phase with superior mechanical properties in additively manufactured Ti-6Al-4V

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The existence of a face-centred cubic (FCC) titanium (Ti) phase in Ti alloys remains under debate over the past decades. In general, Ti has high chemical affinity with interstitials such as oxygen, leading to the formation of intermetallic compounds and dramatically diminishing ductility. Here, we demonstrate that interstitial oxygen can be incorporated into a Ti-6Al-4V alloy to improve its mechanical properties through the formation of an oxygen-containing FCC solid solution phase. This is achieved via selective laser melting, where the combination of high thermal stresses and thermal gradients facilitates a new phase transformation. Electron microscopy, atom probe tomography and density functional theory were used to reveal the crystallography (Fig. 1a) and chemical composition (Fig. 1b) of the new FCC phase. Our mechanical testings revealed that the introduction of the FCC phase dramatically enhances both the strength and ductility of the material (Fig. 1c).

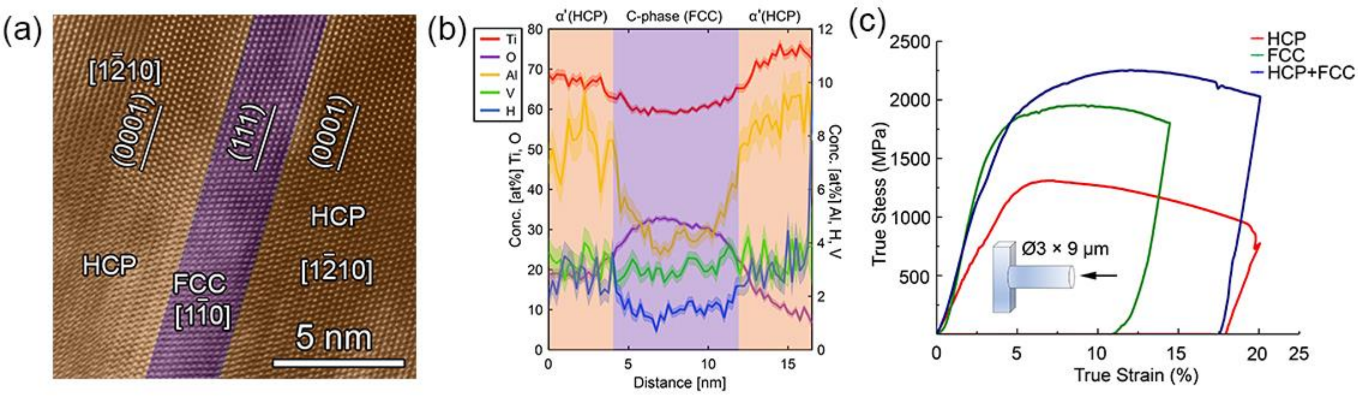

Figure 1. (a) Atomic-resolution image taken from a dual-phase region. (b) Atom probe tomography result revealing the O rich nature of the FCC phase. (c) In-situ micro-pillar compression tests.

Microstructure Modelling and Virtual Testing of Additive Manufactured Haynes®282 for Predictions of Homogenized Anisotropic Elastic Properties

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Additive manufacturing (AM) is usually employed to produce components with complex geometry. Microstructures that result from the AM process often leads to anisotropic mechanical properties of the components. In this study the Ni-based superalloy Haynes®282 is analysed. It has been shown that the microstructure of this polycrystalline material can, in the AM process, be tailored to obtain different grain morphology distributions and crystallographic textures. These are essential factors that determine mechanical properties. In this work, microstructures are modelled to mimic the experimental Haynes®282 microstructures and by utilizing the crystal elasticity finite element method (CEFEM) macroscopic elastic properties are predicted. 2D electron beam scatter diffraction (EBSD) data will be used as input to the numerical model in terms of grain crystallographic morphology and texture. Further, macroscopic tensile tests are used for calibration and validation of the modelled elastic properties. The applied method can be used to predict macroscopic homogenized anisotropic elastic stiffness matrix and local stresses in arbitrary microstructures when exposed to external loading conditions. Preliminary results show good correlation with experimental results which indicate the potential of this method as a tool when selecting AM process parameters for a given component.

Electron beam powder bed fusion of binary Ni-Ti shape memory alloys – On the impact of TiC on functional properties

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Shape memory alloys (SMA), such as Ni-Ti, gain a lot of attention since they are known as promising candidate materials for actuation and damping applications. Whereas thermomechanical processing widened potential applications of these alloys in the last decades, additive manufacturing (AM) processes are still limited. However, the possibility to process near-net shaped functional materials still motivates recent research in the field of AM. Especially the characterization of microstructural and functional properties in correlation with process parameters are in focus. The present study focuses on the impact of an increased carbon content in a Ni-Ti SMA processed via electron beam powder bed fusion. The powder has been processed via vacuum induction melting gas atomization (VIGA). The impact of the chemical composition on the functional properties is discussed in view of chemical and microstructural findings. The results reveal a high reversibility as well as excellent cyclic stability of the superelastic material properties.

Additive Manufacturing of Ti-Ta based High-Temperature Shape Memory Alloys – Microstructure and Functional Properties

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Shape memory alloys (SMAs) are promising candidate materials for actuators and damping devices. Among the numerous SMA candidates proposed so far, binary Ti-Ta alloys received considerable attention for applications above 100 °C due to their relatively high martensite start temperature (M_s) combined with excellent workability and transformation strains in polycrystalline state of up to ~4%. This system is also able to overcome its main drawback, i.e. rapid cyclic functional degradation attributed primarily to ω-phase formation, by alloying with third elements such as Al. However, the fabrication via conventional processing routes is still time-consuming and cost-intensive, since the realization of a homogeneous distribution of the constituents is highly challenging due to the differences in the melting points and densities of the alloying elements. Recently, additive manufacturing (AM) came into focus as a new processing route, being capable to fabricate refractory titanium alloys.

In this work, we reveal for the first time that fully dense Ti-Ta based high temperature (HT)-SMA structures with a high degree in chemical homogeneity can be obtained by powder-based AM techniques, i.e. electron (PBF-EB/M) and laser beam powder bed fusion (PBF-LB/M) as well as direct energy deposition (DED). These (HT)-SMA structures are obtained using novel pre-alloyed powder feedstock material. Detailed microstructure analysis has been conducted to shed light on the microstructural evolution along the whole process chain from feedstock material to additively manufactured bulk material. Furthermore, interrelationships between (process-induced) microstructure, martensitic transformation behavior and functional properties have been elaborated.

Rapid Achieving Ultra-high Strength in Ti-3Al-8V-6Cr-4Mo-4Zr Alloy Processed by Directed Energy Deposition

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Abstract

In this paper, as-built Ti-3Al-8V-6Cr-4Mo-4Zr (Beta C) processed by direct laser deposition (DLD) and post-DLD peak aged samples were analysed, and microstructure evolution and mechanical properties were studied in details. As-built samples show a fully β phase microstructure with a high ductility (total elongation of 23%) but undesired strength (yield strength of 880MPa). Intragranular α precipitates distributed inside the matrix β grains and discontinuous grain boundary α can be detected after direct ageing. Ultimate tensile stress of 1510MPa and yield stress of 1420 MPa were obtained for peak-aged Beta C samples with more noticeable 600 MPa increase compared to those of as-built samples. The further detailed characterization revealed that the size and volume fraction of α phases could be attributed to strength reinforcement. There are the viability and potential as well as production benefits of 3D printing of high strength Beta Ti alloy such as Beta C components by using the DLD process. To achieve a similar ageing response and tensile behavior, conventionally-manufactured Ti-3Al-8V-6Cr-4Mo-4Zr would require cold-working prior to ageing. The effect of carbon additions on the ageing response of the alloys were investigated which showing ageing behavior was fundamentally changed with the C addition.

Keywords: Ti-3Al-8V-6Cr-4Mo-4Zr, microstructure, mechanical properties, α precipitates, strength enhancement

Plasma-treated and bio-functional porous scaffolds as mesenchymal stem cell expansion and carrier platforms

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Cell-instructive, functionally tailorable, high surface area-to-volume porous scaffolds can address the high cell dosage and quality requirements for various mesenchymal stem cell (MSC) applications. (1) 3D polymeric scaffolds can be used to overcome the limitations of conventional 2D expansion systems. However, high cell seeding efficiency and homogenous cell seeding are challenging to achieve on 3D scaffolds. To overcome these issues, we have developed a 3D biodegradable polycaprolactone (PCL) scaffold that aims to functionally recapitulate the native microenvironment of MSCs and a polylactic acid (PLA) holder to promote efficient and uniform cell seeding, to improve cell yield and direct stem cell fate.

PCL scaffolds were surface modified with a 3D plasma treatment called packed-bed plasma immersion ion implantation. This treatment increases hydrophilicity and enabling covalent binding. (2) The use of PLA holders improved the efficiency of cell seeding and uniform cell distribution on treated PCL scaffolds. The biofunctionalisation of PCL scaffolds with a mitogenic growth factor enhanced the growth kinetics of MSCs compared to that on tissue culture plastic vessels, independent of surface area. Our plasma-treated and FGF2 biofunctionalized biodegradable PCL scaffolds reduce reagent usage and can fulfil dual roles of large-scale MSC expansion and *in vivo* MSC implantation.

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3D printing of diamond as a biomaterial using laser metal deposition

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Diamond is an interesting biomaterial with history as a coating material for orthopaedic interfaces and heart valves as well as the electrode system for high profile projects such as the Australian Bionic Eye project. As is well established, 3D printing is changing the way that we as biomedical researchers approach patient specific solutions. The challenge however for a material like diamond is the upscale to complex shapes and parts. By combining 3D printing we can achieve this. I have previously shown that we can use SLM titanium as a substrate for the coating of diamond onto complex parts. Here I will discuss the methods we have developed to combine 3D printing and diamond, discussing the new material and reporting on the superior cell/antibacterial interface (compared to titanium alone). In particular, I will report the results of our new method to use laser metal deposition (LMD) to print free standing diamond-titanium materials for implant engineering.

Design of a Lightweight Mobile Stroke Unit CT Scanner

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In Australia, we have successfully launched a road-mobile stroke unit (MSU) using a standard CT scanner. This allows 20% of patients with suspected stroke to be treated within an hour (door to clot busting treatment time reduced to 40 mins compared to 72 mins nationally). This is critical as the first hour after a stroke is the most important for a stroke patient. In Australia, most rural communities are do not have access to specialized stroke facilities for optimal stroke treatment and thus technology needs to come to them. The road-based MSU is not an option. In collaboration with the Australian Stroke Alliance and Melbourne Brain Centre, we have explored the possibilities and methodologies in reducing the weight and, effectively, the size of an existing CT scanner. Here we will show the progress of our research into the miniaturization of a CT scanner for use in road (road-MSU) or air ambulances (air-MSU) using in part the additive manufacturing of components.

When retrofitting a commercial mobile head CT scanner we used design techniques to modify the scanner for retrofitting, which include:

1. Major components of the mobile head CT scanner;
2. Weight and size of the mobile head CT scanner; and
3. Actuation mechanism of the mobile head CT scanner.

The design process for modifying and retrofitting a CT scanner can be classified into three steps: (1) default structure reduction, (2) support structure design, and (3) integration onto the interior structure of the mobile unit. CATIA (Dassault Systems), computer-aided design software, was used to model both the CT scanner model and the cabin interiors.

Using design part optimization principles, we analysed the key components of a commercial CT scanner to remove any unnecessary components, re-design and re-modelled the new scanner in CATIA for manufacture. As part of this process we used additive manufacturing to complete benchtop models and larger manufacturing of new material and parts to lighten the weight.

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Feasibility Study of an Additively Manufactured Payload System for Space Application

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The Dream Chaser spacecraft is a part of a reusable rocket and shuttle system which will be used for transportation from Earth to space orbit and return with a horizontal landing. An important component of the space-craft is the payload racking system. Enable Aerospace, an Australian company, are providing new designs for the payload system, and RMIT provided a feasibility study for the new designs. This presentation discusses the analysis of a locker element of the system and mounting concepts for the Universal Payload Racking System (UPRS), including: analysis of the locker natural frequencies; analysis of the locker's response to worst-case loads as specified by the NASA Orbiter Mid Deck/ Payload Standard; a discussion of the suitable manufacturing methods and costing for production of lockers using selected advanced manufacturing method.

Isolated influence of upward and downward facing surface roughness of fatigue life of laser powder bed fusion Ti-6Al-4V

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Executive Summary:

A fundamental relationship between surface roughness, inclination angle and fatigue strength has not been established for laser powder bed fusion (L-PBF) Ti-6Al-4V. L-PBF produces components with inherently rough surface finish, however complex geometries and internal features can make it difficult to post process surfaces. Surface roughness is understood to be detrimental to the fatigue life of L-PBF components. Therefore, a thorough understanding of the impact of inclination angle on surface roughness and consequently, fatigue life, is required for the design of fatigue-limited components with as-manufactured surfaces. An experimental fatigue test program involving L-PBF Ti-6Al-4V samples manufactured at six different inclination angles with an as-manufactured surface finish was conducted. In each fatigue test, either the upward or downward facing surface was polished to isolate the influence of corresponding roughness. This work contrasts the experimental data against predictions of the fatigue strength of a component based on the build angle of its critical surfaces.

Keywords: titanium, fatigue, surface roughness

Machine Learning Models for the Optimisation of Powder-Bed Fusion Metal Additive Manufacturing

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The ability to control the formation of defects and anomalies in metal parts during their building using powder bed fusion (PBF) additive manufacturing (AM) processes is a critical strength that can make these technologies more attractive to the industry. The required knowledge is currently generated through dozens of trial-and-error experiments; these inform the selection of the initial values of process parameters and their change during the build process. Machine learning (ML) models present an alternative to the time-consuming and expensive trial-and-error process. By analysing vast amounts of data efficiently, they uncover critical relationships between process parameters that may be hidden from human analysis. Significantly, these models can be used for new parts that have not been made before. In this talk, we discuss the various ML models that may help optimise process parameters to mitigate defects and anomalies in both laser-beam and electron-beam PBF processes.

Additive Manufacturing: Machine Learning, Mechanics, and Metallurgy

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Abstract:
The thermal histories in laser-based additive manufacturing (AM) of metal alloys results in microstructures that may contain phases, grain morphologies, or internal pores different from those seen in their conventionally processed counterparts. These microstructures dictate the resulting mechanical properties of the alloys; thus, to enable the adoption of AM for structural applications, an understanding of the links between microstructure and deformation and/or fracture is required to reliably design against failure. In this talk, I will present our work in three general areas: using in situ process monitoring to link processing signatures to defects and mechanical properties, modeling the impact of internal defects on the multiaxial failure behavior of additively manufactured metallic materials, and the development of a framework for designing functionally graded materials in which the composition is spatially tailored to impart site-specific properties within a 3D component.

HAADF-STEM and APT characterization on precipitation of high-performance Al-based composites produced by additive manufacturing

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High performance Al alloys have been widely used in aerospace and automotive industry due to their light weight and good mechanical properties, which have been regarded as the second metallic structure material just next to steel. Precipitation hardening has been regarded as one of most important strengthening methodologies for high-performance Al alloys. However, precipitation hardening alone has a limited potential to further improve the alloy performance at elevated temperature due to the fact that the main strengthening precipitates (i.e. Al_2Cu in Al-4Cu-0.3Mg (wt.%) based alloys) become coarsening and softening and therefore provide effective strengthening effects only up to 250 °C. How to develop new Al based alloys with an enhanced precipitation hardening is a key point for the further development of Al based alloys. Recently, one Al-4Cu-0.3Mg (wt.%) based composite with a higher amount of TiB_2 (about 3.5 wt.% Ti, 1.5 wt.%B) and Ag (0.7 wt.%) has been successfully developed and has been used to produce many different types of aerospace casting parts due to its excellent castability (higher fluidity, less (if any) hot tearing, less (if any) segregation tendency) and better alloy performance at elevated temperature. These improvements can be mainly attributed to two folds: (i) the presence of 3.5 wt.% Ti and 1.5 wt.%B can refine the grain size of Al grains less than 50 µm via an enhanced heterogeneous nucleation by TiB_2 together with free Ti and an improved growth restriction by free Ti, and (ii) the presence of 0.7 wt.% Ag can improve the formation of omga precipitate (AlCuMgAg) instead of beta precipitate (Al_2Cu), which significantly improve the thermal stability of the Al-4Cu-0.3Mg (wt.%) based composite and therefore can be used at elevated temperatures. Furthermore, the Al-4Cu-0.3Mg (wt.%) based composite was used to produce the powder via inert gas atomization for subsequently additive manufacturing (AM, selective laser melting (SLM)). The AMed Al-4Cu-0.3Mg (wt.%) based composite shows an incredible increase of strength (about 500 MPa) and elongation (about 20% after solution treatment, 12% after over-ageing) due to a very rapid solidification rate (about 10000 °C/s) and thereby a very refiner grain size (about 1 µm). However, there is still a lacking of a detailed investigation on the precipitation of high-performance Al-based composites produced by additive manufacturing. In this contribution, HAADF-STEM EDS and EELS as well as atom probe tomography (APT) was used to characterize the precipitates at atomic scale, with a focus on the omga precipitate (AlCuMgAg) and precipitation free zone along grain boundaries. The differences or similarities between conventional casting process and additive manufacturing were also discussed.

Thermal cycle induced phase evolution in IN718 during additive manufacturing: Gleeble and thermo-kinetic modelling study

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Abstract

Due to its ability to produce complex components with minimal material waste, additive manufacturing (AM) has been widely adopted for making parts of high-performance nickel-based superalloys such as IN718, e.g., for modern aero-engines. However, a complete understanding of the microstructural evolution, such as γ′, γ″, Laves, and δ transformations during printing, is still lacking. The complex AM thermal cycles cause complicated morphological changes to these phases. However, observing these transformations during printing is challenging as sophisticated and in-situ measurement techniques are needed. In this study, we introduce alternate techniques to investigate the effects of thermal cycles on the phase evolution of IN718 components during AM. This involves using the Gleeble physical simulator to simulate cyclic heating and quenching experiments. The MatCalc software package is used for thermokinetic modeling to analyze the phase evolution under specific thermal cycles and predict the expected phases. The inhomogeneous microstructure in AM is shown to be linked to the extent of γ'' and γ' dissolution. Microstructure characterization after thermal cycling is in great agreement with the MatCalc prediction on the evolution of δ, γ'' and γ' phase, highlighting the effectiveness of combined Gleeble and MatCalc analyses in AM research.

Deformation kinetics of additively manufactured 304L stainless steel with hierarchical microstructures and superior mechanical properties

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Owing to the unique melting and solidification dynamics of additive manufacturing (AM), the hierarchically heterogeneous microstructures spanning orders magnitude in length scales could be obtained in the AM fabricated metals and alloys, enabling excellent mechanical properties. For instance, the 304L stainless steel (SS) manufactured by selective laser melting (SLM) technique exhibits a significantly enhanced strength–ductility synergy compared to that of wrought and annealed counterparts. However, the understanding of the deformation mechanisms and kinetics of SLM 304L SS hitherto is still insufficient. In this study, we systematically investigated thermal-related kinetic parameters such as activation volumes and strain rate sensitivity, and back stress strengthening by applying the stress relaxation tests, strain rate jump tests, and loading-unloading experiments, which can be correlated with the microstructural evolution and deformation mechanisms during the plastic deformation of SLM 304L SS. It was found that apparent and physical activation volumes decreased from ~200 b^3 to ~60 b^3 and strain rate sensitivity varied significantly, indicating the shift of dominant deformation mechanisms. The monotonical increase of back and effective stress revealed hetero deformation behaviour due to its hierarchically heterogeneous microstructures.

Effect of Scanning Strategy on the Microstructure and Grain Boundary Network of Additively Manufactured Nickel-based Superalloy Inconel 738

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Inconel 738 is a nickel-based superalloy commonly used in high-temperature applications in the aerospace and nuclear industries owing to its extremely high strength and resistance to corrosion and oxidation. These properties are strongly linked to γ' precipitation and character (crystallography and chemistry) of the grain boundaries. Additive manufacturing (AM) provides a new opportunity to fabricate crack and defect-free nickel-based superalloys with desirable microstructures by controlling the thermo-mechanical conditions. This study unveils the effect of the electron beam scanning strategy on the grain boundary network evolution in electron beam powder bed fusion (E-PBF) printed nickel-based superalloy Inconel 738. It is shown that changing the scanning strategy from linear to random alters the grain morphology from columnar to equiaxed, and randomizes the texture. Random built samples provide larger γ' particle sizes compared to the microstructure after linear scans. Interestingly, both linear and random built samples show exceptionally high thermal stability, owing to the pinning effects of carbides along the grain boundaries. This study highlights the potential for inducing favourable grain boundary networks directly during E-PBF using different scanning strategies, towards improved cracking and corrosion resistance.

Low-cost single digit scalable microprinting

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Projection Micro Stereolithography (PμSL), a digital light processing (DLP) based printing technique, has been widely used for the fabrication of structures across multiple length scales. However, a trade-off exists between the maximum printable object size and the minimum feature size, with higher resolution resulting in a reduction of the overall structure extent. Despite this, the ability to produce structures with high spatial resolution and large overall volume is essential for the development of hierarchical materials, microfluidic devices, and bioinspired constructs. In this study, we present a low-cost PμSL system with an optical resolution of 1 μm, the highest resolution system yet reported for the production of micro-structured parts with dimensions on the order of centimetres. To achieve this, we investigated the limits of PμSL as a function of energy dosage, resin composition, cure depth, and in-plane feature resolution. We also developed a novel exposure composition approach that significantly improves the resolution of printed features at the single pixel level. These results demonstrate the potential of PμSL to accelerate advancements in emerging fields such as 3D metamaterials, tissue engineering, and bioinspired constructs.

Increased process stability and efficiency by digitalization in laser-based additive manufacturing

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Compared to conventional manufacturing routes, additive manufacturing technologies are characterized by an enormous number of process parameters and influences. Even minor variations can lead to significant influences on the behavior of the melt pool and, hence, the associated results of the whole part. Thus, at the micro level, unwanted surface conditions, waviness, cracks or porosity, etc. can occur. Component-wise, distortion, geometric deviations and even a complete process termination can occur at the macro level.
Digitalization can help both on a small scale in tailor-made material placement up to suitable process chain tuning in order to execute additive processes in a more robust, reproducible and resource-saving way.
In the context of the presentation, possibilities that can make a valuable contribution to the aforementioned goals will be identified, in particular on the basis of laser metal deposition LMD (alternative term: directed energy deposition DED). Selected digitization measures as well as case studies will be discussed.

Experiments and modelling of segregating additive manufactured granular mixtures

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Abstract

We report recent findings of our investigation to understand impacts of granular material properties on mixture segregation and enhance quality of predictive modelling. We consider granular mixtures that differ in intrinsic (particle-scale) properties, namely here, as shape and relative size. Our study explores the segregation of binary mixtures in the controlled environment of a Freeman rheometer.

Firstly, we implemented a Discrete Element Method to predict how macroscopic segregation evolves, and then compared results with real lab experiments. The shape and size of granular materials were controlled using powder-based additive manufacturing (AM). We studied impact on segregation for mixtures containing spherical or cubical particles, considering their relative size interdependency. To explore this equivalence, a powder-based additive manufacturing technique was used to fabricate particles for three cases, where a spherical particle is: 1) the inscribed, 2) circumscribed, and 3) for equal volume sphere.

Our results show that the binary mixtures containing cubical and spherical particles can induce significant radial segregation of the bed. We postulate that an important mechanism for radial segregation is percolation due to radial centrifugal forces. This radial migration of cubes leads to the formation of a self-ordered bed structure, that can withstand disruptions from cycles of shear.

Laser-induced forward transfer for printing metallic structures on flexible substrates

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Laser-induced forward transfer (LIFT), a novel one-step, contactless, time, and cost-effective method have gained popularity in additive manufacturing wide range of sensors for various electronic, biological, and chemical applications. Furthermore, advantages such as high resolution and flexibility motivates this research in utilizing LIFT for printing Copper (Cu) sensor electrodes. However, experimental evidence has shown weak adhesion (between deposit-receiver) and poor conductivity (in the deposits). Therefore, numerous efforts are made to mitigate the mentioned limitations for potential flexible thin film applications. For instance, inducing surface roughness via Vat photopolymerization and laser surface texturing techniques to the receiver substrate. Simultaneously, the effects of the aforementioned efforts shall be investigated on soft and hard polymers based on their shore hardness. Finally, the LIFT process is optimized based on the aforementioned experiments and relevant characterizations such as adhesion tests and metallographic studies. Additionally, conductivity tests determine the feasibility of the deposited materials as flexible sensor electrodes. Finally, finite element analysis (FEA) has been made for the LIFT process for effective implementation in process optimization. The versatility of LIFT makes it a perfect choice for additive manufacturing of metals on flexible substrates.

Keywords: Laser-induced forward transfer (LIFT); Finite element analysis (FEA); additive manufacturing; Vat photopolymerization.

Metastable austenitic steels – Pathways to tackle recent challenges in additive manufacturing

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In the last decade numerous alloys have been processed by additive manufacturing (AM) and characterized in depth. Looking at results presented from a general perspective, a number of key challenges can be deduced, including surface roughness, porosity, residual stress and limited damage tolerance. All these issues are a roadblock to application of AM structures in safety critical components, e.g. parts suffering cyclic loads in applications in the mobility sector. In most cases researchers try to address these issues by post treatment of AM processed conventional materials. As an alternative, the material of choice can be adapted to the prevailing process conditions. The present study will highlight and discuss the prospects and challenges of using metastable austenitic steels, showing twinning and transformation induced plasticity (TWIP/TRIP) upon loading, in powder bed AM. It will be revealed that high-manganese steels allow to tackle the aforementioned challenges by exploiting their intrinsic elementary deformation and transformation mechanisms. Here, not only superior damage tolerance in terms of fatigue loadings can be achieved. Moreover, residual stress can be decreased by the intrinsic effects during AM.

Optimization of grain morphology in titanium alloys processed using additive manufacturing

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There has been considerable interest focused on the ability to produce, via additive manufacturing (AM), titanium alloy components that exhibit microstructures with fine equiaxed grains and fairly random textures, such that it is possible to achieve attractive balances of mechanical properties. The problem that must be solved involves avoiding the formation of coarse columnar grains parallel to the build direction in printed components, with attendant relatively strong crystallographic textures, which tend to result in anisotropic properties and often performance deficits. Among possible solutions to this problem, an attractive approach has involved the addition of solute to Ti and some Ti-based alloys. This paper describes research undertaken to demonstrate the usefulness of solute additions for microstructural optimization during AM. Emphasis is placed on identifying the role of these solute additions. The approach employed here permits the development of computational models aimed at predicting appropriate alloying schemes that would result in Ti components fabricated by AM exhibiting attractive balances of properties.

The Attributes of Microstructural Artifacts in Thermal Spray Coatings

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"Beauty is in the eye of the beholder", attributed to Plato. For the materials scientist the beauty goes much deeper due to exploration of phase transitions, grain boundary behaviour and a host of amazing physical metallurgy artifacts. One of the hot buttons for thermal spray is 'microstructure' where the adjective 'ugly' is often used rather than 'beautiful'. The point is that these complex microstructures are employed in a host of low and high performance applications. They exhibit, a lamellar morphology, a rugged surface, a rugged interface against the substrate, porosity, cracks and many other artifacts. They are the 'ugly duckling' of materials engineering but as you become more mature in understanding their exotic microstructure, then the world of beautiful functionalities is revealed.

The science of thermal spray is multi-faceted and becomes quite deep and specialized within narrow disciplines. The character of thermal spray coatings lies in their rich microstructure. It is apparent that thermal spray coatings can be rightly claimed as the original 'nanomaterial', the original 'composite material', a 'functionally graded material', the first modern day 'additive manufacturing technology'; as well as many other materials engineering firsts. Thermal spray opportunities regarding the microstructure include: (i) layered microstructures, (ii) composites that establish tailored material properties, and (iii) rapid cooling rates to create unusual alloys with extended solubility.

The take home messages of this presentation are:

- (i) The microstructure of thermal spray coating is complex.
- (ii) The components of the microstructure can be classified in taxonomy jargon.
- (iii) Thermal spray equipment is versatile and is a processing tool.
- (iv) The microstructure can be designed to suit the need. The microstructure is a palette of artefacts that can be mixed and matched for functionality.
- (v) Processing conditions can be controlled to hit the microstructural target.
- (vi) Intelligent design or 'Spray Smart' will work hand-in-hand with digital twins to accelerate manufacturing.

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Additive Manufacturing-Based Repair of IN718 Superalloy and High-Cycle Fatigue Assessment of the Joint

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The current study investigates the room temperature high-cycle fatigue (HCF) performance of IN718 repaired joint via laser direct energy deposition (DED) under two heat-treated conditions: direct aged (DA) and solution treated and aged (STA). The post heat treatments had negligible effect on the grain morphology of the repaired joint, however, micro-hardness results highlighted the need for the heat treatment to form uniform hardness across the joint. Fatigue tests performed with the loading axis perpendicular to the joint interface revealed that the DED repaired joint exhibited an overall decreased HCF performance, regardless of the heat treatment, although the monolithic DED deposit and the wrought substrate exhibited similar tensile strength. At low stress levels, the STA condition exhibited superior HCF performance than the DA, however, at high stress levels the trend reversed, resulting in a cross-over point on the stress-life S-N plot. Interrupted fatigue tests, combined with microscopy, revealed cracks originating from Nb-rich grain boundary in the substrate near the substrate-to-deposit interface in both cases. However, the final failure occurred in the substrate for the DED joint in the DA condition, whilst in the deposit zone for the STA condition due to the distribution and fracture of the Laves and δ phases.

Creep performance of additively manufactured Ni-based superalloy

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KEYWORDS: Additive Manufacturing, Ni-based superalloy, Creep, Laser powder bed fusion

Abstract:

Creep fracture is a common failure mode for additively manufactured (AM) Ni-based superalloy components at high temperature loading applications. However, recent attempts in AM Ni-based superalloys reported inferior creep properties compared to the superalloys manufactured by conventional techniques, and the understanding regarding the creep properties of AM superalloys is still lean. In this work, a microstructure-based creep model is developed for additively manufactured Ni-based superalloys that specifically considers the correlation between creep behaviour and AM-produced microstructure features, in particular the porosity, columnar grain structure and compositional inhomogeneity. The application of the model provides a quantitative method to reveal the underlying mechanisms between AM-specific microstructure and creep performance. Meanwhile, the established mechanisms are applied to Inconel 718 (IN718) for microstructure-designment through post heat treatment. A 7-times creep lifetime improvement is achieved for laser powder bed fusion (LPBF) IN718 compared to the one that underwent standard heat treatment.

Spatially controlled mesostructure engineering from random powder mixtures in laser powder bed fusion (LPBF)

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Physical mixing of powders with different chemistries has been used in laser powder bed fusion (LPBF) as a cheap way to test the printability of new compositions. The goal here is to produce a homogeneous alloy, and depending on the powders and printing parameters, multiple laser passes or 'remelting' may be required to homogenise the chemical distribution. Sometimes physically mixed powders are also used to deliberately exploit the chemical heterogeneity of the powder mixture to create multiphase micro/meso-structures in the as-built state. In a recent example, a mesostructured duplex stainless steel was obtained in the as-built state from a mixture of 22Cr stainless steel and Inconel 625.

However, the point-by-point, line-by-line, layer-by-layer mode of LPBF also offers the potential for spatial control of the structure, in principle, allowing for control over not only which phase forms, but also the spatial arrangement at the mesoscale. This presentation demonstrates our efforts in 3D mesostructure phase control (FCC vs BCC) from LPBF of a physical mixture of Ni and high-Cr stainless steel powder. We present a physically-based model to predict the chemistry distribution as a function of scan strategy (including remelting), and use this to design prints with spatially controlled mesostructured phase patterns.

3D-printed thermoplastic polyurethane electrodes for customizable, flexible lithium-ion batteries with an ultra-long lifetime

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Three-dimensional (3D) printing technology has demonstrated great potential in fabricating flexible and customizable high-performance batteries. However, significant performance gaps, especially in cycling stability, still exist between the 3D-printed and conventional electrodes, seriously limiting the practical applications of 3D-printed batteries. Here, we developed a series of thermoplastic polyurethane (TPU)-based 3D-printed electrodes via fused deposition modeling (FDM) for flexible and customizable high-performance lithium-ion batteries. The TPU-based electrode filaments, including TPU-$LiFePO_4$, TPU-Li4Ti5O_{12}, TPU-Li(NiCoMn)O_2, and TPU-graphite, are prepared in kilogram-scale. Benefitting from the advantages of FDM and TPU-based electrode inks, as-prepared electrodes are well printed with high dimensional accuracy, flexibility, and mechanical stability. Notably, 3D-printed TPU-LFP electrodes exhibit a capacity retention of 100% after 300 cycles under a rate of 1C, which is among the best cycling performance of all the reported 3D-printed electrodes. Furthermore, the post-analysis, mechanical properties analysis, and multi-physics simulation results verify that the excellent stress cushioning properties of the TPU-based electrodes can accommodate the electrode volume change during the cycling, thus significantly preventing the collapse of the electrode structure. Our findings not only provide a new avenue to achieve customizable and flexible batteries but also guide a promising way to erase the performance gap between 3D-printed and conventional lithium-ion batteries.

Keywords: (3D printing, lithium-ion batteries, additive manufacturing, thermoplastic polyurethane, flexible batteries)

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A generative machine learning method for microstructures prediction in additively manufactured Ti6Al4V alloy

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Abstract: Laser powder bed fusion (LPBF) fabricated Ti6Al4V alloy has been widely researched in recent years as a critical structural material for use in the aerospace and biomedical industries. Exploring the key relationships between the LPBF process parameters and the resultant microstructures has become a research hotspot. However, the existing approach to building these relations heavily depends on time-consuming and costly trial-and-error experiments. Here we present a novel image-driven conditional generative adversarial network (conditional GAN) machine learning network to predict the microstructural features (such as the density of distribution of martensite, the size of primary and secondary martensite) in LPBF fabricated Ti6Al4V and reconstruct micrographs of the microstructure based on input LPBF processing parameters. Scanning electron micrographs of the as-fabricated samples at different processing parameters were used as training datasets. The trained networks are able to accurately predict the detailed microstructural features beyond the training datasets with a relative error of less than 20%. This work paves a route to quantify process-microstructure relationships from a machine learning perspective and will be widely applicable to solving problems of process optimisation, material design, and microstructure control in the broad field of additive manufacturing well beyond LPBF fabricated Ti6Al4V.

Enhancing tribological properties of titanium alloys through laser powder bed fusion

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It is well-known that titanium alloys perform poorly in service conditions that involve tribological contact. As there is increasing interest in using additive manufacturing technologies to fabricate titanium parts, the unique microstructural features that result from such processes could be useful in enhancing tribological properties. In this study, the sliding behaviour of two titanium alloys (Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo) processed by laser powder bed fusion (LPBF), with and without heat treatment, was investigated against hardened bearing steel alongside two as-received conventionally-processed versions of these titanium alloys. Despite being harder than a typical α + β microstructure, the martensitic structures (α′ or α″) that are often encountered in the as-built LPBF-processed condition did not enhance wear or friction behaviour as they tend to decompose under frictional heat. Oxidative wear was found to be enhanced in samples containing nanocrystalline grains which led to reduced friction. A simultaneous reduction in friction and wear rate was achieved in the heat-treated LPBF-processed Ti-6Al-2Sn-4Zr-6Mo alloy due to an ultrahard nanocrystalline α + β microstructure that remained stable under frictional heat.

4D printing of composites

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Abstract

This presentation conveys different aspects of the technique of 4D printing of composites, abbreviated as 4DPC. The technique derives from the concept of 3D printing, in which composite materials with continuous fibers are deposited onto a flat mandrel using an automated fiber placement (AFP) machine. The AFP machine functions similarly to a regular fuse filament fabrication (FFF) 3D printer, in which materials are deposited strip by strip. The difference is that the AFP machine is much bigger than a regular 3D printer, and the AFP machine can deposit continuous fibers embedded in a resin matrix material, whereas most 3D printers can only deposit unreinforced polymer material or polymer material reinforced with short fibers. AFP machines have been used to make major aircraft structures such as the body frame for Airbus 380 or Boeing 787. Another difference is that the matrix resin used in the 4DPC is thermosetting, while most resins used in regular 3D printing use thermoplastics. The main difference between thermosetting resin and thermoplastic resin is that the solidification in thermosetting resin is due to cross linking between small molecules, while the solidification in thermoplastic resin is due to the reduction in the motion of large molecules.

The 4th dimension in 4DPC is due to the reconfiguration of the stack of composites from flat configuration to curved configuration upon curing and cooling to room temperature. The composite layers consist of continuous carbon fibers and epoxy resin. Initially the composite in the form of prepregs (pre-impregnated) layers are deposited strip-by-strip and layer-by-layer on a flat mandrel. The resin in the prepregs is partially cured. Also, the orientation of the fibers in the different layers are chosen to be different from one another. This creates an anisotropic arrangement. After a stack of the layers have been deposited, the material is heated up to the cure temperature (about 177 ºC) for curing. Curing makes the matrix resin hard and this activates the interaction between the layers. Due to the difference in the orientation of the fibers in the different layers, the coefficients of thermal expansion (contraction) in the different layers are different. As the composite structure is cooled from cure temperature (177ºC) down to room temperature (20 ºC), the interaction between the layers makes the composite structure to curl up into a 3D structure. By proper arrangement of the orientation of the fibers in different layers, structures of different shapes can be obtained.

Figure 1 shows a leaf spring made by 4DPC [1]. The spring has 60 layers (thickness of 7.5 mm) and a spring constant of 486 N/cm, which is equivalent to that of many practical leaf springs. The composite spring was subjected to more than 1 million fatigue cycles (from flat to curved)

without failure. Figure 2 shows a composite flower with 4 petals and each petal has 5 leaves. Figure 3 shows a structure with conical shape. These all were made using only a flat mandrel.

Potential applications for 4DPC can be for actuators, for making corrugated core for morphing wings [2] or in effective packaging for shipment to far-away places (such as outer space). For effective packaging, the structure can be shipped in flat shape, which takes less space. Upon arrival at destination, thermal treatment can be done to change the shape from flat to curved.

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Figure 1: Composite leaf spring

Figure 2: Composite flower

Figure 3: Composite cone

HIPing and Characterisation of Cold Spray additive manufactured Titanium

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Cold Spray is a novel technique for the production of a broad range of materials including titanium-based for areospace applications. In additive manufacturing (AM), cold sprayed parts or 'preforms' often require heat-treatment to achieve full density and optimal mechanical properties, in order to achieve performance requirements. To this end, Hot Isostatic Pressing (HIPing) is often specified as the recommended thermal processing step to meet the quality and performance benchmarks for aerospace applications.

In a recent research collaboration, titanium-based parts were prepared using cold spray additive manufacturing with post-deposition heat treatments including HIP. An experimental matrix was developed to an envelope of the thermal processing conditions for cold-sprayed titanium material in order to tailor the desired mechnical and physical properties including density, strength, ductility, toughness, and grain size/structure. This paper shall discuss both post-deposition treatment options and their influence on materials properties.

Investigate the method for fabricating parts with varying geometry through the utilization of surface tension transfer technologies in wire arc additive manufacturing

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In recent years, wire arc additive manufacturing (WAAM) technology has been widely employed in many industries such as aerospace and maritime to fabricate high value-added metallic parts on medium to large scale. Under the current circumstances that the demand for products with complex and customized structures is growing rapidly, it is necessary to develop an effective and reliable method for fabricating parts with varying geometries. The current WAAM systems mainly adopt the cold metal transfer (CMT) welding process as their material deposition method due to its low heat input, little spatter and high stability. However, the CMT process inherently has some limitations on adjusting heat input during the welding process, which makes it challenging to deposit parts with varying geometries. The surface tension transfer (STT) technologies may provide new opportunities to realize the proposed method. This study first investigates and analyses the working principle and process parameters of the CMT and STT welding process respectively. Followed by a comparison of the deposition performance of the two processes in terms of achievable single bead geometry and multi-bead overlapping performance. Finally, an STT-based WAAM method for depositing parts with varying geometries is developed and evaluated through case studies.

ADDITIVE MANUFACTURING OF BETA TITANIUM ALLOYS: INFLUENCE OF THERMO-KINETICS ON PRECIPITATION, STRENGTH, AND STRAIN HARDENING BEHAVIOR

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The overwhelming majority of worldwide activity on 3D printing or additive manufacturing (AM) of metals is presently focused on maturing the metals AM technology for fabricating components of well-established metals/alloys, such as Ti-6Al-4V (wt%), which have traditionally been processed via conventional manufacturing. While these efforts are extremely important, in case of titanium alloys, there exists a tremendous potential of designing and exploiting beta titanium alloys for AM. These alloys do not form an embrittling martensitic phase on quenching, and their microstructure and mechanical properties can be tuned over a wide range. This talk will focus on AM processing of candidate beta Ti alloys, such as the strain-transformable Ti-10V-2Fe-3Al (or Ti-10-2-3) and high strength Ti-1Al-8V-5Fe (or Ti-1-8-5) (all in wt%), alloys. Additionally, the Ti-35Nb-7Zr-5Ta or TNZT biomedical alloy has also been investigated. These alloys have been primarily processed by directed energy deposition (DED), though Ti-10-2-3 has also been processed by laser powder bed fusion (LPBF). The focus is on the influence of the non-conventional thermo-kinetics of these AM processes on microstructural evolution, including second phase precipitation (both omega and alpha) in these alloys, and the consequent influence on mechanical behaviour.
This will be illustrated with three examples:

1. Influence of thermo-kinetics on fine scale omega and alpha precipitation and strain transformability in AM processed Ti-10V-2Fe-3Al highlighting the differences between DED and LPBF processing.
2. Depending on the process parameter dictated energy density in DED processed Ti-1Al-8V-5Fe, a homogeneous distribution of fine scale omega or alpha precipitates form within the beta grains, strongly influencing the mechanical behaviour.
3. These effects have been rationalized based on thermo-kinetic modelling of a multi-layered deposition process.

These representative examples will highlight the power of combining beta Ti alloys with AM processing to achieve an excellent balance of mechanical properties.

The effect of processing parameters on the microstructure and tensile properties of additively manufactured Ti-Cu alloys

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Additively manufactured (AM) titanium copper alloys have shown promising properties as a substitute for AM Ti-6Al-4V. However, few processing parameters have been explored thus far. This study explores the processability window of directed energy deposition (DED) Ti-Cu alloys by investigating a range of scan speeds and powers. The dependence of processability upon the global energy density was evaluated and discussed. Within the identified processability window, specific attention was paid to the effect of scan speed on the pearlitic eutectic microstructure of the DED Ti-Cu alloy. In a wide scan speed range from 400 mm/min to 1200 mm/min, the major difference induced by the change in scan speed was the variation in the lamellar spacing. The lamellar spacing decreased consistently as the speed increased due to a higher cooling rate. Tensile testing of samples produced with a scan speed from 600 mm/min to 1200 mm/min showed that as the scan speed increased, the yield and tensile strength also increased, but the percentage elongation decreased. The variation of tensile properties is proposed to align with the change of microstructure because the finer lamellar spacing is more effective in inhibiting dislocation movement at the sacrifice of plasticity.

Development of a novel filament for fused deposition modelling from recycled polypropylene and recovered carbon fiber

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Carbon fiber-reinforced plastic (CFRP) and Polypropylene (PP) are extensively used in the manufacturing industry due to their preeminent property, such as high strength and good chemical resistance. Annually, a large amount of PP and CFRP waste is generated, which can be used as a sustainable and low-cost feedstock for fused deposition modeling (FDM). In the present study, the recycled carbon fiber, reclaimed from CFRP waste by solvolysis technique, was milled into powder and mixed with recycled PP, recycled from car battery, to make a fully recycled material based FDM composite filament. The filament is fed into the FDM printer successfully and printed into a composite. The microstructure and tensile properties of the printed composite were experimentally investigated by scanning electron microscopy (SEM) and tensile test, respectively. Furthermore, impurities in recycled PP were determined by X-ray fluorescence (XRF) and Raman spectroscopy. The result reveals the significant potential of recycled material-based filament for sustainable construction and circular economy.

Microstructure and Mechanical Properties of Duplex Stainless Steels Manufactured by Laser Powder Bed Fusion

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Recent advancements in the metal additive manufacturing (AM) technologies have enabled near net-shaped production of geometrically complex engineering components from complex alloys such as duplex stainless steels. If the knowledge of the solidification pathway and solid-state microstructural evolution can be advanced, AM will offer many opportunities for microstructure and property engineering. In duplex stainless steels, the melt initially solidifies as nearly fully δ-ferrite owning to the steep thermal gradients in AM, where the subsequent solid-state phase transformation can be controlled via tuning AM and post-processing parameters. This unlocks the potential for altering the phase ratio, precipitate character, dislocation density, grain size, and chemistry of ferrite and austenite, to improve various mechanical and corrosion properties in these steels. The current research intends to establish the connection between AM parameters and the micro-to-nano-scale characteristics of duplex stainless steels produced by laser powder bed fusion, towards advanced mechanical properties. Such process–microstructure relationships in AM and their impacts on mechanical behaviour will provide new insights into property-driven microstructural manipulation in not only duplex stainless steels but also other similar polymorphic alloys fabricated by AM.

Design and structure optimization of 3D-printed electrodes for high-performance lithium batteries

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Abstract

The rise of three-dimensional (3D) printing technologies enables an efficient, cost-effective, and controllable strategy for manufacturing customized lithium batteries. The shape of the components, including electrodes, separators (or solid-state electrolytes), current collectors, and battery cases, could be specifically designed and printed with 3D printing technologies. Utilizing 3D printing allows the direct incorporation of electrodes in precisely designed 3D objects. Understanding 3D printing designs in battery materials and architectures is key to optimize performance and realize the customization of 3D-printed batteries. Herein, we report the problem-oriented design for the electrode architectures and battery configurations to solve the challenges in flexible batteries, lithium metal batteries, as well as for customized design and production. Unique features of 3D printing designs would help solve specific applications and technological problems in both the existing and newly emerging fields of electronics and consumer products.

Fused Deposition Modelling of Fibre Reinforced Polylactic Acid with Heating Techniques

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Abstract

Additive manufacturing (AM), also known as 3D printing, is one of the most promising technologies for fabricating fibre reinforced polymer composites compared to those traditional manufacturing technologies, which are labour intensive, time consuming, and lacking quality assurance. Among 3D printing technologies, Fused Deposition Modelling (FDM) technology is being widely employed in manufacturing 3D printed polymers and composites. Void formation in those 3D-printed part is one of the most challenging issues and it needs to be controlled using optimal FDM process parameters. In this study, an innovative FDM process with pre and post heating technology is developed for fibre reinforced Polylactic Acid (PLA) composites to reduce void formation and improve their material performance. Using standard tensile testing, the FDM printed PLA composites are experimentally investigated, including both pure PLA and chopped carbon fibre reinforced PLA composites for comparison. Specifically, tensile strength of those 3D printed parts is evaluated with varying the main FDM process parameters such as layer thickness, deposition temperature, raster angle, etc. The obtained experimental results prove that the tensile strength can be significantly increased in post heated components, and among those process parameters, layer thickness plays a key role on tensile strength than the others.

Keywords: Additive manufacturing; Fused deposition modelling (FDM); chopped carbon fibre reinforced composites; volume fraction; tensile strength

Qualification of DED metal additive manufacturing by Artificial Intelligence monitoring and Digital Twin analysis

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The objective of this work consists in the development and implementation of a Digital Twin that allows analyzing to later optimize the DED manufacturing process, through an Artificial Intelligence (AI) based algorithm.
The Digital Twin is part of the Add2Man platform, a very powerful software developed at CIMNE for the numerical simulation of the AM-DED thermomechanical process, with an implementation designed for parallel computing in distributed memory (clusters) and the use of automatic techniques of adaptive meshing (AMR).
In this work the Digital Twin is used for the high-fidelity prediction of the temperature field and its temporal evolution at each point of the component and throughout the printing process.
The novelty proposed in this work consists of providing intelligence (AI) to the DED manufacturing process, allowing for the optimization of the process parameters such as the power input, the printing speed, the feeding rate, etc. Feeding on the same input as DED machines (G-code format), the Digital Twin can very faithfully reproduce the power delivery of the laser along its path, as well as the cooling during repositioning pauses, waiting times, etc. The melt-pool temperature is used to continuously monitor and modulate the laser power value. In this way, it is intended to add an active and automated control to AM manufacturing, qualifying this technology for its adoption and integration in the industrial manufacturing chain.

Effect of inorganic PCM/expanded perlite composite on cement hydration and inner temperature regulation of mortar

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Phase change material (PCM) concrete is proven as a novel functional concrete to regulate temperature, reduce energy consumption, and mitigate carbon emissions. There is a large gap in fully understanding the effect of PCM incorporation on concrete. Cement hydration is critical for mortar fabrication where temperature is an important factor. The PCM is sensitive to temperature that influents hydration development. This work incorporates inorganic PCM/expanded perlite mortar and investigates the performance during curing. Temperature distribution and development directly reflect the influence of PCM. The differences in hydration products and microstructure prove the varying cement hydration, which are tested by SEM, XRD, FTIR, etc. The results claim that the intrinsic effect of PCM is significant for the quality of PCM concrete/mortar, besides popular concerned incorporation methods. The function of PCM starts before the cement is hardened (construction is completed) and the research on early-stage concrete/mortar is considerable.

Design and fabrication of patient-specific surgical plates

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Fixation of a fractured bone presents many challenges due to anatomical complexity and variations of bone topography between patients. In this study, an efficient workflow from scratch to final implementation on designing patient-specific bone plate is developed. The design process includes three major steps: (i) processing the X-ray CT volume data, (ii) extracting the required surface and (iii) creating the digital plate using CAD software. The required area of the bone surface for creating bone plate and the location of the screw holes on the generated plate were determined with the input from a group of orthopaedic surgeons. It was observed that the created plate fits perfectly with the bone topography. The designed plate was manufactured with titanium alloy using casting techniques. Finite Element (FE) model was created using the X-ray CT based geometry of the bone and the plate to investigate the detail mechanical behaviour and stress/strain distribution. Then the manufactured plate was used in the surgery in which the plate perfectly fitted with the fractured bone. Furthermore, the current design significantly increases the design efficiency as well as reduces the processing time and complexity.

Development of Environmental Barrier Coatings for Boiler Tubes using Suspension Plasma Spray

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Combustion of solid fuels in boilers generates corrosive-erosive environments. High-temperature corrosion-erosion on boiler heat exchangers can jeopardise their efficiency, cause accidents, and may lead to unplanned shutdowns. To prevent these issues, environmental barrier coatings (EBCs) could be applied to provide heat exchangers with protection against such aggressive working conditions. Suspension plasma spray (SPS) is a relatively new method to produce bespoke coatings used in a wide range of applications including industrial boilers. However, stabilisation of suspensions is required and challenging with new sets of materials to deposit coatings with desired properties.

In the present study, zeta potential and particle size distribution of various water-based multicomponent suspensions were investigated to optimise their stability using varied amount of sodium hexametaphosphate (SHMP) as a dispersant. The optimised suspensions were deposited to form EBCs using SPS process. The coatings were characterised using an X-ray diffractometer (XRD) and a scanning electron microscope equipped with an energy dispersive spectrometer (SEM-EDS).

SHMP showed positive effects on stabilising fine ceramic particles in all water-ethanol mixed suspensions. Agglomeration of particles was not observed in any suspensions; nevertheless, stability of suspensions decreased with increasing amount of ethanol. An ethanol free suspension resulted in a porous SPS coating microstructure with semi-melted particles and poor coating deposition rate. Suspension with 10% ethanol formed a columnar SPS coating microstructure with improved deposition rate; however, the coating was still porous. By increasing ethanol and solid content of suspensions to 20%, denser SPS coatings were achieved. They can potentially provide necessary corrosion-erosion resistance capability for boilers.

Additive Manufacturing in Sustainable Critical Minerals Processing

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Abstract:

Production of clean energy equipment such as wind turbines, electric batteries and solar PV relies upon the supply of critical minerals. The global shift towards clean energy is set to drive a colossal demand for critical minerals which could more than quadruple by 2040.[1] Thus, it is paramount for the rapidly expanding mineral processing industries to uphold strong environmental, social and governance (ESG) credentials.[2]

Sustainability challenges in the mineral industry currently pertain to improvement in the overall resource utilization efficiency which is characterized by reduced energy and water consumption along with minimal waste production. Additive manufacturing (AM) has disruptive potential in addressing the sustainability requirements of the mining industries by enabling the manufacturing of devices and reactors which were previously not possible. Compared to traditional manufacturing, AM exhibits significant economic and technological advantages such as capability for fabrication of sophisticated geometries and reactor internals, rapid prototyping for R&D, high customization capabilities at low cost and short manufacturing times.[3,4]

This presentation will focus on AM of devices, microfluidics and reactors for emerging approaches to sustainable mineral processing such as efficient mineral sampling, liberation, comminution and extraction.

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Laser power modulated microstructure evolution, phase transformation and compression-compression fatigue behavior in NiTi fabricated by laser powder bed fusion

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Laser powder bed fusion (LPBF) additive manufacturing provides great potential for creating the complex geometries that are desired for improved biomedical applications of NiTi. In this work, the role of laser power in controlling element evaporation and oxygen pick-up, and the subsequent microstructure and mechanical properties have been investigated. Two sets of LPBF process parameters with similar energy densities but different laser powers (HP: high laser power with high scanning speed, LP: low laser power with low scanning speed) were chosen to produce nearly fully dense and crack-free NiTi samples. The results showed that the HP and LP samples have different microstructures, phase transformation temperatures, and mechanical properties and also variability in different regions along the building direction. The HP parameters gave better overall properties and were chosen to manufacture porous NiTi with three different gyroid cellular structures (GCSs) with different density distributions. All the LPBF NiTi structures exhibited similar nominal compressive elastic modulus (5-7 GPa) to human bones. GCSs with graded density perpendicular to the loading direction exhibited a similar shear compression failure behavior and slightly better fatigue behavior compared to the uniform structure. In contrast, GCSs with graded density parallel to the loading direction exhibited a different layer-by-layer deformation and collapse behavior under compression while the fatigue life was worse than for the uniform structure.

Keywords: Additive Manufacturing, NiTi shape memory alloy, Phase transformation, Gyroid graded cellular structures, Fatigue behavior

Gas sensing arrays by LTCC and 3D printing technology

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This study presents the development of a hybrid digital material deposition platform for the fabrication of gas sensor arrays using a low-temperature co-fired ceramic (LTCC) and 3D printing technology. The platform utilizes a combination of aerosol jet printing (AJP) and inkjet printing techniques to deposit various materials including conductive, 2D gas sensing, and insulating/LTCC materials on a substrate. The resulting sensor array was tested for its ability to detect gases such as methane, carbon monoxide, and hydrogen. The results showed that the sensor array had a high sensitivity and selectivity towards the targeted gases, with a fast response time and low power consumption. The use of the hybrid digital materials deposition platform allowed for the precise control of the sensor's geometry and composition, enabling the fabrication of highly sensitive and specific gas sensors. This technology has potential applications in the fields of industrial process control, environmental monitoring, and healthcare sectors.

Controlling fracturing process in indirect tensile testing of 3D-printed cement-based materials

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3D printed cement-based materials are inherently anisotropic, due to the layer-by-layer printing process. Therefore, unlike "homogeneous" materials, the strength and fracture behaviour of 3D printed cement-based materials depend on properties and responses of both layers and the interfaces between layers. As a result, standard tests for "homogeneous" cement-based materials may not always be suitable for 3D printed ones, given the effects of layer orientation on both strength and fracture properties, making the fracturing process uncontrollable or unstable. This uncontrollable fracturing process can prevent the applications of advanced image-based instrumentations such as X-ray and Digital Image Correlation (DIC) for insights into failure of the materials. We present the application of AUSBIT (Adelaide University Snap-Back Indirect Tensile test) technique for indirect tensile testing of 3D-printed cement-based circular disc specimens. The use of indirect displacement control in this technique can help stabilise fracturing process and can extend the fracturing time, allowing appropriate use of DIC-based strain measurement for more insights into deformation and failure processes below the specimen scales. As always, challenges are recorded and discussed for future directions.

Effect of residual heat on Aermet100 microstructure produced by laser directed energy deposition

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Aermet100 is an ultra-high strength aerospace steel which is a favoured landing gear material due its enhanced toughness compared to older alloys. While less prone to failure, Aermet100 parts are still at risk of damage during service through wear, fatigue, or impact, leading to costly replacements. Laser directed energy deposition (L-DED) is an emerging repair tool for aerospace components, as it has the potential for extending part life by replacing damaged areas with additively produced material. As bulk heat treatment is not recommended for L-DED repaired parts, the properties of the deposit are dependent on the intrinsic heat treatment achieved during heat treatment. This is a major challenge for Aermet100, as its strength is typically achieved through a complex series of quenching, cold treatment at -72°C, and final tempering for secondary hardening. This study investigates the potential microstructures of L-DED processed Aermet100, with a specific focus on interlayer cooling and the accumulation of residual heat. For each condition, the evolution of carbies and other phases will be tracked and compared to the conventionally processed material, providing insight on the requirements for ideal deposition and limitations of in-situ heat treatment.

New Material Developments in Additive Manufacturing

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Additive manufacturing of metals is becoming increasingly important in various industrial sectors. While in medical applications there is already a widespread use of AM for customized solutions, the strongest innovation boost in AM is coming from aviation industry, followed by the energy sector, automotive industry, space and toolmaking industry. Unlike any other manufacturing technology, AM of high quality parts requires an in-depth understanding of the close relationship between the AM process, the material and the resulting component properties.
Within this lecture, new developments in additive manufacturing of Ni-based superalloys, copper and titanium aluminides will be discussed. Using powder bed-based and nozzle-based (wire and powder) AM processes a large variety of customized solutions is feasible, ranging from micrometer-size parts with filigree features to the meter scale of large-size components. With regard to the processing requirements either high accuracy or high productivity can be achieved, whereas a combination is difficult. To improve the mechanical properties and processability of AM parts, we recently developed AM systems technology that integrates additional modalities, including ultrasonic excitation, inductive heating or static and dynamic magnetic fields. Selected examples and application cases will be presented highlighting the potential but also the limitations of those hybrid AM approaches.

Reducing voids with an interlaced printing method for material extrusion-based additive manufactured parts

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Additive Manufacturing (AM) plays a crucial role in the Fourth Industrial Revolution, which closes the loop between cyber and physical systems. Among its many techniques, Material extrusion (ME) is one of the mostly adopted due to its low equipment and feedstock costs. Despite its advantages, parts manufactured using ME techniques may exhibit internal voids resulting from incomplete material filling of the parts' interiors. These voids can significantly degrade the mechanical, visual, and dimensional properties of the AM parts, impacting their overall performance. The sizes and distributions of the voids are influenced by various factors, including the cross-sectional shapes of material tracks, layers' shapes, and the layer infill strategy. In this work, a new toolpath strategy is developed to reduce void content in MEAM parts by adjusting parts' densities during their manufacturing process. Parts manufactured using a typical desktop 3D printer show a gain in average flexural strength of 17% compared with those produced with a conventional toolpath strategy. The new strategy is designed to be compatible with the most commercially available FDM printers. Through toolpath modifications, it is also expected to work with other MEAM techniques.

Microstructure and property manipulation of Fe-based shape memory alloys fabricated by additive manufacturing

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Fe-based shape memory alloys (SMAs) are a class of smart materials that can recover the original shape after large deformation. The functional properties of SMAs strongly depend on microstructural features, e.g., texture, grain size, and phase fraction. Laser powder bed fusion (LPBF) is an additive manufacturing technique that allows for manipulation of parts' microstructure. In this work, we demonstrate the possibility of integrating different microstructures in a single SMA component when the laser parameters (e.g., laser power, scan speed, scan strategy) are locally modified (Figure 1). In this way, samples with graded microstructure and, therefore, combined and tunable functionalities can be fabricated [1,2].
In order to fully exploit the potential of LPBF for the fabrication of Fe-based SMAs, new lattice structures and metamaterials are also manufactured. Taking advantage of the high flexibility and design freedom which characterize LPBF, 3D complex parts made of Fe-based SMAs are designed and fabricated. This shows that the material-inherent functional behaviors can be combined with additional functionalities deriving from intricate and compliant geometries to facilitate shape morphing, damping capability, auxetic behavior and extraordinary specific strength [3].

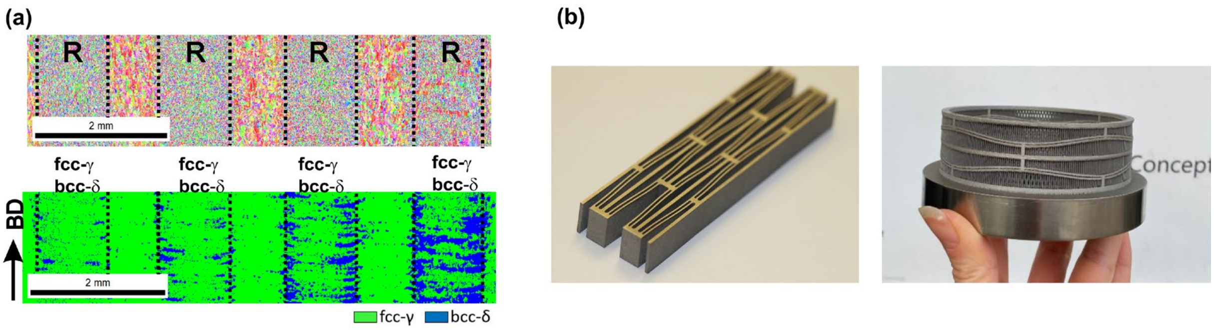

Figure 1: (a) microstructure modification in a Fe-based SMA sample; by rescanning specific areas, grain refinement and bcc-δ ferrite are locally introduced; (b) SMA metamaterials for energy absorption applications;

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Defect Morphology and Fatigue Life in Additively Manufactured Ti-6Al-4V

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Additive Manufacturing (AM) has been a reformative technology being adopted for many metallic alloys, especially Ti-6Al-4V. Since the inception of this technology many studies have investigated the variabilities in the mechanical performance of additively manufactured Ti-6Al-4V, especially the variability in fatigue performance. Although multiple factors attribute to variability in fatigue performance, many have noted the importance of defects. In general, it is agreed lack-of-fusion defects aligned perpendicular to the loading direction are most detrimental to fatigue performance. In this study, coupons were manufactured from three different machines and fatigue tested to failure. The results show most fatigue initiating defects were lack-of-fusion defects. These defects show different morphologies between matching fracture surfaces, indicating the importance of using defect morphologies from both surfaces when correlating them to fatigue life.

Direct fabrication of porous Mg alloy WE43 using Laser Engineered Net Shaping

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Abstract:

Magnesium (Mg) and its alloys are promising materials for bone recovery applications, such as orthopaedic implants, owing to their desirable mechanical and biological features. Mg alloys have similar density with natural bone to minimise the harmful effects of stress shielding and the biodegradability could eliminate the need for second surgery. Additive manufacturing of Mg alloys is of growing interest in both academia and industry due to enabling design capabilities not achievable with traditional manufacturing including complex porous structures and customised bio-implants and its biodegradable nature. However, it remains a challenge to build Mg alloys parts through additive manufacturing due to the high chemical reactivity and low vaporisation temperature.

This study aims to develop a process to fabricate Mg alloy WE43 with porous structures by Laser Engineered Net Shaping (LENS), which is a direct energy deposition (DED) AM method. The relationships between microstructure, defects and porosity and process parameters are established. In addition, the margins of accuracy and printability of porous structures as a function of process parameters are explored. This work is, for the first time, employs a LENS system to fabricate porous Mg alloy structures, which is expected to inspire future studies on 3D printing of Mg based materials.

Key words: Additive manufacturing, Laser Engineered Net Shaping, Mg alloys, Microstructure, Porosity-process relationship

WC-12Co addition in an Inconel 625 metallic matrix deposited through high-speed laser cladding as an alternative for hard chrome plating

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Hard chrome plating is widely used in the mining industry for repairing and refurbishing hydraulic cylinders; however, its use has been limited due to environmental impacts and adverse health effects on people coming from the process. In this present work, an alternative coating to hard chrome was investigated, with a blend of WC-12Co and Inconel 625 deposited using high-speed laser cladding under varying laser powers to produce a hard-facing metallic matrix composite coating. The microstructure features, microhardness and wear resistance were investigated. The generated coatings exhibited good metallurgical bonds with the 4140 substrates, crack-free and minimal porosity and with WC-12Co particles that were not completely melted during the deposition. The coating deposited with 1750W was more homogeneous along the substrate while comparing 1500W and 2000W, a clear relationship between laser power and WC-12Co dilution was observed. The addition of WC-12Co increased the Inconel 625 metallic matrix microhardness and wear resistance of the coating. Moreover, the hardness of the WC particles achieved more than 1000 HV0.2. Based on the results, the blend of Inconel 625 and WC-12Co resulted in a promising alternative for hard chrome plating.

Keywords: high-speed laser cladding, hard chrome plating alternative, carbides, laser power, wear resistance.

Designing and manufacturing of TPMS-structured paediatric metal bone plates

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Introduction
Bone and implant materials properties should be matched to prevent stress shielding resulting in bone resorption and subsequent periprosthetic loosening. The desired structural properties of a metallic implant can be controlled by tailoring the implants' geometrical features and base material.

Method
Using finite element analysis (FEA), various triply periodic minimal surface (TPMS) structures were fine-tuned to achieve similar characteristics to paediatric cortical bone, i.e., by adjusting relative density, yield strength, and stiffness. Ti-6Al-4V samples were manufactured using selective laser melting (SLM), which imposed a lower bound on the wall thickness and pore size to prevent powder entrapment. 3D-printed structures were analysed using a microscope for printing accuracy and surface roughness prior to experimental testing for FEA validation.

Results
Simulated stiffness and plateau stress values agreed with the experimental results considering the manufacturing imperfections (e.g., thickness variability and surface roughness). This allowed obtaining the relative density ranges in which the metallic TPMS structures have a similar stiffness and strength to paediatric cortical bone.

Conclusion
TPMS-structured metallic implant designs for bone fixation plates were manufactured via SLM and shown to fulfill multi-functional biomechanical design constraints.

Toward high strength and high conductivity copper-based alloys via additive manufacturing

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Copper and its alloy are promising materials in the electrification revolution due to their outstanding electrical and thermal conductivity. Copper is generally soft and ductile, so the demand arising from electrification is placing additional mechanical property requirements. While there is a trade-off dilemma between high strength and conductivity, additive manufacturing offers a significant opportunity to build strong and high-conductive components with complex shapes and multifunctional properties, accessing a vast spatiotemporal thermal and stress parameter space. Successful copper-based alloys have been made in metal additive manufacturing; however, there remains much uncertainty about powder characteristics and the correlation with the microstructure, mechanical properties, and conductivity of the additively manufactured copper materials. In this study, we extensively characterise copper-based alloy powders using various microscopy and microanalysis techniques. We also evaluate the printing parameters in laser powder bed fusion. Then we demonstrate how the chemistry, geometry, and microstructure of metal powder and printed part have a correlation with the build part property. Furthermore, slightly different copper-tin powders are compared to understand which powder characteristics lead to an interesting build part property. The results shed light on a pathway toward fabricating stronger and highly conductive copper-based alloys in additive manufacturing.

An Inherent Starin Calibration Approach for Laser Powder Bed Fusion of 17-4PH

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ABSTRACT: Metal Additive manufacturing (AM) is an appraised technology of manufacturing parts directly from a digital model by a layer-by-layer material build-up process. This advanced manufacturing technology can produce dense metallic parts swiftly with high quality and precision. Metal AM is being widely used in biomedical implants, aerospace, chemical, marine and automobile applications due to their freedom of part design and lightweight features. The AM process, e.g., laser powder bed fusion (LPBF) technology, needs to be optimally controlled by setting appropriate process parameters and conducting calibration processes to achieve best quality parts. Minimising residual stresses and mitigating crack-induced build failures are major challenge in this process and the existing techniques are trial-and-error based, not sustainable and efficient enough. This study develops an inherent strain calibration approach for the additive manufacturability of a commonly-used precipitation hardening stainless steel – 17-4PH. This approach optimally controls build and process parameters such as laser power, scan speed, and scan path strategies to minimise residual stresses as a one-stop solution and ensure predictable quality and consistency. It generates a material database for AM calibration process and quality assurance, which can be used to define material models in AM process optimal design for additively manufactured materials without build failures.

Keywords: Metal Additive Manufacturing (AM); laser powder bed fusion (LPBF); 17-4PH; calibration process; residual stress; and build failure.

Mesoscale numerical simulations for WAAM process for prediction of microstructure and its effect on mechanical properties

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Wire Arc Additive Manufacturing (WAAM) is a type of Direct Energy Deposition additive manufacturing process which takes advantage of well-established welding technology. It is consisting of a sequential deposition of weld passes and layers to form bases of engineering components later machined to the final shape. The WAAM process is characterised by high heat input, high deposition rate, high surface roughness and the anisotropy of material properties.

The high heat input leads to significant development of distortion and residual stresses, which can negatively affect the performance of the final component. At the same time, the high input can lead to the development of a highly textured microstructure. Hence, significant effort is underway to address the development of residual stresses, distortion, or anisotropy in the mechanical properties, which depend on the microstructure texture. It is, however, impractical and expensive to test all manufactured components. Therefore, the development of validated numerical models is of technological importance to obtain the required information.

This project is part of a larger project aimed at developing numerical simulations of the WAAM process to predict the residual stresses, distortion, microstructure and mechanical properties.

A Computationally Efficient Multi-Scale Modelling Tool to Aid in EBM Build Strategy Selection

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Additive manufacturing (AM) processes such as electron beam melting (EBM) are incredibly complex, with many variables affecting the build quality of the final product. These variables make it difficult to optimise the design and performance of the final printed product. Integrated experimental and computational approaches to AM have the potential to remove some of these anomalies by bounding the expected performance of the final print. This allows for the development of more targeted build strategies. However, for this integrated approach to AM design to be valuable, the simulation component must be computationally efficient. This capability enables a quick and detailed investigation of build strategies to determine the most effective combinations to be used in prints. In this study, we have developed a multi-scale modelling tool that simulates the process-structure-properties of Ti-6Al-4V, through the integration of various modelling techniques, such as cellular automata and crystal plasticity. We demonstrate how the tool has the potential to run virtual investigations of different build strategies and processing parameters to aid in reducing the experimental burden.

Extended microstructural evolution of cast iron laser cladding interfaces

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Abstract: Laser cladding processes allow for the refurbishment of industrial components via controlled and shallow application of thermal energy, efficient material usage, and the preservation of desirable bulk microstructures. Cast iron components synergise poorly with high thermal gradients produced by laser cladding operations, often producing classically brittle Fe-C heat affected zone (HAZ) microstructures. In the present study, single and multiple-overlapping laser cladding tracks on three grades of cast iron are produced and studied via optical microscopy. A survey of the literature demonstrates commonly clad materials (Ni-based coatings) and the opportunity to explore new cladding parameter windows (higher speed conventional laser metal deposition (1>m/min LMD)) and processes (extreme high speed laser cladding (EHLA)). The emergence and mitigation of cladding defects and heat affected structures are discussed. The size and distribution of graphite nodules in ductile cast irons is shown to affect the entire structure of the HAZ. Local dynamic pre-heating is shown to affect porosity levels in grey cast iron claddings. Novel orientations of the laser processing head are shown to interact with the formation of cladding defects. The cross-grade microstructural learnings contribute to a combined understanding of cast iron laser cladding interfaces.

Microstructural Refinement via High Deposition Rate Wire-Arc Directed Energy Deposited Ti-6Al-4V Using Cold Metal Transfer Technology

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Wire-arc directed energy deposition (waDED) of Ti-alloys via the cold metal transfer (CMT) technique with a novel welding characteristic offers significant cost reduction with higher production rates for 3D printing large-scale aerospace components. However, additive manufacturing (AM) processes with high-speed deposition rates involve complex thermo-mechanical profiles that promote heterogeneous microstructures and anisotropic mechanical properties within Ti-alloy builds.
This work seeks to comprehensively understand the microstructure evolution during CMT of a critical Ti-6Al-4V alloy and its capability to address material processing challenges. Here, CMT successfully stirs the melt pool and limits the epitaxial growth of the β-phase grains. Further, the unique thermal profile of the process refines both α- and β-phase microstructures and promotes the partitioning of alloying elements. Microstructure refinement unlocks more isotropic mechanical response when compared to other AM techniques. The chemical partitioning results in variations in α-lath size and local mechanical heterogeneities. However, it has a negligible effect on the overall mechanical performance of the as-build Ti-6Al-4V alloy. These findings showcase the potential of CMT to become a preferred processing route for manufacturing large-scale engineering parts for future aerospace applications and beyond.

Layer-by-layer model-based adaptive control for wire arc additive manufacturing of thin-wall structures

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Improving the geometric accuracy of the deposited component is essential for the wider adoption of wire arc additive manufacturing (WAAM) in industries. This presentation introduces an online layer-by-layer controller that operates robustly under various welding conditions to improve the deposition accuracy of the WAAM process. Two control strategies are proposed and evaluated in this work: A PID algorithm and a multi-input multi-output model-predictive control (MPC) algorithm. After each layer of deposition, the deposited geometry is measured using a laser scanner. These measurements are compared against the CAD model, and geometric errors are then compensated by the controller, which generates a new set of welding parameters for the next layer. The MPC algorithm, combined with a linear autoregressive (ARX) modelling process, updates welding parameters between successive layers by minimizing a cost function based on sequences of input variables and predicted responses. Weighting coefficients of the ARX model are trained iteratively throughout the manufacturing process. The performance of the designed control architecture is investigated through both simulation and experiments. Results show that the real-time control performance is improved by increasing the complexity of implemented control algorithm: controlled geometric fluctuations in the test component were reduced by 200% whilst maintaining fluctuations within a 3 mm limit under various welding conditions. In addition, the adaptiveness of designed control strategy is verified by accurately controlling the fabrication of a part with complex geometry.

Generating multi-directional compositional inhomogeneity via LMD-integrated rapid powder switch functionality

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Design approaches aiming to produce functionally graded materials (FGM) provide a tool to synergistically combine benefits of multiple materials in a single structure. Additive manufacturing (AM) methods, specifically, directed energy deposition (DED), are tightly bound to the development of FGM structures, in part due to their ability to produce multi-material (MM) gradients, which were shown to, at least partially, improve the interface quality. However, the majority of compositional gradients are one-dimensional (i.e. layer-wise change in composition in building direction). Expanding the MM capability into two and three dimensions (such as compositional change within a single layer and/or bead) is expected to dramatically improve the ability to generate high performance FGMs by AM.

In this work we present a new method of generating compositional gradient in more than one dimension of the build using a Rapid Powder Switch functionality integrated with the laser metal deposition (LMD) system at RMIT Centre for Additive Manufacturing. We show the application of this method to the manufacturing of functionally graded titanium alloys along with characterisation of build quality, generated microstructures and mechanical properties.

A Correlative Microscopy Workflow for Subsurface Sample Analysis

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ABSTRACT

The structure and properties of materials are often interralated and understanding the relationship between the two at the micro- and nano-scale is important in materials research. In view of this, a multi-scale imaging and analysis workflow that range from the macro- to sub-nanometer length scale has been developed. The new Sample-in-Volume Analysis workflow aims to provide navigational guidance to connect modalities necessary for multi-scale imaging and analysis. X-ray Microscopy (XRM) powered by synchrotron-calibre objectives with was deployed to identify the region-of-interest (ROI) within a large sample volume at the submicron scale. The identified ROI was accessed through material ablation using a femtosecond (fs) laser integrated on a Focused Ion Beam Scanning Electron Microscope (FIB-SEM). Once the ROI has been accessed, the site-specific samples may be further polished using the Ga^+ ion column, embedded on the FIB-SEM for high quality sample preparation. The low kV capabilities of the Ion-sculptor ensure high quality sample surface with minimal amorphization damage. The prepared samples can then be analyzed as necessary. In this talk, we use the Additive Manufactured Inconel 738 turbine blade to demostrate the benefit of this correlative microscopy workflow as an inspection tool.

Keywords: Correlative; Microscopy; Subsurface; Analysis; Additive Manufacturing.

Impact of Changing Thermal History on the Evolution of Copper Precipitates in Laser Powder Bed Fusion 17-4 PH stainless steel

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17-4 precipitate hardened (PH) stainless steel sees broad usage in the automotive, aerospace, and marine industries due to its high strength and corrosion resistance. Recent studies have looked at adopting the alloy for use in laser powder bed fusion (L-PBF) due to its good weldability. While several studies have expanded knowledge on the formation of ferrite, austenite and martensite based on the processing parameters, little is known on the formation of copper precipitates that are essential for improving the mechanical properties. Recent studies have shown the formation of Cu clusters and nanosized Cu precipitates in as-built samples, however, none have correlated their evolution based on the thermal history. The current study directly shows the impact of thermal history on the formation of Cu precipitates. Atom probe tomography (APT) was used in conjunction with thermal simulations to explain the evolution of Cu precipitates in a sample printed using a non-standard concentric scan strategy. The outer regions of the build showed no copper precipitation, while a gradual formation of Cu clusters, and then Cu precipitates was revealed moving towards the centre of the sample. Enhanced knowledge on heterogeneities due to site-specific thermal history can enable better control of microstructural evolution during L-PBF.

Grain boundary mobility regimes in fcc metals

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The simulation and interpretation of the microstructure formation during selective laser melting at the mesoscale relies on assumptions of the interface properties. In particular, the existence of temperature gradients reaching the melting temperature and the mechanical constraints of the solidified materials imposes a gradient of thermodynamics driving forces for grain coarsening.

In MD simulations, we address the emerging grain boundary mobility regimes by an external driving force (E.g. elastic anisotropy, shear stress) from cryogenic to the melting temperature. As function of temperature and driving force, the GB mobilities show for both GBs a complex nonlinear behaviour beyond the conventional conjecture of Arrhenius-like temperature-dependence in mobility and linear velocity-driving force relation by the motion of the same constituent GB features.
The observed dynamics regimes are discussed in context of grain growth phenomena in additive manufacturing conditions ranging from abnormal grain growth and the athermal grain boundary migration. These regimes are discussed in terms of the nucleation and propagation of extended GB defects, which rationalise the emergence of the observed mobility regimes.

Microstructure, mechanical properties and corrosion behaviour of heat-treatable beta-21S alloy fabricated by selective laser melting

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Dense (>99.5%) Beta-21S (Ti-15Mo-3Nb-3Al-0.2Si) parts were fabricated by selective laser melting (SLM) to study the properties of heat treatable titanium alloys in contrast to the widely studied Ti-6Al-4V α/β alloy. The microstructure of the alloy was anisotropic with large beta grains that were elongated parallel to the build direction. In the as-built state the alloy had a tensile strength of 860MPa and an elongation of 19%. After an optimised 2-step ageing process the tensile strength increased to 1380MPa and elongation decreased to 5.8%. The corrosion behaviour of the as-printed alloy in chloride solutions (as per ASTM G61) showed no evidence of localised attack and was similar to that observed for SLM and wrought Ti-6Al-4V.

Characterisation of 316L(Si) stainless steel parts made by arc Direct Energy Deposition (DED)

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Arc-DED (also known as wire-arc additive manufacturing, WAAM) holds promise for fabricating large stainless steel parts for various processing industries. Arc-DED 316L(Si) flat plate samples were fabricated, their microstructure analysed, and corrosion and tensile properties measured. Electrochemical corrosion testing (in accordance with ASTM G61) was carried out on the arc-DED samples as well as more traditionally manufactured stainless steels with similar composition. Additional "micro-electrode" corrosion tests were carried out on the Arc-DED samples to attempt to establish which microstructural features were sites of pit initiation. Immersion corrosion tests were used on plate samples with a range of post-build surface finishes (as built, acid washed, acid washed + wire wheel, and cool linished) to establish the likely corrosion behaviour of Arc-DED 316L(Si) parts. The properties (microstructure, tensile, and corrosion) of the arc-DED steel were compared to wrought and cast Cr-Ni-Mo stainless steels of similar nominal composition.

Process controlled automated composite manufacturing: parameter effects on bonding to process monitoring

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The automated fibre placement (AFP) process is an effective additive manufacturing technique where pre-impregnated carbon fibre tows are placed on top of a tool surface for manufacturing composite materials. The choice of manufacturing parameters have a critical impact on the laying quality. An inappropriate selection of input parameters can lead to defects, along with deviations from the design and structural requirements of the parts. It is therefore critical to identify the optimum processing conditions for manufacturing. The influence of process parameters and their interactions on the interlaminar shear strength (ILSS) of CF-PEEK composites made using a hot gas torch-based AFP process was investigated. Multiple process parameter combinations were used to enable a full-factorial statistical analysis which suggested a strong interaction between process parameters. The AFP manufacturing process was also simulated using finite element analysis (FEA) providing the capability to estimate the quality and part characteristics such as the inter-laminar bond quality. The results can be used to predict maintenance issues in real-time which is a focus of smart manufacturing and Industry 4.0 to improve manufacturing operations. A machine-learning based digital tool for process monitoring has been developed which can be used to predict the quality of the layup during manufacturing.

Impact of atomic-scale solute clustering on the high-temperature mechanical properties of additively manufactured Inconel 718

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Inconel 718 is one of the most widely used polycrystalline superalloys to produce turbine disks in gas turbine engines [1]. Its high yield strength while maintaining sufficient ductility and corrosion resistance at 650 °C make it an attractive superalloy for current and future aircraft engine designs [2]. A face-centered cubic γ-matrix provides grain boundary and solid solution strengthening [3]. The sluggish (co-)precipitation of strengthening γ'- and γ"-precipitates, and the limited formation of brittle phases and carbides make Inconel 718 suitable for welding and additive manufacturing (AM) [4]. However, the detailed high-temperature mechanical properties of AM Inconel 718 remained mostly unexplored.
Therefore, this work compares mechanical properties and microstructures of laser powder-bed fusion (LPBF) produced AM Inconel 718 during high-temperature loading. Tensile testing at ambient temperature, 250, 450, and 650 °C reveals pronounced changes in flow serrations. The grain structure and secondary phases, such as carbides and Laves phase, are studied by electron microscopy methods. Changes in the high-temperature mechanical properties are shown to be dominated by the evolution of atomic-scale clustering of Al, Ti, and Nb as quantified by atom probe microscopy. These insights are invaluable to understand the processing-microstructure-properties relationships of AM Inconel 718 for future gas turbine engines.

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Additive Manufacturing of Carbon Fibre Reinforced Polymer Brick-and-Mortar Structures

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Additively manufactured (AM) long carbon fibre reinforced polymer (CFRP) offers a combination of high specific strength, stiffness and design flexibility. However, CFRP generally has relatively low toughness and impact resistance compared to other structural materials, limiting its application. Additive manufacturing was utilised to create architectured materials (structures controlled at multiple length scales ranging from nano to macroscale), to improve the toughness of AM-CFRP. Specifically, the bio-inspired Brick-and-Mortar structure is formed using a combination of unreinforced and carbon fibre reinforced nylon. Typically, Brick-and-Mortar structures have been produced using additive manufacturing techniques whereby the constituents exhibit near-isotropic properties. The formed CFRP Brick-and-Mortar structures fundamentally differ from previously created structures, due to the inherent anisotropy of the uniaxial carbon fibre, and the limitations in intra- and inter-layer bonding of the extrusion-based manufacturing method. A novel extrusion technique using a co-extrusion nozzle, and custom toolpath planning, were used to take advantage of the anisotropic properties of carbon fibre and minimise failure due to poor bonding. Using these techniques, the formed Brick-and-Mortar structure exhibits increased toughness relative to uniaxial AM-CFRP, due to elasto-plastic failure.

The role of nano-oxides in the fracture of Ni-based alloys fabricated by laser-powder bed fusion (LPBF)

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It is common for alloys fabricated by laser powder bed fusion (LPBF) to contain a distribution of nano-oxides. Depending on the oxygen control in powder manufacturing, there may be a little, or a lot. Given their size is typically 20-50nm, they are not usually thought to be too detrimental. Some authors even try to exploit them in LPBF to make a form of oxide dispersed material (e.g. ODS).

In this study, a series of Ni-Cr-Mo based alloys (IN625, C22 and 282), sourced from various powder suppliers, were printed under similar conditions using LPBF. Tensile and Charpy impact tests were performed to assess their mechanical behaviour. Nano-oxides were observed in each alloy albeit with different densities. The IN625 and C22 samples showed a considerably lower impact energy than the 282, despite showing similar tensile responses. The nano-oxide spacing is shown to strongly correlate to the impact performance, despite their small size. The precursor metal powders were identified as the primary source of the oxides. This work demonstrates the critical role of nano-oxides on the fracture properties of these alloys and helps provide an upper limit for oxygen control during powder fabrication.

Reinforced Hollow-Strut Lattices for High Load Bearing Applications

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High-strength cellular materials are desirable as load-bearing space fillers in aerospace and automotive constructs. We aim to enhance the strength of conventional lattice topologies by introducing civil engineering concepts including; hollow-beams, shear walls, and internal and external stiffener plates. The outcome of these reinforcements is hollow-strut lattices that are among the strongest additively manufactured (AM) cellular materials reported. The hollow geometry provides greater resistance to bending, an enlarged core to resist eccentricity and a greater second moment of area. It has been established that the shape factor of a hollow circle will always be more structurally efficient than a solid circle of equivalent area/volume. Furthermore, the stiffener plates resist the localized node buckling of the hollow topologies that generally observe high-stress concentrations, and the shear walls resist in-plane lateral forces to redistribute the stress from the columns to the beams. The cellular materials were fabricated through the additive manufacturing process of laser powder bed fusion (LPBF) with the titanium alloy Ti6Al4V. The resulting reinforced lattices observed relative densities between 10 and 40%, with yield strengths and elastic moduli up to 260 MPa and 10 GPa, respectively. The yield strength properties far exceed comparable solid-strut and standard hollow-strut lattices of equivalent density pushing the envelope of lattice mechanical capabilities to challenge the yield strength of high-strength lightweight metal alloys like AZ91 or AlSi10Mg.

Advances in Multiscale Modelling of Metal Additive Manufacturing

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Metal powder bed fusion has become a key technology in additive manufacturing of parts or components having complex geometries. In this process, highly transient physical phenomena that occur at different length scales are difficult to observe. Additionally, experimental data needed for process understanding and improvement are challenging to obtain. Modelling therefore becomes a crucial tool to provide more insight into the process.

This presentation reports our recent advances in multiscale modelling of metal powder bed fusion process. Physics phenomena such as powder raking, powder melting and solidification, flow of liquid metal in the melt pool, heat transfer, microstructure evolution, and the residual stress and deformation of the component are treated using several different computational techniques. The framework to develop and link different models of different physical processes into a comprehensive model of laser powder-bed fusion additive manufacturing is discussed and demonstrated.

Mechanical Properties and Process Viability of Hybrid AM and HIP of Ti-6Al-4V Parts.

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Laser powder bed fusion (LPBF) for component printing is fast becoming a matured processing/manufacturing method. Despite gaining widespread adoption, the slow production speed of LPBF remains a challenge to overcome. To address this issue, one approach proposed has been a hybrid approach where the outer region ("shell") of a part is processed by LPBF and powder-filled internal region ("cavity") is consolidated via hot isostatic pressing (HIP). This study investigates the viability of using HIP to consolidate non-accessible powder-filled cavities in an LPBF Ti-6Al-4V part through microstructures analysis and tensile behavior. Samples were also fabricated via conventional HIP for comparison. Samples HIP at 850°C or 930°C had equiaxed microstructure within the "cavity" region as opposed to lamellar microstructure found in the shell. At 1010°C, rapid grain growth in the β phase field resulted in a similar coarsened microstructure across the entire material upon cooling. Tensile failure was found to always occurred within the cavity region which highlights the excellent bond across the shell/cavity interface. The strengths values were similar between the hybrid and the conventional HIP samples, though the former had poorer total elongation (~10 %) due to remnant porosity.

Effects of process parameters in 3D printing of short carbon fiber reinforced polymer filaments based on Micro-CT analysis

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Fused deposition modelling (FDM) is a widely used technique for 3D printing short carbon fibre reinforced polymer (SCFRP) composites by melting, extruding and depositing the filament layer by layer. Current research has primarily investigated the impacts of various printing parameters on the macroscopic mechanical properties of 3D-printed composites. However, there is a lack of understanding about how the 3D printing process parameters affect the microstructure and the mechanical properties within single extruded filaments. Micro-computed tomography (Micro-CT) provides a non-destructive solution to examine the microstructure characteristics. Therefore, this study aims to investigate the effects of several printing process parameters on the fibre orientation distributions, void distributions and tensile strengths of the individual extruded SCFRP filaments by undertaking high-resolution Micro-CT scannings and single filament tensile tests. Several levels of nozzle diameters, nozzle temperatures, printing speeds and extrusion rates are selected for experimental design. Image processing techniques are used to segment voids, carbon fibre and thermoplastic matrix and then quantitatively analyze the fibre orientation from the volumetric Micro-CT images. The relationships between printing parameters and the tensile test results are correlated based on the microstructural analysis, which provides insights into optimizing the printing process.

Functional Polymer Development for Additive Manufacturing and Advanced Manufacturing Technologies

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Additive Manufacturing (AM) processes have been in use since the 1980s, ranging from powder-based systems to resin-based systems, and utilise a variety of materials including polymers, metals, ceramics and natural materials. The initial development of AM was linked to the ease of processing thermoplastics and Fused Deposition Modelling (FDM) is among the most widely used processes in industry and the consumer market. Additionally, Direct Ink Writing (DIW) has also proven to be an inexpensive universal technique for producing 3D components in a broad range of materials and feature sizes. The need to produce highly complex end-use parts has led to increased interest in developing polymer composites to increase the functional properties of a pure polymer.

This research combines carbon fillers and boron nitride to explore in-situ printing of electrically conductive elements in a thermally conductive component, utilising both FDM and DIW to address the gap in functional multi-material, multi-technique 3D printing. While various carbon fillers and boron nitride have been used to produce electrically conductive composite polymers and thermally conductive polymers, respectively, this research focuses on simultaneous optimisation of multiple properties to better understand the interaction between conductive fillers and the polymer matrix, specifically to achieve the percolation threshold while maximising mechanical properties.

Resistance curve behavior of AlSi10Mg fabricated by laser powder bed fusion

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Keyword: Additive manufacturing, Crack resistance curve, Mechanical performance, Mesostructure, Anisotropy

Abstract

Laser powder bed fusion (LPBF) processed AlSi10Mg alloys have unique cellular microstructures and melt pool induced mesostructures that are distinct from conventionally processed material. However, our understanding of how processing conditions control these structural features and, in turn, mechanical performance, is weak. Here, we report our work on understanding the effect of processing parameters - layer thickness, hatch spacing, and scan strategy - on both tensile stress-strain behavior and crack resistance curve (*R*-curve) behavior in two orthogonal testing orientations. Results indicate that layer thickness and hatch spacing impact strength due to their influence on both grain size and cell structure. In terms of fracture toughness failure occurs predominantly in the vicinity of the melt pool boundaries which is primarily controlled by scan strategy. The arrangement of weak melt pool boundaries with respect to loading direction and crack front results in strong anisotropy in both tensile stress-strain and *R*-curve behavior, respectively.

A comparative study on the effects of different polishing techniques on tungsten carbide cutting tools

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Tungsten carbide (WC) based alloys are frequently utilised in cutting tools because of their greater tensile strength, compression strength, stiffness, and wear resistance when compared to other carbide-based alloys. The addition of cobalt as a primary binder improves the material's overall strength. In addition to the substrate qualities, geometry, cutting edge profile, and surface quality are crucial to the functionality and lifespan of cutting tools. A high level of control over surface preparation is vital to manufacture high quality cutting tools with desirable working perfomance, where a smooth surface is required for proper adhesion of subsequent coatings.

Currently, there is a growing desire to optimise the polishing process for surface finish and edge preparation of such cutting tools in order to improve performance and lower environmental impact. Various techniques, both in laboratory and industry, ranging from mechanical, chemical to specificially electrochemical polishing methods have been applied to reduce the surface roughness of the cutter and hone the edge radius of diverse tool materials.

However, for hard tool materials like WC, some of conventional polishing methods might not guarantee good surface results. Here-in, we report the effects of dry electropolishing, drag finishing, micro-blasting, grinding and vibrationary polishing on tungsten carbide cutting tools. Results show that dry electropolishing is the most efficient technique and resulted in an approximately 9 nm surface roughness on the surface of hard carbide tools.

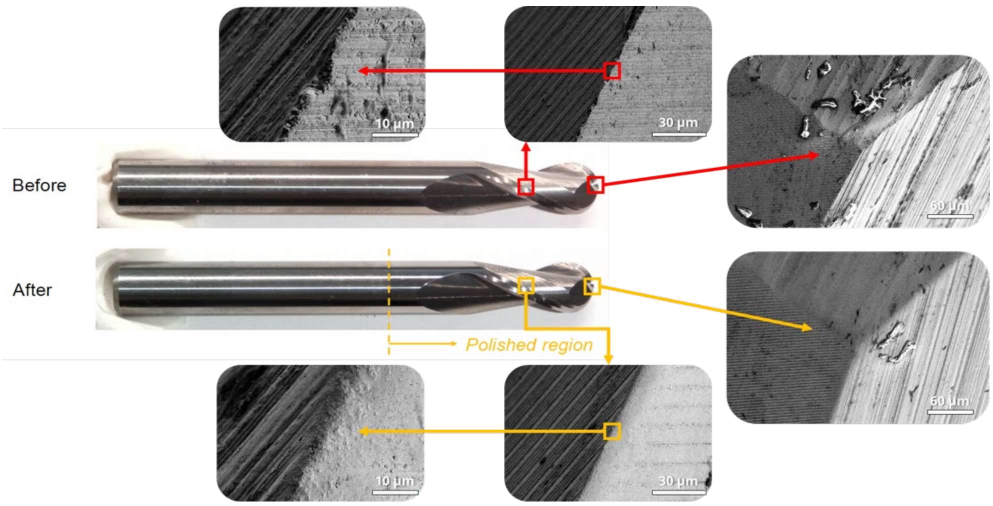

Figure 1. Tool before and after dry electropolishing with smoother surface and honed cutting edge without big defects.

How 3D sensing can enhance cold spray for additive manufacturing and repair

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Cold spray is a solid-state deposition method that uses supersonic speeds to produce coatings and repair worn or damaged components. In this technique, powder materials are converted to dense deposits under the severe localised plastic deformation that results when the particles impact a solid surface at Mach 1.5 – 2.5. Since robotic arms can manipulate a cold spray gun and direct the deposition process by adding material to specific regions, cold spray has gained sustained interest over recent years as an additive manufacturing process. Besides its ability to process oxidation-prone materials like titanium and aluminium, cold spray is attractive because it is capable of processing materials at rates of kilograms per hour. However, the high productivity aspect poses a challenge when making or repairing 3d objects, as geometry defects can quickly appear and propagate through the structure leading to increased local porosity and lack of geometry consistency. 3D sensing methods can be applied to cold spray to enhance the process consistency and reliability through geometry control. This talk will outline how 3D sensing techniques are helping to realise cold spray potential for automated repair and additive manufacturing.

Keywords: Additive manufacturing, Process technology, Titanium, Cold spray.

The Influence of Ultrasound on Laser Metal Powder Deposition: Melt Pool Characteristics and Formation of Equiaxed Grains

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With the advancement of additive manufacturing (AM), new methods and strategies were introduced rapidly to produce products that have improved microstructural homogeneity and mechanical properties. Controlling grain structures and texture during AM by laser metal deposition (LMD) is key to obtaining such desired mechanical properties. In conventional LMD processes of titanium alloy Ti-6Al-4V (wt.%), columnar grains are prevalent along the build direction due to the steep thermal gradient, which results from the intense heat flow from the small melt pool to the build plate and the lack of heterogeneous nucleation events in the liquid ahead of the solid-liquid interface. These coarse columnar grains lead to anisotropic mechanical properties and/or deterioration in the mechanical properties of the as-manufactured parts.

Extensive studies have been carried out to encourage the formation of equiaxed grains by promoting the columnar-to-equiaxed transition (CET). Fine equiaxed grains are favoured to achieve isotropic and improved mechanical properties by the Hall-Petch relationship. This study shows that introducing ultrasound during LMD can result in the formation of fine equiaxed grains, thereby leading to enhanced mechanical properties. The study systematically investigates the effect of different processing parameters coupled with an applied ultrasound on LMD beads and the resulting grain structures.

Additive Manufacturing of Polystyrene Foam: The State of Art, Need, and Applications

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In today's world, many plastic foams, such as expandable polystyrene, extruded polystyrene, polyurethane, and styrene methyl methacrylate foams, have a wide range of applications. Most Foam foundries, large prototyping, and sculpture-related industries uses polystyrene foam because of its unique properties such as lightweight, thermal cutting, cheaper, and ease of availability. The Industries currently practices three methods for shaping polystyrene foam: hot wire cutting, foam molding, and foam machining. All of the shaping options have some restrictions when it comes to creating complicated foam objects, at some extent complex shapes can be realized using conventional method by manufacturing the complex shape in different parts and joining them with hot melt adhesives, this will increase the cost and lead time, Therefore these issues can be resolved by adopting Additive Manufacturing (AM) due to several advantages, such as ability to product complex shapes in one go, better accuracy, and waste minimization. A very little literature available on polystyrene foam AM. This article discusses the need, present state of art, future scope and potential applications of polystyrene foam additive manufacturing.

Keywords: Polystyrene Foam, Additive Manufacturing, Large Prototyping, Foam Foundry

In-situ observation of deformation mechanisms in an additive manufactured CoCrNi medium entropy alloy

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In this work, Gaussian process regression was used to establish the optimized process window for equiatomic CoCrNi medium entropy alloys by laser powder bed fusion (LPBF). Six specimens fabricated with selected different process parameters combination follow the process window shown expected high relative density (>99%), different microstructure and mechanical properties. With increasing the energy, the grain size and melting pool size of as-built specimens are extending, while the texture of the top surface varies from <100>//BD prefer to <101>//BD prefer, which also varies in building surface from <101>//ND prefer to <111>//ND prefer. From the in-situ tensile test results, we found that the grains with different orientations showed different response to the stress. The grains with <101> orientation perpendicular to the loading direction showed more strain than grains with <100> orientation. The anisotropy of CoCrNi by LPBF is caused by two reasons. Firstly, the unmelting defects between the melting boundary will significantly decrease the mechanical properties. Secondly, the heterogeneity of grain structure (fine grains and coarse grains alternation) along the loading direction enhance the mechanical performance. This work gives new and deep insight into the relationship between the process, microstructure, and mechanical properties of CoCrNi by LPBF.

On the structural integrity of Fe-36Ni Invar alloy processed by different additive manufacturing techniques

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Fe-Ni alloys with a Ni content of 30-40 mass% are well-known for their low coefficients of thermal expansion (CTEs) near room temperature. The lowest CTE in the Fe-Ni system can be found in the single γ-phase Fe-36Ni alloy composition. Due to its invariant length with respect to a temperature change, this alloy is better known as Invar alloy. Due to its low CTE and excellent mechanical properties in cryogenic environment it is commonly used as a high precision and highly reliable material in components where superior dimensional stabilities are required. As a result of high ductility and pronounced work hardening combined with a low heat conductivity conventional machining of Invar is challenging. These challenges become most pronounced when machining of complex precision components is required. Additive manufacturing (AM) techniques represent powerful and promising candidates to overcome these challenges as they enable a tool-free near-net shape production of complex freeform components. Since many components made of Invar, e.g. precision optics instruments, are used under very complex loading regimes, often including cyclic loads, the performance under fatigue loading needs to be investigated. Thus, the present study will provide insights on the structural integrity of Fe-36Ni Invar alloy processed by different AM techniques.

Design of novel dispersoid strengthened (DS) alloys for additive manufacturing using an integrated computational materials engineering (ICME) framework.

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Towards the development of high-performance alloys with superior properties (strength and creep), dispersoid-strengthened (DS) alloys manufactured via additive manufacturing (AM) present a promising opportunity for design of high-performance components (gas burner heads). Challenges arise in alloys not designed for AM due to complex laser-material interactions. Hence, the integration of multi-scale multi-physics experimental and computational methods, i.e., integrated computational materials engineering (ICME), in alloy design for AM is a promising approach to address this issue. This presentation emphasizes the use of an ICME framework to accelerate the development of DS alloys, focusing on process-structure-properties-performance relationships. A finite-element (FE) model supported with material properties from CALPHAD simulations presents the AM processing characteristics integrated into the phase-field software MICRESS® to understand the process-structure relationship. Based on the numerical microstructures, the properties and performance of the DS alloys are determined through modelling creep and tensile behavior, and FE analysis. The individual process steps in the manufacturing chain and product's performance under service conditions are described by comprehensive process and material simulations. Finally, a novel DS alloy design framework is developed by combining these material models at multiple scales. The relationships and the robustness of the ICME approach will be critically discussed.

A voxel-based framework for nonplanar robotic 3D printing

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Robotic additive manufacturing (AM) promises affordable automated manufacture of large format components and structures. However, there are still many challenges associated with robot toolpath programming and overall process stability. We have successfully used parametrically driven experimentation to find suitable process parameters for laser metal deposition (LMD) and wire arc additive manufacturing (WAAM). Furthermore, complex geometries such as gears and rocket nozzles have been produced parametrically. Programming and optimising such toolpaths is time-consuming and cost prohibitive for many industrial applications. This talk presents a framework whereby voxels are used to automatically compute nonplanar toolpaths, simplifying path planning on irregular substrates while also eliminating the need for support material. A scalar distance field is swept across all voxels within the build region starting from the substrate. Next, a surface mesh is computed for each layer by interpolating distance values at neighbouring voxels. Concentric nonplanar toolpaths are then generated by sweeping a second wave across each layer. These techniques operate in real-time with enough resolution to model a single weld bead. The voxel approach also shows promise in use as a general framework for comparing sensor data with expected surface topology.

Continuous3D Software for Robotic Additive Manufacturing

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Metal additive manufacturing (AM) using 6-axis robot arms offers the potential to build large objects using high feed rate metal deposition processes such as cold spray, laser metal deposition (LMD) and wire arc additive manufacturing (WAAM). Robots also enable a reassessment of how metal component repairs and modifications are performed. While off-the-shelf hardware is readily available, there is a need for digital tools to derive specialized tool paths, to automate the process of robot program creation and to assist in geometry monitoring and feedback control. CSIRO has been developing software called Continuous3D, which is a digital manufacturing solution for robotic AM. The software integrates sensing and machine vision algorithms with toolpath planners, allowing a robotic system to measure the workpiece geometry and determine an appropriate repair program. Real time sensor data can be processed and displayed during a build, allowing layer-by-layer reconstruction of the build shape and comparison against the original CAD geometry. Procedures are also available for repair of defects on parts where CAD data is not available. This presentation outlines the experimental research that has been conducted to develop and test the algorithms that are incorporated in Continuous3D.

Methodology for the integration of Fiber Bragg Grating (FBG) sensors in an additively manufactured component

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Fiber Bragg Grating (FBG) are fiber-optical sensors that detect temperature and strain. These sensors are resistant to electromagnetic interference, and multiple sensors can be integrated into the same fiber to create a comprehensive sensing system allowing quasi-distributed sensing. FBGs can be helpful as embedded sensors across various applications, e.g., gas burners and heat exchangers, due to their compact and non-intrusive design and the possibility of continuous real-time monitoring. Additive manufacturing (AM) can allow designing and manufacturing channels enabling the integration of FBG sensors. This study focuses on integrating FBGs within components manufactured via metallic laser powder bed fusion (PBF-LB/M), which is particularly challenging due to the high process temperature and manufacturing constraints such as surface quality and dimensional accuracy. This study presents a methodology for designing the sensor channels -considering the bending radius and powder removability- and successfully integrating FBGs during and after the PBF-LB/M process. The challenges and possible solutions required for post-processing the components are also presented to ensure the successful integration of FBGs. Finally, the response of the integrated FBG sensor in a burner tip manufactured from 316L is quantified and compared to that of a thermocouple up to 1000°C.

Keywords: Additive Manufacturing; Laser Powder Bed Fusion; FBG Sensor; Sensor integration; Component design

Global efforts on the development of standards for additive manufacturing

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Additive manufacture (AM) is emerging as a viable manufacturing method for the fabrication of aerospace components, parts on demand for the energy sector or metallic biomedical implants. Further acceleration of the adaptation of AM technologies and the development of new applications require a rigorous development of standards framework. Multiple standards bodies across the globe including ISO, ASTM and Standards Australia joint forces and released several standards. Further work is underway to map out the full AM process chain.

This presentation will provide an overview of the established standards and outline future directions towards regulatory certification and qualification. Additionally, the recent trends towards the use of in-process monitoring data for detection of flaws in metal AM and application of machine learning for real-time analysis will be discussed. It is anticipated that these new tools will facilitate the qualification and certification of produced parts for numerous industries including aerospace, energy and medical.

Environmentally Assisted Cracking and Cavitation Performance of Nickel Aluminium Bronze in Salt Water: Cast vs LPBF

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Nickel aluminium bronze (NAB) is a copper-based alloy used in marine applications due to its combination of high strength, and high resistance to wear, biofouling and corrosion in seawater. NAB also has excellent resistance to environmentally assisted cracking (EAC) and cavitation erosion in chloride environments.

While NAB used in seawater system components (e.g. valves) is traditionally cast or forged, NAB can also be additively manufactured. When fabricated by laser powder bed fusion (LPBF) a very different microstructure is obtained as a result of the rapid cooling. This work compares the environmentally assisted cracking (EAC) and cavitation performance of cast and LPBF NAB in a salt water environment. The LPBF NAB is subjected to a range of post-build heat treatments to sample different microstructures to compare with cast NAB.

EAC testing of NAB was performed by slow strain rate tensile testing (SSRT) in accordance with ASTM G129 within a reticulating salt water chamber. Cavitation resistance testing was performed in salt water by inducing the formation and collapse of cavities on the specimen surface by ultrasonic vibration in accordance with ASTM G32.

Microstructure Evolution in Laser Powder Bed Fusion-built Fe-Mn-Si Shape Memory Alloy

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Abstract

The laser powder bed fusion (LPBF) technique offers design flexibility in fabricating metallic parts but is limited by its requirement for specialty powder composition. This work extends the technique's adaptability by fabricating the first-ever Fe-30Mn-6Si (wt.%) alloy, which has potential use as a biodegradable shape memory alloy (SMA). A fully dense part was achieved after examining the influence of laser power, scan speed, re-scan strategy, and their equivalent linear energy density (LED) on density. Interestingly, different microstructures were observed at different LED values; high LED resulted in columnar structure with strong crystallographic texture, while low LED resulted in almost-equiaxed structure with weak texture. To explain these findings, a finite element analysis (FEA) was conducted from the single-track laser scan experiment, revealing a varying temperature gradient, cooling rates, solidification rates, and temperature profile as a function of LED, which influenced the microstructure. The relationship between hardness, grain size, phases present, and crystallographic misorientation were then analysed with reference to a control alloy of similar composition but prepared by arc melting. This study broadens the application of LPBF to Fe-Mn-Si SMAs and provides new insights into the influence of processing conditions on microstructure and hardness.

Diamond Coatings and Material Characterisation of Additively Manufactured Ti-64 Complex Structure

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Replacement heart valves are predominantly made of metallic alloys owing to their biocompatibility with blood and surrounding soft tissue. However, given that metals are not commonly found in the body, carbon coating have been investigated to improve the interface. Here we have investigated the use of additive manufacturing to create complex diamond-coated heart valves. By coating a complex titanium alloy (Ti-64) structure with diamond, we improved the biocompatibility and corrosion resistance. To achieve best growth, the common technique is to use a Faraday Cage within the chemical vapour deposition (CVD) system to spread the plasma and thus the diamond deposition on a complex surface. However, this technology reduces the peak growth rates and plasma pressure due to overheating of cage and consequently damages the sample. Here we report the development of a novel technique to coat a complex additively manufactured Ti-64 structure with growth of polycrystalline diamond (PCD) film without using the Faraday Cage, providing a better technique to deposit diamond uniformly on the samples. Two diamond deposition conditions were considered for material characterization: (i) non-nanodiamond seeded heart valve samples; and (ii) nanodiamond seeded heart valve samples. Lastly, the microstructure analysis and material characterization (such as SEM and EDX) were conducted to study the diamond coating.

The Present and Future of DED-Arc Technology

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With the continuous development and maturity of technology and market, DED-Arc technology has been gradually applied to various application scenarios, from prototype development to mass production. Due to it's big advantage in cost and efficiency, DED-Arc has also been widely applied to a variety of industries, such as aviation, space, defense, maritime, energy, tooling and molding, and etc. But in order to meet the needs of production, not only reliable digital equipment and qualified material, but standardized management system and professional personnel training as well are urgently needed by industrial users. So what achievements have been made in the past decade ? And what are the prospects and challenges in the coming future?

Cast vs Additively Manufactured Nickel Aluminium Bronze (NAB): Effect of microstructure on mechanical performance

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Nickel aluminium bronze (NAB) is a copper-based alloy used in marine applications due to its combination of high strength, and high resistance to wear, biofouling and corrosion in seawater. Traditionally NAB components have been cast or forged, but additive manufacturing is also an interesting fabrication technique for NAB. The phase formation during solidification of NAB is rich and this translates to a sensitivity to solidification conditions. The microstructures obtained can differ significantly amongst different AM types, and from that typically obtained by casting.

In this work, NAB is additively manufactured by two different methods: laser powder bed fusion (LPBF) and a hybrid laser-wire process, and each is subjected to a series of different post build heat treatments. The resulting microstructure evolution and mechanical properties are compared against two NAB cast alloys. The mechanical performance for each alloy was investigated by tensile and instrumented Charpy impact testing.

CRUSHING BEHAVIOUR OF FUNCTIONALLY GRADED HYBRID LATTICES FABRICATED BY ADDITIVE MANUFACTURING

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The advancement of additive manufacturing has enabled a higher degree of freedom in design approaches of functionally graded (FG) lattices. In this study, two types of grading strategies, i.e., uni-directional density grading and bi-directional density grading were used to design FG hybrid lattices. Three different unit cell topologies were used in designing hybrid structures, namely body-centred cubic (BCC), rhombic dodecahedron (RD), and octet (OT). For different FG lattices, three types of grading methods were employed. In the first method, unit cells kept the same strut diameter, so that density grading was achieved by cell topology. In the second method, a controlled density gradient of 35% in the adjacent layers was achieved by tuning strut diameters in different layers. In the third method, unit cells of different topologies had different strut diameters to maintain the same relative density in all layers. All the structures were fabricated by multi-jet fusion (MJF) using PA 11 and tested in quasi-static compression to obtain stress-strain curves. Finite element models were constructed to further investigate deformation patterns and stress distribution. The study showed that the lattices can be tailored for prescribed crushing performance by introducing hybrid functional grading of both strut diameters and cell topologies.

Application of Metal Additive Manufacturing to Manufacturing of Aluminium Extrusion Dies

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Conventional methods for producing aluminium hot extrusion die rely on subtractive manufacturing methods, which limits design freedom of the die profile and the subsequent extrudates. Furthermore once the die geometry wears it is difficult to repair. Advances in metal additive manufacturing (AM) offer a solution, enabling next-generation dies with extra complexity and the repairable critical geometry to extend die life.

The project aims to build a hybrid extrusion die using PBF-LB and H13 steel which has been traditionally thought to be unweldable. H13 steel was successfully printed on a forged H13 substrate and was optimized to obtain a robust interfacial bond. Tensile testing was able to show that fracture did not occur at the interface. This project will advance the application of AM in producing aluminium extrusion dies and have practical applications for the industry.

Towards Additive Manufacturing of Metallic Wheels for Mars Rovers

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Abstract:

Mars has attracted major space exploration activities in recent years. And advanced space rovers have been developed to explore the Martian surface, which demands better rover wheels to cover various terrains, drive over sharp rocks, and endure extreme temperatures and space radiations. Rover wheels made of common structural alloys, such as the aluminium alloy used for the Curiosity rover wheels, have been reported to have very limited deformation capability and high susceptibility to damages. This work investigates the potential of using superelastic shape memory alloy (SMA) to achieve higher recover rate after large deformation. The deformation behaviour of NiTi SMA is compared with structural alloys AlSi10Mg and Ti6Al4V, all processed by laser powder bed fusion (LPBF) additive manufacturing (AM) process. The chemical composition, phases, transformation temperatures, microstructures and tensile properties are investigated to obtain the best superelasticity. The process issue of excessive Ni evaporation during the laser melting of NiTi powder in the AM process is discussed in detail. At the end, we discussed the potential, advantages, and challenges of using AM to produce high-performance metallic rover wheels.

Predicting the structural compliance of powder bed fusion components using image-based simulation

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Structural compliance is a key consideration in the manufacture of medical prosthetics. A mismatch in stiffness in comparison to bone can lead to negative patient outcomes. Recently, powder bed fusion (PBF) has emerged as a preferred manufacturing route in such applications as complex, porous designs can be achieved to promote bone ingrowth and tailor compliance. However, PBF components frequently contain manufacturing defects which can impact mechanical response and render them unfit for end use. Such defects include pores or cracks in solid material or missing struts or geometric inaccuracy in porous cellular structures.

In this work, we present a method to simulate the elastic deformation response of as-built PBF structures containing defects. The method utilizes X-ray Computed Tomography (XCT) and Finite Element (FE) analysis, technologies widely available in the medical engineering industry. First, the component is imaged in 3D using XCT, then the volume is converted into an FE mesh, capturing the as-built component geometry and manufacturing defects. The elastic deformation response is then simulated in Abaqus to predict the structural compliance and examine the influence of defects. Two case studies are presented, a solid component containing cracks of different orientations, and a porous triply periodic minimal surface (TPMS) structure.

Nanocomposite based dispersion by laser additive manufacturing

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With the advancement in technology, Additive Manufacturing (AM) or 3D printing holds a higher potential in numerous industrial sectors by reducing cost, energy consumption, carbon footprint and elevating functionality and production. In the recent years, Metal AM have gained much popularity in almost every sector. Mechanical and thermal properties of traditionally used metals in laser printing changes. But incorporating nanoparticles into metal layers can enhance their performance. Aluminium deposition was reinforced by nanoparticles layer by layer using laser melting of nanocomposite powders. We observed that the nanocomposite delivers a yield of 1000MPa, Young's modulus of approx. 210 GPa and plasticity of over 12%; which in comparison to aluminium is much higher. This gave higher strength, thermal stability (upto 400 ℃), and ultrafine grain size.

Conductivity Measurements of Additively Manufactured Metals Using a Resonator for the K-Band

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The conductivity of materials plays a significant role in the device performance. Though additive manufacturing is becoming more popular for electronic device and system manufacturing, only very few reports are available to study the conductivity of the materials. In this study, resonating structures are fabricated using additive manufacturing to measure the conductivity of three types of metal disks printed using a selective laser melting (SLM) process. The quality factor of the resonator is measured, and the conductivity of each printed metal is estimated. This work will provide the details of the theory and techniques required to estimate the conductivity of the material. This work will contribute to the understanding of conductivity on additively manufactured metal devices, which can be used in the K-band.

Additive Manufacturing: From Nonequilibrium Interfaces to Strange Grains

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Additive manufacturing (AM) is developing into a viable process for fabricating intricate metallic parts. The velocities of the solid-liquid interfaces present during AM can lead to interfacial nonequilibrium at the moving solid-liquid interface. Moreover, the highly directional nature of the solidification process yields very unusual grain structures. A discussion of the development of grain structure during powder bed AM of stainless steel 316L will be given. The large-scale phase field simulations of the morphological development of grains illustrate the complicated interaction between interfacial mobility anisotropy, weld pool shape, laser scan strategy and multiple powder layers on the resulting grain morphology. A comparison between experimentally measured grain shapes and those predicted by simulation will be given. A thermodynamic description of moving non-equilibrium interfaces is developed that is applicable to concentrated multicomponent alloys. This theory has been integrated with a theory for dendritic growth in multicomponent alloys that incorporates CALPHAD descriptions of the Gibbs free energies. This computational tool yields diagrams for the solidification morphologies of complex multicomponent alloys of industrial importance during additive manufacturing. Solidification morphology diagrams and predictions of primary phase formation in 316L will be discussed.

4D printing of self-expandable scaffolds for bone tissue engineering

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4D printing of smart scaffolds based on fused deposition modelling (FDM) has gained growing interest in treating irregular bone defects. However, it is still constrained by the lack of printable shape-memory filaments and structures comparable to human bone. Herein, we reported 4D printing of bioactive smart scaffolds that are structurally and functionally similar to cancellous bone. A shape memory filament made of TPU and PCL was developed for the FDM printing of smart scaffolds with rectilinear, triangular, and gyroid architectures to investigate the FDM parameters on their mechanical and shape memory performance. An additional bioactive polydopamine coating was also applied to the pore walls of scaffolds. Based on the printability assessment, the nozzle temperature and multiplier extrusion were the most significant parameters affecting the extrudability of the developed smart filament. Thermomechanical cyclic tests demonstrated that the infill pattern and density parameters could tune the shape fixity (R_f), shape recovery (R_r), and recovery rate of programmed scaffolds. The rectilinear scaffold with 20% infill density showed the fastest shape recovery (~5 min at 45°C) with excellent shape memory effect (R_f>92%, R_r>95%). While the polydopamine coating didn't impact the shape memory properties, it remarkably increased the hydrophilicity and cytocompatibility of the PDA-modified scaffolds.

Keywords: 4D printing, Fused deposition modelling (FDM), smart bone scaffold, shape memory filament, Irregular bone defects

Moonshots: The Art and Science of Large-Scale Additive Manufacturing (Metals, Composites, Concrete)

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A "Moonshot" is often used to refer to an audacious plan or aim to do something that seems almost impossible, even to the experts. Ambitious projects seek to stretch the comfort level of otherwise conservative engineers to achieve a desired objective. In doing so, barriers are broken, fundamental challenges are revealed, and scientific research questions can be posed which guide the direction of future technological development. At the Oak Ridge National Laboratory's (ORNL) Manufacturing Demonstration Facility (MDF), a cultural embrace of "moonshots" has led to high profile demonstrations like 3D printed cars, houses, excavator components, and even a nuclear reactor. Each has stretched the bounds of the possible in additive manufacturing and the resolve of even the most senior engineers. In the wake, unexplored opportunity abounds in the unsolved challenges overturned by the chaotic scramble, where state-of-the-art demonstrations can be converted into disciplined scientific research programs aimed at solving some of the worlds most important challenges. In this presentation, Dr. Brian Post, Group Leader of the Manufacturing Systems Design Group at ORNL, will discuss some of the moonshots and the corresponding scientific advancements and impacts that have resulted from this model of innovation at the MDF.

The Investigation of Copper Alloy Fabricated by Laser Powder Bed Fusion (LPBF)

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Copper and its alloys can achieve outstanding thermal and electrical conductivities, which is of great interest as a critical platform technology in the electrification revolution. Additive manufacturing (AM) offers not only the opportunity for complex build parts design due to its high degrees of freedom in the fabrication process, but also the potential to improve mechanical strengths, maintaining superior conductivity. While progress has been made in additively manufactured copper alloys, the powder characteristics-process parameters-as-fabricated properties relationships remain unknown. Concerning the powder characterisation, the complete characterisation of copper alloy powders is rarely done. In this study, we characterise metal powders to develop a rigorous methodology via scanning electron microscopy (SEM), electron backscattered diffraction (EBSD), transmission electron microscopy (TEM) and other microanalysis techniques for quantifying copper alloy powder properties, connecting it to properties of build material produced by LPBF process. Meanwhile, we consider the laser parameters influences in the LPBF process. Furthermore, we correlate the powder-process-as-built property relationships toward developing advanced copper alloys with excellent mechanical properties and superior conductivity.

From Neutron Diffraction to Tool Repair: How Fundamental Scientific Research Translates to Industrial Impact for Hybrid AM Processes

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Hybrid manufacturing systems combining directed energy deposition and subtractive capabilities in the same machine envelope were initially debuted in 2014. However, these systems have seen little industrial adoption. Given that most additive parts are preforms with required conventional post-processing to make them functional, it seems like hybrid systems would offer significant advantages. While more capable, the science of interleaving AM and conventional machining operations is complex. Fundamental understanding of factors like residual stress, microstructural evolution, and geometric distortion in these complex processes remains the primary barrier to success. This presentation details how research into the fundamental thermophysical properties of hybrid processes is being translated to real-world applications. Covering specific developments like a wire-arc hybrid machine installed in ORNL's Spallation Neutron Source and the development of the world's largest metal-wire laser DED hybrid system, the audience will gain an appreciation of the challenges and future opportunities for hybrid AM systems.

Analysis of residual stress measurement for WAAM applications using neutron diffraction and the contour method

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Additive manufacturing methods like wire arc additive manufacturing (WAAM) open a new field to reduce manufacturing costs and minimizing waste for various components. One of the major issues limiting the withstandable mechanical loads and geometrical tolerances of the component and are residual stresses caused by the thermal input during production.

Residual stresses consist of microstress (caused e.g., by different microstructural thermal expansion coefficients) and macrostress (variably induced by the production process and through interactions within the component). As these stresses tend to show 3-dimensional components that are hard to predict, the reliable measurement is crucial.

Multiple measurement methods have to be applied to detect the different components of residual stress. The contour method detects one macrostress component in for a given plane, whereas neutron diffraction is capable to detect all 3-dimentional components of both, mircro- and macrostresses. In the following, the specific opportunities and limitations shall be analyzed and conclusions for facing these challenges will be given.

Defect Detectability and Limitations of X-Ray Micro-Computed Tomography in Laser Powder-Bed Fusion of Ti-6Al-4V

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Reliability and repeatability of Additive Manufacturing (AM) process has been a key issue and the main bottleneck for adoption into applications. The material and process qualification protocols for structural materials have been rigorous, particularly for aerospace. The qualification requirements have been in place to quantify conventional materials and manufacturing processes. All AM processes must demonstrate predictability of mechanical and fatigue properties, reproducibility and stability from build to build. The variability of mechanical properties (static and fatigue) are related to the difference in microstructure and defect distribution. If AM is to be accepted as a mainstream manufacturing technique for Aerospace parts, non-destructive inspection, such as defect detection using X-ray micro-Computed Tomography (µCT), will play a crucial role enabling a path for build quality assurance and rapid certification capability. The aim of this investigation is to provide the current capabilities and limitations of commercial xCT as a means of quality control and qualification assessment. Results showed some fatigue initiating defect was completely missed by both µCT and Synchrotron radiation Micro-Computed Tomography (SRµCT). These defects consisted of a very flat in morphology and likely do not occupy enough spatial resolution through the build direction to be detected by automated threshold-based defect detection algorithms.

Detection of Process-Induced Defects Using Acoustic Emission During Laser Metal Deposition Process

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Laser metal deposition (LMD), also commonly referred to as laser cladding, is a state-of-the-art additive manufacturing technique that can produce free-form metallic and metal matrix composite structures. With continuous improvement, LMD offers numerous advantages for depositing high-quality wear and corrosion resistance coatings onto metallic surfaces. Despite advances in deposition control, there remains a high possibility of process-induced defects (e.g., porosity and cracking) occurring in manufactured parts due to the process parameter settings and dynamic nature of the process. The presence of these defects in manufactured parts reduces the quality of the final part and decreases wear and corrosion resistance. In this study, we report the application of an acoustic emission (AE) based online defect detection technique to identify & quantify process-induced cracks during the LMD process. The acoustic signatures generated from the LMD process were analyzed in-situ with a novel signal processing technique that can identify cracking events during the fabrication process. The robustness of the AE technique to identify the process-induced defects for quality assurance during LMD process is also summarized.

Additive Manufacturing in Chemical Sciences and Engineering

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Abstract:

Additive Manufacturing is one of the key enabling technologies for the fourth industrial revolution (4IR). While the automotive, aerospace engineering, mechanical engineering and biomedical industries have hastily adopted AM technologies for associated benefits, the chemical industries have been lagging in the uptake due to the lack of agility and adaptability in industrial chemical processes.

Application of AM to chemical sciences and engineering engenders benefits such as complete design freedom, capability to manufacture sophisticated geometries, improved material utilization, tool-less fabrication, and shortened lead times.[1] Thus, AM has tremendous potential in facilitating wide-scale upgradation, improvisation, and miniaturization of chemical processing equipment and manufacturing plants in line with the ethics of Industry 4.0. Future chemical reactors will be complex tailor-made devices with design optimized for fluid and particle flow, heat and mass transport, and reaction thermodynamics. This will lead to improved efficiencies of existing chemical processing technologies, improved process economics, environmental compatibility, reduced carbon footprint, and reduction in wastes and emissions.

This talk will focus on the emerging applications of additive manufacturing in chemical sciences and engineering such as clean energy, sustainable critical mineral processing, carbon dioxide capture and utilization, 3D microfluidics, advanced microreactors and sensors.

Reference

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Oxidation Behaviour of $Al_{0.3}CrFeNiTi_{0.3}$ High Entropy Alloy Coating Prepared *via* HVOF

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A focus of high entropy alloys (HEAs) has been their use as part of thermal barrier coatings (TBCs) for gas turbine components, specifically as a bond coat. A challenge for current bond coat materials is the formation of a thermally grown oxide layer that, at high temperatures, can be detrimental to the TBC service lifetime. HEA coatings prepared by thermal spray (TS) methods present a possible solution to this challenge, but their use in replacing current bond coat materials is limited by the understanding of their oxidation behaviour; thousands of compositions are possible and many have not been investigated. Herein, the oxidation behaviour of an $Al_{0.3}CrFeNiTi_{0.3}$ HEA coating, prepared *via* high velocity oxygen fuel (HVOF) spray, is investigated at 500, 700 and 900 °C for 50, 100, 150 and 200hr. XRD, optical profile and SEM-EDS analysis are used to confirm the most suitable sample preparation method, as well as to characterise the elemental makeup and microstructure of the thermally grown oxide layer. The oxidation kinetics are quantitatively determined *via* mass change. After 50hr a layer of mixed oxides appears, followed thereafter by a uniform Al_2O_3 layer. Based on the results, $Al_{0.3}CrFeNiTi_{0.3}$ could be a potential bond coat material for TBCs.

Keywords:

HVOF, TBC, high entropy alloy, oxidation, bond coat, thermal spray.

Can emerging renewable printable polymers empower a more sustainable additive manufacturing?

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The growing environmental awareness concerning the depletion of fossil reserves, greenhouse gas emissions and waste management has been increasingly dissuading companies from investing in traditional fossil-based plastics. As a consequence, the intensive scientific and technological research is leading to the development of new materials with selected technical features which can represent feasible substitutes for the conventional plastic materials currently used also in additive manufacturing technologies. Nonetheless, while the development of new renewable polymers has been rapidly increasing in the last decade, the related range of additives has not been growing that fast. This has resulted in an urgent need of developing a new generation of sustainable additives that can improve the processability and printability of the emerging biopolymers and tune their properties and, at the same time, preserve their renewability.

Mirror Mirror – A 15-year Reflection on Metal Additive Manufacturing

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While additive manufacturing (AM) has been around in many forms for decades, metal AM has come to the recent forefront with its potential to revolutionize manufacturing in a plethora of industries. And with its proliferation, new information and insights are captured at a rate that often outpaces the ability to share across the industry. Having spent 15 years in metal AM, this talk will address several of these lessons related to material characterization along with common myths and misconceptions such as required levels of material property data and definition of qualifications. It will also touch upon the future challenges, particularly related to material development, machine architectures, data management, and artificial intelligence.

Effect of build geometry and parts spacing on mechanical properties of additively manufactured high strength aluminium A205 alloy

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A205 is a lightweight and high strength Al-Cu-TiB_2 alloy powder developed for aerospace applications. A205 has a unique mode of solidification, leading to highly refined, crack-free, and non-dendritic microstructure during additive manufacturing (AM). However, the alloy's microstructure can be affected by prolonged exposure to high temperatures, which can lead to changes in its mechanical properties. Thus, controlling the energy density and thermal cycle to prevent excessive heat buildup is important to maintain build quality. In this study, the effect of build geometry and parts spacing on the as-built microstructure and mechanical properties are investigated. Both flat and cylindrical A205 bars were built vertically using laser powder bed fusion (LPBF). Samples were also built close to each other (~1 mm spacing) to simulate proximity between parts. The flat samples had finer microstructure and higher ultimate strength compared to cylindrical sample built under the same conditions. Proximity between parts resulted in significant loss in overall strength. The variation in strength is attributed to the different thermal history due to laser dwell time and heat retention due to part shape and proximity.

Additive Manufacture of Ceramic Matrix Composites: Opportunities, challenges, and an approach

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High temperature materials are critical to achieving humanities greatest engineering feats. Whether it is for nuclear fusion, hypersonic flight or interplanetary travel, all have in common the need for materials that can withstand high temperatures in challenging environments (e.g.: T>2000°C, oxidising atmosphere, radiation). Ceramic matrix composites (CMCs) are a class of material that offers the unique combination of exceptional high temperature performance and high weight specific properties. For this reason, CMCs are often the material of choice for the most demanding applications in space and defence. Compared to other classes of materials, CMCs have not been part of the 'additive manufacturing boom' to the same extent. Our work in development of thermoplastic Fused Deposition Modelling (FDM) compounds for the additive a manufacture of CMCs will be used as an example to highlight the challenges and opportunities associated with the additive manufacture of CMCs.

Influence of Additive Manufacturing Surface Roughness and Microstructure on Fatigue Failure

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Metal additive manufacturing (AM) for critical applications requires a comprehensive understanding of the fatigue failure mechanisms. The total fatigue life of a component consists of the sum of the crack initiation life and crack growth life. Current approaches to investigate the mechanisms driving fatigue performance of AM material typically report only a total fatigue life. Because in AM the material is built at the same time as the component, aspects of the material structure can be independently controlled through processing parameter modifications, post-processing treatments or indirectly changed based on deposition geometry. Rough as-printed surfaces are a particularly dominating mechanism of fatigue failure. The relationships connecting the contour processing parameters, surface formation and measurement metrics to axial fatigue life will be discussed. Strategic alteration of the processing and post-processing conditions will also be used to modify the microstructure. This work will utilize a single axial fatigue test to decouple the initiation and growth lives, revealing the mechanisms driving each stage of fatigue behavior. Understanding the independent influences of microstructure and surface roughness on fatigue can provide guidance for post-processing requirements and necessary design guidelines.

Titanium metal matrix composite fabrication via cold spray additive manufacturing

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Cold spray additive manufacturing (CSAM) is a solid-state deposition method in which metal powder deposits onto a surface at supersonic velocities to produce a 3D structure. CSAM can process multiple powder feedstocks simultaneously to form a multiphase 'metal matrix composite' (MMC) in which reinforcement particles (added at a minority fraction) embed into the softer metal matrix. Cold spraying a pure metal such as CP Ti with a harder additive can thus produce deposits with increased strength without resorting to spraying an alloy powder such as Ti6Al4V, which generally requires higher deposition velocities and can entail larger residual stresses. In this research, commercial-purity titanium MMCs were cold sprayed using ceramic reinforcement particles (either $(ZrO_2)_{0.92}(Y_2O_3)_{0.08}$, TiB_2, or TiC) or metallic blending (with W). Secondary material choice was found to affect deposition efficiency and bulk density. Following cold spray, the deposits were vacuum heat treated. Final chemical compositions (XRD and ICP-OES), microstructures (backscattered SEM), and tensile mechanical properties were determined for the heat-treated deposits. The results show that 10 wt.% addition improves heat-treated CP Ti deposit strength by 8-27%, depending on the secondary material.

Modelling and Simulation in Additive Manufacturing

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Modelling and simulation are important for additive manufacturing (AM) both because it helps in understanding how to control the processes and optimize printed materials and because it supports everyday engineering applications. Ultimately, simulation tools should be used to accelerate qualification and certification of parts. AM is inherently multiscale because building parts requires deposition of many layers. Microstructure development in fusion-based processes, e.g., is determined at the melt pool scale but conditions vary with location in a part via, e.g., thermal history. A brief overview of the state of the practice alongside the frontiers of algorithm development. Examples are given from the author's experience with topics such as thermal distortion, microstructure development in solidification, crystal plasticity of AM microstructures, hot cracking and stress concentration on surfaces. Machine learning is a pervasively useful toolset. Applications are described to powder analysis, fatigue, melt pool cross-sections, microstructure development: reduced order models represent one route to overcoming the challenges of multiscale problems. Prediction of defects during printing is a prime example; this will be illustrated by reference to use of high-speed visualization with synchrotron x-rays for labeling pore formation events in laser melting for prediction of keyhole pore formation from videography of the melt pool.

Additive Manufacture for Soft Robotics

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Soft robotics is a revolutionary robotics discipline based on the design and fabrication of compliant, deformable structures, with myriad applications across industry, medical technology, and more. Soft Robotics has eagerly adopted 3D printing and other manufacturing technology, moving away from traditional approaches e.g., casting. Printing allows for embedded sensing and actuation, flexible electronics, bioinspired and biomimetic 'skins', functional gradation and digitally blended multi-material embodiments exhibiting complex behaviours. This presentation will cover the intertwined recent history of additive manufacture and soft robotics, and speculate on the direction of the field in the future.

Concurrent Optimisation of Additively Manufactured Parts and Support Structures

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Support structures are required to enable the build of additively manufactured parts. The supports reinforce overhanging regions on the part and/or counteract the thermally-induced residual stresses generated during printing. However, the optimal design of the part for its intended use case is decoupled from the design of the support structures in a conventional design for additive manufacturing (DfAM) workflow. In this work, a novel methodology is presented that simultaneously optimises the part topology and its support structure regions. A two-model topology optimisation approach is considered. One model describes the combined part and support structure regions subject to a pseudo-gravity load and a second model describes the part subject to its intended application load cases. A novel load-aligned trunk and branch support structure is generated from the topology optimisation results. Generating the fine support features in a post-processing step avoids the computational expense of topology optimising the intricate supports directly. Thermo-mechanical simulations of a selective laser melting process confirms that this new approach to optimising support structures can reduce manufacturing process-induced deformation when benchmarked against a conventional DfAM workflow.

3D printed porous nanomaterials for bone regeneration

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Nanomaterials possess unique physical, chemical and biological properties due to the nanosize effects and offer various advantages for biomedical applications such as drug delivery and tissue engineering. Porous nanomaterials are of special interested due to their good biocompatibility, high stability, rigid framework, well defined pore structure, easily controllable morphology and tuneable surface chemistry. Recently, the development of porous with large pores enable the loading and delivery of large therapeutic molecules including proteins and genes. In this presentation I will introduce our works and the recent progress using 3D printed porous nanomaterials for bone regeneration.

A Novel α+β Ti Alloy Designed for Additive Manufacturing

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A novel α+β Titanium alloy for additive manufacturing (AM) has been designed. The Ti-4Cu-4Fe (wt.%) alloy takes advantage of constitutional supercooling to overcome the large columnar grains usually associated with additively manufactured Ti alloys. The as-built microstructure shows the majority equiaxed prior-β grain. High strength and adequate ductility are achieved for structural applications. The high strength is attributed to the retained β-phase, very fine α-phase and the intermetallic phases; Ti_2Cu and Ti_3Cu which most often form at the boundaries between the α and β-phases. This work demonstrates a viable way to fabricate structural components with unique and excellent properties using low-cost elemental powders in AM.

Analysis of residual stress in additive manufactured functionally graded layers for joining dissimilar materials in space applications

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Abstract

Finite Element Method (FEM) has been widely used in various manufacturing processes and materials as well as their assessment. In this presentation, an efficiently analysis approach through combining both the implicit and explicit FEMs is to be introduced. Then, the analyzed thermal elastic-plastic behaviors during additive manufacturing and residual stress using author's developed software JWRIAN-Hybrid are discussed. From the numerical analysis, the reduction of tensile residual stress reduction in additive manufactured functional graded materials becomes possible. Using the additive manufactured middle layers, the titanium alloy sheet and ceramics was successfully joined, the joint strength and the strengthening mechanism was clarified by numerical simulation from mechanics approach. Finally, the influence of material properties of additive manufactured layers on residual stress and its distribution was systematically analyzed. The analyzed results supplied a reference in selection of functional gradient materials in additive manufacturing for space applications.

Challenges and progress in the modelling of Additive Friction Stir Deposition.

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Additive Friction Stir Deposition (AFSD) is a process of layer-by-layer deposition derived from friction stir welding (FSW). Depositions are produced by feeding a printing material (solid rod, scraps, loose or compacted powders, ..) through a hollow deposition tool rotating at high speed. The friction of the rotating feeding material and the substrate or previously deposited layers generates heat which leads to the thermal softening of the feeding material which then plasticises and mixes with them. Subsequent transverse motion of the rotating tool combined with the back pressure applied on top of the feeding material generates the deposition of a printed “layer” of the filler material. After increasing the tool height to accommodate the deposition of more material, subsequent layers are deposited using the same methodology to create a 3D part.

Modelling the AFSD process is challenging as it is a complex thermo-mechanical process involving frictional contact, bonding, large deformation, large strains and strain rates, as well as high temperature gradients.

In this talk, we present how this affects the simulation of AFSD using the classical Finite Element methods and explore how new particle based methods such as Smooth Particle Hydrodynamics or the Material Point Method can help overcome these challenges.

3D Printing of Metal-Organic Framework Composite Materials for Electrochemical and Direct Air Capture Applications

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Additive manufacturing is a powerful technique allowing access to novel and unique geometries of materials. When additive manufacturing is combined with advances in novel materials, such as Metal-Organic Frameworks (MOFs), highly specialised devices can be created.[1] MOFs are a class of highly porous crystalline materials; their modular and tuneable structure allows MOFs to be specifically tuned to certain applications.
In this presentation, two different 3D-printed devices containing MOFs as the active component are reported. The first is a 3D-printed lattice, fabricated by Direct Ink Writing, which shows significant promise for application in the Direct Air Capture of carbon dioxide. By incorporating carbon additives into the system, an in-built resistive heating capability is accessed. The second device manufactured is an electrode for sensing and electrocatalysis applications. The unique structures of the incorporated MOFs make these electrodes extremely sensitive and selective for the analyte of choice.

References:
1. **E. R. Kearns**, R. Gillespie, D. M. D'Alessandro, 3D printing of metal–organic framework composite materials for clean energy and environmental applications, *J. Mater. Chem. A*, **2021**, *9*, 27252-27270.

The Application of 3D Printed Microtextures to Inhibit Marine Biofouling

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Organisms associated with marine biofouling include bacteria, algae, mussels, tubeworms, and barnacles. These organisms attach to surfaces exposed to water, which impact the composition of marine communities and cause an economic burden on industries, such as shipping. Anti-fouling measures have historically been centred around toxic and fouling release coatings; however, the release of toxic compounds associated with this approach has adverse environmental effects. More recently, anti-fouling efforts have been explored through altering the surface texture and thus the nature of attachment points available for fouling organisms. Surfaces with engineered microtextures might be produced rapidly and cost effectively using 3D printers. This project will investigate whether 3D printed microtextures can inhibit biofouling organisms. An additional research question posed by this study surrounds the potential enhancement of these microtextures using a copper embedded filament. Microtextures produced in this study will be deployed in Port Phillip Bay for several months. The effectiveness of these microtextures will be evaluated through measurements of the growth of biofouling organisms.

The effect of aging time and temperature in a T6 heat treatment on the properties of additively manufactured AlSi10Mg

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Laser powder bed fusion (LPBF) is an additive manufacturing technique that is becoming increasingly popular due to the range of part geometries and materials that can be manufactured in this way. Parts produced by LPBF tend to have a fine microstructure due to the rapid cooling of the molten material, producing parts of high strength and hardness at the cost of poor ductility. One solution to improve the ductility of the component is to perform heat treatment. AlSi10Mg is a common LPBF alloy which is often heat treated with a T6 heat treatment, involving solutionising and artificial aging. Part of the complexity surrounding the T6 heat treatment is deciding on the aging time and temperature required to produce the desired microstructure and mechanical properties of a part. This work investigates the effect of aging time and temperature on AlSi10Mg samples on the hardness of samples that have been stress relieved, stress relieved and solutionised, and samples that were left in the as built state. Samples were aged between 30 minutes and 8 hours at temperatures ranging from 150˚C to 190˚C, with each aging temperature demonstrating a different peak hardness value. The time required to reach maximum hardness is shown to be dependant on ageing temperature and preaging treatment.

In-situ observation of the deformation behaviour of dislocation cellular structures in additively manufactured metals

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Additive manufacturing (AM) has attracted significant research interest in recent years due to its large design freedom and near net-shape production capability. As the AM process of metallic materials is inherently associated with cyclic rapid thermal loadings, significant thermal stress and large plastic deformation are introduced, leading to the formation of extensive three-dimensional dislocation cellular structures in AM metallic parts. While such microstructures significantly impact mechanical properties, dynamic deformation behaviours of dislocation cellular structures have not been well understood. Previous studies of the deformation behaviours of dislocation cells were conducted using in-situ straining transmission electron microscopy (TEM). The thin film nature of the TEM specimens with thicknesses of ~100 nm or thinner implies that the three-dimensional dislocation cellular structures with cell diameters of ~500 nm are sectioned to two-dimensional cells. This prevents true reflection of the deformation behaviours of dislocation cells in bulk materials. Besides, the limited strain values provided by in-situ straining TEM only reveals the early-stage deformation behaviours of dislocation cells. In this study, we take advantage of the electron channelling contrast imaging (ECCI) technique, which can be used to image dislocations in bulk samples in the scanning electron microscope (SEM), and an in-situ straining SEM technique to visualise the real-time deformation behaviours of dislocation cells in bulk 316L stainless steel samples produced by laser powder-bed fusion. The microstructural evolution of dislocation cells and their effects on mechanical properties will be discussed in detail.

Unlocking the Potential of Grain Engineering: Novel Approaches to Part Design

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Recent developments in ultrasound-assisted Laser Metal Deposition allow to locally control the grain formation of the deposited material. With these new capabilities, different microstructures with specific material properties can be locally assigned where needed to archive an optimized structural part design with superior mechanical performance. The procedure is denoted as grain engineering and can significantly improve the performance of large structural parts.

While there is already increasing interest and research in multi-material design for functional parts, the new possibilities of grain engineering have yet to be explored. The purpose of this talk is to present recent approaches to part design that incorporate grain engineering. Several methodologies to utilize grain engineering to obtain optimized functional parts with properties unattainable by other manufacturing technologies will be explored. In particular, the transferability of methods from multi-material optimization to grain engineering will be evaluated and possible challenges will be discussed.

Standards in an additive manufacturing world

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Standards Australia (SA) is the nation's peak non-government, not-for-profit standards organisation. As representatives of the International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC), we are also specialists in the development and adoption of internationally-aligned standards in Australia.

Standards are voluntary documents that set out specifications, procedures and guidelines that aim to ensure products, services, and systems are safe, consistent, and reliable.

But, how is a standard created? Who creates them, how and why do they matter?

SA Technical Committee MB-028 Additive Manaufacuting is responsible for the adoption of many international standards relevant to the Australian additive manufacturing industry.

This session will demystify questions on the standardisation process such as how a standard is created, adopted and how industry can drive change through standardisation and the technical governance that underpin consenus driven standards.

The MB-028 committee will provide an overview of its activity, updates on upcoming additive manufacturing standards, and a glimpse at the global additive manufacturing standards landscape. Discussion will conclude on how the participation and creation of standards requires a long-term perspective to understand how standards support additive manufacturing growth into industry including the highly regulated, high-value add industries such as aerospace, defence and medical.

Open-source 3D data analysis and visualization platform for quality assurance of additive manufacturing components

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Additive manufacturing (AM) is increasingly used in various industries to produce parts and components. However, high failure rates associated with AM have raised concerns about its reliability and quality. Quality assurance (QA) is crucial to ensure that the final product is of high quality, meets the required specification, and is fit for purpose. This work develops a QA tool based on an open-source, multi-platform data analysis and visualization application, ParaView. The developed platform was employed to demonstrate data management, process monitoring and visualization (e.g., meltpool size, powder mass flow), defect correlation when coupled with experimental testing, and creation of part reports for the LASERTEC 65. Detailed analysis of the process data can help to optimize the additive manufacturing process, reducing the likelihood of producing defective parts. Moreover, the open-source, cross-platform nature of this tool implies that the range of features and capabilities can be applied to different additive manufacturing processes and data types with ease at a low cost. We believe that this work will contribute significantly to ensuring the reliability, safety, and quality of AM products and hence, the continued growth and adoption of additive manufacturing technologies.

Crystallographic Orientations of Nano-Sized β-Phase Precipitates in Aged Additively Manufactured Ti-6Al-2Sn-4Zr-2Mo

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Additively manufactured (AM) metallic materials have attracted significant attention due to their superior mechanical properties. Post-processing of AM metallic materials is usually required for further improvement of their mechanical properties and thermal stability. For example, ageing has been frequently used to introduce precipitates that strengthen materials. While there have been many studies on the preferred nucleation sites and the growth as we all as the strengthening mechanism of precipitates in various AM metallic materials, few reports are related to the intragranular precipitation in lath martensite in AM Ti alloys. In specific, the formation mechanism of the precipitates and their orientation relationship with the lath martensite matrix in aged AM Ti alloys have not been well explored. Here, we applied scanning electron microscopy and transmission electron microscopy techniques to investigate the different variants of nano-sized β-phase precipitates that are formed in aged ultrafine-grained Ti-6Al-2Sn-4Zr-2Mo martensite produced by laser powder bed fusion. Their orientation relationships with the matrix phase were determined and linked with the formation mechanisms of the precipitates. The impact of these precipitates on the mechanical properties of the alloy will be discussed.

Recycled Photovoltaic Silicon for 3D Printing Lithium-Ion Battery Anodes Using an Open-Source Toolchain

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Silicon is a promising candidate as the anode material for lithium-ion batteries due to its high theoretical capacity and abundance. Silicon anode applications are limited due to the high-volume change and low electrical conductivity. Combining silicon with carbon particles increases the electrical conductivity and alleviates the volume change. This work proposes a novel method to use recycled silicon from solar photovoltaic waste to fabricate 3D-printed anodes for lithium-ion batteries. First, the silicon waste is ground using an open-source ball mill to obtain <50 microns particles. Then, the silicon particles along with dispersant and photoinitiators are mixed with UV-curable resin by an open-source bottle roller. The mixture was then used to print an acrylate-silicon composite lattice using an open-source digital light processing 3D printer. Finally, the composite lattice is pyrolyzed in an inert environment. This provides a free-standing carbon that surrounds the silicon particles, which can dampen the silicon volume change and improve the electrical conductivity. The produced anodes are characterized and compared with the anodes fabricated by conventional methods. The results of the novel method are discussed in the context of using 3D printing to fabricate high-performance anodes for lithium-ion batteries.

Topology optimisation of a flight-critical aircraft component for metal additive manufacturing

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Metal additive manufacturing (AM) enables on-demand fabrication of metal components. This provides several advantages for defence applications, such as on-site manufacturing of replacement parts, increasing overall part availability and decreasing turnaround time for maintenance and repairs. However, the use of metal AM to produce critical components is limited due to the uncertainties in AM part performance. In this work an approach for designing and evaluating metal AM replacement parts for critical components is developed. A flight-critical aircraft part is optimised for metal AM using a soft-kill bi-directional evolutionary structural optimisation (BESO) method. The optimisation objective is to reduce maximum stress in the component to improve the fatigue life, thereby compensating for AM process-induced defects. The optimisation is also constrained to match the compliance of the original part, to ensure the original mechanical response of the surrounding structure is preserved. Non-linear finite element contact analysis is used to obtain the boundary conditions for the optimisation and to validate the performance of the optimised part. The optimised design showed significant reduction in maximum stress and reasonable agreement in compliance compared to the original part. The general methodology developed in this work demonstrates a capability to rapidly design "drop-in" replacement AM parts.

New Aluminium-Scandium welding wires for Additive Manufacturing

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This work explores new welding wire compositions tailored for the emerging technology of Wire Additive Manufacturing (WAM). The 5183 alloy is a commonly used welding wire as it provides strength through the presence of a high content of Mg through solid solution strengthening mechanism. These alloys experience a number of shortcomings such as low strength compared to age-hardenable alloys and are prone to sensitisation when used in marine environment. This work uses co-additions of Sc with Yb, Er and Zr to a 5xxx-series alloy to provide additional strengthening through the formation of $L1_2$ Al_3X particles. The formation of the Al_3X during a tailored heat treatment will be discussed. Tensile tests are conducted to evaluate the impact on the mechanical properties. Atom probe tomography and transmission electron microscopy are used to better explain the role of the different elements on the formation kinetics of Al_3X. The newly developed alloys will enable creating high strength, corrosion resistant WAM structures.

Multiscale modelling of additively manufactured parts

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Additive manufacturing (AM) is an inherently multiscale process in which macroscopic scale parts are built from micrometre scale powders. Therefore, modelling AM becomes a multiscale problem since the various sub-processes constituting AM must be modelled at their natural scales for accurate replication in the digital domain. Additionally, the sub-processes (e.g., powder spreading, laser melting and solidification, microstructure formation, residual stress development and part distortion), which can interact in complex ways, are governed by different physics. Thus, linking the models of the sub-processes needs to account for the multiscale, multiphysics nature of the simulations. Several challenges must be overcome, including finding ways to pass data from one scale to another and from the mathematical solution strategy (e.g., discrete element, finite volume, finite element methods) employed to solve one physics to another. In this talk, we highlight – through illustrations – techniques used by researchers to solve some of these issues. We also explore the possibility of creating machine learning (ML) models of each sub-process that can then be linked to create a complete ML model of the AM process.

Business-as-Usual: Operationalising Additive Manufacturing in Defence

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There is a gap to bridge between the desired benefits of Additive (and Advanced) Manufacturing and an integrated adoption that transforms Defence's supply chains and logistics support paradigm. Only through the combined efforts of Defence and Industry can we bridge this gap. To achieve these goals, Defence has published an *Additive Manufacturing Operationalisation Strategy* (AMOS).

The AMOS provides a foundation and framework for the development of an AM capability which spans the Defence Logistics Enterprise and delivers a source of logistics advantage. The strategy provides clarity on the future vision of AM in Defence and the actions required to achieve this vision, including the path forward from a known baseline. Individuals and organisations alike should use this operationalisation strategy to guide their AM investment, integration and collaboration as it contributes towards a holistic AM capability which is 'Joint-by-Design' and a 'Business as Usual' enabler of Defence capability.

Sliding Wear of Bulk vs Laser Deposited Inconel 625 and 718

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Inconel 625 and 718 are nickel-based superalloys used extensively for aerospace hot-section components due to exhibiting superior mechancial properties at high temperatures. The elevated heat resistance properties of these materials, however, contribute to poor machinability and, consequently, costly production of parts through conventional manufacturing. Laser metal deposition (LMD) is a proven industrial scale additive manufacturing (AM) process capable of producing near net shaped components with material properties comparable to wrought counterparts. By manufacturing Inconel 625 and 718 components additively using the LMD process, it is possible to reduce the net amount of material needed to be machined, extending the life of tooling whilst simultaneously enabling higher part complexity. This study investigates production of as-deposited Inconel 625 and 718 via LMD and compares the sliding wear properties at room temperature with the corresponding conventionally manufactured alloys. The study shows that microstructural changes due to accelerated cooling associated with LMD deposition degraded the as-deposited wear resistance of the AM Inconel alloys as compared with bulk alloys. The results of this study indicates that further efforts are needed to control the microstructural evolution during LMD processing to produce additively manufactured Inconel parts with equivalent performance to conventional counterparts.

Challenges and opportunities in the application of metastable β-Ti alloys produced by wire Directed Energy Deposition

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Metastable β-Ti alloys have emerged as candidate alloys for additive manufacturing because unlike α/α+β alloys their phase fractions and properties can be more readily modified through post build heat treatment. This work explores the suitability of novel metastable β-Ti alloys produced by high energy input Direct Energy Deposition techniques and presents some of the issues including defect susceptibility that require careful management. In conjunction with heat treatments, superior strength and ductility is achievable from this class of titanium alloy in comparison to the α+β benchmarks such as Ti-6Al-4V.

Optimizing island scanning strategy for reducing residual stresses and defects in laser powder direct energy deposition (LP-DED) components

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High residual stress and associated defects during the process in laser powder direct energy deposition (LP-DED) are major problems responsible for inferior surface characteristics and the final part failure. The most influencing factor for such stresses is high temperature gradient. The recently developed island scan strategy is promising to reduce residual stress by using small scan vectors as well as interlayer rotation which helps to achieve uniform temperature distribution. However, process parameters such as overlap rate and interlayer dwell time have not been widely investigated for the optimization of the island scanning strategy. This work studies the effect of interlayer dwell time and overlap rate on the reduction of residual stresses using the island scan strategy for Inconel 718L on the LASERTEC 65. Residual stresses are characterized by X-ray diffraction (XRD) and contour method, and defects such as lack of fusion and porosity are detected by scanning electron microscopy (SEM). By further understanding and optimization the island scanning strategy, we believe that this work will contribute to the enhancement of quality and reliability of LP-DED produced parts.

On-the-fly 3D geometry monitoring approach for cold spray additive manufacturing

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Cold spray additive manufacturing (CSAM) is a robot-controlled additive manufacturing (AM) technique. In CSAM, micron-size particles(1-100µm) travelling at supersonic speeds in a gas stream are deposited in the solid state upon impact. Large-scale components can be manufactured at rates of kilograms per hour using CSAM. However, high deposition rates are also challenging as geometry defects (overbuilt and underbuilt regions) can quickly develop due to variations in the process. These defects tend to become amplified with addition of successive layers. Furthermore, they are associated with internal porosity formation, which compromises mechanical properties. Therefore, monitoring of geometric defects during deposition is a prerequisite for effective process control. However, there are challenges in on-the-fly 3D geometrical monitoring with complex geometries such as sensor accuracy, calibration and field-of-view obstruction. In this study, 2D laser profilers were located at multiple angles from the workpiece to avoid field-of-view obstruction. Automated calibration system was developed without need of special calibration target. Data from individual profilers were combined to continuously reconstruct the 3D surface without interrupting the deposition process. The effectiveness of the 3D geometry measurement system will be discussed in the presentation, along with an assessment of its suitability for defect monitoring and process control in CSAM.

Keywords: Cold spray, additive manufacturing, process monitoring, laser scanning, 3d surface reconstruction.

Advancements in Computer-Aided-Manufacturing for Directed Energy Deposition process

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Industrialization and qualification of several Directed Energy Deposition (DED) processes in aerospace sector has been witnessed in the recent past. Most of the DED systems tend to utilize 6-axis industrial robot(s) for better flexibility and reachability. The process chain of any DED process begins with design for AM, followed by toolpath planning necessary for the robotic system being used. It has been witnessed that toolpath planning and the chosen build strategy has an influence of resulting geometrical and mechanical characteristics of the fabricated component and is very specific to chosen technology, material, feed-stock type, process parameter set and build strategy.
This talk will present algorithms and tools that have been developed to enable intelligent and automatic toolpath planning. In specific, segmentation algorithms and toolpath generation algorithms tailored for processing thin-wall aerospace components will be presented and its influence on component quality will also be presented. A simple cost-effective voxel-based simulation tool for better visualization of toolpaths, build strategy and deposited geometry has been developed. Combining this simulation tool with analytical and empirical models results in the prediction of process stability and toolpath-induced process defects.

Investigation of the impact of far-from-equilibrium process conditions on metal AM microstructure

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Metal additive manufacturing (AM) is a promising approach to manufacture components with complex geometries. However, materials are processed under conditions far-from-equilibrium. The physical metallurgy of AM processes has yet to be unraveled. Inherent rapid heat cycles and extreme gradients result in strong anisotropy in microstructure including formation of unexpected or metastable phases. Relationships between (post)process parameters, site/design-specific microstructure and properties are still hard to predict.
To capture and identify significant trends on all length scales, new approaches in material characterization are required. Electron microscopy (EM) needs to be optimized in terms of feature contrast, automated feature detection, high(er) throughput. Extracting statistically relevant information on property-defining features, such as grain boundaries (GB), formed on a micrometer scale, is essential. Examining EBM-Ti64, high throughput SEM imaging indicated strong differences on microstructure when varying EBM beam scan strategies, EBSD results confirmed an unexpected distribution of GB (mis)orientations. Vickers hardness measurements confirmed a corresponding variation in microhardness.
To better understand the impact of complex spatial-temporal thermal transients in AM (post)processing, we currently develop in-situ EM approaches. Supported by COMSOL Multiphysics simulations, we mimic AM-specific far-from-equilibrium thermal conditions in *in-situ* EM heating studies. Such a (pre)process simulation will be essential for optimizing AM (post-)processes.

Dynamic SEM in-situ studies: A tool to investigate microstructural evolution during metal additive manufacturing?

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An anisotropic microstructure is typical of metal components fabricated by plasma arc additive manufacturing (PLAAM) with a site-specific microstructure, due to non-equilibrium cooling conditions and the unique process parameters. Additionally, previously deposited layers are subjected to cyclic heat inputs during the manufacturing process, which can result in element diffusion, phase transitions, or changes in grain morphology.

In this study, in-situ scanning electron microscopy (SEM) methods are developed to better understand the complex spatial-temporal thermal transients that AM components are subjected to during fabrication. Our emphasis is on developing microscopy techniques required to simulate such a temperature profile on a sufficiently large sample compared to a typical grain size in AM components. The temperature distribution in bulk samples on the MEMS-SEM microheaters is predicted using COMSOL simulations. The dynamic changes in the microstructure are analyzed using electron backscatter diffraction (EBSD) and SEM imaging during a cyclic heating experiment. This study will allow to draw conclusions on the feasibility of using SEM-based heating studies to develop a fundamental understanding of microstructure formation during PLAAM processes

Study of Phase-Transformation Behavior in Additive Manufacturing of Nitinol Shape Memory Alloys by In Situ TEM Heating

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Reversible martensitic transformation, a diffusionless solid-solid phase transition, gives NiTi (Nitinol) alloys shape memory effect (SME) and superelasticity with several-percent recoverable strains. Because of these attractive properties, NiTi alloys are widely applied in actuators, sensors, and dampers. With the recent advent of laser powder bed fusion (L-PBF) additive manufacturing (AM), NiTi with complex geometry can be fabricated by the near-net-shape manufacturing. Since L-PBF processes involve rapid heating/cooling rates, steep thermal gradients and complex histories, locality in NiTi parts exhibits heterogeneity, which dramatically affects their functional properties. Therefore, an in-depth understanding of the correlation between thermal process parameters and structural variations is essential for material design.

Thus, to capture the connections between phase transformation and the local inhomogeneity, TEM samples from different locations in the melt pool area were prepared and placed on a MEMS-based microheater for *in-situ* heating transmission electron microscopy (TEM) experiments. A higher phase transformation resistance was shown at the melt pool boundaries, due to the fine cellular structure and high-density of dislocations. Our results indicate the ability to apply *in-situ* TEM heating experiments to study microstructural transformations for further optimizing process parameters in (additive) manufacturing.

Shape, Size, Temperature and Chemistry – Looking at the AM process though the lens of the powder mechanics

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As industry adoption is increasing the common wisdom that a powder AM material has to be spherical, mondispersed and fine is being challenged, especially in regard to powder reuse. While most metals seem to be largely unproblematic (with the curious exception of Al and Ti) a new front has established itself in the form of polymeric and lately (ceramic) powders.
Polymeric materials in additive manufacturing add a unique difficulty in characterization to a field that is used to deal with metal powders. Due to the molecular structure of these polymer powders, moisture and temperature change their behavior to a larger degree than is to be expected with the more common metal feedstock. Additionally the lower laser intensities necessitate operation much closer to the melting point of the material. However, unlike metals, polymers show a substantial divergence from their room temperature behaviour. This in turn creates the problem of reliably measuring the feedstock at these elevated temperatures to give an accurate picture of their properties during use since they differ greatly from their room temperature properties.
In this work we will have a look at sense and nonsense of measurement techniques both from the perspective of the bulk solid engineer (powder mechanics) as well as the particle scientist, and align this with expectations and limitations of the user.

Prediction of surface modification for additively manufactured SS316L by Plasma Beam Remelting Process (PBRP)

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Abstract

The surface quality and mechanical anisotropy of additively produced components requires post processing which leads to an increase in manufacturing costs and lead time. In this study, we have analysed the effect of altering processing parameters such as plasma power and scanning speed used by plasma beam remelting process (PBRP). This process will result in an increase in contact surface temperature leading to modifications in the mechanical properties and surface quality of the additively manufactured SS316L. Post PBRP, significant refinement in grain size was found up to the sub-micron level. In this paper, FEA will be performed to analyse the temperature distribution and thermal zonal area variations using a commercially available software. The combination of various parameters will be analysed for determining the optimum parameters required for appropriate surface modification. The temperature range through zonal area identification in the x direction was measured for various scanning speed. The length of heat treatment effect zone (HTEZ) as an extended zone was also predicted as the effective area for relieving thermal stresses. The optimum processing parameters were achieved between plasma power of 300-340 W and scanning speed of 63-90 mm/min. These preliminary findings verify the PBRP process's viability as a powerful post-processing tool for surface modification of additively built parts.

Keywords: Plasma beam remelting, Finite Elements Analysis, Thermal zonal area, Heat treatment effect zone (HTEZ)

Bidirectional shape-morphing of pH-responsive 4D printed hydrogels

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4D printing of smart hydrogel actuators with excellent biocompatibility and biodegradation is a viable field of research for fabricating dynamic structures for biomedical applications.4D printing of hydrogels has attracted attention because of its shape-shifting behaviour under stimuli, mimicking living tissues. 4D printing of hydrogel structures is challenging due to its poor printability and poor shape fidelity of printed patterns when direct-ink writing-based 3D printers are used. The existing 4D printing technology is limited to single stimuli responsive. Here we propose a 4D printing strategy with bilayer structures from chitosan (CS)/carboxymethylcellulose (CMC) containing citric acid (CA) as a crosslinker and demonstrated strong adhesion between two layers through electrostatic attraction and chemical cross-linking. These dual stimuli-responsive structures respond to both extreme conditions of pH (i.e., acidic and basic medium). Based on the systematic study of the adapted rheological characterization and printing parameters of the bilayer structure, the effect of programmable variables on the deformation shape was investigated. The diversified printing structure exhibited rich structural changes under one or both pH conditions. The significant difference in the swelling behavior between the positively charged chitosan and the negatively charged CMC layers generated enough force to actuate the performance of the hydrogels as artificial heart valves and intelligent textiles, showing potential applications in a wide range of fields, including biomedicine and smart textiles, etc.

Keywords: 4D printing, pH-responsive hydrogels, chitosan, carboxymethylcellulose, smart actuators, smart textiles

Towards Successful Additive Manufacturing of NiMnGa Magnetic Shape Memory Alloys

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NiMnGa alloys with a near full-Heusler stoichiometry exhibit a magnetically driven type of shape memory effect (SME). The magnetocrystalline anisotropy of the martensite phases in NiMnGa allows for a martensite reorientation process once an external magnetic field is applied giving rise to their magnetic SME. Contrary to thermal shape memory alloys, magnetic shape memory alloys (MSMAs) offer faster actuation and at much greater frequencies, making them ideal for numerous applications. However, their intrinsic brittleness makes them difficult to form into desirable shapes via conventional routes. Hence, additive manufacturing (AM), particularly powder bed fusion (PBF) and directed energy deposition (DED) methods, are believed to be promising avenues for realising their potential. This presentation will discuss the recent advancements, challenges, and future perspectives of PBF and DED fabrication of NiMnGa MSMAs, in dense and lattice forms. Furthermore, the results of our recent work on laser surface remelting of NiMnGa alloys as a gateway towards their successful AM will be discussed. In particular, the effect of laser energy density on their microstructure, martensitic transformation and curie temperatures, texture, and twin boundary mobility will be elaborated on. Moreover, the effect of commonly performed homogenisation and ordering heat treatments on the same quantities within the laser remelted tracks will be discussed.

Microstructure and hardness evolutions of stainless steel 316L–nimonic 90 bimetallic components along the build direction

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Joining dissimilar materials using conventional welding and joining techniques could be challenging due to the formation of brittle intermetallic compounds during solidification, which deteriorates the mechanical properties at the bimetallic interface. Additive manufacturing is a promising technique to overcome this problem as additive manufacturing can alter the composition at the interface to prevent the formation of harmful intermetallic compounds during dissimilar metal joining. In this study, structural components with stainless steel 316L and nimonic 90 dissimilar materials are manufactured using the wire arc additive manufacturing technique with the dissimilar metal interface parallel to the build direction. The microstructural evolution at the interface along the build direction is investigated using electron microscopy. Vickers hardness testing is conducted to explore the hardness along the build direction at the materials interface. The relationship between local microstructure and hardness is presented.

Achieving porosity-free and grain-refined structures in additively manufactured metastable β-Ti alloys via super-transus hot isostatic pressing

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High energy input direct energy deposition can produce parts prone to coarse structures with process-induced defects such as gas porosity that considerably deteriorate the tensile ductility of printed parts. This work demonstrates that by intentionally introducing high-density macro-porosity using low-quality raw materials, a production route hitherto avoided for additively manufactured products, followed by super-transus hot isostatic pressing (HIPing), products initially considered scrap can be salvaged with more desirable microstructure and mechanical properties. Such improvement is achieved by eliminating macro-pore defects while refining the coarse structure through dynamic recrystallisation. This promising production strategy may apply to various alloys produced by other AM techniques and has the potential to help additively manufactured products achieve an entirely uniform equiaxed grain structure.

CSIRO past successes and future directions of Additive Manufacturing for space applications.

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Additive manufacturing with its ability to produce complex geometries that are often used for weight reduction lends itself to applications in the space industry where mass savings are critical. Another less celebrated feature of additive manufacturing is the potential to create unique chemistries and microstructures in the materials being deposited. CSIRO has flight heritage parts that have been launched and is currently working on future solutions. CSIRO is using a combination of additive techniques and materials systems to address problems that are difficult to solve using a single technique or material system.

Ultra-high-resolution PμSL Based 3D Printing and Its Applications

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The trend of miniaturization is evident in a growing number of industries as the demand for smaller parts for medical devices, consumer electronics and robotics grows. Many industries are faced with challenges in manufacturing parts with complex geometries with detailed features and excellent surface quality. While 3D printing has rapidly advanced in recent decades, drawbacks such as resolution and throughput have limited its widespread adoption within certain applications where tight tolerance and high level of customization are required. BMF's unique printing technology, named PμSL (Projection Micro Stereolithography) is set out to remove these technological barriers, offering industrial designers and engineers a way to rapidly prototype and batch produce high-value components. Compared to traditional manufacturing methods such as injection molding and CNC machining, PμSL substantially reduces the cost and lead time by avoiding laborious and tedious fabrication processes. By leveraging light, customized optics, a high-precision printing platform and controlled processing technology, PμSL can achieve down to 2um resolution with ±10μm tolerance and a practical build volume up to 50×50×50mm. In this talk, we will introduce the working principles and advantages of PμSL and highlight some recent examples of PμSL enabled applications, from circuit connectors to scaffolds for tissue engineering.

Directed energy deposition of Ti-6Al-4V for desired microstructures and tensile properties based on process simulation

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Understanding the thermal history of a metal part during additive manufacturing (AM) is essential for process design and microstructural control. In this study, a detailed thermal history simulation was carried out for the laser powder Directed Energy Deposition (DED) of Ti-6Al-4V using the DED module in *Simufact Welding*. The systematic simulations established a large processing window that accommodates numerous DED conditions for the formation of $\alpha-\beta$ lamellae via in-situ decomposition of the α′-martensite in Ti-6Al-4V. Test coupons were fabricated within and outside the processing window using laser metal powder deposition. The flexible microstructures and tensile performances fully support our simulation-informed processing window and design concept. The influence of the wall thickness, coupon shape, or build height can also be simulated before manufacturing so that processing parameters can be adjusted. The increased capacity of process simulation and the flexibility of the AM processing window are expected to enable the fabrication of high-quality complex Ti-6Al-4V components with consistent microstructures.

Crystallographic texture control by metal powder bed fusion

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The attraction of metal addition manufacturing is not only the creation of complex three-dimensional shapes but also the control of the crystallographic texture of the metal, which allows for the control of mechanical properties and the development of mechanical anisotropy. In this talk, we will present the latest findings on the control of crystallographic texture by a powder bed fusion (PBF), which our group (Anisotropic Design & Additive Manufacturing Research Center, Osaka University) has been working on intensively in recent years. The crystallographic texture formation behavior and its occurrence in materials friendly to the PBF method, such as titanium-, iron-, and nickel-based alloys, as well as tungsten, whose thermophysical properties differ significantly from those of these materials, are described based on the melt pool shape. The peculiar textures formed only by the PBF method and their contributions to the mechanical properties are also presented.

Pushing the Boundaries of High-resolution 3D Printing and Precision Manufacturing

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In recent years, the unique capabilities of two-photon polymerization (2PP) have made it possible to create a variety of miniaturized polymer structures and microscale components suitable for biomedical and photonic applications. However, limitations in throughput, build volume, and choice of materials have greatly hindered the usefulness of this fabrication technique. By combining a highly optimized optical system with a powerful 1-watt femtosecond laser and a proprietary adaptive resolution technology, UpNano have revolutionized the two-photon polymerization (2PP) 3D printing process by increasing its speed by a factor of up to 100, making batch and series production of ultra-high-resolution, mesoscale parts a reality. We will present the cutting-edge NanoOne 3D printing technology and highlight several recent works where NanoOne has been used to extend what is currently achievable in precision manufacturing.

A Computational Framework for Designing Sintered Materials

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A low order, quantitative meta model for the efficient design of sintered alloys for binder jet printing is described. This follows a materials systems approach within the context of an integrated computational materials engineering (ICME) framework that integrates processing, microstructure and properties. The model includes a multi-objective genetic algorithm to select the chemical composition and materials processing parameters to simultaneously optimise the sintering response and the resultant properties. The method integrates thermodynamic models to calculate phase stability, kinetic models to calculate the effective diffusivity in multi-component alloys and constitutive models to estimate the mechanical properties. To demonstrate the capability of the method, design exercises for stainless steels, tool steels, aluminium alloys and tungsten carbide hard metals are presented.

Additively Manufactured, Ultrafine-grained Titanium-copper Alloys Tailored for Marine Environments: Antibacterial and Anti-Microbial Corrosion Studies

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The microorganism-rich nature of the ocean imposes great challenges to the structural integrity of metals over their service lifespan, including titanium alloys, which are usually prone to microbiologically influenced corrosion (MIC). In the current study, we investigated the effect of Cu concentration on the MIC resistance of a series of additively manufactured, ultrafine-grained Ti-xCu (x = 3.5, 6.5 and 8.5 in wt%) alloys. Microstructural characterization reveals that uniformly distributed, nanosized Ti_2Cu phase led to increased reactive oxygen species in the bacterial membrane, which resulted in contact kill of the biofilm. Compared to pure Ti and Ti-6Al-4V, additively manufactured Ti-8.5Cu alloy features both high strength (yield stress > 1000 MPa) and the best MIC resistance (97.5%) in the marine bacterial environment.

Design to certification in additive manufacturing: Getting good solutions used

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Novelty is at the heart of innovation but in oppostion to standarization. Additive manufacturing (AM) is challenging typical manufacturing processes and is moving some industry areas from mass production of a single design towards mass customisation. AM's flexibilty to adapt in the design stage, does not align well with traditional component verification and certification pathways.

Trust, knowledge, and know-how are some of the underlying building blocks that are needed to ensure well designed solutions are used. These are demonstrated through experience and evidence while being formalised through certification.

Trusted verification, validation, regulation and certification processes often point to consensus-based international standards. Therefore, these standards underpin the industrial uptake of technologies and compliance to these standards can provide evidence for safety, consistency and reliability.

But how might you utilise these paths and standards to get a good solution used? This talk will present examples to illustrate the flow from innovation to standarisation: from ceramic hips using traditional manufacturing methods, to patient-matched anatomic models manufactured at point-of-care, and a metal ratchet produced at point-of-need in outback Australia.

Additive manufacturing is exciting in the novelty and innovation it can bring to design and the AM certification pathways are responding to enable innovation while providing that crucial ability to trust what is produced.

Can additive manufacturing be integrated into defence? Importance of the end-user and risks around innovating

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Defence is a highly regulated industry due to the inherent risk with the life of people constantly being on the line. Life hangs in the balance so the developed solutions need to reliably work safely. Sometimes these solutions are needed pomptly and in non-standard environments to be the missing part to get a vechicle home safely, a 'get home' part. A developed solution therefore has both high risk and high reward.

This talk will explore the risks of doing versus the risk of not doing in terms of 3D printing integration into defence. It will show examples from 3D printing field trials in defence. It will speak of how a fast-fail methology in the testing phase together with the innovation group, an outside testing body, and most importantly the end-user within defence could help speed technological development and integration. An active end users participation is key, as they can best define the need and evaluate the efficacy of a solution. A fast-fail methodolgy with high end-user engagement at onset, thoughout, and upon completion might enable a rapid understading of gaps in a technology, the knowledge and skills of the users, and the systems it is embedded within. Most importanly, it might enable the production of that 'get home' part just when it is needed.

Thermal Spray High Entropy Alloy Design using the CALPHAD Scheil Model

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In the field of high entropy alloys (HEAs), researchers have explored various approaches, such as the CALPHAD method, to optimize HEA design. The CALPHAD method enables the creation of equilibrium phase diagrams, providing information on the stability and composition of different phases. However, equilibrium phase diagrams assume an infinite slow cooling rate during solidification, which does not reflect the cooling rate in non-equilibrium processing routes such as thermal spraying. To address this issue, CALPHAD simulations incorporating the Scheil model have been developed, considering limited or neglected diffusion in the solidified structure. In this study, the classic Scheil model and Scheil with Solute-Trapping were applied to predict the phases in HEA thermal spray coatings. The results from Rietveld quantitative phase analysis were compared with the Scheil simulations, displaying excellent correspondence. Furthermore, the highest accuracy was achieved with the Scheil simulation with Solute-Trapping at solidification speeds of 0.5 m/s and 1.0 m/s, implying that these speeds are optimal for the HVOF parameters used in the study. Thus, CALPHAD simulations that incorporate the Scheil model can be utilized to efficiently design HEAs in higher cooling rate settings.

Direct FE² Simulation of Defects in Additively Manufactured Re-entrant Honeycomb Auxetics

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Auxetics exhibit great energy dissipating characteristics as a result of their complex geometry. Additive manufacturing provides the required fabrication versatility, but at the same time may induces imperfections (e.g., internal voids) in the product. The resulting discontinuous stress fields alter the failure mechanism, which often negatively affects the material performance. To accurately predict such premature failures, microstructural behaviour of the material should be considered through multiscale analyses, e.g., using Direct FE² (DFE²). Herein, the effects of voids on the energy absorption performance of additively manufactured re-entrant honeycombs are studied using DFE². To this end, fused filament fabrication was used to print re-entrant honeycomb samples in polylactic acid with varying void volume fractions. After characterising the microstructure, a representative volume element (RVE) is constructed to reflect the geometry of the voids. These RVEs are used to perform DFE² analyses whose results are compared to the full-field finite element simulations and experimental data. It was found that microscopic flaws induce stress concentrations in the vicinity of inhomogeneities. In addition, the DFE² was able to accurately simulate the higher stress regions and the resulting premature failure by incorporating the RVEs into the model. The study contributes towards modelling failure mechanisms in imperfect structures.

Alpha-phase variant selections in additively manufactured titanium alloys

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The transformation from the body-centered-cubic (BCC) β-phase to the hexagonal-close-packed (HCP) α-phase in α or α-β titanium alloys normally follows the Burgers orientation relationship (BOR), $(1\bar{1}0)_{\beta}//(0001)_{\alpha}$ and $[111]_{\beta}//[11\bar{2}0]_{\alpha}$. In principle, this could result in 12 α-phase variants with equivalent frequency and six types of inter-α-variant boundary. The dynamic heating and cooling cycles during additive manufacturing (AM) provide a unique environment to study the α-phase variant selection/multiplication. This study reports the experimental results of the α-phase variant selection and cluster formation (Category I or Category II triple-α-variant clusters), and the configuration of inter-α-variant boundary in AM Ti-6Al-4V and Ti-4Al-2V alloys through detailed microstructural characterisation. The underlying mechanisms for α-phase variant selection and its influence on mechanical properties are discussed.

Microstructure characterization and tensile properties of directed energy deposited ATI 425 alloy

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Titanium (Ti) alloy ATI 425 is an α-β Ti alloy with a specific composition of Ti-(3.5-4.5)Al-(2-3)V-(1.2-1.8)Fe-(0.2-0.3)O (wt.%). It was originally developed for defense applications in 1990s and brought into market in 2010. Compared to the benchmark Ti-6Al-4V alloy, ATI 425 adopts the low-cost Fe alloying element to partly replace the expensive V element as a β-phase stabilizer and allows for a higher oxygen content up to 0.3% (vs. < 0.2% for Grade 5 Ti-6Al-4V alloy according to ASTM B381-21) to strengthen the α-phase. The content of Fe is limited to 2.5% (wt.%) in conventional ingot metallurgy processes due to the formation of detrimental β-flecks arising from the Fe microsegregation during solidification. Additive manufacturing (AM) via directed energy deposition (DED) that builds a part layer-by-layer provides a promising approach to mitigating the development of β-flecks. The present work takes Fe-containing ATI 425 alloy as a base material and investigate the influence of further adding Fe on microstructure/texture evolution and mechanical properties of AM ATI 425 alloys. It will help to fully utilize Fe as alloying element in AM Ti alloys.

Synthesis, characterization, and application of Zirconia-Hydroxyapatite-Chitosan (ZHAC) nanocomposite for dental implants

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Nowadays, implants in dentistry commonly used to replace missing teeth are a daily routine. Dental implants are used to inhibit bacterial colonization. Nanotechnology is gaining importance in the field of dentistry due to its wide applications. In this paper, we synthesize zirconia nanoparticles, hydroxyapatite nanoparticles, and chitosan nanoparticles. Then, we prepared a nanocomposite ZHAC from these three nanoparticles. All these nanoparticles and nanocomposites were characterised by FESEM, TEM, FTIR, XRD, and PSA, respectively. Antimicrobial studies were performed with the nanocomposite, and we found a good zone of inhibition against a wide range of microbes. Additionally, cytotoxicity tests of nanocomposite evaluated that these gave excellent cell viability, which makes them an ideal choice for dental implants.

Keywords- Nanoparticles, Nanocomposite, Implants

Computational Modelling of Process–Structure–Property Relationships in Metal Additive Manufacturing

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A sophisticated understanding of the complex physics of AM and process-(micro)structure-property (PSP) relationships is needed to establish a knowledge-based approach and tools to engineer AM materials to achieve enhanced properties. Modelling represents a powerful tool to further advance our understanding of the fundamental relationships between the AM process and parts' mechanical properties and to enhance our prediction capabilities in the PSP space considering a digital twin of AM component. This presentation covers the results of PSP modelling for alloys fabricated by laser powder bed fusion (LPBF) AM. In particular, the finite difference method is used for melt-pool-scale thermal simulations of the LPBF process. The calculated temperature histories become an input for cellular automata simulations of the grain structure evolution during metal 3D printing. The microstructural data are considered explicitly in micromechanical finite element simulations in terms of anisotropic elasticity and crystal plasticity. Effects of some process parameters on the microstructure and mechanical behaviour of AM metallic materials are analysed.
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Challenges associated with printing Alumina monoliths via lithography-based ceramic manufacturing

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The introduction of lithography based ceramic manufacturing (LCM) from photocurable ceramic slurries has enabled the fabrication of dense ceramic structures that have a high level of complexity. The parts manufactured in this study were made on the CeraFab 7500 system, using LithaLox HP 500 [1], a commercially available slurry consisting of high-purity alumina powder, dispersed in a light-sensitive binder. In the past this material has been shown to produce alumina parts that exhibit mechanical properties that are equivalent to conventionally manufactured ceramic materials [2]. The aim of this work was to investigate deformation and crack formation that was observed on monoliths after preconditioning or sintering. A variety of factors such as part geometry, printing parameters, heat distribution in the furnace during sintering or length of UV curing were considered and an overview of the results will be presented.

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High-strength antibacterial Cu-bearing 316L stainless steel fabricated by laser powder bed fusion

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Corrosion-resistant stainless steels with excellent mechanical and antibacterial properties are highly needed in the biomedical field. In this work, the copper (Cu) element was added to 316L stainless steel to produce a new biomedical stainless steel with excellent combinations of strength and antibacterial function by laser powder bed fusion (LPBF). It is found that a fine grain structure consisting of plenty of dislocation cells with the size of 200~500 nm was formed in all as-fabricated samples, and some nanotwins were produced during tensile deformation. The high strength of LPBF Cu-bearing stainless steel is mainly attributed to the synergy of grain refinement strengthening, dislocation strengthening, and nanotwin strengthening. Moreover, the second phase of ε-Cu was introduced in austenitic 316L stainless steel due to the Cu addition. All Cu-bearing stainless steel samples exhibit excellent performance in both *E. coli* and *S. aureus* environments and the antibacterial rate is near 100%, and this is because of the precipitating of Cu irons with good bactericidal ability. These promising results and cumulative analyses greatly enrich the application of Cu-bearing stainless steel.

Additive manufacturing of high-strength and high-conductivity Cu alloy

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Manufacturing Cu by laser powder bed fusion remains a challenge owing to the high reflectivity of the powders. The addition of alloying elements could improve printability, but sacrificing either strength or conductivity is unavoidable. In this work, we combine oxygen and the steep temperature gradient of laser powder bed fusion to prepare cellular microstructures constituted by nano precipitates in Cu-O alloy, thereby simultaneously realizing high strength and high conductivity. Interestingly, an ultra-high strain hardening rate was found in the alloy, which is four times higher than that in pure Cu. The outstanding performance should be ascribed to the adequately precipitated oxygen, the interaction between dislocations and oxide nanoprecipitates during deformation, and the cellular configuration. This study explores the potential of utilizing oxygen and process features of laser powder bed fusion to provoke special microstructures and overcome the dilemma between strength and conductivity in Cu and its alloys.

Interstitial oxygen in additively manufactured titanium alloys

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Additive manufactured Ti alloys have been extensively studied and used widely in many industries. For a long time, oxygen has been referred to as the 'kryptonite' to Ti, capable of invoking a strong hardening effect but resulting in dramatic embrittlement. Here, we demonstrate that the precision control of oxygen addition can significantly benefit the mechanical properties of additive manufacturing Ti alloys.

On the one hand, the oxygens could be incorporated into an additive manufactured Ti-6Al-4V alloy to improve its mechanical properties by forming an oxygen-containing FCC solid solution phase. It was revealed that the oxygen-stabilized FCC-phase dramatically enhances the strength and ductility of the material. On the other hand, the introduction of oxygen in Ti-Fe alloys during additive manufacturing can lead to unexpected performance, in which the interstitial oxygen complex gathers near grain boundaries and impedes dislocation motion inside the material, significantly improving the strength of the alloy. These results provide a significant step towards fabricating low-cost and high-performance alloys using additive manufacturing.

Droplet impact dynamics on the superhydrophobic mesh cantilever beam with application in 3D printing

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Droplet interaction with solid surfaces is particularly important due to its application in different industries, including coating, printing, and additive manufacturing. To achieve accurate microscale printing, the micro-size droplet should be deposited precisely, which can reduce the speed of 3D printing. The impact of Non-Newtonian droplets on the mesh surfaces with micronized pores can provide a tool to print a layer of homogeneous droplets at specific sizes, improving the printing speed. It is well known that changing the Non-Newtonian properties of the liquids usually used in the additive manufacturing industries can change the impact phenomena. The polymer concentration that affects the viscoelasticity of the final liquid is one of the essential parameters. The flexibility of the mesh surface is another factor that can significantly change the impact outcomes. The present study focused on the Newtonian and non-Newtonian droplet impact dynamics on the fixed and cantilever beam superhydrophobic mesh surfaces to provide the fundamental knowledge required to control the droplet outcomes. The studied parameters include the mesh's pore size, surface flexibility, and non-Newtonian properties of the liquid. The results will be used to improve the 3d printing efficiency and reduce the printing time.

Effects of thermal history on solidification microstructure in Ni-Mo-Al single crystals

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A major drawback of metallic additive manufacturing (AM) is the lack of understanding of microstructural evolution during the build process due to rapid solidification conditions. Local thermal conditions within AM melt pools favor dendritic growth, having an epitaxial nature that could be favorable for maintaining crystallographic orientations of single crystals. However, the thermal history imposed on the substrate can cause recrystallization as the melt pool approaches the final fusion interface. This promotes the melt pool to interact with the newly recrystallized grains, causing epitaxial growth with the new orientations. Understanding the recrystallization associated with laser melt pools is crucial to controlling microstructural development. This work explores the relationship between processing parameters and thermal history on microstructural evolution in model Ni-Mo-Al single crystals. Solidification velocities of spot and raster melts were obtained by in-situ synchrotron x-ray radiography captured at the Advance Photon Source. TriBeam was preformed to record 3D microstructural data that can then be understood by coupling solidification velocities with simulated thermal gradients modeled using FLOW-3D, a multi-physics computational fluid dynamics software. This work seeks to develop a fundamental understanding between processing conditions and microstructural evolution.

Refinement mechanisms of tantalum-inoculated aluminum subjected to simulated laser powder bed fusion

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Additive manufacturing (AM) has opened doors to novel part geometries and applications, particularly for aluminum (Al) alloys. Although the outstanding thermal conductivity shown by Al makes it ideal for extracting heat with complex cooling channels, this property, as well as other properties (e.g., a high coefficient of thermal expansion), makes it susceptible to hot tearing. In addition, the high thermal gradients generated by AM, combined with the thermal properties of Al alloys, promotes the formation of columnar grains, which are usually undesirable. Inoculation of Al alloys to induce grain refinement, preventing solidification cracking and columnar growth, has been recently explored. However, more work needs to be done to fully understand the mechanisms by which grain refinement occurs in inoculated Al alloys for AM. In this work, pure Al substrates were subjected to simulated laser powder bed fusion at the Advanced Photon Source (Argonne National Laboratory), while capturing in-situ x-ray radiography measurements. Pure Al and tantalum (Ta)-inoculated Al powders were used to assess the effect of Ta inoculation. Spot and raster track melting experiments were conducted, varying parameters such as laser powder and laser speed. Solid-liquid interface velocities were directly measured and thermal gradients were modeled. Ex-situ characterization was also performed to understand solidification with processing variations and Ta inoculation.

Key words: particle inoculation, laser powder bed fusion, in-situ characterization, aluminum alloys

Hierarchically porous 3D-printed bio-ceramic tissue scaffolds

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We present an approach to producing multiscale porous ceramic bone tissue scaffolds by 3D printing colloidal particle pastes *via* the Direct Ink Writing (DIW) technique. Millimetre-scale porosity is created by the 3D printed scaffold strands. We introduce 20 micron-scale porosity into the scaffold strands using paste formulations where the particles are in aqueous suspension, followed by addition of oil to create pores with either particle-stabilised emulsions or capillary suspensions.

The rheological (flow) properties of the pastes, such as storage modulus and yield stress, must be carefully controlled to produce paste inks suitable for printing by extrusion through the nozzle of the 3D printer. Control of the internal strand microstructure is possible by controlling the amount of oil and surfactant concentrations. Earlier formulations have been developed for alumina[1], and herein we focus on bio-ceramics such as β tricalcium phosphate.

By varying the DIW print parameters, as well as the microstructure of the scaffold strands, we demonstrate the potential of tailoring the physical properties of the scaffolds, such as their porosity and strength. Additionally, such customisation is advantageous in personalising the scaffold's degradation rate for different patients. Lastly, we discover that the viability and growth of osteoblasts is regulated by scaffold architecture.

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Additive Manufacturing at scale

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Stryker is a global leader in medical technology and is known for its innovative medical devices and equipment. Additive manufacturing has emerged as a disruptive technology in the medical industry, enabling Stryker to produce medical devices with increased efficiency, reduced costs, and enhanced functionality. This presentation explores Stryker's additive manufacturing journey highlighting the advantages and challenges of scaling up additive manufacturing for medical devices. One of the successes of Stryker's additive manufacturing program was the development of the Tritanium® porous structure that promotes bone growth and allows for improved fixation. Tritanium has since become a flagship feature on Stryker's products, demonstrating the company's commitment to innovation and its ability to leverage advanced technologies to improve patient outcomes.

High resolution 3D bioprinting of light-activated bioinks

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3D Bioprinting requires specialized bioinks that is able to be printed but also protect the cells during the printing process. These bioinks are often biomaterials with specific rheological properties that allows spatial extrusion in a layer-by-layer manner, but also being cyto-compatible to support cellular viability and function. This talk will cover the different design criteria required for bioinks, as well as the variety of materials being employed to manufacture these bioinks. Specific focus will be placed on the various chemistries used to synthesize light-curable polymers, photo-initiating systems to crosslink the polymers, as well as strategies to maintain bioprinted constructs' stability. Moreover, these chemistries and strategies will also be compared between different biofabrication platforms, including extrusion and lithography-based bioprinting technologies. The versatility of these materials and crosslinking chemistries allows the generation of different tissue analogues including cartilage, bone, blood vessels and cancer models.

An introduction to additive friction stir deposition: A review of process development, material qualification for aerospace and space applications

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Additive Friction Stir Deposition (AFSD), commercialized by MELD Manufacturing Corporation as the MELD® process, is a bulk-near net shape, solid state, additive manufacturing process where the principals of friction stir welding and severe plastic deformation are leveraged to produce uniform microstructures and isotropic properties on a large scale. Unlike many forms of additive manufacturing which require powder, thin films, or wires for the feed material, AFSD uses commercially produced bar stock. The feed stock is fed through a hollow rotating tool and deposited in the solid state onto a metal substrate or a previous layer. While the feedstock is being fed, the tool traverses in the current layer's deposition plane leaving a track of deposited material behind it. Due to the high level of shear deformation experienced, grain refinement is a typical signature of AFSD, leading to elevated strength in the as deposited condition for many materials. Fundamentally, any metal that can accommodate deformation when at elevated temperatures can be deposited via AFSD. Compared to other solid state metal forming processes like rolling, extrusion, and forging, AFSD is unique in that the volume being deformed at any given time is small compared to both the whole part and any given cross section. This allows for much higher levels of deformation to be put into each voxel of material and with more uniformity than if deformation was applied on a larger scale. Just like any other thermomechanical processing method, for the appropriate materials, a heat treatment may be applied post processing to achieve desired tempered properties. Rather than precipitation hardened materials which require heat treatments post deposition, AFSD is particularly well suited for materials with strong Hall-Petch relationships, meaning their yield strength increases significantly with decreasing grain size. Farbi et al. have demonstrated the excellent tensile performance of AFSD Ti-6Al-4V against both other additive methods and traditional processing e.g. wrought, forged, cast, etc. Current applications of AFSD include production of large scale near-net parts traditionally produced via forging or casting. While the resolution of AFSD is not as refined as other metal printing technologies, the value add of the MELD process is the ability to rapidly produce near-net parts that can enable finish machining saving months or years from the typical production schedule. For this presentation, an overview of the development of the MELD process for aluminum and titanium alloys will be reviewed. Specific activity around the development of Al7075 and Ti64 for structural components, including a discussion on key processing parameters, microstructure, chemical analysis, and mechanical properties, will be discussed. This discussion will continue with a review of applications where the MELD process is being used to fabricate large-scale (1-10m) structures such as rings, tanks, and nozzles using aluminum, magnesium, and titanium alloys. This presentation will conclude with an introduction to next generation capabilities, including the deployment of the world's largest metal 3D printer (20 ft x 30 ft x 12 ft) by the US Army to print tank hulls and robotic developments of the process for 6 DOF deposition.

Burn the Boats: A Strategy to Accelerate Adoption of Advanced Manufacturing

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Advanced and digital manufacturing hold the promise to accelerate innovation. However, there is always risk when adopting new manufacturing technologies for product deployment. This is compounded even more when component failure can lead to catastrophic events. In many defense and civilian applications, there is interest in exploring additive manufacturing but fear of the unknown in terms of part quality, reliability, consistency and uncertainty in certification/qualification. This talk will explore these issues and discuss strategies to mitigate these risks enabling companies to "burn the boats" and move forward without a fear of failure.

Additive Manufacturing: Keep it Real, Make it Work

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Additive manufacturing should be better integrated into manufacturing than it is. The technology is sufficiently mature; there are a myriad of examples of applications of the technology and significant examples of excellence sufficient to convince all business that it should be taken seriously. Yet its adoption is arguably erratic. Based on over a decade of working with companies and academia, this presentation discusses why it is yet to reach its full potential and outlines a strategic pathway to better support its integration into existing operations. The work draws on transition research methodologies and explains staging of practice change to reduce risk to a company and its workforce during the adoption process.

Visualizing and Controlling Microstructural Evolution in Metals under Additive Manufacturing Conditions

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In metal additive manufacturing (AM), an alloy (in powder or wire form) is melted by a rapidly moving heat source. A solid layer forms upon cooling, and successive layers are built by melting and solidification to form a three-dimensional (3D) part. AM processes typically produce large temperature gradients, high solidification rates, and repeated cycles of heating and cooling. The local conditions experienced during an AM build (e.g., thermal gradient and solid-liquid interface velocity during solidification) will dictate microscopic structure (i.e., microstructure) evolution. For example, a common characteristic of 3D printed metals is coarse columnar grains that grow along specific directions of the crystal lattice during solidification that may exhibit anisotropic mechanical behavior, so ways to control microstructure evolution and promote grain refinement are of great technological value. AM may also yield metastable phases and unusual defect structures. Here we visualize melt pool dynamics and solidification during simulated metal AM by real-time (e.g., synchrotron x-ray) imaging and modeling and link local processing conditions to microstructural evolution. We also highlight novel microstructures produced by solid-state phase transformations under AM conditions. A deeper understanding of solidification and solid-state phase transformations under AM conditions is needed to optimize processing across AM technologies, control microstructure evolution and resulting properties, and design alloys for AM.

Investigating the Effect of Processing Parameters on the Flexural Properties of 3D Printed Continuous Fibre Reinforced Composites

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The potential of 3D printing using fused deposition modeling (FDM) to produce continuous fibre reinforced composites (FRCs) with complex geometries is well recognized, although their strength has been reported to be inferior to traditionally manufactured specimens. This study investigates the effect of processing conditions on the flexural properties of additively manufactured FRCs, which can be divided into pre-processing (pre-coating of fibre filament), processing (3D printing atmosphere) and post-processing (vacuum dry). Pre-processing of fibre filament with monolayer graphene oxide coating yielded 14% increase in the ultimate flexural stress of glass fibre reinforced Onyx specimen. Processing with constant flow of dry nitrogen gas during the printing resulted in 12%, 19% and 26% improvements in the ultimate flexural stress of the Onyx specimens reinforced with carbon, glass and Kevlar fibre filament respectively. All specimens showed an increase in flexural properties with vacuum dry curing, with a greater increase at 145°C treatment than at 105 °C. The treated glass fibre reinforced Onyx specimens displayed over 70% enhancement in ultimate flexural stress when all three processes were applied sequentially.

3D Bioprinting: Making Stuff that Makes Stuff using Biology

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The quest to 3D print human organs has not been extinguished, merely tempered by the realization that 3D printing scaffolds that facilitate the body to regenerate biological systems would, in itself, be a great leap forward in medical technologies.

So now we consider how the appropriate arrangement of biomaterials and cells might integrate with the living human system, recruit appropriate endogenous cells and rebuild tissue such as skin, bone or cartilage. Biomaterials such as alginate or gelatin based materials have been extensively utilized, while the use of nanocellulose is increasing. The integration of cells retrieved from the patient and in some instances reprogrammed to induced pluripotent stem cells, is an approach that is attracting serious attention in the development of scaffolds that encourage biological regeneration.

We will draw on our experiences to date, highlight some advances and shine a spot light on some remaining challenges in this emerging area.

Laser-based additive manufacturing of a large-scale optical bench for space application

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Next to a sustainable buy-to-fly ratio, additive manufacturing AM with laser-based direct energy deposition L-DED has the potential of building up near net shape metallic components even with beneficial material properties at a large scale. In particular, the possibility of manufacturing large components in a hybrid manner, combining conventional manufacturing processes with AM, enables the economic utilization of these processes. Advanced technical approaches using L-DED allow not just the scaling of AM but also the processing of titanium alloys.

This talk will discuss the application of nozzle-based LMD (powder) for the fabrication of an optical bench for use in the ESA “Athena” mission. One of the key aspects taken into account is the process driven redesign including novel geometrical features. In addition, various system modifications like multiple beam sources, processing optics and tailored process parameters are enhancing manufacturing capabilities in terms of precision as well as productivity. Furthermore, the latter yielding a significant reduction in the post-processing effort while maintaining material properties according to strict requirements for space applications.

Additive manufacturing of shape memory alloys for space applications

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Shape memory alloys (SMA) possess two mechanical responses, shape memory effect (SME) and superelasticity (pseudoelasticity). The space industrial community is interested in developing SMA-based actuating mechanisms to replace the current electric, mechanical, or hydraulic actuating sub-systems. Compared with the traditional space actuating sub-systems, the SMA actuators have a high power-to-weight ratio, a simple actuation mechanism, and do not create dust particles or leak of fluids. They are, therefore, lighter, less complex, more reliable and offer higher degrees of design freedoms. However, commercial SMAs have severe limitations. They can only perform a simple unidirectional non-reversible actuation at one fixed temperature and are only available in simple shapes. This is due to a combination of factors, including the sensitivity and control of the chemistry, the difficulty in processing complex shapes by traditional approaches (i.e., rolling, drawing and melt spinning etc.), and the use of only one of the SME and superelasticity responses (mainly linear and rotational). In addition, the SMA actuators made from solid materials have defined stiffness, mode and scale of the deformation, output force and actuation frequency, which are the key performance indicators for actuators. As a result, the use of the traditional SMA actuators have been limited to simple space applications only, such as one-off releasing, locking, or deploying mechanisms for truss mounting, unfolding structures, and solar panel deployment.
CSIRO's High Resolution Processing Team pioneer on the additive manufacturing of thermal and magnetic shape memory alloys for both superelasticity and SME for space applications. In this talk, case studies will be discussed to illustrate the principles of thermal shape memory and superelasticity in NiTi alloys, and magnetic shape memory in NiMnGa alloys. The recent findings and the current challenges involved in laser powder bed fusion and directed energy deposition of NiTi- and NiMnGa-based functional materials are elaborated on.

Optimising the cell microenvironment to improve engineered tissue structure and function

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Cells are highly sensitive to cues from their surrounding microenvironment, where changes to processes including proliferation, differentiation, and organisation all contribute to the overall success of tissue formation. This presents both challenges and opportunities in designing biomaterials and constructs that can best support these processes, but is further complicated by the need for biomaterials to have appropriate properties to impart effective printability when using bioprinting to create tissue constructs. We have used a variety of systems to build understanding of how cells respond to physical, matrix and geometric cues to aid in the design of biomaterials and constructs suitable for bioprinting that can support tissue formation.

Highlighting the impact of construct geometry, our work with mesenchymal stromal cells (MSCs) shows how interplay between hydrogel composition and construct geometry influences bone formation, with effects from the surface area-volume ratio of the construct as well as the ability of the polymer matrix to support deposition of extracellular matrix by the cells. We have also shown how the architecture of a scaffold can affect the ability of MSCs to adhere to and colonise complex 3D printed structures, responding to specific differences in the curvature and shape of additively manufactured titanium scaffolds. With the aim of developing a cardiac patch, we have also developed a system of xanthan gum crosslinked with gelatin-methacryloyl that is suitable for extrusion bioprinting and able to support the viability, growth and organisation of cardiomyocyte populations. Variation in the hydrogel composition can alter the organisation of the cells, with varying effects on tissue structure and beating rate and force. Together these results build knowledge of the complex interplay of factors that dictate cell fate and can be optimised to support the manufacture of functional tissue constructs for a variety of research and medical applications.

Understanding residual stress and texture in additive friction stir deposited aluminium alloy

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Abstract

Additive friction stir deposition (AFSD) is an additive manufacturing process that joins material through plastic deformation using frictional heat and a rotating tool piece. Since material always remains below melting point, this fully solid-state process offers several advantages compared to other additive manufacturing processes such as no need for processing in an inert environment, low energy input, and the ability to process a wide range of Al alloy grades.

Nevertheless, localised heat generation leads to residual stress in fabricated parts, and tool piece movement, thermal cycling, and layer-by-layer processing create a complex interplay of factors affecting residual stress. Furthermore, mechanical deformation leads to crystallographic texture evolution, affecting fabricated part mechanical properties.

This poster provides information from literature regarding residual stress and microstructure formation in AFSD-fabricated Al alloys. Future research directions and industry potential of AFSD are also shown.

Prediction of AM lattice behaviour: observations and opportunities.

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Additive manufacturing allows the fabrication of complex lattice structures. These structures are typically applied for bespoke high value engineering applications that require robust methods of simulation for prediction of as-manufactured response. Observation of the reported AM structural response allows insight into the assumptions, idealisations and strategies typically applied to characterise AM lattice performance. These strategies are highly influenced by the availability of data on the local microstructure, understanding of variation between idealised and as-manufactured geometry and the challenges of multiscale numerical simulation. Opportunities are presented to avoid sub-optimal prediction strategies, to define common technical and economic compromises, and to formalise research goals to enhance existing strategies of AM lattice prediction behaviour.

Additive Friction Stir Deposition: microstructures, recycling and energy consumption

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Additive Friction Stir Deposition (AFSD) lays down an integral alloy deposit with an as-wrought microstructure. The technique is near-net shape and suitable for large components with wall thicknesses of the order of centimetres. The present talk presents some of the unique microstructures that can be formed. Key to understanding the microstructures are the strain rates and temperatures achieved in the process and estimates for what these are are discussed. Because the total accumulated strain is significant, possibly as much as 100, the process lends itself to consolidation of loosely compacted chips or swarf. Some examples of successful deposits of such material are presented. Finally, the energy consumption of the process is compared to other additive manufacturing processes to reveal its rather modest footprint.

The Fear of Qualification [FOQ]

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Abstract

It is necessary to establish repeatable, robust and reliable processes to ensure the delivery of consistent parts from Additive Manufacturing. There is a great deal of angst in the market with respect to just what is needed, why it is needed and how one can practically go about it. There is a need for statistical confidence in the outcome and considering the inherent variability of the core AM processes, this inevitably leads to “Fear of Qualification” by the participants. It is possible to navigate the Process Qualification landscape – all it takes is some focus and the practical application of the requirements of Specifications and Standards applicable to the subject matter. The presentation addresses practical AM process Qualification and in so doing avoids FOQ setting in…

Addressing the high dimensionality and associated data challenges in metal additive manufacturing

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It is well recognized that additive manufacturing processes have a large number of input variables that can influence the properties and performance of the output material. Applying domain expertise can help to rank the relative importance of process variables and greatly reduce the dimensionality. Careful and thorough design of experiments can further separate out confounded variables that can be difficult for a human expert to identify. Application of machine learning to correlate inputs to outputs can create empirical relationships without the need to solve complex multi-physics problems. Finally, statistical methods that can assign some level of confidence to the data is necessary for critical service applications where a formal qualification procedure is necessary.

This presentation highlights some of the working being done at Colorado School of Mines to address data challenges in additive manufacturing. We will examine data schema methods and graphical mapping tools that allow for visual representation of the entire processing landscape – from powder fabrication all the way to part implementation. We will also look at how reduced order process windows can be useful while also highlighting areas for caution. Finally, we will highlight some non-traditional statistical methods from other domains that can be applied to additive processes to further quantify statistical certainty limits particularly in underexplored regions of the process window space.

NASA's Challenges and Opportunities in Spaceflight Certification of Fracture Critical AM Components

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Abstract
In 2021, NASA released internal Engineering Technical Standard called NASA-STD-6030 "Additive Manufacturing Requirements for Spaceflight Systems" to define qualification and certification strategies for mature metallic and non-metallic AM materials and technologies. While these standards have had an immediate impact on the additive manufacturing (AM) industry, there remain many challenges that have yet to be overcome. NASA and its partners in academia and industry are working together to proactively address these issues. One of the most critical challenges has to do with the type of hardware that users desire to produce which integrates the most complicated of geometries into crucial spaceflight applications. These critical AM parts often offer little or no access for quantitative, post-build surface and volumetric non-destructive evaluations. At NASA, such critical spaceflight applications are subject to a set of requirements intended to prevent catastrophic failure due to an undetected defect. In the absence of reliable inspections to bound the relevant flaw sizes, alternate approaches are needed to support certification of fracture critical AM components with limited or no post-build inspectability. NASA AM Community is working on developing a practical approach that is based on flaw state characterization, identification and control of process escapes, and probabilistic damage tolerance analyses.

Custom-built bioprinting system and synthetic polypeptide based bioresin for biomedical applications

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Biomaterial selection, design and fabrication technology are crucial aspects that contribute towards the successful performance of a bioengineered construct for various biomedical applications. Developing novel bioresins and integrating them with 3D bioprinting technology can lead to the development of innovative 3D scaffolds with different shapes, architecture, and mechanical properties. Among the different bioprinting approaches, vat polymerisation-based techniques offer excellent feature resolutions compared to more commonly used extrusion-based methods and therefore have a greater potential to be utilised for printing complex hierarchical architectures. A custom-built, cost-effective, bioprinting system was developed, which utilized a novel synthetic polypeptide based bioresin to fabricate hydrogel scaffolds with well-resolved filaments. Various physical and biological characterisation of the fabricated hydrogel scaffolds demonstrated its capability to provide structural integrity and support cellular activities. The study highlights a specific advancement in the design and fabrication of 3D substrates that has the potential to uncover the relationship between cells and their physical microenvironment. The bioprinter setup designed has the potential to offer greater fabrication versatility in photopolymerizing a variety of hydrogel materials with desired scaffold geometries, excellent feature resolutions and the potential to incorporate mechanical and biochemical cues.

Regenerative Manufacturing of Bioactive Implants: From Low Modulus Titanium Implants to Platform Bioinks for Biofabrication

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Additive Manufacturing (AM) and Biofabrication (including 3D bioprinting) are revolutionizing fabrication of personalized implants, personalized- and regenerative-medicine. Yet we have not pushed the boundaries on implant design.
The response of bone formation to strain is well established, however investigation into exceedingly soft titanium implants relative to bone is limited. We describe additively-manufactured low-stiffness implants to induce bone formation and assessed their biological performance in a pre-clinical *in vivo* tibial tuberosity advancement (TTA) model [1-2], as well as *in vivo* spine-fusion model comparing titanium spine fusion cages without autologous bone graft to gold-standard Polyetheretherketone (PEEK) with graft. AM of soft titanium implants stimulate early bone formation and have significant importance in future orthopaedic implant design.
Regenerative engineering and Biofabrication technologies offer even greater potential to fabricate living tissues that replicate complex 3D organization of native tissues via automated delivery of cell-laden bioinks and/or bioactive factors.
We describe versatile, photo-clickable and cell-instructive gelatin-based bioinks and photoinitiator system (Ru/SPS) for biofabrication of complex 3D tissues that are printable across multiple biofabrication technologies, including extrusion-, lithography- (DLP) and microfluidic-based bioprinting [3-8].
This work describes a significant breakthrough in development of cell-instructive universal bioink platforms, for advancing biofabrication and regenerative-medicine towards clinical translation [4-5].

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Advanced Manufacturing and Design for Resilient and Sustainable Infrastructure Materials

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In the face of climate change, the world's growing population, and decaying infrastructure, there is a need to develop stronger, tougher, and more resilient civil infrastructure materials. Nature uses sustainable resources of modest materials to obtain flaw-tolerance. Abundant examples in the natural world offer us approaches to obtaining resilient engineering materials. Two primary challenges are engineering the mechanics of natural design schemes and implementing their fabrication via advancing manufacturing processes.

This talk presents how manufacturing can provide advancement in materials design with enhanced mechanics in various "architected" construction materials across multiple scales. A bio-inspired approach to the design of damage-tolerant materials enabled by advancements in additive manufacturing with concrete will be elaborated as an example. Moreover, this seminar presents how laser processes can enable a new understanding of fracture phenomena in brittle materials. A fracture mechanics example in 3D-printed cement-based materials will be presented in which laser processing can help elucidate new understanding.

This talk makes the case that advanced manufacturing offers the opportunity to harness heterogeneities in materials or assist us in studying and understanding them. The development of automated technologies such as robotic additive manufacturing techniques, will be presented as facile tools to achieve resiliency in civil infrastructure.

Additive Manufacturing at Lockheed Martin

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Fundamental knowledge of Additive Manufacturing (AM) processes has increased significantly with the intersection of Computation Materials Engineering, Artificial Intelligence/Machine Learning, and in-situ process data acquisition. This knowledge is used to define a multi-scale digital thread that spans the entire AM workflow. The digital thread is made continuous by the models and data analyses that link the process parameters to the material state, the material state to the bulk properties, and the bulk properties to the component performance (PSPP). The digital thread provides the opportunity for a qualification approach that takes advantage of the fundamental knowledge gains and available data to produce repeatable and reliable components more confidently. This qualification approach is warranted due to the complex nature of AM, and is advantageous since it provides an avenue to reduce testing. This presentation discusses the state of practice across the Lockheed Martin enterprise to identify and assess AM opportunities, extend fundamental knowledge of AM, define the digital thread for AM processes, and develop a rapid qualification approach.

Additive Manufacturing of concrete: a paradigm shift toward sustainability

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Concrete is worldwide used as one of the major construction materials, both in situ and prefabricated. It is cheap, fire resistant and durable. However, the costs of a typical concrete structures consist for about 50% on the formwork needed. Besides, the cement production is responsible for a serious part of the exhaust of greenhouse gasses worldwide. Additive manufacturing of concrete structures potentially could save on the costs, improves productivity and could above all seriously limit the environmental impact by using less material. No slump concrete is required and the materials properties, both in the fresh state and hardened state depend on many environmental parameters, print path and print speed. These relationships need to be known in order to make the print process more robust and the result safe from a structural point of view. The lecture discusses various sustainable approaches adopted by IIT Guwahati 3D concrete printing team aiming to improve the performance and capabilities of the printer while developing new printable concrete taking industrial wastes into account.

Addressing AM sustainability of polymer use

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Plastics, especially those created from synthetic polymers, pose a significant environmental problem. The development of polymer-based additive manufacturing technology needs to address related environmental problems so that it doesn't make things worse. One approach is to develop solutions around filaments made from recycled plastic products. Another is the use of bio-based polymers as a source. Some experiences regarding these approaches will be discussed.

Current developments and future prospects around industrial additive manufacturing of metal products

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This presentation describes experiences in the development of metal additive manufacturing solutions for manufacturers connected to the Fraunhofer Innovation Platform for Advanced Manufacturing at the University of Twente (FIP-AM@UT). A broadening range of manufacturers are seeing benefit in AM technology as part of their offerings. However, there is still resistance to the transition process due the complexities in creating effective business models. A key to success is effective engagement with impartial specialists who can advise on the correct approach towards investment. This is specifically so when considering the large investments required for metal AM, both powder bed fusion and directed energy deposition. For these technologies it is also important to look at the future possibilities that these technologies have to offer.

Additively manufactured Ti-6Al-4V alloy via directed energy deposition of boron nitride nanotubes (BNNT)

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Additive manufacturing, also known as 3D printing, overcomes many design and manufacturing constraints to allow almost direct production of metals into complicated geometries. However, coarse columnar grain structures, up to the millimeter-scale, are commonly produced in titanium and its alloys through the layer-by-layer process and this causes significant anisotropy in mechanical properties. This work is an innovative approach for microstructure refinement of an additively manufactured Ti-6Al-4V alloy via directed energy deposition of boron nitride nanotube (BNNT) decorated powders. With only 0.4 wt% BNNT, this process results in unprecedented grain refinement down to a few micrometers and over 50% strength enhancement. A unique texture-weakened structure comprising fine equiaxed grains is achieved via a novel nanoparticle-mediated nucleation mechanism enabled by local hypereutectic precipitation in the rapid solidification process. This mechanism is highly suited to the metallurgical environment of metal additive manufacturing and creates a pathway for screening effective grain refiners in titanium and other alloy systems.

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Wire Arc Additive Manufacturing for Bridge Maintenance

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Wire Arc Additive Manufacturing (WAAM) technology offers a promising solution for the upkeep and repair of metal structures, including steel bridges. With over 6000 bridges under its purview, Transport for New South Wales (TfNSW) is actively seeking cost-effective alternatives to traditional casting components. This paper explores the potential of WAAM technology as a cost-effective and efficient method for manufacturing large metal components with desired mechanical properties that adhere to relevant standards.

In addition, the paper presents the results of a successful trial conducted in collaboration between the University of Wollongong and TfNSW, where tapered washers for timber truss bridges were manufactured using WAAM technology. This proof-of-concept trial highlights the feasibility of using WAAM for the rehabilitation of historic structures. Further trials are ongoing to examine the impact of residual stress and distortion, as well as to explore the potential benefits of WAAM for maintaining other metal assets.

Non-destructive neutron base characterisation techniques for additive manufacturing

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Several instruments at ANSTO have a unique non-destructive ability to characterize additively manufactured components, in particular determine critical imperfections, characterise texture and measure residual stresses. These measurements can be carried out on real engineering components, mock-ups, or test samples with minimal preparation as well as ex-situ and in-situ. This information provides direct impact into optimization of modern manufacturing processes, improved product reliability, enhanced design performance, reduced production cost, and extended life prediction on significant engineering assets. The versatile team has established a strong record in assisting Australian and international researchers and engineers across a wide range of engineering projects.

Over time, we have built an experience and technical expertise, which is available at the Australian Centre for Neutron Scattering to support academic and industrial research and development.

This presentation will focus on the challenges and opportunities of neutron base techniques for residual stress and defect assessment in additive manufacturing components.

A numerical investigation of artificial reefs design on flow field effect considering 3D printing criteria

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Artificial reefs (ARs) are man-made underwater structures for promoting, restoring and providing habitat for marine life, which helps in upwelling and controlling beach erosion. Restoration of AR needs multidisciplinary approach such as design, simulation study, hydrodynamic analysis, material, and manufacturing to understand their impact on the marine environment. In this study, a bio inspired AR has been designed with current limitation of concrete 3D printer. The performance of bio inspired AR was numerically investigated to understand the effect of flow field and upwelling while varying the design parameters such as hole diameter and shape. Computational fluid dynamics and orthogonal experimental design methods are used for parametric analysis. The results of tool path planning confirm the possibility of 3D printing the proposed AR design using concrete material while the design variables further need optimization for improving the upwelling behaviour.

Additive S&T for Defence

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As a technology, additive manufacturing has significant potential to both enhanced Defence capability and improve Defence ability to sustain its platforms both locally and when deployed. DSTG and its industry and academic partners' role is to fully understand the various additive manufacturing technologies and their benefits and risks in a Defence operating environment. The S&T covers the full range of additive manufacturing opportunities (1) additive repair of current technology designed components, (2) additive manufacture of new replacement components, (3) qualification and validation of AM, (4) multi-scale modelling the AM process and (5) design components for additive manufacturing. DSTG also assesses industry partners' knowledge of AM and the quality of AM proposals to Defence from industry. The advantage of undertaking S&T activities with academia is that the full manufacturing path can be analysed; from feedstock to component along with new AM technologies. This More, Together approach with industry and academia ensures Defence will always have best information to make critical decisions about the use of additive manufacturing.

Design for Acceptance of Additively Manufactured Components

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Component design plays an important role for broadened applications of additive manufacturing (AM). With regard to design for AM (DfAM), most of the previous research and development have been focused on exploiting the enormous design freedoms as provided by the unique AM process, while ensuring manufacturability. The benefits of DfAM has been demonstrated by applications that feature part consolidation, weight reduction and function enhancement.

This presentation aims to introduce key aspects relevant to the design acceptance, which is another important topic for DfAM and needs more investigations. The presentation will focus on metallic components in the context of defence applications. A summary of the latest AM standards development will be provided, highlighting the need for users to specify acceptance criteria. Key considerations on design for acceptance will be illustrated for structural applications. A case study will be presented, demonstrating the sources of challenges, as well as approaches, towards acceptance of the re-design of a helicopter component for additive manufacturing.

3D printed concrete structures subjected to dynamic impact

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ABSTRACT

This study investigates the impact performance of 3D-printed concrete specimens with and without steel fibers under drop weight impact test. The study draws inspiration from the Bouligand structure in the dactyl club of mantis shrimp and explores four different printing patterns with varying pitch angles. The findings reveal that helicoidal patterns perform better than unidirectional patterns in terms of impact duration, peak impact force, and energy absorption for fiber-reinforced specimens. However, pitch angle does not significantly affect impact resistance for specimens without fibers. Micro-CT images demonstrate that printing pattern affects the size and geometry of internal pores, which affects the mechanical response. The study also reveals complex cracking mechanisms for fiber-reinforced specimens, including crack deflection, twisting, branching, bridging, and micro-cracks. Analysis of fiber orientation indicates that fibers aligned in the direction of the toolpath effectively provide crack-bridge actions as cracks propagate during the impact process.

Keywords: *3D concrete printing; dynamic impact; energy absorption; bioinspiration.*

Nature's Lessons and Inspiration for Fracture-Tolerant Design

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ABSTRACT

This study explores the fracture tolerance designs of biological structures and materials that serve as inspiration for modern protective structures subjected to extreme loadings. Nature's lightweight and high-performance composites, such as nacre and porcupine quill (PQ), possess well-organized hierarchical laminar structures over multiple length scales. The microstructure of the quill is examined via non-destructive micro-computed tomography, inspiring the design of bioinspired Voronoi sandwich panels. The study presents the effects of multi-materials and multi-scale designs of nacre, followed by a validation strategy through mimicking. Both representative mimetic architectures of nacre and PQ are realized using 3D printing technology. The study also includes experimental investigations and finite element parametric simulation to gain further insights into the fracture tolerance process.

Keywords: *Biological structures; porcupine quill; finite element simulation; biomimetic; A 3D printing.*

Residual Stresses in Multi-layer Laser Clad Light Rail Components

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Railway networks are relied upon globally for passenger, freight and mineral transit. Due to the low carbon steel grades used to manufacture light rail components such as switches, these networks are prone to rapid wear, fatigue and degradation. This requires the continuous development of new maintenance strategies to avoid regular replacement procedures and keep these critical rail networks safe and operational.

Laser cladding is an additive manufacturing-based repair strategy which can be applied to recondition worn rail components. A high energy laser simultaneously melts a metallic powder and the rail surface to form a metallurgically bonded coating. Although the heat inputs required for laser cladding are lower than those used in welding techniques, a heat affected region is generated below the fusion boundary. This area undergoes microstructural changes, phase transformations and solidification shrinkage which contributes to the generation of residual stresses. The residual stresses which arise during this thermal process must be well understood to ensure the prolonged operational lifetime of repaired rail components.

Laser cladding has been undertaken on light rail components using single- and double-layer depositions of Stellite. Double layer depositions reheat the underlying cladding layer which can alter the microstructure and fatigue performance. The final stress state is further influenced by surface grinding finishing procedures and cladding geometry. In addition to microstructural and mechanical property evaluation, neutron diffraction techniques have been used to non-destructively measure internal strain across the cladding layers, heat affected zone and rail substrate using the Kowari strain scanner at ANSTO. Understanding the influence of laser cladding depositions on residual stress is essential in the development of an additive-manufacturing based repair strategy which can be applied in industry to recondition high wearing components.

On New Methods to Predict Local Properties in Additively Manufactured Ti-6Al-4V and the Possibilities for Gradient Materials

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Phenomenological models have been developed to predict the tensile behavior of Ti-6Al-4V, independent of the processing route, based upon measurements of the composition and microstructure. The properties include yield strength and ultimate tensile strength. The models have been successfully applied to wrought Ti-6Al-4V, large area electron beam additively manufactured Ti-6-4 subjected to various heat treatments, large area laser hot wire additively manufactured Ti-6-4, and selective laser melted Ti-6-4. For the electron beam additively manufactured Ti-6Al-4V, these models have been coupled into an integrated computational materials engineering (ICME) framework to demonstrate the ability to go from a multiphysics process model of the deposition process to probabilistic design allowable curves. As part of this, it became necessary to consider how to quantify texture at large scales. An emerging microscopy technique using surface acoustic waves will be presented. These advances, coupled with recent activities associated with spatially controlling materials state, hint at exciting possibilities for materials in the near future. These possibilities will be discussed.

Speak softly and carry a big stick: how additive manufacturing alliances in defence help us prosper

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Australia is facing some of the most difficult geopolitical circumstances since the Second World War; as a result, defence spending as a proportion of GDP is set to be the highest it has been in modern times. As we head towards a broader trend of onshoring, de-globalisation, and strengthened geo-political alliances, considerations such as sovereign capability and supply chain security have become areas of increasing importance in defence procurement. Additive manufacturing has a key role to play in our ability to supply to many of the defence programs given the technology's ability to deliver on key procurement concerns such as supply chain de-risking, superior product performance, and economical low-volume production. This talk will explore some of the current applications of additive manufacturing in defence originating both from Australia and allied partners, and will demonstrate how additive manufacturing technologies, and the alliances that we have that support them, can secure and strengthen our defence capability.

Effect of post-processing isothermal tempering heat treatment on the mechanical properties of additively manufactured 16Cr-2Ni martensitic stainless steel via Directed-energy deposition

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Directed-energy deposition (DED) is a common category of additive manufacturing (AM) that employs high-energy sources, such as laser or electron beams, to deposit material onto a substrate. The highly targeted heat input of the laser or electron beams result in rapid heating and cooling with material experiencing rapid solidification when the heat input is removed. Whilst DED holds potential for fabricating high-performance structural components, deposited materials often exhibit increased strength and hardness, but significantly lower ductility as compared to conventionally manufactured materials. This challenges the use of DED for fabricating structural parts, including martensitic stainless steel parts such as pumps, turbines, and aerospace components. To address this issue, the present study aims to investigate the effects of post-process isothermal heat treatments on a DED 16Cr-2Ni martensitic stainless steel alloy (AISI 431) obtained by Laser Metal Deposition. The study focuses on examining the influence of tempering temperatures, typically applied for this alloy (350-650°C), on the tensile properties of the AM material, and comparing them with those of commercially available wrought AISI 431 stainless steel tempered under the same conditions. The findings indicate that tempering at over 550°C can be an effective post-processing step to enable DED martensitic stainless steel for industrial AM applications. The study highlights the importance of post-processing in ensuring comparable performance and reliability of DED-produced to conventionally manufactured martensitic stainless steel components.

Investigations on the impact of the microstructure generated by additive manufacturing on the fatigue crack initiation behaviour

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Keywords: Additive manufacturing, fatigue, microstructure tailoring

Additive manufacturing processes, and more especially laser powder bed fusion (LPBF) process, have a strong influence on the obtained microstructure of 316L stainless steel parts. This microstructure is organized at different length scales, resulting in a hierarchical microstructure [1-2]. Recent developments in the understanding of LPBF process, allows generating different grain structures by modifying the additive manufacturing parameters [3]. By choosing additive manufacturing parameters in a clever way, the microstructure can be then controlled at the grain scale. This opportunity has to be catch as a way to study the fatigue-microstructure relationship.

First, an extensive study on the role of laser scan strategy on defect occurrence, microstructure generation and mechanical properties has been realized. The microstructure growth mechanisms and their modifications due to the choice of laser scan strategies has been particularly pointed out. Moreover, the competition between defect and microstructure for fatigue crack initiation has been studied. Several 316L stainless steel microstructures with very different grains size, orientations and arrangements have been obtained with the LBPF process. In consequence, the influence of grain structures on fatigue behaviour, and especially on fatigue crack initiation, has been studied.

Secondly, heat treatments impact on microstructure of the 316L LPBF stainless steel has been extensively studied. It has been shown that heat treatments offer the possibility to tailor the microstructure at a thinner scale than additive manufacturing parameters allows it. In consequence, they have been used in order to investigate the influence of microscopic features on fatigue crack initiation.

The understanding of both influences of grain and microscopic structures on fatigue crack initiation will provide to fill the gap about the understanding of the outstanding fatigue properties of metallic alloys obtained by LPBF. This work let us hope a future improvement in fatigue properties of LPBF metallic alloys by tailoring their microstructures.

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The State of Design Software in Additive Manufacturing

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Additive manufacturing (AM) has become an increasingly popular method for producing complex geometries and custom parts with high precision and accuracy.

However, the software tools used to design, simulate, and control the AM process are quickly evolving with limited representation in education and training of engineers.

In this presentation, we will review the current state of software in AM, the tools available for DfAM (Design for Additive Manufacturing) including generative and lattice design, simulation, as well as slicing, and machine control. The presentation will discuss the strengths and limitations of existing software solutions, as well as emerging technologies and trends that are shaping the future of AM software.

The presentation will also highlight some of the key challenges facing the AM industry in terms of software, such as the need for better integration and interoperability between different software tools, the lack of standardization and best practices, and most importantly, education on the use of new tools.

The goal is to provide a comprehensive overview of the current state of software in AM, and to stimulate discussion and collaboration among researchers, software developers, and industry practitioners to advance the state of the art in this rapidly evolving field.

A novel approach for the mechanical performance prediction of as-manufactured Inconel 718 latticed structures

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Additive Manufacturing (AM) technologies enable the manufacture of complex componentry with intricate features that are otherwise unachievable. Latticed structures have been widely employed in light-weighting structures as they exhibit outstanding potential for manufacturing tunable characteristics. Understanding the deformation behavior of such structures has attracted the attention of researchers and industrialists alike. One of the key tools for studying these lattices' deformation and failure behaviors is finite element modeling. However, due to the stochastic nature of the defects generated during manufacture, today's finite element modeling cannot perfectly predict the lattices' mechanical performance. In the present work, a methodology is developed for more precise performance prediction. X-ray micro-computed tomography was used to visualize the internal defects in the printed samples. The reconstructed structures were then used to assess the printing fidelity and study their impact on the mechanical properties. To further quantify the mechanical response, FE analysis was conducted based on data extracted experimentally from standard quasistatic tensile tests and 3D reconstructions. The experimental results were then compared to the results from the FEA for validation.

3D Printing of Antibacterial PLA-ZnO Nanocomposites for Biomedical Applications

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Polylactic acid (PLA) is a printable, biodegradable, and biocompatible thermoplastic commonly used for the 3D printing of bespoke biomedical devices, though surface contamination remains a major hindrance as it is a source of infection. A solution is to combine PLA with highly antibacterial Zinc oxide (ZnO) nanoparticles to create antibacterial PLA-ZnO nanocomposites. Moreover, ZnO also comes with attractive tissue regenerative properties that have potential tissue engineering applications. This work adopts Fused Filament Fabrication (FFF) as the technique for 3D printing due to its simplicity, affordability, and popularity. However, the mechanical characterization of FFF parts is impeded by their mechanical anisotropy and the lack of test standards to account for such variability. This work includes studies on the anisotropic tensile properties of FFF parts attributed to different print parameters and highlights the significance of standardization in evaluating the performance of 3D printed parts. The optimization of the print parameters then allows the development of PLA-ZnO nanocomposite filaments suitable for FFF printing of biomedical devices. The effects of ZnO concentration, ZnO surface treatment, and the compounding strategies of PLA and ZnO on the printability and the therapeutic functionalities of the nanocomposites are investigated as part of the development process.

Additively manufactured steel joints for structural frames: Concept proposal and numerical simulations

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Wire Arc Additive Manufacturing (WAAM) is gaining traction across the construction industry due to its capabilities in the fabrication of more efficient and lightweight structures. Such advantageous features can be exploited to address the current challenges in the construction of steel structures. Connections play a crucial role in determining the global response of the frame and controlling the collapse behaviour of the entire system. However, the conventional approach for the design and analysis of structural frames offers a narrow range of pre-defined connection types and limited scope for optimising their rigidity and strength, and the fabrication of connections is labour-intensive.

This study aims to investigate the potential application of additively manufactured connections for steel frames by introducing an alternative conceptual design achieved by topology optimisation showing a superior structural performance to that of a conventionally designed connection. An extended bi-directional evolutionary structural optimization (BESO) technique is adopted to deliver optimised connections. Numerical simulations have been carried out on a simple beam-column connection, to quantify the structural benefits achievable by topology optimisation compared to a conventional design solution. Moreover, the structural performance of a two-storey steel frame assembled using the optimised connection solutions is compared to that of a frame constructed using conventional welded connections.

Accelerated digital design of magnesium alloys using machine learning.

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Magnesium (Mg) alloys continue to draw a great deal of research attention due to their low density and high specific strength. Incremental development from empirically driven alloy design, remains an inefficient. In this work, a virtual alternative is proposed that utilises machine learning (ML) to rationalise the complex relationship between alloy composition and processing - with mechanical properties; consequently, allowing an accelerated prediction of target properties. Developing an open-source alloy database, a detailed understanding of the data that exists in the field is provided. An unsupervised ML method of clustering was implemented with the aim of defining a low dimensional alloy representation space. A systematic evaluation of five supervised ML algorithms was also explored to capture the composition-processing-property patterns. Additionally, a graphical user interface (GUI) webtool was developed to facilitate the use of the proposed models. The results demonstrate that a random forest regression model and a neural network with accuracies of ~80%, are robust models for predicting the ultimate tensile strength and ductility of new Mg-alloys.

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Tough Architected Concrete Enabled by Extrusion-based Robotic Additive Manufacturing

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Nature offers abundant relevant insight for developing engineering materials that can overcome often mutually exclusive properties (e.g., strength and toughness). Two primary challenges are engineering the underlying mechanisms of strong and tough design motifs in biological materials into human-made materials. Implementation of the design schemes often requires advancing manufacturing processes and developing niche fabrication techniques. Extrusion-based additive manufacturing techniques are one way to enable the development of relatively complex schemes, thus helping unleash new design strategies.

This talk presents a bio-inspired approach for the purposeful design of two specific examples, namely helical and double-helical *architected* cement-based materials. Distinct toughening mechanisms will be discussed based on the Mantis shrimp's helical architecture and the Coelacanth fish scale's double-helical architecture. Extrusion-based Single-component and two-component robotic additive manufacturing processes with concrete that have been developed to enable these designs will be elaborated. The mechanics of the architected designs of concrete are compared against the conventionally cast monolithic counterparts. Layer-by-layer additive manufacturing commonly leads to processing-induced weak interfaces. An approach to harnessing the weak characteristics of the interfaces for damage delocalization will be discussed.

Introducing hierarchical heterogenous structures using additive manufacturing for superior mechanical properties

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Some heterogeneous structures have been proved benefitial for simultaneous enhancement of strength and ductility of metallic materials. Heterogeneous structures in metallic materials can be introduced by various methods, including surface plastic deformation, laser shock peening of surface, and chemical/physical deposition. Recently, there has been growing interest in using additive manufacturing (AM) techniques to produce heterogeneous metallic structures. AM of metallic materials involves cyclic rapid thermal loadings that significantly impact the microstructure and consequently the mechanical properties of the materials. During the AM processes, different layers experience different thermal histories, leading to microstructure variation along the build direction. Further, the layer-by-layer deposition during the AM processes makes it possible to precisely manipulate local composition. In this presentation, I will examine the impact of structural heterogeneity on the mechanical properties of AM materials and explore the potential for leveraging AM processing to create hierarchical heterogeneous structures for outstanding mechanical performance.

Additive Manufacturing and Design of Continuous Fiber Reinforced Polymer Composites

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Continuous fiber-reinforced polymer composite additive manufacturing (CFRP-AM) provides an efficient and effective solution to fabricate composites with intricate designs and high performance that are unattainable with conventional composite manufacturing technologies. This study will first give an introduction about the state-of-the-art of CFRP-AM technologies along with their applications in industry. It will then focus on the recent development of a robot-assisted CFRP-AM system that is expected to unlock more freedom for composite designs. Finally, the design opportunities within the material, process, and structure domains will also be discussed together with a design case on composite cellular structures.

Keywords
fiber reinforced polymer composites; design for additive manufacturing; computational design; roboti-assissted additive manufacturing

Wire Arc Additive Manufacturing of Titanium Alloy

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Robot-assisted wire arc additive manufacturing (WAAM) is a high deposition process, which creates large-scale near-net-shape metallic components. This work investigates the effects of the deposition orientation and the loading rate on the tensile properties of titanium alloy specimens fabricated with WAAM. The specimens were cut from a WAAM-fabricated bulk plate in the longitudinal and transversal orientations and loaded in tension with the loading rates of 0.1–0.5 mm/min. The test results indicates that the tensile strength of 770–829 MPa, the Young's moduli of 80–98 GPa, the fracture strength of 720–803 MPa, the ductility of 14–18%, and the resilience of 26–40 kJ/m^3 were obtained. All these properties were not significantly affected by the deposition orientation and the loading rate (ANOVA, $p > 0.05$). Although the yield strength values of 635–680 MPa were significantly independent from the deposition orientation (ANOVA, $p < 0.05$), they were significantly affected by the loading rate (ANOVA, $p > 0.05$). Fracture mechanism observed in all tested specimens had predominantly brittle appearance. The future efforts will be focused on the understanding of the fatigue behavior and developing post processes to improve the mechanical properties of titanium alloy components fabricated with WAAM process.