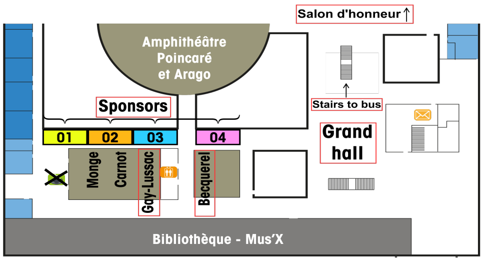
AAMS 2024 final program (overview)

Tuesday 3 Sep		
17:00	21:15	Arrival + Badge pickup + cocktail and dinner (SH)
21:15	21:45	Bus back to Massy-Palaiseau TGV

	Rooms
GL	Amphi Gay Lussac
B	Amphi Becquerel
SH	Salon d'honneur
GH	Grand Hall



Wednesday 4 Sep					
08:00	08:30	Bus from Massy-Palaiseau TGV to venue			
08:30	09:30	Welcome ceremony (GL)			
09:00	09:40	**Keynote: Marc Easton** (GL)			
09:40	10:20	**ECR keynote: Julie Gheysen** (GL)			
10:20	10:40	Coffee (GH)			
10:40	11:00	Al Alloys (GL)	Agricola 544613	Ni alloys and multi-material alloys (B)	Shokri 548778
11:00	11:20		Del Guercio 544187		Park 546146
11:20	11:40		Schmidt 542386		Jamili 545781
11:40	12:00		Smolina 543952		Bulloch 545996
12:00	12:20		Lenoir 545156		Vives 542968
12:20	12:40		Frisk 543983		Richard 545017
12:40	13:40	Lunch + coffee (SH)			
13:40	14:00	Beam shaping + Modelling + Metamater. (GL)	Tarantino 544886	In process/in situ alloys/microstructure engg. (B)	Logé 546264
14:00	14:20		Kitashima 530012		Haghdadi 543585
14:20	14:40		Y. Liang 546082		Abdesselam 544161
14:40	15:00		Barber 544332		Felber 544460
15:00	15:20		Leonardi 544528		Batalha 545577
15:20	15:40		Esmaeilzadeh 544478		Margueret 544468
15:40	16:00		Perez-Prado 544847		
16:00	16:20	Coffee (GH)			
16:20	16:40	Steels (GL)	Smid 574777	Post process HT (B)	Jo 546145
16:40	17:00		Jambor 550464		Stopyra 545213
17:00	17:20		Kosiba 548757		Burlot 545242
17:20	17:30	Break to reassemble in one room (GL)			
17:30	18:10	**Keynote: Guilhem Martin** (GL)			
18:10	19:00	1 minute poster presentations (GL) (See entries below)			
19:00	21:30	Poster session + drinks + dinner (Grand Hall)			
21:30	22:00	Bus back to Massy-Palaiseau TGV			

Thursday 5 Sep					
08:00	08:30	Bus from Massy-Palaiseau TGV to venue			
08:30	09:10	**Keynote: Steven Van Petegem** (GL)			
09:10	09:50	**ECR keynote: Tatiana Mishurova** (GL)			
09:50	10:10	Coffee (GH)			
10:10	10:30	Synchrotron + neutron studies (GL)	Weisz-Patrault 571996	Bulk metallic glasses (B)	Gibbon 549728
10:30	10:50		Ferrari 544761		Hadibeik 531195
10:50	11:10		Gaudez 544714		Sadanand 545459
11:10	11:30		Hocine 544004		Rodriguez-Sanchez 544345
11:30	11:50		Özsoy 546163		Jhabvala 550198
11:50	12:10		De Raedemacker 545128		Moronczyk 545355
12:10	13:30	Lunch + coffee (SH)			
13:30	13:50	Synchrotron + neutron studies (GL)	Y. Chen 549644	Microstr. Modell. (+ valid.) (B)	Santos Macías 560502
13:50	14:10		Semjatov 544144		Tourret 544300
14:10	14:30		Mokhtari 546171		Guillemot 548662
14:30	14:50		Hearn 544180		Dollé 545538
14:50	15:10		Baganis 546278		Després 546426
15:10	15:30	Coffee (GH)			
15:30	15:50	Micromechanisms during AM (GL)	K. Chen 559121	Microstructure of reinforced/composite materials (B)	Gruber 543865
15:50	16:10		He 544098		Aggarwal 546229
16:10	16:30		Rielli 543446		Freundl 543677
16:30	16:50		Luo 543819		Elsayed 539285
16:50	17:10		Köksal 550289		Larini 546167
17:10	17:30		Lasheras 543829		Jandaghi 541711
17:30	17:50		Popov 566130		Vargas 543722
17:50	18:10		Depinoy 547373		Benmabrouk 549041
18:10	19:45	Bus to banquet			
19:45	23:00	Gala cocktail + dinner			
23:00	23:55	Bus back to Massy-Palaiseau TGV			

Friday 6 Sep					
08:00	08:30	Bus from Massy-Palaiseau TGV to venue			
08:30	09:10	**Keynote: Julia Greer** (GL)			
09:10	09:50	**Keynote: Kim Vanmeensel** (GL)			
09:50	10:10	Coffee (GH)			
10:10	10:30	EBM + LPBF (GL)	Di Sturco 545485	WAAM/WaDED + LDED (B)	Courant 550181
10:30	10:50		Wahlmann 543869		Klein 529648
10:50	11:10		Xu 542353		Farabi 543777
11:10	11:30		Tarafder 549967		Neves 536859
11:30	11:50		Hussain 546351		Bréhier 546268
11:50	12:10		Bosio 544230		Stasiak 543908
12:10	13:30	Lunch + coffee (SH) + Closing remarks			

Poster presentation references and order	
1) Aslam 543973	17) Taneike 549139
2) Rassane 546197	18) Bossy 542297
3) Pawlak 545331	19) Rostom 550429
4) Baganis 546165	20) Bourgeois 567491
5) Vela 546054	21) Adomako 545633
6) Gallo 545119	22) Marconot 549931
7) Koutny 549387	23) Arnoulin 544908
8) Das 566133	24) Boualouache 541368
9) Marciano 546366	25) El Haddaoui 548329
10) Kasperovich 538941	26) Rittinghaus (Haubrich) 550374
11) Guillemot 549961	27) Lacondemine 538290
12) Haubrich 544549	28) Le Bas 539379
13) Yang 545904	29) Kim 546206
14) Valilla Robles 544225	30) Chmielewska 549830
15) Azpeleta 543511	31) Amitouche 550004
16) Klein 541616	32) SOTIMECO

A novel high-strength Al-6Zn-4Ni-2Mg-1Cu-Fe alloy for directed energy deposition

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Abstract

The development of novel alloys tailored for additive manufacturing has been research focus in recent years. While substantial progress was achieved using powder-based processes, fewer efforts were reported using wires, and most of the literature is based on commercial welding wires. In wire-arc directed energy deposition (waDED), a wire is used as feedstock, melted using an electric arc and deposited according to a predefined path yielding 3D objects. waDED processes are increasingly incorporated in modern and versatile manufacturing chains. Aluminum alloys currently used for waDED, however, fall short either in terms of the required mechanical properties, or in terms of processability. Therefore, new alloys are needed that show robust processability and high mechanical performance. Thus, an alloy – Al-6Zn-4Ni-2Mg-1Cu-Fe – that has not been tested yet for DED is investigated. To account for the required properties, the coupled use of several intermetallic phases forming during solidification and heat-treatment is exploited in this alloy. After wire fabrication (induction-based casting followed by hot extrusion) and deposition of specimens (Cold Metal Transfer), detailed characterization was performed, and the effects of a post-process heat-treatment were assessed. Employed techniques encompass scanning electron microscopy, electron backscatter diffraction, high-energy X-ray diffraction and differential scanning calorimetry accompanied by microhardness and tensile testing. Characterization results evidence the absence of texture in combination with high mechanical strength, in particular after a solution heat-treatment followed by an artificial aging heat-treatment. The systematic investigations shed light upon the complex microstructures in as-built and heat-treated conditions and their relevance to the mechanical properties.

Keywords: Directed energy deposition, High, strength aluminum, Microstructure evolution, Mechanical properties

*Speaker

Fabrication of a single-crystal-like β structure with unique variant selection for a near-β Ti alloy through laser powder bed fusion using a flat-top laser beam

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Abstract

A single-crystal structure is known for its anisotropy in certain properties and excellent creep resistance at high temperatures. Fabricating a single-crystal structure through metallic laser powder bed fusion is crucial for optimizing the mechanical properties of complex geometric parts intended for high-temperature applications. This research focuses on fabricating a single-crystal-like β structure with unique variant selection in a near-β Ti–6Al–2Sn–4Zr–6Mo alloy through laser powder bed fusion using a flat-top laser beam. The fabrication was conducted in an Ar atmosphere using an SLM 280 HL system equipped with a flat-top laser beam. The laser scanning was bidirectional with a 90◦ rotation of the hatch direction for each layer. The resulting specimen exhibited an acicular microstructure with 12 α-variants. Subsequent β-annealing and air cooling revealed the growth of columnar β grains with a orientation in the build direction from the center outward with increasing height. This resulted in a highly textured β grain structure with a orientation in the build direction and or orientation along the scan direction, forming low-angle grain boundaries (LAGBs) within the β matrix. The predominant < 2-1-10> -oriented and minor < 10-12> -oriented α phases precipitated from the -oriented β matrix according to the Burgers orientation relationship. Notably, the < 10-12> -oriented α phase was observed to form on some LAGBs. A single α variant was predominantly distributed across the highly anisotropic β grain structure without forming multiple variant clusters.

Keywords: laser powder bed fusion, titanium alloy, texture, precipitation, variant selection, single crystal

*Speaker

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Insight into nano- and global-scale optimization of printed Zr-based bulk metallic glass

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Abstract

Laser powder bed fusion (LPBF) of Zr-based bulk metallic glasses (BMGs) is gaining attention for its potential in versatile applications. Achieving the right balance between density, relaxation, and crystallinity is crucial for the 3D printing of amorphous components. This study combines experiments and modeling to understand the atomic and macro-scale structure and mechanical behaviors. Interestingly, the results reveal that the highest relaxation and crystallization enthalpies, obtained at lower heat inputs, do not necessarily correlate with the best mechanical performance. Instead, samples printed with an optimal heat input, normalized enthalpy (ΔH=44), demonstrate the widest density range (~99.95%) and maintain an amorphous structure as confirmed by laboratory-XRD analysis. These samples exhibit the highest flexural strength (2080 MPa), elastic deformation (5.46%), and the lowest Young's modulus (34 GPa). The study also reveals insights into thermal history during LPBF, explaining crystal transformation in heat-affected zones. The study highlights the importance of fine-tuning LPBF parameters for enhanced mechanical properties.

Keywords: Laser powder bed fusion (LPBF), Bulk metallic glass (BMG), Atomic scale optimization

*Speaker

Investigations of TRIP and TWIP mechanisms in titanium AM alloys

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Abstract

Within Additive Manufacturing (AM), wire-arc Directed Energy Deposition (waDED), using an electric arc, a metal wire is melted and deposited selectively layer-by-layer, resulting in a 3D object. With increased deposition rates and less safety risks, waDED, is a possible addition to production chains. Despite intensive development process-intrinsic defects, increased porosity compromises the lifespan of parts hindering its adoption. When applied to expensive materials like titanium alloys, the economic and environmental benefits are noticeable, so decreasing failure by process-intrinsic defects is key. Solutions to these defects are mainly process orientated and often cannot fully resolve these defects. An alternative material-based approach is tested in this study, aiming to influence the dominant deformation mechanism, and improving processability of β-Ti alloys, which are characterized by the coarsened microstructure and decreased mechanical performance. Based on the method proposed by *Morinaga et al.* (1), compositions of alloys are adjusted to achieve TWinning-Induced-Plasticity (TWIP) and TRansformation-Induced-Plasticity (TRIP), which induce hardening and ductility while under stress thus mitigating the influence of defects. Thermodynamic simulations and alloy design methods are used to adapt the compositions, which are then small-scale-cast and tested using the dilatometer. These samples are then characterized using, scanning electron microscopy (SE/EBSD), XRD and micro-hardness measurements. In parallel, commercially available β-Ti alloys will be manipulated and processed via waDED, such as Ti-15333, where the effects of the thermal cycling deformation mechanisms will be assessed. An alternative approach to mitigate defects is shown to be relevant and potentially transferable to alternative AM processes.

Keywords: waDED, Titanium alloys, Stress, induced martensite TRIP, Deformation twinning TWIP

*Speaker
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Alloy combinatory synthesis by hybrid Cold Spray-Laser process

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Abstract

The rapid discovery and synthesis of materials is an issue for strategic domains such as energy or transports. Artificial intelligence is capable of forecasting alloys and their properties but there is a need for high throughput synthesis and characterization. Thus, the possibility to produce custom alloys on demand via additive manufacturing processes appears to be a major opportunity for the development of high performance and sustainable materials.
This work, supported by the transversal skills programs of CEA and the PEPR DIADEM ARTEMIS (22-EXP-0016), aims to use cold spray combinatory deposition with post laser alloying to manufacture custom alloys. A low-pressure Cold Spray system is used to perform a quick composition search. Tuning the composition during manufacturing is effortless, by controlling the multiple powder-feeders simultaneously. The laser alloying processes is studied to obtain dense and homogenous alloys. To this date, the alloyed region is about 50 μm thick and the small gap between the targeted and final composition is currently being optimized.

The density, homogeneity and chemical composition are automatically analyzed by SEM coupled with EDS, per group of up to 8 samples. The crystalline structure is identified by DRX on the sample as produced surface. Specific properties are also investigated depending on the application .
Given the large number of manufacturing parameters and the amount of experimental data to be processed, the setup of an electronic laboratory notebook and the use of Artificial Intelligence is strongly considered to forecast alloys of interest.

Keywords: Low Pressure Cold Spray, Laser alloying, Combinatory synthesis

*Speaker
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NON-DESTRUCTIVE ANALYSIS OF CHEMICAL TREATMENT OF INTERNAL SHAPED CHANNELS IN LPBF INCONEL 718

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Abstract

The laser powder bed fusion (LPBF) method can offer significant technological advantages in the aerospace sector for the production of complex and integrated parts, such as turbine blades or combustion chambers with an internal networks of film cooling holes (1). However, the build direction of parts in LPBF causes sizable differences in the achievable surface qualities. Most critical are the downward facing areas, which suffer from excessive heat due to poor thermal conductivity of the powder underneath, resulting in fusion defects, growth of melt conglomerates and powder particle adhesions. Defects and poor surface quality are particularly problematic in internal cavities difficult to access for post-operative machining. One way to improve the quality of internal surfaces are chemical etching techniques using pressurized fluids. Their evaluation and optimization require careful control by comparative analysis of the original and treated surfaces. The best method for non-destructive evaluation is an X-ray scanning using tomographs or synchrotrons, followed by 3D reconstruction of objects before and after etching and their accurate quantitative representation.
Fragments with internal channels were scanned using the ESRF synchrotron (Grenoble, France) before and after applying two different post-processing methods. The presented method allowed a qualitative analysis of film cooling holes with different diameters ranging from 0.4 to 1 mm, inclinations (from horizontal to diagonal) and configurations (from annular to fan-shaped widening or narrowing into a slit). The comparative equivalent diameters and surface curvature distributions allowed high precision diagnostics of the posttreatment efficiency of LPBF-derived Inconel 718 internal channels.

Keywords: LPBF, Inconel 718, film cooling holes, surface treatment, synchrotron tomography

*Speaker
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Impact of nano-reinforcement addition on LPBF processability and properties of AlSi10Mg/B4C nanocomposites

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Abstract

Extensive research has been conducted on laser powder bed fusion (LPBF) of aluminum metal matrix nanocomposites (AMMNCs), motivated by the industry demand for lightweight and high-performance components. A viable way to increase strength, stiffness, wear resistance, thermal stability, and fatigue resistance is to reinforce the aluminum matrix using nano-ceramic particles. While a variety of carbides, borides, nitrides, and oxides have been researched in relation to different aluminum alloys, there has been very limited research on the use of nanometer-sized B4C as reinforcement for aluminum alloys during the LPBF process. Moreover, additional investigation is still required to ascertain the LPBF processibility of AMMNCs containing a high volume percentage of nanoparticles. The recently established "three-dimensional vibration" method was used in this work to modify AlSi10Mg powder with 1, 3, and 5 weight percent of B4C nanopowder. The LPBF processibility of the three modifications was evaluated in comparison with the unmodified AlSi10Mg as a reference. The tensile properties were assessed at room and elevated temperatures (up to 300 oC). The modified powder morphology showed that the nanoparticles were uniformly dispersed with varying levels of surface coverage. TEM analysis revealed a unique interfacial reaction taking place between the nanoparticles and the matrix. At 1 weight percent, the strengthening impact of the nanoparticles was negligible. At 5 weight percent of B4C, on the other hand, the tensile characteristics at high temperatures significantly improved, with about 60% increment in UTS at 300 oC.

Keywords: Laser powder bed fusion, Metallic nanocomposites, AlSi10Mg, Nanoparticles, Microstructure

*Speaker

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Influence of a Static Magnetic Field on Direct Liquid Metal Deposition

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Abstract

Common metal additive manufacturing (AM) methods use energy-intensive power sources such as lasers or electron beam plasmas to melt metallic powders or wires. This gives those processes a sizeable carbon footprint and generates complex melt pool dynamics, inducing defects such as porosity, residual stresses or anisotropy.
The aim of this research is to contribute to the development of a new, stable, and energy-efficient AM technology suitable for aluminium alloys, in which aluminium wire is fed through a heated nozzle melting the wire and depositing it onto a moving build plate, layer by layer. The resulting thin stream of liquid aluminium solidifies in contact with the build plate at a rate that is high compared to conventional casting processes, yet lower than in current aluminium AM processes.
Challenges to the development of this process exist as liquid aluminium streams are prone to capillary instabilities due to their low viscosity and high surface tension. We explore using the addition of a transverse static magnetic field, which interacts with the thermoelectric voltage generated during solidification, and the current in the flowing liquid metal generating two Lorentz forces. Main process parameters, i.e., wire feeding rate, build plate speed, nozzle offset distance, temperatures of nozzle and build plate and magnetic field characteristics are investigated to determine the process window and study the stream stability, porosity, and microstructure as a function of these parameters. Where stream stability allows, thin walls are manufactured and interlayer bonding together with the microstructural quality of the built structures are characterized.

Keywords: aluminium, magnetohydrodynamics, liquid metal, magnetic field, solidification

*Speaker

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Study of oxide nanoprecipitate formation mechanisms in 316 L stainless steel produced by rapid solidification processes: gas atomization and Laser Powder Bed Fusion (L-PBF)/ effect on impact toughness

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Abstract

In the nuclear industry, components manufactured by additive manufacturing (AM) require a minimum impact resilience of 100 J. The microstructure of FA components tends to contain nano-oxides rich in silicon (Si) and manganese (Mn). Their formation mechanisms have not been fully identified and effective solutions to mitigate or eliminate their impact have not yet been discovered. In this work a characterization of these nanoprecipitates was carried out in both the 316L powder particles elaborated by gas atomization (GA) and in the components manufactured using Laser Powder Bed Fusion (L-PBF) with these powders. As part of this work, a study of the impact of oxygen present in the atmosphere during manufacture was carried out in components manufactured using laser powder bed fusion (L-PBF) using SEM, EBSD and XRD techniques, with Charpy tests carried out at room temperature. The values obtained were consistently lower than the impact toughness of conventionally manufactured 316L stainless steel. The fracture surfaces revealed ductile fracture accompanied by the presence of brittle zones. Ferrite formation occurred at low oxygen concentrations (100 ppm) but was absent at 1200 ppm oxygen. The oxygen concentration governs both the phase formed at the end of the manufacturing process and the composition of the oxides through interaction with chromium and silicon.

Keywords: Laser powder bed fusion, Impact toughness, Austenitic strainless steel, Oxide, Ferrite

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Comparing different techniques to physically simulate microstructures generated by wire-arc directed energy deposition

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Abstract

Titanium alloys are widely used in modern aviation due to their high strength-to-weight ratio, enabling the production of highly loaded and lightweight components. Manufacturing of titanium parts by machining out of solid pre-materials produces much waste material. Wire-arc directed energy deposition (waDED) conversely processes this energy-intensive material highly efficient, however requiring it in wire form for deposition using a welding power source. This process provides a characteristic thermal profile with high cooling rates and cyclic reheating/cooling during buildup, so that established titanium alloys develop large columnar grains in buildup direction, causing anisotropic mechanical properties. The efforts on the process side can hardly resolve the unfavourable characteristic microstructures. Therefore, research focuses on material-based solutions using the interdependence theory, which however entails that testing novel titanium alloy compositions requires wire manufacturing, to assess the microstructure emerging upon additive manufacturing (AM). Physically simulating potential AM microstructures, omitting the wire drawing step of experimental alloys, would accelerate alloy screening. Hence, EBM and Plasma or GTAW are used to fabricate single weld beads without filler wire on wrought and AM titanium substrates. Resulting microstructures compared with unmodified substrate material show the advantages of each technique aiming at the identification of the most relevant. Temperature recordings during weld bead fabrication and reference layer deposition reviews the thermal histories. Characterization is performed using scanning electron microscopy, light microscopy, microhardness measurements and bending tests. This comparison evaluates whether an alternative approach without wire manufacturing and deposition, can create similar microstructures, facilitating the screening of titanium alloys for AM.

Keywords: titanium alloys, microstructure, characterization, wire arc directed energy deposition, alloy screening

*Speaker

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In-situ alloying of AlSi10Mg-TiN through LPBF additive manufacturing

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Abstract

In the laser powder bed fusion (LPBF) of metallic components, often optimized process parameters is attributed to a combination of laser power, scanning speed, layer thickness, and hatching distance to achieve highest relative density. However, factors like rotation angle, printing strategy and remelting would also affect the final part properties, especially in in-situ alloying. Here, parameters must ensure denseness, minimal residual stress, and desired phase evolutions while minimizing unreacted additions in the matrix. This study investigates the microstructural analysis of TiN reinforced AlSi10Mg alloy printed with rotation angles of 0 and 67 degrees. EBSD analysis reveals that a 0-degree rotation angle results in columnar grains with local grain refinement, while a 67-degree rotation angle changes the grain structure to a fish-scale pattern and significantly enhances TiN refinement efficiency. SEM characterization identifies Al3Ti nanoparticles, predominantly formed around melt pool boundaries, as the origin of grain refinement. Obtained results underscore the importance of selecting the optimal combination of process parameters for structural modification through LPBF in-situ alloying.

Keywords: Additive Manufacturing, In Situ Alloying, Process Parameters, Grain Refinement, Microstructure.

*Speaker

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Instrumented LMD-p chemically graded steels: link between thermal history and as built microstructure

Matthieu Bossy*†[1,2], Xavier Boulnat[1], Nicolas Tardif[2], Sabrina Marcelin[1], and Geneviève Foray[1]

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Abstract

Often, two materials are welded together to provide continuity in the structural part. However, these processes weaken the part mechanically, and corrosion resistance is often reduced at the junction. One example comes from the nuclear industry, where austenitic stainless steels, such as 316L, are used in areas requiring good resistance to high-temperature creep or corrosion, and martensitic steels, which offer excellent resistance to swelling and creep under irradiation, in lower-temperature areas. Today, additive manufacturing techniques offer a new possibility for replacing junctions.

For this purpose, samples were produced using Laser Metal Déposition with powder (LMD-p) process with various composition gradient profiles between austenitic stainless steel 316L and martensitic stainless steel EM10 (9Cr-1Mo). A first series of metallographic characterization and hardness tests has been carried out, and the characterization of mechanical behavior and surface reactivity in contact with an aqueous electrolyte is currently underway.

On one hand, the choices made in terms of manufacturing parameters and composition gradient profiles will be presented, as well as the implementation of manufacturing instrumentation to monitor the temperature of the different layers of the part. On the other hand, the metallographic characterization of the samples, which revealed differences in hardness profiles depending on the chosen configuration. These hardness measurements are related to the microstructure (composition observed by EDX, pore size measured with SEM images, grain size and orientation with EBSD), which is itself explained through the instrumentation described above.

Keywords: LMDp Process, stainless steel, composition gradient, hardness, microstructure

*Speaker

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Electron beam powder bed fusion process monitoring by in-melt electron analysis

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[1]Department of Management and Engineering [Linköping] – Sweden
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Abstract

Insightful monitoring is accountable for good print quality by electron beam powder bed fusion (EB-PBF) which shows advantages among additive manufacturing techniques. The interaction of electron and matter provides a wealth of in-melt information simultaneously during the melting. To achieve this, an in-melt electron analysis (IMEA) approach has been developed by analyzing and interpreting the signal from the emitted electrons in the present work. Among the total emitted electrons, the majority population is attributed to secondary electrons, backscattered electrons, and thermionic electrons. Owing to the high correlation of thermionic electrons to the temperature and area of the hottest spot, the melt pool characteristics can be monitored from the signal of emitted electrons. We also demonstrate the applications of IMEA approach to detect the melt pool dynamics such as keyhole mode, estimate cooling rate of spot melting, and assess the print quality by three-dimensional reconstruction, during a real print of 80 layers on 316L stainless steel powder bed. This approach suggests a new reliable process monitoring and quality control paradigm for EB-PBF.

Keywords: Electron beam powder bed fusion, Real, time monitoring, Thermionic electrons, Melt pool dynamics, Keyhole

*Speaker

An Al-Cr Based Alloy System Combining Fatigue Resistance, High Surface Quality and Cost-Effectiveness

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Abstract

Standard alloys such as AlSi10Mg are widely recognized for their good printability, affordability and the ease of transferring print parameters between systems. However, they are generally disadvantaged by lower mechanical properties compared to casting parts and their use tends to be restricted to prototype purposes in the automotive industry. There are different approaches to improve important characteristics such as fatigue resistance, but most of them include adding cost-intensive elements to the alloy, post-processing or optimization during the build job that raise costs and therefore are not an option for most automotive parts. To open the way to additive manufacturing in high volume applications, the main objective of this work is to modify an alloy system to improve the fatigue resistance by reducing defects sensitivity and improving surface quality, avoiding the need for postprocessing. To achieve this, grain refiners Titanium and Zirconium, that can form strengthening phases simultaneously, are added to an Al-Cr-based alloy system. The absence of elements such as Magnesium creates a more stable melt pool, resulting in a smooth, shiny surface. To understand the properties of the new alloy, the microstructure was examined and comprehensive mechanical testing, including tensile and cyclic fatigue testing, was conducted. In room temperature fatigue tests, the alloy showed significantly higher cycle numbers compared to standard alloy AlSi10Mg. However, it shows that the beneficial effects of the added elements cannot be extended indefinitely by increasing their content, as at some point cold cracks begin to occur.

Keywords: Aluminum, fatigue resistance, surface quality, Zirconium, automotive

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ABD®-1000AM: A highly processible superalloy for additive manufacturing, computationally designed for 1000∘C applications

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Abstract

The evolution of additive manufacturing (AM) technology has sparked a growing interest in manufacturing components from nickel-based superalloys for progressively more demanding applications at ever increasing temperatures. A critical challenge has been the development of high volume fraction gamma prime (γ') strengthened alloys for AM, suitable for applications at temperature of 1000∘C or higher, as these are generally considered 'non-weldable'. Due to the nature of the AM process with high heating and cooling rates and multiple melting and solidification cycles, legacy compositions designed with the intent for casting or wrought processes are difficult and often uneconomic to process by AM. This leads to compromises in material performance or part design freedom, limiting AM's potential to replace traditional manufacturing in the most demanding environments.
In response to these challenges, this study introduces ABD®-1000AM, a novel high gamma prime Ni-based superalloy, specifically designed using the Alloys-by-Design computational approach to excel in high-temperature applications within the AM framework. Tailored for AM through using this innovative alloy design approach, and applied to powder bed fusion the newly designed alloy exhibits world leading performance in terms of both processing capability as-well-as high temperature mechanical and environmental performance at 1000∘C. In this talk the alloy design approach will be discussed, highlighting the trade-offs in key performance parameters and the intricate process-microstructure-performance optimization undertaken to achieve the alloy's exceptional creep resistance. Based on the insights gained the future direction of alloy development of superalloys for complex AM components is explored.

Keywords: Additive Manufacturing, Nickel Based Superalloys, ABD®1000AM, Alloys by Design

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Insights into direct aging of 17-4 PH stainless steel manufactured via laser powder-bed fusion

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Abstract

17-4 precipitate hardening (PH) stainless steel is essential in the aerospace, chemical, and marine industries, featuring a distinctive combination of corrosion resistance and high strength. Its weldability unlocks opportunities for processing via laser powder bed fusion (LPBF). Conventionally, the high strength stems from annealing and aging heat treatments, leading to the formation of nanoscale Cu-rich precipitates. However, recent research has revealed sensitivity in the precipitate hardening response of LPBF 17-4PH to compositional variations, posing challenges for widespread adoption (1). Notably, two 17-4 PH stainless steel variants made from different powder feedstocks printed under different gas atmospheres-specifically, Ar and N2 -exhibited different hardening responses.

This talk explores the potential of direct aging to overcome this challenge. By bypassing the standard annealing treatment, direct aging aims to leverage on observed Cu clustering in the as-built N2-printed condition, potentially promoting the growth of strengthening Cu-rich precipitates. Hardness testing and atom probe tomography are employed to analyse the strengthening, clustering, and precipitation behavior. In addition to promoting cost saving, direct aging potentially enables homogeneous hardening response from heterogeneous starting microstructures. These findings seek to demonstrate the feasibility of direct aging as a promising pathway to enhance precipitation and improve hardenability in LPBF 17-4PH, thus facilitating process control and enhancing its applicability in additive manufacturing.

(1) M.S. Moyle, N. Haghdadi, F. Theska, M.P. Haines, X.Z. Liao, S.P. Ringer, S. Primig, Mater Charact 209 (2024) 113768.

Keywords: characterization, post, processing techniques, optimizing, stainless steel, LPBF, atom probe

*Speaker

Study of Dievar and 20MnCr5 Powders for Gear Repair and Manufacturing by Laser Metal Deposition

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Abstract

Gears have a ductile core to minimize crack propagation and a hard case to increase pitting resistance. Moreover, gears also have high fatigue resistance. These factors must be considered when selecting materials for gear manufacturing. This study aims to identify and assess materials for the repair and manufacturing of gears using Laser Metal Deposition (LMD). In this research, we consider factors like hardness, tensile strength and fatigue behavior. Additionally, we analyze some specific problems associated with the powders used in LMD manufacturing. We focused on 2 materials: Dievar and 20MnCr5. We studied the properties (e.g., porosity, granulometry, flowability, and sphericity) of the raw powder feedstock. We also optimized the processing conditions of each material and manufactured several multi-layer prisms. We studied the porosity and hardness of the manufactured samples. These initial tests served as a crucial step in determining the viability of Dievar and 20MnCr5 for their use in LMD repair and manufacturing of gears. We conducted different thermal treatments on some samples and evaluated their effects on the properties of the prisms. We are currently working on the manufacturing of several real gear teeth for the study of high-cycle fatigue bending and tensile tests at the Gear Research Institute, Penn State University.

Keywords: Laser metal deposition, Additive manufacturing, Gear repair, Directed energy deposition

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In-situ Engineering of Microstructures During Metal Additive Manufacturing

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Abstract

Control over the microstructural constituents, i.e., 'microstructure engineering,' can be achieved either during manufacturing (in-situ) or through subsequent post-processing (ex-situ). During additive manufacturing (AM), builds go through repeated cycles of heating/cooling and experience mechanical strain. This provides opportunities to tailor AM cycles and engineer the thermo-mechanical history (i.e., heat and beat) – the two fundamental tools for microstructure control in metals. In the current study, we demonstrate that by leveraging the thermal hysteresis in AM, it is possible to induce desired interfaces, precipitates, and solute clustering directly during printing. Examples include grain boundary engineering in 316 stainless steel by introducing Σ3 boundaries, copper cluster-hardening in 17-4 precipitation hardening steel, and precipitation of fine γ' in Inc738 alloy. These 'dynamic' microstructural refinements eliminate the need for time-intensive and costly ex-situ post-processing, resulting in enhanced mechanical and corrosion properties in the as-built components.

Keywords: Additive Manufacturing, Metals, Microstructure Control

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Impact of TiC Particles on the Thermal Evolution during PBF-LB Manufacturing of Aluminum MMCs

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Abstract

Hard ceramic particles in Aluminum Matrix Composites (AMCs) lead to strengthening of the aluminum. Laser Powder Bed Fusion (PBF-LB) is a promising manufacturing route to overcome the drawbacks of classical casting routes, such as inhomogeneous particle distribution, limited geometry complexity, and difficulty in machining. In the current study, powder blends have been prepared by mixing TiC particles of different sizes (micro- and nano-scaled) with powder of a common aluminum casting alloy (AlSi7Mg0.6). A size-dependent effect of the particles on the processibility has been detected. While the TiC microparticle composites show a beneficial expansion of the process window, the TiC nanoparticle composites reveal a process window shift towards higher laser powers (compared to the pure matrix material). Both TiC particle types improve the absorptivity of the powder blend, but there is no general effect on the melt pool size valid for all composites. For the microparticle composites, the impact is negligible but in the case of the nanoparticle composites, a significant decrease can be observed. Significant lack of fusion porosity is occurring at certain TiC nanoparticle contents, indicating a reduction of effective laser power. It has been shown that high TiC nanoparticle contents even inhibit the disintegration of the oxide skin that surrounds each aluminum particle after powder blending. This impedes sufficient melt pool formation and limits the maximum particle content. It could be demonstrated that it is necessary to distinguish between nano- and micro-composites in terms of processibility due to massive differences in temperature evolution during PBF-LB.

Keywords: metal matrix composites, aluminum matrix composites, composites, advances in processing, temperature evolution

*Speaker

Obtaining parts through selective laser melting (SLM) with metallic or metal-ceramic powders surface-modified using fluidized bed technology.

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Abstract

Selective laser melting (SLM) is emerging as a key component in the future of the industry due to its ability to produce complex parts efficiently. SLM offers significant time, material, and cost savings, as well as increased versatility and the potential for novel properties. However, the production of metallic or metal-ceramic components using SLM still faces challenges. These include the limited range of available raw materials, low reproducibility, and microstructural defects, such as large columnar grains, cracks, and pores, which are common in the final components produced. To solve these problems, it is necessary to adapt raw materials to the characteristics of additive manufacturing (AM) processes. To address these problems, surface modification of powders was carried out using fluidised bed technology to enable the large-scale development of new smart hybrid powders usable in additive manufacturing processes. The obtained powders were evaluated by different techniques to observe certain characteristics such as flowability, morphology, chemical analysis and packing which are key to obtain raw materials adapted to additive manufacturing. Optimal characteristics were found for use in equipment in AM processes. Furthermore, these powders were evaluated to observe the influence on the processability of the parts as well as the effect of the printing parameters using SLM techniques. Finally, the parts obtained by SLM were analysed by evaluating their microstructure, grain size, phases and the effects produced by the modification of the powders.

Keywords: Additive manufacturing, surface modification, fluidized bed, selective laser melting

*Speaker

A novel high-temperature Ti-alloy for wire based directed energy deposition

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Abstract

The development of new titanium alloys tailored for wire-based directed energy deposition (waDED) processes is to enable the wider uptake of this novel processing route by the aerospace and energy industries. While there has been significant focus on developing high-strength Ti-alloys for waDED, the development of new high-temperature titanium alloys has been limited so far despite the high temperatures experienced by parts in aerospace and energy. Further, previous studies have demonstrated that waDED techniques often lead to significant heterogeneity and anisotropy in the mechanical properties of existing high-temperature titanium alloys, such as Ti-6Al-2Sn-4Zr-2Mo. In the present work, a novel high-temperature Ti alloy has been developed, aiming to improve the high-temperature performance via exploiting phase transformations and precipitation to achieve fine and homogeneous microstructures during AM processing. Our new alloy design features combined additions of Si, Cu, Nb, and Y. We study its microstructural evolution during the simulated waDED solidification route and after various heat treatments that replicate cyclic reheating following waDED. Our new alloy shows significant potential for high-deposition-rate waDED processes and exhibits fine and equiaxed β grains after heat treatment. In addition, the presence of Y inhibits β grain growth and the microstructure transforms from a fine lath-like colony α-phase into a coarse lamellar pearlitic microstructure during the heat treatment. High-resolution atom probe microscopy reveals very fine (15–20 nm) core-shell Ti2Cu precipitates with Y in their cores. These precipitates contribute to a significant improvement in mechanical performance, despite observed microstructure coarsening during heat treatment.

Keywords: High, temperature Ti, alloys, Microstructure, Precipitation, Intermetallic phases, Atom probe tomography

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Grain boundary engineering in stainless steel 316L via controlling laser powder-bed fusion process parameters

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Abstract

Grain boundary engineering (GBE) is a promising approach for improving any grain boundary (GB) controlled properties of polycrystalline materials. Traditional GBE is based on repetitive cycles of mechanical and thermal processes to induce recrystallization and/or GB migration, which is therefore not applicable to near-net-shape parts fabricated through additive manufacturing (AM). To address this challenge, an alternative approach involves adjusting the strain energy introduced during AM to generate the required driving forces for recrystallization, eliminating the need for mechanical deformation. In this study, we explore the effects of processing parameter variations (i.e., scan speed, laser power and printing scan strategy) on the as-built microstructure and subsequent recrystallization response of laser powder bed fusion processed 316L stainless steel. It is shown that the observed variations in recrystallization response are linked to differences in the densities of dislocations and the chemical heterogeneity within the solidified microstructure. Moreover, we showcase a capability of site-specific control of GBE using a novel concentric scanning strategy via controlling the cooling rate and dislocation density at different locations throughout the build. This approach enables the design of gradient microstructures. Our findings highlight the potential for harnessing the laser powder bed fusion processing route as a promising avenue for the development of high-performance AM parts with optimized microstructures, superior properties, and complex geometries.

Keywords: Additive manufacturing, Laser powder bed fusion, Stainless steel 316L, Grain boundary engineering.

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Overlay Dilution Prevention Method in a Single Step L-DED Process

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Abstract

L-DED presents an interesting approach for the surface modification of standard structural steel with stainless steel. By employing L-DED to deposit stainless steel onto structural steel, it becomes possible to maintain base material properties with enhanced anti-corrosive and anti-oxidative properties in the overlay areas. Furthermore, it allows the modification of surface morphology to create specialized surface geometries with a high degree of precision. The L-DED procedure involves the fusion of the applied material with partial fusion of the substrate material. Consequently, the chemical composition of the surface is a mix of the powder with the substrate, which potentially modifies the properties of the stainless steel overlay. The commonly applied corrective method to maintain the surface properties to address the described dilution effect, involves the addition of further stainless steel layers through subsequent L-DED deposition process. However, this solution is not the optimal, as it forces to apply additional L-DED processes, which, in ideal conditions, would not be required.

A method for obtaining a stainless steel additive coating by deposition in a single coating process is presented in this work. The method of the present invention allows to compensate the dilution effect by incorporating a counteract powder to the stainless steel during the L-DED process and, thus, obtaining the target chemical composition of the stainless steel coating. The counteract powder is specifically tailored for the selected target stainless steel in each process.

Keywords: L, DED, Stainless Steel, Corrosion, Monocoat

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Role of carbides in grain growth mitigation in additive manufacturing of Inconel 718

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Abstract

Integrating additive manufacturing (AM) into the production of high-value parts often presents a trade-off between as-built porosity and microstructure control. The use of hot isostatic pressing (HIP) to improve part density removes as-built microstructure and results in grain growth. Current research indicates that the incorporation of carbides can mitigate grain coarsening during powder bed laser beam melting (PBF-LB/M) of Inconel 718, but at the expense of ductility. The objective of this study was to develop a method of controlling the grain size of Inconel 718 after PBF-LB/M processing and subsequent thermal treatments, including HIP, without compromising ductility. This was achieved by introducing micron-scale powder modifiers (namely NbC, TiC and B4C) at minimal weight fractions. The study focuses on the effect of these modifiers on powder properties, PBF-LB/M processability, microstructure and mechanical properties of the processed material. The results show that careful processing can control homogenization during HIP and result in higher tensile strength while maintaining the ductility of non-carbide-modified alloys.

Keywords: Inconel 718, Powder Bed Fusion, Hot Isostatic Pressing, Carbides, Composite Powders, Grain Growth

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Processing of refractory metals by electron beam powder bed fusion

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Abstract

Refractory metals and alloys have the potential to vastly outperform common high-temperature materials such as Ni-base superalloys in structural applications. These refractory metals, such as Molybdenum and Tungsten, are difficult to manufacture by conventional methods due to their extremely high melting point, poor machinability, and a brittle-ductile transition at high temperatures. By contrast, additive manufacturing by electron beam powder bed fusion (PBF-EB) allows near-net-shape processing above 1000 ∘C, thereby circumventing the above issues.

In this contribution, we present studies on processing pure W and Mo-9Si-8B (at.%) on a freely programmable Freemelt ONE electron beam powder bed fusion system. Regarding W, we aim at as high as possible build rates by melting with a high beam power of 5 kW. The high heat input leads to challenges in thermal management. We present a thorough thermal analysis of the PBF-EB process and address these challenges by optimized pre-heating and scan strategies.

Furthermore, we present an efficient process window development for Mo-9Si-8B by combining simulative and process monitoring methods. An initial parameter region for building dense samples was identified using high-throughput thermal diffusion simulations, vastly speeding up the process development. Additionally, suitable parameters, i.e., parameters not leading to porosity or bulging, are identified by electron-optical imaging without the need for metallographic preparation. Finally, we report on the microstructures and mechanical properties achieved by various process parameter combinations.

Keywords: Molybdenum, Tungsten, Electron beam, Refractory metals

*Speaker

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Microstructure and mechanical properties of additively manufactured Inconel 617 for high-temperature applications in the nuclear industry

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Abstract

Inconel 617 alloy is a solid solution-strengthened Ni-based superalloy that has been studied for over 50 years. Inconel 617 presents exceptional high-temperature properties, such as promising mechanical strength, good thermal stability, or exceptional creep resistance. Inconel 617 is a potential candidate material for heat exchangers in Generation IV nuclear reactors. Most parts made from Inconel 617 are produced by traditional manufacturing routes, which involve melting and casting. Therefore, the final parts should be machined, which is very difficult for Inconel 617 due to significant work hardening. An interesting solution could be additive manufacturing (AM). The aim of this study is to investigate the microstructure and mechanical properties of Inconel 617 alloy produced under different conditions. The Inconel 617 samples were produced using direct energy deposition (DED) from two different feedstocks (powder or wire). After deposition, different post-processing heat treatments were performed, including different cooling protocols. The microstructure consists of large fcc grains ($> 100\mu m$) and carbides. The TEM characterizations reveal the presence of molybdenum-rich M6C and chromium-rich M23C6 carbides. A higher volume fraction of carbides is present in the samples produced from powder than wire feedstock. Moreover, the annealing leads to a decrease in the volume fraction of carbides. The mechanical properties determined from the tensile tests are very promising. The elongation at room temperature is between 40-55%. The yield strength is between 265-376 MPa, while the ultimate tensile strength is between 477-565 MPa. The obtained results show that the additively produced Inconel 617 presents promising microstructure and properties.

Keywords: Inconel, superalloy, direct energy deposition, microstructure, carbide

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PBF-LB manufacturing and microstructural analysis of nanoalloyed Al5254 alloy

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Abstract

5xxx series aluminium alloys are very popular in various industries. However, it is still a limited group for processing in PBF-LB technology. The main limitation in adapting these alloys for PBF-LB processing is hot cracking. There are several possible approaches to overcome this limitation and one of them is to change the solidification mechanism by introducing fine crystallisation nuclei of equiaxed grains instead of columnar ones. This work presents the microstructure and mechanical properties of a new defect-free Al-Mg-Ta alloy. The nanoalloying eliminates hot cracking during PBF-LB/M processing of aluminium alloy 5254 and improves the mechanical properties. As a result of nanoalloying, the microstructure of the PBF-LB Al5254 alloy changed from columnar elongated grains, with the majority of the grain area fraction having equivalent diameters > 200 μm, to equiaxed grains with an average equivalent diameter of about 2 μm. The reduction in grain size and increase in number of nuclei results in overcoming hot liquid cracking and also provides significant strengthening without compromising ductility.

Keywords: aluminium, PBF, LB/M, microstructure, mechanical properties, nanoalloying

*Speaker

Modelling of precipitation kinetics in additively manufactured Ni-based superalloys using high-throughput thermodynamic and kinetic simulation approach

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Abstract

With recent advancements in production technologies, particularly additive manufacturing (AM), and a growing focus on sustainability, there is a strong demand for high-performance metallic alloys adaptable to meet the specific requirements of the evolving AM processes. In AM, factors such as high solidification rate, repeated remelting, intrinsic heating of already deposited layers, and post-heat treatment determine the unique and complex thermal treatment of alloys that significantly impacts the microstructure. This process influences critical characteristics such as precipitation behavior, grain growth, and susceptibility to cracking. Addressing this multidimensional challenge in the process-structure-property relationship is crucial for developing a sustainable alloying strategy. In this study, we utilize an Integrated Computational Materials Engineering (ICME) approach with the aid of high-throughput CALculation of PHase Diagram (CALPHAD) to evaluate the influence of composition and process parameters on the microstructure, solidification-induced cracking susceptibility, and mechanical properties of additively manufactured alloys. The approach is demonstrated through the optimization of heat treatment of Ni-based superalloys with a focus on their mechanical properties, processability, and sustainability.

Keywords: Additive manufacturing, Ni, based superalloys, precipitation kinetics, intrinsic heating, solidification, precipitation, CALPHAD

*Speaker

Tool for Design of Alloys for Additive Manufacturing by Laser Powder Bed Fusion

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Abstract

New alloys for additive manufacturing by laser powder bed fusion are actively being developed since conventional alloy compositions are not necessarily optimal for this new manufacturing method. The rapid solidification and cooling in LPBF make it possible to supersaturate elements and use them for precipitation hardening. This was for example used in the development of new types of Al-alloys (1), and of a Co-free maraging steel (2). Using computational thermodynamics, it is possible to make accurate predictions of the compositions that can give good precipitation hardening. Cracking susceptibility by hot cracking is a common problem for many alloys, and again computational thermodynamics can be used for predictions. Hot cracking is related to the tendency for micro segregation, and there are several models that can indicate cracking resistance. The calculations needed for alloy design are not necessarily very complex, but they require a good knowledge of the methods, access to software and databases. In the present work a new tool for alloy design, based on computational thermodynamics calculations, is presented. It is simple to use, and rapidly shows composition ranges where new alloys have a good chance of success. For validation of the usefulness of the tool, examples for Al-alloys and Fe-base alloys are shown, comparing predictions with alloys that are well known to be printable and provide good properties. The underling methods and calculations of the tool are described.

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Keywords: Alloy Design, Additive Manufacturing, Computational Thermodynamics

*Speaker

Operando monitoring of multi-laser powder bed fusion process during high-speed synchrotron imaging

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Abstract

Laser powder bed fusion (LPBF) is an emerging digital manufacturing technology that produces parts with intricate shapes using powder feedstocks. This process relies on alternating a powder layer deposition step followed by a laser scanning step using a high-power energy source to selectively fuse the powder particles until the final part is obtained. New industrial machines have been developed to employ multiple lasers working simultaneously to drive down production time, *and thus* enhance productivity. Due to the complex multi-laser scanning strategies, there is a need to investigate these unknown behaviours and unveil the underlying mechanisms governing the multi-LPBF process.

Recent progress in synchrotron X-ray facilities allows investigation of the LPBF processes non-destructively at unprecedented temporal and spatial resolution. A new rig has been developed between University College London and Renishaw plc to replicate an industrial LPBF machine, also known as Quad In situ and Operando Process Replicator (Quad-ISOPR). This unique setup incorporates a scanning head from a RenAM 500Q machine with 4 lasers and has been used to capture the process dynamics at the laser-matter interaction zone using X-ray imaging at framerates up to 500,000 Hz. This rig is also coupled with other optical instruments which are synchronised to capture signals from the top of the powder bed at the same frequency to complete our understanding of the process.

This talk will briefly introduce the full capabilities of the Quad-ISOPR, and will focus on the latest insights into single- and multi-LPBF manufacturing using advance signal processing.

Keywords: synchrotron X, ray imaging, operando, LPBF, multi, LPBF, machine design

*Speaker

Delta-Ferrite to Austenite Phase Transformation Pathways and Mechanical Properties in 2205 Duplex Stainless Steels Manufactured via Laser Powder Bed Fusion

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Abstract

Recent progress in metal additive manufacturing (AM) techniques such as laser powder bed fusion (LPBF) has facilitated near net-shaped production of geometrically complex engineering components from complex alloys such as duplex stainless steels (DSSs). DSSs are widely employed in harsh environments due to their desirable mechanical and corrosion properties. Such materials performance is related to their equilibrium microstructure of roughly equal phase fractions of ferrite and austenite. However, the rapid cooling during LPBF results in a highly non-equilibrium as-built microstructure with $> 99\%$ d-ferrite alongside high dislocation densities and abundant Cr2N precipitates, leading to inferior ductility. Upon a short heat treatment, different types of austenite (intergranular, instability-induced, sympathetic, and intragranular) are formed, attaining a refined duplex equilibrium microstructure with optimal strength and ductility. Using 3D electron back-scatted diffraction, the d-ferrite to austenite phase transformation mechanisms and phase interfaces are studied. It is revealed that the non-Kurdjumov-Sachs/Nishiyama-Wassermann interfaces have lower grain boundary curvatures, and that the ferrite habit planes deviate from the crystallographically and/or energetically favourable planes. These may be caused by the dominant kinetics for the phase transformation being strain minimization rather than interfacial energy minimization. With multi-scale characterization on the heat-treated microstructure, a combination of deformation mechanisms involving dislocation slip, stacking fault emission, deformation nano-twinning, and deformation-induced martensitic transformation is revealed to be responsible for the enhanced ductility. We demonstrate that the high level of microstructural complexity and solid-state phase transformations during LPBF and heat treatment provide

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opportunities for duplex microstructure design via AM and post-processing to unlock desirable properties.

Keywords: Additive manufacturing, Duplex stainless steels, Phase transformation, 3D, EBSD, Crystallography, Mechanical properties, Deformation mechanisms, Mechanical twinning

In-situ synchrotron radiography of melt pool and powder bed dynamics in electron beam powder bed fusion

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Abstract

The development of processing strategies for PBF-EB depends on a fundamental understanding of the phenomena involved in melt pool formation, from thermal diffusion, over evaporation, to fluid dynamics. Simulation models, developed to simulate melt pool dynamics & processing strategies, depend on assumptions and simplifications regarding the underlying physical models to be computationally feasible. Therefore, empirical and time-resolved information on the phenomena involved in powder consolidation is essential to deepen the fundamental understanding of PBF-EB, develop more accurate models and suitable processing strategies.

To uncover some of these melt pool dynamics, we conduct high-speed synchrotron radiography experiments using MiniMelt (1), a PBF-EB machine specifically designed for in-situ investigations with synchrotron radiography and diffraction techniques. The experiments reveal several mechanisms involved in melt pool and powder bed dynamics, like powder particle coalescence, spatter ejection, balling and Smoke. They show, how interfacial relaxations of surface tension during particle fusion create oscillations in the melt pool, how spatter and balling predominantly form close to vapor depressions and how a highly dynamic melt pool can lead to overflow of molten material due to inertial forces. Our experiments reveal how Smoke, usually described as the electrostatic repulsion of charged-up powder particles, takes place over multiple stages, allowing for a deepened understanding of its triggering mechanisms. Finally, our experiments demonstrate, how improved energy distribution during melting can suppress some of these melt pool dynamics, allowing for a much more controlled melt pool formation.

(1) H.-H. König *et al.*, *Review of Scientific Instruments.* **94**, 125103 (2023).

Keywords: electron beam powder bed fusion, in, situ synchrotron radiography, melt pool dynamics, processing strategies

*Speaker

In-process alteration of Ti-6Al-4V microstructure during additive manufacturing

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Abstract

Additively manufactured Ti-6Al-4V can suffer from low ductility due to acicular α' martensite caused by high cooling rates, which can lead to cracks. To limit cracks and improve the ductility, it is necessary to decrease α' and increase α and β phase content. To do so, heat treatments (HT) such as annealing are usually used but are costly, time-consuming and performed outside the AM machine.
In this work, we propose to use in process laser HT as an alternative to traditional ones in order to modify the phase content. Three samples were manufactured with a miniature LMD machine (1) using a bidirectional printing strategy. During fabrication of two of these samples, each deposited layer was subjected to an additional laser HT without powder addition using different laser power for each sample.

AM was followed live using *operando* synchrotron X-ray diffraction (XRD) at the ID31 beamline of the European Synchrotron Radiation Facility (ESRF, France). Rietveld refinement was used on the diffraction line profiles to extract α'/α and β phase fraction during printing and laser HT. XRD alone was insufficient to distinguish between α' and α phases. To that end, scanning electron microscopy was performed.

Despite the HT treatments, Rietveld refinement revealed that they did not result in significant variations in the α'/α and β phase content between different samples. However, SEM analysis uncovered a significant effect of HT on the α' and α content. The result of this study will be presented.
(1) Gaudez et al., *Additive Manufacturing*, 71 (2023) 103602.

Keywords: Synchrotron X, ray diffraction, Operando, Intrinsic heat treatment, Directed energy deposition, Titanium alloys

*Speaker

Evolution of Residual Stresses during Laser Powder Bed Fusion of Structural Steels

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Abstract

Structural steels are often considered unsuitable for Laser Powder Bed Fusion (L-PBF) due to their cracking susceptibility. Cracking forms due to the combined presence of brittle martensite and residual stresses, becoming more prominent as the carbon content increases. This trend is caused by the increase in martensite brittleness with increasing carbon content, however, little is known regarding how carbon effects the evolution of residual stresses.
In this work, in- and ex-situ neutron diffraction measurements were conducted at the Swiss Spallation Neutron Source on Fe-0.2C and Fe-0.45C steel using the n-SLM, which is a miniaturized L-PBF device that was specifically designed for in-situ neutron studies. The in-situ measurements were used to follow the evolution of residual strains at fixed positions along the building and transverse directions. As for ex-situ measurements, these involved Bragg Edge Imaging along the building and transverse directions of already printed samples.
From these results, it was possible to map the evolution of residual stresses as new layers were added. Generally, the change in residual stress increased as more layers were printed, while the magnitude of compressive stresses increased as the carbon content increased. Additionally, the change in residual stress was more pronounced along the building direction than it was along the transverse direction. From Bragg Edge Imaging, strain maps were used the outlined the local strain distribution along both directions for the Fe-0.2C and Fe-0.45C steels. These findings help us better understand how residual stresses evolve and are distributed in structural steels during L-PBF.

Keywords: Laser Powder Bed Fusion, Structural Steel: Residual Stress, In situ

*Speaker

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Unravelling the microstructure development and strengthening mechanisms of AMALLOY3D-HT, an aluminium grade developed for laser powder bed fusion and high-temperature applications

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Abstract

The reinforcement of aluminium (Al) alloys with ceramic particles opens new possibilities for the design of novel grades for Powder Bed Fusion – Laser Beam (PBF-LB) characterized by exceptional specific strength. However, Aluminium Matrix Composites (AMCs) lack on high-temperature tensile performance, owing to the poor thermal stability of the adopted base alloys. In the present work, we investigate AMALLOY3D-HT, a novel Al alloy reinforced with nano-ceramics tailored for the PBF-LB process and high-temperature applications (up to 300◦C). The mechanisms leading to the formation of an exceptionally refined grain structure will be discussed, alongside results from high resolution characterisation methods aiming to examine the in-depth microstructure including the distribution of secondary. Subsequently, the observed outstanding high-temperature tensile behaviour of AMALLOY3D-HT will be resolved, focusing on the deformation mechanisms and interplay between the matrix and strengthening compounds at both room and high temperature.

Keywords: aluminium, high temperature, metal matrix composite, laser powder bed fusion, alloy design, microstructure

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Approaching the Design of Additively Manufactured Functionally Graded Materials (FGMs) coupled with Thermodynamic Simulations.

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Abstract

Thanks to the emergence and extended interest in additive manufacturing of metallic materials, new types of structures such as functionally graded materials (FGMs), can be obtained to suit different types of industrial needs. FGMs are material structures that show a gradual change in any property or characteristic, such as composition, within the same part. This comes as a great option for dealing with dissimilar joints or for creating location-specific properties. Here, we investigate material compatibility and explore processing parameters for parts graded from a stainless steel 316L and a Ni-based superalloy IN718 by combining (1) advanced characterization (SEM, EDX, EBSD, XRD, micro & macro hardness) of quality, microstructure and properties of graded samples manufactured by direct energy deposition (DED) and (2) computational thermodynamics (CalPhaD) exploration of phase diagrams and assessment of thermal properties along the material gradient. This study aims to explore fundamental mechanisms of microstructure selection and properties in metallic FGMs and investigates the appearance of defects, e.g. (micro-)cracks, and phases/constituents in specific regions of the compositional gradient. While doing this, we look to establish a robust methodology for designing, manufacturing, and characterizing metallic-graded materials for several industrial applications.

Keywords: Functionally Graded Materials, CalPhaD, DED

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A journey into alloy design, development, and industrialisation of custom Al alloys for Additive Manufacturing applications

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Abstract

Additive Manufacturing (AM) unlocks the possibility of creating next-generation alloys featuring properties unachievable with the traditional manufacturing routes. Extending the current alloy portfolio is, therefore, a top priority for accelerating the adoption of AM processes in established industrial sectors, such as, aerospace and defence. This talk presents a contribution to this industry mission through the design, development, and industrialisation of high strength aluminium pre-alloyed powders – AMALLOY3D – for Powder Bed Fusion Laser Beam (PBF-LB). In this work, alloy design based on CALPHAD principles were deployed to define a suitable chemical formulation and nanoparticle inoculant to achieve remarkable strength at room temperature paired with low hot crack sensitivity and high additive manufacturing productivity. The high temperature variant of the alloy – AMALLOY3D-HT – demonstrated excellent strength in testing environment heated up to 300 ºC due to a combination of novel precipitates and extreme grain refinement, outperforming the properties of commercial high strength Al alloy grades available in the marketplace today. The talk also dives into the industrialisation journey of TII's proprietary alloys: from in-house ultrasonic atomisation towards industrial powder production and PBF-LB manufacturing using pre-alloyed powder feedstock.

Keywords: Alloy design, Alloy development, Aluminum Alloys, Laser Powder Bed Fusion, Ultrasonic Atomisation

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Diffraction based residual stress analysis for laser powder bed fusion materials: challenges and benefits

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Abstract

The thermal cycles inherent to the laser powder bed fusion process comprising large localized thermal gradients and repeated melting and solidification cycles leads to the generation of high magnitude residual stresses. These residual stresses can negatively affect the geometrical accuracy and mechanical performance of the component, as well as complicate the post-processing. Thus, it is crucial to understand the influence of process parameters on the residual stress and its distribution along the component. However, the experimental determination of the residual stresses is not trivial when complex stresses profiles and unique microstructure, inherent to the process, are involved. Diffraction-based methods for residual stress analysis using penetrating neutrons and high energy X-rays enable non-destructive spatially resolved characterization of both surface and bulk residual stresses. They allow to map stress distribution inside the part along different directions. However, since X-ray or neutron beam interacts directly with the microstructure of the materials, different factors must be taken into account to ensure accurate measurements. Some of the challenges and the insights of possible issues and solutions will be discussed. Thus, one of the issues is the definition of the unstrained reference: it can become location-dependent and needs to be carefully determined. Also, so-called diffraction elastic constants, used for connecting the macrostrain and stress, often are not known for additively manufactured materials. Additionally, high surface roughness might affect the surface residual stress measurements, so it is important to understand which stress profile is expected and choose the suitable experimental technique.

Keywords: residual stress, diffraction

*Speaker

On the occurrence of rapid solidification during laser powder-bed fusion of metallic alloys

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Abstract

Laser powder-bed fusion (LPBF) is often described as a rapid solidification process by virtue of the high cooling rates at play. However, unambiguous signatures of far-from-equilibrium solidification (e.g. solute trapping, kinetic undercooling, or morphological transitions) are scarce in LPBF alloys. Here, we illustrate two recent studies shedding some light on the matter.
First, we focus on laser spot melting experiments of thin single-crystal ternary NiMoAl alloy samples, supported by *in situ* X-ray imaging allowing to track the interface velocity as the melt pool solidifies. Solidified samples exhibit branchless dendritic structures aligned along the < 100> crystal orientations, even as solidification velocities exceed the absolutely stability threshold predicted by the classical Kurz-Giovanola-Trivedi theory. Discussing these results in light of solidification theories, we argue that the solid-liquid interface conditions are still moderately far from equilibrium.

Second, we focus on LPBF-printed samples of biomedical WE43 Mg alloy. Electron microscopy and compositional analyses allow to unambiguously identify "banded" patterns normal to the main growth direction, with featureless segregation-free regions alternating with patterned segregated regions containing secondary precipitates. Such microstructures are known to emerge in rapid solidification conditions (just below the velocity of planar interface restabilization). Using rapid solidification phase-field simulations, we confirm that thermal conditions in the melt pool indeed promote the banding instability induced by a strong kinetics-induced departure of the solid-liquid interface from thermodynamic equilibrium.
These studies prompt the metal additive manufacturing (AM) community to consider whether and when metal AM really is a rapid solidification process.

Keywords: Rapid solidification, Laser power, bed fusion, Metallic alloys

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An analytical approach to scanning parameter selection: adapting normalized enthalpy to complex geometries

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Abstract

Laser based additive manufacturing (AM) techniques enable a degree of control of solidification conditions, and hence of the resulting microstructure that has long been of interest, since this can be utilized to produce components with site-specific properties. However, an accurate prediction of as-built microstructure often entails complex and costly simulations (1,2). A promising alternative is to estimate the shape, size, and overlap of the melt pools, for these will directly influence the ensuing microstructure (3,4). Many efforts have been made to have accurate estimations of these properties through analytical methods, by using Rosenthal's equation and normalized enthalpy calculations (5,6). This approach, while giving a simple and fast guess, needs further improvement to account for additional aspects influencing the build.
In this study, we propose some modifications to the equation of normalized enthalpy to include the effect of hatch distance and scan vector length. These are developed and calibrated with the help of FE thermal models and experimental data. Finally, we present the application of this analytical model to Inconel 939 parts produced via PBF-LB (7), showing its potential as a handy alternative for microstructural design.

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(3) S.M. Elahi et al., https://doi.org/10.1016/j.commatsci.2022.111882.

(4) M. Rolchigo et al., https://doi.org/10.1016/j.addma.2024.104024.

(5) M. Tang et al., https://doi.org/10.1016/j.addma.2016.12.001.

(6) W.E. King et al.,https://doi.org/10.1016/j.jmatprotec.2014.06.005.

(7) I. Rodríguez-Barber et al., https://doi.org/10.1016/j.msea.2023.144864.

*Speaker

Keywords: Microstructural control by design, analytical modelling, Ni, based superalloys, PBF, LB

Relating laser powder bed fusion process parameters to (micro)structure and to soft magnetic behaviour in a Fe-based bulk metallic glass

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Abstract

Fe-based soft magnetic bulk metallic glasses (BMGs) have shown unprecedented magnetization saturation and coercivity values and are thus envisioned as potential candidates to increase the efficiency of electromagnetic components. Laser powder bed fusion (LBPF) allows to manufacture relatively large BMG parts while retaining an amorphous microstructure due to high local cooling rates. However, in practice, the processing parameters that yield the densest prints also cause severe crystallization due to repeated thermal cycles in the layer-wise process. On the other hand, the parameters that allow the material to retain the amorphous microstructure tend to leave structural defects, mainly due to lack of fusion. To date, complex LPBF scanning strategies, which are difficult to replicate, have been the most successful avenue to avoid crystallization of BMG's during fabrication. However, the fundamental relationship between processing parameters, defects, (micro)structure and properties, still remains unclear for many BMG compositions. This work aims to provide a thorough study of the individual effect of the main LPBF processing parameters (laser power, scanning speed, and hatch distance) on the resulting (micro)structure and magnetic properties of a commercial Fe-based BMG alloy. The feedstock amorphous powder is processed using a pulsed-wave laser system and a simple scanning strategy. Complementary experimental techniques such as image analysis, X-ray diffraction (XRD), differential scanning calorimetry (DSC), electron backscatter diffraction (EBSD) and mechanical and magnetic testing were used to characterize the evolution of (micro)structure and magnetic properties. This study defines guidelines for the successful additive manufacturing of Fe-based BMGs by pulsed laser powder bed fusion.

Keywords: Bulk metallic glasses, amorphous metals, soft magnetic materials, laser powder bed fusion, Kuamet

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STUDYING THE KINETICS OF IN-SITU OXIDE DISPERSION FORMATION RESULTING FROM REACTIVE PROCESS ATMOSPHERES

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Abstract

Additive manufacturing processes are typically performed with argon (Ar) as process gas. Replacing the protective Ar atmosphere with a more reactive one, e.g. carbon dioxide (CO2) in PBF-LB leads to a reaction between gas and material during manufacturing and to an oxygen uptake during printing. The formation of nano-oxides upon solidification is observed in pure Fe and enhanced in a CO2 atmosphere. Even higher oxygen contents in the samples are achieved by adding Ti as alloying element, resulting in the formation of TiO particles. Similarly, TiN particles could be formed using a nitrogen atmosphere (N2). Unfortunately, N2 is distinctly less reactive with Fe-based alloys in PBF-LB than CO2 and thus only a low uptake from the atmosphere is expected. However, a possible strategy to enhance interaction with N2 could be the increase in melt pool lifetime and thus the time for the material-gas interaction. In this work, we employ both PBF-LB and DED-LB to process pure Fe and Fe-Ti powders with process parameters spanning a very wide interval in the three different atmospheres. The extreme variation of processing parameters results in melt pools with very different volumes and lifetimes. The composition of the processed materials is measured by inert gas fusion analysis and correlated to the particle fraction and size as obtained by microscopy. Grain size and particle size are expected to depend on the melt pool size. In this presentation, the ability to control in-situ particle reinforcement by controlling kinetics of melt pool formation and solidification is shown.

Keywords: Alloy Design, Material Gas Interaction, Process Atmosphere, In situ ODS alloy

*Speaker

Tailoring the grain structure of pure Cu via in situ recrystallization in Electron Beam Powder Bed Fusion (EB-PBF)

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Abstract

Over the past few years, it has been shown that additive manufacturing offers unique opportunities to produce site-specific microstructures with local changes in grain morphology and texture. In electron beam powder bed fusion (EB-PBF), local changes in microstructures are often achieved by altering the solidification conditions via changes in processing parameters or scanning strategies. This has been well illustrated in superalloys in the EB-PBF literature. In this work, we introduce another strategy to tailor the grain structure of pure Cu fabricated by Electron Beam Powder Bed Fusion (EB-PBF). We first show that by reducing the hatch spacing, it is possible to achieve fully equiaxed microstructures while standard hatch spacing (typically 0.1 mm) leads to coarse columnar grains. The microstructures are characterized using optical microscopy and EBSD. The mechanism responsible for the formation of equiaxed grains is investigated and identified. Equiaxed grains result from in situ recrystallization during the EB-PBF fabrication. Samples are then fabricated by locally adjusting the hatch spacing in order to produce site-specific microstructures via local recrystallization.

Keywords: site specific microstructure, in situ recrystallisation, pure copper, EB PBF

*Speaker

Towards architected microstructures using advanced laser beam shaping in metal additive manufacturing

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Abstract

The Gaussian distribution of laser beam intensity in Laser Powder Bed Fusion (LPBF) machines induces significant thermal gradients in the melt pool and Heat Affected Zone (HAZ), impacting final part microstructure and increasing defect formation likelihood. LPBF of Ti-6Al-4V alloy typically yields α'-martensitic structures within columnar prior β grains due to high cooling rates, necessitating energy-intensive post-processing heat treatments for desired mechanical properties. However, these treatments are time-consuming and particularly transform the part microstructure in a uniform way. In this study, we employed an advanced laser beam shaping module, based on a Spatial Light Modulator (SLM), to customize the intensity distribution and reduce the cooling rate with appropriate processing parameters. Line track experiments using a Non-Standard (NS) laser beam revealed dual-phase $\alpha+\beta$ lamellar structures within a single-track melt pool. Thermal camera monitoring, along with Finite Element Modelling (FEM), confirmed a significant reduction in the cooling rate for the NS beam, compared to the Gaussian profile. Furthermore, Electron Back Scatter Diffraction (EBSD) analysis demonstrated the absence of columnar prior β grains for this beam configuration. The ability to modify the beam profile during the LPBF process allowed for creating architected microstructures, by switching between the Gaussian profile and the NS beam. This technique was implemented in a custom-made machine, resulting in specimens with a mixture of lamellar $\alpha+\beta$ and α'-martensitic structures. Beam shaping was thereby shown to provide new degrees of freedom for the fine-tuning of microstructures at the melt pool scale, and the LPBF building of 3D composites.

Keywords: Laser Powder Bed Fusion, Beam Shaping, Ti 6Al 4V, Thermal monitoring, Numerical Simulation, Microstructure

*Speaker

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Defect sensitivity of LPBF-manufactured architected cellular materials with random pores

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Abstract

Metallic cellular materials with heterogeneous pore features are used in many branches of technology, from lightweight structures to biomedical implants and electrodes. These materials derive their properties from their internal architecture, which is often poorly controlled via conventional manufacturing routes (e.g. foaming, templating).
Here, we combine Laser-Powder Bed Fusion (LPBF) additive manufacturing technology with computer design to produce metallic cellular architectures with heterogeneous, yet precisely-controlled, pore features. The materials of this study contain cylindrical pores randomly dispersed into a dense metallic matrix. Their porous architecture is generated numerically by a Random Sequential Absorption (RSA) algorithm and fabricated by LPBF using AlSi10Mg powders.

By varying systematically the LPBF-process parameters, we first quantify the effect of the laser scanning strategy on defects, formed inevitably during manufacturing. Notably, we show that these are of two types, namely geometric imperfections and matrix density defects. The first ones are qualified as geometric deviations (in both size and shape of the pores) between the as-manufactured and the as-designed cellular structure. The second ones are caused by either the incomplete overlap between melt tracks or by gas trapping during the solidification of the metal.
Using image-based simulations coupled with experimental data, we investigate the influence of both types of defects on the compressive response of the random cellular materials. Collectively, our results show that defect sensitivity for this class of cellular solids is contingent upon the type of defect and differs remarkably from that observed in periodic lattice structures produced by LPBF.

Keywords: LPBF, Architected Cellular Materials, Image based simulation, Defects, Mechanical properties

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LASER POWDER BED FUSION AND TESTING OF COMPRESSOR WHEELS FROM gamma-TITANIUM ALUMINIDE TI48-2-2

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Abstract

The laser-based metal powder bed fusion process (PBF-LB/M) offers significant technological advantages in the aerospace sector for the production of complex and integrated parts. Especially for aeronautic gas turbine or compressor applications, high-temperature materials with high-specific strength such as titanium aluminides (TiAl) are of major interest. During the last years we investigated the PBF-LB/M processing, heat treatments and phase transformations of different titanium aluminides including the b-stabilized TNM-B1 and TNB-V4 γ-TiAl or the orthorhombic Ti-22Al-25Nb. Generally, PBF-LB/M of titanium aluminides requires high preheating temperatures of the build space in order to tackle the high brittle-to-ductile transition temperatures of these intermetallics. In this work we developed a PBF process for γ-TiAl Ti48-2-2 (Ti-48Al-2Cr-2Nb) and applied it to manufacturing of light-weight compressor wheels in order to study the advantages and draw-backs of high-temperature PBF-LB/M. Challenges related to the required high pre-heat temperatures, the microstructure formation, phase compositions and phase conversions under different processing conditions where studied with a variety of methods including synchrotron in-situ high energy x-ray diffraction and the desired material subsequently adjusted. Chemical problems such as minimizing Al evaporation as well as oxygen pick-up were investigated and addressed. A manufacturing strategy for thin-walled structures and overhanging compressor blades without supports causing high post-processing efforts or deteriorating surface qualities was developed and put to use for manufacturing load- and weight-optimized compressor wheels. The achieved material properties and the part design and were successfully validated in spin-tests, highlighting the technical feasibility of using high-temperature PBF-LB/M for such demanding applications.

Keywords: PBF/LB, M, Titanium aluminides, Ti48, 2, 2, phase transformations, in situ HEXRD, compressor wheels, spin testing

*Speaker

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Two novel high-strength and high-productivity alloys for laser powder bed fusion: Mechanical properties of Scancromal® (Al-Cr-Mo-Sc-Zr) in comparison to Scalmalloy®

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Abstract

The variety of alloys for Laser Powder Bed Fusion (L-PBF) is increasing. In the case of aluminum, there is a demand for high-strength alloys that are processable without hot cracking and economically at the same time. While others depend on modified AlSi10Mg or modified alloys of the series 2xxx, 6xxx and 7xxx, Scancromal® is an evolution of the commercially available alloy Scalmalloy®. Scancromal® was developed by Airbus, introduced in 2019 and its feature is the replacement of Mg with Cr and Mo. This replacement prevents the evaporation of Mg, leads to less spatter and smoke during the melting process and showed the possibility for high build rates. This work presents two alloys of the Scancromal® alloying system. One aiming for high strength and one aiming for a moderate strength but lower costs for powder production. Both were processed with 100 μm layer thickness and compared to Scalmalloy® processed with 30 μm layer thickness. Heat treatments and hardness measurements were performed to evaluate peak aged conditions. After that, tensile tests were performed in peak aged condition. Ultimate tensile strengths of 478 and 369 MPa were achieved while maximum elongation remained at a high value of 10,7 and 14,7 %, respectively. Long-time heat treatment at 200◦C revealed thermal stability up to 500 h. SEM observations revealed a different solidification behaviour for the Cr-containing alloys resulting in small dendrites that form along the melt pool boundaries. A comprehensive comparison of the two Scancromal® alloys and Scalmalloy® summarizes their abilities and application possibilities.

Keywords: LPBF, aluminum, mechanical properties, high temperature

*Speaker

Imaging the Cu solute redistribution into Al during operando additive manufacturing experiments

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Abstract

Functionally graded materials (FGMs) combine desirable properties for multifunctional industrial applications, e.g., mechanics, resistance to corrosion/wear and electric/thermal conductivity. Built on gradually changing compositions or structures or both, FGMs take advantage of additive manufacturing's layer-wise approach, enabling a high control over spatial resolution. However, properties are mainly determined by the weak bonding and mixing between materials/structures leading to the formation of macrosegregation, porosity, cracks and brittle phases. Yet, no real-time experimental investigations were performed to study how the two elements mix at the interface during AM. Although numerical simulations were developed to tackle this problem, they are only reliable on ex situ analyses due to the lack of real-time experimental results. This study focuses on the solute redistribution evolution during the printing of a Cu alloy powder onto a thin Al base plate during the LPBF AM process. Imaging experiments, carried out with a polychromatic beam having a peak energy at 19 keV and a frame rate of 80kHz, were performed on the ID19 beamline at the European Synchrotron Radiation Facility using a LPBF machine. The observation of the mixing between Cu and Al elements showed complex fluid mechanisms within the melt pool. Based on the X-ray absorption contrast, quantitative projected compositions were extracted. It was observed that locally the average Cu composition increases and reaches a plateau while its distribution passes by a maximum before decreasing due to the mixing occurring in the melt pool. These imaging experiments were complemented with diffraction and computer simulation.

Keywords: Functionally graded material, Imaging, Operando, Xray, Synchrotron

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Microstructural evolution of laser powder bed fused Inconel 718 during in-situ solution-aging heat treatments and the role of the scanning strategy

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Abstract

Inconel 718 (IN718) is a precipitation-hardened nickel-based alloy that, when processed by additive manufacturing (AM), does not show the same response to traditional heat treatments (HTs) as cast or forged IN718. The optimal HT for AM IN718 is yet to be found, and parts built with different process parameters tend to have different constitutional features. In particular, distinct scanning strategies lead to distinct residual stress (RS) states and dislocation densities, which in turn may affect precipitation during HTs. In this study, IN718 parts built by laser powder bed fusion with two different scanning strategies (one with incremental 67$\circ$ rotations in the laser path between layers, *Rot*, and one with an alternation of two fixed directions, *Alt*) had their RS characterized by laboratory x-ray diffraction (XRD) and were each submitted to one of two different solution-aging HTs during time-resolved in-situ synchrotron XRD (at the beamline ID22 of the European Synchrotron Radiation Facility, ESRF), followed by ex-situ scanning and transmission electron microscopy. The solution HT at the higher temperature (1 hour at about 1025 $\circ$C) successfully dissolved the detrimental Laves phase and avoided the formation of δ, enhancing the subsequent aging due to increased Nb availability. The aging HT (at about 710 $\circ$C) lasted 5 hours for every sample and produced γ" particles about 10 nm long, but qualitative XRD results indicate rapidly diminishing returns past the 4-hour mark and slight differences in phase contents between *Rot* and *Alt*, with a higher fraction of the strengthening precipitates in the *Alt*-scanned samples.

Keywords: inconel, inconel 718, nickel, scanning strategy, microstructure, heat treatments, aging, precipitation, process parameters

*Speaker

Influence of architecture on serrated flow appearance in additively manufactured Inconel 718 metamaterials

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Abstract

The appearance of serrated flow has been reported for several bulk alloy systems under specific loading conditions. Serrations are a manifestation of unstable mechanical behavior and reduced ductility and thus are undesirable. To date, it is not possible to predict the critical strain for the appearance of serrated flow (ec). This phenomenon has been reported recently in additively manufactured Inconel718 strut-based lattices but its occurrence in metamaterials is widely unknown. The aim of this paper is to study serrated flow in several Inconel 718 BCC lattices with different strut diameters and unit cell sizes with nearly identical microstructure that were manufactured by laser powder bed fusion and to establish a comparison with its occurrence in a counterpart bulk sample. With that goal, uniaxial compression and strain rate jump tests were carried out in the lattices and in bulk specimens at temperatures between 25 and 600∘C and at strain rates within a 10-5-10-2s-1 interval. It was found, first, that ec is larger in the lattices than in the bulk samples; second, ec was observed to decrease with the lattice relative lattice density and to exhibit a minimum at 450∘C. Additionally, the serration amplitude was observed to increase with temperature and with strain, and to be smaller in the lattices than in the bulk specimens. Finite element modelling (FEM) was carried out to understand the origin of ec and to build a framework for the prediction of the onset of serrated flow in strut-based lattices.

Keywords: Dynamic strain aging, Critical strain, Additive manufacturing, Lattice, Inconel 718 alloy

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Probing the mechanisms of ductile fracture with random porous metamaterials

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Abstract

Ductile fracture is the most common room temperature failure mechanism in metals. Typically, it results from the nucleation, growth and coalescence of microscopic voids embedded in the metallic matrix. The subject now comprises a vast body of theoretical and experimental work (1). Yet, while significant progress has been made, several open questions still remain. One concerns the competition between plastic localization and damage.
In this work, the mechanisms of ductile fracture are probed at the mesoscale using additively-manufactured porous metamaterials. The metamaterials of this study have a porous architecture in which cylindrical pores, of arbitrary elliptical shape, are randomly-dispersed in an AlSi10Mg matrix. Their porous architecture is generated numerically by means of a random sequential absorption algorithm and is fabricated by laser powder-bed fusion (LPBF) (2). Using FE-based Digital Volume Correlation (DVC) with mesoscale meshes consistent with the pore distribution combined with simulations (3), the mechanisms of void growth and coalescence (during *in situ* tensile straining) are quantified for this class of cellular solids. It is shown that the latter ones are dictated by the interaction between primary cylindrical voids and are promoted by the presence of manufacturing defects, which inevitably form within the matrix.

(1) Pineau et al. *Acta Materialia* 107 (2016): 424-483.

(2) Salvi et al. (2024): submitted for publication.
(3) Buljac et al. *Experimental Mechanics* 58 (2018): 661-708.

Keywords: LPBF, DVC, in situ testing, metamaterials, ductile fracture, X Ray tomography

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Modulation of the thermo-mechanical behaviour of stainless steels obtained by the wire arc additive manufacturing process, to control the in-service mechanical characteristics and optimize their forming.

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Abstract

The last applications in the wire arc additive manufacturing field highlight various issues to solve in order to take full advantage of the potential of this process.
Due to the heating and solidification conditions during manufacturing, this process generates complex thermal, metallurgical et mechanical phenomena that induce strains and residual stresses which are explained by incompatibilities between local deformations induced by thermal expansion and phase transformations.

With the aim of providing answers, we propose to combine three stainless steels with various chemical compositions (one ferritic stainless steel, one martensitic and one austenitic) according to different architectures and in varying proportions. The evolution of the local chemical composition in the architecture controls the phases transformations and the associated distorsions, allowing to counterbalance the volume variations induced by the thermal expansion.
To grasp the most relevant configurations to build these architectures, we looked for the optimal process parameters (wires feed speeds, travel speed and intensity) to optimize the flow rate of the filler metal and the bead geometry. Afterwards, we study the geometric and mechanical characteristics of single-beads obtained for various alloy mixtures. These first results allow us to identify the most promising combinations, for which we obtain the lowest deformations and residual stresses. We implement these data in the disk model, first developed by El Cheikh (El Cheikh 2012), to predict and model the bead geometry. Thanks to these results, we can select relevant chemical compositions and architectures that reduce strains and residual stresses.

*Speaker

Keywords: Double Wire Arc Additive Manufacturing, Tungsten Inert Gas, Stainless steels, Residual strain

The Influence of microstructure on the hot ductility of AD730 manufactured by laser powder bed fusion.

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Abstract

Laser Powder Bed Fusion (LPBF) attracts considerable interest for producing nickel-based polycrystalline superalloys dedicated to high temperature applications. It has been noticed that superalloys processed by LPBF are known to exhibit a decrease of ductility in the service temperature range (600-800◦C) that is larger than the one observed in the cast and wrought counterparts. This study aims to understand the mechanisms behind this difference in ductility between the LPBF process and the cast/forged route in the AD730 superalloy produced by Aubert et Duval, in order to develop a processing strategy for ductility improvement, whose composition has been recently adapted to LPBF. First, sub-solvus and super-solvus heat treatments are implemented to obtain different grain sizes and morphologies, and different populations (size and spatial distribution). High-temperature tensile tests are then performed on these microstructures, coupled with microstructural investigations to identify on the damage mechanisms. It is shown that the ductility drop is sensitive to both microstructure and tensile direction. The ductility decrease coincides with the occurrence of an intergranular failure mechanism, probably facilitated by high-temperature oxidation. The role of the different microstructural features on the high-temperature ductility is finally discussed, highlighting the main differences with the cast and wrought counterparts.

Keywords: Laser powder bed fusion, Ni based superalloy, hot ductility

*Speaker

Temperature field numerical prediction during Directed Energy Deposition of a metallic bulk sample

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Abstract

In the additive manufacturing field, variations in process parameters, such as the laser power, the scanning speed, or the pre-heating temperature during Directed Energy Deposition (DED) process, might lead to large differences in the final product properties and geometry. The sources of these differences can be established and analysed thanks to numerical modelling. It has the advantage of being cheaper than experimental trials and errors, when adjustments need to be made. The major drawback of the DED simulation is the necessity of thorough calibration and validation steps. The purpose of these steps is to adequately adjust a potentially large amount of process parameters, so as to make the model able to accurately predict the results of one or several experiment(s). To determine the values of these parameters, various optimization algorithms are proposed in the literature. Most of these algorithms need to establish the DED result sensitivity related to each parameter, which can be numerically obtained by running successive simulations with a perturbed value of each parameter. Such optimisation procedure can be very greedy from a computation time point of view, especially when a large number of parameters need to be calibrated. The objective of this work is to investigate the determination of the sensitivity matrix for DED applications and to assess the efficiency of optimisation algorithms to reach accurate model parameters. 3D and 2D modelling strategies are tested and compared in terms of accuracy and computation time.

Keywords: DED, numerical analysis, melt pool, M4 steel, TA6V

*Speaker

Synchrotron X-ray nano-tomography study of healing solutions for a Laser Powder Bed Fusion (LPBF) manufactured high-strength Al-Mg alloy

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Abstract

Aluminium alloys are increasingly used and processed by Laser Powder Bed Fusion (LPBF) for aeronautical and aerospatial fields. To avoid replacement of damaged parts and production of new ones, materials able to heal their damaged sites present great potential.

In this research, a new high-strength healable Al alloy processed with LPBF is developed. Zr is dispersed into an Al-Mg alloy to form hardening precipitates. 3D manufacturing allows to obtain a very thin microstructure consisting of an Al matrix enclosed by a Mg-rich low melting point eutectic network, comparable to a biological vascular system ensuring an efficient transport of the healing agent to damaged sites. Two kinds of healing treatment can be applied after damage: a healing heat treatment (HHT), in which the low melting point eutectic phase melts and flows inside defects to seal and weld them upon solidification and a Healing Heat and Pressure Treatment (HHPT), in which the pressure closes the cavities while the temperature welds them similarly to HHT.

The damaged regions were imaged in 3D before and after healing using synchrotron X-ray nano-tomography at beamline ID16B ESRF. Following a HHT at 540∘C for 30 minutes, 42% of the voids were completely healed, and the volume of voids with an equivalent diameter of 2μm or less was reduced by at least 50%. To evaluate the impact of the HHT on the mechanical properties, tensile tests were conducted. The evolution of the microstructure was observed using Plasma FIB-SEM, a critical correlative electron microscopy technique.

*Speaker

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Keywords: Aluminium alloy, high, strength, additive manufacturing, healing

Effect of heat treatments on the high temperature mechanical strength of a novel Al-Mn-Ni-Cu-Zr alloy designed for Laser Powder Bed Fusion

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Abstract

Additive manufacturing enables the production of aluminum alloys dedicated to high-temperature applications by leveraging the unique microstructural opportunities offered by the out-of-equilibrium processing conditions typical of Laser Powder Bed Fusion. Herein, we investigate the high-temperature mechanical properties of a new Al-4Mn-3Ni-2Cu-1Zr alloy (Aheadd®HT1 developed by Constellium). The mechanical properties are evaluated in the stress-relieved condition (SR=4h/300◦C) and after aging at 400◦C using tensile tests conducted from room temperature up to 350◦C at different strain rates (between 10-2 and 10-5 s-1). From room temperature up to 150◦C, the material is softer in the SR condition than after aging at 400◦C for 1h or 4h. For temperatures ≥200◦C, the SR condition shows the highest strength. We discuss the origin of this drop in strength upon aging in light of the microstructural evolutions during aging. The grain structure remains stable upon aging. At the micro-scale, only minor changes are observed after 4h at 400◦C: the intermetallic particles become more globular. The main changes occur at the nanoscale. The solid solution, supersaturated in Mn and Zr in the SR condition, decomposes at 400◦C with the precipitation of Zr-rich and Mn-rich phases. Those results show that at low temperatures (< 150◦C), the nanoscale L12-Al3Zr precipitates contribute to improving the material's strength, unlike above 200◦C, where they become less efficient. At temperatures ≥200◦C, the main strengthening contribution is brought by the Mn-rich solid solution. This explains why the material in the SR condition is stronger at high temperature than the aged material.

Keywords: Laser Powder Bed Fusion, Aluminum alloys, High temperature mechanical properties

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Effect of Hot Isostatic Pressing on the ability to heal cracks in 5xxx series aluminum alloys produced by Powder Bed Fusion - Laser Beam / Melting

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Abstract

Traditional aluminum alloys of the 5xxx series are considered unprocessable in PBF-LB/M technology due to their susceptibility to hot cracking. Despite the formation of defects in the form of porosity and cracks, it is possible to produce geometrically complex shapes with negligible strength properties. We assumed that appropriately selected HIP treatment would allow us to reduce the number of defects and restore strength properties to the manufactured parts comparable to those of traditionally manufactured 5xxx series aluminum alloy parts. To achieve this goal, thermodynamic simulations were developed to determine solidus and liquidus temperatures at atmospheric pressure and the planned HIP treatment pressure. The simulation-determined temperatures for atmospheric pressure were compared with the results of differential scanning calorimetry (DSC) tests. The fabricated PBF-LB/M aluminum alloy 5254 specimens were subjected to internal structure continuity analysis using computed tomography (CT) both before and after HIP treatment. The effect of HIP treatment on the microstructure and strength properties of the samples was then studied.

Keywords: Hot cracking, Hot Isostatic Pressing, Aluminium Alloys, CALPHAD, PBF LB/M

*Speaker

Impact of heat treatments on microstructure and mechanical properties of γ/γ' Ni-based superalloys obtained by DED processes

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Abstract

The development of direct energy deposition (DED) additive manufacturing processes opens up very exciting prospects in the field of polycrystalline γ/γ' Ni-based superalloys. Indeed, these processes can be used to build complex shaped parts, but also to repair and add functionality to existing parts. However, it also brings new challenges in microstructure design and heat treatments management. The good mechanical properties at high temperatures of this class of alloys are inherited from both the granular structure and the precipitation of different populations of γ' precipitates. The as-deposited microstructures are highly dependent on the type of AM processes and alloys used. The dendritic solidification structure induces chemical segregation, which is mainly controlled by the cooling rate during solidification and subsequent re-heating after each layer deposition. This chemical segregation directly affects the initial microstructure, but also the thermal stability and the kinetics of γ' precipitation and evolution during heat treatments. Three different DED processes (WAAM-CMT, LMD-p, TIG), and three different alloys (Waspaloy, Udimet700, Waspaloy 25 %-Udimet700 75 % mix) were to assess. A particular attention has been paid to the effect of heat treatments on the microstructural evolutions and the resulting mechanical properties of specimens obtained by DED. The microstructural evolutions were investigated

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using SEM observations and EDS-X analyses. Mechanical properties were evaluated using microhardness tests, tensile tests at both high and room temperature, and stress relaxation tests. Direct aging seems to be the best way to optimize mechanical properties as well as an efficient heat treatment route for component repair purposes.

Keywords: Ni Based Superalloys, Heat Treatments, Direct Energy Deposition, Precipitation Kinetics, Solidification, Chemical Segregation, Mechanical Properties

PBF-LB/M PROCESS OPTIMIZATION AIDED BY MULTI-OBJECTIVE BAYESIAN OPTIMIZATION

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Abstract

The process of Laser Powder Bed Fusion of Metals (PBF-LB/M) is very complex. Its final result in the case of material structure, internal voids and even geometric accuracy, as well as the chance of success, depends largely on the choice of printing parameters. In many situations, the optimal values of processing parameters are mutually exclusive depending on the set criteria. Process optimization and selection of printing parameters is a time-consuming and costly process. In our study, we used the Multi-objective Bayesian Optimization (MOBO) technique to speed up process optimization while considering three criteria at the same time: relative density, hardness and process efficiency. During our research, four parameters of the AZ31 magnesium alloy melting process were optimized. The optimization process was carried out in just six consecutive steps, evaluating 20 samples from each iteration. A Gaussian process surrogate model was created on 20 empirically generated samples. Thanks to the efficient operation of the selected sampling algorithm, suggesting every time further 20 parameter sets, it was possible to obtain satisfactory results (99% relative density, hardness in the range of 54-66 HV0.3 and build-up rate in the range of 0.7-2.1 mm3/s) in just a few steps. The proposed methodology significantly reduces the number of experiments, thus saving time and resources.
ACKNOWLEDGEMENTS
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Keywords: Multicriterial optimization, magnesium alloy, PBF, LB/M, machine learning

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Alloy development projects enabled by ultrasonic atomization

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Abstract

The development of novel alloys for powder-based Additive Manufacturing is a central theme in numerous current research projects ranging from biomaterials to electric motors and solar receivers. The range of studied alloy compositions is often limited by the scale of industrial gas atomization methods, requiring large amounts of feedstock and industrial facilities. Ultrasonic atomization technology enables the scaling down and flexibility of spherical powder production to better fit the needs of research projects. Apart from a short introduction to the principles of ultrasonic atomization, a series of case studies will be presented, covering the development of ZK60-magnesium alloys for biodegradable implants, FeCrAl alloys for solar receivers, and Fe-based glass-forming alloys for electric motor applications.

Keywords: Atomization, Powders, Mg, BMG, Soft Magnetic

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INFLUENCE OF THICKNESS ON THE (MICRO)STRUCTURE AND THE MAGNETIC BEHAVIOR OF KUAMET6B2 THIN WALLS

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Abstract

Soft magnetic materials (SMM) portray excellent properties with high saturation magnetization (MS) and low coercivity (HC)(1) that can provide new alternatives for energy efficiency in electric motors. Amorphous SMMs can cater to this need as they can substantially reduce the core losses. The Fe-based bulk metallic glasses (BMG) show promise in fulfilling this requirement. The need for high cooling rates to generate a significant fraction of the amorphous phase severely limits their production to thin ribbons resulting from rapid solidification processes such as melt spinning. Earlier work on additive manufacturing (AM) parameter optimization of a Fe-Si-B-based bulk metallic glass has, however, shown promise for the fabrication of relatively large net-shape rotors (2).

In this work, the effect of thickness on the (micro)structure and the magnetic behavior of Kuamet6B2 thin walls is investigated. Walls with thicknesses ranging from 500 μm to 1000 μm were manufactured by laser powder bed fusion (LPBF) and the wall thickness is correlated with the density, the defect structure, the meltpool morphology, the degree of amorphicity, and the magnetic properties such as the saturation magnetization (JS) and the coercivity (HC). To achieve this, structural characterization techniques, including scanning electron microscopy (SEM), X-ray diffraction (XRD), and differential scanning calorimetry (DSC) have been utilized in conjunction with image analysis tools. The magnetic behavior was characterized using a vibrating sample magnetometer (VSM). This work will provide guidelines for the design of Fe-based soft magnetic bulk metallic glass components with more complex geometries and improved energy efficiency.

Keywords: Additive Manufacturing, Bulk Metallic Glasses, Laser Powder Bed Fusion, Soft Magnetic Materials, Heat Affected Zone, Degree of amorphization.

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Preliminary study of the influence of Silicon addition in Molybdenum processed by Electron Beam Powder Bed Fusion

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Abstract

Nowadays, there is a growing interest in increasing the number of materials suitable for Additive manufacturing (AM), such as the electron beam powder bed fusion (EB-PBF) process. The application of EB-PBF to induce in-situ reactions from mixed powders can represent an original strategy to develop new materials for AM. Moreover, the high preheating temperatures of the EB-PBF process can inhibit the formation of cracks in highly crack-sensitive materials, like refractory materials with high ductile-brittle transition temperatures. In the current work, a mixed powder of Molybdenum and Silicon is processed by EB-PBF, in order to study the influence of adding Silicon inside the Molybdenum. Molybdenum is characterized by high melting points and high mechanical properties at high temperatures and the addition of Silicon can provoke the in-situ formation of intermetallic phases leading to an increase in mechanical performance. However, the aim of this initial work is to start investigating the reaction between Molybdenum and Silicon in the melt pool generated by the electron beam. Various process parameters are used to evaluate the effect on the densification of the material as well as study the generated microstructure.

Keywords: Additive Manufacturing, Electron Beam Powder Bed Fusion, Molybdenum, Silicon

*Speaker

Statistical approch through fast model for microstructure prediction

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Abstract

Metal additive manufacturing parts exhibit distinct microstructures due rapid solidification front (R) and high thermal gradient (G) inherent in the process. The resulting microstructure's shape and texture are primarily influenced by thermal activity. The ratio G/R determining solidification mode and the product G.R describing the size. The focused heat source of the Direct Energy Deposition (DED) process melts the previous layer, involving epitaxial growth. Then competitive growth across grains drives the directional solidification until the Columnar to Equiaxe Transition (CET) occurs. The CET is triggered by a critical undercooling that induces heterogeneous nucleation ahead of the solidification front. Based on the aforementioned solidification theory, a recently developed fast model takes into consideration the thermal activity. This model challenges the Cellular Automaton (CA) and Phase Field (PF) models while drastically reducing the degrees of freedom in 3D. A two-color pyrometer completed with a monochromatic infrared camera are set on a DED wire process machine. A near melt pool area was observed for different printing strategies. Numerical models for temperature simulation on DED process, reinforced with this thermal measurements campaign provide suitable 3D information on the thermal activity as inputs for the fast model. A statistical analysis of the resulting microstructure is conducted for different process parameters. The present work focuses on designing printing strategies to reach a targeting microstructure.

Keywords: Solidification, numerical model, microstructure prediction, DED

*Speaker

Assessment of high-carbon steels processability by powder bed fusion - laser beam through microstructural characterization and hardness test

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Abstract

Additive manufacturing (AM) has seen significant adoption by enabling the realization of products with enhanced functionalities and a simplified process chain. Powder bed fusion-laser beam (PBF-LB) is the widest-used metal AM technology. It enables the production of parts with intricate designs such as conformal cooling channels in moulds and tools. Nonetheless, the potential of PBF-LB has not been fully realized since only a few options of materials are available. When it comes to PBF-LB of steels, low carbon and highly alloyed steels such as stainless steels and maraging steels are successfully produced. These materials are well suited for a niche but not necessarily for applications where high carbon steels with inherent high hardness is required. On the other hand, high carbon tool steels are challenging to print by PBF-LB due to their high tendency to crack. The present work aims to investigate the processability of high carbon steels, i.e., Fe-0.76C, Fe-1.0C (W1), Fe-1.1C-0.5Cr (W5), and Fe-1.2C-0.4Cr-4.5W (F2). The alloys were prepared from *in-situ* mixing powders of pure elements in the right proportions and processed by PBF-LB to produce bulk samples, which were submitted to microstructural characterization and Vickers hardness test. The results show that the high cooling rates involved in the PBF-LB lead to a metastable microstructure with martensite and varying fractions of retained austenite depending on the composition of the steel. This is translated in Vickers hardness not necessarily higher in steels with higher carbon content, which is explained by a higher volume fraction of retained austenite.

Keywords: additive manufacturing, powder bed fusion, laser beam, high carbon steels, martensitic structure

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Influence of preheat temperature on the microstructure and hardness of IN718 alloy fabricated via electron-beam powder bed fusion

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Abstract

Optimizing processing parameters in additive manufacturing (AM) is crucial for microstructure-properties relationships. This is often aided by various modeling approaches. In electron beam powder bed fusion (E-PBF) processing, the preheat temperature is a key parameter significantly impacting the resulting microstructures and properties. The current study reveals the significant impact of two only slightly different preheat temperatures (i.e., 1000 and 950○C) on the microstructural evolution of the IN718 alloy during E-PBF. We utilize correlative microscopy as well as thermal and thermo-kinetic (MatCalc) modeling to measure and predict changes in phase fractions and morphologies of various precipitates. The 50○C difference in preheat temperature only marginally affects the solidification conditions, although lower preheating is shown to limit grain growth. The higher preheat temperature induces intergranular δ phase precipitation, enhancing the as-built properties through γ" precipitation. Conversely, lower preheating results in both intergranular and intragranular δ phase precipitation, deteriorating the γ" precipitation potential and hardness. A clear correlation is observed between our simulation and experimental results. Our findings highlight the importance of the preheat temperature in microstructure design and property control in E-PBF.

Keywords: Additive manufacturing, Simulation, Preheat temperature, IN718, Precipitation

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FCC and BCC phases in 316L-CuCrZr multi-material additive manufacturing

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Abstract

Additive manufacturing of 316L/CuCrZr multi-material metallic structures has recently attracted significant scientific attention. In this work, a unique multi-phase microstructure was produced by laser-powder bed fusion (L-PBF), combining 316L thin foils and Cu powders. I*n-situ* XRD, EDS, and EBSD measurements evidence the formation of two distinct Cu and Fe FCC phases that co-exist with Fe-rich BCC spherical particles. Microstructure analysis and thermodynamic simulations lead to plausible phase transformation mechanisms, originating from the miscibility gap of the Fe-Cu system, and explaining the presence of Fe-rich BCC particles. These mechanisms involve the Marangoni effect and elements diffusion across phases. The effect of the BCC phase on mechanical properties and dynamic recrystallization phenomena at room and elevated temperatures (200 ◦C to 800 ◦C) were evaluated using hot compression tests. The design of complex "composite" FCC+BCC microstructures could impart substantial strengthening of the LPBF multi-material 316L/Cu structure.

Keywords: Hybrid additive manufacturing, LPBF, Multi material, Microstructure, Mechanical properties

*Speaker

Understanding Laser Powder Bed Fusion of Stainless Steel: Importance of Considering the Complex Marangoni Effect in Process Optimization

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Abstract

In the rapidly evolving field of metal additive manufacturing, understanding the melt pool dynamics in Laser Powder Bed Fusion (LPBF) is crucial for enhancing the reliability and efficiency of the process. In this study, a high-fidelity computational fluid dynamics (CFD) model of LPBF has been developed using OpenFOAM, aimed at elucidating the intricate fluid flow and heat transfer in LPBF, with a particular focus on stainless steel. These alloys exhibit distinctive melt pool dynamics compared to other alloys, such as Ti-based and Al-based alloys, because of the presence of surfactant elements. This model includes a realistic representation of powder layer distribution and incorporates multiple laser reflections, heat transfer, recoil pressure, and the Marangoni convection. A notable feature of this model is the implementation of a temperature-dependent surface tension coefficient within the Marangoni effect module. This inclusion is critical for accurately modeling LPBF with stainless steel, where surfactant elements significantly alter the temperature-surface tension relationship. The predictive capability of the model has been validated against empirical measurements of melt pool dimensions and fluid velocities obtained from in-situ synchrotron X-ray imaging experiments across different materials. Through detailed simulation of the complex melt pool dynamics in SS316L LPBF, the impact of the pronounced inward flow on heat transfer, melt pool geometry, surface quality, gas pore migration, and conduction-keyhole threshold has been investigated. This study provides a comprehensive mechanistic understanding of the uncommon melt pool behaviors observed in SS316L LPBF, offering valuable insights into the overall process parameter optimization of LPBF with stainless steel.

Keywords: Laser powder bed fusion, Computational fluid dynamics, Melt pool dynamics, Inward Marangoni convection, Keyhole threshold

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Laser powder bed fusion of In718/GRCop-42 bimetallic structures: effect of deposition order and process parameters

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Abstract

The CuCrNb alloy, GRCop-42, was developed for the fabrication of regeneratively cooled combustion chambers with high thermal conductivity, good mechanical properties at high temperatures, and low thermal expansion to reduce thermally induced stresses (1). Recently, the aerospace industry has investigated using additive manufacturing to create bimetallic structures, such as combining the conductive properties of GRCop-42 with the structural and oxidation resistant properties of In718.
This work uses an AconityMIDI+ laser powder bed fusion machine equipped with an Aerosint dual recoater to fabricate In718/GRCop-42 bimetallic samples. The influence of deposition sequence on the phase formation at the interface is studied. Adjustments to the process parameters at the interface are also investigated. The interface was observed using optical and scanning electron microscopy. Grain structure and phase formation was interpreted using a combination of energy-dispersive X-ray spectroscopy, electron backscatter diffraction, and X-ray diffraction.

GRCop-42 derives its exceptional high temperature properties from the precipitation of the Cr2Nb phase throughout the copper matrix. This work shows that the formation of this secondary phase is affected by the deposition order of the alloys. Deposition of GRCop-42 on top of In718 results in greater mixing and subsequently leads to infiltration of iron and nickel into the GRCop-42. This alters the formation of the Cr2Nb phase in the GRCop-42, and produces new phases across the interface.
(1) Y. Chen, C. Zeng, H. Ding, S. Emanet, P.R. Gradl, D.L. Ellis, S. Guo, Thermophysical properties of additively manufactured (AM) GRCop-42 and GRCop-84, Mater Today Commun 36 (2023). https://doi.org/10.1016/j.mtcomm.2023.106665.

Keywords: Multi material, bimetallic, laser powder bed fusion, Inconel, GRCop42, phase formation

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Physics-Informed Prior Means and Kernels in Gaussian Process Thermal-Modeling for the Design of Printable Alloys

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Abstract

In this work we seek to identify processing parameters that are likely to mitigate porosity defects during the AM of refractory alloys in a high-throughput manner. Printability maps have been shown to be an effective method to avoid porosity defects during AM. These printability maps are often based on single-track melt pool dimensions. Unfortunately, there is insufficient experimental data on the printability of refractory alloys to train data-hungry naïve machine learning models. Furthermore, AM experimentation is prohibitively expensive and thus not appropriate for high-throughput chemistry-agnostic alloy design. Fast-acting thermal models such as the analytical Eagar-Tsai (ET) model provide a first-approximation of printability, however typically lack the physics required to capture the keyholing phenomena. To create a thermal model that is both fast-acting and accurate we propose correcting analytical models with experimental data in a Bayesian manner. Specifically, we propose modifying both 1) the prior mean function 2) and the co-variance function of Gaussian Process Regressors (GPR, a Bayesian non-parametric regressor that is fully defined by a prior mean and co-variance) with the physics captured in the ET model. This essentially creates a data-correct version of the ET model. Adhering to best practices, we benchmark the effect of the prior mean and the physics-constrained co-variance function using a 2-fold cross validation scheme, demonstrating our method is effective under data-sparse conditions. Finally, we demonstrate how our method creates more reasonable porosity defect maps than the Eagar-Tsai model and the naïve GPR model.

Keywords: Bayesian, Gaussian Process Regression, Data Fusion, Thermal model, Printability map, processing

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Numerical simulation of melt flow and track morphology in laser powder bed fusion of 316L stainless steel

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Abstract

Laser powder bed fusion (L-PBF) is an advanced additive manufacturing technology, enabling the precise fabrication of components with complex geometries for a wide variety of high-performance metallic materials. The part quality such as defect density and surface roughness can be significantly influenced by the dynamic flow behavior of melt pool tracks. Moreover, the melt pool geometry and associated temperature field governs the formation of solidification microstructure, consequently affecting the overall part performance. In this study, a 3D discrete element method-computational fluid dynamics (DEM-CFD) model is developed to simulate heat transfer and fluid flow during the L-PBF process. The model incorporates the physics of laser beam and metal powder interaction, melt pool formation, recoil pressure effect, and the Marangoni effect. The free surface of the melt pool is captured by volume of fluid (VOF) method. The model is validated by comparing the melt pool dimensions with experimental results from literature. The developed model is capable of predicting melt flow, track morphology, and associated defect formation as a function of laser scan parameters such as laser power and laser scan speed. Discontinuous melt tracks and balling effects are evident at lower energy input, causing lack-of-fusion defects. Furthermore, the influence of recoil pressure and the Marangoni effect on the model's accuracy in predicting melt pool shape is examined. This work contributes to the understanding of complex physical phenomena during the L-PBF process, providing insights into process optimization strategies for L-PBF technology.

Keywords: Laser powder bed fusion, Computational fluid dynamics, Single track, Melt pool, Defect.

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Effect of laser rescanning on thermal conductivity and mechanical properties of Al-1.2Fe alloy fabricated by laser-directed energy deposition

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Abstract

Laser-directed energy deposition(L-DED) has gradually gained attention in additive manufacturing (AM) technology which has significant advantages in the fabrication of complex components due to its high precision. Laser rescanning, a unique processing technology of L-DED, improves manufacturing quality by minimizing defects and surface roughness. On the other hand, aluminum alloys have various characteristics such as light weight, high thermal conductivity and excellent mechanical properties, making them extensively applied across many industries. One possible application of L-DED processed aluminum alloys is heat exchangers of fuel injectors, where intricate geometries with high thermal conductivity are required for the performance.

So far, near-eutectic Al-Si alloys had been extensively used for the AM of aluminum alloys. Al-10Si-1Mg (wt.%) alloy is one the mostly used alloy of this kind, which prevents solidification cracking, narrows solidification range and reinforces mechanical properties through precipitation of Mg2Si phase. In addition, Al-10Si-Mg alloys fabricated by AM exhibited fine microstructures with submicrometric cells of supersaturated alpha-Al surrounded by a eutectic-Si network. While this microstructure provided superior mechanical properties, eutectic-Si network hampered heat transfer, thus decreasing its performance as a heat dissipating material.

To address this limitation, the introduction of Al-Fe alloy commonly utilized in heat exchanger has been proposed. This study explored the potential of Al-1.2Fe (wt.%) alloy fabricated by L-DED as a heat dissipating material. Furthermore, the influence of laser rescanning on thermal conductivity and mechanical properties were investigated and correlated with the microstructure of Al-1.2Fe alloy fabricated by L-DED.

Keywords: L DED, Al Fe alloy, Laser rescanning, Thermal conductivity, Mechanical properties

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Interfacial reactions in multi-material DED printing of aluminum and nickel

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Abstract

Multi-materials are widely applied in industrial construction and manufacturing, where the characteristic features of the different materials are optimized for specific applications to result in value addition and cost efficiency. Particularly, Ni/Al multi-materials can be applied in electronic packaging and new energy automobile since nickel has excellent thermal stability and corrosion resistance while aluminum has low density and excellent thermal dissipation behavior. The fabrication of multi-materials with laser direct energy deposition (L-DED) process offers the advantage of allowing the production of complex multi-material layers. In this study, interfacial reactions between Al and Ni that occur in multi-material L-DED 3D printing were investigated in terms of different laser processing parameters. Inconel 625 and Al10Si1Mg (wt.%) were used as powder and substrate materials. The morphology of the interface was observed by optical microscopy. The microhardness and tensile strength of the interface were measured to analyze the interfacial bonding behaviors. The chemical composition of the interface was analyzed with energy dispersive spectrometer (EDS). It was observed that intermetallic compound (IMC) phases between Ni and Al tend to get thicker with increasing the laser heat input. The microhardness of the IMCs phase was higher compared with Ni and Al. From the EDS results, two different IMCs phase were observed on the interfaces. The IMCs phase close to the Al was assumed to be NiAl and the phase close to the Ni was assumed to be Al3Ni5.

Keywords: multi material, Ni Al intermetallic components, L DED, mechanical properties, interfacial reactions

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Understanding Cracking in Multi-material Laser Powder-bed Fusion via Operando Synchrotron X-Ray Imaging

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Abstract

Additive manufacturing (AM) of multi-material alloy combinations is attractive for many industries that require a balance of thermal conductivity, corrosion resistance and mechanical strength. However, printability of these combinations can be hindered by macroscopic defects such as cracks. This study investigates the mechanisms of cracking during multi-material printing of stainless steel and nickel-based alloys in combination with copper-based alloys. Initially, 316L stainless steel and Inconel 625 thin wall samples were printed separately, and then a CuCrZr alloy layer was printed on top using two different process parameters. To track the solidification and cracking behavior during LPBF, a miniature LPBF system (miniSLM) dedicated to synchrotron studies was used to conduct AM operando synchrotron X-ray imaging experiments at ID19 beamline, ESRF, Grenoble, France. A white X-ray beam with a peak energy of 40 keV was used and the images were collected at 40 kHz frequency using an X-ray microscope. The images were collected over successive layers around the interface during both melting and solidification. For both cases, the cracks were observed to initiate during and immediately after solidification. Further characterization has shown that this behavior originates from the thermodynamic interaction of copper and the alloying elements within the other alloys, causing cracking upon solidification. These results provide a deeper understanding regarding processability of multi-materials using LPBF, and hold promise for further optimization of multi-material components produced by AM processes.

Keywords: multi material, operando xray imaging, metal additive manufacturing

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Operando phase mapping during laser powder bed fusion of 316L and CuCrZr premixtures

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Abstract

Investigations on stainless steel 316L and CuCrZr bimetal composites produced through laser powder bed fusion (LPBF) have been intensely growing in the past few years. The aim is to fabricate parts with combined properties of excellent strength, ductility, and corrosion resistance from 316L, as well as exceptional thermal and electrical conductivities from CuCrZr. Although both metals, when built separately, have a face-centered cubic (FCC) crystal structure, the microstructure of the as-built premixtures exhibits a small fraction of body-centered cubic (BCC) phase, whose amount depends on the weight percent of CuCrZr powder. In this study, we observed the evolution of this BCC phase volume fraction in the whole bulk during printing by means of polarization contrast neutron imaging (PNI) using our in-house-developed downsized LPBF device (n-SLM). This novel device was built specifically for operando or in-situ neutron studies, owing to its versatility. The BCC phase formation was observed to be highly sensitive to the temperature of the preceding substrate and, thus, the cooling rate. The findings were subsequently correlated with ex-situ tomography scans and post-mortem microstructural analysis. This contribution would provide further insight not only into the LPBF processing of these materials but also into the remarkable capabilities of the n-SLM introduced to the community.

Keywords: Laser powder bed fusion, multi materials, operando characterization, polarization contrast neutron imaging

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Effect of combined additions of Sc, Zr and Ti on hot-cracking resistance and precipitation behaviour in Al-Mg alloy processed by L-PBF

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Abstract

The request for high-performance aluminum components prompts research into innovative alloys compatible with laser-based additive manufacturing, leveraging grain refiners to mitigate hot-cracking and enhance strength. While the Sc and Zr addition in Al-Mg alloys has been widely investigated, the high cost and supply risks associated with Sc necessitate its partial substitution with other inoculants.

In the first preliminary phase of the study, the replaceability of Sc with different Zr or Ti concentrations is evaluated investigating the L-PBF processability of three powder feedstocks: a pre-alloyed Al-Mg-Zr-Sc powder, a blend of the previous alloy with addition of Zr particles, and a further blend of a Zr-depleted alloy with added Ti particles. Laser processing reveals crack-free bimodal microstructures in standard and Zr-enriched alloys, featuring fine equiaxed grains at pool edges and coarser grains at their centers. Conversely, Zr-depleted alloys with added Ti exhibit columnar structures and hot-cracking. Thermodynamic simulations of phase formation allowed defining the precipitation kinetics during solidification and direct aging, showing increased precipitation in higher Zr content alloys, while Ti presence resulted in sluggish precipitation. Aging tests demonstrated significant increases in microhardness, with peak values of the modified alloys achieved after 12h at 375◦C.

In the second phase of the study, pre-alloyed powders were atomized to achieve compositions tailored to specific targets identified in the preliminary results. Forthcoming analyses will entail a detailed examination of the microstructure, focusing on characterizing aging precipitates, along with an assessment of mechanical properties via microhardness and tensile testing methodologies.

Keywords: Additive manufacturing, laser powder bed fusion, high, strength Al alloys, microstructure, heat treatment, precipitation behaviour

*Speaker

Processability of nickel self-fluxing alloy by L-PBF

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Abstract

Nickel-based self-fluxing alloys are widely used as hard-facing materials for their outstanding wear and corrosion resistance, even at high temperatures. NiCrBSi deposits exhibit a complex microstructure composed of a ductile nickel-rich matrix with dispersed hard phases, which can be attributed to a cermet. Additive L-PBF process manufacturing suits complex parts and would appear interesting for NiCrBSi alloys.However, these alloys are mainly used as coatings, so there is a lack of literature concerning their processability by additive manufacturing and the resulting properties. The few articles highlight issues regarding lack of density and cracks. This study defines and explores the processability window using a commercial and modified L-PBF device. The baseplate is preheated at various temperatures up to 500 ◦C to limit cracking, and laser rescanning is explored. Process parameters are compared to crack and surface density to assess processability.The microstructure is thin and complex, and synchrotron XRD investigated the various phases. Preheating the base plate to 500 ◦C and carefully selecting process parameters reduces crack density and increases surface density.

Keywords: NiCrBSi, Nickel superalloy, Additive manufacturing, LPBF, material health, Xray tomography, Xray diffraction

*Speaker

About the use of inter-pass time and additional cooling system to control the microstructure and mechanical properties of duplex stainless-steel parts built by wire-arc additive manufacturing

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Abstract

The Wire-Arc Additive Manufacturing (WAAM) building process is an additive manufacturing process, allowing the production of metal components layer-by-layer using an arc welding process. This operation leads to thermal, mechanical, and metallurgical phenomena responsible for the formation of residual strains and stresses (1). In particular, thermal cycles, due to alternating heating and ensuing cooling during multi-pass deposing, significantly contribute to the apparition of those residual stresses. Accurate determination of process parameters is crucial to ensure component quality and to control the heat, especially for melting metallic feedstock in wire form. Inter-pass time management is a key strategy in WAAM, as it directly impacts various aspects such as inter-pass temperature control, the dimensions of the molten pool, the formation of microstructure (affected by solidification and solid-state transformations), and ultimately, the development of residual stresses and strains (2). In addition, active cooling during inter-pass intervals is essential for controlling part temperature, minimizing thermal distortion, and ensuring desired mechanical properties (3). Furthermore, in duplex stainless steel, the cooling rate influences austenite precipitation. Introducing an additional cooling system shows promise for enhancing the cooling rate and deposition rate.
This study aims to investigate the impact of inter-pass time on thermal cycles and explore the use of an external cooling system to limit accumulated heat, providing insight into cooling mechanisms and their implications in WAAM. By understanding these factors, it is possible to optimize WAAM processes for improved component quality and performance.

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(2) doi: 10.1080/13621718.2016.1259031.
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*Speaker

Keywords: Wire Arc Additive Manufacturing, Thermal Cycles, Residual Stress, Inter, pass time, Cooling Systems, High Deposition Rate, Duplex Stainless Steel, Mechanical properties, Austenite Precipitation.

Development of Rotation Continuous PBF 3D Printing System and Optimization of STS304 Process

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Abstract

The application of 3D printing technology in the aerospace industry, especially for manufacturing predominantly cylindrical fuselage components, marks a significant shift from traditional manufacturing methods, which rely on Cartesian coordinate systems and often lack precision for such geometries. Direct Energy Deposition (DED) techniques, designed for cylindrical printing, face challenges in achieving high-precision patterns. Similarly, the traditional Powder Bed Fusion (PBF) approach suffers from excessive powder consumption and inefficiencies in powder coating time due to the necessity of coating the entire bed area. Additionally, the scope of printable shapes is limited by scanner field restrictions.

To address these challenges, this study introduces the development of the Rotational Continuous PBF 3D Printing System, a novel approach engineered for cylindrical applications using PBF technology. This system selectively applies powder to the bed's printing area and conducts continuous laser melting, significantly enhanced by integrating the 'Marking on the Fly' (MOTF) system. The MOTF system facilitates a seamless transition from orthogonal to cylindrical coordinate systems, enabling the accurate printing of cylindrical geometries. This method's application in fabricating STS304 specimens allows for an analysis of microstructural differences with and without MOTF application, alongside process optimization.

The introduction of the Rotational Continuous PBF 3D Printing System promises to revolutionize 3D printing applications within the aerospace sector, featuring improved material properties and reduced waste. This advancement marks a pivotal step towards realizing more efficient and precise additive manufacturing processes tailored to the unique requirements of the aerospace industry, demonstrating significant progress in addressing the current technological challenges

Keywords: Additive manufacturing, Rotational Continuous PBF 3D Printing System, Marking on the fly, STS 304

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Site-Specific Fabrication of Metal Matrix Nanocomposites via Laser Directed Energy Deposition: Efficacy of Direct Nanoparticles Injection and Laser-Induced Remelting Techniques

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Abstract

This study presents an innovative method for fabricating Metal Matrix Nanocomposites (MMnCs) using the Laser Directed Energy Deposition Process, which overcomes the limitations of traditional pre-mixing and in-situ techniques. Our approach features the direct injection of nano-reinforcement particles via a novel pulsating powder feeder injector, allowing for precise control over the characteristics, concentration, and spatial distribution of nano-reinforcements during additive manufacturing. Matrix particles (316L Stainless Steel) are fed using a conventional volumetric feeder, while nanoparticles (Titanium Nitride) are directly supplied through a dense phase powder conveying system designed for materials with poor flowability. This system enables on-demand, site-specific adjustment of grain refinement and mechanical properties within a single component by controlling the dense phase conveying system. Through comprehensive DEM-CFD modeling and ex-situ experimental analysis, we observed that injected nanoparticles do not penetrate the melt pool's surface tension barrier, but rather float and accumulate at its periphery, becoming entrapped over the surface as the melt solidifies. A subsequent laser remelting step during printing promotes Marangoni-driven flow, facilitating the inward movement of nanoparticles and the creation of heterogeneous nucleation sites during solidification. This direct injection combined with laser remelting allows for the site-specific creation of graded Metal Matrix Nanocomposites. Measurement techniques including Scanning Electron Microscopy (SEM), Electron Backscatter Diffraction (EBSD), and Energy Dispersive X-ray Spectroscopy (EDS) confirmed the successful incorporation of nanoparticles and the resultant site-specific grain refinement attributed to heterogeneous nucleation.

Keywords: Directed energy deposition, Metal Matrix Nanocomposites, DEM, CFD modeling, Direct nanoparticles injection, Grain refinement

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Designing LPBF microstructures with advanced thermal paths and in situ alloying

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Abstract

Laser Powder Bed Fusion (LPBF, also known as SLM, Selective Laser Melting) is a well-known Additive Manufacturing technology, among the most studied for metals and alloys. Advanced LPBF now includes the ability to vary the laser parameters during fabrication, perform in situ laser heat treatments, and mix different powders. These recent developments open the possibility of designing new microstructures.

In the present work, we demonstrate how microstructures in LPBF can be strongly modified by properly designed thermal paths and in situ alloying. These can be optimized with the help of thermal modelling combined with thermodynamic computations.Two examples are illustrated, with small/medium variations in chemical composition of 316L steel and Ti-6Al-4V, leading to drastic changes in the LPBFed microstructures and properties. Tuning thermal paths or local chemical composition also provides the opportunity to create architected materials.

Keywords: Laser Powder Bed Fusion, Operando X ray diffraction, 316L steel, Ti6Al4V, Laser Heat Treatment, in situ alloying, 3D architected material

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Microstructure of thin-walled structure with non uniform scanning speed

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Abstract

This paper deals with additive manufacturing, which enables parts with complex geometries to be produced layer by layer. For specific geometries, such as bent parts, it is necessary to vary the bead size within or between layers by modifying process parameters, such as scanning speed. However, it has been shown in the literature that modifying process parameters leads to changes in the microstructure. This paper inspects the impact of continuous variation in scanning speed on the microstructure produced with the LMP-DED additive manufacturing process. An experimental study was carried out on single-bead Inconel 718 thin walls. Scanning speed varied linearly along each bead so that at a given position in the wall, the scanning speed was the same throughout the height of the wall. An EBSD analysis of the microstructure was carried out over a length of about 20 mm for a speed variation ranging from 1125mm/min to 1875mm/min. A continuous variation in microstructure was observed from one end of the sample to the other, passing from a mix of columnar and equiaxed grains with no textured structure to large, highly textured columnar grains. These results show that it is possible to intentionally and continuously vary the microstructure of a part along its length by choosing the proper parameters and strategy. This work is preliminary to the microstructure control of a complex part.

Keywords: Additive manufacturing, Scanning speed, Microstructure, Trajectories

*Speaker

Fabrication, Microstructure Analysis and In-Situ Monitoring of 316L-CuCrZr Multi-Material Structures made through Laser Powder Bed Fusion

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Abstract

316L-CuCrZr Laser Powder Bed Fusion multi-material structures have been a topic of research interest, given on the one side their prosperous material combination and on the other side the manufacturing challenges due to the cracking formation on their interface. In our study, we propose a compositional modification approach, for the annihilation of the cracking phenomena, through the introduction of properly selected premixture layers, between 316L and CuCrZr, that promote the formation of a small fraction of Ferrite. The presence of Ferrite in the multi-material structures is verified by both Polarization Contrast Neutron Analysis (PNI) and EBSD mapping. The phase transformation from austenite to ferrite, as shown through Neutron Bragg Edge Imaging measurements, is correlated with significant variation of the texture evolution of the material and concurrent drop of the Coefficient of Thermal Expansion of the structures, as shown through in-situ annealing treatment. The morphology of the melt pool, for the different selected premixtures, is examined via in-situ radiographic analysis, coupled with the in-situ monitoring examination through acoustic emission measurements. Finally, high speed imaging analysis is used for the estimation of the temperature field and the solidification behavior of the different compositional steps of the multi-material structures.

Keywords: Laser Powder Bed Fusion, Multi, Material Structures, Neutron Imaging

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PBF-LB of a non-weldable Ni-base Superalloy: role of scan strategies on hot cracking

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Abstract

Additive manufacturing of non-weldable CM247LC by powder bed fusion – laser beam of metals (PBF-LB) is challenging due to its high cracking susceptibility. The cracking mechanism can broadly be divided into hot cracking which occurs during the PBF-LB process and solid-state cracking which occurs during post-processing heat treatment. Hot cracking, in particular solidification cracking, occurs during the last stage of solidification within a solidifying melt pool and can also traverse across multiple melt pools along the build direction. On the other hand, solid-state cracking like strain age cracking occurs during the heat treatment. The residual stresses from the PBF-LB process and the γ formation stresses lead to strain age cracking.
The authors have demonstrated in an earlier study on CM247LC that residual stresses cannot be minimized solely by optimizing laser power, speed and hatch. And another ongoing study showed that novel scan strategy enabled through a spot-like melting strategy was able to minimize both solidification cracking and strain age cracking. Using the knowledge gained from the study, the authors have explored other scanning strategies such as scan rotation, remelting, and in-situ heat treatments. Initial results indicate that having more textured microstructure is favorable in reducing the solidification cracking.

This work is an initial step that indicates that novel scan strategies can enable a difficult-to-process material like CM247LC. Furthermore, it could also be beneficial to study the impact of such strategies on residual stresses that is a main hindrance for such alloys.

Keywords: Ni, base superalloy, non, weldable superalloy, solidification cracking, CM247LC, PBF, LB

*Speaker

Additive manufacturing of WC-Co ceramic/metal composites using binder jetting : from powder to sintered part properties

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Abstract

Cemented carbides are used in industry as cutting tools and wear parts, thanks to their high hardness and wear resistance. Traditionally composed of tungsten carbide (WC) and a metal binder of cobalt (Co), these composites are manufactured by powder metallurgy and must have a density greater than 99.5%. Today's environment is prompting us to find ways of saving the materials needed to manufacture industrial products, through the use/development of innovative processes such as additive manufacturing.
However, major technological and scientific hurdles remain : understanding the link between printing parameters, physico-chemical properties of powders, microstructures of printed parts and mechanical properties of sintered parts.

In this purpose, a number of mechanical tests (hardness, toughness, bending test) have been carried out to establish the link between microstructure and mechanical properties of sintered parts. Fine microstructural analysis (composition, grain size, phases present) and thermodynamic calculations in sintering windows (ThermoCalc) will help predict microstructure as a function of debinding/sintering conditions.
In addition, dilatometry tests on green parts printed by Binder Jetting have been carried out to quantify anisotropy, determine its cause and correct it if necessary. The aim of these tests is also to understand the specific features of liquid phase sintering, so as to feed a numerical simulation model of the sintering process.

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Keywords: Binder Jetting, Cemented Carbide, Hardness, Toughness, Microstructure, Dilatometry, Sintering modeling

Orientation, phase and internal stress mapping by TEM applied to additive manufacturing microstructures

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Abstract

The development of metal additive manufacturing drags a strong interest in the microstructures obtained by these types of processes, especially laser powder bed fusion. Indeed, the processing conditions, in particular high cooling rates, lead to very fine microstructures, with nanoscale precipitates, chemical segregations, and dislocation structures developing at the sub-micrometric scale. All these features strongly affects properties. The scale of these microstructures often makes characterization by TEM (Transmission Electron Microscope) necessary. Here, we present an overview of TEM characterizations on microstructures obtained by laser powder bed fusion, with particular attention given to multi-modal mapping, orientation and phase mapping using ACOM/ASTAR and chemical mapping using EDX. This allows performing high-throughput identification of phases in the microstructures investigated. Using the same ACOM acquisitions, internal stresses in dislocation structures can also be measured, and correlate well with theoretical works. Examples of nickel-based superalloys, aluminium alloys, and stainless steels will be given.

Keywords: laser powder bed fusion, characterization, TEM

*Speaker

Portevin-Le Chatelier effect in 316L stainless steels processed by LPBF

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Abstract

316L austenitic stainless steels are commonly used in core components in the nuclear industry, acting as structural materials in the primary circuit of pressurized water reactors (PWR). On the other hand, additive manufacturing technologies are of growing interest of the nuclear industry. Among these processes, laser powder bed fusion (LPBF) is a promising tool for the replacement of obsolete or unique components (1). There is, however, a lack of knowledge on mechanical properties of 316L stainless steels processed by LPBF at PWR operating temperatures, i.e. between 290◦C and 340◦C. Tensile tests at room temperature, 300◦C and 340◦C were carried out on stress-relieved 316L LPBF specimen at four different strain rates ranging from 10-5 to 10-1 s-1. Strain fields during each test were monitored by digital image correlation (DIC). At room temperature, the strain rate sensitivity was positive and similar to the conventionally manufactured 316L. This positive strain rate sensitivity was lost at 300◦C, and serrations were noticeable on the stress-strain curves at lower strain rates, hinting at Portevin-Le Chatelier effect. This was confirmed by digital image correlation, which highlights nucleation and propagation of strain localization bands during tensile tests. Similar observations were made at 340◦C. Further tensile tests performed on specimens heat treated at various temperatures showed the effect of the as-built microstructure on the PLC effect at 300◦C.

Keywords: PLC effect, Laser powder bed fusion, stainless steel

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Magnetic Field-Assisted Direct Liquid Metal Deposition

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Abstract

Common metal additive manufacturing technologies require intensive energy sources such as lasers to achieve the melting and bonding of a metallic feedstock. This leads to a sizeable carbon footprint especially for reflective materials such as aluminium. Moreover, it induces complex and turbulent melt pool dynamics leading to stochastic defect formation mechanisms that are hence difficult to suppress.

We aim to propose an alternative approach similar to what is now practised on a large scale with thermoplastic polymers, *i.e.*, Fused Deposition Modelling. In our technology, a metallic wire is fed through a nozzle and melted using traditional resistive heating. It then exits the nozzle producing a small meniscus before bonding and solidifying onto the previous deposited layer. This is especially challenging for metallic materials due to their combination of low viscosity, high capillary forces which induce instabilities such as bulging, and their propensity for chemical reaction, in particular with air. To achieve our goal, we explore the benefits of the application of a static magnetic field on the meniscus in order to overcome these issues. It does indeed give rise to visible effects on fluid flow and the development of bulging through the interplay between magnetic field, metal flow and the Seebeck effect, known to generate a current in the vicinity of a solidification front.

The current project state will be presented, with a focus on the influence of the process parameters on the physics of direct melt deposition including mechanisms of defect development or suppression, such as the bulging instability.

Keywords: direct liquid metal deposition, magnetic field, aluminium alloys

*Speaker

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DEDp Additive manufacturing of a TiC-renforced case-hardened steel matrix composite

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Abstract

Bainitic steels exhibit toughness and their resistance to cracking and wear resistance can be improved by case-hardening. The hardened layer must represent 7% (Leroux 2011) of the thickness of the part to achieve good fatigue resistance. However, carbon diffusion is limited to 4 mm as long holding times at elevated temperatures lead to geometrical distortion, reduced mechanical properties and cracking.
The aim of the current work is to use additive manufacturing to induce a deep case hardening in 16NCD13 steel, through the diffusion of carbon in the matrix from TiC reinforcement particles.

(Emamian, Alimardani, and Khajepour 2014) have produced TiC-iron composite coatings for different DEDp parameters and TiC volume ratio. They found that scanning speed, laser power and composition had a significant impact on the microstructure and hardness. (Novichenko et al. 2011; Colin, n. d.; Perminov et al. 2021; Kim, Park and Yun 2014) have investigated the manufacturing of these composites in bulk form. While a surface hardening comparable to case-hardening was obtained, Figure 1. Porosities, inclusions, oxides, and cracks were not sufficiently mastered to justify mechanical testing.
Following such works, preliminary trials were carried out to manufacture massive 3D (16NCD13/TiC)) samples with a reinforcement rate lower than 3.8wt.% with DEDp. The current work presents a process parameter optimization (power, scan speed, mass feed rate) aided with instrumented LMDp (high speed and thermal imaging) to allow optimum densification and surface finish. Microstructural analysis provide a first insight into the relationship between hardness and local heating cycles induced by the process.

Keywords: Additive Manufacturing, Laser, Microstructures, Metal Matrix Composites

*Speaker

Thermodynamics of non-equilibrium growing interfaces - Solidification modelling in multicomponent alloys of interest for AM applications

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Abstract

A thermodynamic description of non-equilibrium interfaces behaviour is proposed, dedicated to the investigation of rapid solidification in metallic alloys. The model, called PDM (Partial Drag Model), is applied to investigate phase transformations in multicomponent alloys used in additive manufacturing processes. The solute drag and solute trapping stages are gathered in a unique approach to follow phases evolution.

The model is thus based on the hypothesis of a growing interface developing at an effective composition weighted between the parent and growing phases. The principle of energy dissipation at the interface leads to consider: 1) the advancement of the interface to this effective composition by adsorption effect, 2) the return of the interfacial composition to the composition of the growing phase by solute rejection in the parent phase. This principle, and the associated equations, lead to linking the compositions and differences in chemical potentials to the interface velocity and alloy properties. The model is coupled with the CALPHAD method and calls to the Thermo-Calc software to determine thermodynamic properties.

In its application, the PDM model predicts changes in interfacial compositions with respect to equilibrium values. By exploiting the properties of some multicomponent systems of industrial interest and within the framework of additive manufacturing processes, these deviations are made visible. A presentation of the model will be made and comparisons with approaches previously reported in the literature are proposed. Methodologies will also be investigated to facilitate the exploitation of the diagram, considering analytical expressions of partition coefficients and liquidus slopes.

Keywords: Multicomponent alloys, rapid solidification, thermodynamic coupling, interface diffusion

*Speaker

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Designing a wear-resistant tool steel for laser powder bed fusion

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Abstract

Despite high demand for high-carbon steels for tooling applications, the processability of available powders on the market via laser powder bed fusion (LPBF) is still limited, because pre-heating of the substrate is still required. During LPBF, which is a widely used metal additive manufacturing technology, feedstock is exposed to a repetitive series of rapid melting immediately followed by solidification at ultrahigh cooling rates. The process of building-up layers causes non-uniform cooling conditions, whereby the heat is almost entirely extracted through the already solidified material which then also experiences a short-term heat-treatment. As a consequence, large temperature gradients and thermal residual stresses evolve in the solidified part. This behavior can be further complicated by alloy-dependent solid phase transformations, such as the austenite-to-martensite transformation for high-carbon tool steels. Pre-heating the base-plate is not striven by industry to mitigate evolving residual stresses. Therefore, we demonstrate the development of a novel high-carbon steel that can better withstand the harsh processing conditions and is hence adapted to LPBF.
Here, we present a high-carbon alloy developed for LPBF which can be processed without additional base plate pre-heating. An in-depth characterization allows to further explore the hierarchical microstructure showing a cellular sub-structure and nanoscale carbide network. In addition to mechanical properties, the abrasive wear behavior of the LPBF-fabricated components is studied and the appendant underlying mechanisms revealed. The mechanical and wear properties are compared to the commercially available 1.2379 tool steel (X155CrVMo12-1) which serves as reference.
(K. Kosiba et al., J. Mater. Sci. Technol. 156 (2023) 1–19)

Keywords: Additive manufacturing, Laser powder bed fusion, Steel, Abrasive wear, TRIP

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A Novel Approach to Produce Metal-Metal Composites by Leveraging Immiscibility: Laser Powder Bed Fusion of Nano-Silver Dispersed Titanium

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Abstract

The antimicrobial properties of silver ions are well known and effectively utilized in biomedical applications. Their efficacy heavily relies on the oxidizing surface area, thus favoring nano-sized silver features due to their increased specific surface area. However, the production of such structures by e.g., coating processes poses significant challenges. Consequently, the direct incorporation of nano-sized silver into biomedical, prospectively filigree components with high surface area to volume ratios, represents an innovative approach. In the presented study, the metastable liquid miscibility gap between titanium and silver combined with rapid solidification is exploited to form silver islands within a pure titanium matrix, resulting in the fabrication of dense titanium-silver nanocomposite material. Pulsed Laser Ablation in Liquid (PLAL) is used for the synthesis of silver nanoparticles achieving an average particle size of 17 nm. Composite powder material with varied silver content is created by a light milling process, leading to a stable combination of both ingredients. Laser Powder Bed Fusion (PBF-LB/M) results in homogeneously distributed silver islands sized 0.01-0.02 μm^2. The hardness of the material is increased by up to 30 % with silver addition and the microstructure is considerably refined, transitioning from predominantly columnar to almost equiaxed grains. With increasing silver content of up to 1 at.-%, the microbial adhesion to the sample surface is decreased by up to 70%. Current investigations are focusing on an in-depth study of the antimicrobial effect and corrosion resistance as well as on transferring the successful approach to functional medical alloys.

Keywords: Titanium, Silver, Composite, Immiscibility, Laser Powder Bed Fusion (PBF LB/M), Nanoscale

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Fracture behaviour of a Ni-20 wt.%Cr binary alloy produced by Laser Powder Bed Fusion: Influence of the sample orientation and rotation angle between layers

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Abstract

The fracture behaviour of alloys has been studied for decades to prevent unexpected failure. However the complex microstructures resulting from Additive Manufacturing (AM) processes limits the application of current knowledge to AM materials. A brief litterature review shows a significant influence of the manufacturing parameters on the fracture behavior of widely used AM alloys. This research focuses on the fracture behaviour of a Ni-20 wt.%Cr alloy produced by Laser Powder Bed Fusion. The sample orientation with respect to the building direction (horizontal or vertical) and the rotation angle between layers (67◦ or 90◦) are investigated. Cast material is studied to account for conventional manufacturing methods. Three-point bending tests are conducted in accordance with test standard ISO-12135. A comparison of fracture toughness and tearing modulus is done between the manufacturing configurations to assess the differences in crack initiation and propagation respectively. Post-mortem microstructural observations of the crack path are conducted at meso, micro and sub-micro scales to identify the mechanisms ruling the fracture behavior. Results indicate that crack initiation occurs for the same range of fracture toughness values for all L-PBF specimens, which is much lower than for cast specimens. Once a crack is initiated, cast specimens exhibit a significantly higher resistance to crack propagation than L-PBF specimens. Regarding L-PBF specimens, a rotation angle of 90◦ improves the resistance to crack propagation whereas only a slight improvement is noted for a vertical orientation rather than a horizontal one. Microstructure observations highlighted the sub-microscale as the most influential to the crack propagation.

Keywords: Fracture toughness, Additive manufacturing, Laser Powder Bed Fusion, Nickel alloys

*Speaker

Microstructure control of additively manufactured Ni-based superalloy for improvement of high temperature ductility

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Abstract

One of the major issues in the application of additive manufacturing to Ni-based high strength alloys is the compatibility of material strength and ductility at high temperature. In particular, the high temperature creep properties of additively manufactured Ni-based superalloys are likely to cause problems. The effect of the microstructure on the high temperature strength properties of the alloys formed by the SLM process was investigated. In the SLM process, solidification progresses extremely fast, so very fine crystal grains are formed. In addition, due to the large temperature gradient and the high solidification rate, very fine columnar crystal grains are formed with strong anisotropy. Since the microstructure is formed by rapid solidification in building process, the form of precipitates is also very different from that of conventional alloys. In this research, the effect of microstructural features, such as grain shape and distribution of precipitates, on high temperature strength and ductility was investigated for Ni-base alloys similar to IN 939. In order to improve the high-temperature strength properties, the change of the fine grains was tried. The adjustment of the precipitation behavior based on the phase equilibrium calculation results was carried out. The high temperature strength properties of the additively manufactured alloy were improved through the microstructure control.

Keywords: additively manufactured Nickel based superalloys, selective laser melting, high temperature mechanical strength

*Speaker

Microstructural modification of LPBF-processed high manganese steel by laser parameter alternation

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Abstract

The presented study investigates the influence of laser-based process parameters on the character of microstructure in high manganese steel X30Mn22 fabricated by laser powder bed fusion. Several studies have already shown that the local thermal gradient modification achieved by processing parameter alternation can lead to distinctively different microstructures. This study aimed to utilize this phenomenon as a design tool for obtaining solidification microstructures with various characteristics in terms of crystallographic texture or grain boundary character. Based on the singletrack analysis in a wide range of laser power–laser scanning speed combinations, the optimal parameters have been selected for test cube fabrication and subsequently for tensile specimens. It has been found that significant differences in melt pool shape can be achieved and that such variety is reflected in the character of the as-built microstructure. Depending on the meltpool shape, a fibre structure with fine microstructure or distinct cube texture was achieved. Such variation in microstructural character led to notable differences in elastic moduli indicating various mechanical properties. The results of this study suggest a viable possibility to intentionally modify microstructure with the goal of altering the elastic and plastic behaviour of fabricated material.

Keywords: LPBF, SLM, Laser Powder Bed Fusion, Selective Laser melting, texture, microstructure, HiMnS, high manganese steel

*Speaker

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

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Abstract

The pinnacle of Additive Manufacturing is to manipulate microstructures to create functionally graded mechanical properties. Metastable austenitic steels shine new light on this pathway. Here, a hierarchical and correlative Synchrotron X-ray imaging approach is adopted to establish a well-rounded picture of the material behavior in situ. The approach starts with high-speed synchrotron radiography, which enables both real and, reciprocal space quantification of the laser-matter interaction, including phase evolution during the build process. 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 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.

Keywords: X, ray imaging, Phase transformation

*Speaker

Controlling Crystallisation in an Additively Manufactured Fe-Based Soft Magnetic Metallic Glass

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Abstract

Laser powder bed fusion (L-PBF) can achieve suitably high local cooling rates for amorphous parts; however, the iterative process can lead to crystallisation induced by thermal cycles as subsequent layers are processed. Parameters that process dense, pore-free parts tend to increase crystallinity. Fe-based BMGs are intrinsically brittle, with (micro-)cracks from thermal stresses limiting the available parameter window.

This study used KUAMET 6B2 commercial powder, displaying very low coercivities whilst maintaining a high saturation magnetisation and relative permeability. Experiments were carried out on a multi beam ACONITY MIDI+ with three continuous, gaussian lasers. A parameter optimisation study was first performed to search for a compromise between amorphicity, density and integrity. The amorphous powder cross sections were analysed and subsequent microstructural evolution from different local thermal histories after L-PBF processing were examined. The processing parameters investigated were laser power, scan speed, substrate temperature (up to 500∘C), layer thickness and hatch spacing, with an oxygen content below 600ppm. The ACONITY multi-laser system and CLI+ file format allowed for temperature histories from bespoke scanning strategies to be investigated. SEM and EBSD imaging techniques were employed for density and amorphicity analysis, complimented by XRD.

This study showed that crystallisation during L-PBF predominantly occurs in the HAZ at melt pool boundaries. Therefore, the crystalline areas of a part can be controlled by varying the processing parameters and scanning strategy. Future work will include magnetic characterisation investigating the effect of different semi-amorphous microstructures on soft magnetic performance.

Keywords: Bulk metallic glass (BMG), LPBF, Crystallisation, Soft Magnetic, Metal Additive Manufacturing

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Advanced Processing of High Entropy Alloys

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Abstract

The quest for superior materials has led to the exploration of High Entropy Alloys (HEAs), characterized by their unique composition comprising multiple principal elements. Inspired by the concept of increasing configurational entropy to stabilize single-phase alloys, this research explores computational thermodynamics-guided alloy design and phase stability at elevated temperatures, crucial for maintaining desired properties.
This study investigates the design and manufacturing of complex concentrated alloys for the fabrication by beam-based additive manufacturing technologies with a focus on enhancing phase stability at high temperatures. Employing alloy screening procedures and computational models available in the literature, promising candidates with superior properties are identified. Addressing challenges like segregation and coarse grain formation during solidification in arc and laser melting, metastable phase transformations within HEAs are exploited to refine grain structures without requiring extensive post-processing. The research also sheds light on the solidification fundamentals of HEAs, offering insights into their behaviour across various temperature regimes and cooling rates.
Overall, this interdisciplinary approach combines computational modelling, alloy design strategies and advanced manufacturing techniques to push the boundaries of HEAs, contributing to the development of additive manufacturing technologies and paving the way for improved mechanical properties in extreme environments.

Keywords: HEA, laser processing, additive manufacturing, alloy design, CALPHAD

*Speaker

Testing the state-of-the-art LPBF structures for mitigation of Eddy current losses in ferromagnetic cores

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Abstract

Soft ferromagnetic cores for electrical machines are usually made of thin sheet stacking, with insulator interlayers. This structure permits to decrease drastically Eddy current losses and to allow high frequency operation. Drawbacks of this cores are (i) the number of steps in the process flow and (ii) limitation in the material selection due to low ductility. Laser Powder Bed Fusion (LPBF) is a promising approach to achieve in one step core with a high versatility in the material choice. Recently, new works proposed 3D structures to reduce Eddy current losses resulted in high magnetic performances. Among the variety of works, we objectively selected, tested, computed, and compared performances of structures based on slits (Andreiev *et al*, 2021), on Hilbert curve (Plotowski *et al*, 2020) and on topological optimized structures (Manninen *et al*, 2022). The three cores were made in FeCoV alloy, and a solid sample reference was built. Thermal annealing was performed to allow grain growth and reduction of parasite iron oxide to increase permeability and magnetic performances. Testing and modelling were conducted on a large range of frequency (1Hz – 500Hz) and magnetic excitation (0 – 6kA/m).

Keywords: LPBF, Ferromagnetic, Eddy current losses, 3D

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Modelling the microsegregation process in rapid solidification – Application to the IN718 alloy of aeronautical interest

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Abstract

Laser powder bed fusion (L–PBF) is considered a particularly promising process in the aerospace industry for developing new engine components. However, the reliability and durability of the elements produced by this process depend on the possibility to prevent the appearance of any defect during the production step, in particular, those linked to hot cracking. The latter are due to the liquid film persisting between the grains, at the end of the solidification stage, in a medium that is still partially mushy and undergoing high stresses and deformations. To estimate the risk of occurrence of this hot cracking mechanism in the L–PBF process, an adapted microsegregation model, providing a prediction of the solidification path, is necessary, coupled with a thermomechanical analysis of the evolution of the alloys. In response to this industrial need, a new model is proposed and applied in the cooling conditions encountered in L–PBF process. This approach integrates the initial solidification conditions and follows phases fraction evolutions, as well as their composition, in the region of the interdendritic fluid, leading to an estimate of the weakening range. The dendritic growth model integrates the kinetic effect to compute interfacial compositions, linked to non-equilibrium interfacial growth. The cross-diffusion of solute species in the liquid phase is considered, as well as the thermodynamic coupling with the CALPHAD approach. The model is applied to the nickel-based superalloy Inconel IN718, widely used in the aeronautical industry. The results are discussed regarding their evolution compared to usual solidification path models.

Keywords: Microsegregation modelling, solidification path, rapid solidification, thermodynamic coupling

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The effect of scanning strategies on the microstructure of 316L stainless steel processed by electron beam powder bed fusion

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Abstract

In the electron beam powder bed fusion additive manufacturing, the impact of process variables such as beam power, beam speed, hatch spacing, beam offset etc. are well understood and documented for a number of material systems. However, due to the lack of open architecture, beam scan strategies are mostly predefined in the user interface with very few parameters that the user can define for a customized process. In this study, the movement of the electron beam in Freemelt One® is fully customized to implement eight different scanning strategies during the processing of 316L stainless steel. These are broadly categorized in the following four groups: linear, concentric, spiral, and spot. The aim is to investigate the possibility of generating localized microstructure under different solidification conditions as a result of these different scanning strategies. As the material is processed at a constant high temperature, it is hypothesized that the effect of the residual stress on static mechanical properties will be insignificant. However, the microstructure and grain boundary segregation are expected to have significant impact on the internal structures, dislocation networks, and hence, part properties at mesoscale. As a proof of concept, an impeller will be used as a case study where the effect of microstructural variance will be examined with respect to the mechanical loading on the impeller.

Keywords: Electron beam powder bed fusion, scan strategy, microstructure, 316L stainless steel

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New Additive Manufacturing concept to develop bimaterials with optimal magnetic losses

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Abstract

Additive Manufacturing, implementing processes such as LPBF (Laser Powder Bed Fusion) and DMD (Direct Metal Deposition) attracts attention to overcome some limitation on the design for soft ferromagnetic cores (Gianotta et al, 2023). The ferromagnetic layers could be less than 0.3mm thick and, very particular microstructures are obtained thanks to the high solidification speeds of these processes. Increasing the Si content is possible to maximize magnetic properties while maintaining characteristics mechanics adapted to the final application. Indeed, a feasibility study of the implementation of massive components in iron alloys with a high Si content by LPBF was carried out as part of a previous thesis (M. ZAIED, 2022) to get around the ductility limits of these materials. The frequency losses were found to be higher than those of commercially insulated laminated sheets due to Eddy currents. Mitigating these losses has become one of the main challenges for the massive soft magnetic components. AM could allow the production of laminated components alternating ferromagnetic and insulating layers for Eddy current mitigation, knows as Soft Magnetic Composites (SMC). Our work is focused on the fabrication of SMCs and development of a bimaterial setup in a standard LPBF machine by alternate ferromagnetic layers and ceramic layers. In this perspective, we have developed a homemade laboratory assembly allowing the development of bimaterials or even multimaterials. Our setup is a mixed of DMD and LPBF previously mentioned, to take advantage of both technologies.

Keywords: Additive Manufacturing, bimaterials, multimaterials

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In-process alloying of stainless steels using Dual Wire Arc Additive Manufacturing - Implications for single-strand geometry, deformations and residual stresses

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Abstract

Additive manufacturing processes impose high temperature gradients on the material during part production, resulting in unwanted distortion and residual stresses. In order to minimise these problems, we propose the in-process mixing of two different grades of stainless steel (including austenic 304L, ferritic 430 and martensitic 415) in various proportions using the Dual Wire Arc Additive Manufacturing (D-WAAM) process. 1D to 3D structures were produced using either different proportions of these alloys or different architectural structures. Firstly, the effect of the mixture on the geometric representation of single tracks was analysed. This allowed us to develop both a hybrid model with an analytical representation of the deposit geometry and finite element simulations of the induced temperature field, residual strain and stress. This thermo-mechanical modelling has enabled a successful simulation-experiment comparison of the induced residual strain and stress, in case of the deposition of 304L single track on 304L and complemented by metallurgical aspects for the simulation of 415 single track on 304L baseplate. In particular, it is shown that it is possible to simulate the curvature inversion of the structure under the effect of martensitic transformation during cooling. Secondly, a 3D structure consisting of multi-pass welds of a chamfered structure with different architecture strategies has been built. Microstructural observations, residual strain (by laser profilometry) and stress (by contour method and neutron diffraction) are discussed.

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Keywords: Wire Arc Additive Manufacturing, Dual wire, In, situ alloying, Residual Stress, Stainless Steel, Strain, simulation, hybrid modelling, FEM

3D FEM mesoscale simulations of laser powder-bed fusion of a Zr-based bulk metallic glass

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Abstract

Bulk Metallic Glass (BMG) parts produced by conventional methods are limited in size as high cooling rates are needed to avoid crystallization leading to detrimental mechanical properties. The Laser Powder-Bed Fusion (LPBF) process can be an answer to this problem as the interaction between the laser and the powder is short and confined to a small volume. However, controlling the production of amorphous parts with this technique remains a challenge for most BMGs, and a full understanding of the occurrence of crystallization is missing. In this study, a dedicated 3D Finite Element Modeling (FEM) code, Stratus, is coupled to a Johnson-Mehl-Avrami-Kolmogorov (JMAK) model using data of a TTT diagram measured by FDSC on the exact same Zr-based bulk metallic glass powder that has been printed. This way, not only quantitative crystallization can be predicted, but crystallization can also be positioned in the volume of the samples. The crystallization fractions, measured on printed parts by DSC, range from 73% to almost 0%, and include effects of printing with different machines, beam size change and delay times between scanning lines, to account for various scanning strategies.

Keywords: Laser Powder Bed Fusion (LPBF), Bulk Metallic Glass (BMG), crystallization, Finite Element Modeling (FEM)

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Microstructure Evolution of LPBF Produced Medium Manganese Steel

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Abstract

Steels are known to exhibit the typical strength-formability discrepancy, i.e. either strong and hard or vice-versa. The manganese-containing steels can be counted as an exception with their combination of high tensile strength and elongation at break. The different manganese-containing steels have in common that manganese is substitutionally dissolved in iron and the manganese content is used specifically to stabilize the austenite phase at room temperature. With medium manganese contents , the austenite phase is only partially stabilized, leading to a multiphase structure consisting of austenite, ferrite and/or martensite.
Laser-based additive manufacturing (AM) processes have become increasingly important technology for the production of complex components, such as lattice structures made from a wide variety of metallic alloys. Although it was the focus of many studies before, MMnSs were not investigated for AM route. The cyclic heat input makes it possible to specifically influence the microstructure, texture, phase distribution and phase stability and adjust the mechanical properties. Therefore, a profound understanding of the fundamental relationships in high-performance materials is imperative for exploring the potential of additive manufacturing, both the metallurgical as well as the technological aspects the microstructure development.
This presentation aims to demonstrate the characteristics of the phase evolution of MMnS samples that were produced with 3 different scanning speeds via LPBF method. To identify individual austenite stabilization effects (primary and retained austenite content, distribution, grain size and element segregation); a fundamental material-physical knowledge of the solidification and microstructure development through a combination of experimental investigations and computer-aided simulation methods was developed.

Keywords: Medium Manganese Steel, LPBF, Austenite Stability, Phase evolution, Numerical Methods, Simulation

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Changes in the morphology and chemistry of an oxidation-sensitive β-Ti alloy powder during the processing steps of additive manufacturing

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Abstract

Additive manufacturing (AM) by powder bed fusion (PBF) is a state-of-the-art method for processing titanium-based alloys. Especially challenging is the materials' inherent oxygen affinity. β-Ti alloys provide, dependent on composition and manufacturing, a versatile property profile and are of increasing interest as structural materials since AM eases their production. Simultaneously, the significance of reusability and powder recycling grows, particularly in the context of scarce and valuable elements. Therefore, this study investigates in detail how a gas atomized Ti-35.5Nb-2Ta-3Zr alloy powder undergoes chemical and morphological transformations during laser (PBF-LB) and electron beam (PBF-EB) powder bed fusion. Several ancillary processing steps are considered, e.g., sieving, milling and sintering. The surface and bulk chemistry of powder samples are studied, as well as their morphology and microstructure, and related to the microstructure of printed parts. For this purpose, advanced analytical methods such as X-ray photoelectron spectroscopy (XPS) and high-resolution scanning electron microscopy (SEM) are used. The results show transferable and exciting correlations, especially with regard to the oxidation and deformation behavior of powders, and represent a piece in the puzzle of sustainable AM.

Keywords: titanium, oxidation, chemistry, powder, microstructure, sustainability

*Speaker

Hybrid Material Extrusion Additive Manufacturing Process

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Abstract

Recently, hybrid processes that amalgamate different individual manufacturing techniques have gained considerable attention, especially the ones that incorporate additive manufacturing and conventional processes. In this study, a hybrid manufacturing procedure was developed within the metal material extrusion (MEX) additive manufacturing (AM) process. This research work aims to assess the feasibility of linking a geometrically complex MEX-ed part (e.g. turbine rotor) with a conventionally fabricated piece (e.g. turbine axe). Therefore, several 17-4PH stainless steel specimens were printed and thermos-chemically debinded. After that, a conventionally manufactured part made up of the same material was placed inside 3d printed part and subsequently, the pieces were sintered. Dimensional measurements and tensile tests were conducted on the fabricated parts. The results demonstrate a repeatability in the tensile behavior. This hybrid process is promising for creating intricate parts and robust characterization at low cost and material waste.

Keywords: Hybrid processes, Metal material extrusion, Additive manufacturing, Conventional manufacturing, 17_4PH

*Speaker

Enabling Real-time Characterization of Laser-based Additive Manufacturing through Operando Techniques

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Abstract

Over the past decade, operando synchrotron X-ray diffraction and imaging techniques have emerged as powerful tools for studying rapid transient phenomena within and around the melt pool during laser-based additive manufacturing processes. These measurements necessitate specialized sample environments that are compatible with synchrotron beam lines while closely mimicking the conditions found in industrial additive manufacturing devices. This presentation showcases the approach undertaken at the Paul Scherrer Institute to address this challenge. Several miniaturized devices have been successfully developed to enable operando laser-powder bed fusion experiments, seamlessly integrating with synchrotron X-ray diffraction/imaging, X-ray tomography, and neutron diffraction/imaging. These systems offer real-time insights into the complex dynamics of additive manufacturing processes at the microstructural level. This work presents the design and implementation of these miniaturized devices and highlights their capabilities. Furthermore, their utility in capturing key transient phenomena is demonstrated. Specifically, operando X-ray diffraction is shown to track phase transformations and thermal history in various alloys and multi-materials. Fast X-ray radiography allows tracking the formation of defects, melt pool evolution, and chemical mixing at the interface of multimaterials. Furthermore, it provides ground truths for interpreting signals of real-time sensors. In situ polarized neutron imaging is used to follow the evolution of magnetic phases. Finally it is shown how these experimental observations provide valuable data for validating computational simulations and models.

Keywords: X, ray, Neutron, Diffraction, Imaging, Operando, Laser powder bed fusion

*Speaker

The effect of dislocation cell structures on phase transformations of metastable 304L steel processed by laser powder bed fusion

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Abstract

The specific microstructure of materials processed by laser powder bed fusion (LPBF) method significantly impacts deformation behavior. For instance, dislocation cell structure, chemical segregation, and the presence of precipitates strongly affect corresponding deformation mechanisms. The effect of such microstructural features is amplified in the case of metastable austenitic stainless steels, a material class susceptible to phase transformation upon external loading. The present study examines the effect of the specific LPBF-processed microstructure on the deformation-induced phase transformation. A highly metastable variant of 304L steel in as-built and heat-treated conditions was subjected to a series of straining experiments utilizing in-situ neutron diffraction and feritscope measurements to follow phase evolution. The study is further supported by microstructural post-mortem electron microscopy observations. It was found that the characteristic as-built microstructure accelerates deformation-induced phase transformation at the early stages of straining and also increases the final volume fraction of deformation-induced martensite phase. The specific microstructure originating from the LPBF process fundamentally affects the deformation-induced phase transformation and the results indicate that the alloy metastability can be tailored by heat treatment.

Keywords: laser powder bed fusion, deformation induced martensite, austenitic stainless steel

*Speaker

Silicon mediated twin formation in laser direct energy deposited 316L stainless steel

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Abstract

316L stainless steel (316L) with 0.73wt% Si and 2.2wt% Si were fabricated using laser direct energy deposition (L-DED). A stark difference is found in the density of $\sum 3$ twins in the microstructures of the two materials. Specifically, 316L with 2.2wt% Si exhibits a remarkably high percentage (23%) of $\sum 3$ twin boundaries whereas 316L with 0.73wt% Si shows very low levels (less than 3%) of these boundaries. In this work, we aim to understand the origin of this difference.

EBSD analysis of 316L with 2.2wt% Si reveals that a few twin-related domains (TRDs) are attributed to icosahedral short-range order mediated nucleation due to observation of grain clusters sharing a fivefold symmetry axis (1). The remaining TRDs are attributed to massive transformation from ferrite to austenite (F/MA solidification mode), which is expected due to a high equivalent chromium to equivalent nickel ratio in this sample (1.73) and a high solidification rate during L-DED fabrication. This is confirmed by the presence of refined grains, absence of solidification cells and jagged boundaries between austenite grains.

This result is surprising because a significant number of twins are formed in L-DED 316L, primarily due to variations in Si content. In this talk, we will demonstrate why and how these mechanisms can occur in L-DED 316L.

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Keywords: Twins, additive manufacturing, stainless steel, ISRO, massive transformation

*Speaker

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Intergranular stress and plastic strain formation during laser scanning of additively manufactured stainless steel: An experimentally-driven thermomechanical simulation study

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Abstract

A novel experiment-driven modelling and simulation approach is proposed to study the formation of intergranular stresses and plastic strains during laser scanning of additively manufactured 316L stainless steel. Recently, laser scanning experiments were performed using a unique coupling between a continuous-wave laser and a scanning electron microscope. These experiments form the basis for the development of a thermo-elasto-viscoplastic polycrystal model endowed with the minimum necessary physics of the problem in order to facilitate simulating sufficiently large domains to obtain reasonable stress magnitudes. The case of a single laser line scan performed in vacuum is analyzed in detail. Polar dislocation density magnitudes and distribution predicted from the simulation are compared with those measured experimentally. Results reveal that for 93% of the grains in the lasered zone, a statistical measure of the predicted polar dislocation density (Nye's) tensor lies within a factor of 2 (higher or lower) of the experimental one; this result sets a benchmark for future experiment-simulation comparisons. Subsequent investigation studies the origin of the local residual stresses and plastic strains. On the lasered surface, the grain surface-averaged normal residual stress component and plastic strain component along the scan direction are _˜1.7 GPa and 0.04, respectively. The contribution of elastic anisotropy, plastic heterogeneity and strengthening due to microstructure refinement after laser scanning on the formation of stresses and plastic strains is studied. The results of this study will be presented.

*Speaker

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Keywords: Residual stresses, Crystal plasticity, Dislocations, Finite elements, Modelling

Metal additive manufacturing: insights into controlling microstructure, defects and properties

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Abstract

The extremely high cooling rates associated with additive manufacturing create opportunities and challenges. For example, the short solidification times mean that the microstructure is highly refined but at the same time it is difficult to achieve a fine grain size and columnar grains are typically formed. The small melt pools limit macrosegregation but cracking can be a problem in some alloys due to the high thermal gradients. This talk focuses on development of our understanding of how to engineer alloys with relatively refined homogeneous microstructures. Our work has shown that a fine equiaxed grain structure can be achieved in Ti alloys through the addition of transition metals such as Cu and Fe. The presence of the eutectoid transformation is also crucial to the scale of the grain size. Some aluminium and nickel alloys tend to hot tear, or solidification crack. Controlling the final stages of solidification to limit the solidification range using indices such as Kou and Easton often solves this problem, although there are examples where such an approach is not successful particularly when there is a substantial intermetallic network. Finally, the solidification path of the alloys in multi-material systems can affect the presence and morphology of cracks that are observed.

Keywords: Solidification, multimaterial systems, hot tearing, macrosegregation, eutectoid

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Directed Energy Deposition of titanium alloys for biomedical application

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Abstract

This study is devoted to Directed Energy Deposition (DED) of biomedical Ti-6Al-4V and Ti-6Al-7Nb alloys. The research was conducted at the TAU+ Additive Manufacturing R&D Center at Tel Aviv University. The DED LENS Optomec machine equipped with 2kW laser was used to produce samples from atomized Ti-6Al-4V and Ti-6Al-7Nb powders. The methodology of Design of Experiment (DOE) was used for the process parameters optimization. The optimization is done concerning the selected material characteristic parameters of density and microhardness. The greater cooling rates at the beginning of the DED process, and the decrease of them while moving away from the substrate result in Widmanstätten ($\alpha+\beta$) microstructure in Ti67 samples. All the designed parameter combinations resulted in highly dense samples, with a density above 97% of the theoretical one. The comparative results between these alloys, and samples manufactured by various techniques (including Electron Beam Melting (EBM) and wrought samples) will be presented. The corrosion resistance measurements showed that Ti-6Al-7Nb manufactured via DED has higher corrosion resistance. According to the performed literature survey, the DED manufactured Ti-6Al-7Nb alloy is reported for the first time.

Keywords: Ti6Al7Nb, biomedical alloys, Directed Energy Deposition, DED, additive manufacturing

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Improvement in the mechanical, and electrical properties due to aging of selective laser melted CuNi2SiCr

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Abstract

The utilization of selective laser melting (SLM) allows the fabrication of complex geometry with good dimensional accuracy. However, the SLM of copper alloys is lacking due to its low laser absorption and high thermal conductivity. This limits the application of the SLM in the electrical and electronic industry. Moreover, the CuNi2SiCr has also been investigated for repairing nickel-aluminum bronze marine propellers indicating the feasibility of CuNi2SiCr for mechanical applications. This study focuses on the investigation of mechanical and electrical properties of SLM deposited precipitation hardenable CuNi2SiCr and the effect of heat treatment on the alloy. The heat treatment performed at 450 oC caused the reduction of microstrains and dislocation density while the crystallite size increased. The microstructural changes in the heat-treated sample led to an increase of about 65% in microhardness. Simultaneously, the yield and tensile strength increased by about 88%, and 115%, whereas the elongation was reduced by about 53%. There was no noticeable difference in the texture of the material after heat treatment. The electrical conductivity between room temperature till 300 oC varied between 1.02 × 107 S/m to 0.75 × 10ˆ7 S/m in the printed condition, and between 1.82 × 10ˆ7 S/m to 1.29 × 10ˆ7 S/m for the heat-treated condition. The formation of the nano-sized precipitates during heat treatment is a possible reason for the improved properties.

Keywords: SLM, precipitation hardenable CuNi alloy, aging treatment, mechanical strength, electrical conductivity

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European NUCOBAM project: First L-PBF stainless steel components to meet nuclear safety requirements

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Abstract

The NUCOBAM project aims to develop the qualification process and provide in-service behavior assessment for the use of additive manufacturing (AM) components in a nuclear facility. Once qualified, the use of AM will enable the nuclear industry to address challenges such as component obsolescence by reducing the supply chain and creating new standards to foster the growth of new AM industrial manufacturers. NUCOBAM focused on the Laser Power Bed Fusion process (L-PBF) for alloy 316L and on two demonstrators: a in-core debris filter submitted to radiation and an ex-core valve body under high operating pressure and temperature.
The project first part consists in characterizing the materials manufactured by the L-PBF process in order to establish a qualification and coding methodology. The second part is devoted to the evaluation of the behaviour of AM materials in service. The materials are manufactured and some of them are then post-processed (heat treatment or high isostatic pressure). Results are compared to existing well-known manufacturing processes in nuclear design codes. This work will evaluate and deduce the main parameters required for the specification.
The consortium involves component manufacturers, designers, experts in nuclear risks as well as researchers in mechanical and physical characterization, metal powder qualification from nuclear energy field. Replacing an obsolete component with a new process is a first step, the tomorrow challenges are to manufacture large components, such as those of the primary circuit and to design and optimize the components using the potential of new process to increase efficiency and safety.

Keywords: Nuclear, Additive Manufacturing, Qualification, Codification, Laser Power Bed Fusion process (L, PBF)

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Estimating elastic and thermal contributions from operando X-ray diffraction measurements during additive manufacturing

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Abstract

Lattice strains obtained from operando synchrotron X-ray diffraction (XRD) measurements during metal additive manufacturing (AM) are being increasingly used to estimate temperature evolution during the process. Taking the example of a single-phase material, the lattice strains are only composed of thermal and elastic contributions.

For single-phase materials, temperatures are typically directly estimated from lattice strains by neglecting the contribution of elastic strains, especially in regions where temperatures reach a maximum (underneath the heat source) and thermal strains are typically an order of magnitude larger than elastic strains. However, in the remaining regions, the elastic strain contribution is non-negligible. Overall, decoupling thermal and elastic contributions would not only improve temperature estimates obtained from lattice strains, but also enable stress estimation including in the region where elastic strains are neglected. Meanwhile, even though numerical simulations can be used to predict thermal and elastic strains they do not always perfectly agree with experiments.

This study exploits a fast numerical model of the entire AM process in combination with experimental data to separate thermal and elastic strain estimates such that their sum is exactly equal to the measured lattice strain; thus, these estimates are better than solely numerical predictions. Such a data reconciliation strategy is demonstrated for operando synchrotron X-ray diffraction measurements during directed energy deposition of a 316L stainless steel thin-wall. The fast numerical model is first validated against measured time-resolved lattice strains, and then used in combination with measurements to derive thermal and elastic strain estimates.

Keywords: synchrotron XRD, lattice strain, thermomechanical modelling, direct energy deposition, residual stress

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Intelligentsia of Nano-Architected Hierarchical Materials

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Abstract

Creation of reconfigurable and multi-functional materials can be achieved by incorporating architecture into material design. We design and fabricate three-dimensional (3D) nano-architected materials that can exhibit superior and often tunable thermal, photonic, electrochemical, biochemical, and mechanical properties at extremely low mass densities (lighter than aerogels), which renders them useful and enabling in technological applications. Dominant properties of such meta-materials are driven by their multi-scale hierarchy: from characteristic material microstructure (atoms) to individual constituents (nanometers) to structural components (microns) to overall architectures (millimeters and above). We focus on fabrication, synthesis, and characterization of hierarchical materials using additive manufacturing (AM) techniques, as well as on investigating their mechanical, biochemical, electrochemical, and chemo-mechanical properties as a function of architecture, constituent materials, and microstructural detail. AM represents a set of processes that fabricate complex 3D structures using a layer-by-layer approach, with some advanced methods attaining nanometer resolution and creation of unique, multifunctional materials and shapes derived from a photoinitiation-based polymerization of custom-synthesized resins and thermal post-processing. A type of AM, vat polymerization, has allowed using hydrogels as precursors to produce 3D nano- and micro-architected metals and metal oxides, and exploiting their nano-induced material properties. We describe AM via vat polymerization and function-containing chemical synthesis to create 3D nano- and micro-architected metals, ceramics, multifunctional metal oxides (nano-photonics, photocatalytic, piezoelectric, etc.), and metal-containing polymer complexes, etc., as well as demonstrate their potential in some biomedical, protective, and sensing applications. I will describe how the choice of architecture and material can elicit stimulus-responsive, reconfigurable, and multifunctional response.

Keywords: multi functional materials, vat polymerization, architectured materials, functional properties

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Additive Manufacturing: An Invitation to Revisit the Role of Solutes

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Abstract

Many heritage alloys from casting or forging have been fabricated by additive manufacturing (AM), in particular by laser powder bed fusion (LB-PBF). In addition to the ability of producing sophisticated geometries and reducing tool costs, the out-of-equilibrium processing conditions in LB-PBF can exploit unique microstructure capabilities that can push forward the upper limits of achievable properties. However, traditional alloys such as polycrystalline superalloys strengthened by a large fraction of γ' precipitates or high-strength Al alloys turn

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out to be highly challenging to produce by LB-PBF due to their cracking susceptibility. Thus, over the past few years there has been an increasing research interest in modifying heritage alloys or design new compositions to develop alloys with good processability and excellent properties (equal or better than those achievable by traditional processing routes) while limiting the post-fabrication operations. In this presentation, we will show through a few illustrative examples that metallurgists interested in designing new alloys for AM need to rethink the role of some solutes. Solutes traditionally used in cast or wrought alloys may behave differently under LB-PBF conditions. Solutes with a limited solubility under equilibrium conditions can be efficiently retained in solid solution thanks to solute trapping allowing extended supersaturation and improved precipitation strengthening via direct ageing (no need for solutionizing and quenching). Some solutes usually considered detrimental in cast and wrought products may also be rehabilitated in out-of-equilibrium conditions. These different aspects are illustrated based on investigations recently conducted in our research group in close collaboration with industrial partners.

Keywords: Laser Powder Bed Fusion, Out of equilibrium, Superalloys, Al alloys, Solutes

Utilizing in-situ characterization techniques to probe the heat treatment response and micromechanical performance of LPBF processed and heat-treated Ti-6Al-4V

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Abstract

Ti-6Al-4V is the workhorse among all titanium alloys that are processed by solidification-based AM technologies. Its popularity resides from its interesting combination of quasi-static and dynamic mechanical properties, and its relatively low density, making it a candidate material for lightweight applications.
The structural performance of L-PBF processed Ti-6Al-4V parts, however, is heavily affected by the formation of a martensitic phase during rapid cooling, its partial decomposition during sequential heating and cooling cycles and a macroscopic internal stress distribution within L-PBF processed Ti-6Al-4V parts.

Martensite decomposition and stress relaxation behaviour in L-PBF processed Ti-6Al-4V is investigated using in-situ dilatomettry, allowing to inductively heat a sample while being irradiated by synchrotron X-rays, enabling to simultaneously measure the thermal expansion, phase fraction and internal stress evolution of an LPBF processed Ti-6Al-4V during heating and cooling.

The micromechanical behaviour of as-built and heat-treated two-phase Ti-6Al-4V samples is compared, both in the elastic and plastic regime, based on X-ray synchrotron diffraction spectra recorded during uniaxial tensile loading. The elastic stiffness and plasticity variations in the different hexagonal α and α' phase directions is discussed and compared with numerically predicted critical resolved shear stress values.

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The plastic deformation behaviour, strain localization and fracture onset of bilamellar Ti-6Al-4V, is discussed based on strain fields, obtained by 2D digital image correlation, recorded during uniaxial tensile loading inside a scanning electron microscope.
Generally, recommendations are given on how to heat treat LPBF processed Ti-6Al-4V alloys in order to enhance its quasi-static mechanical performance.

Keywords: LPBF Ti6Al4V, Martensite decomposition, Stress Relaxation, In situ synchrotron X ray diffraction, In situ Digital Image Correlation

Cyclic behaviour and microstructural evolution of metastable austenitic stainless steel 304L produced by laser powder bed fusion

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Abstract

The present study delivers an insight into the cyclic behaviour of LPBF processed austenitic stainless steel 304L and its relation to observed microstructure evolution and strain-induced martensitic transformation. The combination of electron microscopy observations and feritscope measurements enabled to follow dislocation microstructure evolution and the onset of martensite nucleation. The excellent cyclic strength of stainless steel 304L is a direct consequence of cell microstructure containing high dislocation density walls and elemental microsegregation, which effectively inhibit dislocation motion. Cyclic softening was linked with cyclic strain localization into slip bands of decreased dislocation density and heavily altered dislocation cell walls. These bands have been observed for the first time in LPBF processed metals. This microstructural feature seems to be a variant of frequently observed dislocation arrangement, persistent slip bands (PSBs), typically observed in conventionally produced materials. PSBs present the areas of intensive cyclic plasticity where the strain-induced martensitic transformation occurs preferentially. The increasing α'-martensite volume fraction, accompanied by a formation of intermediate ϵ- martensite and deformation twinning, resulted in recorded cyclic hardening. The martensite nucleation sites are strongly determined by the cell microstructure, especially cell walls dislocation density and chemical segregation, which is tightly related to utilized L-PBF process parameters.

Keywords: Fatigue, Laser powder bed fusion, Stainless steel, Strain, induced martensitic transformation, Cyclic behaviour

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