metals

Editorial

Directed Energy Deposition of Metal Alloys

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1. Introduction and Scope

Directed energy deposition (DED) stands as an advancement in material utilization, facilitating the production of highly precise near-net shape components using wire and powders [1–7]. Utilizing wire as a feedstock offers distinct advantages over powder, including a higher deposition rate, reduced porosities in the deposited material, and an improved surface finish. However, this comes with the trade-off of higher heat input. As such, despite its advantages, wire deposition poses inherent challenges in terms of process control.

From a historical context, metal deposition technologies have primarily found application in high-value sectors such as those concerning aerospace, space, and medicine [1]. These industries, which can accommodate the evolving process despite stringent performance and acceptance criteria, have been at the forefront of adopting directed energy deposition techniques. The versatility of this method extends to repairing, remanufacturing, or enhancing semi-finished components via metal deposition. Nevertheless, caution is essential to manage heat input effectively, preventing any compromise in material strength and minimizing distortion.

An inherent challenge in metal deposition lies in the potential anisotropy in mechanical properties due to the layered microstructure and the common presence of residual stresses resulting from steep thermal gradients [8–11]. The thermal histories of metal deposition parts are intricate, contingent on various process variables. The impact of these process parameters on the microstructure is intricate and highly dependent on the specific material system employed. A prevailing concern regarding metal deposition is the inherent difficulty in predicting the properties of components, given the multitude of process variables involved [12–15].

Given this background, this Special Issue on the directed energy deposition of metal alloys aims to provide a dedicated platform for disseminating new findings, sharing perspectives on achievements, and outlining future directions in metal deposition research. Contributions were invited in the form of reviews and original research articles, focusing on metallurgy, process monitoring, control, and other associated topics related to metal deposition. Submissions employing experimental techniques or theoretical calculations to explore the intricacies of metal deposition processes were also particularly welcome.

2. Contributions

Scholars were encouraged to submit novel research papers focusing on "Directed Energy Deposition" and related topics within the realm of specialty alloys. This Special Issue, titled "Directed Energy Deposition of Metal Alloys", comprises a total of nine published research papers, whose contributions are disclosed below. These contributions collectively showcase current research trends in the field, offering valuable insights into the advancements and innovations within the domain of directed energy deposition and specialty alloys.

Suhas Sreekanth et al., contribution 1, researched the influence of laser power, scanning speed, and laser stand-off distance on the geometry, microstructure, and texture of DED single-track specimens. The following observations were made:

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1. The height of the deposits decreased with increased scanning speeds.
2. Stand-off distance had no influence on the height of the deposits.
3. The width increased with increased laser power and stand-off distance but decreased with increased scanning speeds.
4. The depth of the deposit increased with increased laser power and decreased with an increase in stand-off distance.
5. The area of dilution increased with increased specific energy.
6. Powder capture efficiency increased with the production of specific energy and variation in spot diameter size, minutely increasing with increased stand-off distance.

A single-track deposit displayed three distinct regions formed by varied cooling rates. The dominant segregation of Nb-rich phases occurred in the top region of the deposit in all cases. Specific deposits, associated with moderate specific energy conditions, effectively controlled segregation, showing Nb-rich phase fractions of less than 4% in the middle and bottom regions and under 6% in the top region. Scanning speed significantly decreased the area fraction of Nb-rich phases. Higher stand-off distances also hinted at a reduction in segregation. Columnar grains dominated all deposits, with a narrow region of equiaxed grains at the top. Deposits with better aspect ratios confined equiaxed grains to a minute region at the top. Varying energy conditions led to different morphologies and orientations, with the preferred growth direction for columnar grains being <100>. Centerline solidification was noted in grains with <110> and <111> orientations due to their high dilution rate, with interaction angles of nearly 45°. Dilution was influenced by specific energy, impacting the texture morphology affected by power, speed, and stand-off distances. Moderate to high powers (P = 1800 and 2000 W), high speed (V = 1100 mm/min), and high stand-off distances (Lo = 13 mm) proved influential in achieving favorable geometrical, microstructural, and segregation properties. Consequently, these conditions were deemed more suitable for building multilayered deposits, offering improved characteristics in terms of aspect ratio, dilution, and powder capture efficiency. The segregation of Nb-rich phases at the top of these deposits was minimal, and the equiaxed region at the top was confined.

In contribution 2, Kang-Hyung Kim et al. demonstrated that in thin directed energy deposition (DED) processes, the generation of nanoparticle fumes and extensive agglomerated spatter, collectively referred to as evaporation products, occurs as the base metal is heated to form a melt pool. The prevention of evaporation products involves the careful selection of suitable powder and laser sources, accompanied by fine-tuning various process parameters. To address this issue in thin DED, the following factors were investigated:

1. Concentration of Laser Energy:

To reduce evaporation products, it is imperative to minimize the concentration of needle-like laser energy. Continuous wave lasers, especially those with a top-hat mode and rectangular beam, prove more advantageous compared to pulsed lasers or Gaussian beams.

2. Defocus Effect:

Shifting the laser beam focus through defocusing widens the laser irradiation area, effectively lowering the energy density and mitigating evaporation product formation.

3. Powder Particle Size:

Fumes are easily formed with fine particles smaller than five micrometers. Optimal particle sizes for thin DED fall within the range of 30–45 μm to minimize evaporation products.

4. Powder Composition:

To minimize evaporation products, it is essential to reduce the presence of carbon or boron and other components with low evaporation points. Atomized powders and plasma-atomized carbide powders with smooth surfaces are preferred over sintered powders with porous surfaces due to their lower moisture adsorption and better laser absorption characteristics in the air.

5. Powder Feeding Strategy:

Lowering the laser energy density delivered to the melt pool can be achieved by feeding the powder slightly above the focus, resulting in a thinner bonding zone. Additionally, increasing powder recovery and nozzle scanning velocity contributes to minimizing evaporation products in thin DED processes.

The third contribution by Rafael Pereira Ferreira et al. proposed a novel trajectory strategy, termed Pixel, assessed for wire arc additive manufacturing (WAAM). Unlike a singular solution, this innovative strategy is adaptable to diverse and intricate geometries. Pixel is characterized as a sophisticated multitask procedure for optimized path planning, utilizing computational algorithms (heuristics) with manageable computational resources and acceptable computational time. The procedural approach involves fragmenting model layers into squared grids, within which a set of systematically generated dots is distributed, mimicking pixels on a screen. Trajectory planning is then executed over these distributed dots. The Pixel strategy draws inspiration from the travelling salesman problem (TSP) for creating trajectories. Distinguishing itself from existing algorithms, Pixel employs a customized greedy randomized adaptive search procedure (GRASP) metaheuristic. This is complemented by four concurrent trajectory planning heuristics, uniquely developed by the authors. The interactive process involves generating successive trajectories from randomized initial solutions (global search) and iteratively refining them (local search). Upon completion of recurrent loops, a well-defined trajectory is formulated and translated into machine code. To illustrate the impact of each heuristic on the final trajectory, a comprehensive computational evaluation was implemented. Additionally, an experimental evaluation was conducted, involving two intricate shapes that are challenging to print conventionally. This experimental assessment serves to demonstrate the practical feasibility and efficacy of the proposed Pixel strategy in real-world applications.

Maider Arana et al., contribution 4, demonstrated that porosity levels can be effectively minimized to below 0.035% in area in Al-Mg samples produced through cold metal transfer (CMT)-based wire arc additive manufacturing (WAAM). This achievement was made possible by a meticulous selection of the appropriate shielding gas, gas flow rate, and deposition strategy (hatching or circling). Notably, the utilization of three-phase Ar + O_2 + N_2O mixtures (Stargold®) proved advantageous when employing the hatching deposition strategy, resulting in a wall thickness of approximately 6 mm. On the other hand, the circling strategy, characterized by torch movement with overlapped circles along the welding direction, facilitated uniform layer build-up with slightly thicker thickness (8 mm). In this scenario, the application of Ar shielding gas, with proper flow through the torch, effectively reduced porosity. It was observed that reduced gas flows, especially lower than 30 L/min, heightened porosity, particularly in long tracks (exceeding 90 mm) due to localized heat accumulation. Surprisingly, even under the least favorable conditions leading to relatively high porosity levels (up to 2.86% area), the static tensile test mechanical properties were robust. The mechanical properties achieved included a yield stress exceeding 110 MPa, tensile strength surpassing 270 MPa, and elongation greater than 27%, regardless of the building conditions (Ar circling, Ar hatching, or Stargold® hatching). Significantly, anisotropy levels remained below 11% in all cases, which were further reduced to 9% under the most appropriate shielding conditions. These current findings indicate that, owing to the selected layer height and deposition parameters, there was a complete re-melting of the previous layer, coupled with a thermal treatment on the preceding bottom layer. This thermal treatment refined the grain size, eliminating the original dendritic and elongated structure. Consequently, these conditions facilitated the achievement of minimal reported anisotropy levels.

In contribution number 5, Eloise Eimer et al. revealed that the interface between the substrate and the deposited aluminum material exhibits distinct zones, including a fusion zone, partially melted zone, and heat-affected zone, akin to the interface observed between the parent material and the weld bead in fusion welding. Significantly, the stresses generated during wire arc additive manufacturing (WAAM) are found to be lower compared to conventional welding processes. This characteristic opens the possibility of employing alloys traditionally considered unweldable as a WAAM substrate. The study delved into the influence of both substrate alloys and temper, with the findings underscoring the importance of careful substrate selection when manufacturing a component. The substrate's composition must be compatible with the deposited alloy, particularly if a post-manufacture heat treatment is contemplated. Moreover, the temper of the substrate must align with the intended application, whether heat treatment is administered or not. Using the 2319 alloy as a filler wire, the study revealed challenges in achieving homogeneous hardness across the interface without post-deposition heat treatment. Conversely, the combination involving the 2219 and 2050 substrates demonstrated successful heat treatment, with only the interface between the 2219 substrate and the WAAM material achieving homogeneous hardness. While this combination presents a straightforward option, the potential benefits of employing different alloys for substrates and filler wires warrant further exploration. To optimize performance, substrates should be specifically tailored to suit the WAAM process, mitigating the risk of liquation cracking or drastic property changes. This customization is crucial for adapting to the deposited alloy, preventing hot cracking, and aligning with the heat treatment applied to the deposited material. Future research endeavors should focus on assessing the impact of the interface solidification and diffusion mechanism (ISDM) microstructure on the static and dynamic mechanical behaviors of the joint between WAAM material and the substrate.

Alberta Aversa et al., contribution 6, explored the impact of building parameters on the microstructure and tensile properties of AISI 316L stainless steel samples manufactured via laser powder deposition (LP-DED). Initially, the selection of building parameters commenced with an analysis of single scan tracks to assess their morphology and geometrical features. Subsequently, bulk 316L LP-DED samples were constructed using two sets of parameters, and their characteristics were comprehensively evaluated in terms of porosity, geometrical accuracy, microstructure, and mechanical properties. Tensile test data were subjected to analysis using the Voce model, revealing a correlation between the tensile properties and the dislocation-free path. The findings suggest that porosity alone should not be regarded as the exclusive indicator of the quality of an LP-DED part. Instead, a comprehensive mechanical characterization is essential for a more thorough assessment of the part's quality.

In contribution 7, Felipe Arias-González et al. assessed the feasibility of utilizing laser-directed energy deposition for the production of biomedical alloys, specifically Ti-Nb and Ti-Zr-Nb, derived from elemental powders (Ti, Nb, and Zr). Laser-directed energy deposition is an additive manufacturing process that constructs components by simultaneously delivering energy and material. In this process, material is supplied in the form of particles or wire, and a laser beam is employed to selectively melt and deposit material onto a specified surface, where it solidifies. Samples with various compositions underwent comprehensive characterization, including an analysis of their morphology, microstructure, constituent phases, mechanical properties, corrosion resistance, and cytocompatibility. The laser-deposited Ti-Nb and Ti-Zr-Nb alloys exhibited minimal defects, such as pores or cracks. These titanium alloys demonstrated a lower elastic modulus and significantly higher hardness than Ti grade 2, suggesting improved wear resistance. Furthermore, their corrosion resistance was excellent, attributed to the formation of a stable passive protective oxide film on the material's surface. Additionally, these alloys exhibited outstanding cytocompatibility.

Pedro Ramiro et al., contribution 8, studied the impact of heat treatment, as per the Aerospace Materials Specifications (AMS) for cast and wrought Inconel 718, on the microstructure and hardness of both the deposited geometry and substrate of Ni-based alloy 718. The analysis was conducted across various sections of geometry. The microstructure of all samples, including both as deposited and heat-treated specimens, was scrutinized using a scanning electron microscope (SEM) and energy-dispersive spectrometer (EDS). The analysis confirmed the presence of aluminum oxides, titanium nitrides, and carbonitrides in the deposited structure.

In the last contribution (9), Mats Högström et al. developed a methodology for constructing MC-CCT (multiple cycle continuous cooling transformation) diagrams for wire arc additive manufacturing (WAAM) through the integration of physical and numerical simulations. A high-strength low-alloy steel (HSLA) feedstock, comprising a wire and shielding gas, was employed as a case study. In order to maintain the representativeness of the CCT, the multiple thermal cycles typical for additive manufacturing thin walls were identified and replicated in physical simulations using Gleeble dilatometry. The start and end transformations for each thermal cycle were determined through the differential linear variation approach. Microstructure analyses and hardness assessments were conducted to characterize the product after undergoing multiple cycles. Simultaneously, the same CCT diagram was generated using a commercial numerical simulation package to ascertain the shape of the transformation curves. A range of austenitic grain sizes was explored to identify the curve position aligning with the experimental results. The combination of experimental data and numerically simulated curves facilitated the estimation of the final CCT diagram.

3. Conclusions

This Special Issue, titled "Directed Energy Deposition of Metal Alloys", presents a compilation of research articles exploring key topics in the field. As the Guest Editor, the aim is to provide a valuable resource for researchers, fostering more studies and discussions in order to enhance the understanding of the additive manufacturing performance in metals. Thus, this Special Issue focuses on "Directed Energy Deposition", with nine research papers covering various aspects of specialty alloys. Key contributions include investigations into laser power, scanning speed, and laser stand-off distance affecting geometry and microstructure; a novel trajectory strategy for wire arc additive manufacturing; optimization strategies for minimizing porosity in Al-Mg samples; interface analysis between substrate and deposited material; the exploration of building parameters for AISI 316L stainless steel; and the application of laser-directed energy deposition for biomedical alloys. The findings of these contributions demonstrate advancements in the field, providing insights into innovative techniques, material properties, and manufacturing processes.

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Conflicts of Interest: The author declares no conflicts of interest.

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