DIRECT ENERGY DEPOSITION

DEFECTS AND THEIR TREATMENTS

Aditya Kumar, Priyanshu Rao, Rajeev Kumar | ME549 – Additive Manufacturing | 05 Oct, 2024

A subset of additive manufacturing (AM) techniques known as directed energy deposition (DED) involves delivering a powdered or wired feedstock material to a substrate that is simultaneously focused by an energy source like an electron beam, laser beam, or plasma/electric arc. This creates a tiny melt pool and continuously deposits material, layer by layer.

Contents:

1. Abstract

Directed Energy Deposition (DED) is a versatile additive manufacturing technique known for its capability to build, repair, and customize complex, high-performance components. Utilizing focused energy sources such as lasers or electron beams, DED melts feedstock materials layer-by-layer, allowing precise control over deposition in applications that range from aerospace and defense to biomedical and automotive sectors. Despite its advantages, DED faces significant challenges that hinder its adoption, particularly in the control of thermal gradients, residual stresses, and microstructural defects, which can compromise mechanical integrity, dimensional accuracy, and surface finish. Additionally, high energy consumption, material wastage, and limited feedstock compatibility present ongoing barriers to DED efficiency and cost-effectiveness.

This paper proposes a series of innovative solutions to address these challenges, combining advanced in-situ monitoring, adaptive control systems, and data-driven optimization. Key contributions include a novel real-time feedback system that adjusts deposition parameters dynamically, minimizing porosity, cracking, and anisotropy within the built structures. We explore machine learning models integrated into DED control systems to predict defect formation and optimize energy distribution, improving overall build quality while reducing material and energy consumption. Additionally, this research presents new alloy compositions and hybrid feedstock solutions that enhance compatibility across multi-material and high-performance applications, expanding the range of feasible materials for DED. Through extensive experimental validation and computational modeling, our work demonstrates improved microstructural uniformity, reduced residual stress, and enhanced process stability.

The solutions outlined in this paper aim to transform DED from a promising manufacturing approach to a reliable, high-precision technology capable of producing components with superior mechanical properties and tailored functionalities. By addressing the fundamental challenges and proposing practical, scalable solutions, this research contributes to the broader adoption of DED in critical industries, advancing the field of additive manufacturing and paving the way for new applications in complex, high-stakes environments.

2. Introduction

High-value metallic components can be produced, repaired, and refurbished using Directed Energy Deposition (DED), a well-known additive manufacturing (AM) technology. By melting a feedstock material, either in wire or powder form, using a high-energy heat source like a laser, electron beam, or plasma arc, DED constructs structures layer by layer in contrast to traditional manufacturing procedures that subtract material to generate a product. Because it can handle a variety of materials, such as high-performance alloys, ceramics, and composites, and because it can create complex, near-net shape geometries, this technique has attracted a lot of interest.

DED was first created for quick prototyping, but it has now expanded into a flexible instrument with a broad range of industrial uses. DED's ability to precisely create big, intricate, and lightweight parts has led to its early adoption in the energy, automobile, and aerospace industries. For instance, DED is used in aircraft to fix turbine blades, lowering maintenance costs and extending the life of vital parts. Similar to this, the method is employed in the biomedical industry to create customized implants, where exact shape and biocompatibility are crucial.

But DED also has its own set of difficulties. The final part's quality and mechanical characteristics can be impacted by a number of extremely sensitive parameters, such as scanning speed, feedstock delivery rate, and laser power. Additionally, because of its many cycles of heating and cooling, DED is susceptible to flaws such porosity, residual strains, and cracking. Notwithstanding these difficulties, continuous developments in material science, process optimization, and in-situ monitoring continue to improve DED's capabilities and dependability, making it an essential technology for manufacturing's future.

3. Directed energy deposition – principles, advantages, and disadvantages

The additive manufacturing (AM) process known as Directed Energy Deposition (DED) builds or repairs three-dimensional things by melting feedstock material using a concentrated energy source and depositing it layer by layer. DED systems usually create a melt pool on the surface of a substrate using a high-energy heat source, like a laser, electron beam, or plasma arc, into which material is continually delivered as wire or powder.

- Energy Source: In DED, the energy source is essential for melting the substrate and feedstock. The most often used energy sources are plasma arcs, electron beams, and lasers. Because of its accuracy and capacity to concentrate energy in a tiny area, lasers are utilized extensively to provide localized melting with few heat-affected zones. Although less accurate, plasma arcs and electron beams provide higher deposition speeds and are appropriate for larger parts.

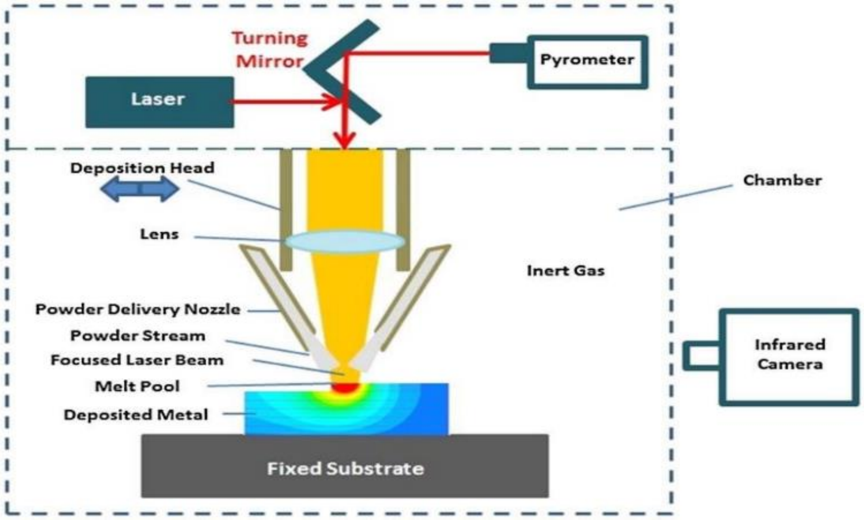
- Feedstock Delivery System: The feedstock material in DED is usually supplied as wire or metal powder. Through a nozzle, the feedstock is moved into the melt pool that the energy source has produced. While wire-based systems offer higher material utilization and are often less expensive due to the lower cost of metal wire compared to powder, powder-based systems offer greater flexibility in terms of material mixing and alloying.
- Deposition Process: To start the DED process, the energy source is directed onto a substrate or component, forming a melt pool. The energy source travels along a predetermined path as the feedstock material is supplied into this melt pool, where it melts, combines with the substrate material, and solidifies. Layer by layer, the part is constructed by the deposition head, which houses the energy source and feedstock supply system. It follows predetermined routes determined by a CAD model. The nozzle speed, feedstock delivery rate, and energy input can all be changed to regulate the thickness of each layer.
- The freedom to construct near-net-shaped parts, carry out localized repairs, or add features to pre-existing components is provided by DED's layer-by-layer construction method. Complex geometries can be produced with little material waste thanks to the energy source and feedstock delivery system's constant motion. The deposition head goes upward to create the subsequent layer once each layer has been deposited and cemented, creating a three-dimensional structure in the end.
- Material Cooling and Solidification: A monolithic structure is formed when the material cools and solidifies and merges with the layers that were previously deposited. Depending on the material and energy source, DED cooling speeds can be quite quick, resulting in the creation of distinctive microstructures. Rapid cycles of heating and cooling can occasionally result in residual stresses or flaws like porosity and cracking, which call for post-processing methods or process optimization.

Advantages of direct energy deposition

- Precision and Repair Capabilities: DED's high precision material depositing capabilities allow for both the creation of new parts and the restoration or repair of worn-out or broken ones. This makes it especially useful in sectors where component life-extension is crucial, including aerospace and military.
- Multi-Material Deposition: DED's adaptability allows for the deposit of several materials in a single build, including components with site-specific characteristics and functionally graded materials (FGMs). DED is perfect for sophisticated applications that call for different material properties in a single part since it can blend materials during deposition.

Disadvantages of direct energy deposition

- Process Control: DED necessitates exact control over process variables like as laser power, feedstock flow rate, and scan speed because of the quick melting and solidification required. Defects like porosity, cracking, or partial fusion might result from any change in these parameters, endangering the final part's mechanical qualities.
- Significant temperature gradients can be produced by the high energy input and localized heating in DED, which can leave residual strains and cause part distortion. Large or complicated components are especially susceptible to these effects, which calls for careful process planning and, occasionally, post-processing procedures like stress-relief annealing.



4. Application of direct energy deposition

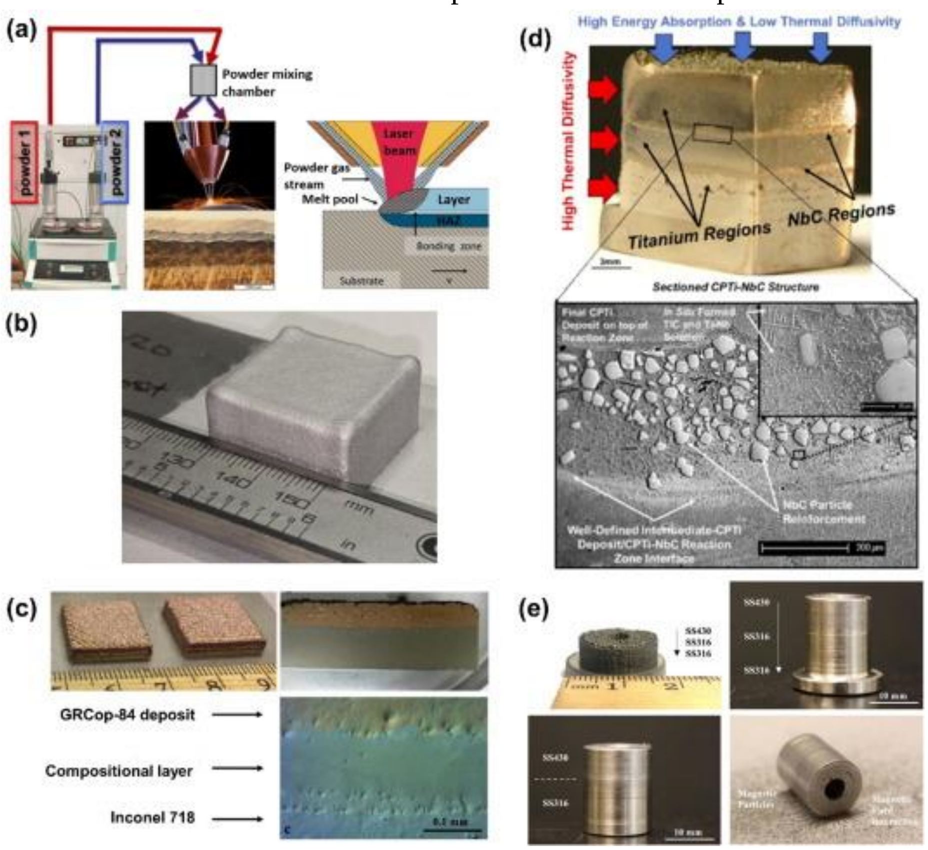
In businesses that need complicated geometries, high-performance materials, and precision, Directed Energy Deposition (DED) has emerged as a useful technology. Its use in a variety of industries, especially the aerospace, automotive, biomedical, and energy sectors, has been fueled by its capacity to deposit material with great accuracy, repair existing components, and produce multi-material parts.

- DED technology also helps the energy sector, especially in power generation. Turbine blades and other vital parts that are exposed to high temperatures and wear can be repaired using it. DED offers an economical and practical way to prolong the working life of power production equipment by directly depositing high-performance alloys onto damaged areas. Furthermore, DED is utilized to produce parts for renewable energy systems where performance and durability are crucial, including parts for hydropower and wind turbines.

- DED is used in the automotive sector to fix expensive tools like molds and dies. DED makes it possible to precisely repair these tools, which minimizes material waste and eliminates the need for brand-new equipment because these tools are subjected to severe wear and tear. Additionally, DED is being used more and more in the automotive industry to create strong and lightweight parts, especially for electric vehicles (EVs), where lowering total weight can increase driving range and battery efficiency. The development of hybrid components, which integrate materials optimized for performance in various parts, is also made possible by DED's capacity to produce parts with graded qualities.

- A major factor in the aerospace industry's early adoption of DED technology was its requirement for intricate, long-lasting, and lightweight components. Turbine blades, engine casings, and structural elements are among the high-value parts that are frequently repaired and renovated using DED. Conventional repair techniques frequently call for removing engine or structural components, which is expensive and time-consuming. DED provides an effective remedy by enabling localized material deposition straight onto damaged regions, returning them to their pre-damaged state. As a result, costly aerospace components have less downtime and a longer lifespan. Furthermore, complex parts for next-generation airplanes are made using DED, where material performance and weight reduction are essential for increasing fuel economy and lowering emissions.

Directed energy deposition's adaptability has made it a crucial technique in fields that demand high precision, material performance, and the capacity to work with intricate geometries. Its uses range from the manufacture of novel, high-performance parts that satisfy the requirements of contemporary technical difficulties to the restoration and repair of essential components.



5. Current Challenges in DED

Despite the rapid growth of Directed Energy Deposition (DED) technology, several scientific and technical challenges need to be addressed to make it a more versatile additive manufacturing (AM) platform. Currently, Powder Bed Fusion (PBF) is more widely used for metal AM due to its superior tolerances compared to those achieved with DED. Recently, hybrid additive manufacturing (HAM) systems combining DED with CNC machining are gaining popularity for meeting tighter tolerances. In a HAM setup, a DED head is integrated with a CNC machine, allowing layers to be machined after deposition for precision. While this approach yields parts with a machined finish rather than a typical AM appearance, the build time is relatively long. Additionally, extensive CNC programming and process planning are required for each unique part, depending on its geometry and complexity, to determine the sequence of machining and material deposition. Operating HAM systems also requires more expertise than PBF or standalone DED systems. Furthermore, metal chips from machining can mix with excess powder from the DED head, resulting in greater material loss.

For multi-material parts, another challenge arises with powder capture rates. Typically, only 20–75% of the powder reaches the part, with the remainder scattered in the deposition tray. Separating mixed powders is difficult, leading to higher powder waste and DED operation costs. Pre-mixed powders are sometimes used instead to reduce waste from unused powders. However, the recyclability of powders in DED is also a concern. Questions remain about how many times powders can be reused, how they behave when mixed with fresh powders, and how their flowability changes after multiple DED operations. Metallurgical compatibility is also critical for DED's advancement in multi-material manufacturing. DED involves rapid cooling rates controlled by non-equilibrium thermodynamics, making conventional equilibrium-based phase diagrams less applicable. Producing multi-material structures may require extensive trial-and-error experiments to identify the appropriate processing windows that avoid defects like cracking.

Moving forward, predictive capabilities through computational materials science, advanced machine learning, and in situ monitoring and control techniques will be instrumental in addressing metallurgical compatibility issues. These methods can enable better predictions of physical, chemical, and thermal properties for manufacturing both monolithic and multi-material parts. Some challenges are also machine-related. For instance, most DED deposition heads have three-axis movement, but five-axis or free-axis deposition heads would allow for manufacturing more complex geometries and improved repairability. Most DED systems utilize 500W or 1000W lasers as heat sources; although higher power lasers increase printing speed, they may reduce part resolution. Lastly, while most DED processes use metal powders as feedstock, wire-feed DED systems offer a more cost-effective alternative. Metal wires are less expensive, safer, and easier to store than powders, although melting them requires higher laser power, which increases the cost of wire-feed DED systems.

6. Laser-Material interaction

To fully understand and eventually control the thermal environment in Directed Energy Deposition (DED), it's essential to grasp how the laser beam, powder, and melt pool interact (often referred to as LB-P-MP interactions). Having a clear understanding of the underlying mechanisms that govern DED can enable more precise control over the resulting microstructure, residual stresses, and any defects that may arise, with the ultimate goal of enhancing material properties and performance. This section looks at related factors, such as the heating of powder particles in flight, the spatial and temporal thermal fields in the melt pool, the interactions between particles and the melt pool, and how these can be monitored in real-time. There's also a short discussion on how heat sources interact with wire material, though this area is less developed than powder-based processes.

In laser powder-based DED, powder is fed at a set and controlled rate using an inert gas that acts as a carrier. The powder is directed toward the melt pool through multiple nozzles, forming a cone shape as it exits the nozzles and moves toward the melt pool. The streams of powder converge as they near the melt pool, causing particles to collide with each other and interact with the laser beam and melt pool. During the DED process, heating, melting, vaporization, and solidification occur, leading to a layered structure in the deposited material. This structure goes through multiple thermal cycles and typically includes pores and residual stresses, as shown in fig.4 . In the area next to the melt pool, injected powder particles interact with both the laser beam and the melt pool. The melt pool itself experiences turbulent flow, and sometimes, the deposition conditions cause the formation of a "keyhole," which is due to metal vapor created by high laser beam intensities.

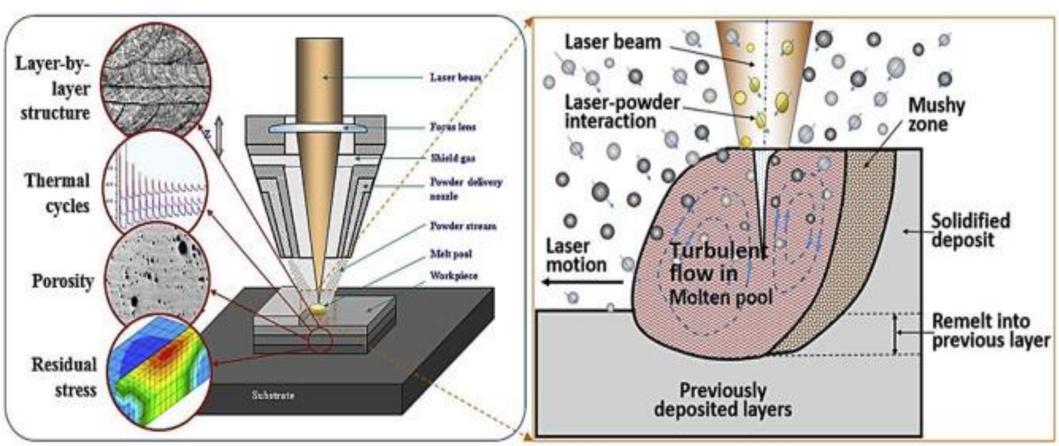


Fig. 4. issues in powder interaction with laser beam and melt pool

These processes depend heavily on the thermal and physical characteristics of the material being deposited and on various parameters, such as the laser power and intensity profile, powder flow rate, powder velocity and path, and the geometry and frequency of laser scans. Because of this, a lot of current research is aimed at building a thorough understanding of these underlying DED mechanisms to allow for adaptive control of the microstructure, residual stresses, and defects, ultimately aiming to optimize material properties and performance.

Inflight particle heating

The injected powder particles exit the nozzle and come into contact with the laser beam. Based on the specific process conditions and local power density, the particles both scatter the laser beam and absorb heat. This means the particles heat up—and sometimes even melt—as they travel toward the surface of the substrate, affected by the surrounding thermal and momentum fields. Figure 5a shows a thermal image of powder particles interacting with a laser beam, and Figure 5b demonstrates how particle trajectory and angle of impact can influence the temperature of particles reaching the melt pool. The amount of thermal energy absorbed by these particles depends on factors like particle density, thermophysical properties, shape, and size distribution. Residence time in the laser beam and the speed of the carrier gas also influence how much energy particles absorb.

In a related study, researchers examined energy distribution during DED using 316L stainless steel powder and an Nd: YAG laser. Both numerical and experimental data showed that the substrate absorbed around 30% of the laser power, reflected 54%, while the powder reflected 11%, with 4% lost from dispersed powder, and only 1% was absorbed by the deposited material. Similar observations were made in another study focused on how powder paths and residence time in the laser beam impact the process.

The distribution of laser energy during DED is also closely linked to the working distance (WD), which is the gap from the nozzle plane to the surface of the material being deposited. During the process, the WD stabilizes at an equilibrium distance, influenced by the accumulation of thermal energy first in the powder mass and then in the deposited material. The energy absorbed by the powder either transfers to the melt pool during deposition or dissipates into the surrounding chamber if the powder does not reach the melt pool, as shown in Figures 5c and 5d. A thorough understanding of the LB-P-MP interactions in DED is crucial for controlling its thermal environment, although this is challenging due to the small size of the melt pool, high thermal gradients, and fast-moving solid/liquid boundary. For example, when feedstock powder heats significantly before hitting the melt pool, the localized deformation upon impact and resulting temperature and microstructure change, depending on its position within the melt pool. High-speed photography, thermal imaging, and numerical simulations are valuable tools for studying the effects of particle attenuation on the laser beam, particle melting, and particle-pool interactions in DED. High-speed thermal imaging provides insights into thermal behaviour, like temperature gradients and cooling rates, near the melt pool.

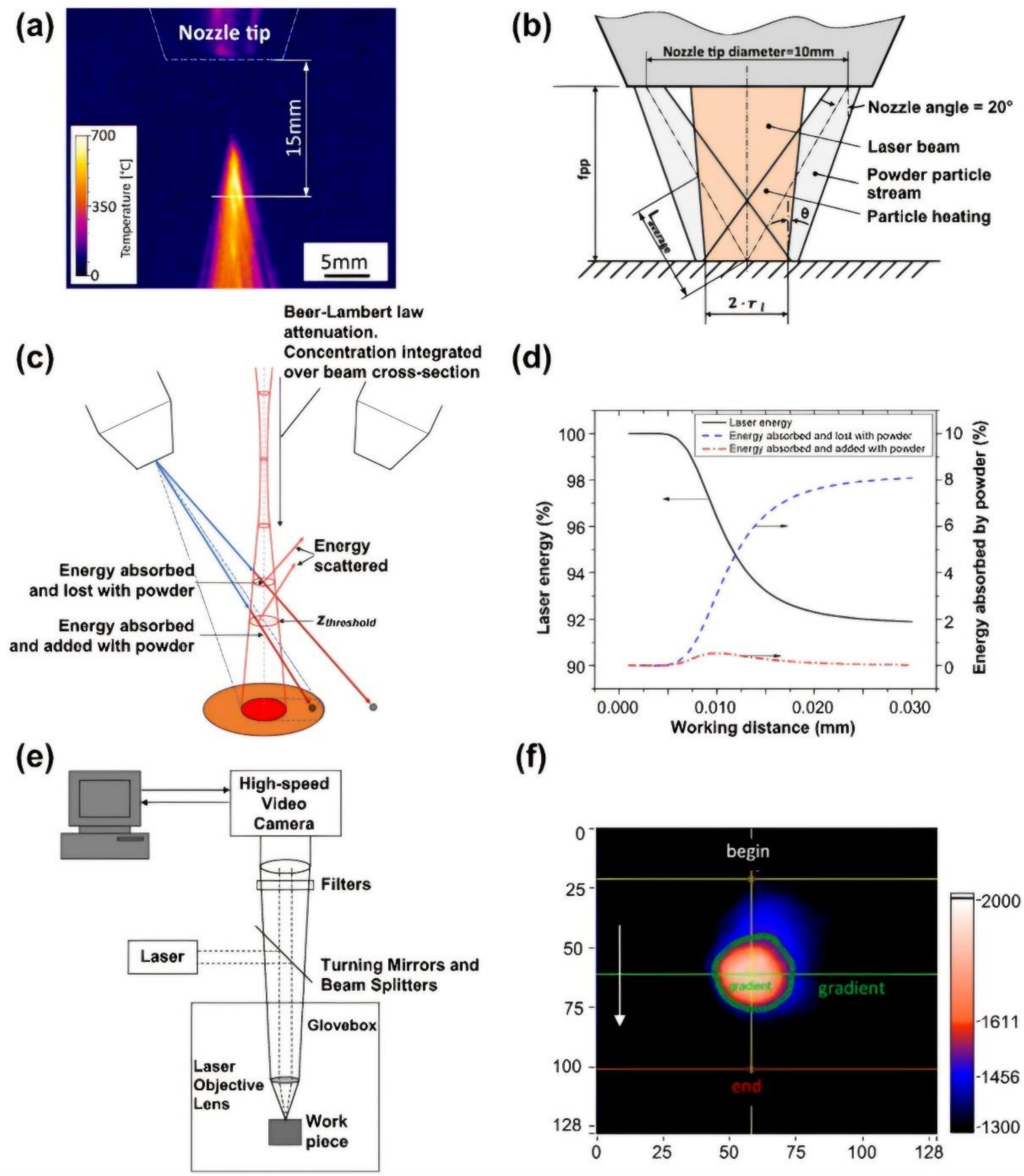


Fig.5. Inflight Particle Heating

Thermal Behaviour of the Melt Pool

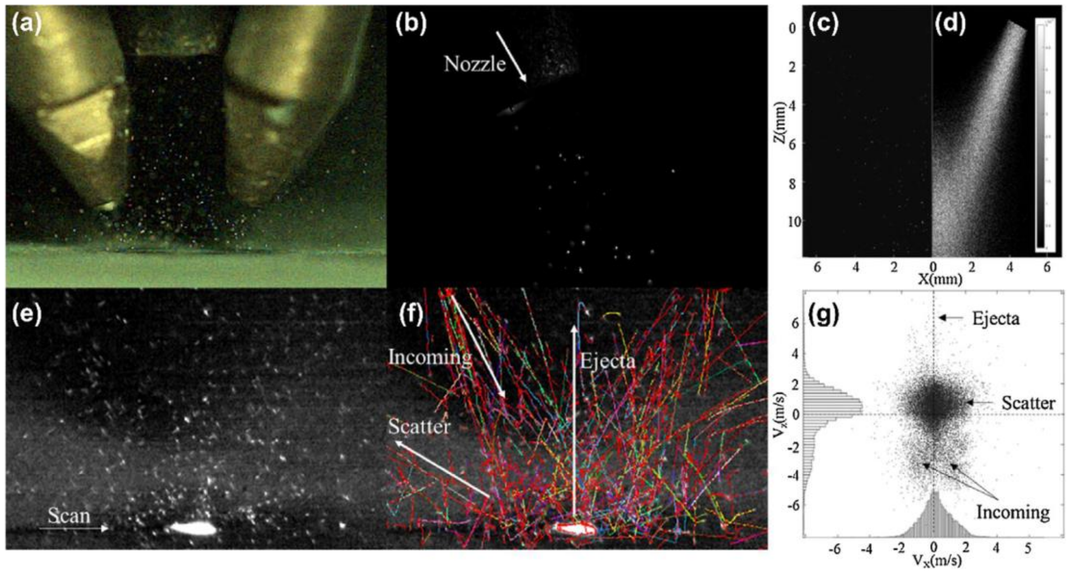
The laser beam hits the surface of the material being deposited, creating a fast-moving melt pool during DED. Understanding how the microstructure forms during DED requires insight into not only the laser's effect on the melt pool but also the spatial and temporal thermal fields within it. Monitoring thermal signatures—such as temperature gradients and cooling rates in the melt pool—during deposition helps predict microstructural characteristics (like dendrite spacing and grain formation), mechanical properties (such as tensile strength and wear resistance), and potential defects (like porosity and cracks). Non-contact thermal imaging methods, like visible and near-infrared radiation pyrometry, are useful for measuring melt pool temperature and cooling rates. In one study, a single-wavelength high-speed digital CCD camera measured thermal images of a 316L SS sample deposited via DED. Using a 650 nm broadband pass filter and telephoto lens, researchers captured the deposition path's image, revealing a solidification temperature of 1650 K for 316L SS. They found that melt pool size increased with laser power up to 275 W, with cooling rates around 10^3 K/s; the highest cooling rates were achieved with lower power and higher laser scan speeds. Another study used a stationary high-speed digital CCD camera focused on the laser's focal point to observe the melt pool, regardless of x, y, and z positioning. The study of WC-Co cermet's thermal behaviour during DED was conducted using in situ high-speed thermal imaging from above (Figures 4e and 4f) along with finite element analysis (FEA), providing insights into factors that impact microstructure development. The image in the study uses colour to represent temperature in Kelvin, with x and y-axis values indicating pixel size, and a white arrow showing the laser beam's direction. High-speed thermal imaging helps measure thermal gradients and cooling rates near the melt pool, while 3D FEA covers the entire deposited area. For particles that do not rebound, there is a height threshold below which particles enter the melt pool and above which they miss it entirel.

A two-wavelength pyrometer is another thermal imaging tool used to study DED processes. It relies on the relative intensities of radiation at two different wavelengths, which helps provide accurate temperature measurements without needing an absolute emissivity value, with a margin of error around ±6°C . Thermal behaviour of 316L SS processed through DED was examined using an imaging pyrometer in the range of 1500 to 2500 K. The temperature gradient from the melt pool center was around 10^2 to 10^3 K/mm, while the cooling rate in the DED zone was approximately 10^2 to 10^4 K/s. However, thermal imaging methods face limitations in capturing the entire thermal history of deposited materials, particularly temperature variations in solidified components.

Particle–Melt Pool Interactions

In situ monitoring can provide critical insights into the influence of process parameters on powder flow, such as laser-melt pool and laser-particle interactions, melt pool dynamics, and pore formation. A recent study used high-speed cameras to observe particle behaviour during flight and interaction with the melt pool. This research provided valuable information on particle melting and particle-pool interactions during the DED process. Figure 5 shows frames capturing detailed particle movement as they travel and hit the melt pool. The results show individual particles reaching the melt's surface, forming ripples, and staying on the surface for 0–600 ms before being absorbed. Occasionally, particles bounced off the surface after interacting with others on it. To analyze particle velocity profiles, powder trajectories were tracked from high-speed images (Figure 5f). The study also developed a three-phase (gas, liquid, solid) computational fluid dynamics (CFD) model to understand particle impact, melt pool dynamics, and wettability. The CFD model results were compared to experimental data for 316L SS particles. This study illustrated how factors such as material thermophysical properties, residence time, particle size and temperature, impact speed, melt pool conditions, and surface tension influence the DED process. In a foundational study, Cunningham et al. examined single-track laser-material interactions using a Ti–6Al–4V baseplate. Through in situ imaging (Fig. 6a), they observed that the formation of vapor depressions and keyholes depended heavily on the laser's input energy. Lower laser power and input energy tended to slow the effective drilling rate of the laser, thereby reducing keyhole formation.

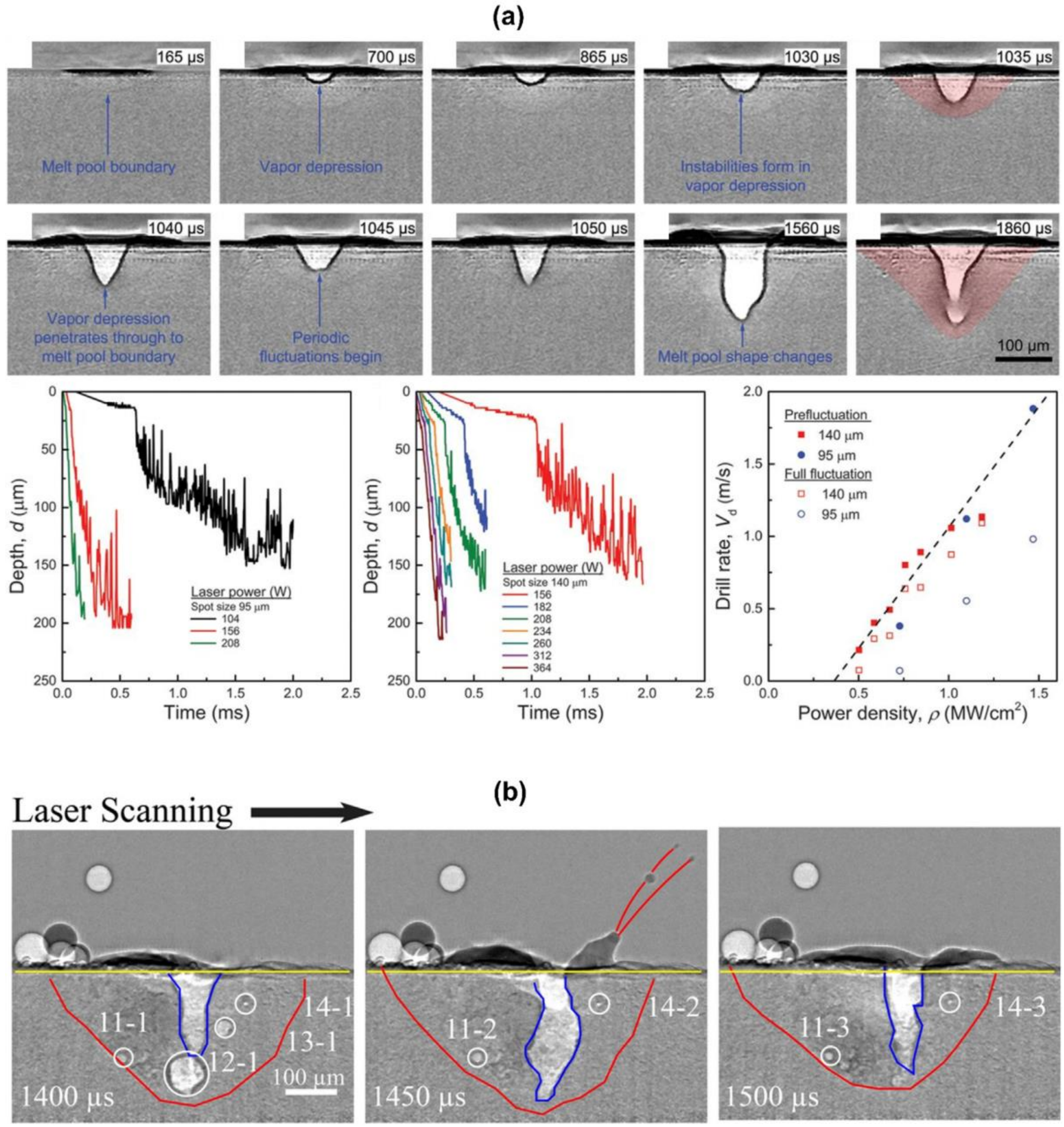
Another study used high-speed X-ray imaging to capture both powder flow and the laser's interaction with the melt pool during DED. Using a specially designed DED setup, researchers examined Ti-6Al-4V powder deposition and provided insights into how laser-melt pool interactions influence porosity formation. Figure 6b shows the evolution of gas pores from keyhole cavities. The collapse of a cavity at the bottom of the melt pool can lead to ejected particles, or "spattering," which occurs due to large pressure gradients and recoil pressure from the vapor-plasma plume. This spattering can stabilize the melt pool but may also increase surface roughness and create defects.



Laser–Wire Interactions

In laser wire-based DED, which is based on laser welding with wire filler, interactions between the laser and wire are crucial. Unlike powder-based DED, laser-wire interactions require unique considerations, as factors such as laser power, speed, and wire feed rate significantly impact the process. Additional parameters, such as the angles of the laser/wire and laser/substrate, wire tip position relative to the melt pool, wire protrusion distance, and feed direction, also need careful adjustment. Typically, wire is deposited through methods such as globular transfer, smooth transfer, or plunging, and it is essential for the molten wire tip to maintain continuous contact with the melt pool to ensure a defect-free result.

Closed-loop monitoring systems with visual sensing and image processing have been developed for laser wire-based DED to enhance stability. A CMOS camera can monitor the interactions between the wire tip and the melt pool during deposition, providing visual feedback to identify any process disruptions and assess the controller's effectiveness. The time from when the wire tip enters the laser beam to when it reaches the melt pool depends on the nozzle's position and angle. Excessive energy can cause the wire tip to melt prematurely, creating molten droplets and weak connections instead of smooth transfer. If the wire feed rate is too high relative to the melt pool's energy input, the wire may not melt properly, increasing the risk of lack of fusion (LoF) defects. Literature suggests that more research is needed to fully understand the underlying laser-wire interaction mechanisms.



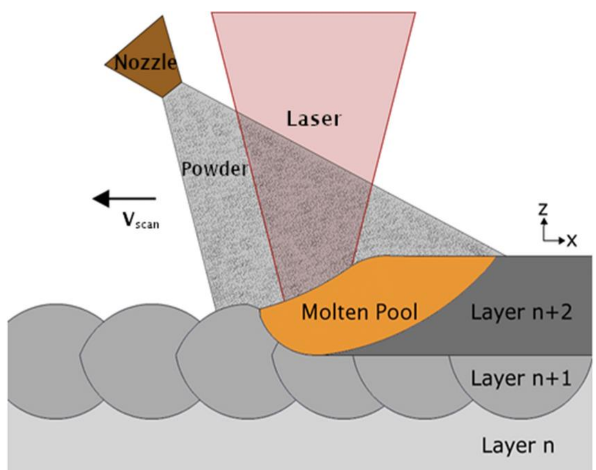
As visualization techniques such as high-speed imaging advance, they will continue to improve our understanding of critical scientific aspects of DED processes, including pore formation and residual stress development. These advancements in imaging and visualization will support the creation of complex DED components, such as functionally graded composites, directionally solidified structures, and non-equilibrium microstructures, which require unique combinations of process parameters.

7. Dominant Processing variable in DED

Producing high-quality parts through DED technology involves managing a multitude of processing variables, each influencing the thermal history, solidification behaviour, and overall quality of the deposited material's microstructure and mechanical properties. This section examines the key parameters that shape the DED process, their impact on the microstructure and properties of the deposited material, and current and emerging approaches to process optimization.

Despite advancements, implementing sophisticated in situ simulation-monitoring-control techniques remains challenging. For instance, detecting and addressing defects during processing—such as porosity, lack-of-fusion (LoF) defects, distortions, and inclusions, as well as other parameters like melt pool geometry, temperature, and deposit height—within a suitable response time is difficult. Recent developments in adaptive control methods and in situ monitoring utilizing machine learning algorithms are promising, offering the potential to fine-tune numerous process variables, monitor operations in real time, and control the deposition process as it happens.Traditional experimental optimization methods, such as Design of Experiments (DOE), are commonly used to refine DED processing parameters, though the complex interdependencies between parameters and their combined influence on the material's microstructure, mechanical, and physical properties have yet to be thoroughly explored .

Typically, laser power, laser scan speed (also called traverse speed), and powder mass flow rate (PMFR) are the primary parameters manipulated in DED processes. Additional factors, such as hatch spacing, energy source diameter, z-step, and working distance, are often held constant based on initial material-specific testing. This approach often includes single or double track deposits tested under varied conditions.



The effective energy density E (J/mm^2) and powder density F (g/mm^2) are widely used as combined parameters for evaluating continuous deposition and deposit aspect ratios. The formulas for E and F are given by:

$$Energy\ Density, E = \frac{P}{md}$$

where P is laser power in (J/s), m is laser scan speed in (mm/s), and d is laser beam diameter in (mm).

$$Powder\ Density, F = \frac{G}{md}$$

where G is the powder mass flow rate (g/s).

These combined variables govern the laser's effective residence time, influencing melt pool temperature, cooling rate, and microstructure. Powder flow rate also plays a role by affecting laser attenuation at the consolidation plane of the powder, impacting energy density indirectl. A recent study by Traxel et al. introduced the comparison parameter S, calculated as:

$$S = \frac{P}{mG}$$

This parameter, related to Simcha's energy input relationship, has been found particularly useful for DED processes. Another recent investigation used DED to deposit Inconel 718 and noted that as-deposited microstructural features, such as grain morphology, dendritic arm spacing, and porosity, varied with laser energy density. Compared to wrought Inconel 718, the DED-produced material showed a reduced average grain size and finer dendritic spacing, attributed to high cooling rates inherent in DED. Additionally, experiments with Ti–6Al–4V revealed that increasing powder flow rate within the SSS parameter decreased energy input, as more mass required additional energy for complete melting. For these tests, complete particle melting was prioritized to ensure quality, while other factors like aspect ratio and build height were secondary. Research on AISI M4 tool steel has also demonstrated a linear relationship between energy and powder densities with deposit height, providing a predictive model for single-layer deposition height based on energy and powder inputs.

In the Directed Energy Deposition (DED) of Inconel 718, laser energy density has proven to be a strong parameter, yielding comparable porosity levels in materials processed at similar energy densities. However, recent findings indicate that even with consistent energy densities, the density outcomes for materials like Al-Mg alloy vary. This variation suggests that energy density alone cannot reliably act as a sole process parameter; additional aspects, such as feedstock characteristics and powder mass flow rate, must also be considered. The feedstock's properties—including laser reflectivity, thermal conductivity, and melt pool surface tension—can directly impact the properties of the deposited material and the occurrence of defects. For instance, Al-based alloys require high energy input for complete melting due to their high surface reflectivity and thermal conductivity. This can lead to an unstable melt pool and excessive thermal energy build-up, potentially causing defects like cracks and pores in the deposit. Moreover, high energy levels may lead to the vaporization of low-melting-point alloying elements, such as Mg and Zn, altering the final chemical composition and impacting microstructure, porosity, mechanical properties, and corrosion resistance. Conversely, insufficient energy might lead to incomplete melting, resulting in defects such as balling or void formation along the perimeter.

In blown-powder DED methods, feedstock is directed into the melt pool through the deposition head nozzles. Therefore, powder mass flow rate is critical in determining the quantity of feedstock introduced into the melt pool, while the laser scan speed (associated with the deposition head movement) also affects this by modulating both energy density and material delivery rate. Studies have demonstrated that laser scan speed significantly impacts solidification behaviour, thereby influencing the microstructure and mechanical characteristics of the deposit. Together, powder flow rate and laser scan speed determine the laser's effective residence time over the powder introduced into the melt pool. Generally, a higher residence time allows more powder to enter the melt pool, increasing energy input and deposit size. However, powder density alone does not determine powder catchment efficiency; the efficiency with which the powder is incorporated into the molten pool also depends on material characteristics such as melt pool temperature, surface tension, and dispersion properties of the powder flow, all of which affect the deposit’s geometry.

The development of melt pool and deposit geometry in Inconel 718 has been investigated through 3D numerical simulations alongside validation experiments. Findings showed that while higher laser power does not significantly influence the height of the deposited layer, it does increase the melt pool’s width and penetration depth (Fig. 10). This is because increased laser power enlarges the molten pool's surface area, enhancing catchment efficiency. As a result, more powder is distributed across a wider melt pool, resulting in minimal effect on deposit height.

With DED applications like 3D part production, surface cladding, and repair growing in high-demand industrial sectors, efficient process optimization is essential. Although substantial research has aimed to elucidate the effects of DED process variables on deposit microstructure, defect formation, and overall properties, a comprehensive understanding of the governing mechanisms and the complex interactions among these variables remains incomplete.

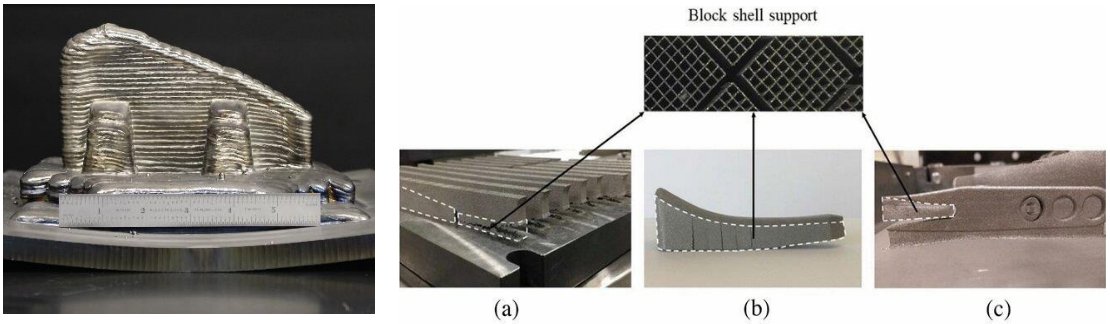
8. Defects in Deposited Material and Their Characterization with Mitigation Strategies

DED is a non-equilibrium processing technique characterized by rapid cooling and high thermal gradients. These conditions contribute to complex phase transformations, microstructural changes, non-uniform residual stresses, distortions, porosity, and cracking, all of which can degrade corrosion resistance, reduce mechanical performance (e.g., ductility and fatigue strength), and lead to premature failure. This section explores the mechanisms behind these defects, as well as their measurement, modeling, and possible mitigation strategies. Table 3 summarizes common defects, their origins, effects on material properties and part quality, and relevant characterization techniques. The following subsections cover these topics in detail.

Residual Stresses and Distortion

Origin of Residual Stresses: Residual stresses are a typical outcome of thermomechanical manufacturing methods. In DED processes, the layer-by-layer approach subjects the material to a complex thermal history, involving cycles of melting, remelting, and reheating. Figure 11a depicts a model illustrating residual stress formation during heating and cooling, and Figure 11b shows thermocouple readings taken during LENSTM deposition of an H13 steel box, with each peak corresponding to the laser passing over the thermocouple. DED, as a non-equilibrium process, exhibits rapid cooling rates (102–104 K/s) and steep thermal gradients (104–105 K/m), as shown in Figures 11c and d. These conditions can lead to complex phase transformations and microstructural modifications. The residual stresses induced in DED can be highly non-uniform, varying in spatial distribution and build direction, with gradients reaching up to around 102 MPa/mm. The fundamental mechanisms driving residual stress formation and distortion in DED are similar to those in fusion welding processes. Residual stresses are generally classified into three types based on their scale of effect, ranging from large-scale macro-stresses (Type I) to atomic-level stresses (Type III).

Effects of Residual Stresses on Deposited Materials and Parts: Residual stresses in additively manufactured parts can have various effects, including phase transformations driven by residual stress, distortion , loss of geometric accuracy, cracking, part delamination from the substrate, accelerated crack propagation under cyclic loading, and ultimately premature failure of structural components.



Residual Stresses developed in materials

Residual Stress Measurement: Measuring residual stresses is challenging and often involves calculating additional measurable properties like displacement/distortion, lattice spacing, or sound velocity. Techniques for residual stress measurement are classified into destructive and non-destructive methods. Destructive methods rely on mechanical stress relief and include techniques like hole drilling, serial sectioning, and ring-core drilling. Non-destructive approaches measure lattice spacing (diffraction methods), sound speed, or Barkhausen noise (sound emitted by ferromagnetic materials in an external magnetic field. Most methods rely on assumptions, and it is important to ensure these assumptions are valid for the specific component being analysed. Comprehensive reviews of residual stress measurement methods can be found in. Computational models, often based on solving thermal-stress equilibrium equations, are also used to predict stress and displacement changes over time in 3D models.

Mitigation Approaches for Residual Stress and Distortion

1. Substrate and Chamber Preheating

    - Substrate Preheating: Preheating the substrate mitigates temperature gradients by elevating the base temperature, thus reducing the rate of cooling and lowering residual stress. Research has shown that preheating to temperatures around 400°C can decrease the severity of stress-induced distortions and reduce the peak residual stresses. This technique has been particularly effective in high-stress materials like Inconel and Ti-6Al-4V, where initial substrate preheating reduced part distortion by 27.4%.

    - Build Chamber Heating: In addition to substrate preheating, heating the entire build chamber maintains a uniform thermal environment. For instance, in experimental setups where chamber temperatures were maintained around 200-300°C, residual stresses decreased significantly, allowing for improved dimensional stability. However, chamber heating may be limited in application for larger parts due to the associated costs and thermal regulation challenges.

2. Process Parameter Optimization

   - Control of Laser Power and Scan Speed: High laser power and low scan speeds can exacerbate thermal gradients, leading to increased residual stress. By lowering the laser power and increasing scan speed, the amount of heat input per unit area is reduced, mitigating stress concentrations. Additionally, maintaining an optimal laser power-to-scan speed ratio helps manage the cooling rates and reduce stress accumulation. This technique requires careful calibration to balance the need for full fusion with the avoidance of overheating and stress accumulation.

   - Layer Thickness Adjustment: Thinner layers help reduce residual stresses by allowing each layer to cool more gradually. Studies indicate that using thinner layers, particularly in metals with high thermal conductivity like aluminium alloys, effectively minimizes thermal stress by reducing the total heat input per layer. However, thin layers may increase build time, making this a trade-off between dimensional accuracy and production efficiency.

3. Optimized Scan Strategy

   - Hatch Pattern Variation: Different scan strategies, such as checkerboard or island scanning, help distribute residual stresses more evenly by altering the heating and cooling sequence across layers. For example, an "island" scan pattern, where the laser scans in small patches rather than long lines, allows localized areas to cool partially before the next scan, reducing stress build-up.

   - Fractal and Rotational Scan Patterns: Fractal and rotated patterns, such as the Hilbert curve, create a more even thermal distribution across the build surface. Studies have shown that these scan strategies reduce stress and prevent warping by ensuring no area undergoes continuous heat cycling. In particular, fractal strategies reduce temperature gradients by following a non-linear path, achieving a more uniform temperature distribution across each layer.

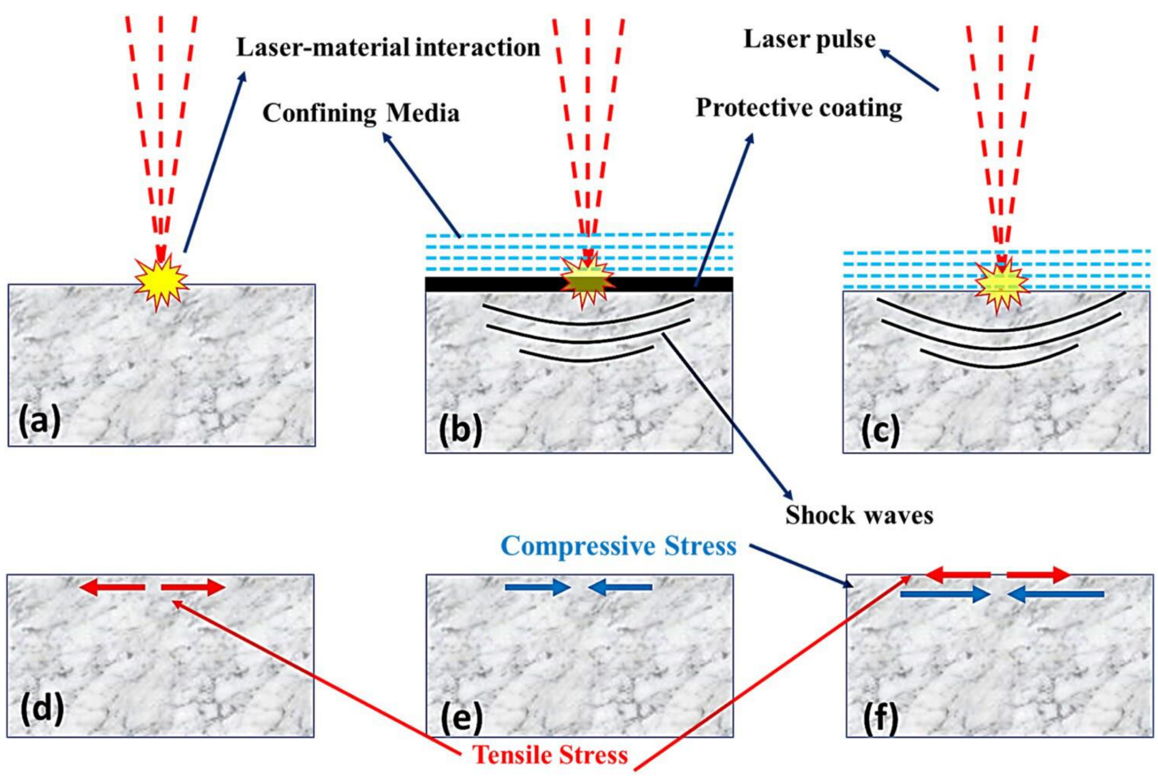
4. Post-Processing Stress Relief Techniques

   - Thermal Stress Relief: Thermal stress relief involves heating the part after fabrication to a temperature just below its recrystallization point, allowing internal stresses to redistribute. For instance, heat treatment of Inconel 718 at 650–700°C for several hours has been shown to relieve most residual stresses while preserving microstructural integrity. This method is widely used for metal parts that require high fatigue resistance, as stress relief can improve part lifespan under cyclic loads.

- Hot Isostatic Pressing (HIP): Besides reducing porosity, HIP also minimizes residual stress by applying isostatic pressure and high temperatures simultaneously. The pressure reshapes internal microstructures to a more uniform state, redistributing stress concentrations. HIP is especially effective for critical applications in aerospace and medical fields, where dimensional accuracy and material homogeneity are essential.

5. Mechanical Stress Relief Techniques

- Laser Shock Peening (LSP): LSP is a surface treatment technique that introduces beneficial compressive stresses to counterbalance residual tensile stresses in the surface layers. By using high-energy laser pulses, LSP creates compressive waves in the material, which redistribute and neutralize surface-level tensile stresses. This method has been successful in increasing fatigue life and reducing the risk of cracking in Ti-6Al-4V and stainless-steel parts manufactured via DED.



Effect of Laser Shock Peening

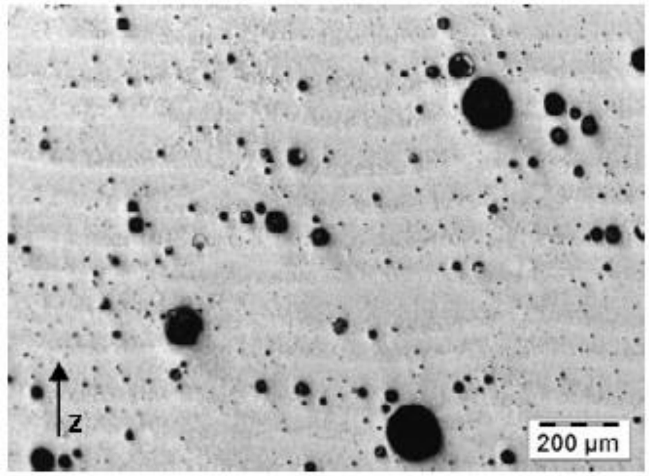
- Surface Rolling or Shot Peening: For components where distortion is a concern, mechanical methods like shot peening and surface rolling apply compressive forces on the surface. This redistributes tensile stresses and helps prevent distortion and cracking. While these treatments are effective, they may not reach deeper layers and thus are best used alongside thermal treatments for comprehensive stress relief.

DED, characterized by rapid heating and cooling rates, high thermal gradients, and complex thermal cycles, often generates residual stresses, porosity, and other defects. Although considerable efforts have been made to measure, model, and reduce residual stresses in AM parts, achieving a thorough understanding of the mechanisms behind residual stress formation remains challenging. Studies indicate that optimizing process parameters and scan strategies can reduce residual stresses in printed parts, but additional post-processing, such as hot isostatic pressing (HIP) or surface treatment, is still needed to fully relieve these stresses, adding to manufacturing time and cost. Measuring residual stresses accurately in DED parts remains difficult due to trade-offs in time, cost, and precision, often limiting the number of samples measured and the reliability of findings. Furthermore, most residual stress studies focus on alloys commonly used in AM, such as Inconel 625 and 718, 304 and 316 stainless steels, Ti-6Al-4V, and AlSi10Mg. Since residual stress behaviour is highly material-dependent, further investigation is needed to understand these mechanisms in other materials, such as metal matrix composites and FGMs.

Porosity

Causes of Porosity: Porosity is one of the most common defects in Directed Energy Deposition (DED) and can originate from several mechanisms. The primary causes include: (1) keyholes, which form due to high energy density during deposition, leading to localized vaporization and gas entrapment (Fig. 14a); (2) gas porosity, which may arise from gas trapped in the feedstock, selective evaporation of alloy elements, or shielding gas trapped in the molten pool; and (3) lack of fusion (LoF), which results from insufficient melt pool penetration into the substrate or previous layers due to inadequate energy input (Fig. 14b). Interlayer porosity (LoF) and intralayer porosity are common distinctions, with the latter being randomly distributed throughout the sample's bulk.

Types of Pores: Pore shapes vary with their origin. Keyhole pores are relatively large, circular when viewed horizontally, and elongated in the build direction or tapered with a wider top. Gas pores tend to be the smallest and most spherical. LoF pores are generally larger (comparable to the melt pool size) and irregularly shaped. Sphericity factors can help differentiate pore types: values below 0.6 suggest LoF, values above 0.7 indicate keyholes, and values over 0.92 suggest gas porosity.



Quality Control through Density Measurement: Porosity reduces mechanical strength and promotes crack formation, so density measurement is a key quality control method. DED processes aim to achieve a density above 99.5%. In powder-based DED, porosity levels are influenced by the powder feed rate (Fig. 14c), energy input (laser power, spot size, scan speed), and powder porosity.

Impact of Porosity on Properties**:** Porosity significantly weakens the mechanical properties of DED-manufactured components, especially affecting fatigue resistance, anisotropy, and the oxidation and corrosion resistance of the printed parts. Irregular or clustered pores can serve as stress concentrators, making them more damaging to mechanical properties than spherical pores, particularly if they're aligned perpendicularly to the load direction. Due to the complex impact of pore shape and distribution on fatigue life, there tends to be considerable variability in fatigue data and increased uncertainty. For example, the fatigue life of LENS-deposited Ti–6Al–4V is primarily influenced by pore size (with larger pores being more harmful), proximity of pores to the surface, and, in low cycle fatigue (LCF) conditions, the shape and grouping of pores (closely spaced pores have a more pronounced negative effect).

Methods of Measuring Porosity**:** Advanced process control and optimization now allow for routine DED fabrication of parts with densities exceeding 99%. Various techniques are available to assess porosity and density in additive manufacturing (AM) parts, including the Archimedes method, ultrasonic pulse-echo velocity measurements, metallographic cross-section image analysi, X-ray microcomputed tomography (μ-CT), synchrotron hard X-ray imaging, and gas pycnometry.

Mitigation Strategies:

1. Optimization of Energy Density
    - Laser Power and Scan Speed Adjustment: One of the primary methods to control porosity is adjusting the laser power and scan speed to balance energy input and fusion. High energy densities can result in "keyholing," where vaporized metal leads to gas entrapment within the melt pool, creating porosity. Conversely, low energy density might not fully melt the powder, causing lack-of-fusion (LoF) porosity. An optimal range for energy density, such as 125 J/mm^3 in AlSi10Mg, has shown to reduce porosity while maintaining adequate fusion. Additionally, employing volumetric energy density (VED) calculations helps optimize the input energy to achieve a porosity-free structure.
    - Powder Mass Flow Rate Control: Another important variable is the powder mass flow rate, which affects how much powder reaches the melt pool. Higher powder flow rates can increase the likelihood of LoF porosity due to insufficient laser power to fully melt the powder. Lowering powder mass flow while keeping laser energy density constant improves melt pool quality and ensures thorough bonding between layers.
2. Powder Feedstock Quality Control
    - Use of High-Quality Feedstock: The quality of powder feedstock significantly influences porosity in DED. Powders produced through plasma atomization or gas atomization typically exhibit spherical shapes and low internal porosity, improving flowability and reducing gas entrapment in the melt pool. Researchers observed that powder produced through plasma atomization consistently yielded lower porosity levels compared to mechanically milled powders due to fewer impurities and better flow characteristics.
    - Powder Drying and Storage: Moisture and contaminants in powder feedstock can introduce additional gas porosity when vaporized during the DED process. Studies have demonstrated that drying powder before use drastically lowers porosity. For instance, drying Inconel 718 powder at 110°C for six hours reduced porosity from about 0.41% to 0.07%, demonstrating the importance of moisture control in maintaining part quality. Proper storage in sealed, low-humidity environments also preserves powder integrity over time.
3. Post-Processing Hot Isostatic Pressing (HIP)
    - HIP for Porosity Elimination: Hot Isostatic Pressing (HIP) is a common post-processing technique to eliminate residual porosity in DED

components. HIP subjects the part to high temperature and isostatic pressure, collapsing internal pores and enhancing part density. In materials like Ti-6Al-4V, HIP treatment at 900°C and 100 MPa for two hours closed LoF pores and improved ductility by aligning the internal structure more closely to a cast or wrought microstructure.

- Limitations of HIP: While effective, HIP may not eliminate all porosity if entrapped gases are chemically bonded within the material. For materials like aluminium or titanium alloys that oxidize readily, entrapped oxygen can become difficult to remove through HIP alone. Thus, HIP is most effective as a supplementary treatment following optimized DED parameter controls.

4. Advanced In-Situ Monitoring and Closed-Loop Control Systems
   - Real-Time Monitoring: In-situ monitoring using thermal cameras, X-ray imaging, and acoustic sensors enables the detection of porosity as it forms. Advanced in-situ systems can capture data on melt pool characteristics, temperature gradients, and particle trajectories, allowing real-time feedback on the quality of deposited layers.
   - Closed-Loop Control Systems: Closed-loop control systems can dynamically adjust laser power, powder flow rate, and scan speed to address the conditions that lead to porosity formation. These systems rely on machine learning algorithms trained on process data to predict porosity occurrence and adjust parameters accordingly. Such adaptive control systems have proven highly effective in reducing defects and producing denser parts.

Much of the current research on porosity in DED focuses on specific metals or alloys and cannot easily be generalized across all DED processes. A more comprehensive understanding of how material properties—such as laser absorptivity, thermal expansion, thermal conductivity, and surface tension—affect porosity formation in DED is essential to reduce the need for extensive process optimization.

Cracking and Delamination in DED-Fabricated Components

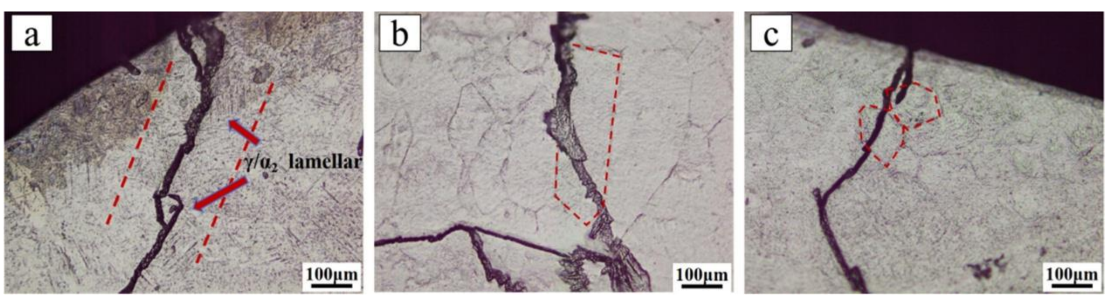
Origins of Cracking and Delamination: In additive manufacturing (AM), especially Directed Energy Deposition (DED), cracking and delamination are common issues exacerbated by thermal stresses from rapid heating and cooling cycles. Delamination, which is the separation between layers or between the initial layers and the baseplate, occurs when interlayer residual stresses exceed the material's yield strength. This defect often arises due to the inclusion of unmelted or partially melted powder or inadequate remelting of underlying layers. It is most likely to appear at the build-baseplate interface where stress concentrations are high.

Cracking is a significant barrier to the widespread industrial adoption of metal AM, as metals prone to cracking in traditional fusion welding are similarly susceptible in AM. Cracks in AM parts generally fall into three types:

(i) *Solidification cracking* (hot cracking), which occurs along grain boundaries due to the higher contraction of upper, hotter layers compared to underlying layers or the baseplate, generating high tensile stresses. This type of cracking can result from excessive energy application relative to material requirements and depends on solidification characteristics;

(ii) *Liquation cracking* in the partially melted zone (PMZ), where grain-boundary precipitates melt during rapid heating near the liquidus temperature. Tensile stresses in the PMZ arise during cooling due to solidification and thermal contraction. Alloys with a wide solidus-liquidus temperature range (e.g., Ni-4V) and high thermal contraction (e.g., aluminium alloys) are especially susceptible; and

(iii) *Ductility dip cracking*, an intergranular cracking at elevated temperatures affecting certain face-centered cubic (FCC) alloys.



Impact on Material Properties: Both cracking and delamination lead to reduced static and dynamic mechanical properties, lower corrosion resistance, and increased likelihood of premature failure in DED parts.

Characterization Methods: Cracking and delamination can be assessed through destructive and non-destructive tests, as well as computational modeling. Destructive methods include metallographic cross-sections and fractographic analysis of cracks using scanning electron microscopy (SEM). Non-destructive testing (NDT) options include magnetic particle inspection, radiographic testing, X-ray microcomputed tomography (μ-CT), and ultrasonic testing.

Mitigation Strategies for Cracking:

1. Preheating of Substrate and Build Chamber
   - Mechanics: Preheating the substrate and chamber minimizes the difference between the base temperature and the temperature of the deposited layer, thereby reducing the thermal gradients responsible for high tensile stresses. This technique lowers the cooling rate, allowing the layers to solidify more uniformly, which reduces crack initiation and propagation.
   - Application and Examples: Studies show that preheating to temperatures around 200-400°C significantly reduces the incidence of cracking in high-stress materials like Inconel and titanium alloys. For example, when titanium alloy Ti-6Al-4V was preheated to 400°C, cracking was reduced by nearly 50% in DED-produced components due to lower residual stresses and a more controlled cooling rate. This preheating method is especially effective for materials with a high thermal expansion coefficient.

2. Optimized Process Parameters
   - Laser Power and Scan Speed Adjustments: High laser power and low scan speeds increase the energy input, which can cause severe thermal gradients and cracking. Optimizing laser power to ensure adequate fusion without excessive overheating can reduce stress concentration, while higher scan speeds minimize the energy per unit area, reducing thermal accumulation in one spot.
   - Powder Feed Rate and Layer Thickness: Reducing the powder feed rate and layer thickness helps distribute energy more evenly, reducing the temperature differential between layers. Thin layers solidify more quickly and evenly, which decreases thermal contraction in the melt pool, minimizing the risk of cracking.
   - Experimental Evidence: In DED of Inconel 718, optimizing scan speed and laser power to maintain a stable melt pool reduced cracking significantly, resulting in uniform microstructures and improved mechanical properties. Layer thickness adjustments in aluminium alloys also demonstrated up to a 40% reduction in solidification cracking by ensuring uniform cooling.

3. Control of Cooling Rates

- Application of Controlled Cooling: Managing cooling rates is essential for alloys prone to cracking, like nickel-based and aluminum alloys. Controlled cooling can be achieved by adjusting scanning strategies (discussed below), or by reducing laser power progressively as layers are built.
- Use of Active Cooling Systems: While passive cooling through process adjustments is common, some DED setups use active cooling systems, such as air or gas jets, to manage temperature gradients in real-time, preventing rapid thermal contraction that can lead to cracking.

4. Optimized Scanning Strategies

- Hatch Pattern and Rotation: Employing optimized scan patterns like checkerboard or island scanning helps control the heat input distribution, thus reducing stress build-up. By avoiding long continuous paths, these patterns create localized heating that allows areas to cool before further heating, minimizing residual stress concentration.
- Fractal and Hilbert Curve Patterns: More complex scanning patterns, such as the Hilbert curve, distribute heat more uniformly, reducing the chances of crack initiation. Studies on fractal and rotational patterns in alloys like Ti-6Al-4V have shown a reduction in cracking due to the consistent, even distribution of heat across the surface.
- Case Study: An experimental study on stainless steel 316L used a rotating scanning pattern and reduced cracking by up to 30%, achieving a homogenous structure with fewer internal stresses.

5. Material-Specific Alloy Modifications

- Alloying Additives: Some materials are inherently susceptible to cracking due to their thermal properties. Adding specific alloying elements can alter the solidification characteristics, reducing susceptibility to thermal cracking. For example, adding boron to nickel-based superalloys has shown improved ductility at high temperatures, which helps to reduce cracking during cooling.
- Grain Refinement: By modifying alloy composition to encourage grain refinement, finer microstructures can be achieved. Finer grains have better resistance to crack propagation as they distribute stress more evenly. Researchers found that incorporating elements like niobium in steel alloys improved the resistance to thermal stresses, reducing crack formation.

Mitigation Techniques for Delamination

1. Improved Powder Feedstock Quality
    - High-Quality Powder: Using high-purity, spherical powder enhances interlayer bonding due to improved packing density and flow characteristics. Plasma-atomized powders generally have fewer contaminants and more uniform particle size, which facilitates better melting and bonding between layers, thereby reducing delamination.
    - Powder Drying and Storage: Proper storage and handling of powders minimize contamination and moisture, which can interfere with bonding. For example, preheating the powder before deposition removes adsorbed moisture, which helps prevent layer separation caused by gas release during deposition.
2. Substrate Surface Preparation
    - Surface Roughening and Texturing: Ensuring the substrate surface is roughened or textured improves the initial layer bonding, helping prevent delamination at the interface between the substrate and the first layer. Techniques like grit blasting or laser texturing provide mechanical interlocking that enhances adhesion.
    - Chemical Cleaning: For materials susceptible to oxide formation, like aluminium and titanium, surface cleaning using chemical etchants removes surface contaminants and oxides that may weaken layer bonding.
3. Process Parameter Optimization
    - Layer Thickness and Energy Density Control: Setting an optimal layer thickness ensures that each layer fuses completely with the previous one, minimizing gaps that could lead to delamination. Ensuring adequate energy density further enhances bonding by maintaining a stable melt pool, which reduces the likelihood of incomplete fusion.
    - Interlayer Dwell Time: Allowing time for layers to partially cool before depositing the next layer improves bonding by allowing a controlled level of fusion. Studies have shown that an interlayer dwell time of around 5–10 seconds between layers reduced delamination in DED-produced steel parts.
4. Optimized Scanning Strategy for Interlayer Bonding
    - Checkerboard and Island Patterns: These patterns help to distribute heat more evenly, reducing localized stress that could lead to delamination. For instance, checkerboard scanning creates a controlled overlap between

layers, ensuring better bonding and reducing the chances of separation between layers.

- Spiralling and Outward-Inward Scans: These patterns apply a gradual thermal load, starting from the inside and working outwards, reducing stress between the layers. Outward-inward scans, particularly useful in large-area deposits, ensure that the edges (more prone to delamination) are cooled more uniformly, improving overall layer adhesion.

5. Thermal Management and Preheating Techniques

   - Chamber Heating: A preheated chamber mitigates temperature gradients and minimizes the risk of delamination. Studies have found that heating the chamber to ~200°C, in conjunction with substrate preheating, resulted in a 20% reduction in delamination in DED-built nickel alloys.

   - Interlayer Preheating: Interlayer preheating, where subsequent layers are re-melted slightly to enhance bonding, can also prevent delamination. Controlled reheating between layers encourages bonding without adding significant thermal stress.

High Surface Roughness

Origin of Surface Roughness: Directed Energy Deposition (DED) is recognized as a near-net-shape manufacturing process, necessitating subsequent post-processing techniques, such as machining or polishing, to achieve the desired tolerances and surface finish. The elevated surface roughness observed in DED-manufactured components primarily arises from:

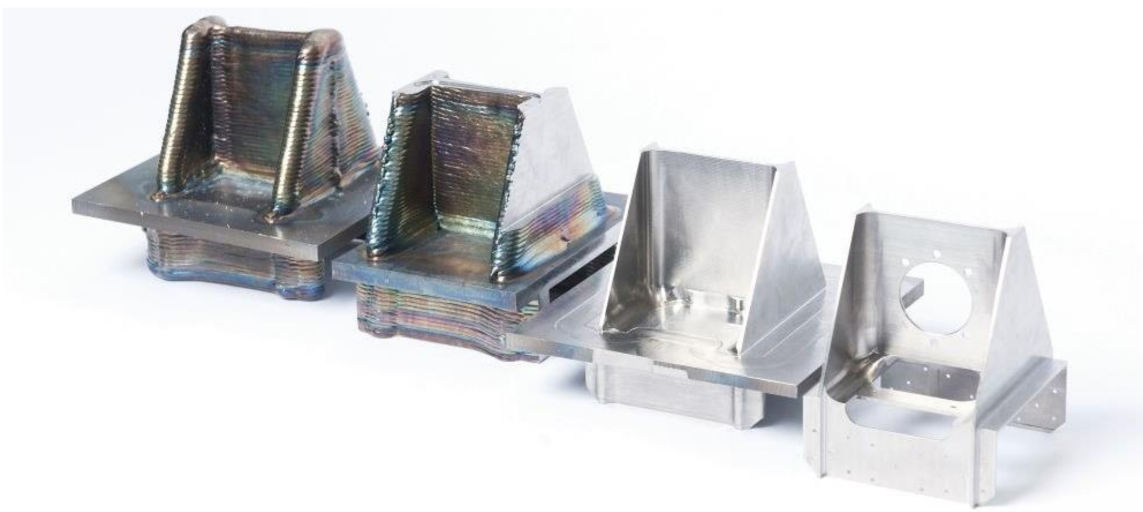
(i) the adhesion of partially melted powder particles to the surface due to inadequate heat input and the use of larger powder particles, as well as balling effects resulting from Rayleigh instability at high laser scanning speeds, which fragment the molten pool into smaller islands that are pushed to the edges of the molten area (12, 194, 195; 12, 192);

(ii) the stair-stepping phenomenon, which is a limitation in all layered manufacturing methods, particularly when creating inclined or curved surfaces (196);

(iii) the splashing of molten material (197). Surface roughness is influenced by a variety of factors, including the type of material feedstock, design of the part, processing conditions, and post-processing techniques (12).

Effects of Surface Roughness on Deposited Materials and Parts: The roughness of the surface can significantly impact the dimensional accuracy and geometric tolerances of the produced parts, critically affecting their mechanical characteristics, especially fatigue resistance. Research has shown that a surface roughness of approximately 200 μm can lead to a reduction in fatigue strength by 20–25%, depending on the additive manufacturing process employed (198).

Surface Roughness Measurement: Various analytical techniques can be utilized to assess surface roughness, including both contact methods (such as atomic force microscopy (AFM) or stylus profiling) and non-contact methods (such as confocal laser scanning microscopy (CLSM) or white light interferometry). Recently, a novel optical gauging method has been introduced for measuring the surface roughness of DED-processed alloys, employing a commercial video system and a multisensory measurement apparatus with a broad measurement range, which has shown favorable comparisons with white light interferometry results (70).



Surface Roughness Treatment

Mitigation Techniques for High Surface Roughness

1. Layer Thickness Optimization

    - Mechanics: By reducing layer thickness, the stair-stepping effect is minimized, which is especially important for sloped or curved surfaces. Thin layers also ensure a smoother surface, as each layer requires less material deposition, reducing the risk of particle aggregation and surface roughness.

    - Case Study: In a DED study involving stainless steel, reducing the layer thickness from 0.4 mm to 0.2 mm reduced the average surface roughness by approximately 35%, leading to a more refined finish and improved dimensional accuracy.

2. Laser Power and Scan Speed Adjustments

   - Laser Power Optimization: Excessive laser power can cause splattering and spatter adhesion on the surface, increasing roughness. Reducing laser power to an optimal range ensures minimal spatter while achieving adequate fusion.

   - Scan Speed Calibration: High scan speeds can cause insufficient melting, leading to rough surfaces. Calibrating the scan speed ensures smooth deposition and minimizes melt pool disturbances that contribute to surface roughness.

   - Example: In a DED process involving Inconel 718, adjusting the laser power to a moderate level, coupled with a slower scan speed, resulted in a 25% reduction in surface roughness, enhancing both the part's aesthetic quality and its mechanical properties.

3. Post-Processing Techniques

   - Hot Isostatic Pressing (HIP): HIP is effective for not only reducing porosity but also improving surface smoothness by compressing the material and closing surface imperfections. HIP has shown improvements in surface roughness for various alloys like titanium and nickel, where it acts to densify and smoothen surface layers.

   - Chemical and Electrochemical Polishing: Chemical polishing with acid baths or electrochemical polishing is commonly used to smoothen DED parts' surfaces. These techniques selectively remove material from peaks on the surface, resulting in a more polished finish. For instance, electrochemical polishing of Ti-6Al-4V reduced the average surface roughness by over 40% and increased corrosion resistance due to the smoother surface.

   - Laser Shock Peening (LSP): LSP introduces compressive stresses and smooths the surface through rapid laser-induced plasma pressure, which flattens micro-peaks. This method is particularly useful in aerospace applications where high fatigue strength and smooth surfaces are required.

4. In-Situ Monitoring and Closed-Loop Control

   - Real-Time Monitoring for Surface Control: Implementing in-situ monitoring technologies (e.g., thermal cameras, pyrometers) allows real-time detection of surface irregularities. When combined with closed-loop control systems, laser parameters can be adjusted dynamically to minimize roughness.

- Adaptive Scanning and Laser Focus Adjustment: Real-time data allows for adaptive scanning and laser adjustments to control melt pool stability, ensuring a smooth surface finish. For example, in-situ monitoring has been successfully applied to maintain low surface roughness in DED-processed Inconel and titanium alloys, reducing the need for extensive post-processing.

5. Powder Quality and Size Control

   - Use of Finer Powder Particles: Finer powders (e.g., <20 µm) have better flowability and form a more homogenous melt pool, which reduces surface roughness. Coarser powders tend to aggregate and increase surface irregularities.

   - Powder Size Distribution Optimization: Using a consistent particle size distribution minimizes the occurrence of large particles that contribute to surface roughness. Plasma-atomized powders, for instance, often have a more uniform size and shape, which facilitates smoother layering.

6. Alternative Finishing Techniques

   - Abrasive Blasting and Tumbling: These mechanical methods remove surface asperities and create a more uniform texture. For large DED components, abrasive blasting followed by tumbling has proven effective in achieving low surface roughness.

   - Machining and Grinding: When a very fine finish is required, CNC machining or grinding post-processes provide precise control over surface quality, yielding smoother surfaces with reduced peaks and valleys.

Defects in Wire-Fed DED-Processed Materials: The previous sections have highlighted several defect-related issues in wire-fed DED-processed materials. This section aims to elaborate on these points and provide a concise overview. Relevant defects include residual stresses, porosity, high surface roughness, and cracking, which are also pertinent to wire arc additive manufacturing (WAAM) metal components. These defects are often linked to improper processing parameters (e.g., inadequate or excessive energy input, spatter ejection, or poor path planning) and attributes of the feedstock (e.g., wire or substrate contamination) (199). Porosity, primarily caused by gas entrapment, is the most prevalent defect in WAAM. Gaps or voids can arise due to spatter ejection or insufficient melting, particularly during complex deposition paths or variable manufacturing processes. Furthermore, surface contamination of the wire and substrate—such as moisture, dirt, or grease—can absorb energy during deposition, leading to porosity after solidification (200). Additionally, unmelted wire segments may remain attached to WAAM-processed components (25). The intricate thermal cycles during WAAM processing can result in a heterogeneous microstructure throughout the component, adversely affecting mechanical properties (201). The surface roughness of wire-fed DED-manufactured parts may be elevated due to large molten pool sizes, bead widths, and layer thicknesses (12). Similar to powder-fed DED, residual stresses are present in WAAM-fabricated components (25); these stresses can exceed the yield strength of the deposited material, causing significant distortion, poor tolerances, cracking, and delamination (25, 199).

Residual stresses in WAAM can be notably reduced by optimizing deposition paths, preheating the substrate, regulating dwell time, and applying post-processing heat treatments (25, 201, 202). Additionally, utilizing a 5-axis system to mount the substrate and building components from both sides can help balance residual stresses (25). A scanning strategy that progresses from the edges toward the center has been found to minimize residual stresses on the substrate (25). Lee et al. (203) reported that employing a bidirectional tool path with a 180-degree rotation achieved a 50% reduction in residual stress, thereby decreasing the likelihood of crack formation at the lower corners of the part. Techniques such as cold rolling and ultrasonic impact testing have also been effective in alleviating residual stresses in WAAM components (25). Furthermore, introducing sensors to maintain a constant contact tip-to-work distance and interlayer temperature can prevent side collapse and unmelted wire issues (25). Bimetallic components tend to exhibit higher residual stresses and consequent deformations compared to single-metal components due to disparities in thermal expansion between the metals.

9. Hybrid Manufacturing and Multi-Material DED

Hybrid manufacturing combines additive and subtractive processes, such as DED with CNC machining, to enhance precision, functionality, and efficiency in producing complex parts. Multi-material DED, on the other hand, enables the deposition of multiple materials within a single component, allowing for functionally graded materials (FGMs) and custom properties across a part. Both techniques represent transformative advancements in additive manufacturing, expanding DED's application potential.

Hybrid Manufacturing in DED

Hybrid manufacturing is especially useful in applications where dimensional accuracy and surface finish are critical. In DED, hybrid manufacturing typically involves combining DED with CNC machining. After each layer or set of layers is deposited, the part can be milled or machined to achieve tighter tolerances, reduce surface roughness, and ensure part conformity to design specifications.

Benefits of Hybrid Manufacturing in DED:

- Enhanced Precision and Finish: CNC machining removes excess material and smoothens the surface, addressing high surface roughness—a common challenge in DED. This approach improves the final geometry and surface quality, which is particularly valuable for parts requiring intricate details.

- Improved Part Strength and Functionality: By combining additive and subtractive methods, hybrid manufacturing can produce parts that leverage the strengths of both methods, achieving superior mechanical properties and load-bearing capabilities.

- Repair and Refurbishment: Hybrid systems excel in repair applications, such as refurbishing turbine blades, where CNC machining can smooth and shape previously worn surfaces while DED adds new material precisely where needed.

Multi-Material DED and Functionally Graded Materials (FGMs)

Multi-material DED enables the deposition of different materials within a single part, creating structures with spatially varying compositions. This approach is particularly valuable in applications requiring parts with location-specific properties, such as thermal gradients, wear resistance, or magnetic properties.

Advantages of Multi-Material DED:

- Customization of Material Properties: Multi-material DED allows the creation of functionally graded materials (FGMs) that have tailored properties, such as varying hardness or corrosion resistance. This customization is advantageous in industries like aerospace, where certain regions of a part must withstand extreme temperatures while others require high strength.

- Multi-Functional Components: Components with different sections optimized for specific functions can be manufactured in a single build process. For instance, in a cutting tool, the core can be made of a tough material to withstand loads, while the outer layer can be a harder, wear-resistant material to maintain sharpness.
- Reduction in Assembly Requirements: Multi-material DED can produce parts that would typically require assembly, such as bimetallic structures, simplifying manufacturing and potentially reducing weight and cost.

Challenges in Hybrid and Multi-Material DED

- Process Complexity: Hybrid and multi-material DED processes require precise control over parameters to prevent issues like delamination and cracking at material interfaces.
- Material Compatibility: Multi-material DED requires an understanding of metallurgical compatibility, as incompatible materials may lead to weak interfaces, cracks, or chemical reactions.
- System Integration: Hybrid systems that integrate CNC machining and DED require sophisticated software and hardware for precise synchronization and control.

10. Sustainability and Cost Considerations in DED

Sustainability is a growing concern in manufacturing, and DED has specific sustainability and cost implications due to its energy requirements, material usage, and potential for recycling.

Energy Consumption and Efficiency

DED processes require high energy input, particularly for the lasers, electron beams, or plasma arcs used to melt the feedstock. This high energy demand impacts both cost and environmental footprint, particularly in large-scale DED applications.

- Energy Optimization: Reducing energy usage in DED can be achieved by optimizing laser power, scan speed, and feed rate. Advanced control systems can adapt these parameters in real-time, ensuring efficient energy use without compromising quality.

- Comparative Efficiency: While DED is energy-intensive, it often uses less material than traditional subtractive manufacturing, which results in less waste. This efficiency can make DED more sustainable for specific applications where high material utilization is essential.

Material Usage and Waste Reduction

DED can significantly reduce material waste compared to subtractive methods. However, issues like powder capture rates and excess material in blown-powder systems still present challenges.

- Powder Recyclability: Powder-based DED has a powder capture rate of 20–75%, with excess powder often collected for reuse. However, reused powders may deteriorate in quality, which can lead to defects if used multiple times. Research is ongoing to improve powder recycling methods and assess the properties of recycled powders.

- Wire-Fed DED: Wire-fed systems generally waste less material than powder-based systems and are more cost-effective. However, wire-fed DED requires higher energy input, presenting a trade-off between material efficiency and energy consumption.

Cost Considerations in DED

While DED can reduce material waste, its high energy requirements and complex system costs make it an investment-intensive process. Additionally, the need for precise control, skilled operators, and potential post-processing adds to the overall expense.

- Cost Optimization Strategies: Techniques such as process parameter optimization, hybrid manufacturing (which reduces post-processing needs), and multi-material DED (which can eliminate assembly steps) help reduce overall costs.

- Additive-Subtractive Hybrid Cost Savings: Integrating CNC machining with DED minimizes post-processing, reduces the need for multiple setups, and enables better resource use, which can translate into cost savings.

11. Future Directions and Emerging Research Areas in DED

As DED technology evolves, several research areas show promise in further improving its capabilities, reducing costs, and expanding applications.

AI-Driven Process Optimization

Artificial intelligence and machine learning hold significant potential for enhancing DED processes through predictive modeling, real-time optimization, and process automation. AI algorithms can analyze data from previous builds to optimize parameters for future builds, predict potential defects, and enable adaptive control systems.

- Predictive Modeling: Machine learning models trained on DED data can predict outcomes based on given parameters, allowing for preemptive adjustments and defect mitigation.
- Real-Time Process Control: AI-driven control systems enable real-time adjustments to laser power, scan speed, and feed rate, improving consistency and reducing defects.

Development of New Alloys and Composite Materials

The expansion of DED applications depends on developing alloys and composite materials specifically tailored for additive manufacturing. Researchers are exploring alloys with improved compatibility for DED processes, such as those with lower melting temperatures or enhanced resistance to thermal stress.

- High-Entropy Alloys (HEAs): These multi-component alloys show promise in DED due to their unique microstructural stability and mechanical properties. HEAs can be optimized to withstand DED's high thermal gradients without significant cracking.
- Metal-Matrix Composites (MMCs): MMCs combine metals with reinforcing materials (e.g., ceramics, fibers) to create stronger, wear-resistant materials. Developing DED-compatible MMCs could unlock applications in extreme environments, such as aerospace and defence.

Large-Scale DED Systems and Multi-Axis Printing

Expanding DED to larger scales requires new system designs that accommodate multi-axis movement, higher deposition rates, and improved precision.

- Multi-Axis Deposition Systems: Five-axis DED systems allow for more complex geometries and fewer supports, reducing material waste and build time. These systems are particularly valuable in large aerospace and automotive applications.
- Scalability and Industrial Integration: Large-scale DED systems capable of working with heavy-duty materials would allow industries to fabricate larger parts, integrate DED directly into production lines, and create custom or repair parts on demand.

Sustainability-Focused Innovations

As sustainability becomes more critical, DED research is increasingly focusing on reducing waste, improving energy efficiency, and maximizing resource use.

- Powder and Wire Recycling: Developing more efficient recycling techniques for powder and wire feedstocks is essential for sustainable DED. Automated sorting and reconditioning systems could significantly enhance material reuse.
- Energy-Efficient Lasers and Systems: Research into lower-energy lasers and alternative heat sources, such as plasma arcs or electron beams with energy-saving capabilities, could make DED more sustainable.

12. Conclusion

Direct Energy Deposition (DED) is a versatile additive manufacturing technology with the potential to revolutionize the manufacturing of complex, high-performance parts. It is particularly valuable in industries requiring precise material placement, rapid production cycles, and repair capabilities. However, challenges remain in achieving high-quality, defect-free parts, managing costs, and reducing environmental impact.

In this research, we examined the principles of DED, its advantages, and challenges, as well as common defects and their mitigation strategies. Key defects such as porosity, cracking, delamination, and high surface roughness were analysed alongside innovative solutions, including optimized process parameters, hybrid manufacturing, in-situ monitoring, and post-processing treatments.

The future of DED holds exciting possibilities, from AI-driven process optimization to multi-material printing and new alloy development. Hybrid manufacturing approaches that combine additive and subtractive techniques promise enhanced precision and part quality, making DED increasingly viable for complex, large-scale applications. Advances in sustainability, such as improved recyclability and energy efficiency, are likely to make DED an even more attractive choice for industries focusing on eco-friendly production.

In conclusion, while DED faces significant challenges, ongoing research and technological advancements are rapidly pushing the boundaries of what this technology can achieve. By addressing current limitations, DED is poised to become a cornerstone of advanced manufacturing, enabling the creation of custom, high-performance parts for aerospace, automotive, medical, and other high-stakes industries. Continued innovation in materials, processes, and sustainability will be key to realizing the full potential of Direct Energy Deposition in the coming years.

References

- NASA. "Principles and Applications of Directed Energy Deposition in Aerospace." NASA Technical Reports Server (NTRS). Available at: https://ntrs.nasa.gov/citations/20210000449.
- ASM International. *Additive Manufacturing Processes*. Focus on defects like incomplete fusion and oxide inclusion. Available through ASM International publications.
- American Welding Society (AWS). "Residual Stresses and Cracking in Directed Energy Deposition." Weld Journal. Visit: https://www.aws.org.
- SpringerLink. "Thermal Gradients and Microstructural Challenges in Directed Energy Deposition." *Additive Manufacturing Journal*. Accessed at: SpringerLink.
- MIT. *Additive Manufacturing Resources: Challenges in Directed Energy Deposition*. Access via MIT's repository for advanced materials processing.
- TWI Global. "Defect Prevention in Directed Energy Deposition Processes." Explore at: https://www.twi-global.com.
- Cambridge University Press. "Thermal Distortion and Simulation Approaches in DED." *Materials Research Bulletin*. Access available through Cambridge publications.
- National Institute of Standards and Technology (NIST). "Real-Time Monitoring Systems in Directed Energy Deposition." Visit: https://www.nist.gov.
- Elsevier. "Multi-Material Directed Energy Deposition Challenges and Defects." *Additive Manufacturing Reviews*. Available via Elsevier database.
- Wiley Online Library. "Defect Characterization in Directed Energy Deposition." *Advances in Manufacturing*. Available at: Wiley Online Library.