DIRECT ENERGY DEPOSITION

DEFECTS AND ITS TREATMENT

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Submitted to-

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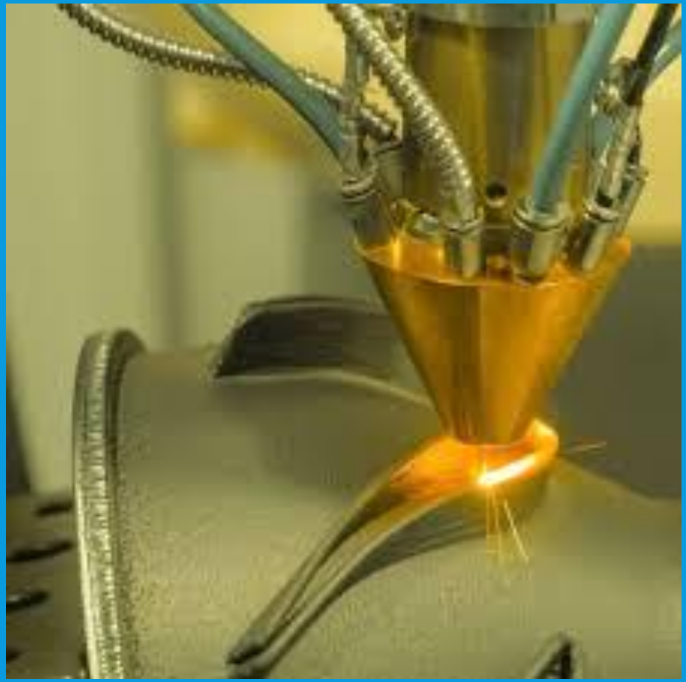
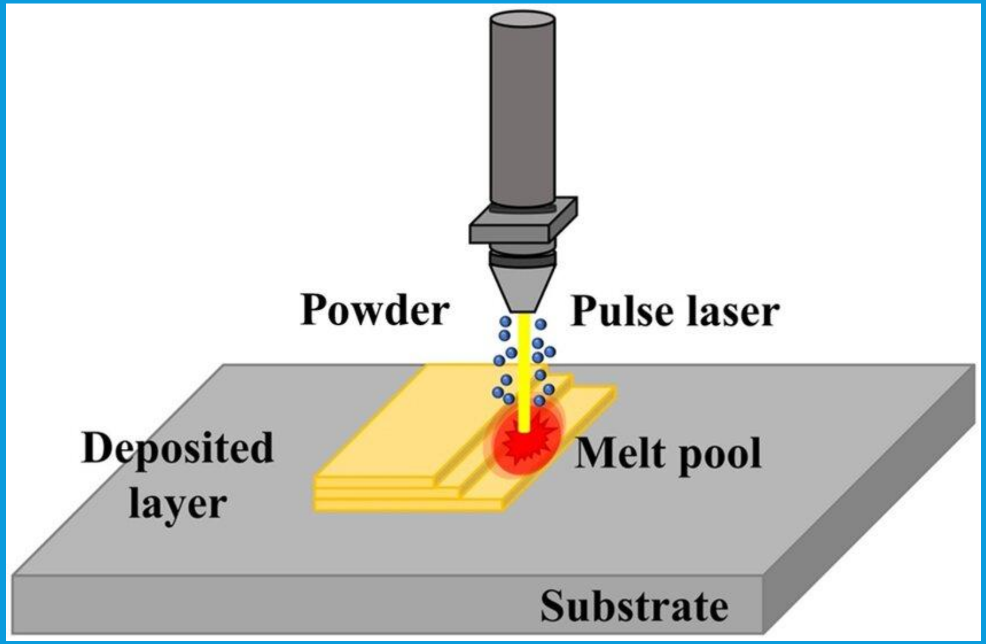
INTRODUCTION

•Directed Energy Deposition (DED) is an additive manufacturing technique that uses a high-energy heat source (laser, electron beam, or plasma arc) to melt wire or powder feedstock, building parts layer by layer.
•DED can process a variety of materials like high-performance alloys, ceramics, and composites, producing complex, near-net shape geometries.
•Originally developed for rapid prototyping, DED is now widely used in industries such as aerospace, automotive, and energy for making intricate and lightweight components.



PRINCIPLES OF DED

- Directed Energy Deposition (DED) builds or repairs 3D objects by melting feedstock material (wire or powder) using a concentrated energy source (laser, electron beam, or plasma arc) and depositing it layer by layer.
- Lasers are commonly used for precision and localized melting, while plasma arcs and electron beams offer faster deposition for larger parts.
- The feedstock material is delivered into the melt pool, where it combines with the substrate and solidifies, with the energy source following CAD-based paths to build the part layer by layer.
- The cooling and solidification process forms a monolithic structure, but rapid thermal cycles can lead to defects like porosity and cracking, requiring post-processing or optimization.



ADVANTAGES OF DIRECT ENERGY DEPOSITION

- DED offers high precision for creating new parts and repairing damaged components, making it valuable in industries like aerospace and military for extending component life.

- It supports multi-material deposition, enabling the creation of parts with specific properties in different areas.

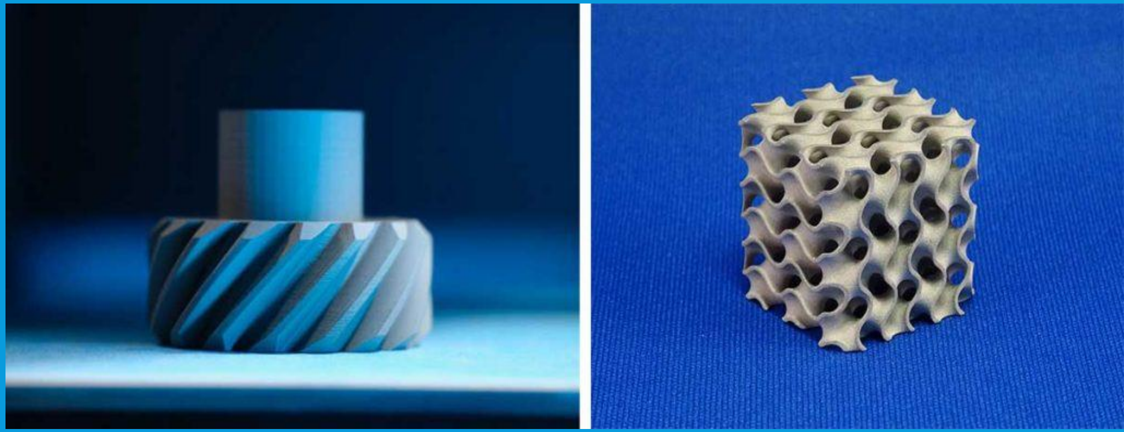
- DED is ideal for advanced applications, allowing for the production of functionally graded materials (FGMs) with varied material characteristics in a single build.

DISADVANTAGES OF DIRECT ENERGY DEPOSITION

DED requires precise control of process variables such as laser power, feedstock flow rate, and scan speed to prevent defects like porosity, cracking, and partial fusion.

High energy input and localized heating can create significant temperature gradients, leading to residual stresses and part distortion.

Large or complex components are particularly vulnerable, often requiring careful process planning and post-processing techniques, like stress-relief annealing, to mitigate these effects.

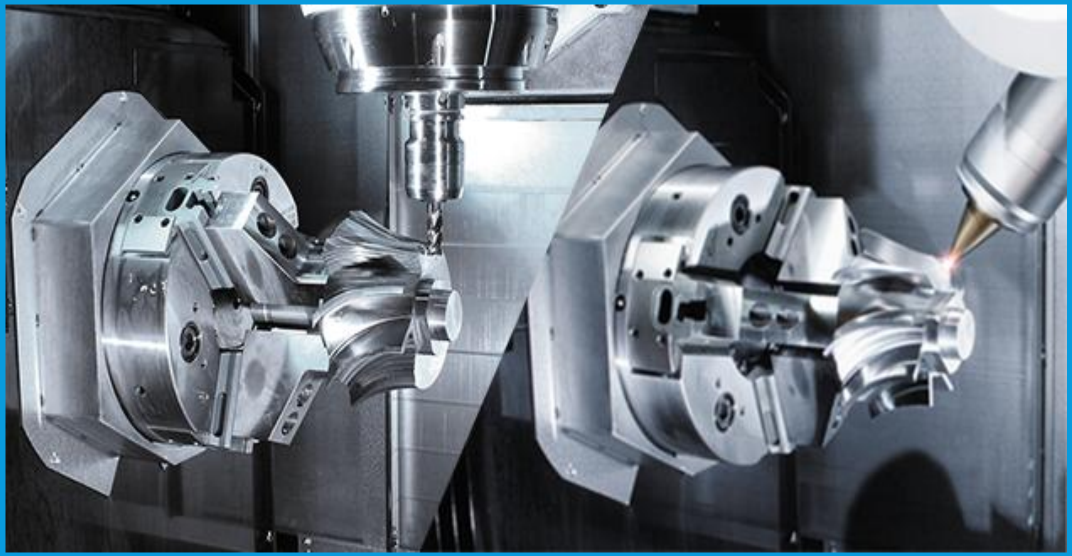


APPLICATION OF DIRECT ENERGY DEPOSITION

- DED is widely used in industries requiring complex geometries and high-performance materials, such as aerospace, automotive, biomedical, and energy, for precision material deposition and multi-material parts production.
- In the energy sector, DED efficiently repairs critical components like turbine blades and produces durable parts for renewable energy systems, extending the life of power generation equipment.
- The automotive industry uses DED to repair expensive tools like molds and dies and to produce lightweight, high-performance components for electric vehicles (EVs), improving energy efficiency and reducing waste.
- DED plays a vital role in aerospace, allowing for the localized repair of high-value parts like turbine blades and engine casings, reducing downtime and improving fuel efficiency in next-generation aircraft.

CURRENT CHALLENGES IN DED

- **Scientific & Technical Challenges**: DED faces limitations compared to Powder Bed Fusion (PBF), including inferior tolerances and the need for more precise control in hybrid systems (HAM) combining DED with CNC machining.
- **Material Loss & Recyclability**: Only 20-75% of powder reaches the part, leading to higher waste, complex recycling, and challenges in using pre-mixed powders for multi-material parts.
- **Metallurgical Compatibility**: Rapid cooling and non-equilibrium thermodynamics make it difficult to apply traditional phase diagrams, requiring trial and error to prevent defects like cracking in multi-material structures.
- **Machine-Related Issues**: Three-axis DED heads limit geometry complexity, and higher laser power may improve speed but reduce part resolution. Wire-feed DED systems offer a cost-effective alternative but require higher laser power.

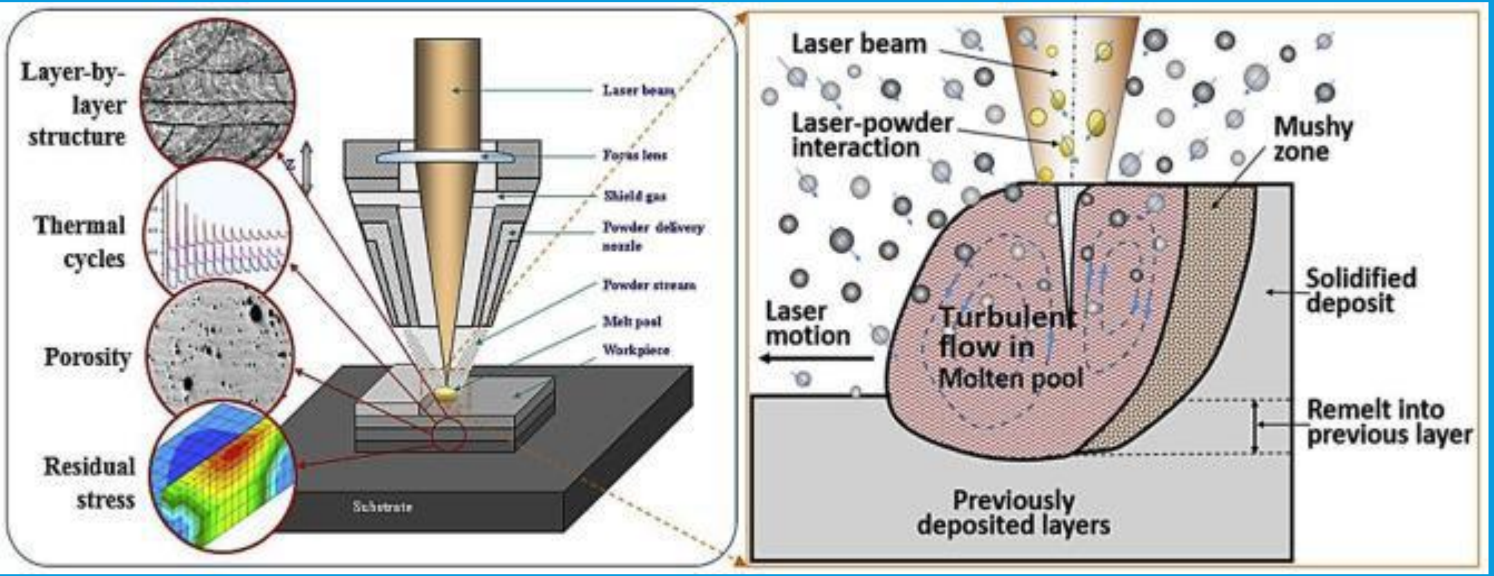


Hybrid Additive Manufacturing

LASER-MATERIAL INTERACTION

Laser-Powder Interaction

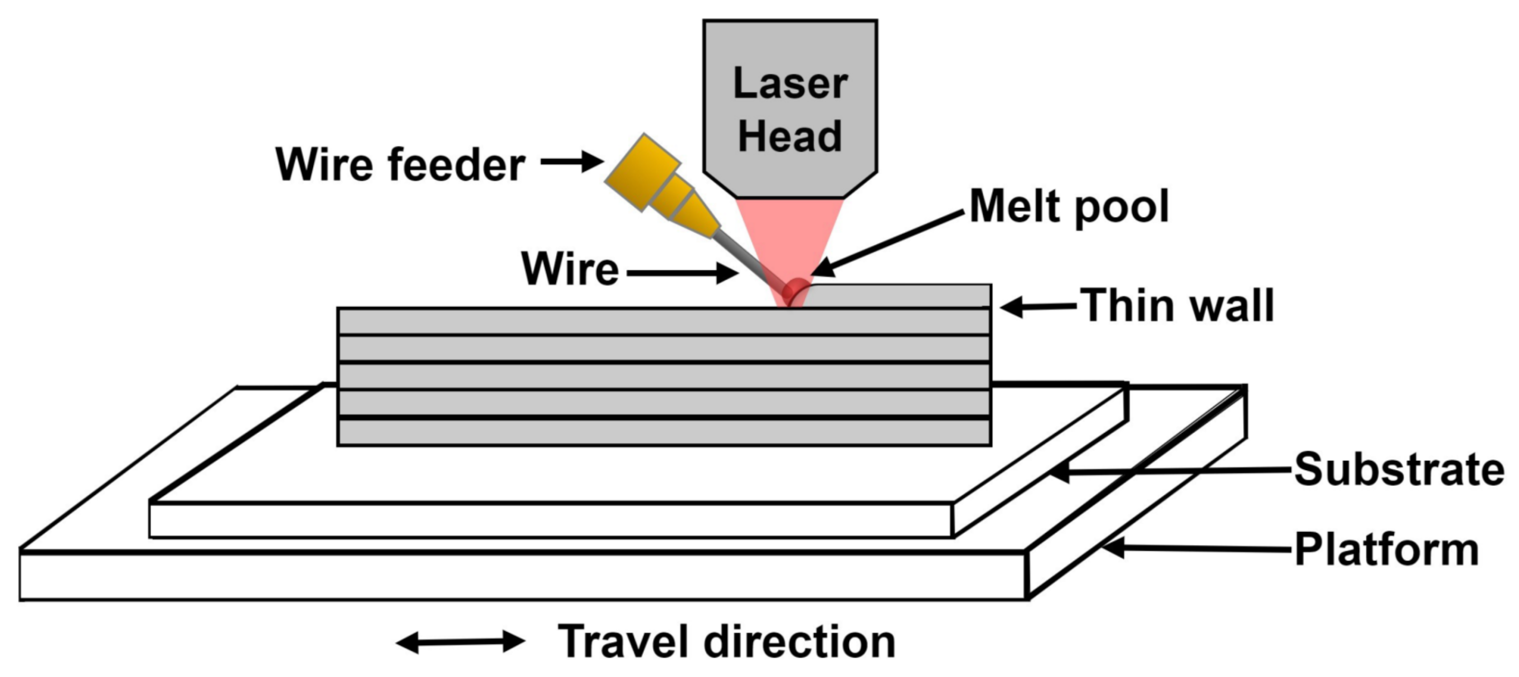
In laser powder-based DED (Directed Energy Deposition), powder is fed with an inert gas and directed toward the melt pool through multiple nozzles. The powder streams converge, interacting with the laser beam and melt pool. As a result, the material undergoes heating, melting, and solidification, forming layers. The process involves repeated thermal cycles, leading to pores and residual stresses in the deposited structure, as shown in the figure.



Laser–Wire Interactions

In laser wire-based DED, precise control of laser-wire interactions is essential, with factors like laser power, speed, and wire feed rate having a major impact. Additional parameters, such as the angles, wire tip position, and feed direction, also require careful adjustment. Wire is deposited through methods like globular transfer or plunging, and continuous contact between the molten wire tip and melt pool is crucial for defect-free results.

Closed-loop monitoring with visual sensing in laser wire-based DED improves stability by tracking wire tip interactions with the melt pool. Excess energy or improper wire feed can cause defects, and further research is needed to fully understand laser-wire interaction mechanisms.



DOMINANT PROCESSING VARIABLE IN DED

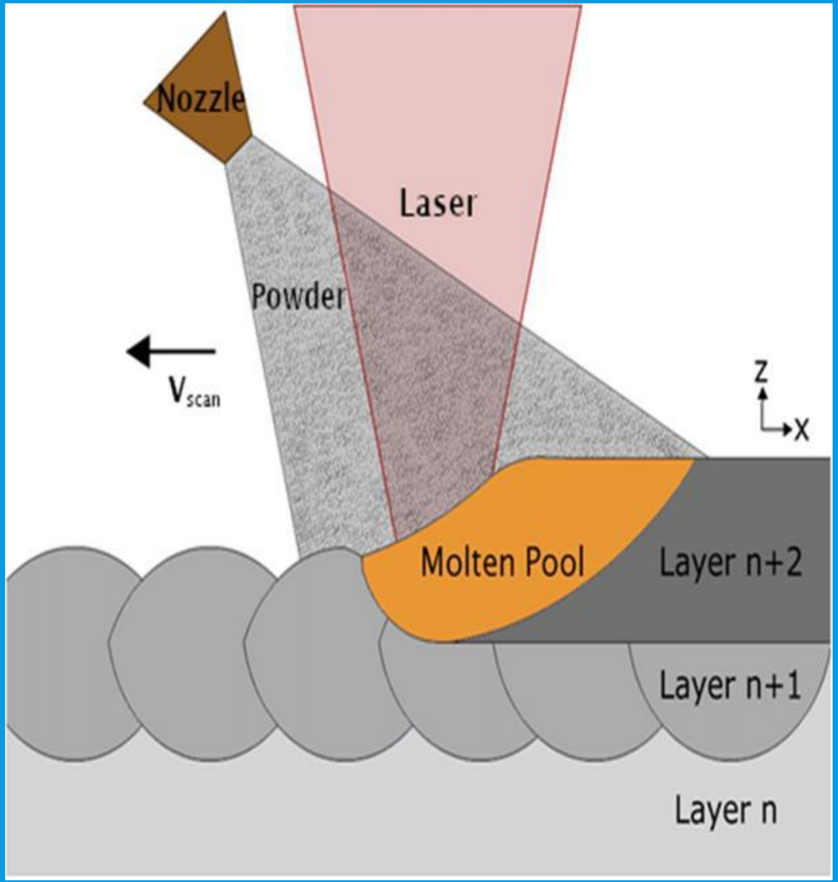
- The effective energy density E (J/mm^2) and powder density F (g/mm^2) are widely used as combined parameters for evaluating continuous deposition and deposit aspect ratios. The formulas for E and F are given by:

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

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).

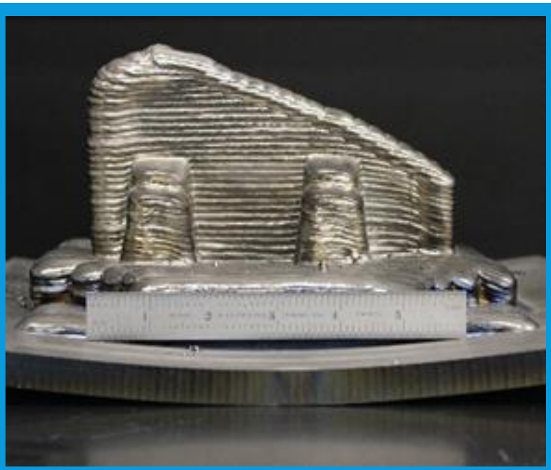


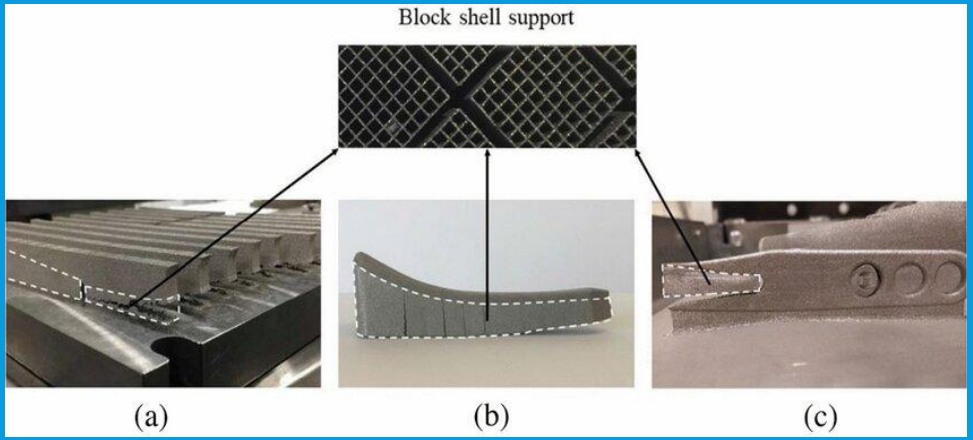
DEFECTS IN DEPOSITED MATERIAL AND THEIR CHARACTERIZATION WITH MITIGATION STRATEGIES

- Residual Stresses and Distortion
- Porosity
- Cracking and Delamination in DED-Fabricated Components
- High Surface Roughness

1. RESIDUAL STRESSES AND DISTORTION

- **Origin of Residual Stresses:** In DED processes, residual stresses arise from the layer-by-layer deposition, causing complex thermal cycles of melting and reheating. These rapid cooling rates and steep thermal gradients lead to phase transformations and microstructural changes. Residual stresses can be non-uniform and vary in spatial distribution, similar to stresses seen in fusion welding.
- **Effects on Materials:** Residual stresses can cause issues like distortion, loss of accuracy, cracking, delamination, and accelerated crack growth, potentially leading to premature part failure.
- **Measurement of Residual Stresses:** Residual stresses are measured using destructive methods (e.g., hole drilling) and non-destructive techniques (e.g., diffraction and sound speed methods). Computational models also predict stress distribution over time.





Residual Stresses developed

MITIGATION APPROACHES FOR RESIDUAL STRESS AND DISTORTION

1. Substrate and Chamber Preheating:

•Preheating the substrate reduces thermal gradients, lowering residual stresses and distortions, especially in high-stress materials like Inconel and Ti-6Al-4V.

•Chamber heating further reduces stresses but may be cost-prohibitive for larger parts.

2. Process Parameter Optimization:

•Controlling laser power and scan speed helps manage cooling rates and stress accumulation.

•Thinner layers reduce residual stresses but may extend build time.

3. Optimized Scan Strategy:

•Varying scan patterns (checkerboard, fractal) distribute heating more evenly, reducing stress build-up and warping.

4. Post-Processing Stress Relief Techniques:

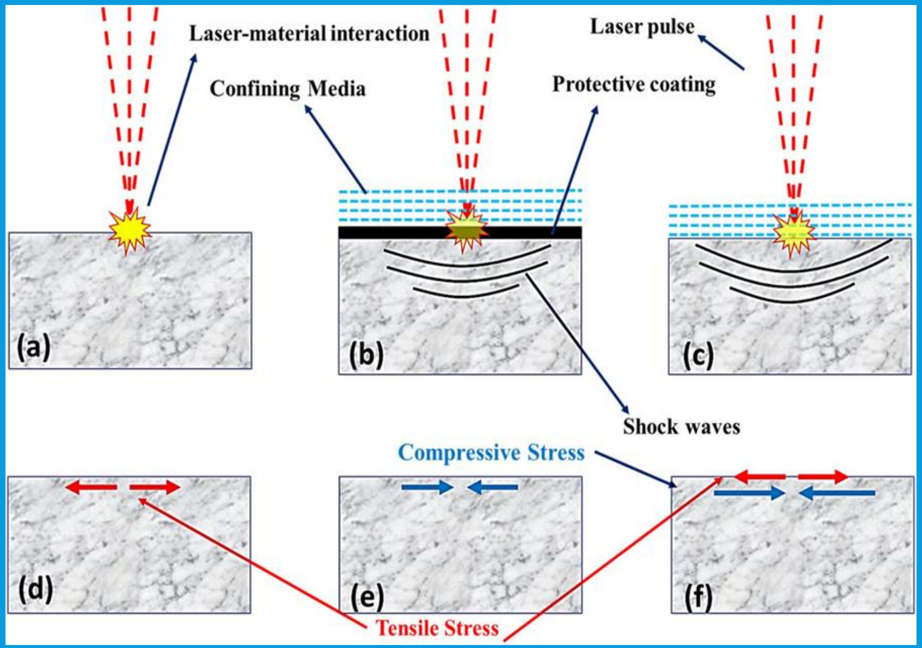
•**Thermal Stress Relief:** Heating parts after fabrication redistributes stresses, improving fatigue resistance.

•**Hot Isostatic Pressing (HIP):** Simultaneous high pressure and heat reduce residual stresses and porosity, ideal for aerospace and medical applications.

5. Mechanical Stress Relief Techniques:

•**Laser Shock Peening (LSP):** Induces beneficial compressive stresses to counter surface-level tensile stresses.

•**Surface Rolling or Shot Peening:** Applies compressive forces to prevent distortion and cracking but is limited to surface layers.



Effect of Laser Shock Peening

2. POROSITY

❑**Causes of Porosity in DED**:

•**Keyholes**: Form due to high energy density during deposition, causing vaporization and gas entrapment.

•**Gas Porosity**: Arises from gas trapped in the feedstock, selective alloy element evaporation, or shielding gas in the molten pool.

•**Lack of Fusion (LoF)**: Occurs when the melt pool does not penetrate the substrate or previous layers due to insufficient energy input.

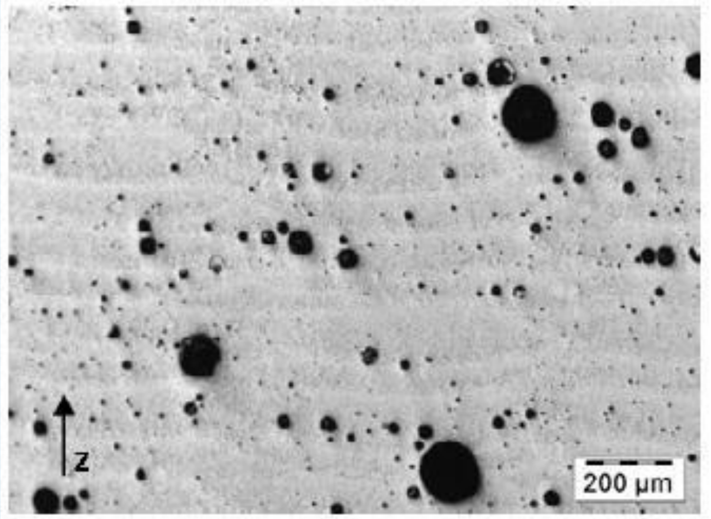
❑**Types of Pores**:

•**Keyhole Pores**: Large, circular horizontally, elongated or tapered in the build direction.

•**Gas Pores**: Small and spherical.

•**LoF Pores**: Larger, irregularly shaped.

•**Sphericity Factors**: Below 0.6 for LoF, above 0.7 for keyholes, over 0.92 for gas porosity.



MITIGATION STRATEGIES FOR POROSITY

1. Optimization of Energy Density:

•**Laser Power and Scan Speed Adjustment**: Balancing energy input is crucial to control porosity. High energy can cause keyholing, while low energy may lead to LoF. An optimal energy density (e.g., 125 J/mm³ in AlSi10Mg) reduces porosity.

•**Powder Mass Flow Rate Control**: Adjusting the powder flow rate helps control the amount of powder reaching the melt pool, preventing LoF porosity and ensuring thorough bonding between layers.

2. Powder Feedstock Quality Control:

•**Use of High-Quality Feedstock**: Powders produced via plasma or gas atomization, which are spherical with low internal porosity, improve flowability and reduce gas entrapment, minimizing porosity.

•**Powder Drying and Storage**: Moisture and contaminants in powders can cause gas porosity. Drying powders (e.g., Inconel 718) reduces porosity, while proper storage prevents moisture contamination.

3. Post-Processing Hot Isostatic Pressing (HIP):

- **HIP for Porosity Elimination**: HIP uses high temperature and pressure to collapse internal pores, improving density and ductility. It is effective for eliminating LoF pores but may not remove chemically bonded gases like oxygen.
- **Limitations of HIP**: Not all porosity is eliminated, particularly if gases are chemically bonded within the material.

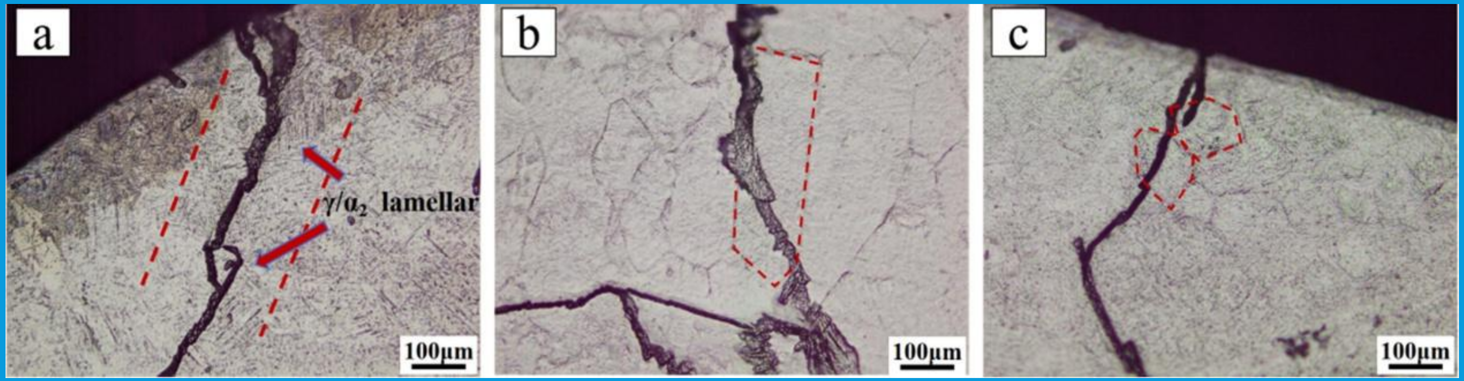
4. Advanced In-Situ Monitoring and Closed-Loop Control Systems:

- **Real-Time Monitoring**: In-situ systems (e.g., thermal cameras, X-ray, acoustic sensors) detect porosity during deposition, providing feedback on melt pool characteristics.
- **Closed-Loop Control Systems**: These systems adjust parameters (laser power, powder flow rate, scan speed) in real time, using machine learning to predict and reduce porosity during the deposition process.

3. CRACKING AND DELAMINATION

Origins of Cracking and Delamination in DED:

- **Delamination**: Separation of layers or from the baseplate caused by residual stresses exceeding the material's yield strength. It often results from unmelted powder or inadequate remelting of layers, particularly at the build-baseplate interface where stress concentrations are high.
- **Cracking**: A major challenge for metal AM, especially for metals prone to cracking in traditional welding. Cracks typically fall into three types:
    - **Solidification Cracking (Hot Cracking)**: Occurs along grain boundaries due to higher contraction in hotter upper layers, causing tensile stresses.
    - **Liquation Cracking**: Happens in the partially melted zone (PMZ) when grain-boundary precipitates melt and tensile stresses arise during cooling and solidification.
    - **Ductility Dip Cracking**: Intergranular cracking at elevated temperatures in certain face-centered cubic (FCC) alloys.



MITIGATION STRATEGIES FOR CRACKING

1. Preheating of Substrate and Build Chamber:

•Reduces thermal gradients and cooling rates, minimizing stress and crack initiation.

•Preheating to 200-400°C (e.g., Ti-6Al-4V) reduces cracking by up to 50%.

2. Optimized Process Parameters:

•**Laser Power & Scan Speed**: Adjusting to balance energy input prevents excessive thermal gradients.

•**Powder Feed Rate & Layer Thickness**: Lower feed rates and thinner layers ensure even energy distribution, reducing cracking.

•**Control of Cooling Rates**:

•Controlled cooling and active cooling systems (air/gas jets) prevent rapid thermal contraction, reducing cracking risk.

3. Optimized Scanning Strategies:

•Use patterns like checkerboard or island scanning for more even heat distribution.

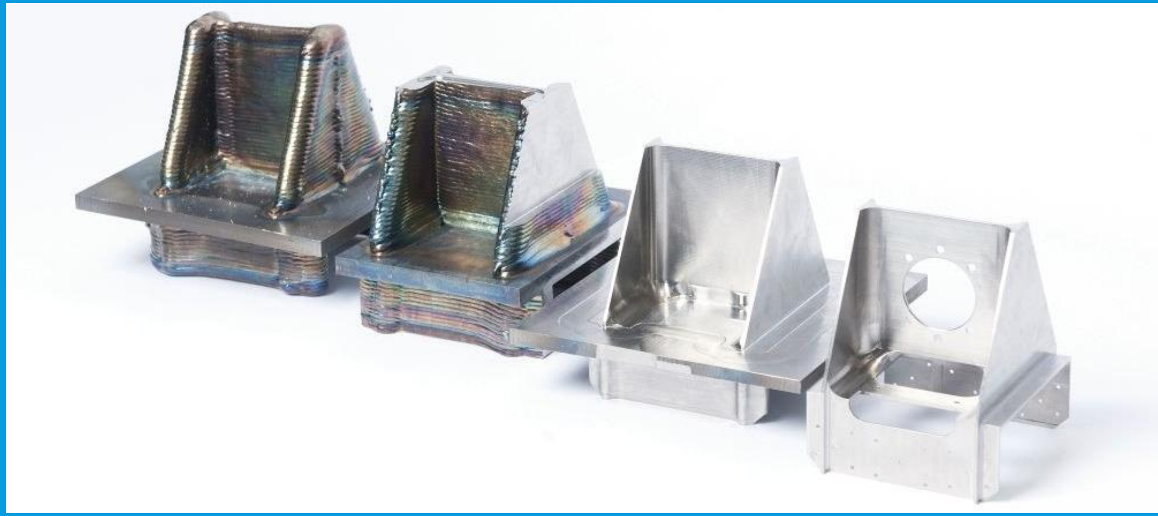
•Complex scanning (e.g., Hilbert curve) further reduces stress and crack formation.

4. SURFACE ROUGHNESS

❑**Origin of Surface Roughness**:

Surface roughness in Directed Energy Deposition (DED) results from several factors:

- **Partially melted powder particles**: Caused by insufficient heat input and the use of larger powder particles.
- **Balling effects**: Due to Rayleigh instability, leading to fragmentation of the molten pool at high laser speeds.
- **Stair-stepping phenomenon**: A limitation in layered manufacturing, especially on inclined or curved surfaces.
- **Molten material splashing**: Contributing to uneven surface finish.



Surface Roughness Treatment

MITIGATION TECHNIQUES FOR HIGH SURFACE ROUGHNESS

1. Layer Thickness Optimization:
Reducing layer thickness minimizes the stair-stepping effect, especially on sloped or curved surfaces. This results in smoother surfaces and reduced roughness.
•*Example*: Reducing layer thickness from 0.4 mm to 0.2 mm reduced surface roughness by 35% in stainless steel.

2. Laser Power and Scan Speed Adjustments:
•**Laser Power**: Excessive power causes splattering; optimizing power minimizes surface roughness.
•**Scan Speed**: Calibrating scan speed prevents insufficient melting, ensuring smoother surfaces.
•*Example*: Adjusting laser power and scan speed in Inconel 718 reduced surface roughness by 25%.

3. Post-Processing Techniques:
•**Hot Isostatic Pressing (HIP)**: Reduces surface imperfections and improves smoothness.
•**Chemical and Electrochemical Polishing**: Smoothens surfaces by selectively removing material from peaks.
•**Laser Shock Peening (LSP)**: Reduces micro-peaks by introducing compressive stresses, useful for aerospace applications.

4. Powder Quality and Size Control:
•**Finer Powder Particles**: Provide better flowability and smoother melt pools.
•**Optimized Powder Size Distribution**: Ensures uniform melting, reducing roughness. Plasma-atomized powders offer better size and shape consistency.

SUMMARY

Direct Energy Deposition (DED) is a versatile additive manufacturing technology that enables precise material placement, rapid production, and repair of high-performance parts. Despite challenges like porosity, cracking, delamination, and high surface roughness, solutions such as optimized process parameters, hybrid manufacturing, in-situ monitoring, and post-processing treatments are being developed. The future of DED includes AI-driven process optimization, multi-material printing, and advances in sustainability, improving its precision and eco-friendliness. As ongoing research addresses current limitations, DED is poised to play a key role in industries like aerospace, automotive, and medical.

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