

A COMPREHENSIVE REVIEW OF SCANNING PATTERNS IN DIRECT LASER METAL DEPOSITION FOR OPTIMIZING PROCESS AND PART QUALITY

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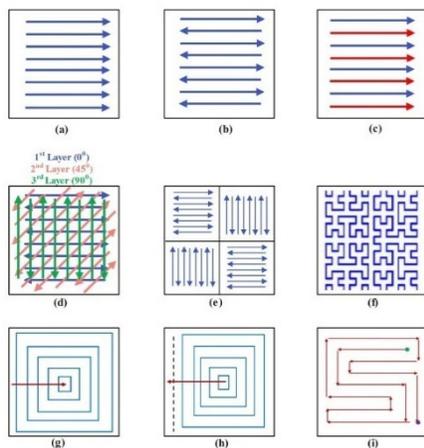
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Article history

Received
31 December 2024
Received in revised form
14 April 2025
Accepted
25 June 2025
Published online
28 February 2026

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Graphical abstract



Abstract

Directed Energy Deposition (DED) has emerged as a transformative technology in additive manufacturing, enabling the efficient repair of high-cost metal parts and the creation of complex, customized components. This paper critically reviews the influence of scanning patterns in powder-based laser DED on part quality, focusing on how different patterns develop common defects such as cracks, porosity, distortion, and residual stresses. By synthesizing past research, this review reveals the impact of scanning patterns on key factors, including surface texture, substrate deformation, microstructure, and the anisotropy of mechanical properties. A comparative analysis of different shaped scanning paths highlights their respective advantages and limitations in achieving optimal part performance. While established patterns like raster and S-shaped paths show promising improvements in dimensional accuracy and surface finish, issues such as poor fusion, porosity, and uneven heat distribution persist. The review concludes that while carefully applying current scanning patterns can enhance part quality, further optimization is essential to reduce defects and improve fusion and residual stress management. Future research should focus on refining conventional scanning patterns or the development and application of innovative deposition patterns to maximize the potential of laser-based DED.

Keywords: Directed Energy Deposition, Direct Laser Metal Deposition, Additive Manufacturing, Scanning Paths, Scanning Patterns

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1.0 INTRODUCTION

1.1 The Rising Significance of Metal Additive Manufacturing

Additive Manufacturing (AM) is process that constructs three-dimensional (3D) solid metal objects layer-by-layer, starting from the bottom and following the computer-aided design (CAD) data and instructions provided by computer programs [1]. In the era of Fourth Industrial Revolution (Industry 4.0), metal additive manufacturing technology is being considered crucial component [2,3]. This innovative manufacturing method has gained widespread adoption for producing test prototypes and final components in various research and development labs, as

well as in industrial sectors. The industries such as automobile, medical, robotics, aerospace, and maritime, which use advance materials (e.g. Inconel, titanium alloys and stainless steel) to produce complex geometries are showing significant interest to AM [4,5]. This technology allows for the direct manufacturing of components from designs, which are otherwise difficult to fabricate using conventional machining process [6].

1.2 Classification of Additive Manufacturing Processes

The ISO ASTM-F42 committee outlines [7] categorizes additive manufacturing processes into seven commercially recognized methods, as shown in Figure 1. These seven methods operate

based on three cores AM technologies called “sintering”, “melting” and “stereolithography”. These categories include Vat Photopolymerization (VP), Powder Bed Fusion (PBF), Directed Energy Deposition (DED), Material Jetting (MJ), Binder Jetting (BJ), Material Extrusion (ME), and Sheet Lamination (SL).

1.3 Benefits of Metal Additive Manufacturing Over Traditional Methods

AM for metals can offer the following benefits over traditional subtractive manufacturing methods [8–12]:

- **High design freedom:** Enables the creation of complex, customized designs that are difficult to achieve with traditional methods.
- **Enhanced product efficiency:** Allows for optimized performance, reducing weight and improving functionality compared to conventional parts.
- **Ability to accommodate intricate part designs:** Facilitate the production of parts with complex geometries and internal structures that conventional methods struggle to achieve.
- **Flexibility in shaping:** Supports the rapid production of varied shapes without extensive retooling or setup changes.
- **Reduced assembly time:** Integrates features and complex designs into a single build, minimizing the need for traditional assembly and saving time.
- **Shorter design cycles:** Accelerates the process from design prototype, allowing for faster revisions and quicker product development.
- **Decreased raw material costs:** Uses only the material needed for the part, reducing waste and lowering material expenses.
- **Alignment with green manufacturing:** Contributes to sustainable practices by minimizing waste reducing energy consumption, and enabling the use of recycled materials.

- **Minimal human interaction:** Advanced systems require less manual intervention, improving efficiency and safety in the production process.
- **Precise part replication:** Ensures accurate duplication of parts with tight tolerances and high consistency, which is essential for maintain quality and meeting stringent specifications.

1.4 Market Growth and Projections for Metal AM

Metal additive manufacturing has surpassed growth in polymers and ceramics, with the automotive, aerospace, and energy sectors projected to account 52% of metal AM revenue by 2027 [13,14]. The global AM market is set to grow at a 22.0% compound annual growth rate, reaching \$16.06 billion in the year (2023), predicted to hit \$34.22 billion in the year 2027 [15].

Remarkably, Powder Bed Fusion (PBF) and Directed Energy Deposition (DED), the two main metals AM technologies that can produce fully dense parts for different industrial uses share 54% and 16% of the metal AM industry, with DED's revenue share expected to surge further in the next five years [16,17]. SmartTech also predicts DED's market contribution to reach nearly \$755M by the year 2025 [18].

1.5 Overview of Direct Energy Deposition in Metal AM

Directed energy deposition (DED) is a rapid AM process known for its high deposition rate and volume density as compared to the PBF process [19]. DED technology enables the construction of arbitrary shapes on flat, uneven, or tilted substrate, and its simplified system, in comparison to the complex PBF apparatus, facilitates integration with different machining processes to form hybrid manufacturing solutions [1]. Also, DED can allow the printing of multiple materials simultaneously [20–22]. These properties of DED processes are growing the industry's interest exponentially. Applications of DED include repair or

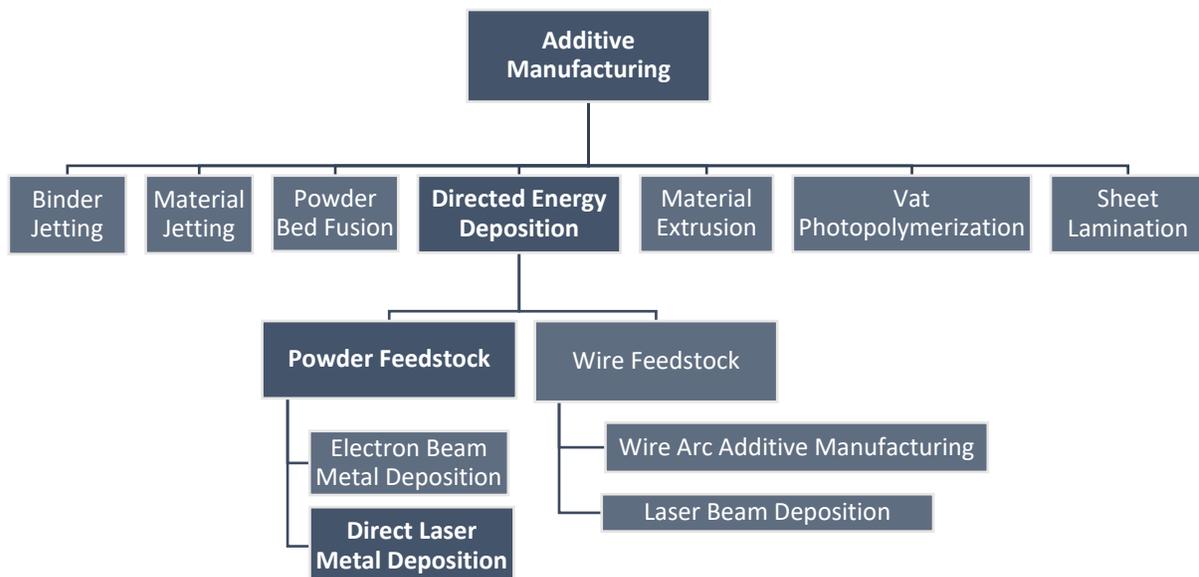


Figure 1 Classification of DED Additive Manufacturing Process

refabrication of damaged parts, rapid printing, production of larger parts (up to meters) and near net shape manufacturing of complex geometries [6]. In DED based AM, metallic material, typically in powder or wire form [23,5], is repeatedly fused using a thermal energy source, such as plasma, a laser, or an electron beam [24]. The fundamental working principle of DED mechanism is illustrated in Figure 2. In this process, a mixture of metallic powder with inert gas is sprayed through multiple nozzles around the laser beam, or a metallic wire is fed through a nozzle to a plasma arc. An inert gas is also supplied through additional nozzles to shield the material from oxidation. The plasma arc or high-energy laser beam melts and deposits the material at target areas on a substrate surface or previously deposited material, following path instructions from CAD data translated into CNC codes. The entire deposition process, executed on a computer-controlled numerical (CNC) machine or on a robot arm, allows for the manufacturing of complex profiles and component repair. DED technology encompasses various methods, including direct laser metal deposition (DLMD), laser engineered net shaping (LENS), wire arc additive manufacturing (WAAM), laser consolidation, and 3D laser cladding [25].

1.6 Focus On Laser Type Powder-Based DED Technology

DED technology has gained a surge in research during recent years due to its versatility and potential applications in various manufacturing sectors. It is now recognized for its high -rate material deposition with precision and minimal waste, making it an attractive option for metallic parts fabrication in additive manufacturing [26]. DED's capability to bond materials layer by layer using high-energy sources like laser, plasma, or electron beams has garnered attention for repairing, enhancing, and remanufacturing existing components [27]. Furthermore, the technology's multi-material deposition capabilities, coupled with ongoing research on improved alloys and composite materials, have expanded its potential scope in aerospace, marine, automotive, and medical applications [28]. As a transformative manufacturing technique, DED is growing, driven by current research focused on enhancing part quality and reducing process costs through materials development, process

parameters optimization, and in-situ process monitoring [23,29–43]. While various energy sources and material types can be used in DED processes, recent reviews [6], [25], [44], [45] highlight laser type powder-based directed energy method as the most popular, particularly for manufacturing, repairing or refabrication high-value engineering components from advanced materials like nickel, titanium, and steel alloys. Therefore, powder-based directed energy method known as Direct Laser Metal Deposition – DLMD DED technology (Figure 3 refers) is the primary focus of current review, chosen for its higher resolution, ability to fabricate complex geometries, capability to print multi-materials, better surface finish, and better dimensional accuracy as compared wire-based DED processes [44].

DLMD is becoming a prominent subject of research studies due to its significant potential to fabricate complex shapes from advanced materials like Titanium and Inconel alloys [46,47]. It is recognized for repairing previously irreparable valuable parts [48–50] and processing functionally graded materials, composite and high entropy alloys [51]. Particularly, DLMD has been demonstrated to repair underwater parts [49], optimize conditions for minimizing internal defects in nickel alloy type Inconel 718 [52], join different metals such as titanium alloy and stainless steel [53], and fabricate SS316L-Inconel 625 functionally graded materials with varying chemical compositions [23,33]. Additionally, DLMD has successfully shown its potential to process aluminium composite (SiC/AlSi10Mg) [54].

1.7 Aim of the Review

Numerous comprehensive reviews have been published on DED additive manufacturing technologies, especially DLMD process [4,6,10,25,26,45,55–68]. These reviews mainly focus on the deposition technologies, applications, and materials. They particularly emphasize laser metal interaction, defects formation, material types, mechanical behaviour, microstructure development, mapping, optimization, and control of key process parameters (laser power, scanning speed, powder flowrate), as well as thermal phenomena. While only a

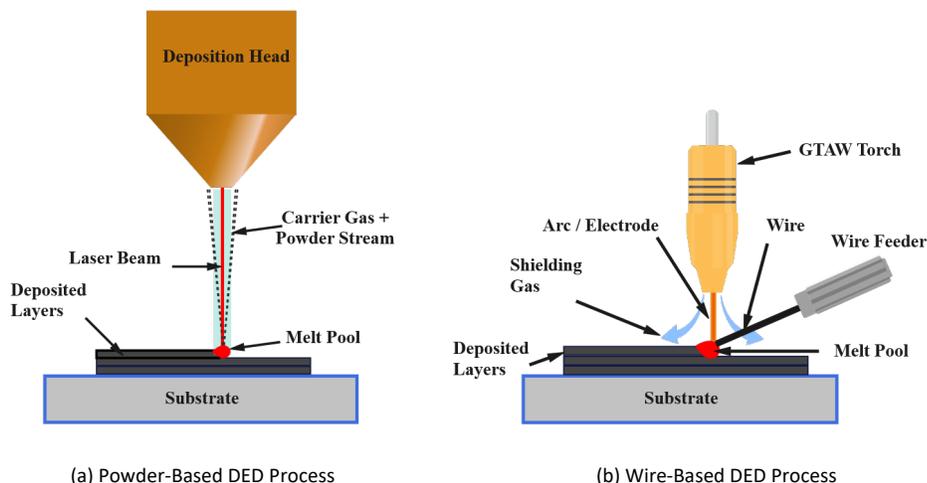


Figure 2 Concept of Directed Energy Deposition Processes

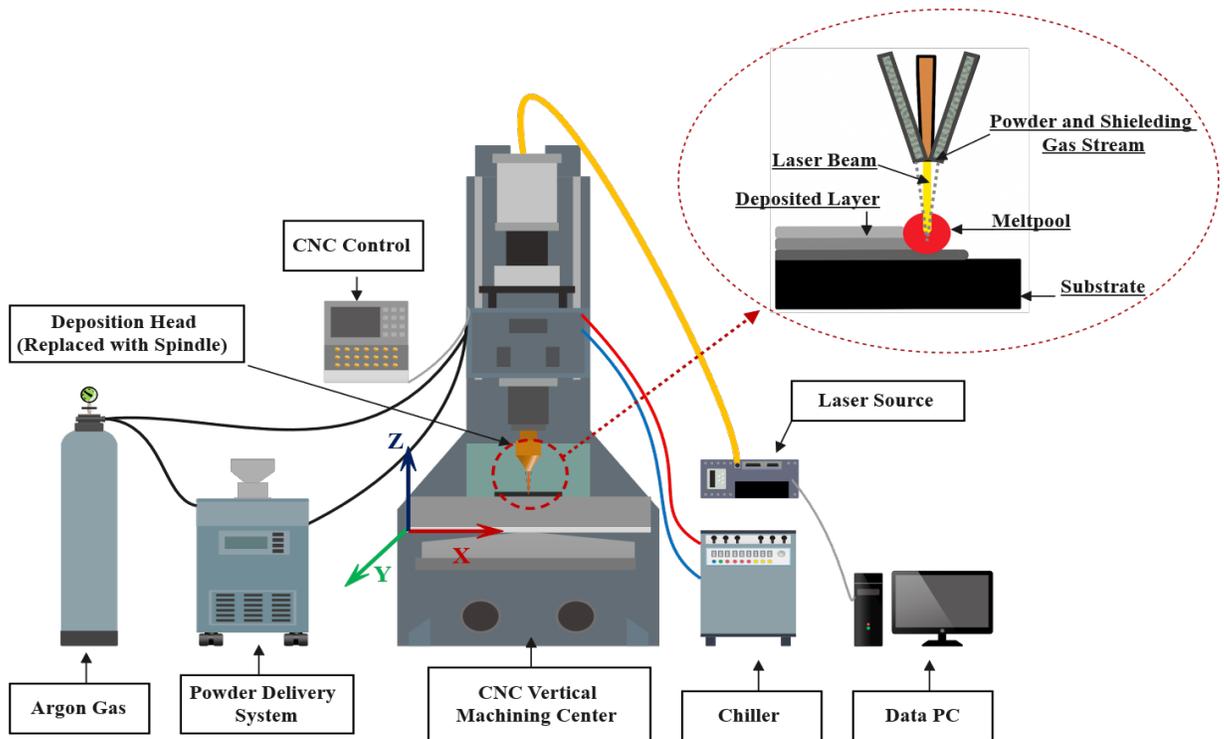


Figure 3 Schematic of DLMD System

few reviews have focused on scanning patterns in additive manufacturing [69,70], there is limited attention specifically on direct laser metal deposition DED process. In the recent decades, several studies with various research objectives on scanning patterns in the laser-based DED have been published. However, existing review studies on this topic are limited, emphasizing the necessity for a more systematic summarization of past research. Therefore, the present review centres on the state of the art in scanning strategies in direct laser metal deposition, providing unique insights into future research directions. This study deeply delves into the critical role of scanning patterns in the DLMD, exploring their impact on part quality and offering valuable understandings for researchers and manufacturing engineers. The paper is organized into following sections. Section 2 highlights significant parameters of DLMD process and their effects of part quality. Section 3 presents an in-depth overview of past research contributions that have focused on conventional deposition patterns applied in Direct Laser Metal Deposition process. Section 4 emphasizes the significance of scanning patterns, and their effects on common defects, including cracks, porosity, distortions, and residual stresses, as well as their influence on the anisotropy in mechanical, microstructural properties, and thermal history. Based on previous studies, advantages and limitations of common conventional deposition patterns have been summarized in Section 5. Finally, Sections 6 presents the conclusion and future recommendations.

2.0 DIRECT LASER METAL DEPOSITION PROCESS OVERVIEW

2.1 Process Description

Direct Laser Metal Deposition, considered in current study, is a powder-blown directed energy deposition additive manufacturing process in which a metallic material, in powder form, is fused over and over by focusing an applied thermal energy source directly on the material. Basic working principle of DLMD is shown in Figure 2 (a). The applied source of energy is a high-power laser beam. In the working principle of DLMD, a high-energy laser source with a certain power heats the powder material to form a melt pool on the surface of a workpiece which can be either a substrate or previously deposited material. A processing head points out this laser beam towards the deposition area while using mirrors or an optical fiber cable as guiding mechanisms. The guiding mechanism further defocuses the beam towards the working plane by forming a beam spot size of a specific diameter which a result creates a melt pool with certain dimensions. The metal powder is blown into the melt pool by the processing head at a certain flow rate from nozzles with the aid of an inert carrier gas, usually argon or helium. An inert gas stream is also supplied separately from the processing head which protects the molten metal in the melt pool area from oxidation. A fraction of blown powder hits the melt pool and gets deposited on the workpiece. This ratio of deposited metal to blown metal is called catchment efficiency. The distance between the processing head tip and the substrate top surface is known as the standoff distance. The processing head moves over the workpiece at a certain speed known as scanning

velocity, which enables the laser beam to push the melt pool over the workpiece, resulting in the formation of a welding bead with a specific width. Hence, in the DLMD process, the melt pool serves as the main tool that governs the deposition mechanism, while the laser beam, powder, scanning speed, and inert gas function as subsystems that control this tool. Within the melt pool, a certain proportion of workpieces exists along with the melted powder material. This proportion of the workpiece is referred to as dilution, and it influences the microstructure within the heat-affected zone.

DLMD physical system consists of four main units: a laser source, a CNC machine installed with a laser head, a powder feeder unit, and an inert gas source (Figure 3 refers). The powder delivery system supplied the required quantity of the metallic powder with the aid of an inert gas to the printing head. From the printing head, the powder is sprayed on the substrate surface through multi-nozzles surrounding the laser beam. The high-energy laser beam spot directly melts and deposits the powder material at target places on a substrate surface. The laser head and the build platform are moved simultaneously following the path instructions according to CAD design data translated into CNC codes (Figure 4 presents complete process flow of DLMD). This whole process is performed in a closed environment shielded by an inert gas like argon to avoid the oxidation of the molten metals.

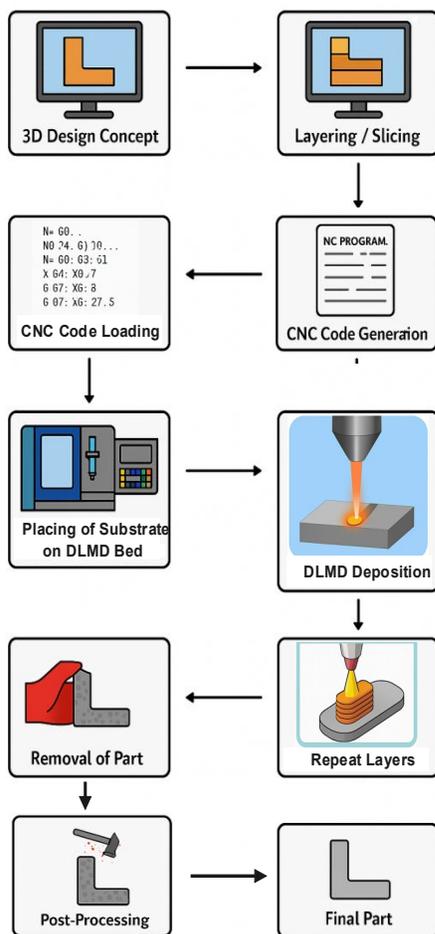


Figure 4 Process flowchart of Direct Laser Metal Deposition

2.2 Applications

Applying the powder-based DED technology, a broad range of metal alloys including titanium, titanium alloys, Inconel alloys, stainless steel (300 series), aluminium alloys, tungsten, copper-nickel, and zinc alloys can be processed to manufacture near-net-shape components. DLMD technology has been successfully utilized to fabricate parts from Ti6Al4V alloy, demonstrating mechanical properties such as microhardness, yield strength, and ultimate tensile strength with average values of 460 HV, 976 MPa, and 1099 MPa, respectively, which are higher compared to wrought or casted parts [71]. Additionally, the technology has been employed to join dissimilar metals, such as titanium alloy and stainless steel, with intermetallic analyses conducted on the Ti-Fe metals involved in the process [53].

This technology is being confidently used in various industrial sectors including aerospace, marine, medical, tools and die manufacturing, and automobile [72]. Major applications of DLMD are near-net-shape fabrication of new functional parts, rapid prototyping, repair and restoration of damaged components or remanufacturing of obsolete spares, manufacturing of porous structures, coating of different materials, and simultaneous deposition of dissimilar metal alloys and functionally graded materials [6,47–49]. Aerospace is one of the important sectors in which the Laser Metal Deposition process has been widely used. The ability to construct components with larger dimensions compared to those manufactured using the L-PBF technology is the prime aspect attracting the usage of the DLMD technique in this industry. The National Aeronautics and Space Administration (NASA) [73,74] has fabricated integrated-channel nozzles using DLMD - called blown powder DED technology. The dimensions of this nozzle were 1120 mm in diameter and 1220 mm in height. DLMD technology helped to reduce more than 50% production cost and lead time. In another example, using a 5-axis DLMD system, TWI [75] effectively manufactured a combustion chamber of a helicopter engine from Inconel 718. The size of the fabricated chamber was 90 mm in height and 300 mm in diameter. The accuracy of this build chamber was less than 0.25 mm as compared to CAD geometry. Using DLMD, production time was reduced to 7.2 hours from 2 months.

2.3 Significant Parameters of DLMD Process

Despite its interesting practical applications, the stability of the DLMD process remains a concern due to the high sensitivity of several process parameters, including laser power, scanning speed, beam spot size, powder delivery rate, bead overlap, and deposition patterns, among others [25,55]. The process parameters or factors shown in Figure 5 are suggested as most critical process variables which directly influence the final component's properties by governing the concentrated heat source during deposition [56]. Understanding the significant parameters of DLMD process is crucial for optimizing part quality and achieving desired performance properties. This is a sophisticated additive manufacturing technology that involves precise control of different process parameters to produce high quality metal parts. Inappropriate selection of process parameters can lead to fluctuating temperature gradients, rapid microscale solidification, columnar microstructural patterns, and varied textures [35]. Consequently, DLMD-built parts may exhibit quality issues such as poor surface finish, defects (cracks,

porosity, delamination), and anisotropy in mechanical properties[76]. This section explores the most critical parameters and their effects on components quality, providing insight into how tuning these parameters can lead to improvements in the final part.

accuracy and lower energy consumption compared to infrared lasers [30,83,84].

2.3.2. Powder

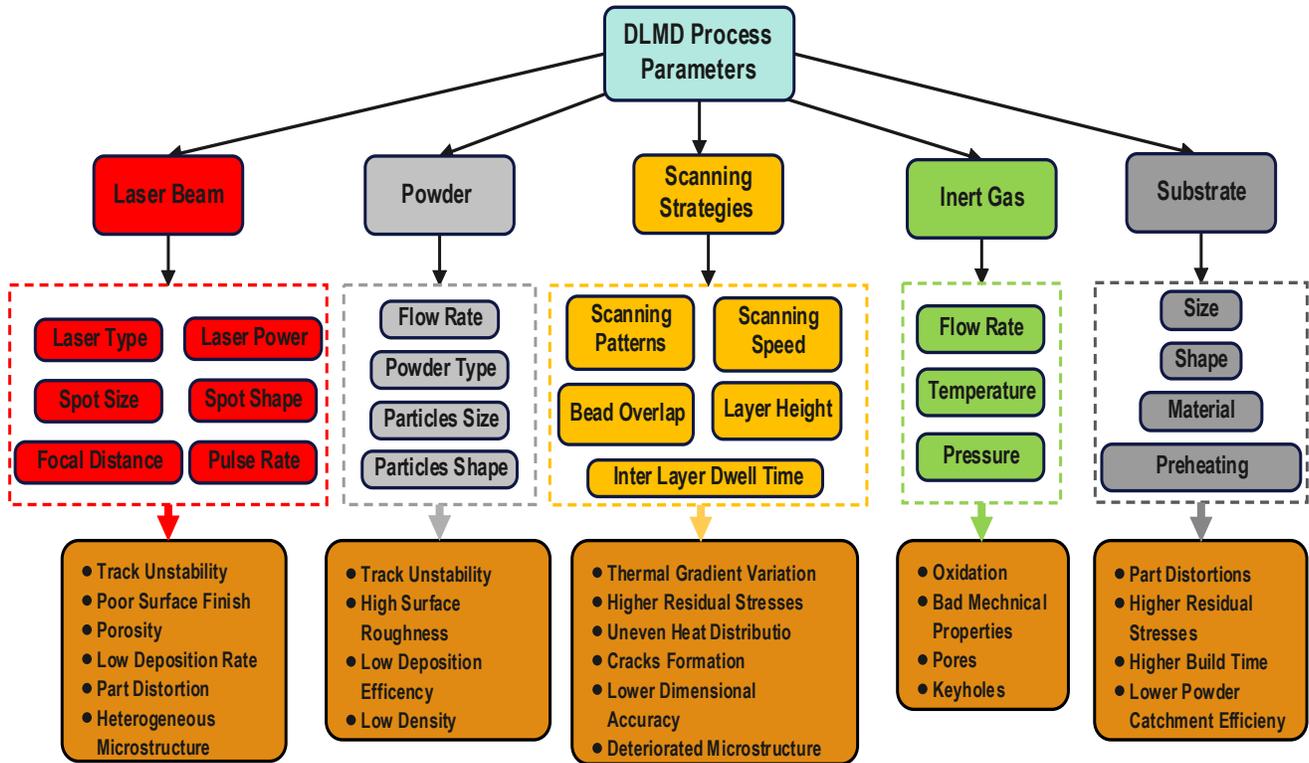


Figure 5 Significant Parameters and Their Effects on Part Quality in DLMD

2.3.1. Laser Beam

The energy supplied to the metal powder is determined by the power of the laser beam, which in turn influences the melt pool's size and depth. Laser power is considered a sensitive parameter that directly impacts process stability, with higher power levels potentially leading to quicker deposition rates [55]. However, this can also result in increased distortion and porosity. Although increasing laser power can reduce porosity defects, excessively high power may cause excessive dilution and negatively affect the dimensional accuracy of the part in DLMD [33]. Additionally, laser beam power significantly impacts surface roughness, with higher power leading to a poorer surface finish [77]. Increasing laser power results in larger grain sizes. The larger grain size at high laser power is attributed to the increased temperature, which reduces the solidification rate [78].

Laser beam is crucial in DLMD influencing the melting and deposition of metal powders. Various laser types, including CO₂, Nd: YAG and fiber laser, each offer distinct advantages, such as beam quality and energy efficiency, are being used in this technology [79]. Laser spot size, power distribution, and wavelength significantly influence the process, with different materials showing varied energy absorption [57,80–82]. Recent studies highlight blue light lasers as an effective alternative for reflective materials like copper and aluminum, providing better

The rate of powder delivery to the melt pool knowingly influences build characteristics like bead geometry in DLMD process [85]. Increasing the flow rate reduces dilution and enhances track width and height as more energy is used for melting the powder [25,55]. Lower feed rates are associated with improved surface finish and reduced porosity, under specific conditions [41,77].

The morphology of metal powders, including particle size, shape, and distribution, is critical for producing stable melt pool. Spherical powders, typically 30-150 μm, produced via Gas Atomization (GA) or Plasma Atomization (PA) are preferred due to their uniformity and smooth texture [58,59,86,87]. Experimental studies show that GA powders offer higher deposition rates and hardness, while PA powders minimize porosity and dilution [88–90]. Challenges like powder flow fluctuations require advanced control systems, with factors such as particle size and shape being critical for maintaining consistent flow and part quality [41,91–93].

2.3.3. Inert Gas

In Direct Laser Metal Deposition, the flow rate of carrier and shielding gases is vital for regulating the powder stream and protecting the melt pool from oxidation. The design of the nozzle, type of gas used, and flow rate meaningfully effect the

quality of the deposited material. Improper gas flow can lead to defects like splashing and poor cladding quality [94,95]. Studies have revealed that optimizing gas flow can improve microstructure and surface finish, with specific configurations required for different materials [96–98]. As a result, careful selection and control of gas parameters are essential for achieving high-quality DLMD results.

2.3.4. Substrate

The quality of builds in DLMD is significantly influenced by substrate material, thickness, and preheating. The thermal conductivity of the substrate material affects heat dissipation, impacting cooling rates and residual stress formation. Thicker substrates offer greater thermal mass, reducing distortion but increasing heat absorption, which can affect melt pool stability. Preheating the substrate mitigates thermal gradients, reducing residual stresses and improving adhesion between layers by slowing the cooling rates [99,100].

2.3.5. Scanning Strategies

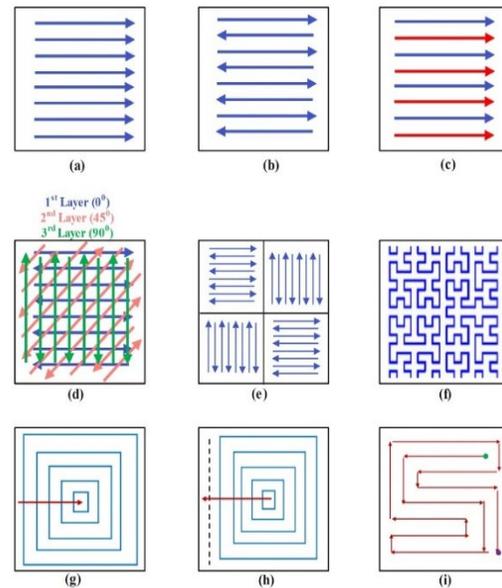
Laser scanning speed, or traverse speed, in DLMD can change part characteristics, including solidification, microstructure, and mechanical properties. Higher scanning speeds reduce cladding layer width and track height, and influence component shape and porosity levels, with slower speeds decreasing porosity [101]. The effect of scanning speed on porosity is more pronounced than that of laser power [55]. The other scanning parameters like layer height and overlap distance also affect surface quality and part integrity; improper settings can lead to defects like porosity, dimension errors and poor surface finish [102].

One of the main process variables influencing the manufactured metal parts' quality is the laser scanning patterns employed. Various scanning patterns can be used depending on how the printed parts are really shaped [103]. The scanning methodologies that are currently being considered in DLMD are raster, zigzag, rotational, hybrid, contour, and islands. However, it is challenging to comprehend how scanning patterns affect deposition process because of the multiple factors that are related to the scanning paths [104]. Shrinkage, warping, porosity, density, surface roughness, microstructure, mechanical performance, residual stress, and heating cycle are all impacted by changes in scanning patterns, direction, and length during the deposition process between layers [56]. These features are mostly influenced by the thermal history generated by different deposition patterns.

3.0 SCANNING PATTERNS TESTED IN DLMD

Deposition path in powder-blown DED-based additive manufacturing can significantly impact the metallurgical and mechanical properties of the material [6,70,105,106]. The scanning path of the laser beam, in conjunction with other process parameters, plays a crucial role in determining the build quality of 3D printed components [107]. The scanning pattern directly influences the temperature gradient and cooling rate of each layer, thereby affecting surface finish, geometry accuracy, and microstructure formation [70]. The profile of the scanning

path greatly determines the material addition rate and printing time, thereby affecting wastage and speed. Innovative deposit



(a) Raster (Unidirectional) (b) Zigzag (Raster-Bidirectional)
(c) Raster in alternative lines (d) Orthogonal (Rotation between layers)
(e) Islands (f) Hilbert (Fractal) (g) Outside-in contouring (Offset In)
(h) Inside-out contouring (Offset Out) (i) S-Shaped

Figure 6 Common Deposition Patterns Applied in DLMD

strategies or optimized build paths have the potential to modify thermal stresses, build quality, and mechanical characteristics, enabling the attainment of desired properties without necessitating changes to machine parameters [107]. Various deposition patterns, such as raster, bi-directional, orthogonal, islands, spirals, contours, and zigzag (illustrated in Figure 6) have been employed in DLMD additive manufacturing process. The subsequent comprehensive literature review, as summarized in Table 1 explores the impact of diverse deposition patterns on the properties of multi-layered 3D parts produced through this process.

3.1 Raster Paths

Researchers have extensively analysed the impact of raster and zigzag scanning strategies on properties in LMD. Gao et al. [108] investigated the effect of eight different deposition patterns (raster uni and bi-directional in longer and shorter dimensions, contour-offset in, contour-offset out) on the deformation of an arched substrate during direct laser fabrication (DLF) of Inconel 718 cylinders. Their findings reveal that zig-zag laser scanning patterns along the shorter dimension resulted in minimum substrate deformation (1.54 mm), while scanning patterns along the longer dimension led to the maximum deformation (3.44 mm) among all the applied deposition strategies. Oniuke and Bonny [52] investigated four scanning paths, observing that parts produced under the diagonal (45° rotation) build strategy exhibited lower coefficient of friction (between 0.2 and 0.3) and improved compound wear compared to other patterns (0.3 to 0.5). These findings highlight the importance of scanning

strategies in influencing deformation and quality in LMD processes. Lee et al. [109] studied interlayer cooling time and three deposition strategies called unidirectional, bi-directional, and bi-directional with 180-degree rotation in laser metal deposition for Ti-6Al-4V alloy components. Their finding shows a bidirectional tool path with 180-degree rotation minimizes deformation and reduces cracking risk by 50% due to symmetrical residual stresses. Lu et al. [110] explored Ti-6Al-4V samples with six scanning paths, revealing that reducing dwell by increasing back speed and shortening longitudinal scanning decreases part warpage and residual stresses.

Ri-sheng et al. [106] investigated the impact of different scanning schemes - long-edge back-and-forth, short-edge back-and-forth, and inter-layer rotational back-and-forth on crack formation in Ni60 alloy using FEM based modelling and simulation. They emphasized the significant influence of scanning patterns on cracking failure in thin-wall components produced by laser direct deposition. The study recommended an interlayer orthogonal scanning strategy to mitigate residual stresses and reduce cracking. Likewise, Bhardwaj and Shukla [111] emphasized the influence of scanning patterns on crystallographic texture, surface finish, and mechanical properties in direct laser metal deposition of Ni margining steel 300. They applied bidirectional and cross-directional (90-degree rotation) raster scanning schemes, finding that the cross-directional path produced 99.62% dense parts with a 2.457 μm surface finish. However, variations in microhardness and residual stresses were observed for both scanning paths. Ren et al. [112] also underscored the significant impact of the laser deposition pattern on heat distribution, part distortion, and residual stress in LMD. Employing computational methods and experiments, they investigated the effects of two laser scanning patterns, ZigzagX (widthwise) and ZigzagY (lengthwise), on thermal history and substrate deformation in LMD additive manufacturing of 316L steel alloy. The study revealed that width-wise Zigzag scanning achieved a more uniform stress distribution in the x-axis direction and reduced part distortion compared to other zigzag patterns.

Few researchers have also investigated the impact of rotation angles per layer in zig-zag patterns on the properties of stainless-steel alloys processed through powder-type DED additive manufacturing. Saboori et al. [113], for instance, examined the effects of two rotational raster deposition patterns (670 and 900 rotation per layer) on the residual stress, microstructure, and tensile strength of stainless steel alloy 316L. Their findings revealed that an increased rotational angle per layer increases the cooling rate, leading to a finer microstructure and lower oxide content. The 90° rotation per layer strategy resulted in better ultimate tensile strength (with a 35% higher elongation before fracture) and lower residual stresses, although it produced higher stresses on lateral surfaces. However, both rotation patterns showed higher metallic inclusions and oxidation compared to previous work, potentially affecting the mechanical properties of large parts. In another research assessment for DED of stainless steel 316 L, Aversa et al. [114] have noted that residual stresses were influenced by the by the inter-layer rotation angle, while hardness values remained unchanged under different rotation angles. They found that the 0-90 degrees orthogonal strategy resulted in smooth residual stress distribution with lower values (positive stress values in the range of 100 to 240 MPa). Similarly, Zhao et al. [115] propose that, among bidirectional scanning patterns, the 90 degrees

rotation angle patterns with a 2-minute time interval between subsequent layers offer an optimized deposition plan for printing 24CrNiMo alloy steel samples. This results in a finer grain size (3.61 μm), leading to high tensile strength (1214 MPa) and microhardness (400 HV) compared to forged alloy (1000 MPa). Li et al. [116], based on the advantages like uniform heat distribution, minimum residual stresses and high density, have considered orthogonal patterns with 90° inter-layer rotation a standard deposition strategy in their investigations. Tan Zhi'En et al. [107] explored the effects of longitudinal zig-zag, zigzag with 90° rotational and traverse zigzag raster build strategies on stainless Steel 316 L. They observed that to maintain high homogeneity in the melt pool, more energy is required during the longitudinal zig-zag scan scheme compared to other build patterns. The specimen fabricated using the longitudinal zig-zag scan strategy exhibited finer grain, higher tensile strength, and fracture strain compared to the zig-zag with 90° rotational (bidirectional) and traverse zig-zag building paths, although Young's modulus values were lower in the long unidirectional scan strategy. Recently, Tiwari et al. [117] have discovered that the surface texture, microstructure, and mechanical properties of Inconel 625 alloy during directed energy deposition are significantly influenced by inter-layer rotation angles of 0°, +45°, and +90°, impacting the solidification rate. The sample produced using 0° - 90° rotation strategy demonstrated lower anisotropy (1.06%) and higher microhardness value around 241 HV among all the strategies applied.

Kim et al. [118] highlighted the substantial impact of substrate preheating, deposition direction, and rotational angle between subsequent layers on thermomechanical characteristics and residual stress. Employing sixteen raster scanning strategies (eight alternative direction and eight unidirectional) with inter-layer rotation, they observed that alternative deposition scanning strategies resulted 16% less symmetrical residual stresses as compared to unidirectional scanning strategies. Furthermore, Tang et al. [119] examined the impact of build orientation on the anisotropic fatigue performance of LMD Ti-6Al-4V. They found that specimens in the X (direction of hatch) and Y (in direction of scan) exhibited identical fatigue lifetimes, but these were significantly prolonged (twice as long) compared to specimens in the Z build direction. However, their study, limited to zigzag deposition strategies, could not address anisotropy in fatigue behaviour resulting from microstructure variations. Likewise, Roucou et al. [32] demonstrated that fracture propagation in SAF2507 super duplex stainless steel, using a zigzag strategy, is also influenced by build orientation.

3.2 Contouring and S-Shaped Patterns

In contrast to the above-mentioned studies, the effects of alternative scanning patterns, specifically contouring or offset (Outside-in and Inside-out), in Direct Laser Metal Deposition technology have also been examined. For example, Ren et al. [120] applied computational methods, simulations, and experimentation to investigate the effects of contouring scanning schemes on thermal history and substrate deformation during LMD additive manufacturing of 316L steel alloy. They compared the effects of spiral-inward, spiral-outward, transverse zigzag, longitudinal zigzag, and zigzag with alternative paths. The study found diverse distributions of heat and substrate distortion across all scanning patterns. Contradicting Gao et al.'s [108] findings, Ren et al. proposed that zigzag along

the Y-axis (longitudinal) caused the least substrate deformation (4.332 mm compared to a maximum of 6.532 mm) and created a more homogeneous temperature distribution. Ribeiro et al. [121] reported that using an outward contour scanning path in the powder-based DED process, AISI 316L workpieces could be fabricated with greater form accuracy, better surface finishing (35 μ m), and higher density (7.919 g/cm³) and microhardness (210 HV), approaching conventional 316L material. They experimented with four deposition paths - unidirectional, bi-directional (zig-zag), chessboard (island), and contour outward - and study their effects on shape accuracy, surface finish, morphology, microhardness, and microstructure. Sun et al. [122,123], using a finite element-based numerical simulation, assessed the effects of six deposition patterns - raster, zig-zag, alternate-line, contouring in-out, contouring out-in, and S-type contouring - on warpage, temperature, and residual stresses on aluminium alloy 2319 material. They found that the proposed S-type pattern is the optimum strategy for printing square structures, resulting in a more uniform temperature distribution, lower residual stresses, and less distortion as compared to the other patterns. Ghasempour et al. [124], in a similar FEA-based study, investigated the impact of two contouring types (outside-in and inside-out) deposition patterns on temperature distribution, geometrical nonconformity, residual stress distribution, and area deviation. Their simulation results suggested that among the four scanning strategies, the outside-in contouring strategy resulted in the minimum generation of residual stresses and less workpiece dimension deviation. However, the inside-out scanning strategy generated the least area change as compared to the outside-in contouring strategy.

3.3 Fractal Paths

The impact of fractal-shaped deposition paths has also been investigated in the LMD method. Yu et al. [125] employed the fractal scanning pattern in the laser solid forming method and compared its effects on part distortion, inner defects, and machinal properties with other three different deposition patterns: raster, offset-in (spiral-in) and offset-out (spiral-out). Among these scanning paths, the fractal patterns resulted in less part distortion and superior mechanical properties, followed by offset-out profile due to a smaller thermal gradient. However, parts produced by fractal and offset-out patterns also showed a larger inner porosity (poor fusion) due to incomplete overlap of laser spots at corners, attributed to the presence of many square corners for both deposition patterns.

3.4 Island Patterns

The island scanning strategies in DLMD additive manufacturing have also been tested for their impact on deposited sample properties. Yan et al. [126] used island patterns in Ti64 alloy deposition, resulting in 71% less deformation compared to raster, but oscillating residual stresses persisted. Various island sizes and scanning orders were explored to optimize the methodology, yet challenges with buckling and balancing deformation and residual stress remained. Woo et al. [127], found both orthogonal and island scanning strategies effective in mitigating stress profiles, but island scanning without layer shift led to internal defects. Porosity in the island was attributed to insufficient fusion. Conversely, bidirectional, or orthogonal scanning patterns showed no discernible macroscopic defects.

Wang et al. [128] explored island and laser jump plans in laser metal deposition. They reported reduced deformation and residual stress by decreasing island sizes and increasing laser jump distances. However, effects on microstructure, mechanical strength, and microhardness were not explored.

The above paragraph's provide deep insight into the importance of deposition patterns in DLMD additive manufacturing, exploring strategies like raster, zigzag, contouring, islands, and fractals patterns. These patterns play a crucial role in forming material properties such as deformation, substrate distortion, temperature distribution, and residual stresses in various alloys. Numerous alloys, including Inconel, Ti-6Al-4V, and stainless steel, are covered in the studies that are discussed. The direct relationship between these patterns of deposition and the product of the manufactured components is prominent. Researchers highlighted the need for choosing scanning paths carefully to enhance build quality, mechanical properties, and microstructure formation, highlighting the various ways the deposition patterns affect outcomes in additive manufacturing processes.

These findings summarized in the Table 1 highlight that the quality and properties of components produced by DLMD are affected by the scanning paths of the laser applied during the process. Researchers suggest that shorter zigzag patterns with interlayer rotations can minimize deformation and residual stresses. Likewise, other strategies such as 90-degree rotations and bidirectional paths enhance tensile strength and microhardness. Applying alternative paths like contouring and island patterns can reduce substrate deformation, however, these patterns may cause internal defects, surface roughness or oscillating stresses. However, none of the scanning paths can be considered an optimum solution that collectively improves or provide overall better-quality part.

4.0 EFFECTS OF DEPOSITION PATTERNS ON PART PROPERTIES

The scanning paths applied in Direct Laser Metal Deposition (DLMD) can largely affect the quality and performance of the deposited material and the final component. Variations in path shapes, directions, and overlaps are crucial factors influencing characteristics like accuracy, strength, microstructure, and mechanical properties of fabricated parts. In the subsequent sub-sections, some found effects of scanning strategies on properties in DLMD additive manufacturing technology are discussed.

4.1 Thermal Effects

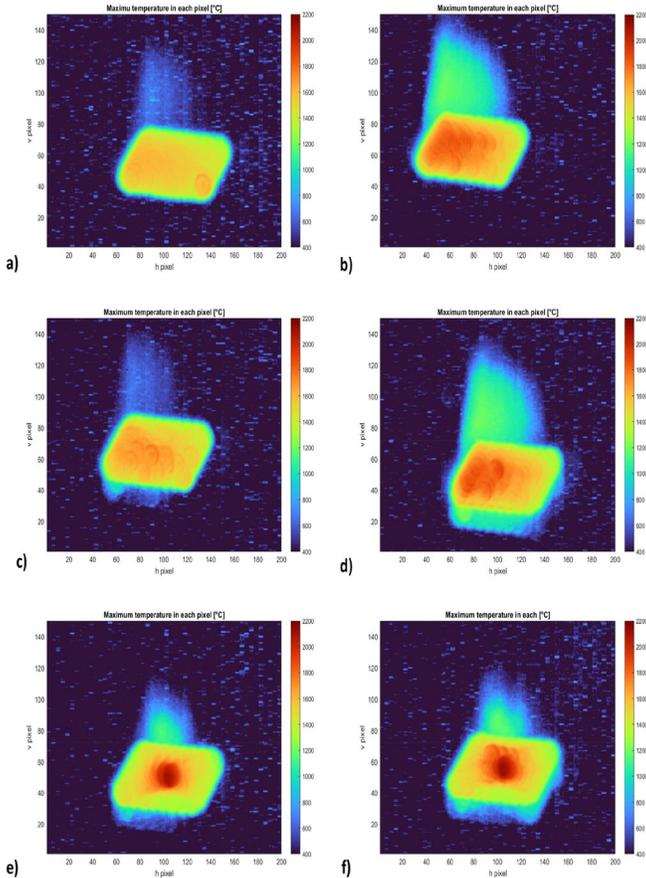
In DLMD additive manufacturing, the interplay of local temperature, laser-powder interaction, and heat transmission parameters creates a thermal environment. The deposition process subjects metal powder to rapid heating and cooling, generating a significant temperature gradient and residual stresses. This can lead to substrate deformation and workpiece cracks. Laser heat melts the metal powder, forming a molten pool that shrinks during solidification, with complex shapes and uneven temperature causing varied shrinkage [129]. In multi-layer deposition, pre-solidified layers adjacent to the molten pool undergo a complex thermal cycle, causing material

expansion and contraction, heightening residual stress. If this stress exceeds the material’s yield strength, the part may deform or crack, impacting dimensional accuracy and integrity. Laser scanning path strategies are the key aspects of the thermal environment in DLMD [55]. The fundamental understanding of these conditions is essential so that properties such as microstructure, defects, and residual stresses can be regulated properly to achieve high-quality results and desired properties in the manufactured components [25]. Optimizing scanning paths of laser is vital for precise temperature control, enhancing desired metallurgical properties [64]. The overall thermal behaviour is influenced by material types and their varying properties, with cooling rate during solidification shaping the final microstructure and mechanical properties [129]. Rapid cooling often leads to anisotropic grained structures, impacting mechanical strength. However, this swift local heating and cooling can induce thermal stresses, causing cracks and distortion in the final component [64]. Other heat transfer modes, such as conduction and convection, also affect the characteristics of fabricated parts [130].

In DLMD process, infrared (IR) radiation pyrometry and thermal cameras monitor the thermal environment, capturing melt pool temperature and cooling rates directly [25,130,131]. These images aid in studying the thermal mechanism, laser-powder interaction, and heat transmission, predicting defect formation, mechanical properties, and microstructural

evolution. Mazzarisi et al. [42] studied the temperature field generated by laser metal deposition process during the multitrack deposition of a nickel-based superalloy using an IR thermal camera. They analysed six deposition paths, such as unidirectional, bidirectional, and contouring, studying their impact on thermal gradient, thermal cycles, maximum temperature, and cooling rates. Figure 7 displays thermographic images of six deposition paths applied, offering insights into thermal geometry and maximum temperature distributions [42]. The images reveal distinct thermal maps based on different deposition trajectory, even with constant process parameters. Unidirectional deposition produced a more uniform temperature field, minimising component overheating, (Figure 7(a) and (b) refer). Adding a single contouring trace has negligible impact on temperature circulation (Figure 7(c) and (d) refer). Contouring patterns exhibited high temperatures in the middle, exceeding 2000 °C, the temperature is high in the middle of the deposition (with temperatures exceeding 2000 °C, due to smaller squares retaining more heat. The maps also indicate the temperature of hot shielding gas nozzles (Figure 7(e) and (f) refer), particularly noticeable in bidirectional paths. The rate of cooling significantly influences the final microstructure and solidification time in laser deposition.

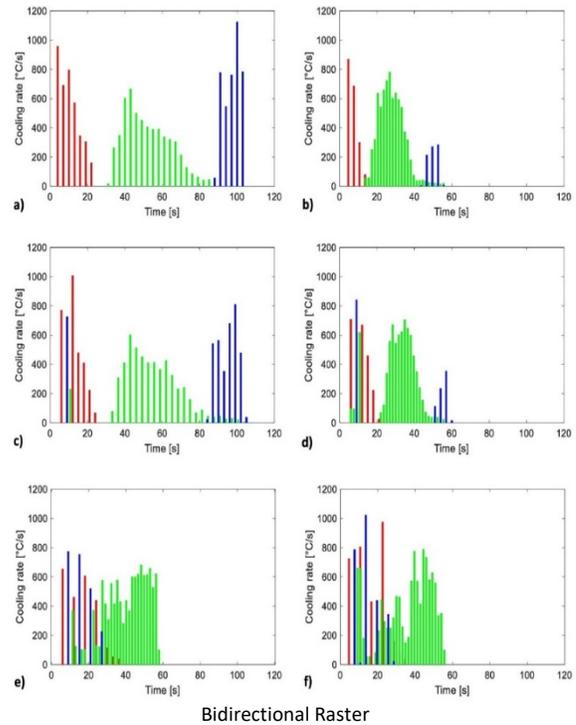
Figure 8 illustrates the cooling rates for different scanning patterns. Unidirectional raster paths show a consistent high cooling rate, while raster-bidirectional paths display a bell-shaped pattern with higher rates at the start and lower values later due to an ongoing process. Contouring paths exhibit a complex cooling scenario with a rapid sequence of thermal cycles, resulting in a broad range of cooling rates (Figure 8(e) and (f) refer).



(a) Raster-Unidirectional, (b) Raster-Bidirectional, (c) Contouring+Unidirectional Raster, (d) Contouring + Bidirectional Raster

(e) Unidirectional Contouring, (f) Bidirectional Contouring

Figure 7 Temperature Distribution Under Different Scanning Patterns (Reproduced from Mazzarisi et al. [42] with permission from Elsevier)



Bidirectional Raster

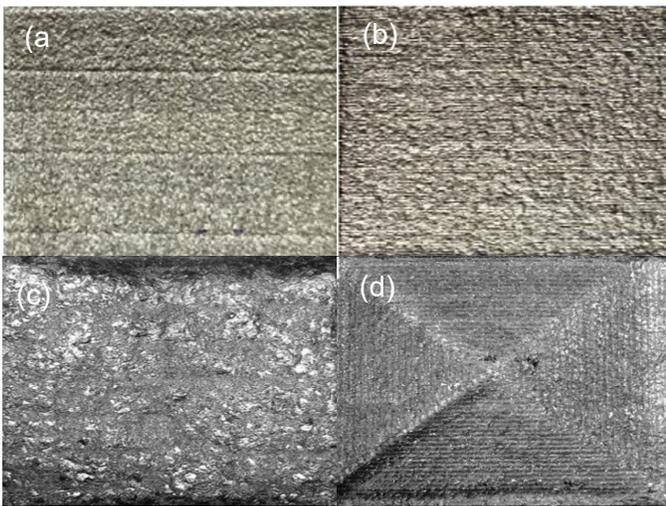
Figure 8 Trend of Cooling Rates Under Different Scanning Patterns (Reproduced from Mazzarisi et al. [42] with permission from Elsevier)

Table 1 Study of Conventional Scanning Patterns in DLMD: A Comparative Summary

Author (Reference)	Scanning Path Applied	Test Material	Results / Remarks
Gao et al. [108]	Raster Uni and Bi-Directional	Inconel 718	Zig-zag along shorter dimension minimizes deformation (1.54 mm), longer dimension leads to max deformation (3.44 mm).
Onuikie and Bonny [52]	Diagonal (45° Rotation)	Inconel 718	Diagonal build strategy has lower coefficient of friction (0.2-0.3) and improved compound wear.
Lee et al. [109]	Unidirectional, Bi-Directional, Bi-Directional with 180-degree Rotation	Ti-6Al-4V	Bi-directional with 180-degree rotation minimizes deformation and reduces cracking risk by 50%.
Lu et al. [110]	Six Scanning Paths	Ti-6Al-4V	Reducing dwell by increasing back speed and shortening longitudinal scanning decrease part warpage and residual stresses.
Ri-sheng et al. [106]	Various Scanning Schemes	Ni60	Scanning patterns strongly influence cracking failure in thin-wall components. Interlayer orthogonal scanning reduces residual stresses and cracking.
Bhardwaj and Shukla [111]	Bidirectional, Cross-Directional (90-degree Rotation)	Ni Margining Steel 300	Width-wise Zigzag scanning achieves more uniform stress distribution and reduces part distortion.
Saboori et al. [113]	67° and 90° Rotation Per Layer	Stainless Steel 316L	90-degree rotation per layer results in better ultimate tensile strength and lower residual stresses, despite higher stresses on lateral surfaces.
Aversa et al. [114]	Inter-Layer Rotation Angle	Stainless Steel 316L	0-90 degrees orthogonal strategy results in smooth residual stress distribution with lower values.
Zhao et al. [115]	90-degree Rotation Angle	24CrNiMo Alloy Steel	90-degree rotation angle with 2-minute interval offers optimized deposition plan for high tensile strength and microhardness.
Li et al. [116]	Orthogonal Patterns with 90° Inter-Layer Rotation	--	Orthogonal patterns with 90-degree inter-layer rotation are considered a standard deposition strategy for uniform heat distribution, minimum residual stresses, and high density.
Tan Zhi'En et al. [107]	Longitudinal Zig-Zag, Zigzag with 90° Rotation, Traverse Zigzag	Stainless Steel 316L	Longitudinal zig-zag scan exhibits finer grain, higher tensile strength, and fracture strain.
Tiwari et al. [117]	0°, +45°, +90° Rotation Strategy	Inconel 625	+90-degree rotation strategy shows lower anisotropy and higher microhardness.
Kim et al. [118]	Sixteen Different Raster Scanning Strategies	--	Alternative deposition scanning strategies result in 16% less symmetrical residual stresses.
Tang et al. [119]	Zigzag Strategy	SAF2507 Super Duplex Stainless Steel	Fracture propagation affected by build orientation.
Ren et al. [120]	Various Conventional Scanning Schemes	316L Steel Alloy	Zigzag along Y-axis causes least substrate deformation and more homogeneous temperature distribution.
Ribeiro et al. [121]	Contour Outward	AISI 316L	Contour scanning path results in greater form accuracy, better surface finishing, higher density, and microhardness.
Sun et al. [122,123]	Raster, Zigzag, Alternate-Line, Contouring In-Out, Contouring Out-In, S-Type Contouring	Aluminium Alloy 2319	S-Type pattern is optimal for printing square structures, resulting in more uniform temperature distribution, lower residual stresses, and less distortion.
Ghasempour et al. [124]	Outside-In and Inside-Out Contouring	Stainless Steel Alloy	Outside-In contouring results in minimum residual stresses and less workpiece dimension deviation. Inside-Out strategy generates least area change.
Yu et al. [125]	Fractal Scanning Pattern	--	Fractal patterns result in less part distortion and superior mechanical properties, but with larger inner porosity.
Yan et al. [126]	Island Patterns	Ti64 Alloy	Island patterns result in 71% less deformation compared to raster but with oscillating residual stresses. Poor diffusion between islands.
Woo et al. [127]	Orthogonal and Island Scanning	--	Island scanning without layer shift leads to internal defects, while bidirectional or orthogonal scanning shows no discernible macroscopic defects.
Wang et al. [128]	Island and Laser Jump Plan	--	Reduced deformation and residual stress by decreasing island sizes and increasing laser jump distances. Effects on microstructure, mechanical strength, and microhardness not explored.

4.2 Surface Texture

The control of surface texture – surface roughness or finish – in additive manufacturing is important to the overall functionality and performance of the manufactured components. Improved surface quality not only increases the aesthetic appeal but also effects mechanical characteristics, corrosion resistance, and functional properties. A meticulous consideration of significant process parameters is therefore imperious for achieving optimum surface characteristics in DLMD method. Researchers [111,125] highlight that Scanning patterns, including raster unidirectional and bidirectional influence surface texture (Figure 9 refers). Zigzag patterns give uniform heat distribution reducing surface waviness and surface roughness. In comparison, irregularities in contour or fractal paths result in uneven material buildup, causing heightened surface roughness [111,125].



(a) Raster Unidirectional (b) Zigzag (c) Fractal (d) Contouring

Figure 9 Surface Texture of the Parts Under Different Deposition Patterns (Reproduced from references [111] and [125] with permission from Elsevier)

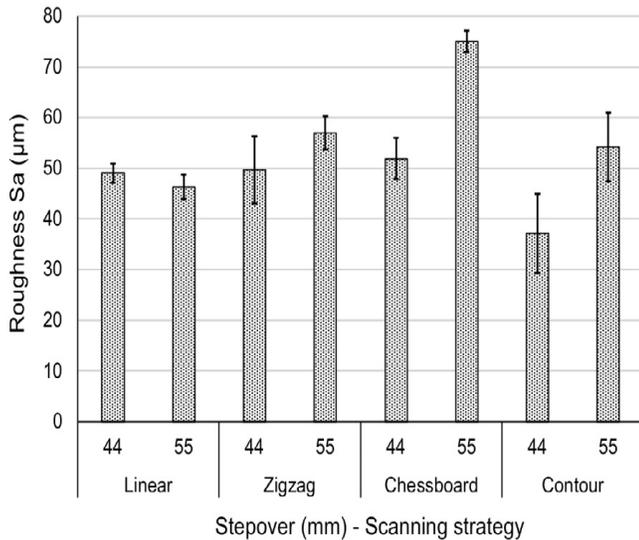


Figure 10 Average Surface Roughness by Different Scanning Strategies (Reproduced from Ribeiro et al. [121] with permission from Elsevier)

Figure 10 illustrates average surface roughness values for six parts studied by Ribeiro et al. [121] under different scanning paths. Interestingly, these results contradict those presented by previous researchers. Despite minimal differences in roughness between linear and zigzag strategies with similar stepover, contouring produced the best surface finish. Island patterns showed the highest roughness. Nevertheless, these strategies fall short of achieving desired surface texture, requiring additional treatments like machining due to surface irregularities and defects. Maleki et al. [132] highlight that surface roughness significantly diminishes the performance of components in DLMD additive manufacturing, limiting their potential applications. Surface roughness adversely affects part fatigue life, wear resistance and dimensional stability. Defects such as balling effects and staircase effects are contributed by layer-by-layer deposition paths, along with inadequate fusing, result in irregular microstructures. Thus, further investigation is needed to access the impact of DLMD scanning paths on material strength, surface finish and the uniformity of manufactured components.

4.3 Substrate Deforming Effects

The overall quality of parts manufactured through Direct Laser Metal Deposition also largely depends on the dimensional stability of the substrate. A stable substrate offers a dependable base to minimize distortions and ensuring precise geometry during the laser -based additive manufacturing process. Therefore, DLMD applications, it is paramount to comprehend and control substrate dimensional stability to achieve better parts quality. Figure 11 reproduced from the work of Yu et al. [125] shows that various deposition patterns including raster, contour-in, contour-out, and fractal, exhibit distinct impacts on part distortion. Fractal paths, among these patterns, result in minimal substrate distortion, followed by contour paths. Distortion in DLMD primary stems from nonuniform heat distribution and irregular heating-cooling cycles during deposition, causing thermal mismatches and resulting in elastic and plastic strains in the part layers. Both contouring-out and fractal patterns create concentrated temperature zones due to abrupt changes in scanning direction, with similar heat-affected zones compared to raster patterns [125]. The gradual nature of fractal and spiral patterns raises uniform heat distribution, reducing substrate warping and improving part accuracy. However, challenges like poor surface finish and inadequate fusion compared to raster deposition patterns persist with contouring and fractal scanning strategies.

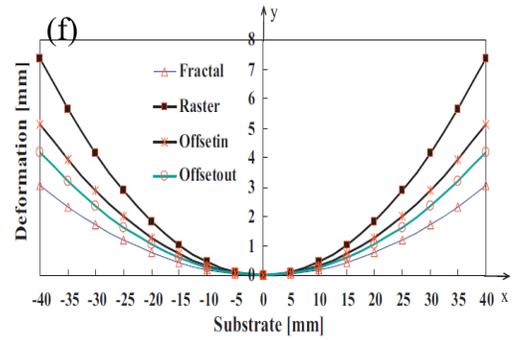
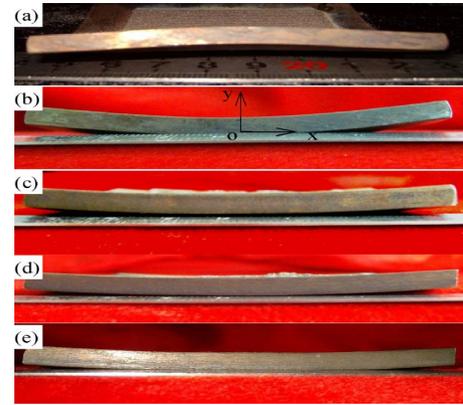
4.4 Microstructure

The deposition pattern also alters part microstructure by affecting the orientation and size of grains [104,121]. Rapid heating and cooling in certain areas, as caused by diffident deposition patterns, leads to smaller grains, while slower cooling results in coarse grains. Figure 12 compares the microstructures of the workpieces produced by Ribeiro et al. [121] using different scanning patterns. Among the different deposition patterns applied, outward contour paths produced a more homogeneous microstructure, while other patterns show variations in the grain structure, resulting in different properties within the part. This is

because in the contour outward strategy (D), initially heat is applied at the centre and then it is distributed uniformly outwards. The inclined grains in the Figure 12 (D) indicate that the laser was pointing from right to left, so the grains began to solidify from the lower to the higher part of each bead. Grain growth occurs from the bottom towards the centre of the cross section because the melt pool may have a rounded bottom and solidify from the outer to the inner region. This occurs because heat is initially lost to the surroundings of the bead and the lower layer.

4.5 Residual Stresses

The residual stresses, a critical consideration in process optimization, are significantly impacted by scanning patterns in DLMD additive manufacturing. The rapid heating and cooling inherent in the process lead to the formation of residual stresses. The shape of scanning paths, delineated by Sun et al. [122,123] plays a crucial role in determining the quantity and distribution of the stresses within deposited parts. The sequence of the melt pool and overlap distance between deposition paths largely affects heat transfer rates, temperature distribution, and, consequently, residual stress generation. Effective strategies involving minimizing extra overlap between successive passes to reduce heat accumulation and residual stresses. The study highlights that alternate line scanning and S- shaped patterns result in a uniform temperature distribution and minimal residual stresses. However, all deposition patterns, as shown in Figure 13, generate tensile residual stress, which can negative impact strength and fatigue performance.



(a) Bidirectional Along Z Axis, (b) Bidirectional Along X Axis, (c) Contour-In (d) Contour-Out (e) Fractal (f) Comparison of deformation values

Figure 11 Effect of Deposition Patterns on Parts Deformation (Reproduced from Yu et al. [125] with permission from Elsevier)

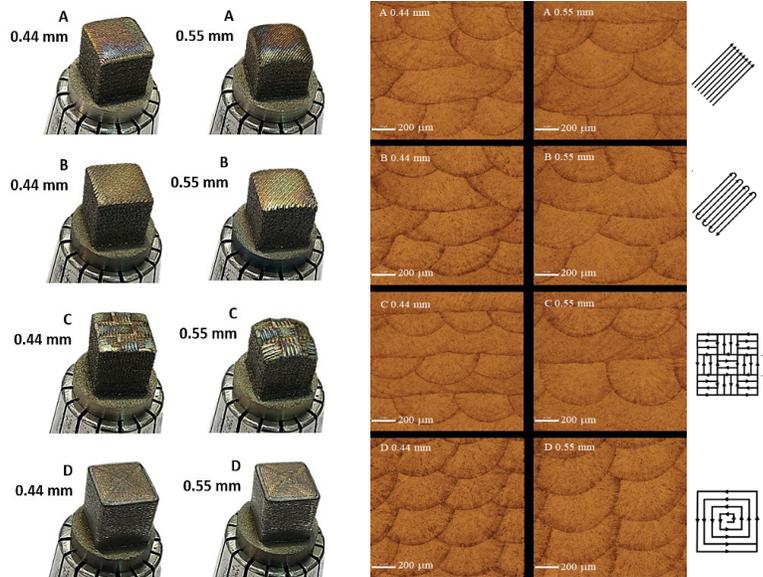
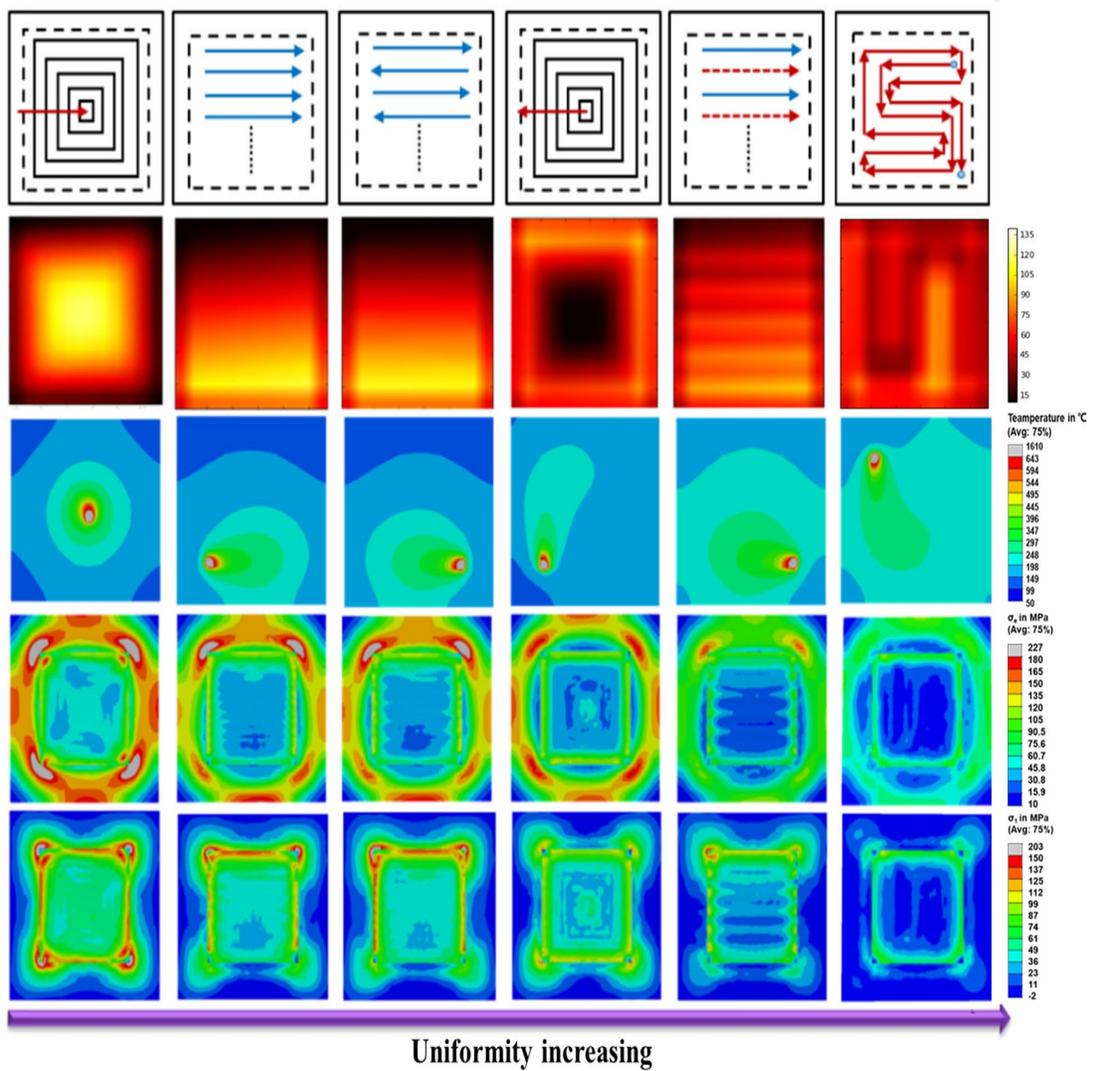


Figure 12 Microstructures of the Samples Produced Using Different Deposited Deposition Strategies (Reproduced from Ribeiro et al. [121] with permission from Elsevier)



Rows 1 to 5 from top to bottom: (1) Shapes of Applied Six Deposition Patterns (2) Localized Heat Accumulation and Distribution (3) Transient Temperature Areas (4) Equivalent Residual Stresses (5) Maximum Principal Residual Stress Fields

Figure 13 Results of Temperature and Residual Stresses Distributions of the six Conventional Deposition Patterns

(Reproduced from Sun et al. [122]- an open access article)

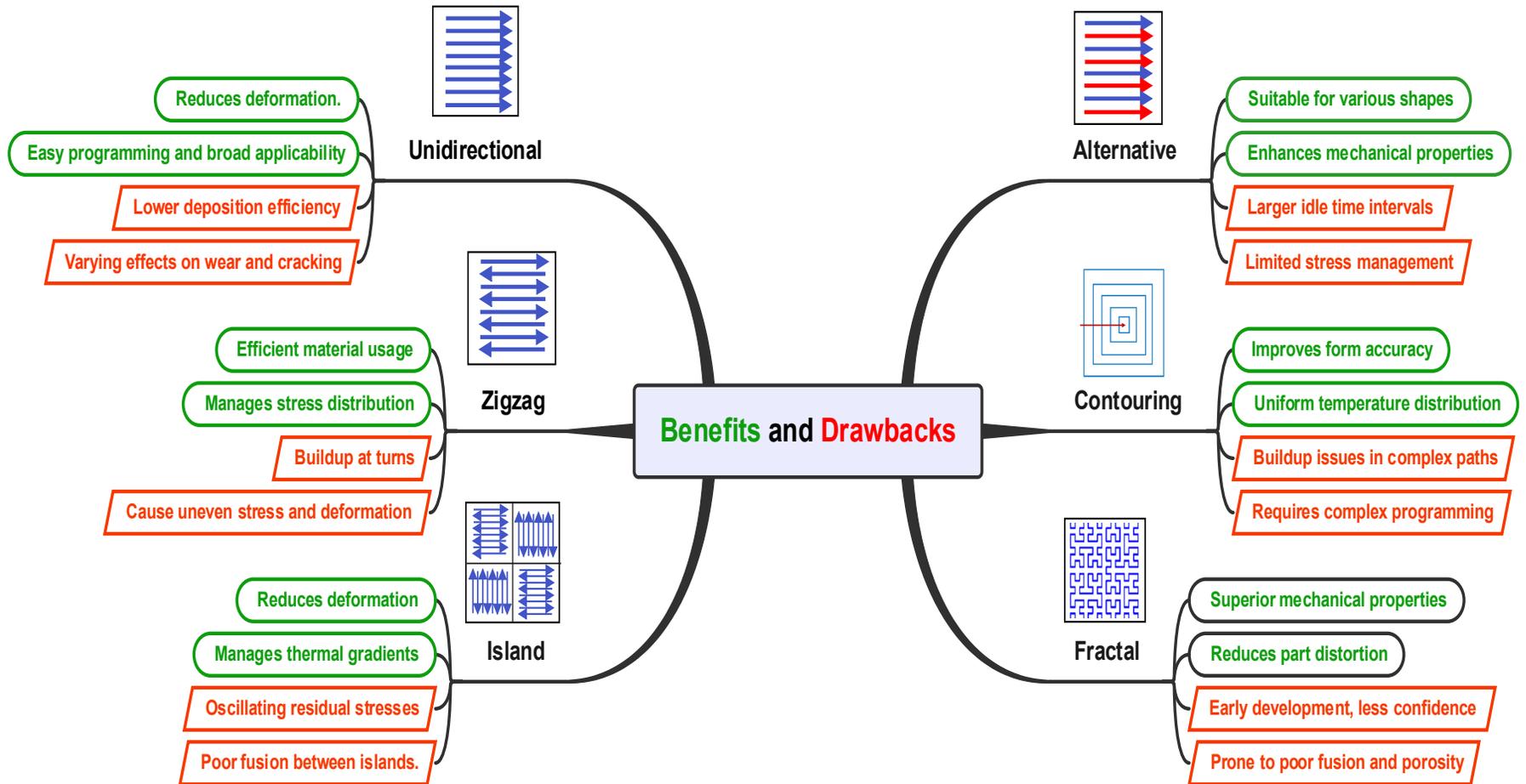


Figure 14 Comparative Summary of Scanning Paths Applied in DLMD

5.0 SUMMARY

The above discussion on deposition patterns in Direct Laser Metal Deposition (DLMD) additive manufacturing emphasizes their significance in shaping the properties and performance of fabricated components. As illustrated in Figure 14, deposition patterns have a big impact on several aspects of part manufacturing, including residual stresses, microstructure, surface properties, thermal behaviour, and dimensional stability. These patterns are central to determining the overall quality and performance of manufactured parts. The figure provides a concise overview, while the subsequent subsection offers a detailed comparison of the advantages and disadvantages associated with each deposition pattern, further elaborating on their specific effects.

5.1 Comparative Analysis of Deposition Patterns

- **Raster Paths:** As shown in Figure 11, unidirectional scanning paths frequently reduce substrate deformation and improve mechanical qualities. Zigzag and diagonal scanning patterns show differing effects on deformation, wear resistance, and cracking risk. Raster patterns, including direction-parallel, orthogonal, and contour-parallel variants, are widely used in DLMD due to their ease of programming, planning techniques, and broad applicability. These patterns offer better part quality and are suitable for various shapes. However, alternative line patterns suffer from lower deposition efficiency due to larger idle time intervals.
- **Zigzag Paths:** Figure 12 shows that Zigzag patterns, particularly straight and zigzag orthogonal, are efficient but require precise parameter management to avoid issues like excessive buildup at turning points, substrate deformation, and uneven stress distribution.
- **Contouring and S-Shaped Patterns:** As highlighted in Figures 13 and 14, contouring paths offer improved form accuracy and surface finishing, while S-shaped patterns prove optimal for square structures due to uniform temperature distribution and reduced residual stresses. Spiral patterns, designed to reduce turning points, and S-shaped patterns, blending zigzag and contour-parallel approaches, aim for high deposition efficiency and dimensional accuracy but still face challenges with buildup.
- **Island Patterns:** Island scanning paths offer reduced deformation compared to raster patterns. However, they often result in oscillating residual stresses, and internal defects and poor strength due to a lack of fusion between islands. Optimization of island sizes and scanning orders becomes necessary to address these issues.
- **Fractal Paths:** Fractal patterns demonstrate superior mechanical properties and reduced part distortion. However, these patterns are in early development stages and lack confidence in DLMD due to numerous corners and turning points, leading to poor fusion and inner porosity in produced parts.

5.2 Deposition Patterns Influence on Part Properties

- **Thermal Effects:** Figure 7 shows that all deposition patterns exert a deep impact on the thermal environment during

DLMD, significantly effecting temperature gradients, cooling rates, and residual stresses. Optimizing scanning paths is critical for precise temperature control and enhancing metallurgical properties.

- **Surface Texture:** Figure 9 depicts that scanning patterns directly affect surface roughness and waviness, which are important for functionality, mechanical properties, and aesthetics of the components. Some patterns like zigzag provide surfaces that are smoother, but still have imperfections that require post-processing steps.
- **Substrate Deformation:** Variations in the patterns of deposition have different effects on substrate distortion, which is important to maintain geometric precision and dimensional stability while fabricating (Figure 11). Strategies like fractal and contour paths can be considered to mitigate substrate warping, enhancing part accuracy.
- **Residual Stresses:** Figure 14 illustrates that scanning patterns have a significant impact on residual stresses in DLMD. Stress accumulation can be minimized by employing strategies like S-shape, contour and raster alternative that minimize unnecessary overlap between passes, although all patterns tend to induce tensile residual stresses.
- **Microstructure:** Grain size and orientation are significantly influenced by depositional patterns, which are crucial in forming component microstructure (Figure 12 refers). Rapid heating and cooling inherent in certain patterns like contour result in finer grains, while other patterns show variances that produce different properties within the part.

6.0 CONCLUSION

Exploring deposition patterns in Directed Laser Metal Deposition (DLMD) additive manufacturing represents a significant advancement in understanding how component performance and quality are affected by scanning paths. Numerous studies highlight the important role of deposition schemes in determining properties of various alloys, including residual stresses, surface roughness, substrate deformation, thermal impacts, and microstructure. Thermal effects and surface texture are significantly impacted by scanning paths, while substrate deformation and residual stresses are also important factors for considerations to minimize distortion and achieve uniform stress distribution. Issues such as insufficient fusion and surface imperfections persist, requiring further research and improvement. The necessity for customized material qualities is highlighted by the importance of microstructural features, such as grain size and orientation. In general, improving the mechanical qualities and build quality requires careful path selection and optimization.

Acknowledgement

The authors gratefully acknowledge the financial support provided by Universiti Teknologi Malaysia through the UTM COE/RG grants (Grant Nos. Q.J130000.5024.09G98 and Q.J130000.3824.24H00).

Conflict of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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