STUDY ON THE MECHANISM OF CRACK FOMATION IN INCONEL 625 FORMED BY DIRECT LASER METAL DEPOSITION

NGHIÊN CỨU CƠ CHẾ HÌNH THÀNH VẾT NỨT TRÊN CHI TIẾT HỢP KIM INCONEL 625 CHẾ TẠO BỞI CÔNG NGHỆ DLMD

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ABSTRACT

Direct Laser Metal Deposition (DLMD) is one of the contemporary forming technologies with significant potential for application across critical industries. This technology proves its worth in the manufacture of intricate components from challenging materials, such as nickel alloys and titanium alloys... DLMD represents a complex process, where the structural and mechanical properties of the formed material are heavily reliant on technological factors. Crucially, the assessment of defects residing within the deposition layers emerges as a focal yardstick, commanding current research endeavors. This paper investigates the influence of energy density within the molten region on crack formation within the deposition layers of Inconel 625 nickel alloy formed using DLMD technology. Results show that lower energy densities lead to poor adhesion between the forming layers and the substrate material, thereby initiating cracks within the deposition layer. The outcomes of the analysis unveil the existence of clusters comprised of aluminum oxide and titanium oxide within the fissures. These clusters stand as contributory agents to the diminished cohesion between the deposition layers, ultimately instigating the emergence of cracks at locations where these oxide aggregates reside. Subsequently, these cracks propagate along the paths delineated by crystalline structures, traversing through the deposition layers.

Keywords: *Direct laser metal deposition (DLMD), crack, microstructure, Inconel 625.*

TÓM TẮT

DLMD là một trong những công nghệ tạo hình hiện đại, có tiềm năng ứng dụng rất lớn trong các ngành công nghiệp trọng điểm. Công nghệ này được sử dụng để chế tạo những chi tiết từ các vật liệu khó gia công như hợp kim niken, hợp kim titan... DLMD là một quá trình phức tạp, tổ chức và cơ tính vật liệu tạo hình phụ thuộc rất lớn vào các yếu tố công nghệ. Khuyết tật trong lớp tạo hình là một trong những chỉ tiêu chất lượng quan trọng đang được các nhà khoa học quan tâm. Bài báo này nghiên cứu ảnh hưởng của mật độ năng lượng vùng nóng chảy đến sự hình thành vết nứt trong lớp tạo hình hợp kim niken Inconel 625 tạo hình bằng công nghệ DLMD. Kết quả nghiên cứu cho thấy, khi mật độ năng lượng thấp sẽ dẫn đến sự không liên kết giữa lớp tạo hình vơi vật liệu nền, hình thành vết nứt trên lớp tạo hình. Kết quả phân tích cho thấy sự tồn tại của các ô xít nhôm, ô xít titan trong các vết nứt, đây là một trong những nguyên nhân gây nên liên kết yếu giữa các lớp tạo hình, vết nứt được hình thành tại các vị trí có ô xít và phát triển dọc theo các tinh thể, xuyên qua các lớp tạo hình.

Từ khóa: *Công nghệ DLMD, vết nứt, cấu trúc tế vi, vật liệu inconel 625.*

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1. INTRODUCTION

The technique for fabricating products through the application of Direct Laser Metal Deposition (DLMD), wherein metal powder is directly fused using laser-induced processes, stands as one of the contemporary advancements in metal shaping methodologies. This technology commenced its developmental journey during the 1990s, entailing the amalgamation of laser technology, computer numerical control (CNC), computational advancements, and material science [1]. Employing laser energy to induce fusion within metal powder, the resultant products are meticulously constructed layer by layer in accordance with the additive manufacturing principle. Subsequently, this technology underwent rapid evolution, leading to its extensive integration across sectors including aerospace, the automotive industry, maritime engineering, military applications, and the medical field [2].

Experimental research has highlighted the numerous variable parameters within the DLMD process that can influence the mechanical and metallurgical properties of additive manufactured parts. These parameters encompass laser beam power, scanning speed, scanning strategy, hatch distance, and powder layer thickness [3-4]. For instance, Zhang et al successfully achieved a defect free Al-Cu-Mg alloy using a relatively slow scanning velocity [5]. In another study on LMD of 5087 Aluminum alloy, preheating of the substrate proved beneficial in reducing porosity and cracking [6]. The effects of pulsed laser parameters on Inconel 718 and Ti-6Al-4V direct laser deposition were also investigated.

Results showed that powder mass flow significantly influenced crack propagation during deposition, indicating the need for its reduction to minimize cracking in samples [7]. C.Y. Kong's research into the DLMD of Inconel 718, a nickel-based superalloy, has revealed that the combination of a low heat input and a high deposition rate yields samples characterized by minimal porosity and a notable reduction in cracking. [8]. In a similar manner, the optimization process conducted by Kempen and colleagues has bolstered the AlSi10Mg aluminum alloy components produced through laser melting decomposition. This enhancement has led to an increased relative density in block samples, characterized by the absence of substantial voids and cracks, ultimately achieving an impressive 99.2%. [9]. Metel et al sought to enhance the DLMD process by applying an additional laser beam modulator, which improved process efficiency [10]. Meanwhile, Choo et al investigated the effect of laser power on metallurgical characteristics, finding a linear increase in porosity from 0.13 to 0.88% as laser power decreased [11].

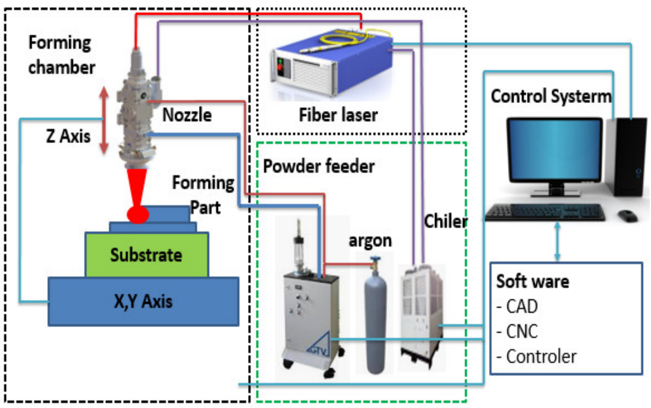
Inconel 625, a nickel-based superalloy, is the main material for forming aircraft engine parts such as turbine blades and stiffeners. They are difficult to fabricate using traditional casting and forging methods. Therefore, the use of DLMD to form thin-walled Inconel 625 components will have a significant impact on the development of the aviation and aerospace industry [12-14]. Inconel 625 is a multi-component superalloy, and the melting points of each element differ significantly. During the forming process, the local part of the component is rapidly heated and then cooled, which cannot make the composition diffuse uniformly. As a result, the chemical composition inside each grain is uneven, resulting in significant stress concentration. Under the thermal stress generated during the solidification process, cracks occur and propagate at the grain boundaries. Cracking of the cladding layer directly affects the quality of the component [15].

Numerous studies in DLMD have utilized various Inconel powders to produce parts. Inconel 718, a well-known nickel-based superalloy, finds extensive applications in aircraft engines, marine reactors, chemical industries, aerospace, and nuclear reactors due to its excellent mechanical properties and welding capability [16-18]. Studies on high-deposition-rate laser metal deposition of Inconel 718 and Inconel 625 using a 12kW diode laser have been conducted by Zhong et al [19]. Inconel 718 exhibits higher porosity compared to Inconel 625, and the microstructure of Inconel 625 is slightly smaller. The melting pool contour of Inconel 625 is more homogeneous, corresponding to the laser beam intensity distribution used, and solidification in Inconel 625 appears to be faster, possibly due to stronger heat transfer in the melting pool. Mahmoud Moradi et al investigated the AM of Inconel 718 powder using continuous and pulse mode laser. The pulse wave laser additive manufacturing results in a melting pool with a heartbeat-like pattern and doubled cooling rate. The pulse mode laser AM microstructure shows finer and better columnar dendrites due to the unique heat input during laser shutdown periods and at the end of the process [20].

In this paper, specimens subjected to Direct Laser Metal Deposition (DLMD) were employed to elucidate the underlying mechanism responsible for the occurrence of cracking within the Inconel 625 superalloy.

2. EXPERIMENTAL PROCEDURE

The DLMD forming system, as illustrated in Figure 1, comprises a 0.5kW Fiber laser, powder feeder, powder nozzle, and a three-axis linkage workbench. In this experiment, Inconel 625 super alloy powder was utilized, with a particle size ranging from 15 to 55µm, as presented in Table 1 and Figure 2 [21], supplied by Sandvik. The substrate material was 316L stainless steel, with a geometric dimension of 150×200×10 (mm). With excellent heat transfer properties and strong affinity for Inconel materials, 316L stainless steel is the appropriate choice for the substrate material, as showed in Table 2 from thyssenkrupp Materials company [22-23]. The thin wall component with dimensions of 40×0.5×10 (mm) is formed using reverse direction of scanning methods, as demonstrated in Figure 3(e). The process parameters are presented in Table 3. Prior to the experiment, the metal powder was dried in a vacuum drying oven at 200°C for 4 hours to eliminate moisture. The substrate was polished with sandpaper and then cleaned with acetone and ethanol to remove grease and stains.



(a)

(b)

Figure 1. DLMD system: (a) DLMD diagram; (b) DLMD equipment

Table 1. Composition of Inconel 625 powder (wt%)

Ni	Cr	Fe	Mo	Nb+Ta	C	Mn	Si	P	S	Al	Ti	Co
>58	20-23	<5	8-10	3.15-4.15	<0.1	<0.5	<0.5	<0.015	<0.015	<0.4	<0.4	<1

Table 2. Composition of 316L substrate (wt%)

C	Cr	Ni	Si	Mn	Mo	P	S	Fe
≤0.03	16.5-18.5	10-13	1.0	2.0	2.0-2.5	0.045	0.015	Bal

Table 3. Process parameters

Sample	Laser power (W)	Scanning speed (mm/s)	Powder feeding rate (g/min)	Laser diameter (mm)
N_o1	260	12	2.8	0.5
N_o2	240	10	2.8	0.5
N_o3	220	8	2.8	0.5

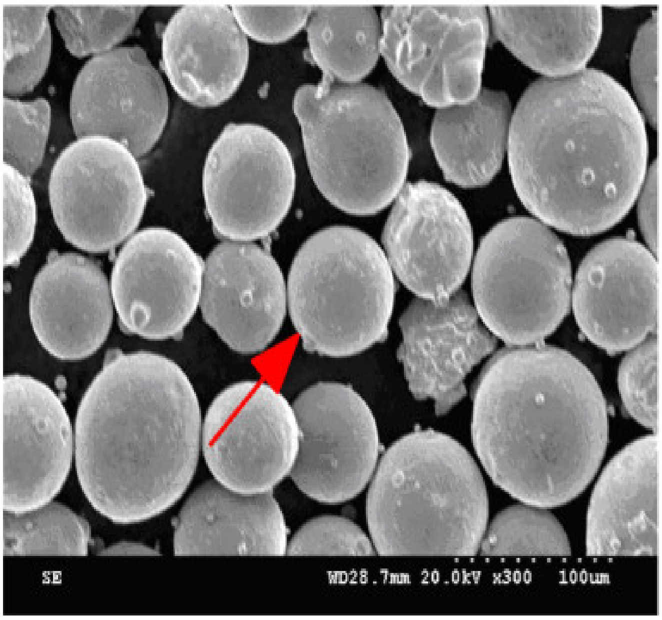


Figure 2. SEM micrograph of Inconel 625 powder

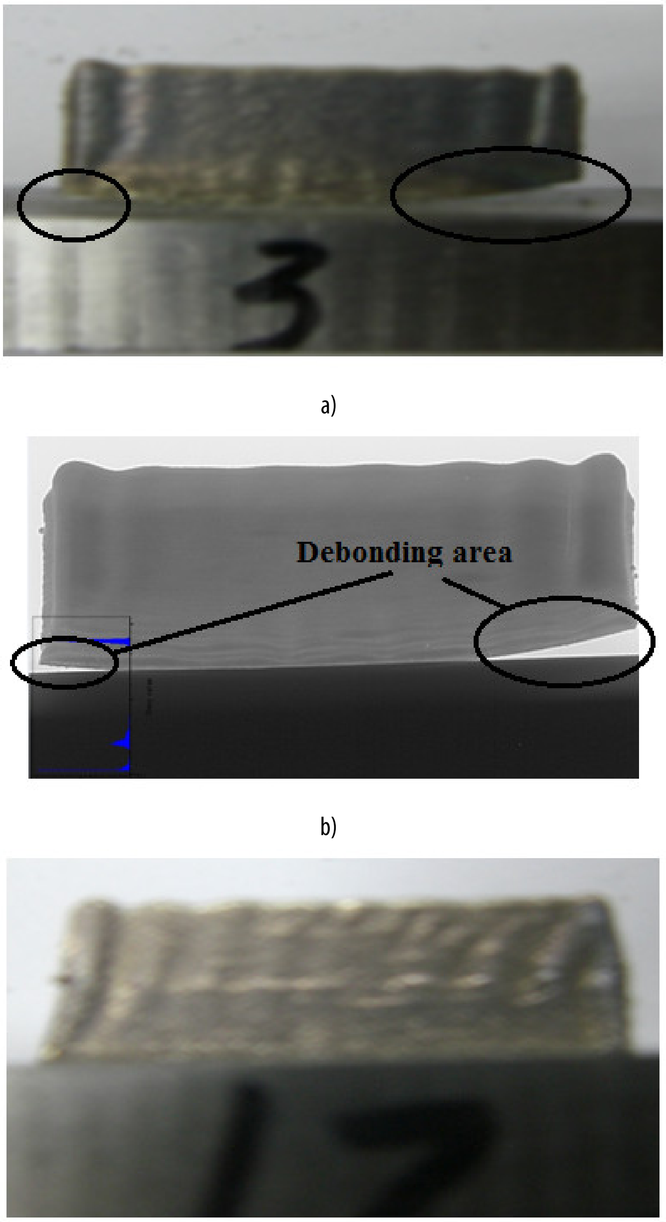
3. RESULTS AND DISCUSSION

3.1. Effect of energy density on the cracking susceptibility

During DLMD, laser power, scanning speed, and powder flow rate play an important role in determining the quality of the deposit. No macroscopic cracks were observed in sample N_o1, but debonding of the thin wall deposit from the substrate was noted in Figure 3 (a-b).

The issue of debonding between the deposit and the substrate has been resolved in the sample N_o2. However, macrocracks have been observed in sample N_o2, as illustrated in Figure 3(c-d). These cracks propagate along the build direction and have a length of approximately 2 - 5mm. Both Sample N_o1 and Sample N_o2 underwent processing at scanning speeds of 12mm/s and 10mm/s, corresponding to energy densities of 43.3J/mm² and 48J/mm², respectively. The energy density is calculated using formula 1 [24]:

$$E = \frac{P}{d \times V} \quad (J/mm^2) \qquad (1)$$



a)

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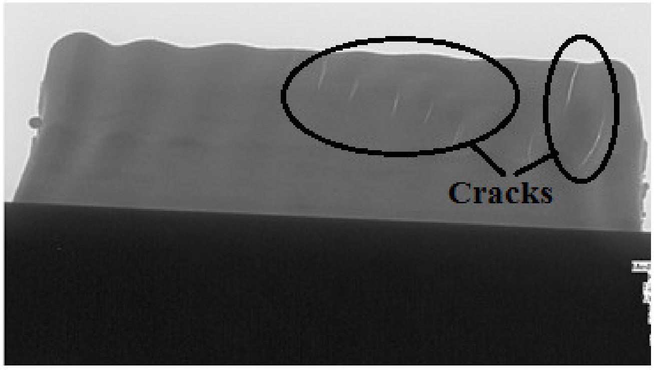
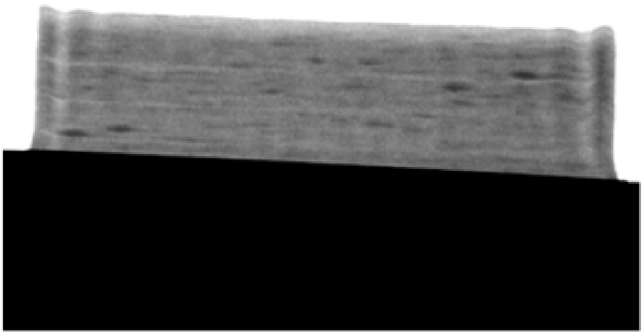


d)

e)



f)

Figure 3. The sample image and the X-ray image: (a) Sample N_o1; (b) X-ray image of Sample N_o1; (c) Sample N_o2; (d) X-ray image of Sample N_o2; (e) Sample N_o3; (f) X-ray image of Sample N_o3

During DLMD, the deposited material undergoes rapid cooling as the injected metal powders are rapidly heated and melted by the focused laser beam as it passes the point. In the case of deposition at higher scanning speeds in samples N_o1 and N_o2, the thermal gradient between the top of the deposit and the heat-affected zone (HAZ) is high. This high gradient produces significant tensile stress in the previously deposited layer (HAZ), resulting in the initiation of strain-age cracks at higher scanning speeds. On the other hand, sample N_o3 was deposited using a low laser power (220W) and low scanning speed (8mm/s), corresponding to 55J/mm^2. This combination led to the development of relatively low tensile stress in the HAZ. It is also evident that increasing the heat input due to the rise in energy density yields a crack-free deposit. Consequently, sample N_o3 was successfully deposited with no relevant cracks or defects. Egbewande et al. demonstrated that increasing the welding speed reduced cracking susceptibility [25]. In contrast, during DLMD, a reduction in the scanning speed resulted in a crack-free deposit observed in sample N_o3.

where E is energy density, P is laser power, d is laser diameter, V is scanning speed.

3.2. Cracking mechanisms

One of the main defects during DLMD is undoubtedly the cracking observed. Figure 4 shows the Optical Microscope image of sample N_o2. The results show mostly a dominant cracking pattern along the intergranular region and some crack path deviation along the transgranular regions. Cracks were mostly observed in the top part of the deposit along the Z direction in the range of 2 - 5mm.

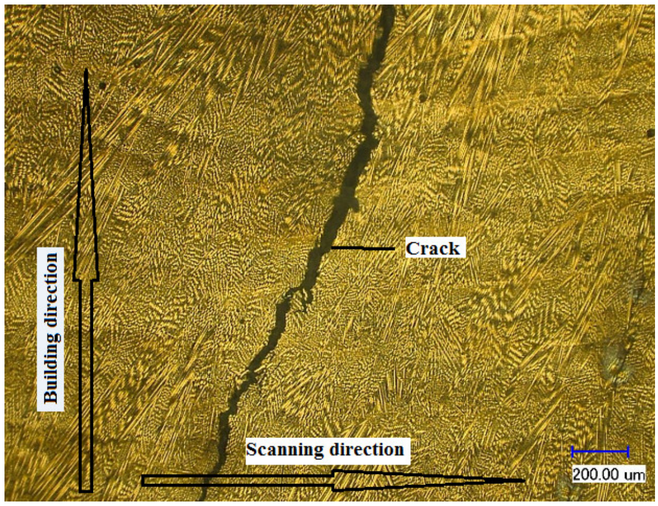


Figure 4. Optical Microscope image of sample N_o2

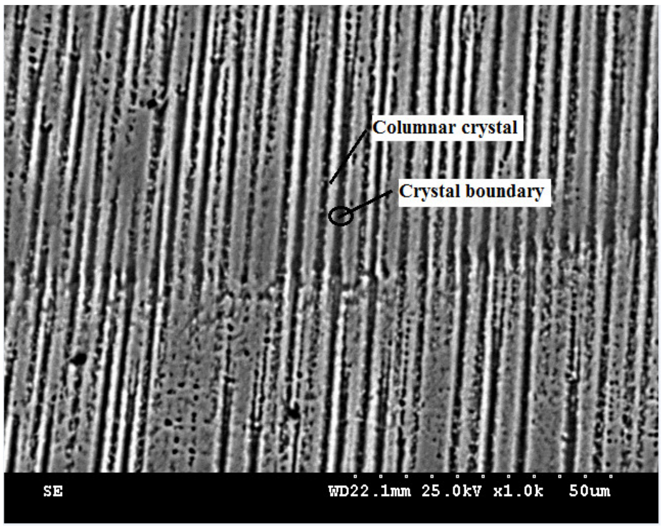
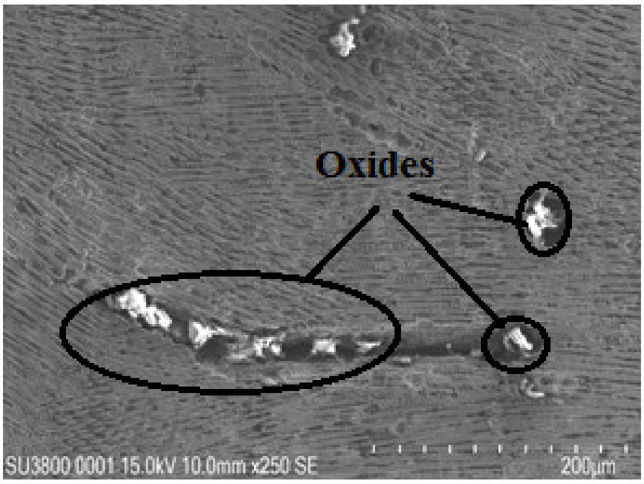
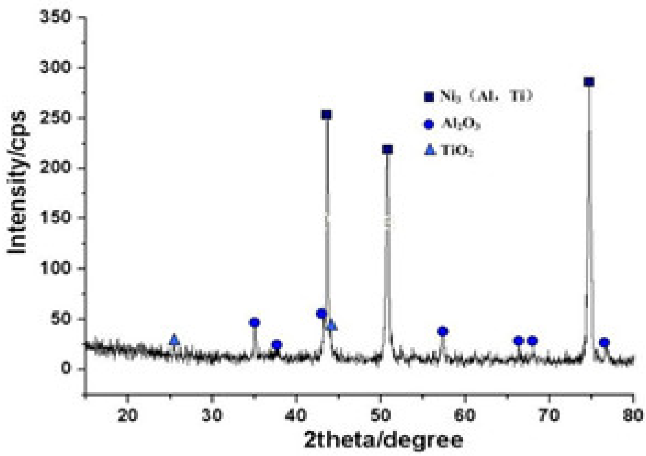


Figure 5. SEM image of microstructure

An important characteristic of Inconel 625 alloy material when shaped using DLMD technology is the presence of very small, long, vertically developed columnar crystal structures, as illustrated in Figure 5. This is due to the rapid crystallization rate and large temperature gradient, resulting in small and uniform crystal structures. The crystallization process occurs at the boundary surface between the solid and liquid phases, ensuring that the liquid and solid phases remain in contact throughout the entire process. This type of crystal structure is typical of columnar crystals. Figure 5 also depicts the continuous bonding between the formed layers, which not only enhances the material's mechanical properties but also ensures the continuous development of crystal structures between the layers.



(a)



(b)

Figure 6. The SEM and XRD images of crack on the component

(a) The crack morphology; (b) Image of the XRD analysis results of the bright region in Figure 6 (a)

Figure 6(a) depicts an SEM image of the crack, wherein bright-colored entities are discernible within the fracture. Employing X-ray Diffraction (XRD) apparatus for compositional analysis of these entities, Figure 6(b) presents the XRD analysis results pertaining to these luminous constituents. The analytical findings suggest that the illuminated entities comprise clusters of aluminum oxide, clusters of titanium oxide, and nickel elements. This indicates that the crack formed due to high-temperature conditions, thus, the observed crack is a typical sample of a hot crack.

The DLMD is technology utilizes a unique process where the shaping material is rapidly heated to a molten state, followed by a fast cooling process during crystallization. When subjected to a high-energy laser beam, the metal area and its surroundings reach an extremely high temperature and partially melt, causing the affected material area to expand and undergo compressive stress, which is constrained by neighboring areas. This results in a decrease in stress value as the temperature increases. However, the stress value at the center of the molten area may exceed the allowable limit, leading to plastic deformation under elastic deformation.

During the crystallization process, the constrained molten area is subjected to tensile stress as it is not free to shrink and must be confined by surrounding areas. The extremely fast cooling rate, causes an uneven distribution of chemical components, resulting in high melting point elemental clusters crystallizing before low melting point ones. This leads to liquid membranes separating from the crystal cluster boundary, which creates cracks. Due to the columnar crystal structure of the DLMD material, these cracks tend to develop along the boundary between crystal clusters.

4. CONCLUSION

The formation of cracks within the deposited layer of Inconel 625 nickel alloy using DLMD technology is influenced by energy density. Insufficient energy density in the molten zone leads to a lack of cohesion between the deposition layer and the substrate material, resulting in the initiation of cracks within the deposition layer. However, the occurrence of crack formation can be controlled when the energy density in the molten zone reaches a specific threshold value.

During the forming process, the elevated temperature of the molten region oxidizes susceptible elements such as aluminum and titanium, forming oxide clusters. These oxide clusters act as entities that diminish the interlayer bonding forces. A distinctive aspect of DLMD technology is its rapid heating and cooling process for materials, inducing substantial tensile and compressive stresses between the deposition layers. At the boundaries of the deposition layers, where aluminum oxide and titanium oxide clusters are present, the cohesion between these layers becomes weaker than in other areas. Consequently, when the bonding force between two layers is smaller than the tensile stress, cracks emerge.

The crystal structure of the deposition material is columnar in nature, perpendicular to the deposition layers. Therefore, the interconnection between these crystals is weakest in the direction perpendicular to the shaping direction, and cracks tend to propagate along the boundaries between these crystals.

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THÔNG TIN TÁC GIẢ

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