



Article

Microstructure and Mechanical Properties of Aluminum Alloy Studs Using Wire–Laser Directed Energy Deposition

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Abstract

In this study, an annular laser beam shaping optics and a wire feeding system are used for additive manufacturing. A discrete concentric layering trajectory strategy (DCL-TS) and a continuous deposition trajectory strategy (CD-TS) for the laser-directed energy deposition (WL-DED) of aluminum alloy stud structures are developed. Initially, combinations of parameters, such as laser power, transverse speed, and wire feeding speed, which lead to a process that produces a single-layer structure with good morphology and no visible pores and cracks, are identified. Then, DCL-TS and CD-TS manufacturing strategies are used to produce aluminum alloy studs of similar dimensions. The EBSD results indicate that the CD-TS produces finer grains in the aluminum alloy studs compared to the DCL-TS; correspondingly, mechanical testing reveals superior microhardness and tensile strength in the circularly fabricated studs. The latter tensile value testing verifies that aluminum alloy studs using WL-DED on the substrate can meet the requirements for practical application in mobile phones, computers, etc. This research method enhances the mechanical properties of additively manufactured items. Consequently, manufacturing efficiency is significantly improved, providing a promising solution for rapid production.

Keywords: coaxial wire feeding; additive manufacturing; aluminum alloy studs; trajectory strategy

1. Introduction

On the substrate of electronic products, studs need to be manufactured to fix components such as batteries and mainboards [1]. The main methods for manufacturing studs are Computer Numerical Control (CNC) machining or welding. In CNC machining, the relatively thick substrate (usually over 15 mm) needs to be gradually milled away, which generates significant material waste and is time-consuming. On the other hand, welding requires pre-manufacturing the studs and then connecting them to the substrate [2]; the welding process must have minimal thermal effect and no deformation, which greatly increases the production process and manufacturing difficulty. Therefore, maximizing manufacturing efficiency without compromising processing quality has become a key objective in the advancement of manufacturing technology.

Laser additive manufacturing (LAM) is a process that uses a laser as the energy-carrying beam to deposit melted materials in specific areas on the substrate [3,4]. It has the advantages of minimal heat influence, high manufacturing accuracy, and easy process



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control. It can be used to produce complex components that have good quality, low residual stress, and few distortions. Therefore, LAM has a wide breadth of prospects for application in metal manufacturing [5,6].

LAM processes are commonly classified as powder-feed processes and wire-feed processes [7–9]. Powder-feed processes have many issues, including a greater risk of oxygen or hydrogen contamination (present due to humidity) than with wire [10]. Moreover, there may be issues such as uneven particle size distribution, impurities, internal pores in particles, or non-spherical particles in the powder, which can lead to deposition defects. When using wire-feed processes, the surface roughness of the manufactured products is low, and the material utilization rate is almost 100% [11–13]. Currently, wire-feed processes have become a research focus in laser additive manufacturing. For instance, A. G. Demir et al. [14] used the filament–laser fused deposition method to manufacture a wall structure. L. Gao et al. [15] developed a filament–laser-directed energy deposition box structure using a back-and-forth oscillation deposition strategy and analyzed its microstructure and properties. M. O. Shaikh et al. [16] used laser–wire-feeding deposition to manufacture a thin vertical wall structure.

In summary, current research primarily focuses on structures such as walls and thin-walled features, with limited attention given to stud structures. However, stud structures exhibit substantial demand in industrial applications, making systematic research on their additive manufacturing an urgent necessity. Additionally, existing DED processes predominantly employ layer-by-layer fabrication methods. In such approaches, when processing a subsequent layer, the heat applied reheats the previously deposited layer. This increases overall heat input, promoting phenomena like recovery and recrystallization, which can compromise mechanical strength [17].

To address these issues, this study utilizes WL-DED to fabricate studs, aiming to enrich the structural possibilities of additive manufacturing and provide a technical reference for practical production. The innovative use of a CD-TS enabled the completion of stud structures through continuous helical deposition, in contrast to the DCL-TS used in conventional approaches.

To compare against the stud structures fabricated using a CD-TS (continuous helical deposition), we also designed a DCL-TS (discrete concentric layering) for manufacturing stud structures. Spiral trajectory strategies are recognized for their high efficiency and have been adopted in laser welding [18]. Moreover, to the authors' knowledge, few studies have reported the use of a DCL-TS with a spiral trajectory for the laser additive manufacturing of stud structures.

In this paper, WL-DED is used to directly fabricate aluminum alloy stud structures on an aluminum alloy substrate. We innovatively designed two trajectories for the laser additive manufacturing of stud structures, named CD-TS and DCL-TS, and compared their effects on the microstructure and mechanical properties.

2. Materials and Methods

2.1. Materials

The substrate material was 6061 aluminum alloy, with dimensions of 100 mm × 100 mm × 7 mm. ER4043 wire with a diameter of 1.6 mm was used as the feeding material. According to the reference literature, using ER4043 as the filler wire for the laser welding of 6061 aluminum alloy can reduce cracks and improve the mechanical properties [19]. Both the substrate and the wire were supplied by TRIO METAL (GZ) Co., Ltd. (TMC, Zengcheng, Guangzhou, China). The chemical compositions (wt. %) of both the substrate and wire are shown in Table 1. All substrate surfaces were cleaned with acetone before

laser additive manufacturing, and argon gas was used for protection during the additive manufacturing process to prevent material oxidation.

Table 1. Chemical composition of 6061 and ER4043 aluminum alloy (wt. %).

Materials	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Substrate material	0.4	0.5	0.3	0.1	1.2	0.18	0.21	0.1	Bal.
Wire	4.5	0.8	0.3	0.05	0.05	/	0.1	0.2	Bal.

2.2. Systems

2.2.1. Laser Metal Deposition System

The overall structure of the WL-DED system is shown in Figure 1a. The system primarily consists of a laser system, an X-Y-Z axis motion control system, a Charge-Coupled Device (CCD) visual positioning system, and an integrated wire-feeding mechanism within the laser processing head, as illustrated in Figure 1b. A 6 kW fiber laser (RFL-C6600S, Ruike, Wuhan, China) was used to generate a laser beam with a wavelength of 1080 ± 5 nm and a fiber core diameter of 600 μm . The automated wire-feeding additive manufacturing process proceeds as follows: First, the X-Y-Z axis motion control system moves the fixture holding the substrate into the processing location. Next, the CCD visual positioning system performs a visual alignment of the substrate. Finally, the laser processing head carries out additive manufacturing on the substrate while simultaneously supplying argon gas for shielding and feeding the wire.

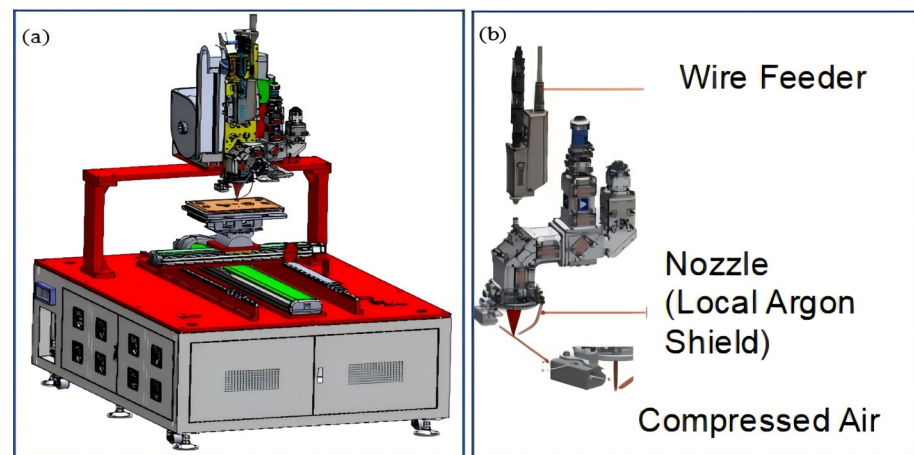


Figure 1. Experimental set-up: (a) main system components and (b) laser wire feeding head.

The laser processing head is a wire–laser coaxial processing head (CoaxPrinter, Precitec Germany GmbH & Co. KG, Gaggenau, Germany), which enables coaxial wire feeding, as shown in Figure 2a. The emitted laser beam from the laser core is a Gaussian beam, which is then guided through the beam-shaping lens with a pair of axicons and a convergent lens, which collimate and transform the Gaussian beam into an annular-shaped beam. The annular beam is guided coaxially to the axis of the wire by means of two reflective mirrors, and is finally focused on the materials by a focusing lens.

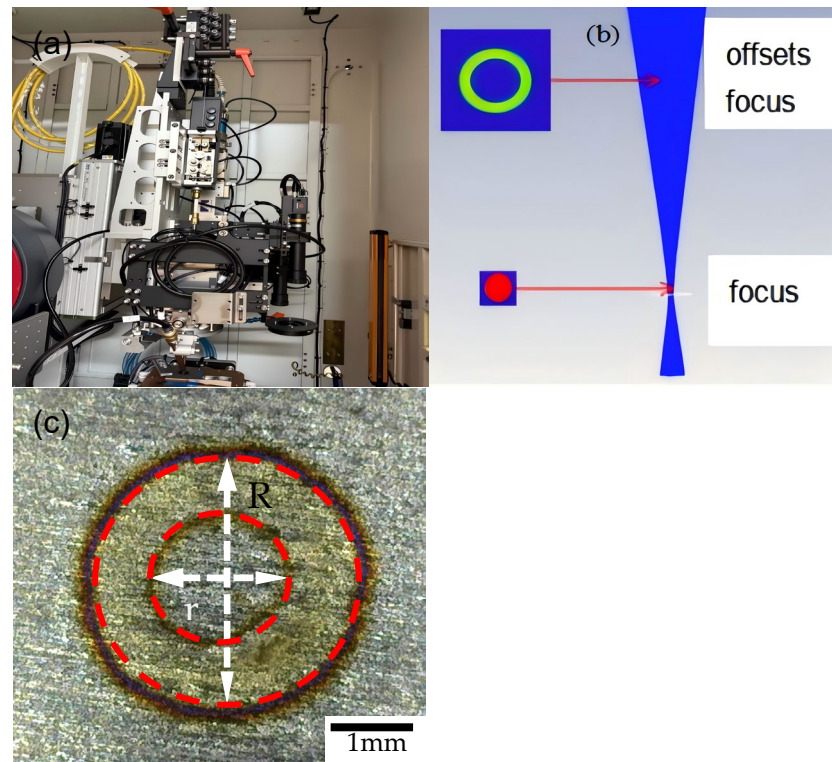


Figure 2. (a) Laser processing head; (b) laser processing head; (c) laser beam when offsetting annular beam on the titanium plate.

As shown in Figure 2b, in the laser focus state, the laser beam is a circular beam, while in the defocused state, it is an annular beam. In this experiment, negative defocus (-6 mm) was used, forming an annular beam with an inner diameter (r) of 1.4 mm and an outer diameter (R) of 2.2 mm on the material surface (in Figure 2c, the white dashed arrows is the distance between the solid lines and the red dashed circles is the outer edge and the inner edge of the ring), which enables the 1.6 mm wire to pass through and be preheated. Figure 2c illustrates the size of the annular laser spot, which was captured on a titanium plate using a laser power of 600 W and an exposure time of 5 ms.

2.2.2. Optical and Mechanical Properties Measurement

The WL-DED samples were cross-sectioned using an abrasive cutting machine, and then mounted and polished with 600 , 800 , 1000 , and 1200 grit emery papers, followed by $9\text{ }\mu\text{m}$, $6\text{ }\mu\text{m}$, $3\text{ }\mu\text{m}$, $1\text{ }\mu\text{m}$, and $0.25\text{ }\mu\text{m}$ abrasive suspension. Then, the specimens were subjected to chemical etching using Keller's reagent (2.5 mL HNO_3 , 1.5 mL HCl , and 1 mL HF in $95\text{ mL of H}_2\text{O}$) for 60 s. The macroscopic morphology of the samples was tested using an optical microscope (KEYENCE VHX-600, Keyence Corporation, Osaka, Japan), and the microstructure of the samples was tested using a metallographic microscope (Leica DM4000M, Leica Microsystems CMS GmbH, Wetzlar, Germany). Microhardness measurements were carried out from the substrate material to the additive manufacturing zone using a Vickers microhardness tester (HV-1000SPTA, Laizhou Huayin Testing Instrument Co., Ltd., Laizhou, China). A load of 200 g with a dwell time of 15 s was applied for all indentations, and the distance between two indents was maintained at 0.5 mm . An average of 3 indentations taken in identical locations was reported.

The material structure and chemical composition were characterized using a scanning electron microscope (GeminiSEM 360, Carl Zeiss, Oberkochen, Germany) with an elemental analyzer (EDS). The grain size, grain orientation distribution, and texture features were analyzed using electron backscatter diffraction (EBSD, DAX Hikari Plus detector, EDAX

Inc., Mahwah, NJ, USA, attached to an FEI Nova NanoSEM 450, Thermo Fisher Scientific, Hillsboro, OR, USA). The additive manufacturing samples were cut into tensile test specimens, as shown in Figure 3a. The physical image of the tensile specimens is shown in Figure 3b. The tensile test was conducted using a tensile machine (QJ211S, Shanghai Qingji Instrumentation Co., Ltd., Shanghai, China), with a loading rate of 1 mm/min. The average tensile strength value of 3 specimens, as measured for the same parameters, was reported. The fracture morphology of the tensile specimens was observed using a scanning electron microscope (SEM, GeminiSEM 360, Carl Zeiss, Oberkochen, Germany).

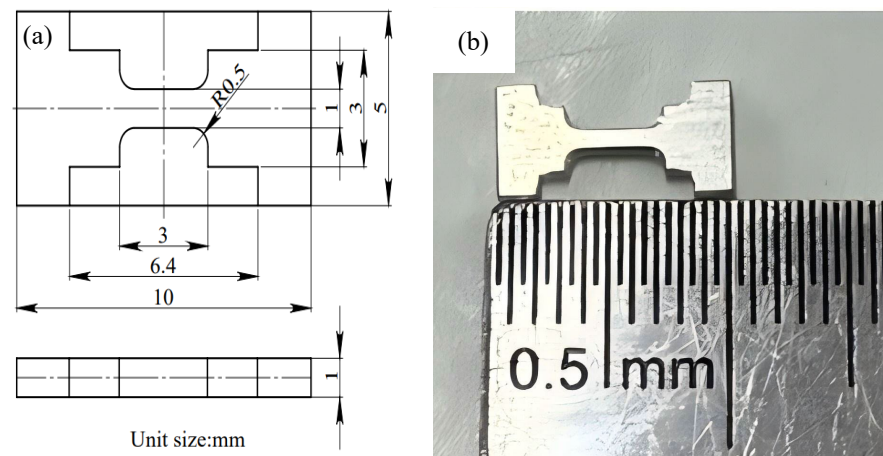


Figure 3. Tensile testing piece. (a) Geometrical dimensions of the test piece; (b) image of the test piece.

2.3. Methods

2.3.1. Single-Track Experiments

According to references [20,21] and the experimental results for the process parameters, it was observed that laser power, wire feeding speed, and transverse speed all significantly influenced the stability of the deposited tracks. An initial assessment was performed by additively manufacturing a 30 mm long single track on the substrate surface. The evaluation was conducted by analyzing top-view images of the scan tracks, through which the optimal combination of process parameters was determined.

Figure 4 illustrates the morphologies of a single track at various laser powers, transverse speed, and wire-feeding speed. A lower laser power of 4200 W and higher transverse speed of 10 mm/s resulted in the deposition of unmelted wire, as insufficient heat input prevented the wire from melting and depositing properly. When the wire-feeding speed exceeded 2 m/min, the metal wire melted before coming into contact with the substrate surface, resulting in droplet and lumping; when the wire-feeding speed was lower than 2 m/min, the materials fed into the metal were insufficient, resulting in poor appearance and shaping. The corresponding process parameter combination is shown in Table 2. The resulting single track under the conditions of a laser power of 4200 W, a wire-feeding speed of 2 m/min, and a transverse speed of 10 mm/s is shown in Figure 4a. The corresponding metallographic image in Figure 4b demonstrates good fusion between the deposited zone and the substrate, with no obvious pores or cracks.

Table 2. The best processing parameter combinations.

Laser Power in W	Wire feeding Speed in m min^{-1}	Transverse Speed in mm s^{-1}
4200	2	10

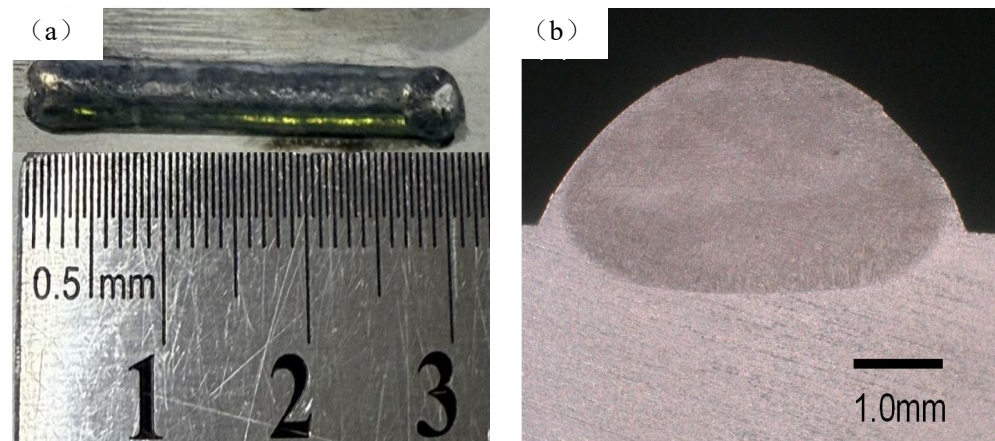


Figure 4. The appearance of the WL-DED sample. (a) Appearance, (b) cross section.

2.3.2. Fabrication of Stud Samples

Keeping the laser power at 4200 W, wire-feeding speed at 2 m/min, and transverse speed at 10 mm/s, two deposition strategies, namely, the DCL-TS and CD-TS, were adopted for the WL-DED stud samples on the substrate. When applying the DCL-TS, the parameters for the single-layer helical deposition path were first defined. These include the trajectory's inner radius (R), the spacing between adjacent helical turns (b), and the outer diameter of the helix (a). As illustrated in Figure 5a (the dashed arrows indicate the distance between the solid lines), the inner radius R was set to a fixed value of 0.02 mm. The outer diameter, a , determines the final diameter of the additively manufactured threaded stud section. The deposition direction, indicated by the arrow, proceeds from the inside outward. The helical turn spacing b controls the overlap ratio between successive turns, a parameter critically important to deposition quality and morphology, analogous to its role in spiral welding applications [18].

Single-layer helical depositions were produced with helical spacings b ranging from 2.0 mm to 2.8 mm. The resulting deposit morphologies are shown in Figure 5b–d. With $b = 2.0$ mm (Figure 5b), the overlap ratio is high, resulting in a steep edge slope at the periphery of the deposited track. This geometry is unfavorable for the stable deposition of subsequent layers. With $b = 2.4$ mm (Figure 5c), the overlap ratio is moderate, producing a shallow edge slope. This morphology promotes stable and continuous multi-layer deposition. With $b = 2.8$ mm (Figure 5d), the overlap ratio is too low, leading to the formation of void defects within the deposit. This condition is detrimental to the integrity of the subsequent layers.

When using the DCL-TS, the laser begins at the center of the helix and completes its path at the outermost circle. Since the start and endpoints are at different locations, the laser head must first cease emission and return to the starting point—the center of the helix—before the next layer can be deposited. The laser head is then raised along the Z-axis by a distance corresponding to the single-layer deposition height. In this study, this Z-axis increment was set to 2.2 mm per layer. The trajectory of the multi-layer deposition process is shown in Figure 6a: the red dashed line represents the idle travel path of the laser head, while the green dashed arrow indicates the running direction of the trajectory on the Z-axis plane.

When using the CD-TS, the laser starts from a point on the circumference. After completing the CD-TS for one layer, the endpoint becomes the starting position for the next layer. The laser head is then raised directly along the Z-axis, while the XY axes execute a circular motion, forming a connecting layer for additive manufacturing. Throughout the process, the laser operates continuously without interruption, significantly reducing the

overall manufacturing time, as illustrated in Figure 6b (note: the single-layer deposition height is 2.2 mm, so the Z-axis increment per layer is also 2.2 mm), where the green dashed arrow indicates the running direction of the trajectory on the Z-axis plane and the black dashed arrow indicates the distance between the solid lines. This approach saves considerable processing time by eliminating the need for the laser head to return to the initial starting point.

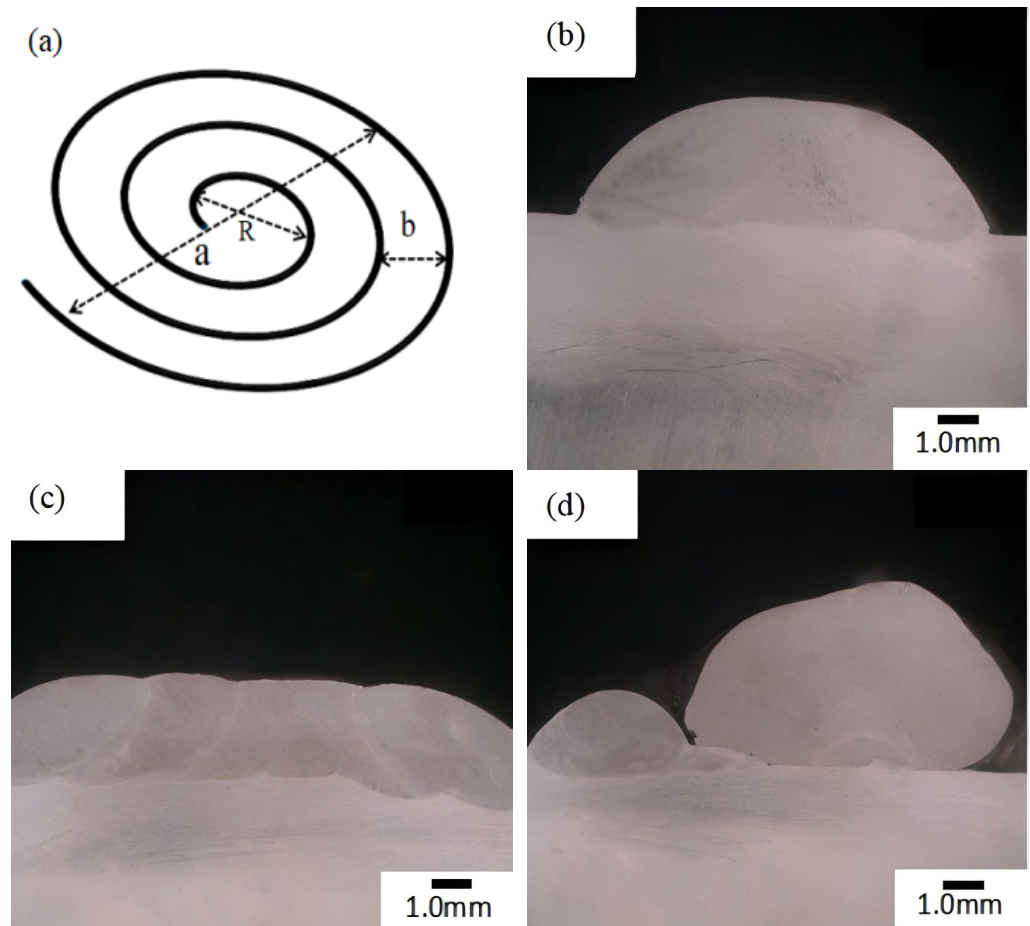


Figure 5. Spiral trajectory and cross section at different spacings. (a) Spiral trajectory; (b) spacing of 2.0 mm; (c) spacing of 2.4 mm; (d) spacing of 2.8 mm.

The circle diameter d plays a critical role in the additive manufacturing process. Circle diameters were set from 5.0 mm to 8.0 mm. Cross-sections of the fabricated samples are shown in Figure 6c–f. At $d = 5.0$ mm and 6.0 mm, no hole defects were observed in the deposited region. At $d = 7.0$ mm, small hole defects appeared. At $d = 8.0$ mm, large hole defects occurred. Since the single-layer deposition width is limited, a larger diameter results in a lower material overlap rate at the center, preventing complete filling and leading to defects. Therefore, when applying the CD-TS, the maximum recommended diameter d is 6.0 mm, yielding an additive stud diameter of 9.4 mm. If the required stud diameter exceeds 9.4 mm, the DCL-TS should be adopted instead.

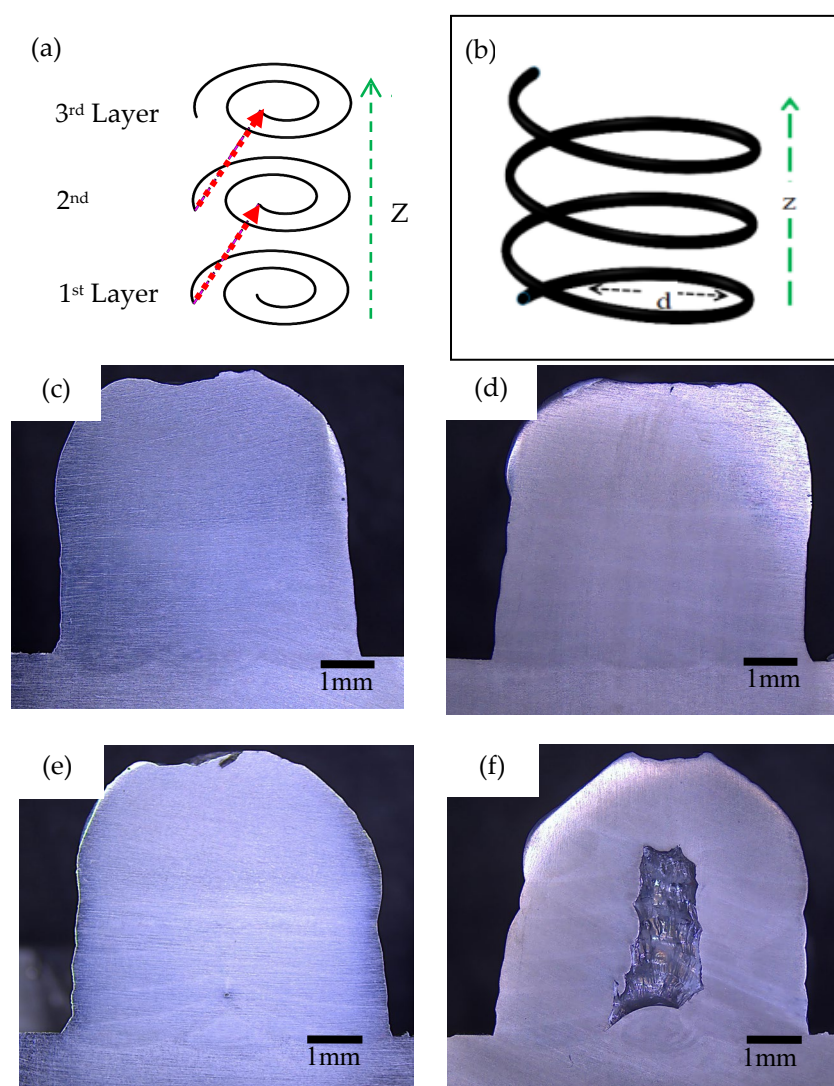


Figure 6. Trajectory and cross section for different diameters. (a) Trajectory of multi-layer processing; (b) CD-TS; (c) diameter of 5.0 mm; (d) diameter of 6.0 mm; (e) diameter of 7.0 mm; (f) diameter of 8.0 mm.

3. Results and Discussion

3.1. Parameter Comparison

The DCL-TS and CD-TS were used for the WL-DED of aluminum alloy studs, respectively, and the microstructure and mechanical properties were evaluated. The parameters of WL-DED and the dimensions of the aluminum alloy studs are listed in Table 3.

Table 3. The parameters of WL-DED and dimensions of the aluminum alloy studs.

Strategy	Spacing b in mm	Diameter a in mm	Diameter of Studs in mm	Height of Studs in mm	Cycle Time of Manufacturing in s
DCL-TS	2.4	/	10.3	9.4	9.2
CD-TS	/	6.0	10.0	9.3	6.0

3.2. Microstructure and Elemental Analysis

Figure 7 shows the microstructure of the aluminum alloy studs developed using WL-DED with the DCL-TS and CD-TS, respectively. In Figure 7a,c, the red dashed line represents the fusion line between the base material zone (BZ) and the additive zone (AZ),

and the red solid arrow represents the direction from the BZ to the AZ. No obvious pores or cracks are observed, demonstrating good fusion between the additive zone and the base material zone for both strategies. Figure 7b shows that the microstructure using the CD-TS is mainly fine-grained. Figure 7d that shows the microstructure using the DCL-TS is mainly grained with a larger grain size.

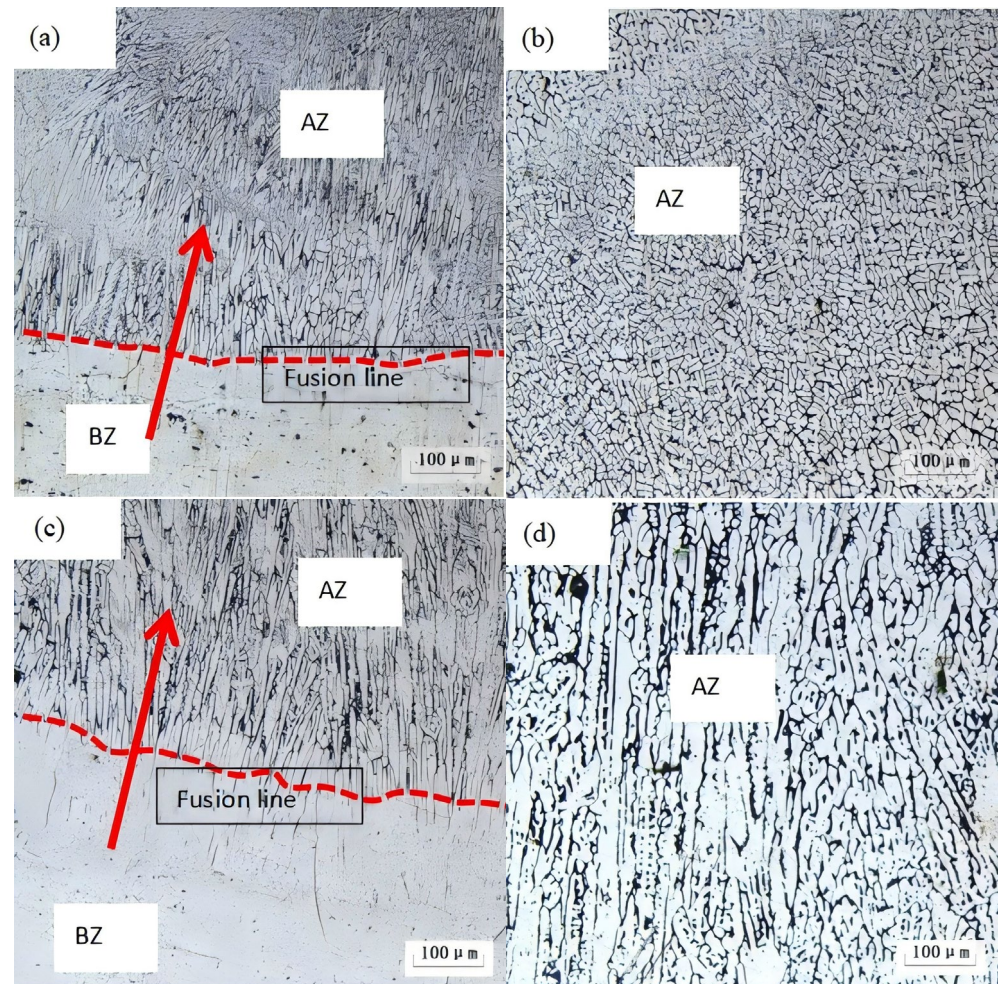


Figure 7. Microstructures. (a,b) CD-TS, (c,d) DCL-TS.

Elemental composition EDS analysis was performed on both the substrate and the WL-DED region. As shown in Figure 8a, the SEM and EDS results for the substrate indicate that the main element is Al, accompanied by Mg and Fe. The dark areas represent the aluminum matrix, while the light areas correspond to the second phase. Mg is distributed uniformly, whereas Fe exhibits an island-like distribution that is complementary to that of Al. The elemental composition of this area is presented in Table 4, revealing that the atomic ratio of Mg to Si is approximately 2:1. According to references [22,23], strengthening phases such as Mg_2Si are present in the substrate.

Figure 8b and c display the elemental composition in the WL-DED regions fabricated using the CD-TS and DCL-TS, respectively. These regions similarly consist of a gray aluminum matrix and white second phases. Elemental mapping shows that the primary elements are Al and Si, with Si distributed in a network-like pattern. The corresponding elemental composition is summarized in Table 4. The main elements detected are Al and Si, with no Mg observed. This finding is consistent with the composition of the ER4043 aluminum alloy filler wire used in the process. Given that ER4043 contains very little Mg,

trace of Mg is detected in the additive regions after laser additive manufacturing, and consequently, no Mg_2Si strengthening phase forms in these areas.

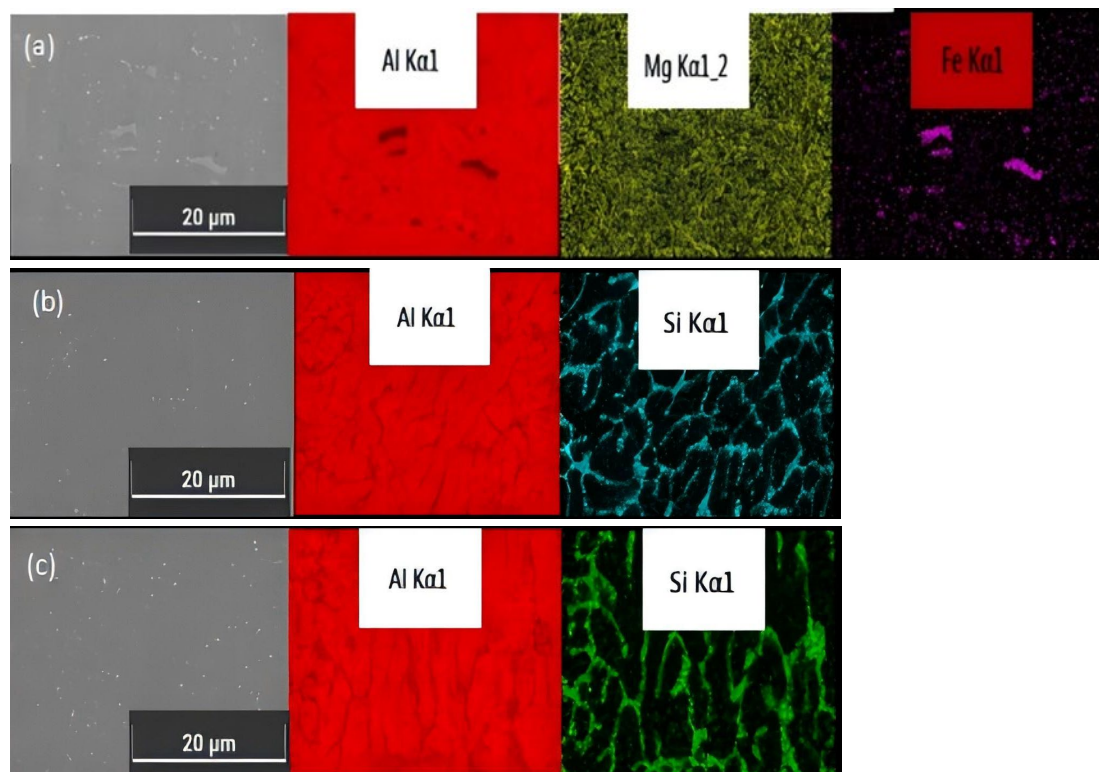


Figure 8. EDS testing for (a) substrate material, (b) CD-TS, and (c) DCL-TS.

Table 4. Chemical composition of substrate material and WL-DED parts (wt. %).

Material	Si	Fe	Mg	Al
Substrate material	0.47	0.72	0.75	98.06
WL-DED using the CD-TS	4.74	trace	trace	95.26
WL-DED using the DCL-TS	5.06	trace	trace	94.94

3.3. EBSD Analysis

For a deep analysis of the influence of the two strategies on the microstructure of WL-DED, EBSD was used for comparative crystallographic analysis, as shown in Figure 9. The strength of the texture from the laser additive manufacturing using the CD-TS is 12.618, while using the DCL-TS is 14.778. In the aluminum alloy grains manufactured using the CD-TS, the proportion of grains with a diameter less than 100 μm is 28.97%, while for the DCL-TS is 14.32%. The proportion of grains with a diameter less than 200 μm has similar results: using the CD-TS is 66.17%, while for DCL-TS is 43.52%. The average grain size of the additive area using the CD-TS is 8.65 μm , which is significantly lower than using the DCL-TS at 12.80 μm .

These differences can be attributed to the distinct process characteristics of the two strategies. In the DCL-TS, each layer has different start and endpoints. When fabricating the next layer, the laser head must return to the starting point (i.e., the center of the spiral), resulting in secondary heating of the previous layer and a longer total processing time of 9.2 s. This extended cooling period promotes grain growth. In contrast, the CD-TS features a continuous, uninterrupted trajectory with a significantly shorter total processing time of 6.0 s. This leads to faster cooling and solidification, which is conducive to grain refinement [24].

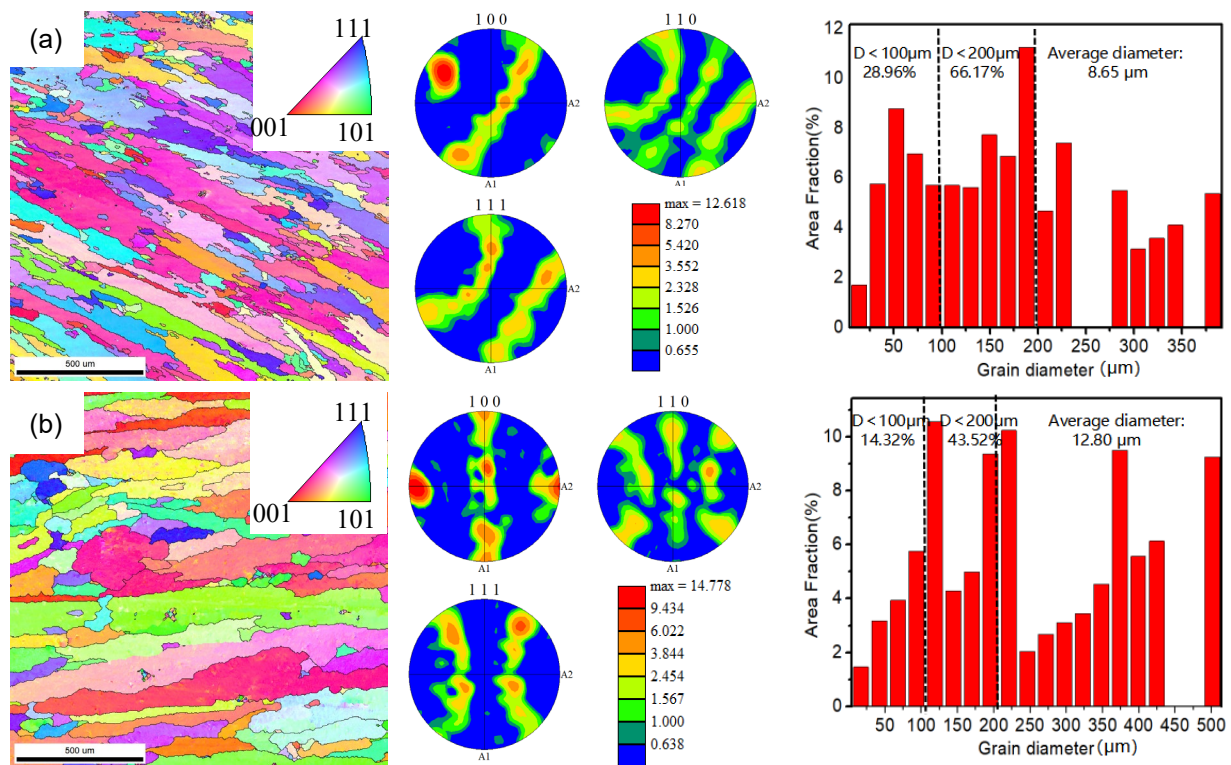


Figure 9. Inverse pole figures produced in columnar structure. (a) CD-TS, (b) DCL-TS.

3.4. Microhardness Analysis

Figure 10 shows the microhardness test results for the WL-DED samples fabricated using the CD-TS and DCL-TS. Both values are lower than that of the aluminum alloy substrate, which ranges from 70 to 80 HV 0.2. The reason for this is the absence of the strengthening phase of Mg_2Si in the additive areas, leading to a decrease in microhardness [25]. The microhardness value of the additive area using the CD-TS is higher than that of the DCL-TS; the microstructure of the additive area using CD-TS has finer grain sizes, which is conducive to increasing its microhardness value [26].

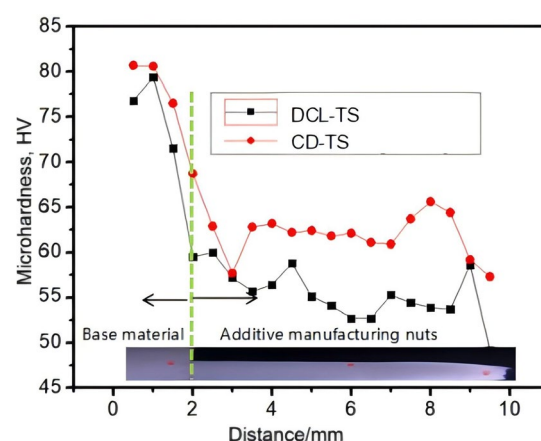


Figure 10. Microhardness in different zones.

3.5. Tensile Strength Analysis

Figure 11 shows the stress–strain curves of the aluminum alloy studs fabricated by WL-DED using the two strategies. As can be seen from the figure, the tensile strength of the studs fabricated by WL-DED using the CD-TS is 150 MPa, compared to 140 MPa

for those produced with the DCL-TS. Moreover, both the tensile strength and elongation of studs fabricated via the CD-TS are higher than those achieved with the DCL-TS. This can be attributed to the finer grain size in specimens produced with the CD-TS, which is conducive to improving both the strength and ductility of the material [27].

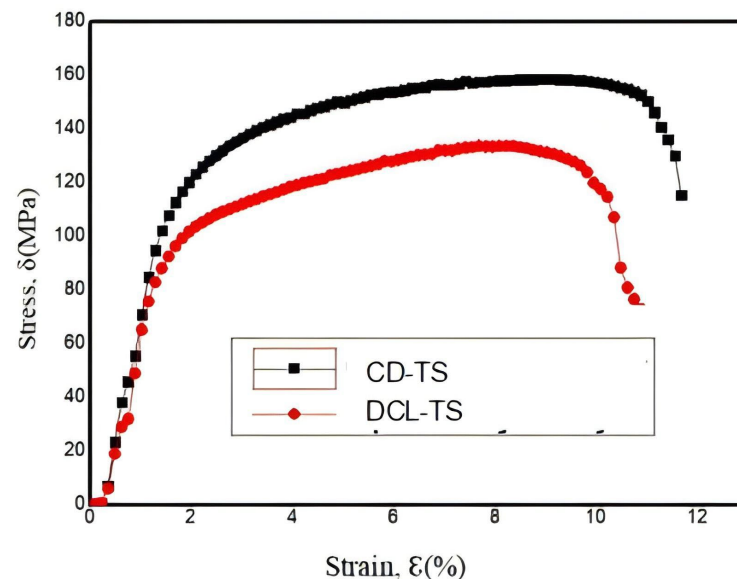


Figure 11. The tensile properties of aluminum alloy studs.

Figure 12 shows the fracture morphology of the aluminum alloy studs produced by WL-DED. The fracture of the studs manufactured using the DCL-TS is shown in Figure 12a,b (Figure 12b is the magnified view). The pore size is relatively small, approximately 10–20 μm , and the elongation rate is high. The fracture of the studs manufactured using the CD-TS is shown in Figure 12c,d (Figure 12d is the magnified view). The pore size is relatively bigger, approximately 60 μm . The size of the pores has a certain impact on the material's elongation, but it is not the determining factor. Although larger pores typically lead to reduced ductility, grain refinement also contributes to improved elongation. The increase in plasticity resulting from grain refinement outweighs the decrease caused by the larger pores, ultimately leading to the superior ductility observed in the CD-TS samples.

Figure 13a is a schematic diagram of the CD-TS layer-by-layer upward additive manufacturing. It can be observed that the morphology exhibits vertical layering. The corresponding EBSD Grain Orientation Spread (GOS) map is shown, where blue regions represent recrystallized areas with GOS values ≤ 2 , yellow regions indicate subgrain areas with $2 < \text{GOS values} \leq 7$, and red regions denote deformed areas with GOS values > 7 . The diagram shows that the recrystallized fraction in the CD-TS accounts for 47.8%, the subgrain fraction accounts for 51%, and no deformed grains are present.

Figure 13b illustrates the schematic of the DCL-TS layer-by-layer additive manufacturing. It can be seen that the morphology involves both horizontal and vertical layering. The recrystallized fraction accounts for 82.4%, the subgrain fraction accounts for 10%, and no deformed grains are present. It is evident that the recrystallized fraction in the DCL-TS is 34.6 percentage points higher than that in the CD-TS. The reason for this is that CD-TS additive manufacturing involves a single-pass formation process without horizontal layer-by-layer processing, resulting in less heat input compared to the helical trajectory. In contrast, the DCL-TS not only involves heat input from the upper layer to the lower layer, but also includes heat input from the same layer to its adjacent horizontal layers. The greater heat input promotes an increase in the recrystallized fraction and grain growth, leading to a decrease in hardness and tensile strength [28].

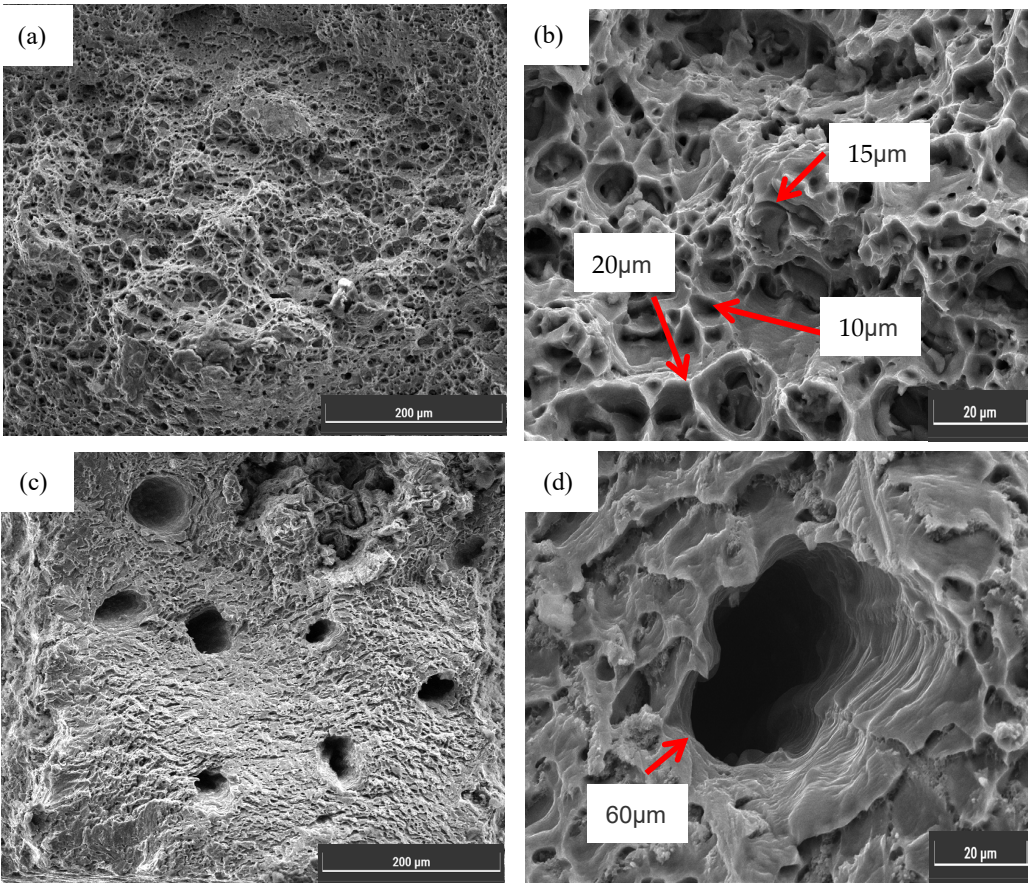


Figure 12. Fracture morphology. (a,b) DCL-TS, (c,d) CD-TS.

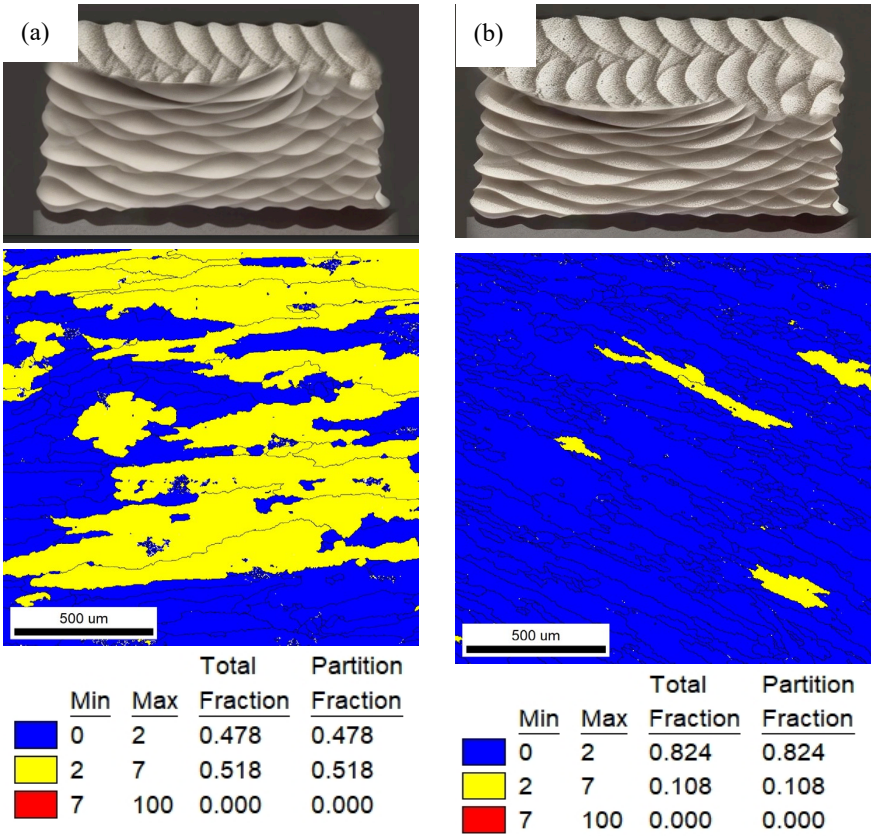


Figure 13. Schematic diagram and GOS. (a) CD-TS, (b) DCL-TS.

3.6. Practical Application Test

Aluminum alloy studs with a diameter of $9.4 \text{ mm} \pm 0.3 \text{ mm}$ and a height of 10 mm were fabricated using the CD-TS and the DCL-TS, respectively. Then, the rods were processed into nuts using CNC. The diameter of the CNC-processed nuts was 7 mm, the height was 8.0 mm (the excess parts of the rods were removed), and the diameter of the threaded holes was 2.0 mm. The test screws were inserted into the nuts as shown in Figure 14a. The measured tensile force values for nuts produced with the CD-TS and the DCL-TS were 2012 N and 2003 N, respectively. In both cases, failure occurred due to fracture of the test screw, while the WL-DED regions remained intact, as shown in Figure 14b. This indicates that the failure loads of the studs exceed 2000 N, which is higher than the failure load of screws used in actual production, thus meeting practical application requirements. These results demonstrate that both the CD-TS and the DCL-TS are viable for WL-DED on substrates, offering a replacement for conventional CNC subtractive machining or welding methods. This approach reduces material waste and simplifies the manufacturing process.

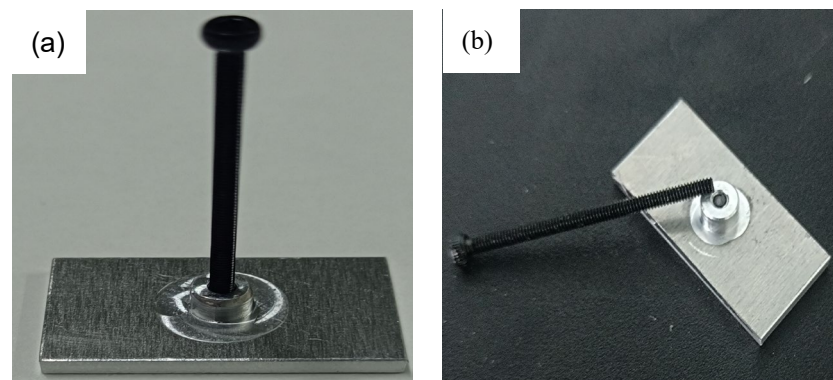


Figure 14. Stud-testing process. (a) Inserting the screw; (b) failure mode after tensile test.

4. Conclusions

This study systematically investigated the microstructure and mechanical properties of aluminum alloy studs fabricated via WL-DED using the CD-TS and the DCL-TS. The key findings are summarized as follows:

- (1) Through process parameter optimization, excellent metallurgical bonding between the deposited region and the substrate is achieved at a laser power of 4200 W, wire-feeding speed of 2 m/min, and transverse speed of 10 mm/s. A defect-free single-layer deposition without obvious pores or cracks is successfully obtained.
- (2) Two scanning path strategies, namely, the CD-TS and DCL-TS, were innovatively designed and compared. The DCL-TS requires the laser head to retract and reset between layers. In contrast, the CD-TS achieves continuous helical deposition with an uninterrupted upward build, eliminating the need for laser head retraction or resetting. This continuous approach significantly reduces manufacturing time (6.0 s vs. 9.2 s) and effectively lowers heat input.
- (3) Microstructural analysis revealed that the studs fabricated using the CD-TS exhibit finer grains (average grain size: $8.65 \mu\text{m}$) and a lower recrystallized fraction (47.8%). In contrast, the DCL-TS results in significant grain coarsening (average grain size: $12.80 \mu\text{m}$) and a higher recrystallized fraction (82.4%), owing to repeated thermal cycling between layers and between adjacent tracks within the same layer.
- (4) Mechanical test results indicated that the CD-TS yields a higher microhardness than the DCL-TS. It achieves a tensile strength of 150 MPa, which is superior to the 140 MPa obtained with the DCL-TS. Ductile fracture characteristics are observed on the fracture

surfaces of both groups. Additionally, the CD-TS provides better elongation, attributed to the grain refinement strengthening effect.

- (5) Practical application validation demonstrated that the studs fabricated by both strategies, after CNC machining into nuts, all exhibited tensile failure loads exceeding 2000 N, with fracture occurring in the test screw rather than the additively manufactured region.

These results fully satisfy industrial production requirements. This study successfully validates the feasibility and high efficiency of WL-DED technology for the rapid fabrication of aluminum alloy studs. Compared with the DCL-TS, the CD-TS delivers superior mechanical properties owing to the lower heat input and finer grain structure. This technology provides a novel, efficient, and low-consumption solution for stud manufacturing in electronic device fabrication, offering a promising alternative to conventional processes.

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