Effects of Process Parameters on the Structure and Hardness of Components in Laser Direct Metal Forming

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Abstract. As a typical additive manufacturing (AM) technology, Laser Metal Direct Forming (LMDF) integrates the characteristics of laser cladding technology and rapid prototyping technology. Because LMDF process has important application value in the field of rapid mould manufacturing and additive remanufacturing process, the effects of main technological parameters (laser power, powder feeding rate and scanning speed) on the microstructure and hardness in the process of forming were studied. To verify this influence rule, the experimental study on LDMF with different process parameter combinations were carried out with 45 steel as matrix and iron-based alloy powder as cladding material. Experimental results was consistent with the theoretical analysis results. In a word, experiments show that LMDF process can obtain uniform and compact metal cladding layer. The forming process parameters and their reasonable matching are closely related to the structure and performance of components. With the increase of laser power, the grain size of metallographic structure increases and the hardness decreases. To a certain extent, properly increasing the scanning speed and powder feeding rate can refine the grain size of metallographic structure, which increased the hardness of the component and enhancing its surface wear resistance.

1. Introduction

Based on computer aided design (CAD) model, additive manufacturing technology refers to a near net forming process, which manufactures components with complex geometry by joining materials layer by layer [1]. Laser Additive Manufacturing integrating laser, digitalization and material science is a new manufacturing technology. It has the advantages of reducing latitude manufacturing, complex forming and high material utilization rate [2]. As a typical laser additive manufacturing process, laser metal direct forming technology integrates the characteristics of laser cladding technology and rapid prototyping technology. It takes metal powder as raw material, and uses high-energy laser as energy source. According to the predetermined path, metal powder sent synchronously is melted layer by layer, solidified rapidly and deposited layer by layer. Thus it realize the direct manufacturing of metal parts [3]. This process can obtain metal components with large size range, complex shape and compact structure [4]. Based on the above characteristics, laser metal direct forming technology has significant advantages in mold cladding manufacturing. Due to the application condition, the forming surface of the mold must meet the requirements of good structure, high hardness and good wear resistance. The research shows that the process parameters of LMDF technology are closely related to the above
Therefore, exploring the influence of technological parameters of LMDF technology on the structure and performance of components and seeking a reasonable combination of technological parameters have become one of the hotspots of industry research. From the perspective of combining theory with experiment, this study discusses the influence of the main process parameters of LMDF technology on the structure and surface hardness of metal components. The results provided the technical support for the research on LMDF technology and the application in industrial fields.

2. Analysing the effect of LMDF process parameters to structure of components
LMDF manufacturing process is a very complex metallurgical process. There are many factors affecting the structure of components, including process parameters, powder state, forming path [5] and thermal process under the action of laser beam [4]. The cooling rate and temperature gradient of the thermal process change with the change of process parameters. In this paper, the effects of processing parameters such as laser power, scanning speed and powder feeding rate on the structure and hardness of components are studied.

2.1. Laser power
Laser power reflects the size of laser energy. With the increase of laser power, the size of molten pool increases and the maximum temperature increases [6]. During the forming process, the change of temperature field has a significant effect on the product organization [7]. Lin Xin [4] research group has studied the typical organizational characteristics of LMDF. In the laser additive manufacturing process, high energy density laser beams interact with metal materials in a very short time and in a very small area. Due to the rapid heating of the local area of the material surface and the strong heat transfer of the cold base material around the molten pool, the laser pool and its heat affected zone usually have high cooling rate, showing typical characteristics of rapid solidification and solid phase transformation. Therefore, as long as the consistency of the composition of the deposited powders is guaranteed, there will be no macrosegregation as a whole, and the micro-segregation will be limited to a very small scale corresponding to its fine solidification sub-structure, so that the structure of the deposited powders will be obviously refined. The research group of Li Dichen [3] studied the control law of LMDF on component materials microstructure. Controlling the ambient temperature of the forming process can control the internal structure of the part to be columnar crystal and directional growth, that is, the forming process is a directional solidification process, as shown in Figure 1 (a). In order to control the temperature gradient and prevent the transformation from directional crystals to equiaxed crystals, the team adopted cryogenic argon conformal cooling to fix cryogenic argon nozzles and coaxial powder feeding nozzles together, and then cooled the parts conformally to effectively control the formation of directional crystalline structures, as shown in Figure 1 (b).

In conclusion, the structure of LMDF is closely related to the thermal process of metal materials under laser beam. In the forming process, with the increase of laser power, the energy per unit volume of the cladding layer increases, the temperature gradient of the cladding layer decreases, and the grain
size of the microstructure increases. Therefore, we can refine the structure and obtain directional crystalline metal components by increasing the cooling rate, so as to ensure the good performance of the components.

2.2. Scanning speed
Scanning speed refers to the distance of laser beam movement per unit time. Contrary to the influence of laser power, the maximum temperature of molten pool decreases with the increase of scanning speed [6]. Zhu Sheng [8] made Al-Ni-Y-Co-La amorphous composite cladding layer on the surface of 5083 aluminum alloy by laser cladding technology, studied the effect of scanning speed on the structure and properties of cladding layer. The results show that with the increase of scanning speed, the structure of cladding layer changes from coarse bar (column) grains to fine equiaxed grains. When the scanning speed is 300 mm/min, the cladding layer has the best formability and wear resistance. When the scanning speed increases to 400 mm/min, the molten pool towing matrix rolls up and floats up. It results in serious segregation of composition, and decreases the formability and wear resistance of the cladding layer.

It can be seen that the scanning speed of additive manufacturing is closely related to the structure of metal forming components. With the increase of scanning speed, the crystal structure becomes smaller and more compact. However, there is a reasonable interval. The reasonable range of scanning speed for different cladding materials can be determined by simulation [9] and experiment.

2.3. Powder feeding rate
Powder feeding rate refers to the quality of coaxial powder feeding per unit time of laser material manufacturing. For the temperature of molten pool, keeping the laser power and scanning speed as a fixed value, the metal powder can not melt rapidly in a short time when the powder feeding rate is high, the energy per unit volume of the cladding layer decreases, the temperature gradient increases, and the cooling rate increases, then the micro-structure morphology of the formed metal components becomes smaller. However, part of the powder can not be fully melted because of the high feeding rate, resulting in poor uniformity of the microstructure of the formed components. Therefore, it is necessary to explore suitable powder feeding rate for different cladding powder materials through simulation and experiment.

3. Effect of LMDF process parameters on hardness of components
There are many factors affecting the hardness of materials in the cladding process of LMDF Technology. This paper analyzed the influence of partial parameters, such as laser power, scanning speed and powder feeding rate, on the hardness of formed metal components.

It is well known that the micro-crystal structure of materials has a great influence on the hardness of components. The second section of this paper analyzed the effects of laser power, scanning speed and powder feeding rate on the micro-structure characteristics of the formed components. Based on the above analysis, we can further analyze the influence of this factors on the hardness of components. Among the three parameters mentioned in this paper, when the other two parameters remain unchanged, changing a single parameter, such as increasing laser power, decreasing scanning speed and decreasing powder feeding rate, will result in the coarsening of crystal structure of micro-structure. As a result, the hardness and wear resistance of the components are reduced.

Therefore, according to different cladding powder materials, scholars hope to further analyze the reasonable range of process parameters and their matching, and apply them scientifically to engineering practice. This has become an important research hotspot in the field of additive manufacturing. With the deepening of the research, some scholars have carried out the research on the typical structure characteristics about metal components of laser additive manufacture, and have obtained schematic diagrams of temperature gradient G and solidification velocity VS varying with the depth of molten pool at the solid-liquid interface of the longitudinal section of the cladding deposit.
during direct metal forming. (As shown in Figure 2, the direction of Z in the figure is the direction of increasing the height of the coating layer.).

Figure 2. Schematic diagram of temperature gradient G and solidification velocity VS changing with the depth of molten pool.

With the increase of the coating height, the temperature gradient decreases and the solidification speed increases, which results in the columnar epitaxy growth of the specimen as a whole. However, this equiaxed crystal layer is retained at the top of the part because no further remelting occurs[4]. With the change of the height of the cladding layer, the micro-crystal structure changes, resulting in the change of the hardness of the cladding layer.

4. Experimental study

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.

4.1. Test scheme

This test is aimed at LMDF additive manufacturing process. Considering the practical application of die surface coating at present stage, the researchers used 45 steel as matrix material and XY-26F-104 iron-based alloy powder (Fe78Cr15.3B1.2Si1.28Ni1.9Mo1.45Mn0.55) as cladding material. In this paper, the effects of laser power, powder feeding rate and scanning speed on the structure and properties of formed metal components are experimentally studied.

4.2. Test process, results and analysis

The test process shows that there is a matching problem between LMDF process parameters. The results of several experiments show that the performance of the components obtained is stable when the scanning speed is 10 mm/s. At the same time, it is found that there is interaction between powder feeding rate and laser power. In the case of low power, if the powder feeding rate is high, the powder can not be fully melted, then it will affect the forming effect. For this reason, after many experiments, the combination of technological parameters shown in Table 1 was used to carry out the experimental research.

Table 1. Combination of Process Test Parameters for LMDF Test

| Process parameter group | Power (W) | Powder feeding rate (g/min) | Scanning speed (mm/s) |
|-------------------------|-----------|-----------------------------|----------------------|
| A                       | 1800      | 2.0–3.0                     | 10                   |
| B                       | 1200      | 1.0–2.0                     | 10                   |

Based on the above process parameters, we obtained two kinds of samples, and carried out microstructure observation and hardness test for different samples.

Fig. 3 is the results of metallographic examination of two samples obtained by processing parameters of group A and group B. The upper part is cladding layer, and the lower part is dark as matrix. When the laser power is higher, it can be seen from the figure that the microstructures of the cladding layer are slightly coarser, and the crystallization has obvious directional solidification characteristics. The main microstructures are columnar crystals, and the overall structure is uniform. It shows that the performance of the cladding layer is excellent, which is consistent with the theoretical analysis conclusion.
At the same time, we tested the hardness of two samples and obtained the distribution of hardness with different laser power and thickness of cladding layer, as shown in Fig. 4. It can be seen from the figure that the hardness of the cladding layer is obviously higher than that of the matrix; the laser power near the interface has little effect on the hardness of the formed parts, and the hardness decreases slightly with the increase of the cladding thickness. According to the experimental results, the temperature gradient of matrix accessories is relatively large, and the influence of laser power on temperature gradient is not obvious. With the increase of cladding thickness, the influence of laser power on temperature gradient appears, resulting in the difference of micro-structure, which leads to the difference of hardness of formed parts.

5. Conclusion
(1) LMDF technology, as a typical process of metal additive manufacturing, can produce forming parts with uniform structure and compact structure. However, the technological parameters and their reasonable matching in the forming process have important effects on the structure and properties for metal components.

(2) As the source of manufacturing energy, laser power has a great influence on the forming process of components. With the increase of power, the grain size of metallographic structure increases and the hardness decreases. The hardness also change with the increase of the thickness of the cladding layer.

(3) To a certain extent, increasing the scanning speed and powder feeding speed properly can refine the metallographic grains of the formed parts. This way can increase the hardness of the components and enhance their surface wear resistance.

In the manufacturing process of LMDF, the influence of various process parameters should be considered comprehensively to ensure the quality of components. However, at present, the research on the influence of LMDF process parameters and the interaction between each parameter on component performance is not comprehensive enough. The establishment of a systematic and perfect database for added material manufacturing needs the joint efforts of scientists and technicians.
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