Microstructure and Property of Thin-wall Part by Laser Additive Manufacturing

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ABSTRACT

Laser Additive Manufacturing (LAM) of metals is a new rapid manufacturing technology, which combines with computer aided design, laser cladding and rapid prototyping. The advanced technology can build fully-dense metal components directly from CAD files with neither mould nor tool. Based on the theory of this technology, the comprehensive experiments are carried out with metal powder to systematically investigate the characteristics of microstructure morphology and mechanical property of as-formed thin-wall part. As a result, the grain-microstructure exhibits preferential growth direction; there are different microstructure distributions of as-formed thin-wall metal part; and SEM morphology of tensile fracture surface indicates the as-formed parts possess rather high ductility. Accordingly, significant processing flexibility with the LAM system over conventional processing capabilities is recognized, with potentially lower production cost, higher quality components, and shorter lead time.

INTRODUCTION

Laser Additive Manufacturing (LAM) is a rapid prototyping process that fuses gas-delivered metal powders within a focal zone of a laser beam to produce 3-dimensional metal components [1-2]. The focal zone of the laser beam is programmed to move along or across a part cross-section, and coupled with a multi-axis worktable, complex metal geometries can be produced, as depicted in Figure 1(a). The LAM technique offers unique advantages over conventional thermomechanical processes in that many labor and equipment intensive steps can be avoided. For example, typical processing of metals into desired shapes and assemblies involves casting and metal forming (rolling, stamping, forging, extrusion) followed by machining and joining operations. The LAM process yields a final geometry from a single piece of equipment and the appropriate software control [3-4].

Since LAM processing offers unique capabilities and advantages for rapid prototyping of complex metal components, the examinations of the microstructure
and property are required to define and optimize the processed materials. The intent of this study is to address the microstructure morphology and mechanical property during LAM processing of simple geometries to characterize the technique.

**FABRICATION EXPERIMENT OF THIN-WALL METAL PART**

The experiments were performed with LAM equipment, as shown in Figure 1(b). The nickel-based superalloy powder was employed, whose chemical composition is listed in Table 1, and powder size is about 200 mesh. The experimental parameters can be seen in Table 2. A3 steel plate was cut into a lot of substrates with the size of 60 mm x 30 mm x 8 mm, and the surface of substrates were carried out the phosphating treatment in order to increase the laser absorption rate. The experimental process is performed with argon atmosphere protection, but without preheating and heat preservation device.

![Figure 1. LAM setup: (a) schematic diagram; (b) real photograph.](image)

| Table 1. Composition of nickel-base alloy powder (wt. %) |
|---------------------------------------------------------|
| Composition | C  | Al  | Si  | Cr  | Fe  | Ni  |
| Content (wt. %) | 4.643 | 0.329 | 0.368 | 19.140 | 1.257 | 74.263 |

| Table 2. Processing parameters in LAM experiments. |
|---------------------------------------------------|
| Processing parameters | Laser power (W) | Spot diameter (mm) | Scanning speed (mm/s) | Powder feeding rate (t/s) | Scanning layers (PCS) | thickness of stratification (mm) |
| Numerical value | 600 | 3 | 6 | 0.04 | 50 | 0.2 |

Figure 2 is the thin wall part fabricated by LAM technology. Through simple grinding and finishing, the size of the part is 50 mm × 2.9 mm × 9.5 mm in average.

![Figure 2. Thin wall part fabricated by LAM technology.](image)
FRINGE ANALYSIS BETWEEN THE LAYERS OF THIN-WALL METAL PART

Firstly, the deposited thin wall metal part was cut out from the substrate. Next, it was cut apart from the middle position along the forming height direction, and then clamped by fixtures. Finally, after grinding, polishing and etching, the metallographic specimen was successfully fabricated.

In metallographic microscope, first observed microstructure is the relatively parallel and evenly adjacent light bands vertical to the growth height direction. The parallel spacing of these light bands are about 0.2 mm, so it can be proved that these parallel light bands are the dividing lines between the adjacent scanning cladding layers, namely the interlayer stripes, as shown in Figure 3(a).

Figure 3(b) is the interlayer stripes of SEM photos. It can be seen from the photo that the interlayer stripes are the organization very difficult to corrode. The various grains in the cladding layers grow from the interlayer stripe microstructure, but the interlayer stripes don't completely interfere with the microstructure between layer and layer, which makes the microstructure keep a certain continuity between layer and layer. It can be deduced that in addition to the last layer, the microstructure of the metal thin-walled part is obtained from repeated tempering under the effect of laser cycle. As a result, only the microstructure in last layer can suitably indicate the organization condition derived from the laser rapid cladding, while the microstructure in other layers will reflect the transformed microstructure after repeated tempering.

![Figure 3. Interlaminar stripes in thin-wall part (a) metallograph (40×); (b) SEM photograph (150×).](image)

MICROSTRUCTURE DISTRIBUTION OF THIN-WALL METAL PART

Figure 4 shows the cross section of thin-walled part. From the top, middle and bottom of the section of part, three points A, B, C were respectively chosen to carry out the microscopic observation and analysis.

![Figure 4. Section photograph of thin-wall part.](image)  ![Figure 5. SEM photo of point A (60×).](image)
Figure 5 exhibits the SEM photo of point A. The vast majority of refined cellular grains and a small number of dendritic crystal grains can be observed in this figure. In the point of relatively macroscopic view, it can be seen that the tiny cellular grains also present the dendritic distribution trend, which is the remarkable characteristic of rapid directional cladding process.

Figure 6 is the photo of point B observed under optical microscope. It can be seen in the photo that the relatively coarse equiaxed grains appear in the middle of the thin-wall part. The grains are obviously not derived from the rapid directional cladding. Accordingly, it can be proved that the equiaxed grains are generated by the repeated tempering under the cycle effect of laser beam. Since the formation process of grains mainly depends on the heat transfer process, compared with other locations of thin-wall part, at the point B the temperature gradients in spatial heat dissipation directions are almost identical, which can create conditions for the formation of equiaxed grains.

At point C, the vast majority of grains are dendrites, as shown in Figure 7. The dendritic structure in the proportion of the microstructure of the thin-wall part is very large, and the growth of almost all of dendritic structures are the same as that of thin-wall part. The reason for this is that the temperature gradient in the growth direction of thin wall part is relatively large, so most of the heat dissipating is along this direction to the substrate, thereby promoting the orientation growth of the grains.

Through the comprehensive analysis of the cross section of thin-wall part, it can be found that the vast majority of microstructure of thin-wall part is dendrite. In addition, the refined cellular grains appear on the top of thin-wall part, and the coarse equiaxed grains arise in the middle of thin-wall part.

MECHANICAL PROPERTIES OF SAMPLES FABRICATED BY LAM TECHNOLOGY

In terms of the composition of alloy powder (see Table 1) and experimental parameters (see Table 2), the sheet metal part was formed by the LAM technology, which was cut out from the substrate by wire-cutting processing. After mechanical processing it is fabricated into some standard tensile samples, whose real photo and dimension sketch map were shown in Figures 8(a) and 8(b) respectively [5-6].

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Figure 8. Standard tensile samples fabricated from sheet metal part by LAM technology.

The tensile test was performed along with the direction perpendicular to the dendritic growth direction. The tested results of mechanical performance were as follows: the yield strength $\sigma_s = 355$ MPa, the ultimate strength $\sigma_b = 430$ MPa, and the elongation $\delta = 9\%$, which indicate that the as-formed parts possess the favorable mechanical properties. Figure 9 exhibits the fracture appearance of tensile specimens, which presents a sawtooth shape. It proves that the sample suffers from a large plastic deformation prior to fracture.

Figure 10 shows the fracture morphology of the scanning electron microscope photo. Through the observation of microstructure morphology of fracture, it is found that the serrated fracture corresponds to the torn edges. This part is the final fracture location, and the tiny stripe is crack generation location, as shown in Figure 10. It can be seen that on the fracture surface there are lots of evenly distributed equiaxed little toughening pits, which proves that they suffer from the maximum normal stress before they are destroyed. The toughening pits appearing on the fracture surface toughness indicate the high toughness of composed phases. Due to the fine grains, small and uniformly distributed phases, the localized necking and burst prone to occur in these areas, thus forming the toughening pit fracture. Consequently, the fracture characteristics of nickel-based alloy parts formed by LAM technology are consistent to these fabricated through common techniques, both of them are ductile fracture.

Figure 9. Fracture macrograph of tensile sample.

Figure 10. SEM morphology for fracture surface of tensile sample by LAM technology (500×).

SUMMARY

Laser Additive Manufacturing (LAM) of metals is a state-of-the-art rapid manufacturing technology, which combines with computer aided design, laser cladding and rapid prototyping. The advanced technology can build fully-dense metal components directly from CAD files with neither mould nor tool. Based on the theory of this technology, the comprehensive experiments are carried out with metal powder to systematically investigate the characteristics of microstructure.
morphology and mechanical property of as-formed thin-wall part. As a result, the grain-microstructure exhibits preferential growth direction; there are different microstructure distributions of as-formed thin-wall metal part; and SEM morphology of tensile fracture surface indicates the as-formed parts possess rather high ductility. Accordingly, significant processing flexibility with the LAM system over conventional processing capabilities is recognized, with potentially lower production cost, higher quality components, and shorter lead time.

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