Direct manufacturing of Cu-based alloy parts by selective laser melting

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The frequent defects of the metal parts, such as non-fully melting, thermal strain, and balling, which are produced by selective laser melting (SLM) that is a novel method of one-step manufacturing, are analyzed theoretically and experimentally. The processing parameters significantly affect the quality of the final parts, and simultaneously, the appropriate laser mode and the special scanning strategy assure a satisfying quality of the final parts. The SLM experiment is carried out using Cu-based powder. The metal part is divided into several scanned regions, each of which is scanned twice at the cross direction with different scanning speeds. The microstructure is analyzed on microscope. The results show that the part is metallurgically bonded entity with a relative density of 95%, and the microstructure is composed of equiaxial crystal and dendritic crystal whose distributions are mainly decided by the scanning strategy.

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Selective laser melting (SLM) developed from selective laser sintering (SLS) is a novel rapid prototyping (RP) method to directly manufacture the metallurgically bonded metal parts with near full density[1]. SLS can also produce metal parts, but in most of the SLS processes, the laser with a low energy density is used to melt either the metal component with a low melting point or the polymer binder. The molten materials bind the un-melted metal components with higher melting points together forming a three-dimensional (3D) object. This mechanism decides that the SLS parts are always full of voids and their surfaces are rough. Even more badly, their mechanical properties are unsatisfying. The SLS parts need complicated post-processing such as re-melting and metal infiltrating[2] when they are used. Fortunately, SLM produces metal parts with near 100% density and metallurgically bonded structure which can be put into use after simple post-processing such as sandblast and polishing. Furthermore, their hardness and tensile strength are even higher than those produced by fusion casting. Besides, unlike SLS, SLM fits for the single-component metallic material as well as the alloys[3].

However, it is necessary and important to avoid the defects such as non-fully melting, thermal strain, and balling for producing metal parts with high density and metallurgical bonding by using SLM method. In this paper, the effects of the processing parameters such as the scanning speed, the laser power, and the layer thickness on SLM parts were analyzed, and the microstructure of a SLM part and its forming mechanism were studied.

The experiment was conducted on a SLM machine (DiMetal-240) as sketched in Fig. 1. The processing course followed the basic principle of RP. The focused laser beam was guided under the control of the computer to fully melt the metal powder on the built cylinder layer by layer according to a special scanning strategy. The SLM processing was carried out in a hermetic chamber full of inert gas. The major technical parameters of DiMetal-240 included: laser type is diode pumped Nd:YAG laser with power of 100 W, focus diameter is 100 μm, maximum scanning speed is 3 m/s, and layer thickness is < 350 μm.

The Cu-based alloy powder used in this study was a mixture of 84.5 Cu, 8 Sn, 6.5 P, 1 Ni (wt.-%). The grain size was below 75 μm. Argon was used as shielding gas during SLM processing.

A piece of Q235A steel plate was used as the substrate in the experiment, and a Ni-based alloy powder was sprayed onto the surface of the substrate to fuse the first layer of the part and the substrate well. The relative density of the SLM sample was tested by Archimedes method, and then the sample was eroded by using the mixture of $FeCl_3$ (5 g), HCl (50 ml), and water (100 ml). The eroded sample was observed under microscope by magnifying the microstructure 200—500 times.

To direct produce metallurgically bonded metal parts with high density, the following problems need to be solved: 1) how to fully melt the metal powder during SLM processing; 2) how to decrease the buckling deformation caused by thermal stress; (3) how to reduce or smooth away the balling effect.

In SLM processing, the metal powder needs to be fully melted, and simultaneously, it must be melted to an appropriate depth. For TEM00-mode laser beam, within the laser spot, the energy absorbed by the metal powder

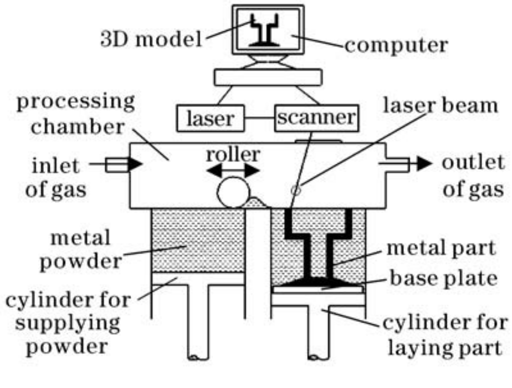

Fig. 1. Schematic diagram of SLM machine (DiMetal-240).

can be described as[4]

$$E(y,z) = (\frac{2}{\pi})^{1/2}(\frac{P}{\omega V_s})\exp(-Az - \frac{2y^2}{\omega^2}), \qquad (1)$$

where P is the laser power, ω the radius of the laser spot, V_s the scanning speed, z the powder depth, y the distance to the laser spot center along the horizontal plane.

In order to melt the metal powder with a depth of z, the energy absorbed by the powder at the depth of z must be able to raise the powder temperature up to the melting point of the material. The best method to achieve this aim is to reduce the layer thickness. However, the layer thickness cannot be made thin enough sometimes due to the limited precision of the powder distributing system.

From Eq. (1), at a certain scanning speed, increasing the laser power or decreasing the radius of the focused laser beam both make the powder absorb more energy. However, the larger heat affected zone by a higher laser power will lead to more serious deformation because of the thermal stress developed during rapid cooling. In SLM, it is preferred to focus the laser beam to a smaller spot size to increase the energy absorption. At the same time, the spot size of the focused laser beam determines the minimal processing dimension. Therefore, a diode pumped Nd:YAG laser with good beam quality, which can focus the laser beam to a power density of 5×10^6 W/cm^2 and a spot size of 100 μm, was used in DiMetal-240 in this study.

Notable thermal stress exists in the sample because of the large temperature gradient caused by rapid cooling during SLM processing. Thermal stress can induce thermal strain, and buckling deformation is the main representation. Buckling deformation not only reduces dimensional accuracy, but also intermits the processing course[5]. Thus, it must be reduced in order to obtain good manufacturing quality and guarantee the normal processing course.

The temperature gradients between the upper section and the bottom section in a same layer and among co-adjacent layers both induce buckling deformation because of thermal stress[3]. It is a key factor to reduce the temperature gradient inside one layer and among the co-adjacent layers to eliminate the buckling deformation.

Rescanning is an effective method of reducing and even eliminating the buckling deformation. The metal layer is scanned again after the first scan which fully melts the powder in the selected area and forms the metallic slice, and the rescanning direction is perpendicular to the first scanning direction[6]. It is reported that this method can decrease the residual stress by 55%[7], and accordingly the buckling deformation can be diminished or avoided.

It will be better if a large scanning zone can be divided into several small scanning regions[8]. The reciprocity of the thermal stress in different directions in the small regions holds the buckling deformation back. Also, the thermal stresses in each scanning regions are too small to reach the material yield stress because of isolated small scanning regions.

An important disadvantage during SLM processing is the so-called balling. It occurs when the molten material does not wet the underlying substrate due to surface tension which tends to sphere the liquid metal[9]. Serious balling phenomenon will cause a rough and bead-shaped surface, obstruct a smooth layer deposition, and decrease the density of the produced part.

Balling is a time-dependent process. If the solidification is rapid enough, that is, the solidifying speed is greater than the balling speed, the balling effect will be weakened or even be smoothed away. For a certain alloy, the solidifying speed is determined mainly by the laser radiation time which depends on the scanning speed. Increasing the scanning speed can accelerate the solidification, and simultaneously decrease the molten depth. In actual SLM processing, the balling can be eliminated by increasing scanning speed, and accordingly increasing the laser power to guarantee the satisfying molten depth.

A group of tentative experiments at different scanning speeds and different laser powers were conducted in order to find out the proper processing parameters. Figures 2 and 3 show some samples in these experiments. From these experiments it can be outlined that: 1) Low scanning speed leads to serious balling effect. Increasing the

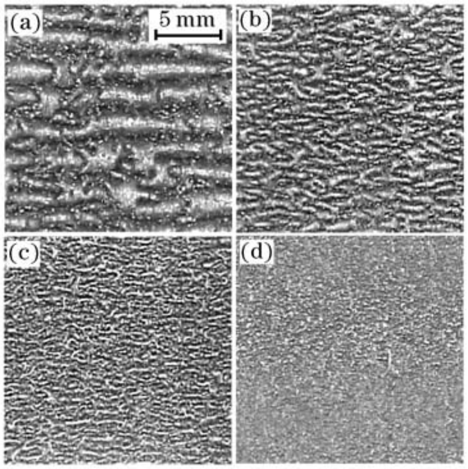

Fig. 2. Some single layer samples at varying scanning speeds of (a) 0.1 m/s, (b) 0.2 m/s, (c) 0.5 m/s, and (d) 1 m/s. Power is 123 W, scanning space: (a), (b) 0.1 mm; (c), (d) 0.07 mm.

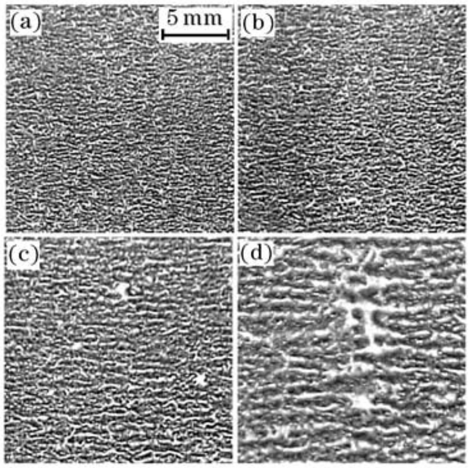

Fig. 3. Some single layer samples at varying laser powers of (a) 80 W, (b) 100 W, (c) 120 W, and (d) 140 W. Scanning speed is 0.4 m/s, scanning space is 0.07 mm.

scanning speed can weaken the balling effect rapidly. 2) The balling effect becomes more and more serious with the increase of the laser power. 3) Scanning speed has more influence on balling than laser power. When increasing the scanning speed to weaken the balling effect, the laser power should be accordingly increased to guarantee the molten depth. 4) Scanning speed of 0.5 m/s and laser power of 90 W is one of the proper processing parameters pairs.

Based on the above analysis, an experiment for producing 3D metal parts was carried out. The adopted processing parameters are listed in Table 1. A scanning strategy as shown in Fig. 4(a) was used in order to reduce buckling deformation. A SLM part is shown in Fig. 4(b), and the macro configuration of the multi-layers of the part is shown in Fig. 5(a), which can be clarified by Fig. 5(b). The microstructures at the different sites of Fig. 5 (labeled A, B, C, and D) are shown in Fig. 6.

From Fig. 4(b) it can be seen that the balling effect is weak, and the surface of the part is even without the pearl looking. Also, no cracking and buckling deformation is observed in the part.

The scanning strategy is the main factor contributing to the formation of the multi-layered configuration, which results from the first scan overlapping the repeat scan. As shown in Fig. 5(b), the microstructure of the multi-layers can be categorized to three regions: the pure color region, the thick line region, and the scale-like region.

1) Pure color region: The molten depth of the repeat scan was smaller than that of the first one because of the greater scanning speed (layer 1 was excepted). The metal powder was fully melted after the first scan and was formed to be a solid entity emerging as the scale-like microstructure, then the repeat scan at the perpendicular direction re-melted part of the solid entity. The re-melting and re-solidification of the solid entity erased the scale-like microstructure in the re-melted region, and the homogeneous microstructure was observed in this region for the incised section was parallel to the repeat scan direction (see Fig. 4). This is the reason why this region appears the pure color.

Table 1. Processing Parameters for Producing 3D Metal Part

Parameter	Value	
Scanning Speed of First Layer (m/s)	First Scan	0.2
	Repeat Scan	0.2
Laser Power of First Layer (W)	120	
Scanning Speed from Layer 2 to 25 (m/s)	First Scan	0.5
	Repeat Scan	1
Laser Power from Layer 2 to 25 (W)	90	
Scanning Space (mm)	First Scan	0.07
	Repeat Scan	0.03
Powder Layer Thickness (mm)	0.32	

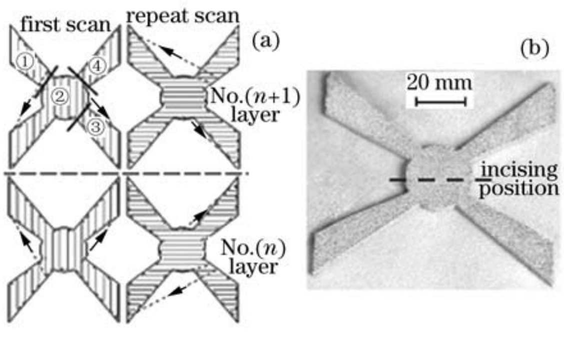

Fig. 4. A metal part for producing 3D parts. (a) Scanning strategy; (b) SLM part.

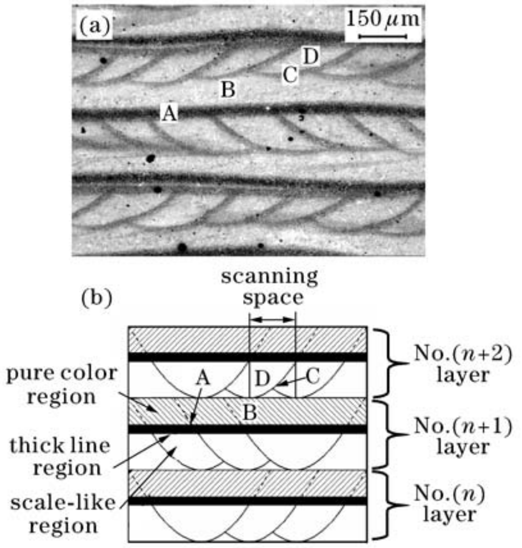

Fig. 5. (a) Multi-layered cross section; (b) analytic model of the multi-layered cross section.

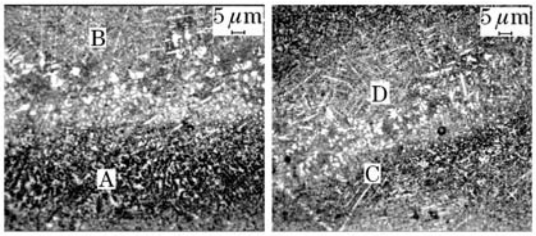

Fig. 6. Microstructures of the SLM part at (a) A and B and (b) C and D labeled in Fig. 5.

Because the incised position happened to lie in the interior of the molten pool of the repeat scan, and the interior sites of the molten pool were enclosed by plenty of liquid metal with high temperature. The cooling rate was lower due to a low degree of super-cooling. Therefore, lots of dendritic crystals are formed in the case of enough time for liquid metal crystallizing and grains growing up (labeled "B" in Figs. 5 and 6).

2) Thick line region: This region was located on the bottom edge of the molten pool of the repeat scan. In this region the temperature was lower and the cooling rate was higher than those in the upper region. In addition, the chill effects of the lower layer help the small equiax crystals form, as shown in regions labeled "A" in Figs. 5 and 6.

3) Scale-like region: This region was far from the laser irradiating surface, whose temperature was still below the melting point after the repeat scan. So, the observed microstructures remain those formed by the first scan, just as shown in Fig. 5.

The scale-like contour lines that are composed of fine equiax crystals, as shown in label "C" in Figs. 5 and 6(b), are the edges of the molten pools. And the bottoms of the scale-like contours are the joints of the two adjacent layers. From Figs. 5(a) and 6(b), it can be seen that the two adjacent layers are metallurgically bonded.

The microstructure of the internal portion of each molten pool (labeled "D" in Figs. 5 and 6) is dendritic crystals. The reasons why equiax crystals and dendritic crystals form are similar to the above analysis.

According to the above analyses, the metal part produced in this experiment is a metallurgical bonded solid entity. While a few blowholes and anomalous holes exist because some organic impurities were mixed with metal powder and burned out during SLM processing, the relative density was measured to be 95% through Archimedes method.

In conclusion, high laser power is not appropriate for SLM processing, and focusing laser beam to a very small spot is necessary in order to fully melt the metal powder and guarantee the processing accuracy. A laser with good beam quality is important. In actual SLM processing, the balling phenomenon is weakened by increasing the scanning speed, and accordingly increasing the laser power to guarantee the appropriate molten depth. A metallurgically bonded 3D metal part with density of 95% was produced by SLM. No buckling deformation is found in the part. The microstructures of the SLM part are composed of equiax crystals and dendritic crystals whose distributions are mainly determined by the scanning strategy.

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