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Fabrication of directional solidification components of nickel-base superalloys by laser metal forming

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Abstract: Straight plates, hollow columns, ear-like blade tips, twist plates with directional solidification microstructure made of Rene 95 superalloys were successfully fabricated on Nickel-base superalloy and DD3 substrates, respectively. The processing conditions for production of the parts with corresponding shapes were obtained. The fabrication precision was high and the components were compact. The solidification microstructure of the parts was analyzed by optical microscopy. The results show that the solidification microstructure is composed of columnar dendrites, by epitaxial growth onto the directional solidification substrates. The crystallography orientation of the parts was parallel to that of the substrates. The primary arm spacing was about 10 μm, which is in the range of superfine dendrites, and the secondary arm was small or even degenerated. It is concluded that the laser metal forming technique provides a method to manufacture directional solidification components.

Key words: laser multi-layer cladding; laser metal forming; directional solidification; single crystal

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1 Introduction

Laser metal forming is a promising manufacturing technique that could significantly reduce the time between initial concepts and finished parts and is an investigated focus in the manufacturing area recently. During the processing, substrates are moved in the *X*-*Y* plane beneath the laser beam to deposit a thin cross-section, thereby creating the desired geometry for each layer. After deposition of each layer, the powder delivery nozzle and focusing lens assembly is incremented in the positive *Z*-direction so as to build a three-dimensional component layer additively [1-3]. Compared with the conventional manufacturing method, the predominance of this technique is that a 100% dense metal part can be made without the need for intermediate processing steps and can manufacture large structural components in less time and at lower cost. Mechanical property tests for the tensile yield strength of Ti-6Al-4V, produced by LMF, fell in the equivalent range for wrought materials, however, the elongation was only 6% compared to 10% and higher for conventional cast and wrought products [4]. The mechanical property of heat-treated LMF slice samples was systematically investigated. The results show that the yield strength of LMF samples is about 97.9 % of that of tensile samples obtained by the powder metallurgical technique while the plasticity of LMF samples overpass 80% of tensile samples obtained by the powder metallurgical technique [5]. In order to realize laser direct forming of components with directional solidification microstructure, it is necessary to optimize the processing characters such as laser power, powder feeding, protective gas, scanning velocity, overlapping rate, twist angle, height of the cladding layer and the increase of *Z* axis *et al.* [6-9]. In this paper deep analysis on obtaining different directional solidification samples was investigated. Straight plates, circular, ear-like samples, and twist plates with directional solidification microstructures were fabricated using the lateral nozzle, co-axial nozzle and computerized numerical control (CNC) worktable.

2 Experiment procedure

Laser metal forming experiments were performed on a 5 kW CW (continuous wave) CO_2 laser. The powder delivering system combines a cladding head with a lateral powder jet and a laminar flow of protective gas. The chemical composition of powder and substrate used in the laser cladding process are shown

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in **table 1**. The processing parameters selected according to the calculated results described in reference [5] are as follows: laser power, 3.5 kW; scanning velocity, 10 mm/s; powder feeding, 10 g/min; beam diameter, 4 mm; protective gas flux, 5 L/min. The circular information was added to the program to improve the formation rate and guarantee fine cladding status. Straight plate, twist plate and hollow column samples were prepared using a lateral nozzle, and a coaxial nozzle was used to manufacture an ear-like sample as the former one can not guarantee the shaped precision in different cladding directions. Both the component and the microstructure were examined using optical microscopy images after corruption.

Table 1 Chemical compositions of powders and substrates (mass fraction in %)

Chemical composition	Powder	Substrate	
	Rene 95	Nickel-base superalloy	DD3
Al	3.46	3.24	5.70
B	0.01	—	Trace
C	0.04	—	0.06
Co	8.04	9.08	5.00
Cr	13.05	16.00	9.50
Fe	0.22	—	—
Mo	3.42	2.47	4.20
Ni	Bal.	Bal.	Bal.
Ti	2.66	3.66	2.30
W	2.00	5.45	5.20
Zr	0.04	—	<0.005
Nb	3.50	—	—

3 Results and discussion

3.1 Plate sample

For laser metal forming directional solidification, it is very critical to obtain a plate sample with columnar grains in the whole component because the plate sample is one of the bases of different components. The morphology of the sample is shown in **figure 1**. The selected substrate was DD3 and the powder was Rene95. The obtained dimensions of the sample were 5 mm × 35 mm × 125 mm. It is obvious that there appear apparent traces related to different cladding layers due to the discontinuity of the progress as can be seen in figure 1(a). To increase the working efficiency, every 10 cladding layers are belonging to one processing circular and there are 250 cladding layers in all. The lateral side of the sample is straight under the stable processing conditions. As the powder feeding system combined a lateral nozzle, the cladding layers is not so much level due to the angle of the direction of powder delivering and scanning velocity. Figure 1(b) shows another plate sample in which the whole numbers of cladding layers are 99, thus the distance between every two cladding layers was enlarged. The top of the cladding layer is not level due to the unmatched processing parameters of the height of each layer and the ascending height of Z axis every circle. So the LMF system must be strengthened. Hardware configures such as adopting a location censor that can measure the height of the cladding layer in-situ through the modification of processing parameters can guarantee the success of the experiment.

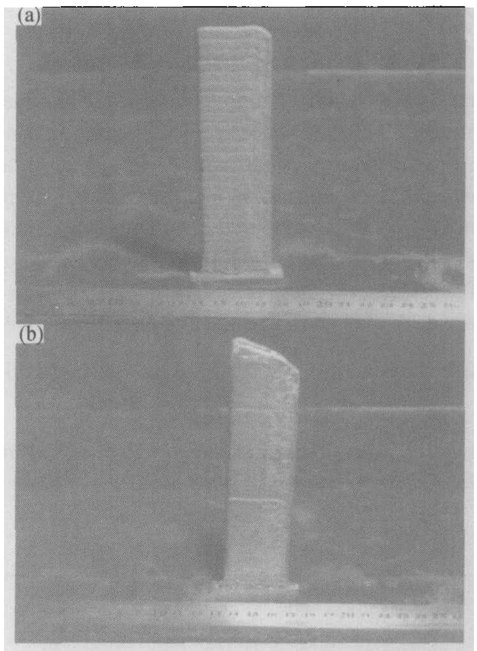

Figure 1 Morphologies of plate components using LMF: (a) fine profile (b) bad profile.

The optical microscopy morphology of the plate sample (corresponding to figure 1(a)) after surface processing is shown in **figure 2**. It shows that the medium part of the sample is made up of fine grains with better unidirectional effect (along arrow 1). While at the side of the sample (the upper part in this figure), there appear grains deviated from the original crystallography orientation (along arrow 2) and this area, corresponding to the right part of the component, formed on the end of the deposition of one layer. The formation of incline slopes in the cladding layer is a result from the changes of the solution field after one layer was deposited. In order to patch the slopes of the end of the sample, the cladding head moves to-and-fro that causes heat accumulation. Heat flux flows along the normal of the incline slopes, which leads to the deviated grains shown on the top of the sample.

3.2 Ear-like single crystal and column directional solidification samples

The aim of the directional solidification technique is to obtain directional solidification samples with a certain shape by laser metal forming. In this section, single crystal DD3 was selected as the substrate and experiments were performed on the (110) crystallography plane to acquire an ear-like sample. The directional solidification nickel-base superalloy was selected to attain a column directional solidification sample and experiments were performed on the (100) crystallography plane. The ear-like sample was about 20 mm high and 3.5 mm wide by machining off. The length of the diagonal is about 50 mm. The inner radius of the circular sample is about 15 mm, and the width of the cladding layer is 4 mm.

Figure 2 Optical microscopy morphology of the plate component using LMF.

Figure 3(a) shows the optical micrograph of the ear-like sample after macro-corruption. There are no boundaries of the multi-grains both in the inner and outer surfaces of the sample, *i.e.*, a single crystal sample can be obtained on the substrate of DD3 single crystal. Cutting off part of the sample to analyze the microstructure, it can be found that the microstructure in the cladding layer is the same as that in the substrate, both are thinner directional solidification columnars. And epitaxial growth occurs between the cladding layer and substrate (see figure 3(b)). As the crystallography plane of the substrate is <110>, epitaxial dendrites on the substrate are not so symmetry.

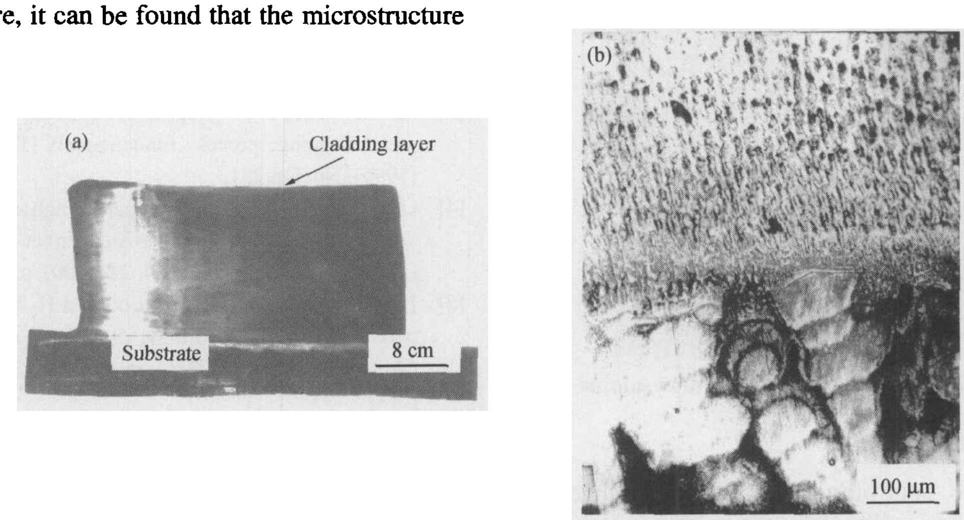

Figure 3 Optical microscopy analysis of the ear-like sample: (a) single crystal in the sample; (b) microstructure of the interface between the sample and the substrate.

Figures 4(a) and **(b)** show the morphology and the solidification microstructure of the directional solidification hollow column after macro-corruption, respectively. It can be evidently seen from figure 4(a) that the directional solidification grains grow epitaxially from the underlying claddings. Figure 4(b) displays the solidification microstructure in the inner part of the cladding layer, which is made up of thin and dense directional solidification dendrite, the size of which is about 10 μm.

Comparing figures 3 with 4, it can be concluded that directional solidification grains have a fine crystallography orientation identical with those of the substrate.

3.3 Twist plate

It is obvious that laser directional solidification is a potential technique in the aeronautical area. In fact, some samples such as turbine blades, are not completely straight blades but have a certain twist angle. References have already reported that the copper and stainless steel twist components have been manufactured [2, 10]. In this section, twist blades are investigated. The selected principle of the twist angle is on the base of meeting the practical requirement and combination with the width and height of the single cladding layer. If the twist angle is too large, the influence of the melting pool on the cladding layer during laser cladding decreases. The powder, melted incompletely, destroys the structure stability of the processing and cladding layers. On the other hand, the unmelted powder adhered to the sidewall influences the forming precision of the sample, or even destroys the continuous growth of directional solidification columnar dendrites. If the twist angle is too small, the formation efficiency decreases. **Figure 5** shows the twist blade without machining. From this figure it can be found that the forming state is better except the unevenness on the top of the cladding layer. After macro-corruption, fine directional solidification grains continuously grow through different layers from the bottom to the top of the cladding layers.

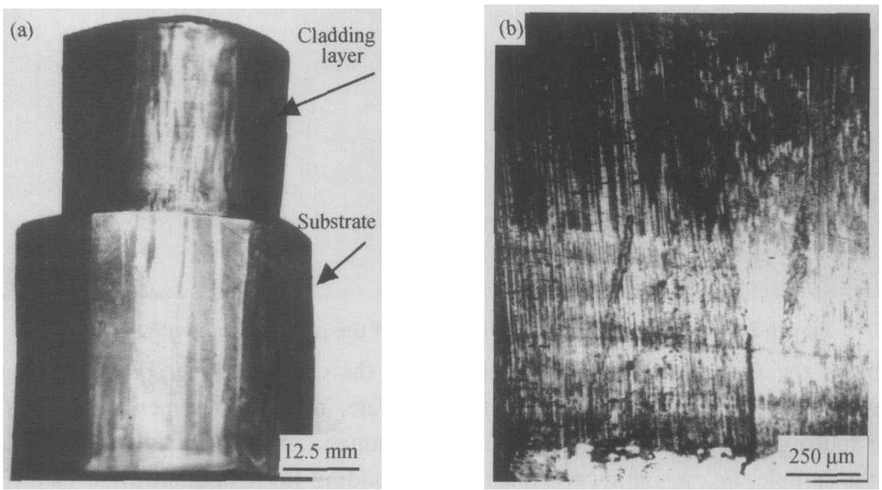

Figure 4 Optical microscopy analysis of the hollow column sample: (a) directional solidification multi-grain of the sample; (b) solidification microstructure of the inner part of the sample.

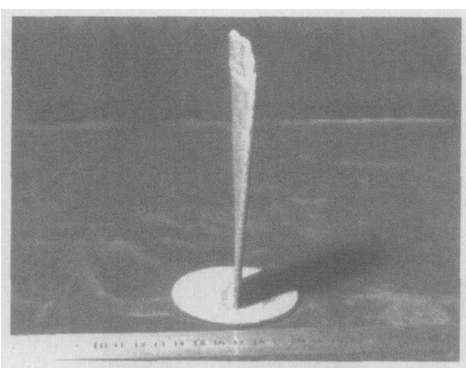

Figure 5 Twist directional solidification sample

4 conclusions

(1) Through controlling processing parameters, such as laser power, powder feeding, protective gas, scanning velocity, overlapping rate, twist angle, height of the cladding layer, and increase of Z axis *etc.*, straight plates, circular, ear-like samples, and twist plates were obtained using laser metal forming.

(2) Columnar dendrite epitaxy from the substrate in all the components was acquired. The primary arm spacing was about 10 μm.

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