Process Research on the Laser Rapid Manufacturing Technology

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Keywords: laser rapid manufacturing, stainless steel 316, CET (Columnar to Equiaxed Transition), directional solidification, metallurgical bonding

Abstract. Laser additive direct deposition 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 the information transferred from a computer file by depositing metal powders layer by layer with neither mould nor tool. Based on the theory of this technology, an experimental setup for laser rapid manufacturing process was developed. Through this state-of-the-art automated apparatus, some cladding experiments were performed to grasp the process features of laser rapid manufacturing technology. Finally, the columnar/equiaxed grain growth transition model is used to explain the morphology characteristic. Accordingly, the appropriate microstructure can be obtained by adjusting the processing parameters.

Introduction

Laser rapid manufacturing brings us the novel idea of manufacturing that combines computer-aided design with laser processing technique. It becomes attractive in manufacture industry because metal parts can be manufactured directly by this method without intermediate procedures and equipment, therefore saving much time and expense [1,2].

Laser rapid manufacturing of metal parts is an additive process that can be regarded as the repetition of layers deposited by laser cladding. Laser cladding is a modern process of producing metallurgically well-bonded coatings of a great variety of materials of intermediate thickness. Since stainless steel has a relative high mechanical properties and better high-temperature performance than plain carbon steel, and is the main material for laser rapid manufacturing experiment, it is very necessary to carry out the study on laser cladding of stainless steel.

Technical Experiments

Experimental Setup. Fig. 1 shows the experimental setup for laser direct deposition experiment. Experimental setup is primarily composed of four components: energy supply system, motion control system, powder delivery system, and computer control system. These components have their specified functions, but work in association with each other.

![Fig. 1 Components of the laser rapid manufacturing setup. (a) real photo. (b) schematic diagram.](image-url)
Experimental Material. The experimental material for laser direct deposition experiment is stainless steel 316 whose powder size is about 200 mesh. The substrate used for multi-layer laser cladding is A3 steel plate with the dimension of 200 mm×200 mm×10 mm.

Microstructure Analysis

The laser cladding is the foundation of laser rapid manufacturing technology, so a set of processing parameters (laser power 1000 W, scanning speed 8 mm/s, powder feeding rate 4 g/min, spot diameter 2 mm) were selected to perform the cladding experiments. Subsequently, the microstructure of SS316 clad obtained with such parameters was carefully analyzed.

Micro-morphology of Bonding Zone. Fig. 2 shows the morphology of bonding area formed with the deposition of SS316 powder on the A3 substrate. The cross-section of cladding layer is composed of substrate, bonding zone, and clad. There is a narrow white bright band located between laser clad and substrate, which is the solid solution bonding layer formed by the alloy interdiffusion on condition that the clad and substrate are heated continuously. Its morphology is planar crystal zone with several microns in width, and presents white bright color after corroded. It is composed of γ-(Fe,Ni) solid solution phase, and its existence indicates that the favorable metallurgical bonding is already generated between the clad and substrate. Furthermore, above the white bright band, there is a zone, whose width is ten microns or more, without distinct microstructure properties, which is the inorganization zone caused by the epitaxial growth of planar crystal into the clad. On the top of this zone, there is the dendritic structure growing perpendicularly to the bonding zone.

The laser cladding process can be considered as the directional solidification. At the bottom of molten pool, the value of shape control factor G/V (G and V denote temperature gradient and solidification rate respectively) is very high, so the solidification microstructure grows in the form of low-speed planar crystal, thereby forming the white bright band which is composed of solid solution phase and the structure zone where there is no obvious microstructure characteristic. With the increase of distance from the bottom of molten pool, the shape control factor decreases sharply. Subsequently, the planar crystal interface becomes instable, and the grain growth mechanism predominates, which induces the appearance of columnar dendrite. With the propulsion of solid-liquid interface, the solidification proceeds continuously. During this process, the liquid metal always keeps in touch with the solid-phase basement, so the microstructure represents the typical characteristic of epitaxial growth. The epitaxial growth of dendrite from bottom to top of the molten pool is due to that the component of temperature gradient along the vertical direction is larger than that along other directions in the most position of molten pool. Because the growth direction of dendrite is mainly determined by the preferred orientation, the preferred orientation closest to the temperature gradient direction is usually liable to dominate the most beneficial status during the dendritic growth [3]. As a result, the dendrite growing along this direction can gradually eliminate the dendrite whose orientation is substantially different to the temperature gradient. However, the dendritic growth direction can exhibit slight slope along the normal propulsion direction of solid-liquid interface at the bottom of molten pool.

The laser rapid manufacturing is a large-gradient and high-speed directional solidification process, and the heterogeneous nucleation is remarkable during the solidification. The reason is that there are two kinds of extant solid-liquid interface under the function of laser. One is the suspending particle or grain debris of high melting impurity, and the other is the surface, which is heated to slightly melting condition at the boundary of molten pool, of substrate grain or phase boundary. The heterogeneous crystal nucleuses are attached to those kinds of surface to nucleate. This type of nucleation leads to the high promotion of nucleation rate, which can significantly refine microstructure. With the effect of directional temperature gradient and preferred orientation feature, the microstructure wholly represents the directional solidified dendrite characteristics, such as uniform and thin morphology, parallel growth, and perpendicular orientation to the bonding interface. It is well known that the refinement of solidification microstructure can relieve the
segregation degree of element, make the second phase distribute dispersively, gain the microstructure with considerably uniform component, and improve the property of material. It can be seen from Fig. 2 that the width dimension of solidified dendrite of SS316 is about 5–10 µm, while the feature size of SS316 in the cold-rolled annealing state is approximately 100 µm. Accordingly, it can be concluded that the microstructure of parts fabricated by laser rapid manufacturing is at least 10 times thinner than that manufactured by conventional methods. Because of the dramatically thin and uniform clad microstructure, the corrosion resistance and mechanical properties of stainless steel can be ameliorated substantially.

**Integral Morphology of Clad.** Fig. 3 shows the metallographic panorama of clad. It can be observed in this low-magnitude metallograph that in addition to the white bright band, which indicates the metallurgical bonding, appearing between clad and substrate, all the microstructure represents the thin dendrite in the parallel, continuous, and epitaxial growth state.

The reason why there are epitaxial dendrites, rather than equiaxed grains, appearing at the top of SS316 clad can be explained with the columnar/equiaxed grain growth transition theory. In terms of the experimental material SS316, the improved columnar/equiaxed grain growth transition model (namely GTK model) established by the correlated researcher at northwestern polytechnical university [3~5] is adopted. The analysis and calculation process of Fe-17Cr-12Ni ternary alloy is stated clearly in these references. In order to simplify the discussion in improved GTK model, the critical volume fraction of equiaxed grain, which determines whether the transformation occurs or not, is confirmed as 0.5. If the volume fraction of equiaxed grain is greater than the critical value, the equiaxed grain growth works; otherwise, the columnar dendrite growth does.

Fig. 4 depicts the CET (Columnar to Equiaxed Transition) curve of SS316 calculated through the improved GTK model. It is known from above-mentioned the experimental results that in the clad of SS316 gained with this set of processing parameters, the local solidification condition of molten pool induces that except that near the molten pool interface, the solidification speed is zero and the microstructure is planar crystal interface, the solidification microstructure in other positions of clad all exhibits the dendritic formation. From the bottom to the top of molten pool, the temperature gradient gradually decreases, while the solidification speed gently increases. Therefore, the solidification parameters of laser rapid manufacturing are at continuous range. The shadow part in Fig. 4 roughly indicates the range of temperature gradient and solidification speed produced during the laser rapid manufacture of SS316 part with the appropriate processing parameters. As shown in Fig. 4, with regard to the suitable parameters, the solidification microstructure is all located in the range of columnar dendrite growth, and the CET does not occur. This transition prediction model is consistent to the experimental result described in Fig. 4: The microstructure of clad integrally demonstrates the epitaxial columnar dendrite, and there are no equiaxed grains existing at the top of the clad. Consequently, the correct of improved transition model is proved. It can be seen that the appropriate adjustment of processing parameters can make the solidification condition meet with the different microstructure-formed regions, control or alter the morphology of microstructure, and obtain the ideal solidification structure.

**Microstructure of Clad Interior.** Fig. 5(a) and 5(b) display the local microstructure metallographs of left and right part of cross-section of SS316 clad separately.

It can be seen from Fig. 5 that the interior of SS316 clad takes on the dendrite morphology with obvious epitaxial growth. Not only does the integral morphology of cross-section of clad present the
shape of arc, but also the solidified metal droplet of the interior of clad also exhibits the solidified dendrites with continuously epitaxial growth along the arc radius direction due to the function of surface tension. Furthermore, the metal droplets solidified successively form the arc-shaped interface with each other. Fig. 5 indicates that at the bottom of clad, the primary dendrites are coarse and the secondary dendrites are developed, while at the top of clad, the dendrites are thin, and the spaces between the primary and secondary dendrite arm both lessen. The reason can be explained as follows: During the cladding, the microstructure at the bottom of the clad is heated in a long period, and the top section can produce the tempering effect on the bottom section while cladding layer by layer. The accumulated heat can provide adequate energy to the growth of dendrites, and make them coarse and large. Comparatively, at the top of clad, due to the cooling effect of shielding gas and external environment, the dendrites solidify rapidly. They nucleate increasingly but have no time to grow coarsely. In addition, it can be learned from Fig. 5 that there are few microstructure defects, such as porosity and metallurgical inclusion. The reason is that the effects of convection and mass-transfer produced by laser beam can sufficiently mix the molten pool, which causes the air inclusion in molten pool to float and expel, generates the denser coating, and assures the quality of clad.

![Image](a) ![Image](b) Fig. 5 Metallographs representing the interior position of SS316 clad. (a) left and (b) right part of cross-section.

**Conclusions**

Laser cladding prototyping is the foundation of the laser rapid manufacturing technology. The latter can be regarded as the process repetition of the former in nature. Through the state-of-the-art automated laser rapid manufacturing setup, some cladding experiments were performed to grasp the process features of laser rapid manufacturing technology. The existence of white bright band indicates the firm metallurgic bonding generated between clad and substrate, which means that the laser rapid manufacturing technology can meet with the strength requirement. The microstructure of SS316 parts mainly consists of thin columnar dendrites that show the continuous, epitaxial, and parallel growth from the substrate. There is typical directional solidification microstructure appearing along the height direction. However, the equiaxed grains are not found at the top of clad. This phenomenon can be explained by the columnar/equiaxed grain growth transition model. Consequently, the appropriate adjustment of processing parameters can make the solidification condition meet with the different microstructure-formed regions, control or alter the morphology of microstructure, and obtain the ideal solidification structure.

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