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Microstructure Characteristics of Inconel 625 Superalloy Manufactured by Selective Laser Melting

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Selective laser melting (SLM), an additive manufacturing process, is capable of manufacturing metallic parts with complex shapes directly from computer-aided design (CAD) models. SLM parts are created on a layer-by-layer manner, making it more flexible than traditional material processing techniques. In this paper, Inconel 625 alloy, a widely used material in the aerospace industry, were chosen as the build material. Scanning electron microscopy (SEM), electron back scattering diffraction (EBSD) and X-ray diffraction (XRD) analysis techniques were employed to analyze its microstructure. It was observed that the molten pool was composed of elongated columnar crystal. Due to the rapid cooling speed, the primary dendrite arm space was approximately 0.5 μm and the hardness of SLM state was very high (343 HV). The inverse pole figure (IPF) indicated that the growing orientation of the most grains was <001> due to the epitaxial growth and heat conduction. The XRD results revealed that the austenite structure with large lattice distortion was fully formed. No carbides or precipitated phases were found. After heat treatment the grains grew into two microstructures with distinct morphological characters, namely, rectangular grains and limited in the molten pool, and equiaxed grains along the molten boundaries. Upon experiencing the heat treatment, *M*C carbides with triangular shapes gradually precipitated. The results also identified that a large number of zigzag grain boundaries were formed. In this study, the grain formation and microstructure, and the laws of the molten pool evolution were also analyzed and discussed.

1. Introduction

Inconel 625 is a nickel based solid solution strengthening superalloy, which is largely strengthened by Mo and Nb elements. Inconel 625 has been widely applied to various areas especially in the aerospace industry since the 1960s. This material has drawn particular attention due to its excellent characteristics including perfect combination of good yield, tensile and creep strengths as well as strong resistance to high temperature corrosion on prolonged exposure to aggressive environments[1,2]. However, it is difficult to control the performance when casting or forging for this material. Selective laser melting (SLM) utilizes a laser beam to melt pure metal or pre-alloyed powders layer-by-layer according to the given computer-aided design (CAD) model, directly creating nearly fully dense metal parts with complex geometries[3–5]. It shows unique advantages in material saving, process control and parts performance. At present, extensive work has been conducted on producing nickel based superalloy parts. Yadroitsev et al.[6,7] studied the influence of different scanning interval and scanning strategies on Inconel 625 powders fabricated with porous components. It was identified that the tensile strength of Inconel 625 is much higher than forgings standard level. Mumtaz and Hopkinson[8] used a pulsed laser to explore the impact of different laser pulses on Inconel 625 forming ability. Vilaro et al.[3] investigated the microstructure and phase composition of Nimonic 263 nickel based alloy and the mechanical properties were studied under different heat treatment conditions. They found that the resulting microstructure is quite homogeneous but remains out-of-equilibrium[3]. All the above researches obtained nickel based parts with high densities, good surface quality and mechanical properties by designing different experiments and optimizing the process parameters.

However, Inconel 625, as a solid solution strengthened superalloy, is normally subjected to varying application conditions, including continuous mechanical and thermal stresses, and other

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environmental factors such as corrosion. The internal microstructure of the parts has significant influence on its macroscopic properties[9]. The majority of the current studies concentrated on the macroscopic properties, paying less attention on the microstructure and the phase composition. Dinda et al.[9] used laser aided direct metal deposition to fabricate Inconel 625 superalloy samples and the microstructure evolution and thermal stability was also studied. Nevertheless, the laser deposition process uses a higher heat input, resulting in a larger single track and lower temperature gradient, which is different from the SLM process. For instance, the cooling speed can be as high as 10^6 K/s for SLM process[10]. As a consequence, the SLM parts exhibit different properties in the microstructure and phase composition in comparison to the traditional casting and forging parts. Although the SLM parts presented good mechanical properties[11], they also showed a strong anisotropy due to the directional columnar grain growth caused by directional thermal conduction during SLM process[10]. The texture has significant influence on the mechanical properties. Unfortunately, little literature gives a deep analysis about the texture so far. In the meantime, due to the differences in application conditions, the original structure of the SLM parts may not be ideal in terms of long time use. Therefore, it is necessary to explore the influence of heat treatment on the SLM manufactured parts, which is aimed at improving its mechanical properties.

In this study, several Inconel 625 samples were fabricated using SLM and the microstructures of both the *X–Y* and *Y–Z* sections have been observed and analyzed by scanning electron microscopy (SEM). By applying the electron back scattering diffraction (EBSD) method, the texture and grain morphology were studied to show the anisotropy of the SLM parts. The effect of annealing temperatures on the microstructures related to the micro-hardness, the lattice constant and the distribution of the carbides was also analyzed.

2. Experiments

2.1. Materials and processes

A commercial Inconel 625 powder (H.C. Starck GmbH, Germany) produced by gas atomized process with the average particle size of 34.63 μm was used. Fig. 1(a) illustrates the SEM morphology of the powder. The shape is approximately spherical and the surface is smooth. The powder is composed of 53.5 Ni, 21.5 Cr, 0.96 Fe, 3.71 Nb, 8.8 Mo, 0.47 Mn, 0.41 Si in wt%. The powder was heated at 50 °C for 5 h prior to the SLM process. This procedure was to eliminate the water vapor inside the powder and get a good flow ability of the powder.

The parts were fabricated on an HRPM-II machine developed by Huazhong University of Science and Technology, China. The machine is equipped with a 200-W fiber laser, of which the laser spot is 50–80 μm in diameter and scanning speed ranges from 200 to 1000 mm/s. The chamber was evacuated followed by filling in a high-purity argon gas to form an oxygen-free atmosphere. The optimized processing parameters obtained by our group were adopted for manufacturing of almost fully dense Inconel 625 parts, including the laser power of 160 W, the scan speed of 500 mm/s, the hatch space of 0.06 mm, and the layer thickness of 0.02 mm. Bidirectional scan mode was used as shown in Fig. 1(b).

2.2. Microstructures

The samples were then subjected to mechanical polishing with a grit size of 1 μm. Subsequently, the polished samples were etched for 30 s in a mixture solution comprising of 10 ml HNO_3, 10 ml HCL and 15 ml CH_3COOH. The distribution characteristics of the elements were analyzed by the energy dispersive spectrometer (EDS). The grain orientation, grain size and grain boundary characteristics were determined by using the EBSD system mounted on the scanning electron microscopy machine (JEOL 7600F). EBSD-scans were conducted on the *Y–Z* and *X–Y* sections of the SLM samples. For this purpose, mechanically pre-polished samples were electro polished for 20 s at 20 V in a 5% perchloric acid solution. The data was analyzed using HKL Channel 5. The crystal structure and the lattice parameters of the samples were tested using XRD Cu *K* radiation at 40 kV and 100 mA. All samples were scanned in the standard geometry from 30° to 100° with a 0.01° step size and 1-s dwelling time. In order to evaluate the microstructure evolution after heat treatment, a set of samples were annealed respectively at 700, 1000, 1150 °C for 1 h followed by cooling in still air. The Vickers hardness was measured under 500 g load applied for 30 s. Each hardness value is the average of 5 measurements.

3. Results and Discussion

3.1. Microstructures and characteristics of the SLM samples

Fig. 2(a) shows the surface morphology of the samples prior to polishing. A very clear "V" shape morphology is identified, which normally appears in welding processing. This phenomenon has

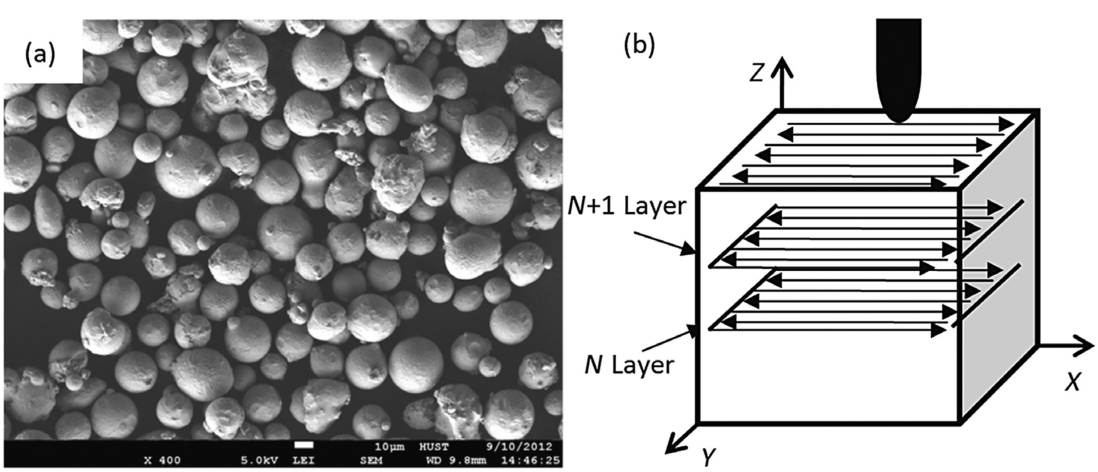

Fig. 1. (a) SEM morphology of Inconel 625 powder, (b) illustration of the bidirectional scan mode. The arrows indicate the movement of the laser.