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A comparative study of Inconel 718 formed by High Deposition Rate Laser Metal Deposition with GA powder and PREP powder

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ABSTRACT

A comparative study on the metallurgical properties and material microstructures of Inconel 718 (IN718) deposited by High Deposition Rate Laser Metal Deposition (HDR-LMD) using Gas Atomization (GA) and Plasma-rotating Electrode Process (PREP) powders has been carried out. Initially, powders of same nominal particle size produced by different methods were selected and the chemical composition, porosity and morphology of which have been characterized. After that, parallel experiments have been designed and performed, and the metallurgical properties and material microstructures have been analyzed. It is found: compared to IN718 deposited with PREP powder, material formed by GA powder has higher porosity and higher dilution zone whereas finer dendrite structure, lower Nb element segregation and lower volume fraction of Laves phase. In order to figure out the reasons, the mechanisms of pores formation, the laser energy allocation, heat dissipation and solidification of the processes using different powders have been qualitative and quantitative analyzed. It concludes: the high porosity of GA IN718 is due to that more gas has been drawn into the process because of the characteristics of GA powder; the microstructures of GA IN718 is superior to that of PREP powder, showing finer dendrite structure, lower Nb segregation and lower Laves phase fraction, which is due to its higher cooling rate.

1. Introductions

Laser Metal Deposition (LMD) is an important Laser Additive Manufacturing (LAM) technology which is also called Direct Laser Deposition (DLD). It can be used to fabricate functional and structural three-dimensional metal components. During LMD a molten pool on the surface of the metal substrate or a previous layer is generated by high power laser radiation. Simultaneously, metal powder is injected into the molten pool by a powder feeding nozzle and melted completely. By moving the working table and/or the laser head, a metallurgical fused bonding is formed. Due to the various advantages of LMD such as low material waste, high production efficiency as well as high flexibility for especially individualized production there has been a growing interests in its development in recent years, from parametric study [1–3] to process monitoring [4,5], from process modelling [6,7] to microstructures and material performance [8–10], and so on.

Inconel 718 (IN718), a thermal resistant nickel-based super-alloy, has high strengths and high creep-rupture resistance at elevated temperatures to about 700 °C, and it is widely used in the field of aircraft industries [11,12]. Moreover, it is also commonly used as critical rotating parts, airfoils, supporting structures, and pressure vessels, and it is one of the most widely used nickel-based superalloy in the aircraft engine industry [13,14]. Investigations on the LMD of IN718 have been attracting more and more attentions [15–18]. These previous works provide a strong basic for further investigations, and actually, more and more developed LMD processes have been already used in industries. However, most of these conventional LMD processes for manufacturing of IN718 have a relative low deposition rate, normally lower than 0.5 kg/h, which satisfies no longer the growing economical expectations in industries. However, studies regarding high deposition-rate LMD (HDR-LMD) of IN718 are rare. Therefore, research on increasing deposition rate, developing HDR-LMD of IN718, are highly motivated.

In this field, C. Zhong, et al. from Fraunhofer Institute for Laser Technology ILT (Germany) have done quite some basic research with the funding of the European Commission in the AMAZE Project (Additive Manufacturing Aiming towards Zero Waste & Efficient Production of High-Tech Metal Products) [19–22]. Initially, they have developed a novel method using mixed process parameters for process window development of HDR-LMD of IN718 [19]. After that, as it is found that the material defects, especially porosity, in HDR-LMD of IN718 is more serious than that of conventional LMD of IN718, a experimental study for

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reducing porosity of HDR-LMD of IN718 have been carried out [20]. Then, they have studied the effects of main process parameters on deposition properties [21]. Based on the developed process, C. Zhong et al. have also done research on microstructures and tensile properties of IN718 formed by HDR-LMD [22]. They have investigated the microstructures and tensile properties of the as-deposited and heat-treated material, and the results showed that the tensile strength of the as-deposited material can be dramatically improved by adapted heat treatments. Reviewing the former investigations on HDR-LMD of IN718, we found that compared to conventional processes, HDR-LMD is more sensitive to powder characteristics/natures that is mainly decided by powder production methods. The commonly used IN718 powders for LMD are produced by Gas Atomization (GA) and Plasma-rotating Electrode Process (PREP). Gas Atomization is the most significant and the most common method of powder production, during which the molten steel is atomized thanks to inert gas jets into fine metal droplets which cool down during their fall in the atomizing tower [23–25]. Plasma-rotating Electrode Process is a centrifugal atomization process developed by Starmet in which plasma arc is involved, and this method is currently a leading candidate for titanium powder production [25–27]. Powders produced by GA and PREP methods have essentially different characteristics since their different production mechanisms. The advantages and disadvantages of metallurgical properties and microstructure characteristics of IN718 deposited with GA powder and PREP powder are not clear. However, they are strongly related with material performance which decides the value and areas of material applications. Therefore, the current study has been carried out.

2. Material and experiments

2.1. Materials

The powders used in the current study were GA and PREP IN718 powders. The main chemical compositions of the used powders as well as the relevant specification have been listed in Table 1.

As seen in Table 1, the two powders have similar chemical composition, and the chemical composition of them satisfy the requirements for IN718.

The nominal particle size of both powders is 45 μm–90 μm. Optical micrographs showing metallographic prepared cross-sections (polished) and SEM (scanning electron microscope) micrographs showing surface and powder microstructures are shown in Fig. 1.

As can be seen from Fig. 1 that the powder characteristics of the two powders are significantly different. For GA powder, there exists a large fraction of a) powder particles featured satellites, b) irregular shaped particles and c) particles with enclosed pores. For PREP powder, almost all the powder particles are spherical in shape, and the circularity of it is significant higher than that of GA powder. Powder particles featured satellites, irregular shaped particles and particles with enclosed pores which have been observed in GA powders have not been found in PREP powder. In addition, the surface of PREP powder looks smoother than that of GA powder, as shown in SEM micrographs.

2.2. Experimental

The experimental setup consists of a collimator, a standard optic, a zoom optic and a coaxial powder nozzle. The movement of the lenses in the zoom optic and the tool axis are controlled by the NC-control of a 4-axes tool machine. A 12 kW diode laser source is linked via a glass fibre. The powder is fed by the use of Helium (He) (4Nl/min) with a powder feeder.

For this comparative study, the experimental conditions are exactly identical, only different powders were used. To prevent the molten pool from interacting with atmospheric gases, Argon (Ar) is used as shielding gas (12Nl/min). The set laser power $P_L = 2950$ W, and the scanning speed $v = 1500$ mm/min. Powder flow rate $\dot{m}$ is set with same volume fraction at 30% rotation of the powder feeding disk (Approx. 2 kg/h), and the used laser spot diameter d_L is 4 mm.

Five tracks with GA powder and PREP powder were deposited, respectively. The metallurgical analysis of them shows: a) the cross-section of every deposited track is consistent; b) the track with same powder is reproducible.

3. Metallurgical properties

3.1. Porosity

Porosity were measured using image processing method by processing the optical micrographs of the cross-sections of the deposited tracks, calculating the rate of the sum of the black areas (pores) on the track cross-section to the whole cross-section area. The measurements were carried out using the integrated image processing software of the used optical microscopy. For each track, the polished cross-sections of five different positions have been observed and analyzed, and the result showed that the track geometry and porosity are consisted. The optical micrographs showing the polished cross-sections of single tracks deposited using GA and PREP powders are presented in Fig. 2. The porosity values are also listed in this figure.

It can be seen from Fig. 2 that porosity of track deposited by GA powder is significant higher, about 16 times, than that of PREP powder.

Porosity is the consequence that part of the gas involved in the process has not escaped to the outside environment before the solidification of the liquid metal, being entrapped in the solidified material. Considering the powder morphologies (Fig. 1a and b) and that these tracks were deposited under exactly same experimental conditions, it is reasonable to infer that more gas was involved in the process with GA powder, which is the main reason for its higher porosity. This conclusion is plausible because: a) unlike PREP powder particles, there is a large fraction of particles with enclosed pores in GA powder, b) compare to the spherical-shaped PREP powder particles, it is expected that the irregular-shaped GA powder particles and particles featured with satellites would draw in more gas to the molten pool during powder feeding, and c) this conclusion agrees well with the results of material microstructures in Section 4.

3.2. Track and molten pool

In order to analyzing the molten pool and material microstructures, the deposited tracks (one of GA powder and one of PREP powder) were etched at five different positions and observed using optical microscope. It showed that the track and the molten pool geometry are constant. The etched cross-sections of tracks deposited with GA powder and PREP powder are illustrated in Fig. 3.

It is supposed that the slightly non-symmetric molten pool of PREP powder shown in Fig. 3 is the consequence that the powder focus and the focus of laser beam were not 100% concentric. Due to that the

Table 1
Main chemical composition of IN718 in wt.%.

	Ni (+Cr)	Cr	Nb (+Ta)	Mo	Ti	Al
Specification	50.00–55.00	17.00–21.00	4.75–5.5	2.80–3.30	0.65–1.15	0.20–0.80
GA	53.07	18.48	4.86	3.01	0.92	0.33
PREP	51.3	19.2	5.2	3.0	0.99	0.56