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Experimental investigation on selective laser melting of 17-4PH stainless steel

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ABSTRACT

Selective laser melting (SLM) is an additive manufacturing (AM) technique that uses powders to fabricate 3Dparts directly. The objective of this paper is to perform an experimental investigation of selective laser melted 17-4PH stainless steel. The investigation involved the influence of separate processing parameters on the density, defect, microhardness and the influence of heat-treatment on the mechanical properties. The outcomes of this study show that scan velocity and slice thickness have significant effects on the density and the characteristics of pores of the SLMed parts. The effect of hatch spacing depends on scan velocity. The processing parameters, such as scan velocity, hatch spacing and slice thickness, have effect on microhardness. Compared to the samples with no heat-treatment, the yield strength of the heat-treated sample increases significantly and the elongation decreases due to the transformation of microstructure and the changes in the precipitation strengthening phases. By a combination of changes in composition and precipitation strengthening, microhardness improved.

1. Introduction

Selective laser melting (SLM) is an additive manufacturing (AM) technique which can fabricate 3D parts directly from metallic powders without tooling [1–3]. Due to the layer-wise fabrication paradigm, SLM technology is suitable for building complex shape of metal parts [4]. SLM can manufacture parts with nearly full density without the need of post-processing treatment [5,6]. In recent years, more and more materials processing by SLM have been studied.

17-4PH stainless steel is a Martensite Precipitation Hardening stainless steel. Owing to its high strength and excellent corrosion resistance, 17-4PH has been used in a wide range of area such as aerospace, defense and so on [7–9].

Many studies on SLMed 17-4PH stainless steels have been done recently and these studies were focused on many aspects. The effects of processing parameters on the characteristics of SLM process were investigated in several papers. The results have shown closely connection between the energy density and the porosity as well as the microstructure [8]. In addition, different processing parameters have been set up and used for experiments which also proved the correlation between energy input, porosity level and mechanical properties [9]. Besides, different gas atmosphere resulted in different composition of martensite and austenite [10]. Single layer experiment has also been done to prove that the processing parameters and scan strategy have the impacts on stability and quality [11]. For the studies about mechanical behavior, besides work hardening and the strain-induced transformation has been published [12]. Moreover, detailed experiments about different heat treatment have been published to demonstrate the effects of retained austenite on subsequent thermal processing and mechanical properties [13]. Among them, the fact that energy density may not be a good indicator for SLM when processing at low scan velocity and laser powers has been pointed out [8]. In summary, the separate processing parameters' influence has been mentioned rarely. So this study will pay more attention to the separate processing parameters' influences on density, defect and microhardness, to enhance the understanding of the SLM process, thereby providing quality control of SLM parts. Finally, high-density SLMed 17-4PH stainless steel parts with high mechanical strength were obtained after the heat treatment.

2. Material and methods

Gas atomized 17-4PH stainless steel powders supplied by Hengji Powder Technology China were used in this experiment. The range of particle size of the powders was 10–74 μm with an average diameter of 45.2 μm. The particle size was measured using the Malvern UK Mastersizer 3000. The scanning electron microscopy (SEM) image of powder (Fig. 1) shows that it is almost spherical in shape. Table 1 gives the chemical composition of

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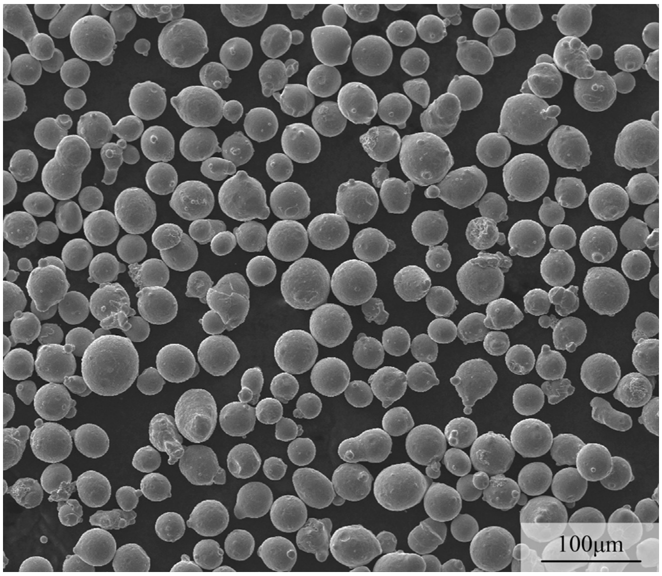

Fig. 1. SEM image photo of 17-4PH stainless steel powders.

starting 17-4PH stainless steel powder that meets A564/A564M-13 [14]. A self-developed SLM machine (LSNF-I) was used in this experiment. This machine consists of a continuous wave IPG YLR-200 fiber laser (λ = 1.7 µm, 100 µm spot size) with maximum laser power of 200 W, a chamber with atmosphere control and an automatic powder delivery system. More details concerning the SLM system and processing procedure were given in our previous papers [15,16]. The processing parameters used are tabulated in Table 2. In order to maximize the efficiency of laser processing, the maximum laser power (200 W) is chosen and this processing parameter is kept constant in this study. The energy density flux at powder layer is $2.55*10^4$ W/mm^2. For each parameter combination, two samples with size of 5*5*8 mm^3 were built in an argon atmosphere with the concentrations of H_2O and O_2 both controlled below 200 ppm in order to study the effect of separate processing parameters on the density, defect and microhardness of SLMed 17-4PH stainless steel samples. After SLM processing, samples fabricated by using the processing parameters which can achieve the highest density in this research were heat treated with the following schedule: solution treatment (1040 °C, 0.5 h, air cooling) followed by aging (550 °C, 4 h, air cooling).

The density of the SLMed samples was determined using Archimedes method in deionized water. Each sample was measured three times. After mechanical polishing, six vertical-sectional optical micrographs with a magnification of 50 × were watched by optical microscopy (LOM, Nikon EPIPHOT300) and analyzed by the Image-Pro Plus 6.0 software to evaluate the porosity and defect of the SLMed samples. In addition, one optical micrograph with a magnification of 200 × was captured to show the characteristics of the defect. Besides, microhardness tests on cross and vertical sections were carried out with a HVS-1000 microhardness tester at a load of 500 g and a holding time of 20 s.

Tensile test specimens were designed according to Chinese GB/T 228-2002 standard [17] (nearly equivalent with ISO 6892-1998 [18]), as shown in Fig. 2. Two series (three samples in each series) of standard deposited and heat treated 17-4PH tensile test specimens were examined using the Zwick/Roell tester to evaluate the tensile properties at room temperature (RT). After rupture, the fracture surfaces were observed by the scanning electron microscopy (SEM, FEI Quanta 650). Phase identification was performed through an X′Pert-Pro X-ray diffractometer (XRD).

Table 2
SLM process parameters used in this experiment.

Process parameter (Unit)	Value
Laser power (W)	200
Scan velocity (m/min)	10, 20, 30, 40, 50, 60, 70, 80, 90, 100
Hatch spacing (µm)	90, 110, 130
Slice thickness (µm)	20, 30, 40
Hatch angle (°)	90

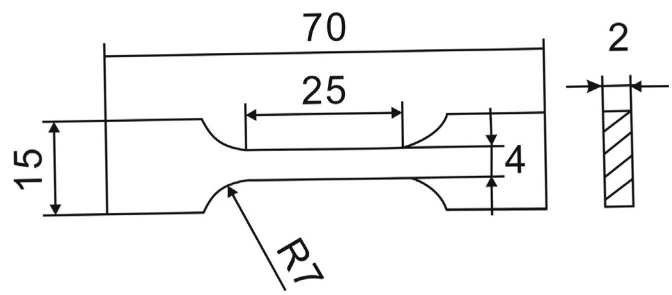

Fig. 2. Configuration of tensile test specimen used in this experiment.

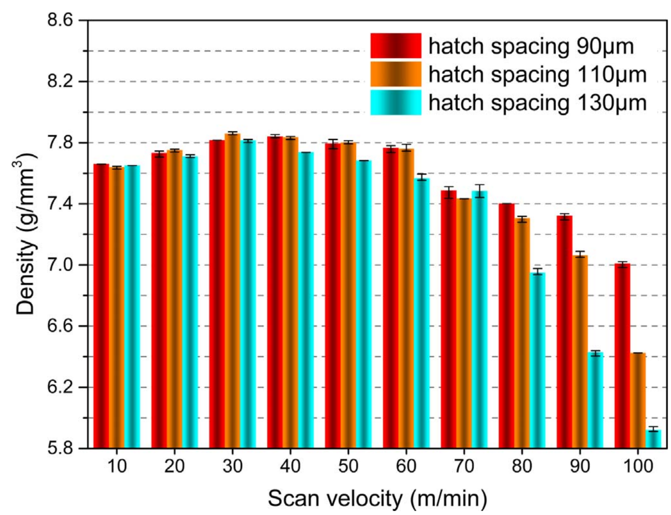

Fig. 3. The density vs. velocity under different hatch spacing.

3. Results and discussions

3.1. Density and defect analysis

Fig. 3 shows the relationship between the density of samples and various scan velocity under different hatch spacing with a constant slice thickness of 20 µm. From Fig. 3, it can be found that velocity is a remarkable factor that influences on the density. With the increasing in scan velocity, the density increases at first and

Table 1
The chemical composition of starting 17-4PH stainless steel powder.

Element	C	Si	Mn	P	S	Ni	Cr	Cu	Nb & Ta	Fe
Wt (%)	≤ 0.07	≤ 1	≤ 1	≤ 0.04	≤ 0.03	3–5	15–17.5	3–5	0.15–0.45	Bal.