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SLM-manufactured 30CrMnSiA alloy: Mechanical properties and microstructural effects of designed heat treatment

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A B S T R A C T

Microstructures and mechanical properties of 30CrMnSiA alloy parts fabricated by forged annealing and selective laser melting (SLM) processes were compared in this study. SLM fabricated (SLMed) 30CrMnSiA alloy parts possess higher hardness and tensile strength than forged annealed (FAed) parts, however, a characteristic of low plasticity and impact toughness was observed in SLMed parts. Therefore, this research designed a reasonable heat treatment mode, which was divided into three periods to modify the microstructure in SLMed 30CrMnSiA alloy parts. The first period was repeated full annealing at 900 °C for 1 h to eliminate microstructure inhomogeneity, especially carbides segregation and ununiformed grain morphologies. The second period was air blast quenching from 900 °C to ambient temperature to achieve super saturation solid solution or martensite in parts. The last period was tempering at 650 °C for 1 h to fulfill martensite decarburization and carbides spheroidization. As a result, tempered sorbite as an equilibrium microstructure in ambient environment was obtained in SLMed 30CrMnSiA alloy parts. The optimum comprehensive mechanical properties of SLMed parts with an average hardness of 24.8 HRC, a tensile strength of 860 MPa, a plasticity of 16.9% and an impact toughness of 29.1 J were achieved by performing the designed heat treatment mode. It considerably enhanced the plasticity and impact toughness of SLMed 30CrMnSiA alloy parts, which were 1.41 and 2.55 times of parts without heat treatment. Accordingly, industrial applications of SLMed 30CrMnSiA alloy parts were supposed to be widened by this study.

1. Introduction

30CrMnSiA alloy is a type of medium carbon steel, which has a high tensile strength and good weldability and been broadly applied in pressure vessel and aerospace industrial fields [1–3]. In recent decades, manufacturing methods of 30CrMnSiA parts contains casting, forging and extrusion and so on [4–6]. Those traditional processes generally need external moulds or tools, and the design-to-manufacturing period always takes a lot of time. Moreover, they are difficult to fabricate complex structures in some application fields [7]. Therefore, the shortcoming of traditional processes limits further applications of 30CrMnSiA alloy. At present, selective laser melting (SLM) has been one of the advanced technology to manufacture metal parts [8]. It has a high flexibility for structure designing, and its direct forming characteristic needs no external moulds or machining tools [9,10]. Therefore, SLM process enables to fabricate geometrically complex structures, at the same time, it has a great potential to reduce the time of design-to-manufacturing period by replacing a series of traditional production steps with a single forming process [11,12]. However, SLM manufactured (SLMed) parts usually have different features from traditional produced parts. Firstly, material solidification rate may reach to 10^6 °C/s during SLM process, which could lead to distinctive microstructure in SLMed parts [13]. Chen et al. [14] has reported that martensite transformation was taken place in local region of SLMed tool steel parts due to the quick cooling rate of molten pool. Aboulkhair et al. [15] investigated that Al-Si eutectic phase segregating at the grain boundaries of AlSi10Mg parts during SLM process. Secondly, because of the steep temperature gradient (10^4 °C/mm) of molten pools, large thermal stresses are remaining in materials [16]. As a result, low ductile phase in microstructure and stresses concentration probably lead to bad plasticity and toughness of SLMed parts.

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Over the past few years, microstructures and mechanical properties of 30CrMnSiA alloys through traditional manufacturing methods [17–19] and heat treatment processes [20–22] have been widely studied. However, microstructures and mechanical properties of 30CrMnSiA parts manufactured by SLM process are rarely studied. In this paper, microstructures and mechanical properties (especially the plasticity and impact toughness) are comparatively analyzed between FAed and SLMed 30CrMnSiA alloy parts. Then, a reasonable heat treatment mode is designed to modify microstructures in SLMed parts to improve their plasticity and impact toughness, and the comprehensive mechanical properties with or without heat treatment are comparatively investigated among SLMed parts. Correspondingly, the mechanism between microstructures and mechanical properties of SLMed parts influenced by heat treatment is discussed in detail by this work.

2. Experiments

2.1. Materials

The 30CrMnSiA alloy powders used in SLM experiments were prepared via gas-atomization (supplied by Zhejiang Asia General Soldering & Brazing Material Co. Ltd., China) and stored in vaccum tanks. The chemical composition of powders is given in Table 1. Moreover, Fig. 1 illustrates surface morphology and particle size distribution of 30CrMnSiA alloy powders. Most of powders are in spherical shapes (as seen in Fig. 1(a)). According to data given by Fig. 1(b), the diameter range of 80% particles are from 24.3 μm to 56.8 μm, and the average particle size *D*[50] is determined as 38.1 μm.

2.2. SLM process

SLM experiments are performed by a specific equipment (Renishaw Ltd., AM250), which containing a fiber laser system with the maximal power of 200 W and a certain laser wavelength of 1064 nm. The working volume in equipment is 250 mm × 250 mm × 300 mm. All experiments are under argon atmosphere with the oxygen content below 800 ppm. Before SLM process starting, the substrate is pre-heated to 180 °C to decrease temperature gradient in materials, which could dispel the influence of thermal stress on mechanical properties of SLMed parts. Tracks scan is accomplished by point exposure scanning method. The laser scanning strategy obeys Chessboad scanning mode, whose scanning direction rotates by 67° for each powder layer processing.

Table 2
Experimental SLM process parameters for 30CrMnSiA alloy parts fabrication.

Process parameters	Value
Laser power	180 W
Laser spot diameter	135 μm
Laser point exposure time	140 μs
Scanning point distance	130 μm
Scanning hatch spacing	130 μm
Layer thickness	30 μm

Table 2 listed the optimized SLM process parameters for 30CrMnSiA alloy parts fabrication. Fig. 2(a) displays the regarding geometry of parts used for testing and their build orientation, meanwhile, the appearance of SLMed parts are given in Fig. 2(b). The parts used for Charpy impact tests are notched later by machining with a V-shape. The notch depth is 2 mm, whose direction is coincided with building direction. In experiments, SLMed parts have an average relative density of 99.8%.

2.3. Heat treatment process

The heat treatment of SLMed 30CrMnSiA alloy parts is carried out by a vacuum heating cabinet (MADAS energy tech. Ltd., 1200ZQLB). The effective heating volume of cabinet is 600 mm × 600 mm × 600 mm, and the absolute vacuity in cabinet is less than 6.3×10^{-3} MPa. It has maximal working temperature of 1500 °C, while the temperature homogeneity is ±3 °C. As Fig. 3 illustrated, a specific mode of heat treatment is designed to modify the microstructure of SLMed samples. The heat treatment mode contains three process periods, which are defined as full annealing (FA), air blast quenching (AQ) and tempering [23]. Herein, air blast quenching actually means the part was cooled in the air accelerated by a fan, which has a quicker cooling rate than part cooled in the still air. All processes have the same heating rate of 15 °C/min. Specifically, samples in FA period experience respectively

Table 1
Chemical composition of 30CrMnSiA alloy powders used in SLM fabricating experiments.

Element	C	Si	Mn	Cr	Ni	Co	Mo	Cu	Fe
wt%	0.25	0.97	1.21	1.65	1.66	0.058	0.48	0.02	Balance

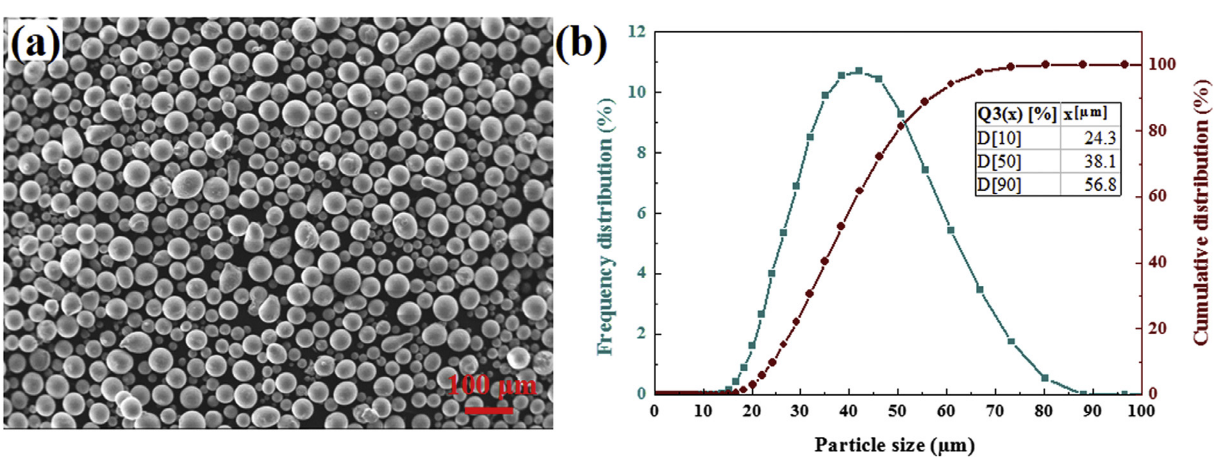

Fig. 1. Experiment used 30CrMnSiA powders characteristic: (a) surface appearance and (b) particle size distribution.