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Microstructure and composition homogeneity, tensile property, and underlying thermal physical mechanism of selective laser melting tool steel parts

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ABSTRACT

This paper systematically investigated the crystallization thermodynamics and dynamic process within melt pool of 5CrNi4Mo steel fabricated by selective laser melting (SLM). The experimental results in conjunction with finite element analysis (FEA) demonstrated that the nucleation rate during SLM process was determined by the combined effects of supercooling degree and transfer capacity of atoms near solid/liquid interface; variant nucleation rate in different region of melt pool caused microstructure heterogeneity. Chemical compositions, including Cr, Ni and C, were observed to be homogeneously distributed due to the rapid solidification of the material. Specimens built along different orientation exhibited discrepant tensile properties due to the different deformation mode during loading. All the as-fabricated SLM-processed tensile specimens showed unfavorable ductility due to heterogeneous microstructures and residual stress concentration. After post-vacuum heat treatment, for horizontally built specimens, the elongation was significantly elevated from 5.6–9.7% and the toughness was enhanced form 63.68 J/m^3 to 134.12 J/m^3. The tensile strength increased marginally from 1576 MPa to 1682 MPa. These promotions were mainly caused by pronounced relief of intrinsic residual stress and recrystallization effect.

1. Introduction

One present trend in manufacture is the reduction in lead times for product development. New processing technologies, especially those in the field of layer by layer additive manufacturing (AM), support this trend [1,2]. Selective laser melting (SLM) is a key AM technology that enables the quick production of complex shaped three-dimensional (3D) parts, which cannot be fabricated by traditional manufacturing methods. Starting with a CAD model of the part, the process proceeds by laser melting sequential powders layers and obtaining the cross-sections of the final product layer by layer, thus achieving direct fabrication of structural or functional parts [3]. Consequently, there is a strong demand across a broad range of sectors, including aerospace, medical, and automotive, for fabricating tailored products with demanded properties by SLM technology [4].

Compared to cast and forged components, there are some specific characteristics in SLM-processed parts, including grain refinement, extended solid solubility, chemical homogeneity and reduction in quantity and size of phase segregation, which contribute to excellent mechanical properties [5]. However, because of the vigorous Marangoni convection induced by high thermal capillary forces, SLM suffers from the instability of the molten pool and thus causing microstructures uncontrollability. Moreover, variant thermodynamics behaviors (e.g. solidification rate, cooling rate and thermal gradient, etc.) at different region of melt pool give rise to microstructural heterogeneity and accordingly have negative effects on the plasticity and toughness of SLM-processed parts. The basic principle of the SLM process in terms of non-equilibrium crystallization and phase transformation process, affected by rapid melting and quenching as well as complicated thermal history within the melt pool, is not yet well understood and requires further investigations.

5CrNi4Mo steel type is a medium-carbon, cold work steel used to make tools for cutting, coining and injection molding. Excellent elastic strength, hardness and wear resistance are all essential properties

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Table 1
Chemical compositions of as-used 5CrNi4Mo steel powder.

Element	Fe	C	Cr	Ni	Mo	Si	Mn	P	S
Content (wt %)	Balance	0.45	1.35	4.0	0.25	0.25	0.40	≤0.025	≤0.005

when choosing a tool steel. It is well known that microstructures in steel determine its properties. Therefore, before a tool is put into use, it requires tedious heat treatment procedures, like quenching and tempering, to meet the service demand. Interestingly, during SLM process, the considerably large cooling rate in melt pool can directly induce martensite transformation without any heat treatment. As such, SLM is a good method to avoid these follow-up processes but still obtain demanded properties, which can not only guarantee quenching quality, but also lower costs and shorten cycle times. Colaco et al. [6] took advantages of laser surface melting (LSM) technology to directly obtain martensite with high proportions of above 80% by optimizing composition and processing parameters. Nevertheless, the repeated rapid heating and cooling during laser processing generally resulted in large residual thermal stress in the workpieces, which would have a considerable influence on the mechanical properties of laser-processed parts and significantly limit their industrial applications. AlMangour et al. [7] and Badrossamay et al. [8] prepared tool steels using SLM and indicated that the tool steels were challenging to process because the parts with high-strength and low toughness were greatly susceptible to cracking. Holzweissig et al. [9] reported on SLM processing of ferritic/martensitic steels without post-heat treatments and demonstrated the unpredictability of microstructures of tool steels due to repetitive heat flux during melting of overlying powder layers.

Based on the previous works conducted in different types of steels concerning different aspects, such as densification, microstructure and mechanical properties investigations [4–9], it can be summarized that there are still numerous objects requiring to be illuminated and understood, such as the crystallization process located in different regions of melt pool and the controllability of solidification microstructure of SLM-processed tool steel parts. Therefore, the melt pool dynamics and solidification process during SLM were deeply investigated in this paper, so as to reveal the nucleation mechanism and forming principle of microstructure heterogeneity of SLM-processed parts. The elements segregation behavior was also studied and compared to other researches, because the extent of elements segregation can severely affect the load-bearing capacity of structural components [10]. In addition, based on the available published literatures, there are little previous studies focusing on the investigations of ultimate strength and ductility of SLM-processed tool steel part. Authors believed that the tensile property characterization is of great significance because the inherited major stresses in SLM-processed parts will negatively influence the strength and strain if the stress is not relieved. As such, a post-vacuum heat treatment was also conducted in this paper and the tensile properties of as-fabricated and heat-treated were compared.

2. Experimental procedures

2.1. Powder materials and SLM process

Spherical gas-atomized 5CrNi4Mo steel powder was used in this study with a mean particle size of 21.6 μm and the chemical compositions are listed in Table 1. The SLM system was independently developed and consisted mainly of a YLR-500 ytterbium fiber laser with a power of ~500 W and a spot size of 70 μm (IPG Laser GmbH, Germany), an automatic powder layering device, an inert argon gas protection system, and a computer system for process control. A stainless steel substrate plate was horizontally fixed on the building platform during the whole SLM process with a dimension of 150 mm×150 mm×30 mm. In order to obtain samples with satisfactory densification level, the laser power (P) was set at 77.5 W. Layer thickness (h) and hatching spacing (s) were set at 30 μm and 50 μm respectively, based on a series of preliminary experiments. Meanwhile, various scan speeds (v) were set by the SLM control program, in order to change the processing conditions during one batch of experiments. The applied laser volume energy density η, which was defined by [11]:

$$\eta = \frac{P}{vsh} \tag{1}$$

were used to assess the laser energy input to the powder layer being processed.

2.2. Microstructural characterisation and mechanical testing

The Archimedes principle was used to measure the density of the specimens. Phase identification was performed by X-ray diffraction (XRD) using a D8 Advance X-ray diffractometer (Bruker AXS GmbH, Germany) with Co Ka radiation at 40 kV and 40 mA, using a continuous scan mode. A scan at 2°/min was conducted over a wide range of 2θ=30–85° to give a general overview of the diffraction peaks. Samples for metallographic examinations were cut, ground and polished according to standard procedures and etched with a solution consisting of HNO_3 (4 ml) and CH_3CH_2OH (96 ml) for 20 s. Microstructures were characterized using a PMG3 optical microscopy (Olympus Corporation, Japan) and a S-4800 field emission scanning electron microscope (FE-SEM) (Hitachi, Japan) at 3 kV.

Tensile samples were fabricated both vertically and horizontally for mechanical testing according to the standard of GB/T228-2010 (Fig. 1). Some of the SLM-processed samples were also heat treated to study the influence of post heat treatment on mechanical properties. A post-vacuum heat treatment was used which included heating of samples from room temperature up to 640 °C with a heating rate of 10 ℃/min and dwelling at 640 °C for 3 h and then cooled within the furnace to the room temperature. The tensile test was conducted at room temperature on a CMT5205 testing machine (MTS Industrial Systems, China) at a cross head velocity of 2 mm/min. The toughness of material which could show the ability to absorb mechanical energy of

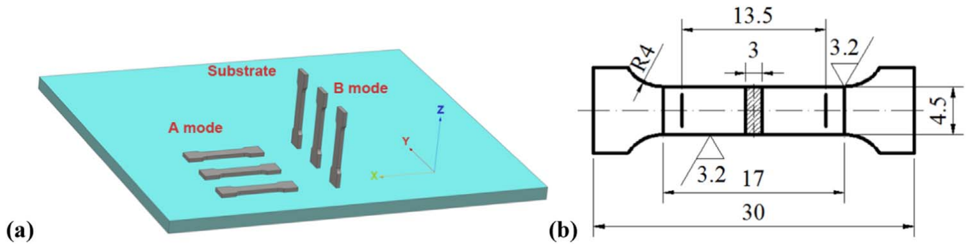

Fig. 1. (a) 3D view of the tensile test specimens: A horizontal build-up; B vertical build-up. Geometry of SLM processed sample for tensile testing (b).