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The influence of aging temperature and aging time on the mechanical and tribological properties of selective laser melted maraging 18Ni-300 steel

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ABSTRACT

Selective laser melting (SLM) is an additive manufacturing and 3D printing technology which offers flexibility in geometric design and rapid production of complex structures. Maraging steels have high strength and good ductility, and therefore have been widely used in aerospace and tooling sectors for many years. This work aims to study the influence of aging temperature and aging time on the microstructure, mechanical property (hardness, strength and ductility) and tribological property of SLM maraging 18Ni-300 steel. The results reveal that the aging conditions had a significant impact on the strength and wear-resistance of the SLM maraging steel. The optimal aging conditions for the SLM maraging steel produced in this work were 490 °C for 3 h under which strength and wear-resistance were maximised. Lower or higher aging temperature led to under-aging or over-aging phenomena, reducing the strength and wear-resistance performance. Shorter or longer aging time also resulted in the decrease of strength and wear-resistance performance of the SLM maraging steel as compared with the optimal conditions. The variation of the mechanical and tribological properties is primarily due to changes in phase compositions and microstructures of the SLM maraging steels.

1. Introduction

Selective laser melting (SLM) is an additive manufacturing and 3D printing technology, which is predominantly used for the production of metal-based components (i.e., pure metals, alloys and metal matrix composites). With SLM, a high-power laser beam is used to selectively melt powder feedstock according to a pre-defined computer-aided design (CAD) model. The liquid melt pool created by the laser rapidly cools to form a solid track which when combined with neighbouring tracks and layers, can form near-net-shape components [1]. SLM offers several unique advantages over other conventional manufacturing processes, such as flexibility in geometric design, rapid production of components with complex geometry and high spatial resolution (e.g., turbine disc and cellular lightweight structures), customization of products at an acceptable cost (due to the lack of tooling), and little material waste through the recycling of unprocessed powder [1–3]. Components fabricated via SLM under optimized manufacturing parameters can be almost fully dense and have equivalent mechanical properties as compared with wrought counterparts. SLM is hence well recognized as a novel manufacturing technology of the future.

Steels have excellent mechanical properties such as high strength, toughness and good machinability, and have been widely used in the modern industry. Due to their excellent wettability and low reflectivity, steels are candidate alloys of high interest for SLM [1,2]. To date, a number of studies have been carried out to study the microstructure and properties of SLM steels, such as austenitic stainless steels [4–19], precipitation hardenable stainless steels [20–23] and maraging steels [24–35]. Among these, high-strength and high-ductility maraging steels have been widely used in aerospace and tooling sectors which has resulted in these alloys being a focus of SLM studies in recent years. Studies demonstrated that high-density and high-performance maraging steels can be produced through SLM using optimized laser parameters and scanning strategies [29,34–36]. SLM maraging steels typically have very fine cellular structure in the as-fabricated state due to the very high cooling rates and rapid solidification during manufacture [37–39]. Therefore, SLM maraging steels generally have higher yield strength, tensile strength and hardness as compared with wrought counterparts [28,29]. However, such high strength and low ductility

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also results in a low transition fatigue life of the SLM maraging steel [40].

Aging treatment is known to be an effective way to improve the hardness and strength of precipitation hardenable alloys due to the formation of intermetallic precipitates [41,42]. In terms of SLM maraging steels, studies have confirmed that the microstructure and mechanical properties of SLM maraging steels can be improved through proper aging treatment [20,22,24–30,33]. The aged SLM maraging steels can have much higher strength than the as-fabricated steels with reduced ductility. Although existing studies have demonstrated the importance of aging treatment in improving the mechanical performance of SLM maraging steels, systematic investigations on the aging parameters (aging temperature and aging time) for SLM maraging steels are not prevalent. In addition, maraging steels are mainly used in aerospace, tooling and mold industries where the working environments are normally aggressive and excellent wear-resistance performance is necessary. Hence, investigations on the tribological properties of SLM maraging steels are also greatly needed. Considering the aforementioned points, this paper aims to explore the influence of aging temperature and aging time on the microstructure, mechanical properties (hardness, strength and ductility) and tribological property of SLM maraging steels.

2. Experimental methodology

2.1. Manufacturing procedure

Spherical maraging 18Ni-300 steel powder (EOS GmbH, Germany) with a size range of between 33 and 40 μm was used as the feedstock. Fig. 1a shows the surface morphology of the maraging steel powders observed by scanning electron microscope (SEM, Carl Zeiss ULTRA, Germany). Fig. 1b shows the cross-section of a maraging steel powder after etching. It can be seen in Fig. 1b that the microstructure of the maraging steel powder is dendritic which is a typical microstructure of rapidly cooled steels. EOS M290 SLM system (EOS GmbH, Germany) was used to produce the maraging steel samples. Experiments were performed in a nitrogen environment with substrate preheating to a temperature of 40 °C. Optimized scanning parameters were used in this experiments with a laser power of 285 W, a hatch distance of 110 μm, a laser beam speed of 960 mm/s, a laser spot diameter of 100 μm, and a layer thickness of 40 μm [29]. The laser scanning trajectory follows a zigzag pattern with an angle of 67° between adjacent layers. Fig. 2 shows a photograph of three SLM maraging 18Ni-300 steel samples manufactured using the optimized parameters, highlighting the reliability of these parameters. Note that these samples were only produced for demonstration purposes rather than mechanical or tribological testing. Following the manufacture of the maraging steel samples, aging treatment was carried out under various temperatures (from 390 to 590 °C) and time (from 1 to 7 h) without pre-solution treatment. The aging parameters were chosen based on the findings of previous studies

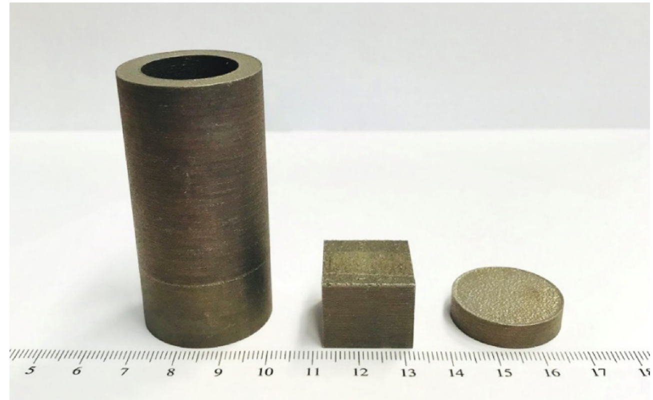

Fig. 2. Photo of three SLM maraging 18Ni-300 steel products manufactured using the optimized parameters.

[24,26,36]. Aging treatment and sample cooling were both performed in air.

2.2. Materials characterization

The relative density of the SLM maraging steel samples was measured by an analytical balance (ABZ 200C, PCE instruments, Germany) based on Archimedes principle using the following formula:

$$\frac{\rho_{SLM}}{\rho_{standard}} = \frac{\rho_{water} \cdot m_{SLM(air)}}{\rho_{standard} \cdot (m_{SLM(air)} - m_{SLM(water)})} \tag{1}$$

where, ρ_{SLM} is the density of SLM sample; $\rho_{standard}$ is the standard density of maraging steel; $m_{SLM(air)}$ is the weight of SLM sample in air; $m_{SLM(water)}$ is the weight of SLM sample in water; ρ_{water} is the density of water. Three samples were tested and averaged to determine the relative density. The cross-sectional microstructure of the SLM samples was studied using an optical microscope (OM) and SEM. As a preparation for the microstructure analysis, the samples were polished using standard metallographic procedures with the final polishing applied using 0.06 μm silica solution. Polished samples were etched with a modified Fry's reagent of 1 g $CuCl_2$, 25 ml HNO_3, 50 ml HCL and 150 ml water to observe and study the grain structure. To examine the phase transformation after aging treatment, the SLM samples were examined by an X-Ray diffractometer (XRD, Siemens D500, Germany) with the Co (λ = 1.789 Å) source at a current of 40 mA, voltage of 35kV, scanning step of 0.02° and scanning speed of 6 s per step. In order to accurately analyse the phase fraction of SLM maraging steels before and after aging, Rietveld analysis was conducted using JADE 6.0 software based on the measured XRD spectrum through phase retrieval, pattern fitting and Rietveld refinement.

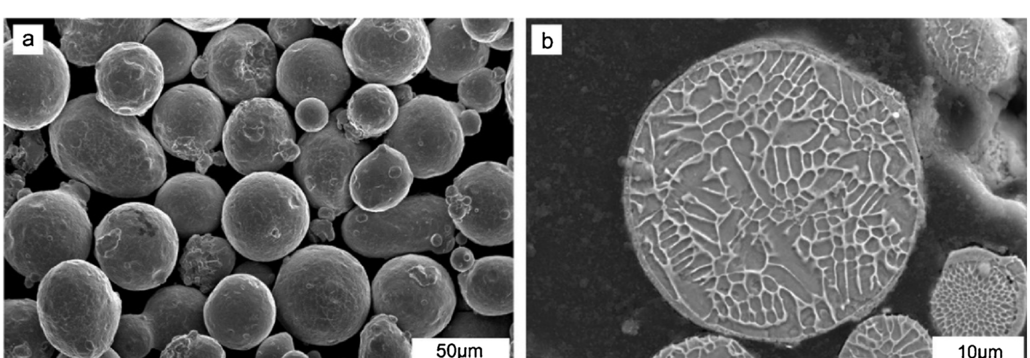

Fig. 1. Maraging 18Ni-300 steel powders used in the experiments. (a) surface morphology, and (b) cross-sectional view after etching.