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## Microstructure and tribological property of selective laser melted Fe-Mn-Al-C alloy

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### Abstract

To investigate the microstructure and tribological property, Fe-16Mn-10Al-1.5C alloy was fabricated via selective laser melting technology at different laser scanning speeds for the first time in this study. The results show that the microstructure of Fe-Mn-Al-C alloy is composed equiaxed grains and columnar dendrites. And this alloy is mainly composed of  $\gamma$ -Fe. This alloy has high microhardness and low coefficient of friction (COF). The microhardness of the SLM part increases with the decrease of the laser scanning speeds. The sample prepared at the highest speed not only has the lowest COF, but also the lowest wear rate amongst these SLM parts and its wear mechanism is mainly abrasive wear and adhesive wear. The wear mechanism of the samples V0.4 and V0.28 is not only abrasive wear but also abrasive wear that produces grooves, which generates a large number of grooves during the wear test.

**Keywords:** Fe-Mn-Al-C steel, SLM, Microstructure, Wear and tribology

### 1 Introduction

Additive manufacturing is a technology that has been considered as a potential method to replace conventional casting in the future [1]. Selective laser melting (SLM) is one of the most common additive manufacturing technologies. This technology is particularly suitable for fabrications of various

metallic parts and alloys because of its rapid solidification ( $10^3\sim 10^6$  K/s) [2]. In the field of the automobile industry, the criteria used for evaluation of the fuel efficiency and emissions requirement are of greater concern, hence, the design of the automobile lightweight also become urgent [3]. One of the most effective methods of reducing the weight of a vehicle is using several types of materials with low density [4]. To satisfy this demand, Fe-Mn-Al-C alloys have been received heated attention recently as a class of automotive steels due to their low density, high strength and extended ductility [5]. Traditionally, Fe-Mn-Al-C alloys are manufactured by casting. Hwang et al. [6] indicated that the duplex Fe-20Mn-9Al-0.6C steel fabricating by hot rolling after induction melting was in a ferrite/austenite duplex structure after annealing. The steel also showed a good combination of tensile strength and elongation. Zhang et al. [7] obtained the same conclusion in the investigation of Fe-12Mn-8Al-0.8C steel. Additionally, Wu et al. [8] reported that increasing Al content and aging time can increase the volume fraction of coherent shearable  $\kappa$ -carbide precipitates of aged low density Fe-Mn-Al-C steels. Note that the investigations about Fe-Mn-Al-C steel only focused on the microstructures, mechanical properties and their evolution of the parts processed using induction melting [9]. However, there are rare reports about Fe-Mn-Al-C alloys fabricate by SLM. Therefore, this research focuses on the investigation of the microstructure and tribological property of the Fe-Mn-Al-C alloy manufactured by SLM technology.

## **2 Experimental details**

### **2.1 SLM samples preparation**

The chemical compositions are as follow (wt. %): Fe: balance, Mn: 16.38, Al: 9.88, Ni: 4.86, C: 1.49. Samples were printed using an EOS M290 (EOS GmbH, Germany) system. The parameters are as follow: laser scanning speeds: 0.5, 0.4, and 0.28 m/s respectively, laser beam focus: 100  $\mu$ m, laser

power: 100 W, layer thickness: 30  $\mu\text{m}$ , hatch distance: 80  $\mu\text{m}$ . The samples were named here V0.5, V0.4 and V0.28 respectively according to the laser scanning speeds.

## 2.2 Microstructural characterization

The polished specimens were etched by  $\text{HNO}_3$  at room temperature for 10s. The microstructure was characterized by scanning electron microscopy (SEM) and X-ray diffraction (XRD).

## 2.3 Microhardness and dry sliding wear tests

The Vickers hardness was measured using a microhardness tester (Leiz-Wetzlar, Germany) at a load of 100 g and an indentation time of 25 s. Vickers hardness measurements were carried out at different locations on the XY plane, and the average of 10 measurements is recorded. Dry sliding wear tests were investigated at ambient temperature by a CSEM tribometer implement (MS-T3001). The counterpart material was a  $\text{Si}_3\text{N}_4$  small ball with 4 mm diameter. The wear test requirements included a testing load of 5 N, a rotational speed of 382 r/min and a rotation radius of 3 mm. The COF was recorded during sliding. After the friction test, the macroscopic morphology and the cross-sectional areas of the worn tracks were measured by a 3D surface profilometer. The surface of the worn samples was observed by SEM. The wear rate ( $\omega$ ) was calculated via the equation (1) and counted the average value after five measurements.

$$\omega = \frac{V}{FL} = \frac{2\pi rS}{FL} \quad (1)$$

where r is the radius of the wear track, mm; S is the cross-sectional area of the worn tracks,  $\text{mm}^2$ ; F is the testing load, N; and L is the sliding distance, m.

## 3 Results and discussion

The microstructures (XY, YZ plane) of these alloys are presented in Fig. 1. As presented in Fig. 1(a)-(f), the microstructures of Fe-Mn-Al-C alloys are composed of equiaxed grains and columnar

dendrites [10]. It could be seen that some micron poles which were introduced during the SLM processing are presented in the macrostructure characterization. Comparing Fig. 1(a)-(c), the grain size in the fine grain region of the sample V0.5 is larger than that of V0.4 and V0.28. The grain size of V0.4 and V0.28 are nearly equivalent. Fig. 1(d)-(f) are enlarged views of Fig. 1(a)-(c). As shown in Fig. 1(e)-(f), it can be found that the grain size in the coarse grain regions of the sample V0.5 is almost equal to that of the sample V0.4. Similarly, the same conclusions as above can be obtained after comparing Fig. 1(g)-(i), which are presented the YZ plane microstructures of the specimens.

The XRD patterns are shown in Fig. 2(a). Only peaks related to  $\gamma$ -Fe were found in the XRD patterns. It can be confirmed that Fe-Mn-Al-C alloys are mainly composed of  $\gamma$ -Fe. Meanwhile, it's clear that the intensity of diffraction peaks of each sample is a little difference, especially for the sample V0.5. It indicates that the grain orientations of SLM parts are inconsistent due to the different scanning speeds, which lead to different linear energy input. The average microhardness of them is 472.3 HV<sub>0.1</sub>, 523.4 HV<sub>0.1</sub>, 540 HV<sub>0.1</sub>, respectively as displayed in Fig. 2(b). As mentioned above, the cellular grain size of the sample V0.28 is the smallest in these three samples, hence, its microhardness is the highest. On the contrary, the average microhardness of the sample V0.5 is the lowest among these specimens with a coarse microstructure. The COF-Time profiles and wear rate are revealed in Fig. 2(c)-(d), respectively. It can be observed that the average COF of the sample V0.5 is only 0.3, while, V0.4 and V0.28 are 0.56 and 0.58, respectively. During the wear process, the load and the size of the ball used as counterpart was kept in a balance value, samples V0.28 and V0.4 with higher hardness presence more debris and pits (as shown in Fig. 3), which increase the roughness of the worn surface, and then increase the COF. As the microhardness of the V0.5 is the lowest amongst the three samples, its average COF is the lowest. Correspondingly, as shown in Fig. 2(d), the wear rate of V0.5 is

$9.05 \times 10^{-6} \text{ mm}^3/(\text{N}\cdot\text{m})$ , while V0.4 and V0.28 are  $18.34 \times 10^{-6} \text{ mm}^3/(\text{N}\cdot\text{m})$  and  $17.57 \times 10^{-6} \text{ mm}^3/(\text{N}\cdot\text{m})$ , respectively. Since its microhardness is already at a relatively high level, at this moment the key factor determining the wear rate is the COF, therefore, the wear rate of V0.5 is the smallest. Meanwhile, because of the almost similar microhardness of V0.4 and V0.28, their COF and wear rates are also almost similar.

Fig. 3(a)-(c) displays the worn surface morphology of the SLM parts. It can be observed that the worn track of sample V0.5 is relatively flat and smooth with no obvious cracks. However, obvious craters and cracks are found at the worn track of samples V0.4 and V0.28. Besides, some scratches distributed along the friction direction are observed, especially in sample V0.28. The reason for these phenomena is also that the hardness of the V0.4 and the V0.28 is higher than the V0.5. In the process of friction, the abrasive particles are affected by compressive stress and shear stress. Abrasive wear is in the case of hard particle and soft material and for soft particle the wear can be adhesive. Therefore, the wear mechanism of sample V0.5 is mainly abrasive wear and adhesive wear [11], and its worn track is relatively smooth, which can also be proved by its 3D surface topography (Fig.3(g)). Owing to the hardness of samples V0.4 and V0.28 are both similar, which are higher than that of sample V0.5. Hence, not only abrasive wear but also abrasive wear that produces grooves occurred during the friction process of these two samples [12]. As a result, the craters have remained in their worn track, which can also be observed from their 3D surface topography (Fig.3(h), (i)).

#### 4 Conclusion

- (1) The microstructures of Fe-Mn-Al-C alloys are composed of fine grains, such as equiaxed grains, and coarse grains, i.e. columnar dendrites. And this alloy is mainly composed of  $\gamma$ -Fe.
- (2) The microhardness exhibited an increasing tendency with the decrease of laser scanning

speeds, illustrating the highest microhardness value at 0.28 m/s. which achieves 540 HV<sub>0.1</sub>.

- (3) The sample V0.5 manufacturing at the highest speed has the lowest COF (0.3). Its wear mechanism is mainly abrasive wear and adhesive wear. **The wear mechanism of the samples V0.4 and V0.28 is not only abrasive wear but also abrasive wear that produces grooves, which generates a large number of grooves during the wear test.**

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## Figure Captions

Fig.1: Microstructures of the XY planes: (a) V0.5; (b) V0.4; (c) V0.28; and (d-f) enlarged view, and YZ plane: (g-i): the V0.5, V0.4, V0.28 sample.

Fig. 2: (a) XRD patterns; (b) microhardness; (c) COF -Time profile; (b) wear rate.

Fig. 3: Worn surface morphology of (a-c): V0.5, V0.4, V0.28 sample, and (d-f) enlarged view; 3D surface topography of (g-i): V0.5, V0.4, V0.28 sample.



