Short-time induction treatment to improve fatigue strength and wear resistance of Ti-6Al-4V alloy formed by laser powder bed fusion

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Although Ti-6Al-4V alloy which is a typical α+β type titanium alloy has high specific strength and excellent corrosion resistance, it is inferior to wear resistance and formability comparing with the other metals. The usage of laser powder bed fusion (LPBF) can allow us to flexibly form Ti-6Al-4V alloy products with complex shapes. However, the fatigue strength of the titanium alloy fabricated by LPBF is significantly low due to stress concentration induced by surface roughness and molding defects generated inside. In this study, we attempted to simultaneously improve the fatigue strength and the wear resistance of Ti-6Al-4V alloy fabricated by LPBF through short-time induction heating (60 s) in air. The obtained results showed that the microstructural control and the formation of the surface hardened layer with the above heat treatment were markedly effective to improve the fatigue strength and the friction-wear properties.

Keywords: *laser powder bed fusion, Ti-6Al-4V alloy, fatigue strength, wear resistance, short-time induction heating*

1. Introduction

Although Ti-6Al-4V alloy which is a typical α+β type titanium alloy has high specific strength and excellent corrosion resistance, it is inferior to wear resistance and formability comparing with the other metals. The usage of laser powder bed fusion (LPBF), one of the three-dimensional additive manufacturing methods, is effective to overcome the above disadvantage of Ti-6Al-4V alloy concerning formability. However, Ti-6Al-4V alloy fabricated by LPBF has a serious problem of low fatigue strength due to stress concentration induced by surface irregularities and molding defects generated inside [1)]. In our previous paper, we showed that the short-time induction heat treatment we developed is very effective to improve the fatigue strength of Ti-6Al-4V alloy fabricated by LPBF [2)]. In this study moreover, we attempted to simultaneously improve its fatigue strength and friction-wear properties through applying short-time induction heating (60 s) in air.

2. Materials and experimental methods

In this study, the following two materials were used: A-material (as-formed material) which was formed in an argon atmosphere by LPBF with Ti-6Al-4V alloy powders, and A-IQ material which was induction-heated at 1323 K for 60 s in air and then water-quenched (IQ treatment). For comparison, the wrought material of Ti-6Al-4V alloy (W material) was used. The specimen surfaces of W material were finished as the mirror surfaces.

The surface feature of each material was observed by scanning electron microscopy (SEM) and its microstructure was examined by electron backscatter diffraction (EBSD) analysis. The fatigue tests were carried out by a plane bending fatigue machine (R=-1). The friction-wear tests were conducted using a pin-on-disk type friction-wear testing machine shown in Fig. 1. In the tests, the specimens with the circular arc surfaces were on the pin side and the round discs made in alumina were used as the mating materials. After the tests, the sliding parts were observed by a laser microscope.

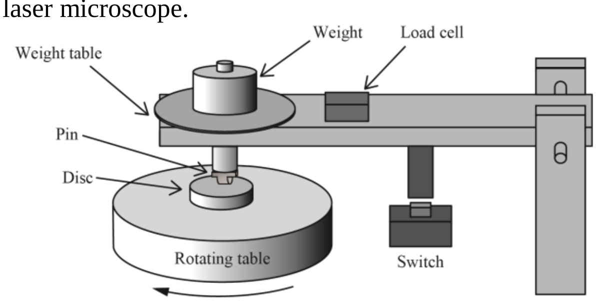

Fig. 1 Illustration of friction-wear testing machine.

3. Results and discussion

3.1 Microstructure

Figure 2 shows the surface features of W, A and A-IQ materials. Figure 3 shows the phase maps obtained near the surfaces on the cross-sections of W, A and A-IQ materials. The phase map of W material showed that its microstructure was composed of the two phases, that is, the α and β phases. On the surface of A material (Fig. 2), the almost entire particles retained their shapes without melting and particle-like unevenness was observed. As understood from its phase map (Fig. 3), the acicular α' martensite was generated by rapid cooling during LPBF. Although the other black regions directly meant the ones in which no EBSD data were obtained, they were considered to be the regions in which the metastable β-phase remained if based on our previous study [3)].

The particle-like irregularities were also observed on the surface of A-IQ material and its maximum undulation, Wz, was almost the same to that of A material (Fig. 2). From the phase map of A-IQ material, it was understood that the α phase existed near the surface since oxygen and nitrogen, stabilizers of the α phase, diffused from the surface during the heat treatment in air. The material was water-quenched after heating at the temperature over the β transformation temperature, the acicular α' martensite in the substrate became more fine. Moreover, it was estimated that the

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amount of the metastable β phase was increased because of rapid cooling by water-quenching.

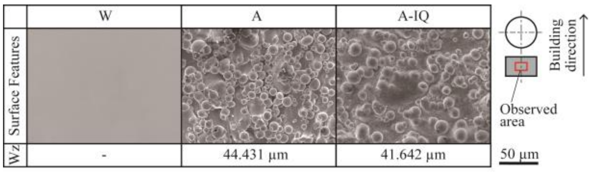

Fig. 2 Surface features of W, A and A-IQ materials.

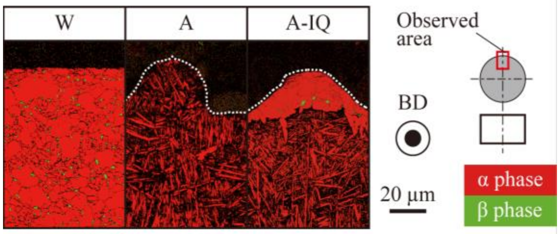

Fig. 3 Phase maps obtained near the surfaces on the cross-sections of W, A and A-IQ materials.

3.2 Fatigue properties

Figure 4 shows the S-N curves of W, A and A-IQ materials. The fatigue strength of A material was significantly lower than that of W material since the stress concentration at the bottom of the surface undulation accelerated the initiation of fatigue cracks.

The IQ treatment was markedly effective to improve the fatigue strength. Namely, this heat treatment improved the fatigue strength of A material from 80 MPa to 440 MPa and the improvement ratio reached 450 % in fact. Our previous paper reported that the fatigue strength of notched specimens of Ti-6Al-4V alloy was markedly improved by short-time heating and quenching since the propagation of cracks from the bottoms of notches was strongly arrested by the stress-induced transformation of the metastable β phase existing near the surface [4]. In addition to this, we reported that high compressive residual stress was induced by the IQ treatment and it can contribute to improve the fatigue strength [5]. From the above, it can be thought that the causes for the marked improvement of the fatigue strength with the IQ treatment were also the crack closure resulting from the stress-induced transformation of the metastable β phase and high compressive residual stress induced by quenching from high temperature.

3.3 Wear resistance

Figure 5 shows the sliding surfaces of all materials observed after the friction-wear tests. In W material, the sliding surface evenly wore and a lot of wear line were observed on it. On the other hand, numerous particles that had not completely melted remained as protrusions on the sliding surface of A material. Therefore, only such protrusions wore and the speckled wear marks were observed. In the case of A-IQ material, the sizes of the speckled wear marks became significantly smaller due to the formation of the hardened layer and the wear resistance greatly improved. Furthermore, the coefficient of friction was reduced to 0.17 by the decrease in the true contact area. The above results clearly showed that IQ treatment was markedly effective not only to improve the wear resistance but also to reduce the coefficient of friction.

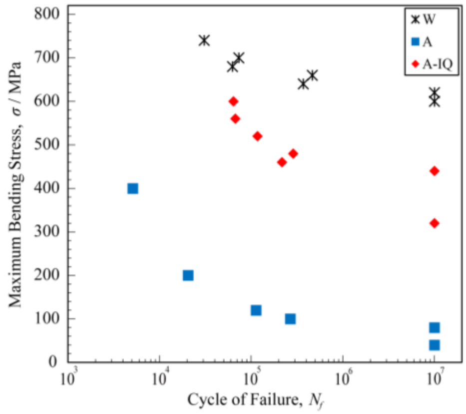

Fig. 4 S-N curves of W, A and A-IQ materials.

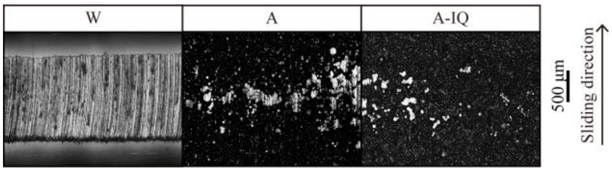

Fig. 5 Features of sliding surfaces of W, A and A-IQ materials.

4. Summary

In this study, we investigated the effect of the IQ treatment on the fatigue strength and the friction-wear properties of Ti-6Al-4V alloy fabricated by LPBF. It was shown that the IQ treatment was markedly effective to improve the fatigue strength and the improvement ratio reached 450 %. Moreover, the remained numerous particles that had not completely melted during LPBF were hardened by the IQ treatment. As a result, the wear resistance improved and the coefficient of friction greatly reduced due to the decrease in the true contact area.

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