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COMPARISON OF PEENING EFFECT BETWEEN ADDITIVE MANUFACUTRED AND DRAWING TITANIUM ALLOY

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Abstract

Although additively manufactured (AM) metals are attractive materials, their remarkable weak fatigue properties are an obstacle to their practical application. Thus, post-processing to improve their fatigue properties is required. In the present study, powder bed fusion using laser sintering titanium alloy, i.e., PBF-LS/Ti6Al4V was treated by shot peening (SP), submerged laser peening (SLP), cavitation peening (CP), and fine particle bombarding (FPB), then the fatigue properties were investigated by a torsional fatigue test, comparing with drawing Ti6Al4V. It was revealed that the fatigue strength at 10^7 was 446 ± 5 MPa for PBF-LS/Ti6Al4V treated by FPB+CP, 359 ± 9 MPa for LS/Ti6Al4V treated by SLP and 457 ± 22 MPa for drawing Ti6Al4V treated by SLP, whereas it was 210 ± 10 MPa for as-built (AB) PBF-LS/Ti6Al4V and 346 ± 26 MPa for non-peened drawing Ti6Al4V. Namely, the fatigue strength of PBF-LS/Ti6Al4V treated by FPB+CP exceeded that of non-peened (NP) drawing Ti6Al4V.

Keywords additive manufacturing, fatigue strength, residual stress, cavitation peening

Introduction

AM metals such as PBF-LS/Ti6Al4V are useful metals for medical implants, as it can be formed from computer-aided design/computer-aided manufacturing data directly. However, the fatigue properties of PBF-LS/Ti6Al4V are considerably weak, comparing with drawing Ti6Al4V, those are obstacle at the practical applications of PBF-LS/Ti6Al4V. Then, the post-processing for the improvement of fatigue properties of PBF-LS/Ti6Al4V is required.

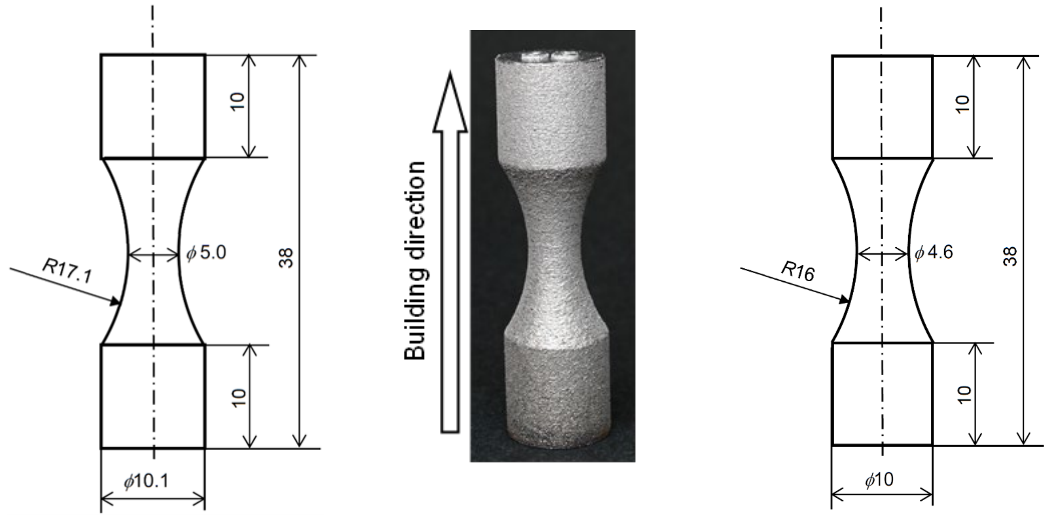
It was reported that mechanical surface treatments such as SP improve the fatigue strength of PBF metals [1-3]. Hot isostatic pressing (HIP) can reduce the crack propagation rate [4, 5] and improve fatigue properties [6-9]. However, HIP cannot reduce or remove surface defects [10]. Thus, it is necessary to remove surface defects and/or reduce surface roughness using other methods such as cavitation abrasive surface finishing (CASF) [11-13], ultrasonic cavitation abrasive finishing (UCAF) [14] and hydrodynamic cavitation abrasive finishing (HCAF) [15,16]. A peening method using a pulsed laser, that is laser peening (LP) or laser shock peening, has been developed, and LP also improved the fatigue strength of PBF/Ti6Al4V [3,13,16-23].

In the case of LP, there are two types. The first is performed using a relatively high-energy pulsed laser, and a water film is formed on the target materials [24-26]. In the second method, the target is placed in a water-filled chamber and a pulsed laser of several hundred microjoules irradiates to the target [21,27,28], and it is called as SLP in the present paper. At SLP, a bubble is generated after laser ablation (LA), and the bubble behaves like a cavitation bubble, which produces impact at bubble collapse. Then, SLP is a kind of CP using the pulsed laser [21,29]. A spherical bubble collapse near solid boundary generating a microjet [30] is very famous, however, impact induced by a hemispherical bubble on a solid boundary is more intense comparing with the microjet-type collapse [31,32]. In the case of conventional CP, a submerged high-speed water jet is used for generation of cavitation [21,33,34] and used cavitation is vortex cavitation [35,36]. As fine particle bombarding (FPB) also improved the fatigue strength of PBF-LS/Ti6Al4V [37,38], the effect of FPB on the fatigue properties of PBF-LS/Ti6Al4V was also investigated.

In the present study, to demonstrate the improvement of fatigue strength of AB PBF-LS/Ti6Al4V by post-processing beyond that of drawing Ti6Al4V, AB PBF-LS/Ti6Al4V was treated by SP, CP, SLP, FPB and their combination process. The fatigue properties of PBF-LS/Ti6Al4V with and without post-processing was comparing with drawing Ti6Al4V.

Materials and Experimental Procedures

Figure 1 shows the geometry of specimen for torsional fatigue test. The specimens were additively manufactured by direct metal laser melting using EOS M290 at standard condition: the laser power, the laser spot diameter and the layer thickness were 400 W, 100 μm and 60 μm, respectively. In accordance with ISO/ASTM 52900:2021 standards, this paper refers to it as power bed fusion using a laser sintering PBF-LS. The diameter of used particle of Ti6Al4V was about 30 μm. Minimum diameter of test section was 5.0 mm for PBF-LS/Ti6Al4V and 4.6 mm for drawing Ti6Al4V, to investigate the effect of surface defects of PBF-LS/Ti6Al4V, which were located with 0.2 mm, by FPB. In the case of PBF-LS/Ti6Al4V, it was annealed at 923 K for 3 hours to remove residual stress, then solution annealing was performed at 1208 K for 105 minutes and cooled with argon gas. After solution annealing, the bars were aged at 978 K for 2 hours and cooled with argon gas. The cooling rate from the solution anneal and aging anneal steps were about 450 K/h and 410 K/h, respectively. After these heat treatments, the diameter of the grip section was reduced to 9.995 ± 0.005 mm using a lathe to hold by an attachment tightly. In the case of drawing Ti6Al4V, same solution annealing and ageing heat treatments were carried out.



(a) Geometry of PBF-LS/Ti6Al4V (b) Photo of AB PBF-LS/Ti6Al4V (c) Geometry of drawing Ti6Al4V

Figure 1. Specimen for torsional fatigue test.

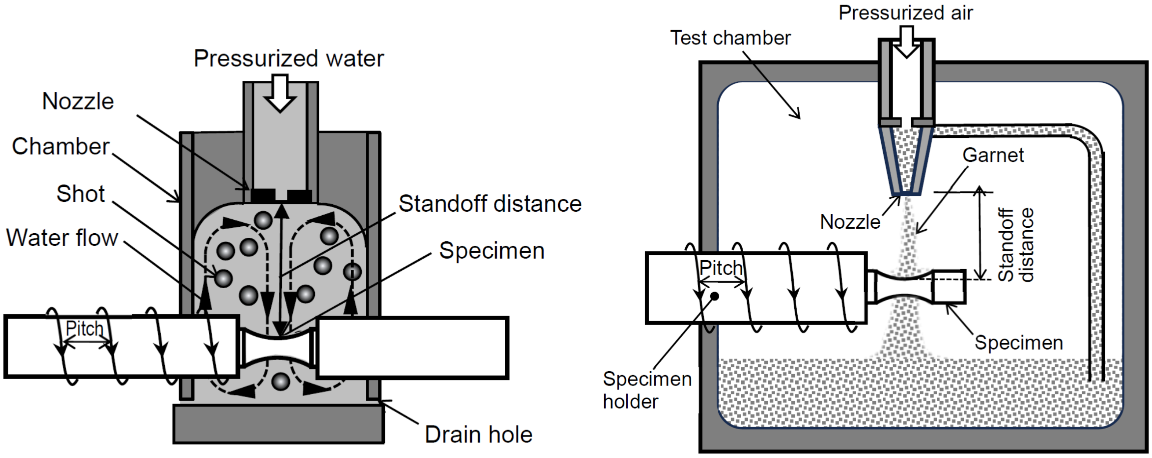
Figure 2 (a) shows test section of SP system. At SP, 500 stainless steel shots 3.2 mm in diameter were installed in the chamber, and they accelerated by water jets through 0.8 mm three holes located 16 mm in pitch diameter, and recirculated. The injection pressure of the jet was 15 MPa. During SP, the specimen was moved in axial direction with rotation as shown in Fig. 2 (a). The pitch was 2 mm. The processing time per unit length t_p was defined by Eq. (1), wherein n and v_a denote the number of scans and the axial speed.

$$t_p = \frac{n}{v_a} \tag{1}$$

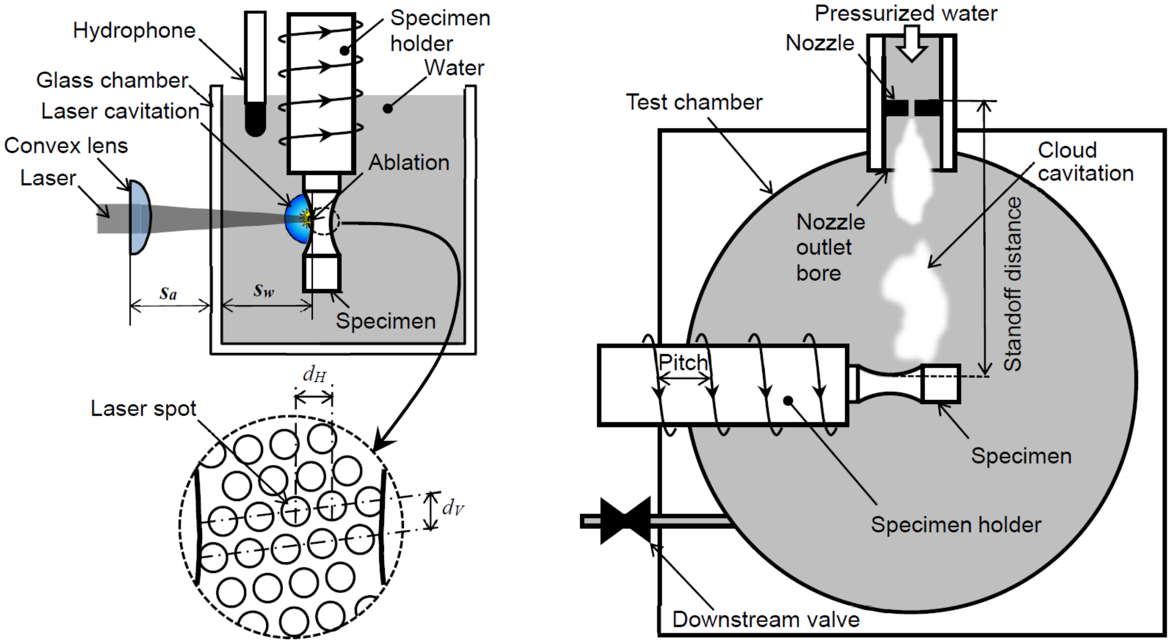
Figure 2 (b) illustrates the test section of FPB system[38]. The garnet #150 was used for FPB. The garnet was accelerated by pressurized air of 0.7 MPa. The specimen was moved in axial direction with rotation as same as SP system. The definition of t_p was the same as Eq. (1).

Figure 2 (c) reveals the test section of SLP system. At SLP, a Nd:YAG laser with Q-switch was used. The wave length, the repletion frequency, the pulse energy and the pulse width were 1064 nm, 10 Hz, 0.35 J and 6 ns. The standoff distances from the final convex lens to the specimen surface in air s_a and in water s_w were set at 67 and 34 mm, as same as previous report [3]. The specimen with the holder was moved upward with rotation by two stepping motors. The laser pulse density ρ_L was controlled by horizontal distance d_H and vertical distance d_V, and it was defined by Eq. (2). Note that ρ_L was defied at the minimum diameter of the test section of specimen.

$$\rho_L = \frac{1}{d_H\, d_V} \tag{2}$$



(a) Test section of SP system (b) Test section of FPB system [38]



(c) Test section of SLP system (d) Test section of CP system

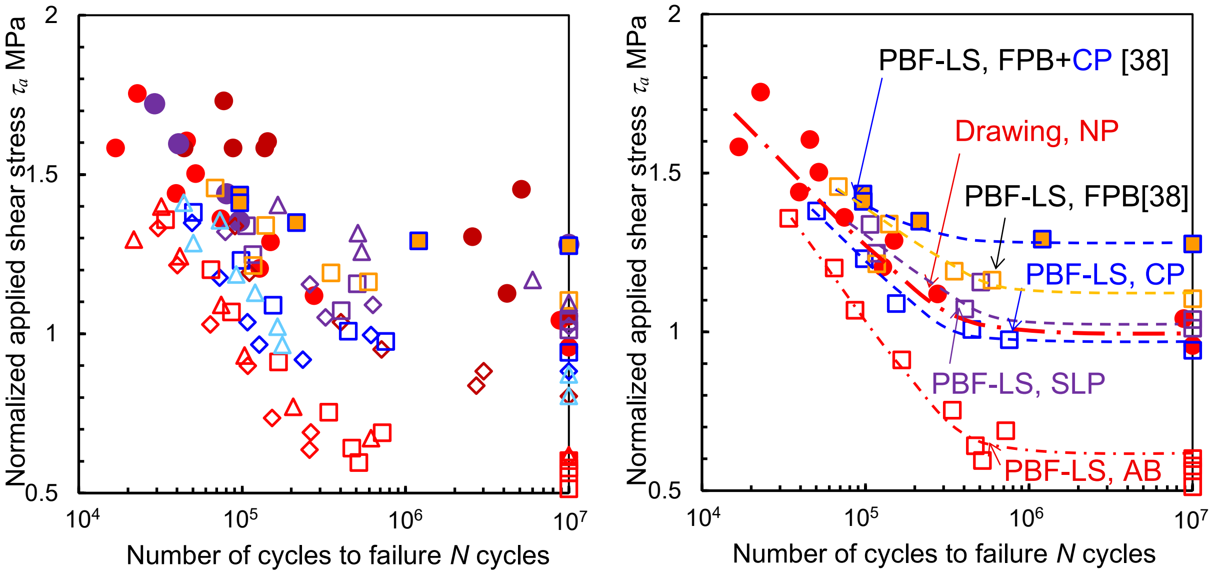
Figure 2. Test section for post-processing system.

Figure 2 (d) describes the test section of CP system. The specimen was placed in the water filled chamber. The cavitation was generated by injecting the high-speed water jet into the chamber. The injection pressure of the jet was 30 MPa and the diameter of nozzle was 2 mm. The specimen was moved as same as SP and FPB.

Results

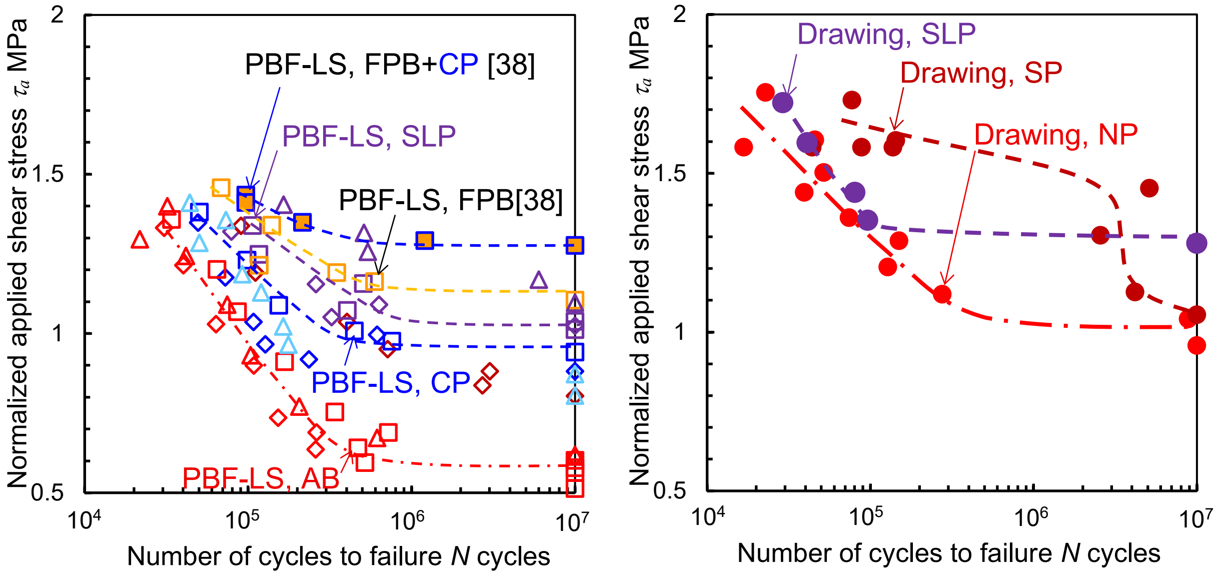
Figure 3 shows the *S-N* curves for NP, SP and SLP of drawing Ti6Al4V, and for AB, CP, SLP, FPB and FPB+CP of PBF-LS/Ti6Al4V, with the result of previous papers [3,16,38]. The symbol and its color legend of Fig. 3 are shown in Table 1. The fatigue strength at $N_f = 10^7$, τ_f, was obtained by Little's method [39] (see Table 1). The applied shear stress τ_a was normalized by τ_f of NP drawing Ti6Al4V, i.e., 347 MPa. Fig. 3 (a) reveals all *S-N* data. Fig. 3 (b) shows the present data of PBF-LS and drawing NP. As shown in Fig. 3 (b) and Table 1, τ_f of SLP, FPB and FPB+CP of PBF-LS [38] were larger than NP drawing, whereas τ_f of AB PBF-LS was about 60% of NP drawing. Fig. 3 (c) illustrates the *S-N* data of present results with *S-N* data of previous reports [3],[16]. Even though the specimens of the different lots were used, the tendency of post-processing is similar. Fig. 3 (d) shows the S-N of drawing data with and without peening. As shown in Fig. 3 (d), the fatigue life of SP at relatively high applied τ_a was better than that of SLP, however, τ_f of SLP was better than that of SP.

In Table 1, relative τ_f, which was obtained from τ_f divided τ_f of NP or AB, was also shown. When relative τ_f was compared with drawing and PBF-LS, it was 1.32 for SLP of drawing and



(a) All *S-N* data

(b) *S-N* of present PBF-LS and drawing NP



(c) *S-N* of all data for PBF-LS

(d) *S-N* of drawing data with and without peening

Figure 3. S-N curves of tested Ti6Al4V.

Table 1 Fatigue strength τ_f of tested Ti6Al4V

Symbol	Material	Treatment	τ_f [MPa]	Normalized τ_f	Relative τ_f
●	Drawing	NP	347 ± 26	1	1
●		SP	379 ± 22	1.09	1.09
●		SLP	457 ± 22	1.32	1.32
◇	PBF-LS [3]	AB	217 ± 7	0.63	1
◇		SLP	361 ± 8	1.04	1.66
◇		CP	313 ± 11	0.90	1.44
◇		SP	285 ± 10	0.82	1.31
□	PBF-LS	AB	210 ± 10	0.61	1
□		CP	333 ± 10	0.96	1.59
□		SLP	359 ± 9	1.03	1.71
□		FPB[38]	393 ± 18	1.13	1.87
■		FPB+CP[38]	446 ± 5	1.29	2.12
△	PBF-LS [16]	AB	224 ± 16	0.65	1
△		SLP	393 ± 22	1.13	1.75
△		HCAF	319 ± 28	0.93	1.45

1.71 for SLP of PBF-LS. And also, it was 1.09 for SP of drawing and 1.31 for SP of PBF-LS [3]. Namely, relative τ_f of SLP and SP of PBF-LS was larger than that of drawing specimen. Then, it can be concluded that peening effect on PBF-LS was larger than that of drawing.

To investigate the reason of the fatigue strength improvement by post-processing, Fig. 4 illustrates the relation between the surface residual stress σ_R and τ_f for drawing Ti6Al4V and PBF-LS/Ti6Al4V. The σ_R was measured by X-ray diffraction method. The symbols in Fig. 4 were as same as symbols in Fig. 3 and Table 1. As shown in Fig. 4, It can be seen that the greater the compressive residual stress, the greater the fatigue strength. The correlation factor r between σ_R and τ_f was 0.581. When the number of datasets was 15 at r = 0.581, the non-correlation probability was 2.4%, and it was smaller than 5%. Then, it can be said that the relation between σ_R and τ_f was significant. Therefore, it can be concluded that the main factor contributing to the improvement in fatigue strength by post-processing in both drawing Ti6Al4V and PBF-LS/Ti6Al4V is surface residual stress.

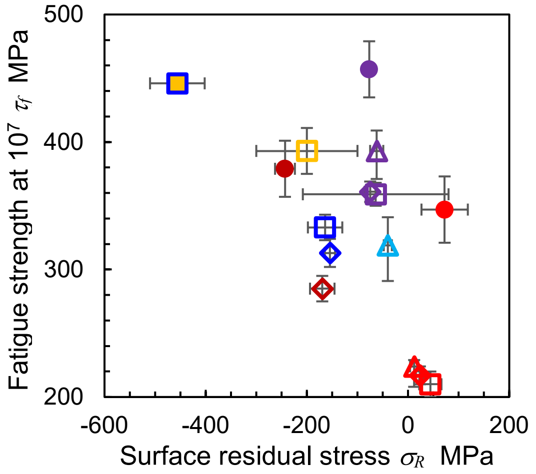


Figure 4. Relation between surface residual stress and fatigue strength for tested Ti6Al4V.

Conclusions

To compare peening effect between drawing Ti6Al4V and PBF-LS/Ti6Al4V, drawing Ti6Al4V and PBF-LS/Ti6Al4V were treated by post-processing such as SP, SLP and CP. The fatigue properties were evaluated by the torsional fatigue test. The results are summarized as follows.

(1) The fatigue strength of AB PBF-LS/Ti6Al4V is enhanced by post-processing beyond NP drawing Ti6Al4V, whereas the fatigue strength of AB PBF-LS/Ti6Al4V is 60% of NP drawing Ti6Al4V.

(2) The peening effect on AB PBF-LS/Ti6Al4V is larger than that of NP drawing Ti6Al4V.

(3) The main factor on improvement of fatigue strength by post-processing for both drawing Ti6Al4V and PBF-LS/Ti6Al4V is the introduction of compressive residual stress into surface.

Acknowledgments

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Nomenclatures

AB	As-built
AM	Additive manufacturing
CASF	Cavitation abrasive surface finishing
CP	Cavitation peening
FPB	Fine particle bombarding
HCAF	Hydrodynamic cavitation abrasive finishing
HIP	Hot isostatic pressing
LA	Laser ablation
LP	Laser peening
LS	Laser sintering
NP	Non-peened
PBF	Powder bed fusion
SLP	Submerged laser peening
SP	Shot peening
UCAF	Ultrasonic cavitation abrasive finishing

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