Improvement of Fatigue Strength of Additive Manufactured Metals by Solid-Liquid-Gas Interfacial Phenomena Induced by Pulse Laser

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Abstract. Although additive manufactured (AM) metals are attractive materials, the fatigue strength of AM metals are considerably weak comparing with that of wrought materials. The mechanical surface treatment such as shot peening can improve the fatigue strength of metallic materials. Recently, a novel mechanical surface treatment using solid-liquid-gas interfacial phenomena induced by pulse laser has been developed. In the present paper, in order to demonstrate the improvement of fatigue strength of AM metals by solid-liquid-gas interfacial phenomena, titanium alloy Ti6Al4V manufactured by electron beam melting EBM was treated by submerged pulse laser and tested by a plane bending fatigue test. The key factors were investigated by evaluating the relation between the fatigue properties and mechanical properties of the surface treated by submerged laser peening, cavitation peening and shot peening.

1. Introduction
Metallic materials manufactured additive manufacturing (AM) processing is attractive processing for biomedical and aero-space area, as it is easy to make components directly from computer-aided design CAD with weight saving and design freedom without having to consider machining. Unfortunately, the fatigue strength of AM metals are considerably weak comparing with that of wrought materials [1, 2]. One of methods to improve the fatigue strength of AM metals is mechanical surface treatment [1, 3-5]. Thus, it is necessary to investigate the improvement of AM metals by mechanical surface treatment.

One of most popular mechanical surface treatment is shot peening. Shot peening can improve fatigue strength and elongate fatigue life. However, the increase of surface roughness by shot collisions sometimes decreases fatigue properties. In these days, novel peening methods, in which shots are not required, such as cavitation peening [6, 7] and laser peening [8-11] have been developed. It is worthwhile to investigate effect of improvement of fatigue strength by cavitation peening and laser peening.

As shown in Figure 1, in the case of mechanical surface treatments, the local plastic deformations produced by solid/liquid collision impacts or shock wave impacts were generated, and they changed mechanical properties such as residual stress, yield stress, hardness, roughness etc. However, the quantitate effects of each factor are in “black box”, thus conventional way to enhance fatigue properties by mechanical surface treatments is a kind of try and error. Once inside of “the black box” was clarified, the fatigue properties can be enhanced effectively.
Figure 1. Surface mechanics design on improvement of fatigue properties by mechanical surface treatment considering mechanical properties.

In the case of cavitation peening and submerged laser peening, phase change phenomenon from liquid-phase to gas-phase is used to generate the local plastic deformations. Figure 2 shows (a) the typical aspect of bubble induced by a pulse laser and (b) output signal from PVDF sensor [12, 13] were shown [7]. After laser ablation, a bubble, i.e., gas-phase, was developed from water, i.e., liquid-phase, and impact was produced to the solid surface at bubble collapse. As the bubble induced by pulse laser produced the impact at bubble collapse, the bubble was named as “laser cavitation”. As shown in Fig. 2 (b), the impact induced by laser cavitation was larger than that of laser ablation. Namely, submerged laser peening is a kind of mechanical surface treatment using solid-liquid-gas interfacial phenomena induced by pulse laser.
In the present paper, in order to demonstrate the improvement of AM metals by submerged laser peening and cavitation peening, the titanium alloy Ti6Al4V manufactured by electron beam melting EBM was treated by cavitation peening, submerged laser peening and shot peening, and tested by a plane bending fatigue test. And also, in order to make clear the inside of “the black box”, the duralumin A2017-T3 was treated by submerged laser peening, cavitation peening and shot peening, and tested by a load controlled plane bending fatigue test. As the surface of Ti6Al4V manufactured by EBM was very rough, and it is very difficult to measure the crack propagation rate caused by the fatigue, thus the duralumin treated by the mechanical properties were examined. The mechanical properties of duraluminum such as residual stress, surface roughness and crack propagation rate were evaluated.

2. Experimental Facilities and Procedures

Figure 3 illustrates a schematic diagram of submerged laser peening system in which solid-liquid-gas interfacial phenomena induced by a pulse laser was used for mechanical surface treatment. Q-switched Nd:YAG laser was used as source of the pulse laser. The fundamental harmonic and the second harmonic of a Nd:YAG laser are 1064 nm and 532 nm. The maximum energy at 1,064 nm was 0.35 J. The beam diameter, the pulse width and the repetition frequency of the laser pulse were 6 mm, 6 ns and 10 Hz, respectively. In order to avoid damage of glass chamber, the diameter of the laser beam was expanded by concave lens and then focused into the water using two convex lenses. The pulse density for the treatment of Ti6Al4V manufactured by EBM was 5 pulse/mm² considering previous report [7]. The standoff distances in air $S_d$ and in water $S_w$ were optimized by measuring arc height of metallic plate. In order to compare the other peening method, the specimens were treated by shot peening and cavitation peening. The used shot peening system was a recirculating shot peening accelerated by a water jet which injection pressure was 12 MPa [14]. Note that the water jet without shot could not introduce compressive residual stress.

Figure 3. Schematic diagram of submerged laser peening system. The pulse laser was focused on the solid surface of specimen which was placed in water.

In the case of cavitation peening, a submerged water jet was used to generate cavitation (see Figure 4). The injection pressure of the jet was 30 MPa and the nozzle throat diameter was 2 mm. In order to enhance...
cavitation aggressively, the cavitator and the guide pipe were installed in the nozzle and their geometries were optimized. The cavitator was feeding the cavitation nuclei and the guide pipe enhance cavitation aggressively by controlling vertical flow around the jet. Even though the submerged water jet peening, the water column in the jet center can produce the plastic deformations. The mechanical surface treatment using water column impacts is called as “water jet peening”. In the case of water jet peening, a large injection pressure is required. On the other hand, in the case of cavitation peening, the relatively low injection pressure with large nozzle is suitable. Note that the peening intensity of cavitation peening is larger than that of water jet peening. The peening condition of cavitation peening is distinguished by the standoff distance, which was defined by the distance from nozzle to the specimen surface. At the present experiment, it was 262 mm.

![Diagram of cavitation peening system](image)

**Figure 4.** Schematic diagram of cavitation peening system. The submerged water jet was injected into a water filled chamber.

In order to demonstrate the improvement of fatigue strength of AM metals by mechanical surface treatment, Ti6Al4V manufactured by EBM was treated by above mentioned submerged laser peening system. The EBM conditions were follows. The averaged diameter of the powder, the spot size of electron beam for selectively melting and the stacking pitch were 75 μm, 0.2 mm and 90 μm, respectively. The solution heat treatment was carried out at 1,208 K at vacuum condition for 105 minutes then argon gas cooling. After that, aging treatment was done at 978 K at vacuum condition for 2 hours then argon gas cooling. The stress ratio at the plane fatigue test was \( R = -1 \). In order to investigate the comparison of peening methods on the improvement fatigue strength, the specimen was also treated by cavitation peening and shot peening [4].

In order to investigate the relation between fatigue properties and mechanical properties, specimen made of duralumin JIS A2017-T3 was treated by submerged laser peening, cavitation peening and shot peening [15], and crack propagation rate, residual stress, surface roughness and hardness were measured. The crack propagation rate was evaluated by using a load controlled plane bending fatigue tester. The applied stress \( \sigma_a \) was 200 MPa. Peening intensity was evaluated by curvature \( \kappa \) of duralumin plate JIS A2017-T3 of 3 mm thickness treated by various peening.

### 3. Results

Figure 5 reveals the fatigue strength of titanium alloy Ti6Al4V manufactured by EBM. The fatigue strength was obtained by Little’s method [16]. The fatigue strength was 221 ± 11 MPa for the non-peened specimen, 371 ± 7 MPa after shot peening, 406 ± 11 MPa after cavitation peening and 450 ± 3 MPa after laser peening. Thus, the fatigue strength was improved by 68 % by shot peening, 84 % by cavitation peening and 104 % by submerged laser peening. Namely, mechanical surface treatments can improve fatigue strength of AM metals.
Figure 5. Improvement of fatigue strength of titanium alloy Ti6Al4V manufactured by EBM by means of shot peening, cavitation peening and submerged laser peening.

In order to investigate mechanical properties on the improvement of fatigue strength of light metallic materials by mechanical surface treatment, Figure 6 reveals the relation between the stress intensity factor range $\Delta K$ and crack growth rate $da/dn$ to show the fatigue property of peened material. Tested material was duralumin JIS A2017-T3. Figure 6 shows the range of $10^{-8} < da/dn < 10^{-6}$, in which Paris law was observed. As shown in Figure 6, peened data were shifted to right hand side or downward. When the constant $\Delta K$ condition was considered, the crack propagation rate was decreased by submerged laser peening LP, cavitation peening CP and shot peening SP. If the constant crack propagation rate was assumed, $\Delta K$ was shifted to right hand side by the peening. Note that the approximation line of non-peened specimen was described by the following Eq. (1).

$$\frac{da}{dn} = 1.155 \times 10^{-11} \Delta K^{3.7622}$$  \hspace{1cm} (1)

Figure 6. Improvement of fatigue property treated by submerged laser peening LP, cavitation peening CP and shot peening SP comparing with non-peened NP by describing the relation between stress intensity factor range and crack growth rate (Duralumin plate JIS A2017-T3).

Table 1 shows mechanical properties of treated surface by shot peening SP, cavitation peening CP, submerged laser peening LP and hybrid peening HP with various peening intensity $\kappa$, comparing of non-peened NP. In the present paper, the hybrid peening is combined peening with different peening methods. For example, HP of LP0.4 $\rightarrow$ CP0.4 means that 1st peening was submerged laser peening at $\kappa = 0.4$ m$^{-1}$.
and 2nd peening was cavitation peening at $\kappa = 0.4 \text{ m}^{-1}$. As shown in Table 1, compressive residual stress was introduced by peening methods and the Vickers hardness was increased. When the peening intensity was increased, the maximum height of roughness profile was increased and it seems to be saturated. As grain size $D$ was decreased, the yield stress was increased with Hall-Petch law. And, the full width at half maximum $\beta$ of X-ray diffraction pattern was increased with $1/D$. Thus, $\beta$ was used as the parameter of inverse of grain size. As shown in Table 1, $\beta$ of shot peening was drastically increased with the increase of peening intensity. In the case of cavitation peening, $\beta$ was also increased with the increase of peening intensity. On the other hand, $\beta$ of laser peening was slightly increased with the increase of peening intensity, as submerged laser peening gave the thermal effect to the surface. As shown in Table 1, the number of cycles to failure $N_{f\text{exp}}$ was roughly increased by peening methods. The $N_{f\text{exp}}$ of submerged laser peening at $\kappa = 0.6$ of 0.2 J was 4.5 times larger than that of non-peened specimen. The $N_{f\text{exp}}$ of hybrid peening at LP0.4$\rightarrow$CP0.4 and CP0.4$\rightarrow$SP0.6 are 5 and 5.2 times larger than that of non-peened specimen. Namely, $N_{f\text{exp}}$ of the hybrid peening at optimum condition is larger than that of single peening at optimum condition.

Table 1. Mechanical properties of peened and non-peened specimens.

| Peening method | Peening intensity $\kappa$ m$^{-1}$ | Residual stress $\sigma_R$ MPa | Vickers hardness $H_v$ | Maximum height of roughness profile $R_z$ m | Full width at half maximum $\beta$ deg | Number of cycles to failure $N_{f\text{exp}}$ |
|---------------|------------------|-----------------|------------------|-----------------|-----------------|------------------|
| NP            | 0                | -20             | 130              | 7.55            | 1.80            | 21,423           |
| SP            | 0.2              | -175            | 150              | 19.5            | 1.89            | 16,629           |
|              | 0.4              | -212            | 149              | 35.2            | 1.98            | 22,733           |
|              | 0.6              | -275            | 167              | 26.7            | 2.08            | 61,634           |
|              | 0.8              | -248            | 177              | 29.1            | 2.33            | 69,817           |
| CP            | 0.2              | -204            | 142              | 17.4            | 1.89            | 14,620           |
|              | 0.4              | -214            | 154              | 35.9            | 1.91            | 18,848           |
|              | 0.6              | -288            | 154              | 38.5            | 1.95            | 65,645           |
|              | 0.8              | -297            | 160              | 56.7            | 1.98            | 18,149           |
| LP            | 0.4              | -222            | 171              | 13.8            | 1.91            | 76,852           |
|              | 0.6 (0.1J)       | -212            | 241              | 15.9            | 1.90            | 74,822           |
|              | 0.6 (0.2J)       | -205            | 220              | 19.6            | 1.91            | 95,883           |
|              | 0.8              | -211            | 278              | 19.0            | 1.92            | 39,620           |
| HP            | LP0.4$\rightarrow$CP0.4 | -238            | 325              | 21.9            | 1.92            | 107,533          |
|              | CP0.4$\rightarrow$LP0.4 | -271            | 207              | 50.2            | 1.96            | 58,208           |
|              | SP0.6$\rightarrow$CP0.4 | -241            | 138              | 44.8            | 2.06            | 44,659           |
|              | CP0.4$\rightarrow$SP0.6 | -219            | 147              | 32.1            | 2.11            | 112,331          |

4. Discussion

In order to key factors on the improvement of fatigue strength of light metallic materials by mechanical surface treatments, the relation between the fatigue life and the mechanical properties was investigated using the data of Figure 6 and Table 1. As Figure 6 was obtained by the test at $\sigma_a = 200 \text{ MPa}$, Eq. (1) is expressed by following Eq. (2) at $\Delta K = 18$, as $\Delta K = F \sigma_a \sqrt{\pi a}$. Here, $F$ is the constant.

$$\frac{da}{dn} = 1.155 \times 10^{-11} \times 0.09^{3.7622} \times \sigma_a^{3.7622} = 1.343 \times 10^{-15} \sigma_a^{3.7622}$$

When the residual stress $\sigma_R$ is considered, the compressive residual stress reduces the applied stress $\sigma_a$ at certain ratio $b$, thus Eq. (2) is described as follows.

$$\left(\frac{da}{dn}\right)' = 1.343 \times 10^{-15} (\sigma_a - b \sigma_R)^{3.7622}$$
As the estimated fatigue life \( N_{f_{\text{est}}} \) is proportional to inverse of Eq. (3), \( N_{f_{\text{est}}} \) can be obtained from Eq. (4), as \( H_v \) and \( \beta \) affective positively and \( R_z \) affects negatively. The \( b, c, d \) and \( e \) are constant, and these are obtained by a least square method. Note that the subscript \( _{NP} \) means the value of non-peened value and the subscript \( _P \) means the value of peened specimen.

\[
N_{f_{\text{est}}} = N_{f_{NP}} \frac{1}{1.343 \times 10^{-15} (\sigma_{\alpha} - b \sigma_{\sigma_{P}})^{2.7822}} \left( \frac{H_v}{H_v_{NP}} \right)^c \left( \frac{R_z_{NP}}{R_z_P} \right)^d \left( \frac{\beta_P}{\beta_{NP}} \right)^e \tag{4}
\]

The obtained \( b, c, d \) and \( e \) are 0.331, 1.138, 1.358 and 3.266, respectively. The calculated estimated number of cycles to failure \( N_{f_{\text{est}}} \) is shown in Table 2. Figure 7 reveals the relation between experimental number of cycles to failure \( N_{f_{\text{exp}}} \) and estimated number of cycles to failure \( N_{f_{\text{est}}} \). As the secondary crack was propagated in the peened specimen treated at the condition of \( R_z > 30 \mu m \), the symbol * was marked in Table 2 and the open circles were used for the data. As shown in Fig. 7, \( N_{f_{\text{est}}} \) is roughly proportional to \( N_{f_{\text{exp}}} \). The correlation constant of 11 points except \( R_z > 30 \mu m \) was 0.654, and the probability of non-correlation is 3 %. As it was less than 5 %, the relation between \( N_{f_{\text{exp}}} \) and \( N_{f_{\text{est}}} \) is significant. Namely, the proposed equation shown in Eq. (4) can estimate the fatigue life. Thus, it can be concluded that the fatigue life treated by the mechanical surface treatment is affected by the residual stress, surface roughness, Vickers hardness and grain size.

**Table 2.** Estimated number of cycles to failure \( N_{f_{\text{est}}} \). The symbol * revealed at the condition of \( R_z > 30 \mu m \).

| Peening method | Peening intensity \( \kappa \) m\(^{-1}\) | Estimated number of cycles to failure \( N_{f_{\text{est}}} \) |
|----------------|------------------|------------------|
| NP             | 0                | 21,423           |
| SP             | 0.2              | 24,761           |
|                | 0.4              | 17,785*          |
|                | 0.6              | 64,808           |
|                | 0.8              | 67,460           |
| CP             | 0.2              | 35,283           |
|                | 0.4              | 16,345*          |
|                | 0.6              | 33,467*          |
|                | 0.8              | 24,070*          |
| LP             | 0.2              | 25,603           |
|                | 0.4              | 72,127           |
|                | 0.6 (0.1J)       | 79,012           |
|                | 0.6 (0.2J)       | 51,396           |
|                | 0.8              | 75,187           |
| HP             | LP0.4→CP0.4      | 94,923           |
|                | CP0.4→LP0.4      | 27,700*          |
|                | SP0.6→CP0.4      | 17,690*          |
|                | CP0.4→SP0.6      | 26,213*          |
Figure 7. Relation between experimental number of cycles to failure $N_{f_{exp}}$ and estimated number of cycles to failure $N_{f_{est}}$. The open circle revealed the data of $Rz > 30 \mu m$.

5. Conclusions

In order to demonstrate the improvement of fatigue strength of additive manufactured metallic materials by mechanical surface treatment using pulse laser, titanium alloy Ti6Al4V manufactured by electron beam melting EBM was treated by submerged laser peening and tested by a plane bending fatigue test. And also the duralumin plate A2017-T3 was treated by the submerged laser peening, cavitation peening and shot peening in order to make clear the mechanical properties on the improvement of fatigue strength of light metallic materials by the mechanical surface treatment. The results obtained can be summarized as follows.

1. The fatigue strength of Ti6Al4V manufactured by EBM at $N = 10^7$ was improved by 104 % using submerged laser peening. Namely, mechanical surface treatment using solid-liquid-gas interfacial phenomena induced by pulse laser can improve the fatigue strength of the additive manufactured metallic material.

2. The other mechanical surface treatments such as cavitation peening using a submerged water jet and shot peening can also improve the fatigue strength of Ti6Al4V manufactured by EBM.

3. The estimation method for the fatigue life of light metallic materials enhanced by the mechanical surface treatments was proposed. It was revealed that main factors on the improvement of the fatigue life by the mechanical surface treatment were residual stress, surface roughness and grain size.

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