



Surface smoothing of additively manufactured Ti-6Al-4V alloy by combination of grit blasting and large-area electron beam irradiation

Togo Shinonaga¹ · Hiroya Kobayashi² · Akira Okada¹ · Toshiya Tsuji³

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Abstract

Additively manufactured (AMed) titanium products are typically produced by electron beam melting (EBM), since oxidation of titanium alloy surface can be suppressed in vacuum environment. The surface roughness of AMed titanium products becomes more than 200 $\mu\text{m Rz}$, and the very rough surface would lead to reduction in fatigue strength. Therefore, a post surface finishing process is required. Abrasive blasting is one of the common surface smoothing processes of AMed metal products. Large surface roughness can be decreased, and compressive residual stress can be introduced to the surface. However, there is a limitation to reduction of surface roughness to several $\mu\text{m Rz}$. On the other hand, it was recently found that AMed metal surface produced by powder bed fusion with laser beam could be smoothed by large-area electron beam (LEB) irradiation. However, it is difficult to smooth surface with large initial surface roughness, and a tensile residual stress may be generated on the surface. In this study, surface smoothing and change in residual stress of AMed titanium alloy (Ti-6Al-4 V) were proposed by combination of grit blasting and LEB irradiation. Surface roughness of AMed Ti-6Al-4 V alloy significantly decreases from 265 to about 2.0 $\mu\text{m Rz}$ by combination of grit blasting and LEB irradiation. Reduction rate of surface roughness by LEB irradiation linearly increases with decreasing mean width of blasted surface. Influence of the mean width on smoothing effect by LEB irradiation can be explained by thermo-fluid analysis. Moreover, tensile residual stress caused by LEB irradiation can be reduced when LEB is irradiated to blasted surface.

Keywords Additive manufacturing · Electron beam melting · Titanium alloy · Ti-6Al-4 V · Blasting · Large-area electron beam · Surface smoothing · Thermo-fluid analysis · Residual stress

1 Introduction

Additive manufacturing (AM) process for metal products has been developed recently. This process is suitable for producing three-dimensional (3D) objects with complex shapes such as porous structure, lattice structure, and metal

mold with complex cooling channel, as reported by Bennett et al. [1] and Guddati et al. [2]. Schmidt et al. [3] showed application of AM process by using laser beam in industry and academia. Powder bed fusion (PBF) and directed energy deposition (DED) have been commonly applied to produce the AMed metal products in the industry field [4, 5]. In the PBF process, metal powders are selectively melted and re-solidified by scanning the laser beam or electron beam (EB), layer by layer. Then, AMed metal products with relatively high shape accuracy can be produced by the PBF.

Titanium alloys such as Ti-6Al-4 V alloy have been widely applied for metal implants in human body, since they have excellent corrosion resistance and strength. Electron beam melting (EBM) is typically applied to producing AMed titanium alloy products, since oxidation of titanium alloy surface can be suppressed by EBM in vacuum environment [6]. Yan et al. [7] showed that three-dimensional mesh titanium scaffold can be produced by the EBM.

✉ Togo Shinonaga
shinonaga@okayama-u.ac.jp

¹ Faculty of Environment, Life, Natural Science and Technology, Okayama University, 3-1-1, Tsushima-Naka, Kita-Ku, Okayama-Shi, Okayama 700-8530, Japan

² Graduate School of Natural Science and Technology, Okayama University, 3-1-1, Tsushima-Naka, Kita-Ku, Okayama-Shi, Okayama 700-8530, Japan

³ SINTOKOGIO, LTD, 3-28-12, Meieki, Nakamura-Ku, Aichi, Nagoya-Shi 450-6424, Japan

Patient-specific titanium cellular meshes can be successfully fabricated according to a wide range of designs and modified directly from CAD data. However, in general, AMed metal products have rough surface, since relatively large beads are arranged on the surface of AMed metal products. In particular, the surface roughness of AMed metal products by EBM becomes more than 200 $\mu\text{m Rz}$, which is very large roughness. In addition, surface irregularities such as spatter and cavity are generated on the AMed metal surface. The rough surface and surface irregularities would lead to reduction in fatigue strength. Therefore, post surface finishing processes are required to smooth the surface of AMed metal products [8].

Abrasive blasting has been commonly applied for efficient surface finishing of AMed metal products. In this process, blasting media gives a large impact to the surface, and large surface roughness can be decreased efficiency. In addition, Zebrowski et al. [9] showed that surface topography of blasted surface is changed by blasting conditions and shape of blasting media such as shot media with circular shape and grit media with angular shape. In addition, compressive residual stress can be also introduced to the blasted surface, and fatigue strength is improved. However, there is a limitation to reduction of surface roughness to several $\mu\text{m Rz}$ and blasting media may remain on the AMed metal surface. Gong et al. [10] reported that milling has been also applied for shaping and surface smoothing of AMed products. Although high shape accuracy can be obtained by milling, this process needs longer processing time, and larger tool wear would occur in milling of AMed metal products than in that of bulk ones. Electro-chemical polishing can smooth freeform surfaces of lattice and porous structures [11], but it is difficult to maintain shape accuracy and this technique leads to environmental burden. Recently, Alfieri et al. [12] and Lee et al. [13] revealed that surface roughness of AMed metal products is reduced by laser polishing. However, it is difficult to smooth the wide area of metal surface uniformly, since laser beam with small spot diameter must be scanned and overlapped on the surface.

On the other hand, in large-area electron beam (LEB) irradiation method, the LEB with 60 mm in diameter can be used for melting the wide area of metal surface uniformly and instantly. Proskurovsky et al. [14] showed that surface smoothing can be performed efficiently by the LEB irradiation. This technique could be applied to the surface smoothing and modification of mold steel [15], titanium alloy [16], stainless steel [17], and cemented carbide [18]. Bottom surface of high aspect ratio hole could be also smoothed by guiding LEB under control of magnetic field [19]. Shinonaga et al. [20] recently found that surface irregularities such as spatter and cavity of AMed maraging steel and aluminum alloy produced by PBF with laser beam could be repaired efficiency by the LEB irradiation. Moreover, the surface

roughness of AMed metal products could be reduced to several $\mu\text{m Rz}$. Since electrons easily concentrate on the convex parts [21], the convex parts of bead and spatter of AMed metal products are preferentially melted and/or evaporated by the LEB irradiation. However, it is not easy to smooth the surface with large surface roughness of more than 100 $\mu\text{m Rz}$ by the LEB irradiation. In addition, tensile residual stress may be generated on workpiece surface by rapid heating and cooling of surface during the LEB irradiation. Therefore, it is highly expected that the combination technique of grit blasting and LEB irradiation may have great potential to reduce surface roughness significantly and reduction of tensile residual stress.

In this study, surface smoothing and change in residual stress of AMed titanium alloy (Ti-6Al-4 V) were proposed by combination of grit blasting and LEB irradiation. At first, the AMed Ti-6Al-4 V alloy surface was blasted by using grit media to reduce the initial large surface roughness to some extent. Surface topography such as maximum height in surface roughness Rz and mean width in roughness curve Rsm was changed by blasting conditions. Then, LEB was irradiated to the blasted surface to further reduce the surface roughness. Influence of surface topography of blasted surface on smoothing effect by LEB irradiation was investigated and discussed by thermo-fluid analysis. Finally, residual stress distributions in depth direction of AMed Ti-6Al-4 V alloy after grit blasting and LEB irradiation were measured to investigate the possibility for reduction of tensile residual stress caused by LEB irradiation.

2 Experimental procedure

2.1 Formation of AMed Ti-6Al-4 V alloy by electron beam melting (EBM)

Titanium alloy (Ti-6Al-4 V) powder was used in the EBM process. The particle size is in the range of 45 to 106 μm . Thermal and physical properties of Ti-6Al-4 V alloy [22–25] are shown in Table 1. Figure 1 schematically shows scanning pattern in EBM process. Table 2 shows the EBM conditions. Arcam EBM A2X machine was used for EBM process. In

Table 1 Thermal and physical properties of Ti-6Al-4 V alloy [22–25]

Melting point	θ_m	[K]	1941
Boiling point	θ_b	[K]	3560
Specific heat	c	[kJ/(kg·K)]	0.546
Thermal conductivity	λ	[W/(m·K)]	7.5
Density	ρ	[kg/m ³]	4420
Viscosity	μ	[mPa·s]	4.82
Surface tension	γ	[g/s ²]	1870

Fig. 1 Schematic of scanning pattern in EBM process

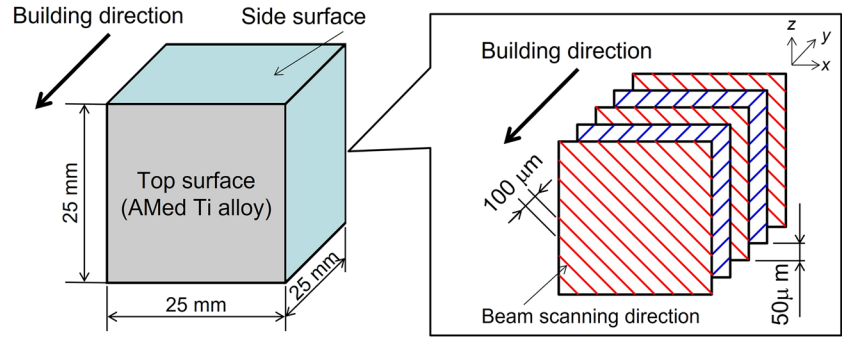


Table 2 EBM conditions

Particle diameter of powder	d_p	[mm]	45–106
Spot diameter	D_s	[μm]	500
Scanning speed	V_s	[m/s]	≤ 3
Scan spacing	D_p	[μm]	100
Layer thickness	d_L	[μm]	50
Temperature	T_e	[K]	873

the EBM process, an EB with a spot diameter of 500 μm was scanned on the metal powder. The EB scan spacing was fixed to 100 μm , and the layer thickness was also fixed to 50 μm . The EB scanning direction was alternated with orthogonal directions (90°), layer by layer. AMed Ti-6Al-4 V alloy with cuboid shape of 25 \times 25 \times 25 mm was produced.

2.2 Grit blasting method

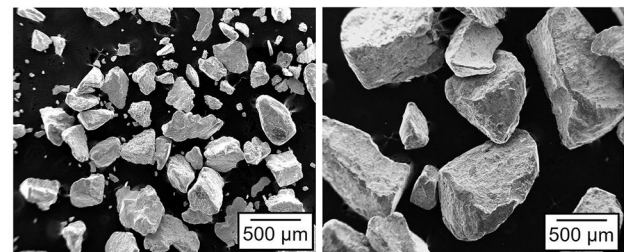
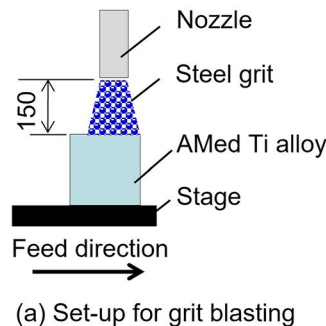
A set-up for grid blasting is schematically shown in Fig. 2(a). The steel grit with angular shape was used as the blasting media. SEM images of the steel grit with different sizes are shown in Fig. 2(b). Grit blasting conditions are listed in Table 3. In the case of blasting condition F , first and second conditions were used. After workpiece surface was blasted with condition first of F , the surface was blasted with condition second of F . Steel grit gives impact to the side surface of AMed Ti-6Al-4 V alloy, and nozzle stand-off distance was set to 150 mm. Then, an area

with 25 \times 25 mm was blasted by moving the stage under constant nozzle feed rate of 200 mm/min. Figure 3 shows maximum height in surface roughness R_z and mean width in roughness curve R_{sm} of the blasted surface with different blasting conditions. As shown in the figure, the surface topography of blasted surface is changed by the blasting conditions. The blasted surfaces with almost same surface roughness of 63 μm R_z and different mean width R_{sm} of 390 μm R_z and 690 μm R_z were obtained as shown in Fig. 4. Meanwhile, the blasted surfaces with almost same mean width R_{sm} of 390 μm and different surface roughness of 54, 62, and 72 μm R_z were also obtained.

Table 3 Grit blasting conditions

	Hardness HV_g [HV]	Grit size D_g [μm]	Air pressure P_b [MPa]	Scanning number N_b
A	> 800	300	0.30	13
B	> 800	700	0.15	30
C	600	700	0.30	13
D	450	700	0.30	5
E	450	700	0.15	15
F	1st > 800	700	0.15	10
	2nd > 800	200	0.30	15

Fig. 2 Grit blasting method and SEM images of steel grit



Steel grit ($D_g=300 \mu\text{m}$)

Steel grit ($D_g=700 \mu\text{m}$)

(b) SEM images of steel grit

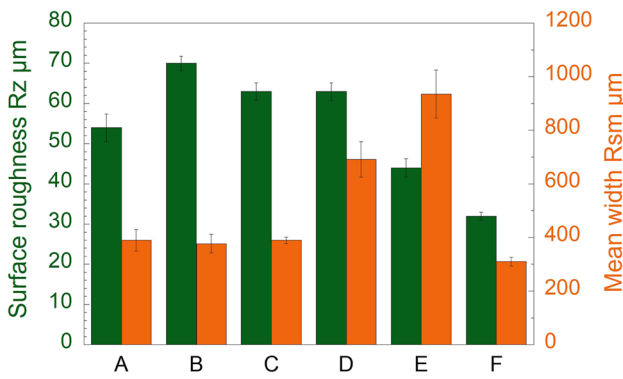


Fig. 3 Surface roughness and mean width of blasted surface with different blasting conditions

2.3 LEB irradiation method

Figure 5 schematically shows LEB irradiation equipment (Sodick Co., Ltd., PF-00A). The LEB irradiation is performed at pressure of 10^{-2} Pa under argon (Ar) gas ambience. The LEB with high energy density and uniform distribution can be irradiated to the workpiece surface by explosive electron emission from cathode. Principle of the explosive electron emission is explained by Mesyats G.A [26]. The LEB of approximately 60 mm in diameter can instantly and uniformly melt metal surface without focusing the beam. In the experiment, the LEB was irradiated to a side surface of AMed Ti-6Al-4 V alloy after grit blasting. LEB conditions are listed in Table 4. Energy density E_d was fixed to 15 J/cm^2 , and number of irradiation N was also fixed to 50 shots.

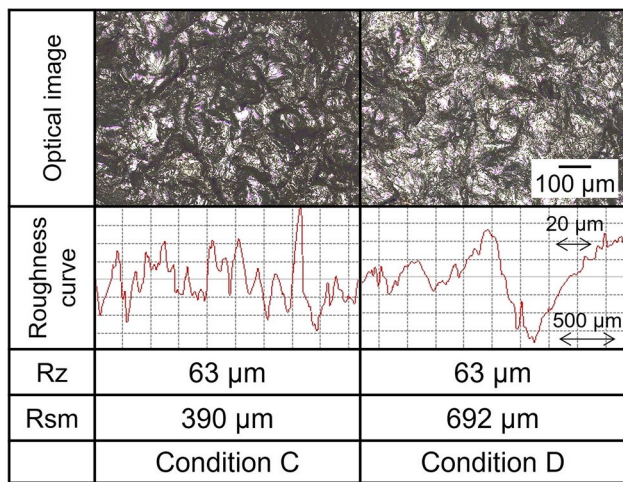


Fig. 4 Optical images and roughness curve of blasted surface with different mean width

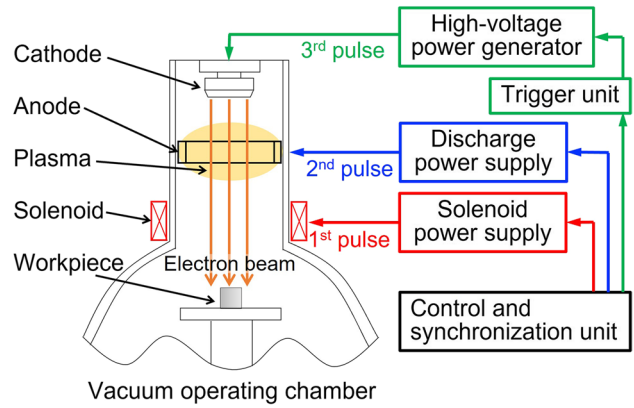


Fig. 5 Schematic of LEB irradiation equipment

3 Experimental results

3.1 Smoothing effect by grit blasting or LEB irradiation

At first, smoothing effect of AMed Ti-6Al-4 V alloy only by grit blasting or only by LEB irradiation was examined. Figure 6 shows optical images and roughness curves of the AMed Ti-6Al-4 V alloy surface, that after grit blasting and that after LEB irradiation. Surface roughness was measured in perpendicular to bead direction by a contact type surface profilometer (TOKYO SEIMITSU CO., LTD., SURFCOM-1400D). The surface roughness measurement was performed, based on standard of ISO 4288: 1996. Then, maximum height in surface roughness Rz and mean width in roughness curve Rsm were evaluated. As shown in the figure, the AMed Ti-6Al-4 V alloy surface by EBM has very large surface roughness of about 265 μm Rz . After grit blasting, surface topography is changed to small protrusion with small mean width, since steel grit with angular shape gives impact to the AMed Ti-6Al-4 V alloy surface. Mean width in roughness curve Rsm decreases from 510 to 390 μm . However, the surface roughness of blasted surface is about 63 μm Rz , and it is still large.

On the other hand, the small convex parts of AMed titanium alloy surface are melted, and smoothed by the LEB irradiation. However, the large undulation of AMed Ti-6Al-4 V alloy surface still remains after the LEB irradiation. The mean width of LEBed surface is 550 μm , and surface roughness of about 48 μm Rz is still large. These results indicate that it is difficult to reduce the very large surface roughness with more than 200 μm Rz of AMed Ti-6Al-4 V alloy to several μm Rz only by grit blasting or only by LEB irradiation.

Table 4 LEB conditions

Energy density	E_d	[J/cm ²]	15
Shot number	N	[shot]	50
Pulse duration	D_p	[μs]	2.0
Pulse frequency	F_p	[Hz]	0.125

3.2 Influence of surface topography of blasted surface on smoothing effect by LEB irradiation

Influence of surface topography of blasted surface on smoothing effect by LEB irradiation is investigated in this section. Figure 7 shows optical images and roughness curves of blasted surface with different mean width Rsm before and after LEB irradiation. The LEB is irradiated to the blasted surfaces with almost same surface roughness of 63 μm Rz and different mean width of 390 and 692 μm. The surface roughness of blasted surface with small mean width of 390 μm decreases to 4.3 μm Rz by LEB irradiation. Meanwhile, the surface roughness of blasted surface with large mean width of 692 μm decreases to 9.9 μm Rz. Then, the reduction rate of surface roughness by LEB irradiation α was calculated. The reduction rate α is expressed as following Eq. (1),

$$\alpha = \left(1 - \frac{R_{za}}{R_{zb}}\right) \times 100 \tag{1}$$

where Rza is the surface roughness after LEB irradiation, Rzb is the surface roughness before LEB irradiation. The reduction rate α on blasted surface with small mean width of 390 μm is as very high as 93%, while the reduction rate with large mean width of 692 μm is 84%. These results suggest that smaller mean width is effective for the reduction of surface roughness by LEB irradiation. Thus, influence of

mean width of blasted surface on reduction rate of surface roughness α is investigated.

Figure 8(a) shows relationship between mean width Rsm of blasted surface and reduction rate of surface roughness α. As shown in the figure, there is a good relationship between the reduction rate of surface roughness and the mean width of each blasted surface. The reduction rate almost linearly increases with decreasing mean width of blasted surface. Correlation coefficient between mean width of blasted surface and reduction rate is -0.95. Influence of surface roughness Rz on reduction rate of surface roughness α is also shown in the Fig. 8(b). As shown in the figure, the reduction rate is not influenced by the surface roughness of blasted surface. The correlation coefficient between surface roughness of blasted surface and reduction rate is 0.12. It was made clear that smoothing effect by LEB irradiation is much improved when the LEB is irradiated to blasted surface with appropriately small mean width.

The reduction rate reaches about 93% and surface roughness becomes 2.3 μm Rz in the case of blasted surface with small mean width of 309 μm as shown in Fig. 9. Thus, the surface roughness of AMed Ti-6Al-4 V alloy surface significantly reduces from 265 to about 2.0 μm Rz by the combination of grit blasting and LEB irradiation.

3.3 Residual stress distributions

Possibility for reduction of tensile residual stress caused by LEB irradiation was investigated. The residual stress was measured by X-ray residual stress measurement system (PLUSETEC Industrial Co., Ltd., μX-360 s). Debye ring was captured by the system with cos α method. X-ray irradiation angle was set to 25° and spot size of X-ray on the workpiece surface was about 1 mm in diameter. In order to measure the residual stress distribution in depth direction, the workpiece

Fig. 6 Optical images and roughness curves of the AMed Ti-6Al-4 V alloy surface, that after grit blasting and that after LEB irradiation

LEB conditions: $E_d=15 \text{ J/cm}^2$, $N=50 \text{ shots}$

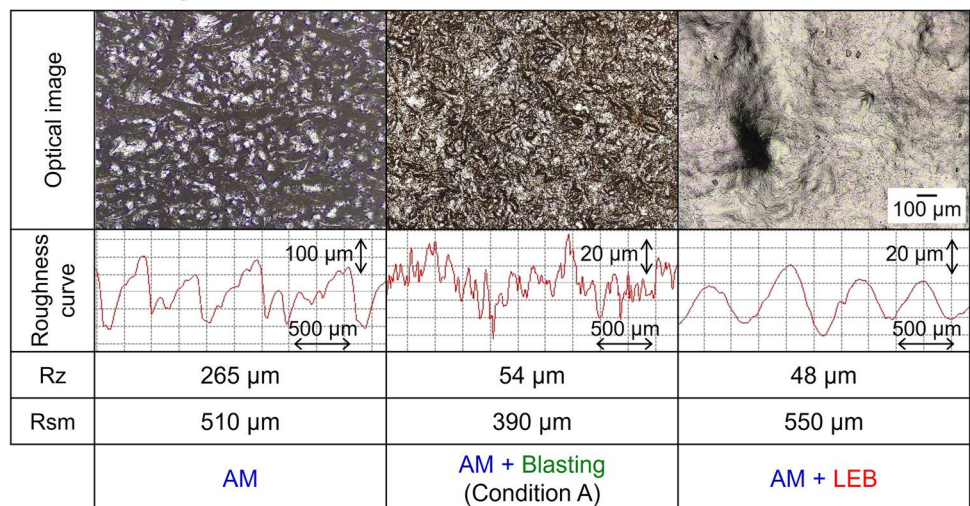


Fig. 7 Optical image and roughness curve of blasted surface with different mean width before and after LEB irradiation

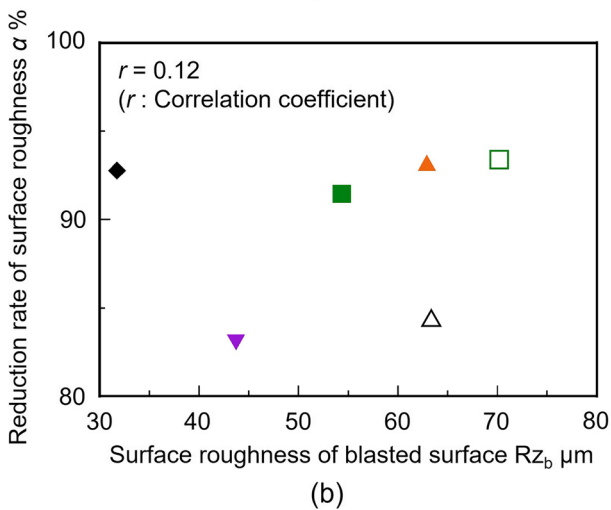
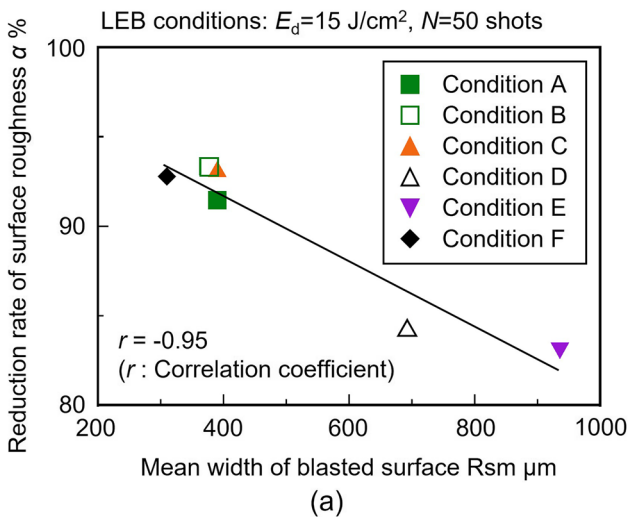
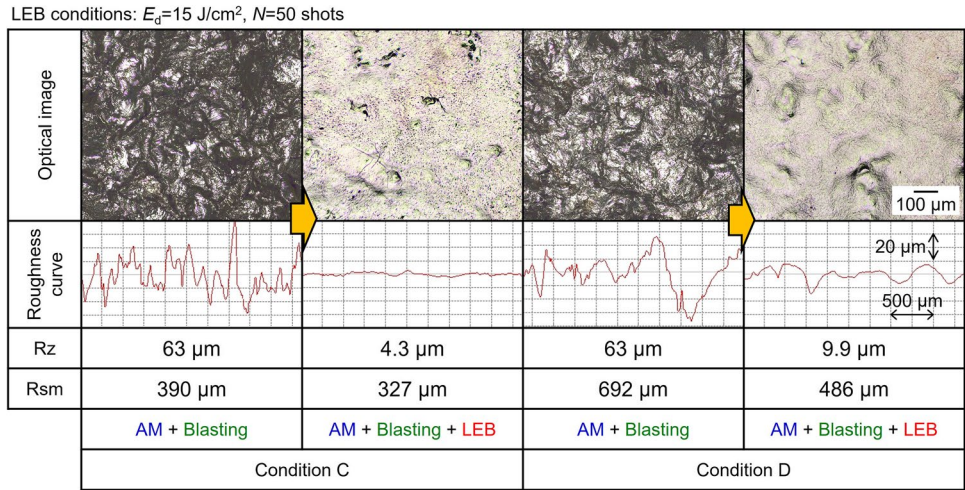


Fig. 8 Influence of (a) mean width Rsm and (b) surface roughness Rz of blasted surface on reduction rate of surface roughness for AMed Ti-6Al-4 V alloy

surface was electropolished for each measurement. It was reported that AMed metal product has anisotropic characteristics, and residual stress of AMed metal product is changed in scanning direction and/or building direction [27, 28]. In the X-ray residual stress measurement, the residual stress for side surface of AMed Ti-6Al-4 V alloy was measured perpendicular to the building direction regardless of grit blasting and/or LEB irradiation.

Figure 10 shows the residual stress distributions in depth direction from the top surface of AMed Ti-6Al-4 V alloy that after grit blasting, that after LEB irradiation, and that after grit blasting and LEB irradiation. In the case of AMed Ti-6Al-4 V alloy, there is almost no residual stress. Meanwhile, compressive residual stress of about 600 MPa can be introduced to top surface only by grit blasting, and the compressive residual stress is introduced into a depth of about 250 μm. On the other hand, tensile residual stress of 670 MPa is generated on the top of AMed Ti-6Al-4 V alloy surface only by LEB irradiation, and the tensile residual stress remains from top surface to a depth of about 150 μm.

In contrast, in the case of blasted and LEBed surface, the maximum tensile residual stress of top surface reduces to about 600 MPa, and the depth of tensile residual stress also reduces to about 25 μm as shown in the Fig. 11. In addition, the compressive residual stress generated by grit blasting remains at a depth of more than 25 μm. It was made clear that the tensile residual stress caused by LEB irradiation reduces and depth of tensile residual stress also reduces, when the LEB is irradiated to blasted surface.

4 Discussion

Previous chapter shows that the mean width of blasted surface greatly affects the reduction rate of surface roughness by LEB irradiation. In this section, mechanism for

Fig. 9 Optical image and roughness curve of blasted surface with appropriate mean width before and after LEB irradiation

LEB conditions: $E_d=15 \text{ J/cm}^2$, $N=50$ shots

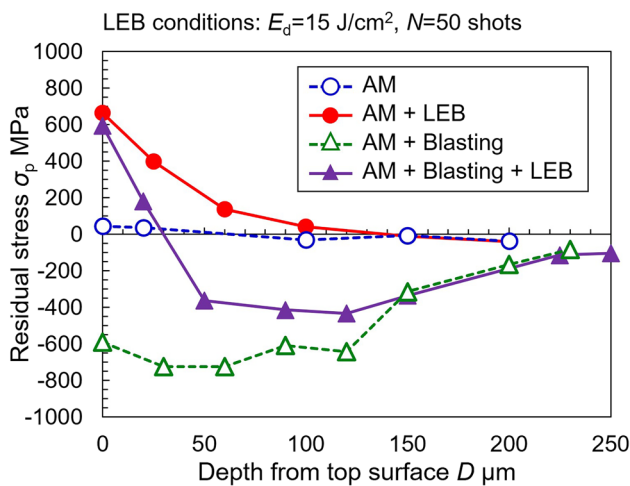
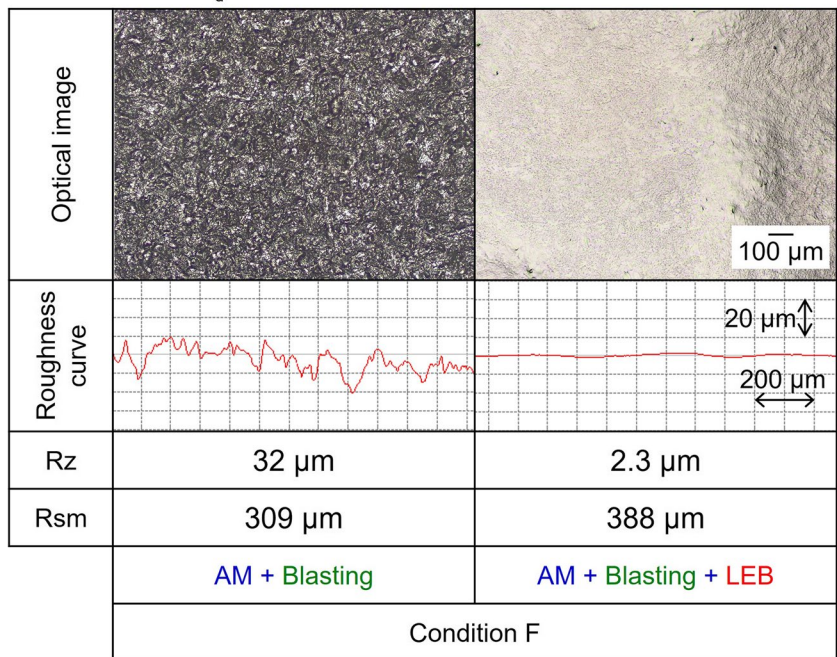


Fig. 10 Residual stress distributions in depth direction from the top surface of AMed Ti-6Al-4 V alloy, that after grit blasting, that after LEB irradiation, and that after grit blasting and LEB irradiation

improvement of smoothing effect by LEB irradiation to blasted surface with smaller mean width was discussed. Thermo-fluid analysis was conducted to investigate flow and re-solidification of molten metal in LEB irradiation. Commercial software (Flow Science, Inc., FLOW-3D) was used for the analysis. Thermo-fluid analysis model using the volume-of-fluid (VOF) method was build, which can consider the flow of molten metal as a liquid with free surface [29]. In the VOF method, the analysis model is generally divided into cubic cells and fluid fraction is defined in each

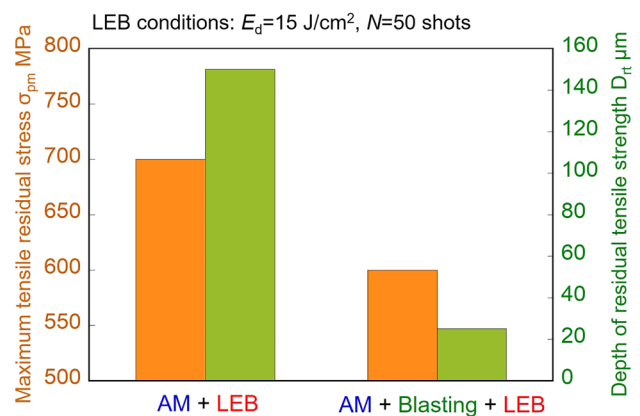


Fig. 11 Reduction of maximum tensile residual stress and depth of residual tensile strength by combination of grit blasting and LEB irradiation

cell. The fluid fraction shows the state of each cell. The fluid fraction of 0 indicates a void region, and the fluid fraction of 1.0 indicates a fluid region. In addition, the fluid fraction between 0 and 1.0 indicates boundary of free surface. The fluid fraction can be calculated in each cell at each time by using this advection equation. Then, the shape and motion of the free surface is determined. Therefore, unsteady state of molten metal flow and material temperature distribution can be calculated by the thermo-fluid analysis with VOF method.

Figure 12 shows the schematic of our analysis model. The workpiece has same maximum height in surface roughness Rz of 50 μm, and different mean width Rsm of 300

and 600 μm . A vacuum atmosphere of 2.0×10^{-2} Pa was set above the workpiece surface. The analysis conditions of the model are shown in Table 5. Ambient temperature was kept constant at 300 K, since the temperature did not change in the chamber when the temperature was measured with a thermocouple set about 200 mm far from the workpiece. Emissivity of workpiece surface was set at 0.2 which was measured by using an infrared thermo viewer. Heat transfer from workpiece to vacuum environment was set to 0, since it is known that the heat transfer by convection of gas can be neglected under the pressure of 10^{-2} Pa [30]. Thermo-physical properties of Ti-6Al-4 V alloy shown in Table 1 were used in the analysis. On the other hand, a heat energy input with considering the waveform of cathode voltage in pulse duration of 2.0 μs [31] was given on the workpiece surface.

Figure 13 shows the time variations of liquid fraction distributions of workpiece with different mean width at shot number of 1shot. In the liquid fraction, the region above the melting point is defined as the liquid phase (liquid fraction of 1.0), and the range of the melting region is shown by contour. At the time of 2.0 μs which is the finish time of heat input, the workpiece surface is uniformly melted during LEB irradiation. Then, the convex parts round due to surface tension and difficulty of heat diffusion at the parts. At the time of 5.0 μs , the depth of the molten metal increases due to heat transfer from top surface, and the molten metal at the convex parts flows into the concave parts significantly. The thickness of molten metal at the convex parts for smaller mean width of 300 μm is larger than that of larger mean width of 600 μm . These results suggest that the temperature of molten metal at the convex parts for smaller mean width is higher than that of larger mean width. Thus, temperature distributions are investigated at the time of 5.0 μs .

The temperature distributions and liquid fraction at the time of 5.0 μs are shown in the Fig. 14. In the case of small mean width of 300 μm , temperature at convex parts is higher than that of mean width of 600 μm , since heat accumulation at convex parts with smaller mean width easily occurs compared with the larger mean width. Then, preferential melting at the convex parts increases, and amount of molten metal also increases. In addition, the molten metal begins to flow from convex parts with high temperature to inclined surface with low temperature due to surface tension, since the surface tension at low temperature parts is larger than that at high temperature parts. It is expected that the molten

Table 5 Analysis conditions

Material		Ti-6Al-4 V
Analysis region	[μm]	1800 \times 2 \times 220
Cell size	[μm]	1.0
Energy density	E_d [J/cm^2]	12
Number of irradiation	N [shot]	1
Heat transfer coefficient	h [$\text{W}/(\text{m}^2\cdot\text{K})$]	0
Emissivity	ϵ	0.2

metal on workpiece with smaller mean width more flows than larger mean width, since temperature at convex parts is higher than that of mean width of 600 μm . At the time of 10.0 μs , it is confirmed that the molten metal on workpiece with smaller mean width significantly flows at inclined surface near the convex parts due to surface tension as shown in Fig. 15.

After the molten metal flows into the concave parts, the molten metal completely re-solidified at about 25.0 μs in the case of small mean width of 300 μm as shown in Fig. 13. The time of re-solidification in the case of large mean width of 600 μm is about 24.0 μs , which is slightly earlier than that of 300 μm . Then, the height difference between convex and concave part after re-solidification in the case of small mean width of 300 μm is smaller than that of large mean width of 600 μm . Thus, analytical results show that smoothing effect by LEB irradiation is much improved when the LEB is irradiated to the workpiece surface with smaller mean width.

5 Conclusions

Surface smoothing of AMed Ti-6Al-4 V alloy with very large surface roughness by combination of grit blasting and large-area EB (LEB) irradiation was proposed. Influence of surface topography of blasted surface on smoothing effect by LEB irradiation was also examined and discussed by thermo-fluid analysis. In addition, the possibility for reduction of tensile residual stress caused by LEB irradiation was investigated. Main conclusions obtained in this study are as follows:

1. It is difficult to reduce very large surface roughness with more than 200 μm Rz of AMed Ti-6Al-4V alloy to several μm Rz only by grit blasting or only by LEB irradiation.

Fig. 12 Thermo-fluid analysis model

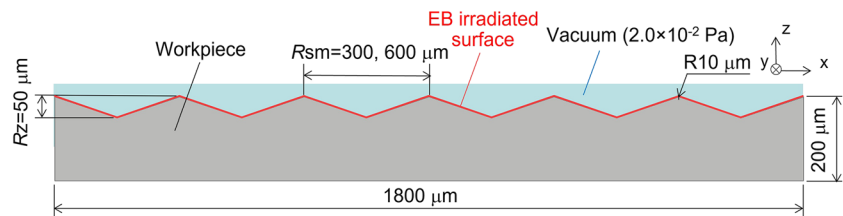


Fig. 13 Time variations of liquid fraction distributions of AMed Ti-6Al-4 V alloy with different mean width of 300 and 600 μm in LEB irradiation

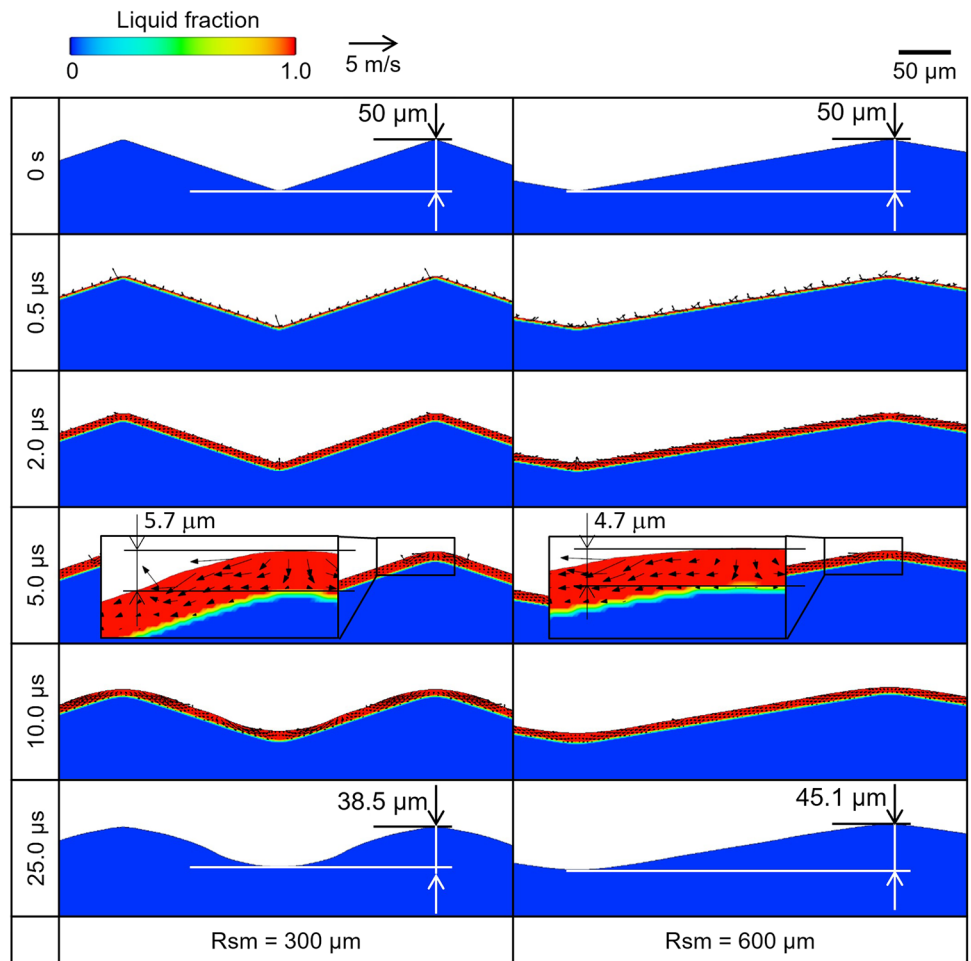


Fig. 14 Temperature distributions and liquid fraction distributions of AMed Ti-6Al-4 V alloy with different mean width of 300 and 600 μm at 5.0 μs in LEB irradiation

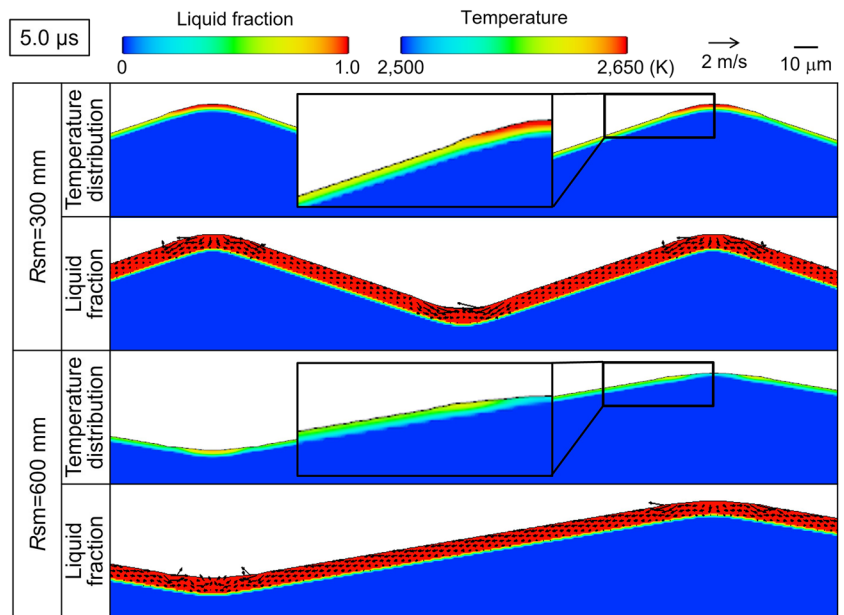
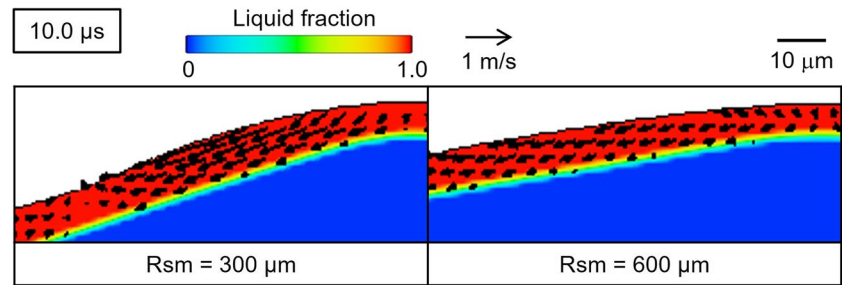


Fig. 15 Liquid fraction distributions of AMed Ti-6Al-4 V alloy with different mean width of 300 and 600 μm at 10.0 μs in LEB irradiation



2. Surface roughness of AMed Ti-6Al-4V alloy can be significantly reduced to about 2.0 μm Rz by combination of grit blasting and LEB irradiation.

3. Reduction rate of surface roughness by LEB irradiation almost linearly increases with decreasing mean width of blasted surface. Thus, smoothing effect by LEB irradiation is much improved when LEB is irradiated to blasted surface with appropriately small mean width.

4. Influence of mean width of blasted surface on smoothing effect by LEB irradiation can be explained by thermo-fluid analysis. The analytical results show that temperature at convex parts of small mean width is higher than that of large mean width, since heat accumulation at convex parts for smaller mean width easily occurs compared with the larger mean width. Then, preferential melting at convex parts for smaller mean width increases, and the amount of molten metal also increases. The molten metal at the convex parts for smaller mean width significantly flows into the concave parts due to surface tension. Finally, height difference between convex and concave part after re-solidification in the case of small mean width is smaller than that of large mean width.

5. Tensile residual stress caused by LEB irradiation reduces and depth of tensile residual stress also reduces, when LEB is irradiated to blasted surface.

6. Combination of grit blasting and LEB irradiation is effective for surface smoothing and change in residual stress of AMed Ti-6Al-4V alloy.

Author contribution Togo Shinonaga performed the conceptualization and original draft. Hiroya Kobayashi contributed to the experiments for large-area EB irradiation and simulation. Akira Okada revised this manuscript. Toshiya Tsuji conducted the experiments for blasting and measurement of residual stress.

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Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

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