Investigation on Magnetic Polishing Characteristics of Metal Additive Manufactured Ti-6Al-4V

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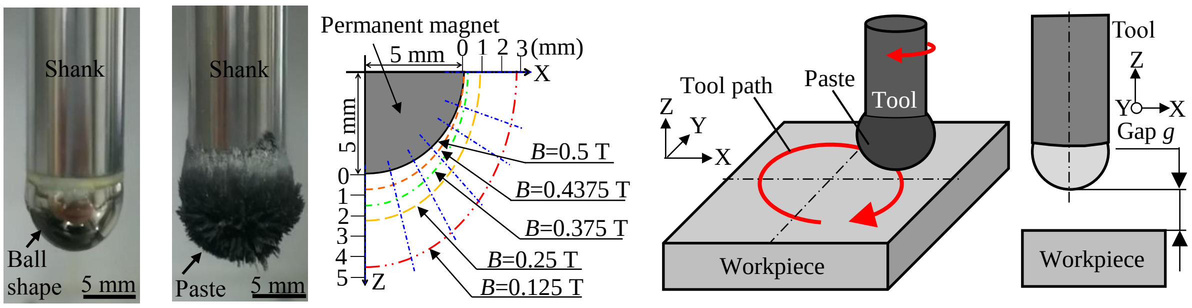
Abstract. Metal additive manufacturing (AM) of Ti-6Al-4V is expected to fabricate artificial replacement products, with high efficiency. In recent years, a hybrid additive manufacturing machine that combined machining center has been developed. It is possible to obtain a desired shape, although it is difficult to generate a high-quality surface roughness. However, these products need the high surface quality. Since these products are generally polished with the hand work, deterioration of shape accuracy or increase of non-machining time occurs. Therefore, in this study, a magnetic polishing method that can polish Ti-alloy on the hybrid metal AM machine is developed. In this report, workpiece made of Ti-6Al-4V was fabricated by the metal AM machine, and was ball end-milled to flat shape. Next, workpiece was magnetic polished on the machining center, and pressing force, polished amount and surface roughness were measured. Moreover, Preston constant of additive manufactured Ti-6Al-4V was calculated. In addition, a typical Ti-6Al-4V was also magnetic polished, and Preston constant was calculated. From the above, it was found that a Preston constant of additive manufactured Ti-6Al-4V is approximately 0.78 times smaller than the typical Ti-6Al-4V.

Introduction

Recently, a demand of artificial replacement components such as artificial joint or artificial bone has been increased in accordance with a growth of aging society. These components are typically fabricated with following method [1]. First, a workpiece is machined with cutting on a machining center into desired shape. Second, the workpiece is generally polished with handy-craft or special machine tool. On the other hand, this fabrication method has several problems. A shape deviation is easy to occur by the handy-craft or the positioning error associated with chucking and un-chucking of workpiece. In addition, number of excellent handy-craftsman rapidly are decreasing. Therefore, this study is aiming to develop novel fabrication method of artificial components that combined from shape generation to finish polishing. We focused on a hybrid metal additive manufacturing (AM) machine that composed metal additive manufacturing machine and machining center [2, 3]. A proposed method is follows: First, the workpiece is additive manufactured into the near-net desired shape with metal AM machine. Second, the workpiece is semi-finish cut into the desired shape in the metal AM machine. Finally, the workpiece is magnetically polished by use of ball end-mill typed permanent magnet tool in the metal AM machine. This proposed method can fabricate the component with one-chucking, and does not need the excellent handy-craftsman. However, the reports related to magnetic polishing characteristics of additive manufactured material are not reported. Consequently, in this report, the magnetic polishing characteristics of additive manufactured Ti-6Al-4V that is used as the material of artificial components is evaluated. In order to evaluate a difference between additive manufactured Ti-alloy and general Ti-alloy, the general Ti-6Al-4V (Bulk material) is also magnetically polished. First, the effects of several magnetic polishing conditions are investigated, and an optimum polishing condition is decided. Next, Preston constants that indicates polishing easiness are calculated.

Magnetic Polishing Method Using Machining Center

A schematic illustration and photograph of magnetic polishing method that is used in this study are shown in Fig. 1. The permanent magnetic polishing tool having tip radius of 5 mm adsorbs the magnetic paste as shown in Fig. 1(a). the magnetic paste is composed of oil based magnetic fluid, WA abrasives (Mean diameter: 1 μm), Fe particles (Mean diameter: 100 μm), α-cellrose fiber and mineral oil. This polishing tool is attached to tool spindle of machining center, and is rotated/scanned on the workpiece. Fig. 1(b) shows the distribution of equal magnetic flux dencity line. The magnetic flux dencity becomes small in accordance with the distance from the magnetic tool. Thus, it is possible to change the pressing force that effects to the workpiece, by changing the distance between tool tip and workpiece. It has been found that a circular tool path which is shown in Fig. 1(c) can obtain high polishing efficiency in the past report [4]. Therefore, this report also applied the circular path. In this polishing method, a gap *g* between polishing tool and workpiece is needed, to retain the polishing paste as shown in Fig. 1(c).



(a) Overview of tool (b) Distribution of *B* (c) Polishing method and gap

Fig. 1 Photographs and schematic illustrations of magnetic polishing method.

Experiment Method and Conditions

As the workpiece to evaluate the magnetic polishing characteristics, the metal additive manufactured Ti-6Al-4V was fabricated with the hybrid metal additive manufacturing machine LUMEX Avance-25 (Matsuura Machinery Corp.). This machine is powder bed fusion type. The fabricating conditions are follows: powder material was Ti-6Al-4V, Yb-doped fiber laser (1000 nm) was used, laser power was 120W, spot diameter was 0.2 mm, layer thickness was 50 μm, maximum powder diameter was 45 μm and atmospheric gas was Ar (99.999%). As the base plate, a pure titanium (*W*125 x *L*125 x *t*30 mm) was used. These conditions are recommended conditions of machine builder. The workpiece size was *W*30 x *L*30 x *t*5 mm. 9 workpieces were fabricated on the base plate. After the workpieces were additive manufactured, the workpieces were cut with wire electro discharge machine. Since the surface roughness of additive manufactured workpieces is large, these were ball end-milled into a flat shape by using zig-zag cutting path. As the reason using ball end-mill, the hybrid AM machine is good at fabrication of complex shaped product. Therefore, because the ball end-mill is most used as cutting tool, the ball end-mill was used even in this study. Since the metal AM machine requires an airtightness, it is difficult to put the measuring equipment into AM machine. Thus, the ball end-milling and magnetic polishing were carried out with a vertical 3-axis machining center MD-46VA (Okuma Corp.) to measure the machining force. In order to decrease the anisotropy of surface roughness, the ball end-milling conditions are calculated by using Eq. 1 [5].

$$\Delta x_b = f'_b = \sqrt{(8R \cdot Rz_{th})/2} \quad (1)$$

Where, Δx_b is pick-feed in X direction, f'_b is feed rate per tool revolution, R is tool radius and Rz_{th} is theoretical surface roughness. Since the Δx_b and f'_b are equal, the anisotropy of surface roughness becomes small. The calculated ball end-milling conditions are follows: tool radius R was 1 mm, number of cutting edge was 2, helix angle was 30°, theoretical surface roughness Rz_{th} was 1 μm*Rz*, cutting speed was 100 m/min, feed rate per revolution f'_b was 0.06 mm, pick-feed Δx_b was 0.06 mm, axial depth of cut was 0.2 mm and coolant was emulsion type. Finally, the ball end-milled workpieces were magnetically polished under several conditions. The magnetic polishing conditions are below. Polishing tool is Ball shaped permanent magnet (Max. flux density: 500 mT, R5 mm), tool rotational speeds are 5, 10, 15, 25 and 40 m/min, polishing gaps are 0.3, 0.5 and 1.0 mm, amount of paste is 0.4 g and revolution radius of tool path is 5 mm. In order to decide the optimum condition, gap g and tool rotational speed V were changed. Since the tool rotational speed much larger than the tool feed speed, the tool feed speed was set as constant value. Surface roughness and polishing depth of workpiece were measured with a point autofocus probe 3D measuring instrument NH-3N (Mitaka Kohki Co., Ltd.), and the removal mass of workpiece was measured with a precision electronic balance. The hardness was measured with a micro vickers hardness meter. The pressing force was measured with a three-dimensional cutting dynamometer 9257B (Kistler Corp.). In addition, the Preston constant k was calculated based on the investigated optimum polishing condition. In order to evaluate the difference between additive manufactured Ti-alloy and general Ti-alloy, the malleable Ti-alloy (Bulk material) was also machined with same experiment method.

Experimental Results

Additive Manufacturing of Workpiece Made of Ti-6Al-4V. The overview of fabricated workpiece is shown in Fig. 2. The workpieces cracked in a slightly remote position from base plate. Since thermal conductivity of Ti-alloy is small, the workpiece temperature is easy to increase. Thus, it is considered that the cracks occurred by the increase of tensile stress which is caused by the temperature gradient between workpiece and base plate. On the other hand, the cracks did not occur in accordance with the increase of distance from the base plate.

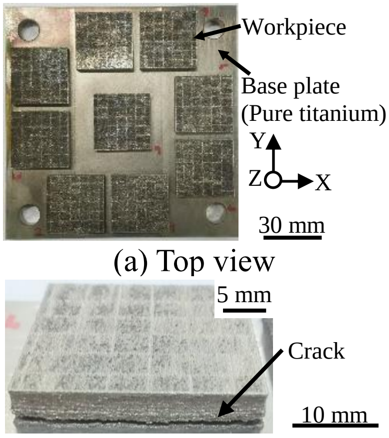


Fig. 2 Fabricated workpieces.

Ball End-Milling of Additive Manufactured Surface. The surface images of ball end-milled workpiece are shown in Fig. 3. The various sizes of pores were occurred. The small pores occurred by the trapped gas which was occurred when the powder was melted [6]. In the microscopic image of large pore as shown in Fig. 3, it is seen that the irradiation mark before one layer appeared. Thus, the large pores were occurred for lack of melt pool area. From the above, the change of additive manufacturing conditions is needed. In addition, the hardness was

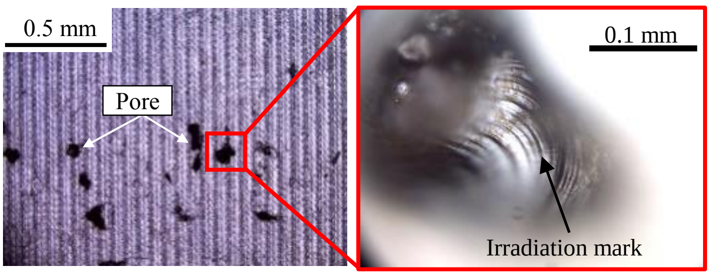


Fig. 3 Microscopic images of ball end-milled surface.

evaluated. The hardness of metal AM Ti-alloy was 519 HV, and the hardness of general Ti-alloy was 368 HV. It was found that the hardness of metal AM Ti-alloy became 1.4 times larger than the general Ti-alloy by metallographic structure was densified by the quickly heating and cooling.

Effect of Changing Magnetic Polishing Conditions. Fig. 4 shows the effect of changing gap *g* on the removal amount *M* of workpiece. The removal amount of AM Ti-alloy after the tool rotated 40 laps is 10 times larger than the general Ti-alloy. There are two reason. First, the polishing efficiency will decrease in accordance with increase of extension coefficient [7]. Since the hardness of AM Ti-alloy is large, it is assumed that the extension coefficient became small. Second, it is considered that the non-melting powder dropped out by the polishing force. Comparing *g*=0.3 mm and *g*=0.5 mm, the removal amount of *g*=0.5 mm became large. Where, Fig. 5 shows the relation between gap and pressing force. If based on Preston's law which is defined as Eq. 2 [8], the removal amount should increase in accordance with the increase of pressing force.

$$M=kpVt \tag{2}$$

Where, *M* is removal amount, *k* is Preston constant, *P* is polishing pressure, *V* is polishing relative speed and *t* is polishing time. It is considered that the experiment result contraried to Preston's law occurred with decreasing effective magnetic polishing paste by the centrifugal force of tool. From this experiment, it was found that the optimum gap *g* is 0.5 mm.

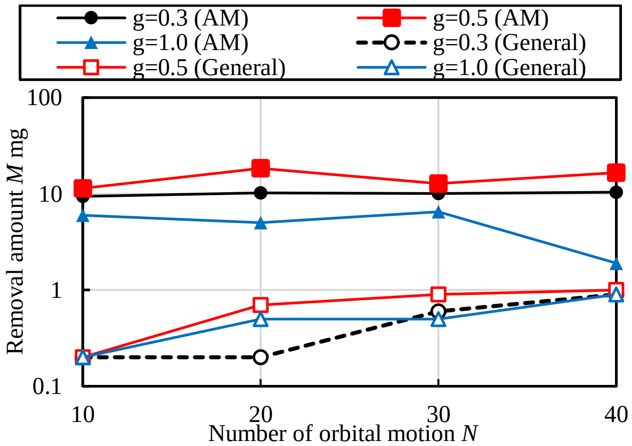


Fig. 4 Relation between gap and removal amount.

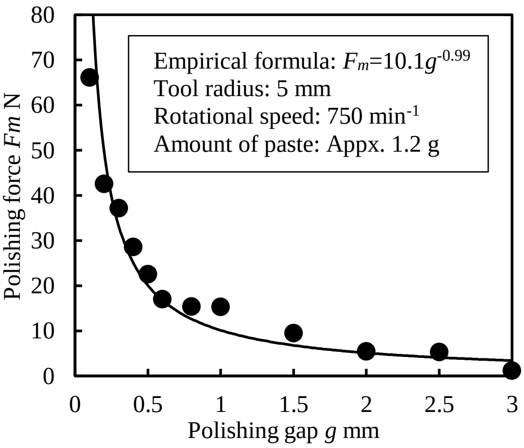


Fig. 5 Effect of gap on pressing force.

The effect of tool rotational speed on the removal amount is shown in Fig. 6. In the case of applying *V*=15 m/min, the removal amount became largest. In the low rotational speed (*V*=5, 10 m/min), since these removal amount were small, these results follow Preston's law. If *V*=25 and 40 m/min, the rotational speed is high, nevertheless these removal amount became small. Fig. 7 shows the relation between rotational speed and pressing force. The pressing force decreases in accordance with increase of rotational speed. Therefore, it was found that the effective magnetic polishing paste decreases by the centrifugal force of tool. From the above, the optimum tool rotational speed *V* is 15 m/min.

Investigation of Preston Constant *k*. The Preston constant *k* under the optimum polishing condition was calculated based on the past report [4] that defined the prediction model of polishing amount. In order to measure the effective contact diameter of polishing paste, the acrylic plate which was painted the black body was magnetic polished. The effective contact diameter was 14 mm from the photograph of polished acrylic plate as shown in Fig. 8. The tool revolution radius was 7.5 mm. As the required polishing amount to calculate Preston constant, since the removal mass is easy to occur a measured mass error by the drop-out of un-melted Ti-alloy powder, the cross-section profile of polished workpiece shape as shown in Fig. 9(a) was used. In addition, the polishing depth after the tool revolved 140 laps was used. The calculated Preston constant k is shown in Fig. 9(b). The average k of AM Ti-alloy was 2.84×10^{-7} mm^2/N, and the average k of general Ti-alloy was 3.68×10^{-7} mm^2/N. Therefore, it was found that the magnetic polishing efficiency of Ti-alloy made by metal AM is 0.78 times smaller than the general Ti-alloy. Fig. 10 shows the before-and-after of machined surface. The cutter-marks were completely removed, and the smooth surface was obtained.

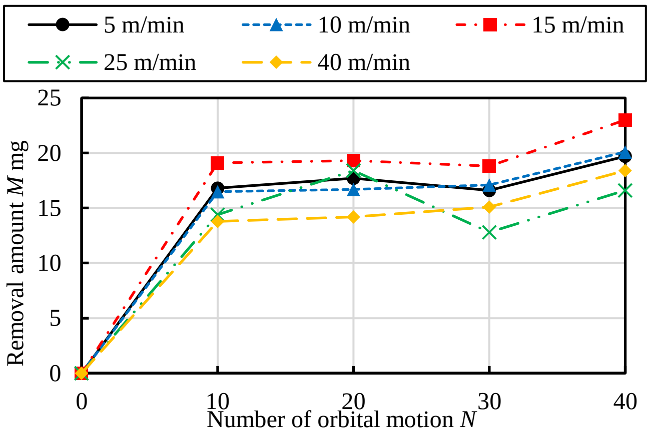


Fig. 6 Effect of rotational speed on removal amount.

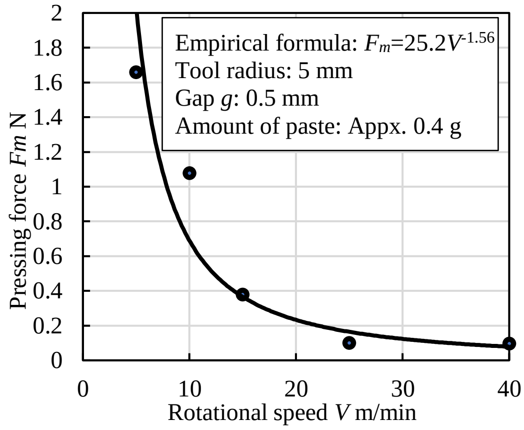


Fig. 7 Effect of V on pressing force.

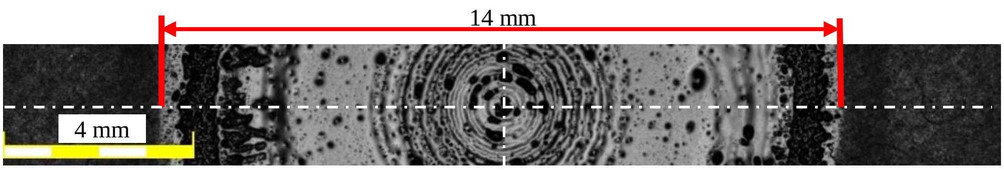
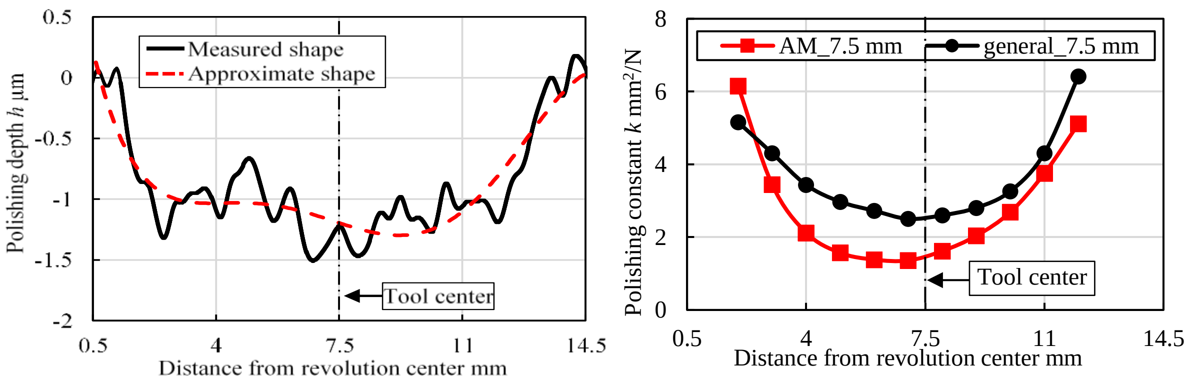


Fig. 8 Measuring of effective contact diameter (Photograph of polished acrylic plate)



(a) Measured cross-section profile of workpiece (b) Calculated Preston constant k

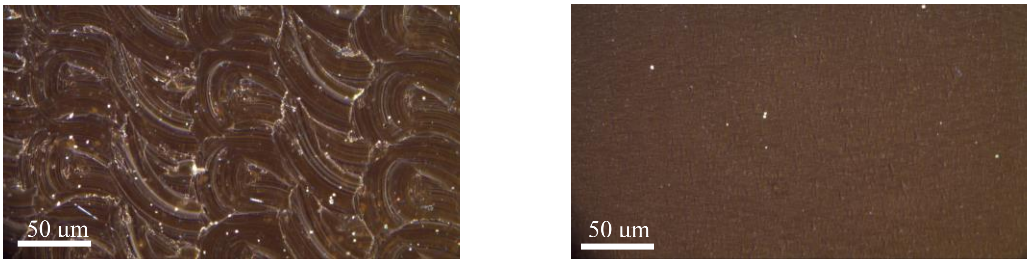
Fig. 9 Polished workpiece shape and calculated Preston constant k.

Summary

In this report, the magnetic polishing characteristics of Ti-alloy made by metal AM and optimum condition, Preston constant k were evaluated, and the following results were obtained.

1) The optimum magnetic polishing condition that considers polishing efficiency and surface quality were g=0.5 mm and V=15 m/min.

2) Preston constant *k* of Ti-alloy made by metal AM that was calculated with optimum polishing condition was 2.84×10^{-7} mm^2/N, and is 0.78 times as low as the general Ti-alloy.
3) The proposed polishing method can obtain the smooth polished surface that was removed the cutter marks of semi-finish cutting.



(a) Ball end-milled surface before polishing (b) Magnetic polished surface

Fig. 10 Comparison between ball end-milled surface and magnetic polished surface.

Acknowledgments

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