FINISHING OF ELECTRON BEAM MELTED TITANIUM (Ti6Al4V) USING SHAPE ADAPTIVE GRINDING TOOLS

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INTRODUCTION

Electron beam melting (EBM) is a cutting-edge, additive manufacturing (AM) process used to produce three dimensional shapes by melting layers of metal powder with an electron beam in a vacuum. Unique to this process is not only the presence of a vacuum, but a dual scan of each layer. The first scan serves as a pre-heat stage, and the second scan fully melts the powder. This procedure achieves more uniform part temperature during the process as compared to other AM techniques. The result is a fully dense part with a significant reduction in residual stresses. This translates to material properties that are superior to other AM methods and leads to its use in orthopedic implants [1-2]. Unfortunately, for many applications, the resulting rough surface produced by additive manufacturing techniques demand a secondary finishing operation to improve the surface quality prior to usage.

Current methods to reduce the surface roughness include traditional machining for solid structures, chemical etching for porous structures, and laser polishing [2-5]. A reduction to 2-3 µm *Ra* (originally 22-45 µm *Ra*) was reported for laser additive manufactured titanium alloy parts using laser polishing. Other methods achieve similar results in the order of 1 µm *Ra*.

Although some of these finishing methods have a distinct advantage, such as being able to finish porous structures, their resulting surface roughness is still limited. To expand on additive manufacturing's many applications, it is desired to further decrease the part's surface roughness while limiting the number of finishing operations.

In this abstract, we introduce a novel process that uses nickel and resin bonded diamond shape adaptive grinding (SAG) tools to finish titanium (Ti6Al4V) workpieces manufactured by EBM, as shown in Figure 1.

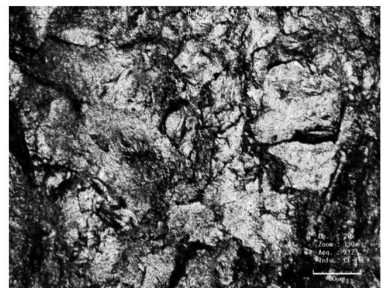


FIGURE 1. Laser microscope image at 20x of a Ti6Al4V workpiece produced by EBM.

SHAPE ADAPTIVE GRINDING

This process expands upon the precessed bonnet concept where an inflated, bulged, spinning membrane-tool is used to polish a surface [6-8]. This tool, termed a bonnet, is previously covered with a polishing cloth and a stream of slurry (e.g. cerium oxide) is directed at the tool and recirculated. As the bonnet presses against the surface of the workpiece (decreasing tool-offset), the contact-spot diameter is increased.

In shape adaptive grinding, however; the inner rubber polishing bonnet (elastic tool) is combined with an outer nickel/resin bonded diamond pad. As shown in Figure 2, the deformability of the rubber layer allows the tool to conform to a workpiece's surface during finishing. The workpiece can be of any general shape, including convex, concave, flat, aspheric, or freeform. Simultaneously, however, at smaller scales, the diamond pellets act as a rigid tool and allow for grinding to take place. The result is a flexible grinding process with the benefits of both polishing and grinding techniques. This allows for greater material removal than standard polishing techniques while producing low surface roughness, and without sacrificing form accuracy.

The spindle speed, attack angle, tool offset, and surface speed of the tool can be actively controlled by a 7-axis CNC machine as it traverses the surface of the workpiece. This allows for control of the grinding spot in order to vary the spot size and removal rate. The air pressure inside the bonnet can also be manipulated in order to control the force.

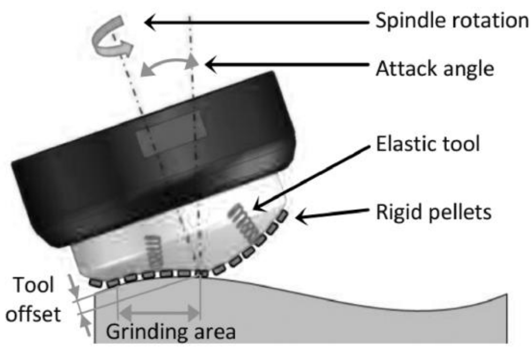


FIGURE 2. Shape adaptive grinding principle.

EXPERIMENTAL RESULTS

The Ti6Al4V workpiece produced by EBM shown in Figure 1 was used for the experiments in this paper. A series of experiments were initially conducted to determine the optimal parameters for this SAG process. A 5 mm x 45 mm flat section of the titanium sample was ground using the machine parameters given in Table 1 at four separate feedrates (25, 50, 100, and 200 mm/min) for three SAG tools. With each successive grinding trial, the diamond size of the SAG tool was decreased to achieve an ultra-smooth surface (40 µm NBD, 9 µm NBD, and 3 µm RBD). For each tool and feedrate, a series of grinding runs were performed until no further improvement of the surface was witnessed. Figure 3 shows a laser microscope image at 20x and 100x of the surface after grinding with each tool. Figure 4 shows three-dimensional surface profiles taken with a white light interferometer at 10x magnification.

TABLE 1. Machine parameters.

Parameter	Value
Spindle Speed	1500 RPM
Tool Pressure	1.0 Bar
Attack Angle	20°
Tool Offset	0.3 mm
X/Y Spacing	0.2 mm
Feedrate	25, 50, 100, 200 mm/min

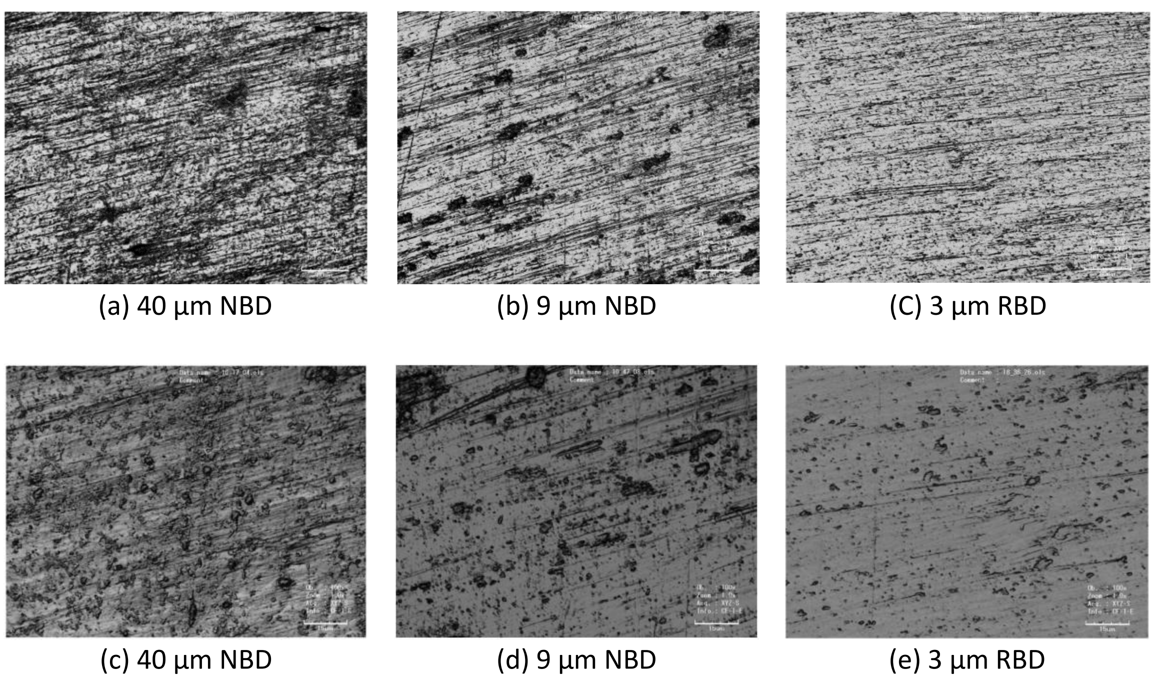
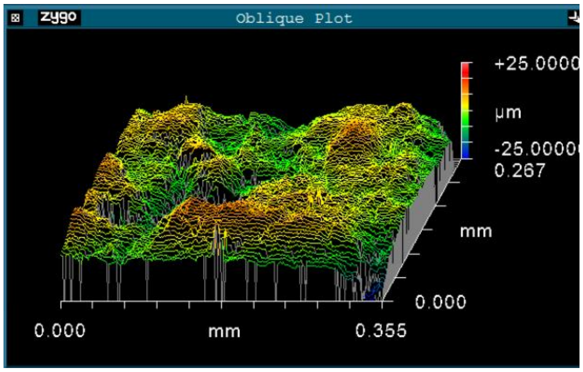
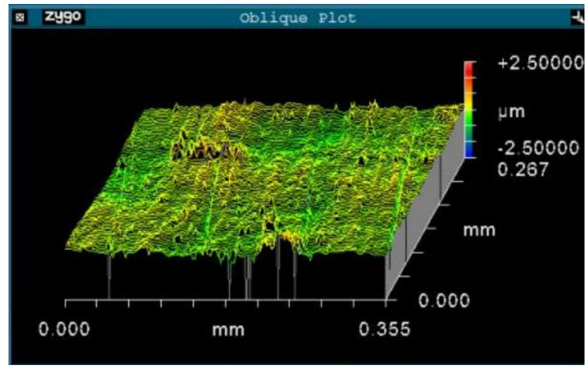


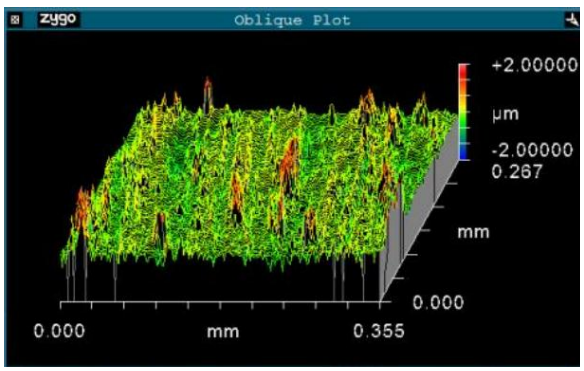
FIGURE 3. Laser microscope images taken at 20X (top) and 100x (bottom) after successive grinding trials



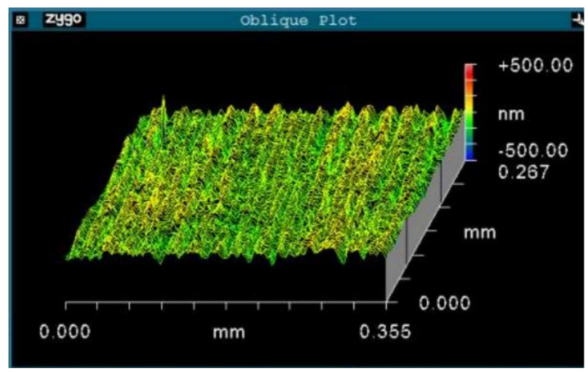
(a) Unfinished surface



(b) 40 µm NBD



(c) 9 µm NBD



(d) 3 µm RBD

FIGURE 4. 3D surface profile of surface at 10x magnification after successive grinding trials

Due to the rough initial surface seen in Figure 1 and Figure 4(a), a coarse 40 µm grit nickel bonded diamond (NBD) SAG tool was initially used to remove the layered surface. Figure 3(a and c) and Figure 4(b) show the resulting surface, void of layered material. This allows for further grinding with subsequently finer SAG tools. A 9 µm NBD tool was used next on the same area using the same parameters. Further reduction in surface features is shown in Figure 3(b and d) and Figure 4(c) and a directional surface texture begins to emerge. The final tool used for grinding employed a 3 µm resin bonded diamond (RBD) SAG tool. The final surface is uniform with directional scratches as seen in Figure 3(c and e) and Figure 4(d). If desired, further trials using other polishing media could remove the SAG tool marks and further improve the titanium surface appearance.

An optical image of the workpiece is shown in Figure 5. This picture shows the surface condition at each successive grinding process from right to left: after 40 µm grinding, after 40 µm and 9 µm grinding, and after 40, 9, and 3 µm grinding (the left edge of the workpiece shows the original surface condition). The surface becomes more reflective after each successive grinding trial. In terms of surface roughness variance, it was found that the best results were obtained by using a feedrate of 100 mm/min for the 40 µm and 9 µm nickel bonded diamond SAG tools and 25 mm/min for the 3 µm resin bonded diamond SAG tool.

The surface roughnesses *Sa* and *RMS* at 2.5 x, 10x and 50x magnifications were measured using a white light interferometer (It was not possible to get an image at 2.5x magnification of the initial surface due to its rough nature). The results are plotted in Figure 6 and Figure 7. The surface roughness *Sa* is drastically improved after the initial SAG process. Additional grinding reduced the final roughness *Sa* to 50.24 nm, 27.66 nm, and 31.44 nm *Sa* at 2.5x, 10x and 50x, respectively. The same trend is witnessed for the *RMS* roughness, with final values of 63.83 nm, 34.56 nm, and 40.37 nm at 2.5x, 10x, and 50x, respectively. These results show substantial improvement over current finishing methods for post-processing of AM parts, opening the door to further applications.

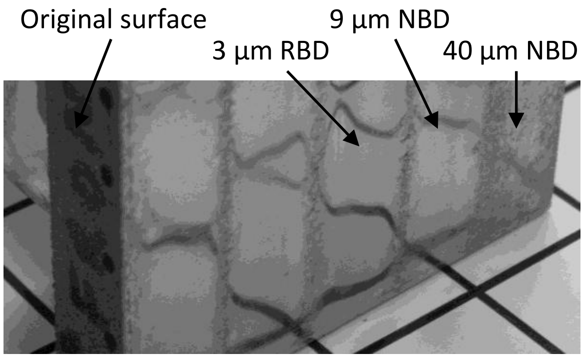


FIGURE 5. Photograph of finished surface

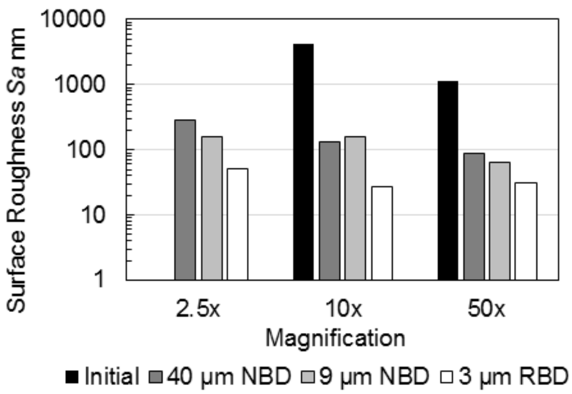


FIGURE 6. Surface roughness results.

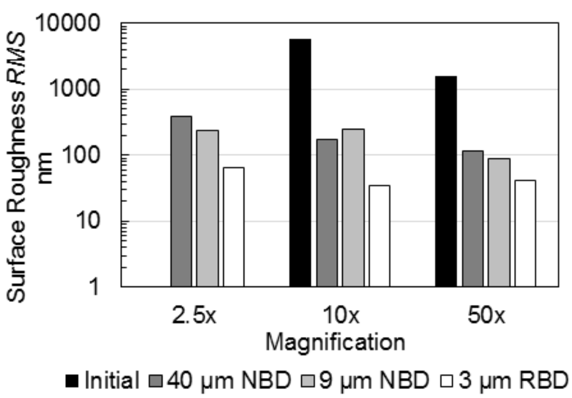


FIGURE 7. Surface roughness results

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