Material Forming - ESAFORM 2023 Materials Research Forum LLC
Materials Research Proceedings 28 (2023) 1341-1346 https://doi.org/10.21741/9781644902479-145

Superfinishing processes applied on the biomedical implants surface to improve their performance

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Keywords: Burnishing, Biomechanics, Surface Integrity

Abstract. The demand of biomedical implants characterized by more and more advanced performances is expected to grow as well as their service life is expected to increase. Therefore, the necessity to research new material properties and production techniques in producing biomedical implants, characterized by higher durability, is strongly required. Regarding permanent prosthesis, the surface conditions play a key role on the prostheses overall mechanical performance. This work aims, through the application of burnishing process, to combine innovative machining finishing operations coupled with environmentally friendly lubricooling techniques to improve the surface integrity of biomedical devices in order to increase their quality, durability and reliability.

Introduction

Nowadays, the demand of products characterized by advanced performances that can provide great societal and environmental benefits is continuously increasing, especially in the biomedical field [1]. Surface integrity modification is one of the available strategies that can be used to enhance the in-service life of a component. As a matter of fact, Severe Plastic Deformation (SPD) processes have been extensively reported for modifying surface properties by altering the surface metallurgical characteristics (e.g. microstructure, hardness, precipitates amount and characteristics, roughness, residual stresses) [2]. Not only mechanical processes are used to change surface characteristics but also thermal processes as laser are employed to modify the surface properties, for example in adhesive joints of non-ferrous materials as shown in this study [3].

Burnishing is a SPD process since it is capable to greatly affect surface integrity due to the high level of strain induced in the workpiece material.

Several studies on different metals of industrial interest were carried out to understand the relationship between the burnishing parameters and post-processed surface integrity. As example in [4] roller burnishing tests were performed on the *Ti6Al4V* titanium alloy, enabling to find a set of processing parameters and lubrication conditions capable to significantly improve the surface quality of the final component. Furthermore, according to [4], the burnishing process aided to improve the surface finish and hardness, also generating compressive residual stresses that contributed to extend the fatigue life [5].

Burnishing is applied to titanium alloys, which represent the most used material for producing orthopedic prostheses like hip and knee implants. Generally, these prostheses, which stay permanently in the human body, need to be revised as a consequence of wear, corrosion and oxidation, which all initiate at the implant surface and may lead to leakage of ions dangerous for the human body [6]. In this case, burnishing is applied in order to increase the wear resistance of titanium alloys. An experimental campaign of burnishing process on cylindrical bars of *Ti6Al4V* was carried out. In particular, the tests were performed under MQL lubrication conditions and by varying process parameters, such as burnishing force, at fixed burnishing speed, feed rate and tool radius. The choice of using MQL lubricant condition was taken in order to achieve sustainable machining [7] and because the provider of the burnishing tool recommended to not work in dry conditions but to use lubricant as in this case vegetable oil emulsion. Afterwards, the surface integrity was assessed by means of microstructural analysis, roughness and micro-hardness measurements below the machined surface with the aim to analyze the mechanical property improvements after burnishing.

Results showed that the advanced manufacturing technology was able to thoroughly modify surface integrity of the investigated biomaterials. Furthermore, burnishing process enhances surface integrity in correspondence of the subsurface region of *Ti6Al4V*, in terms of grain refinement, surface roughness reduction, and hardness increase, in accordance with the fundamental characteristics required in the biomedical field to achieve the highest product performance and increasingly durable implants.

Experimental Procedure

The titanium alloy involved into the ongoing experimental campaign was the *Ti6Al4V*, grade 5. The as-received material was in form of a bar, with microstructure consisting of α equiaxed grains and intergranular β with 5 μm mean grain size. The bar roughness before processing was equal to 1.2 μm while after the turning process reached a value of 0.8 μm and up to a minimum value of 0.4 μm post burnishing.

Burnishing is a chipless SPD process, which allows increasing the product performance modifying the surface quality by smoothing the roughness, refining the grain structure and increasing the hardness [8. 9].

A deeper analysis concerning the influence of the burnishing process parameters on the *Ti6Al4V* surface integrity was carried out. The burnishing tests were performed using cylindrical bars of *Ti6Al4V* with 30 mm starting diameter, under MQL lubrication conditions. Roller burnishing tests were carried out on a high-speed CNC turning center equipped in particular with Quick Turn Nexus 200-II CNC machine. The lubricant, consisting of a vegetable oil, was delivered at the tool-workpiece interface through an external nozzle.

Table 1. Experimental plan for burnishing.

Burnishing	Value
Cutting speed v (m/min)	150
Feed f (mm/rev)	0.05
Force F (N)	1000 – 1500 – 2000 – 2500
Tool radius R (mm)	2.5
Number of passes	2

The burnishing tool was the SKUV20 (Yamato) with the roller made of hardened steel. Before performing the burnishing process, the bar was previously turned with standard semi finishing parameters, namely 30 m/min of cutting speed, feed of 0.15 mm/rev and 0.1 mm of depth of cut, while the burnishing parameters are reported in Table 1.

In order to control the effective achievement of the fixed burnishing force and monitor the temperature evolution, a three components piezoelectric dynamometer and an infrared thermo-camera were used during the tests. Fig. 1 shows the burnishing process set-up.

The burnished samples were cut in the transverse direction. The cross section was firstly mounted using a thermosetting black epoxy hot mounting resin, and then mechanically polished. These operations were carried out to obtain a mirror-like surface suitable for the metallographic analysis. Before performing the metallographic analysis with the optical microscope (Leica), the samples were etched using the Kroll's reagent able to oxidize the samples in order to highlight and

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measure the grain edges, then using an automatic procedure provided by ImageJ software, the grain size was measured. Furthermore, a portable surface profilometer (Pocket Surf®) was used to measure the mean surface roughness (Ra) while the Vickers micro-hardness (HV0.1) of the surface and subsurface layer was measured by means of an instrumented micro indenter.

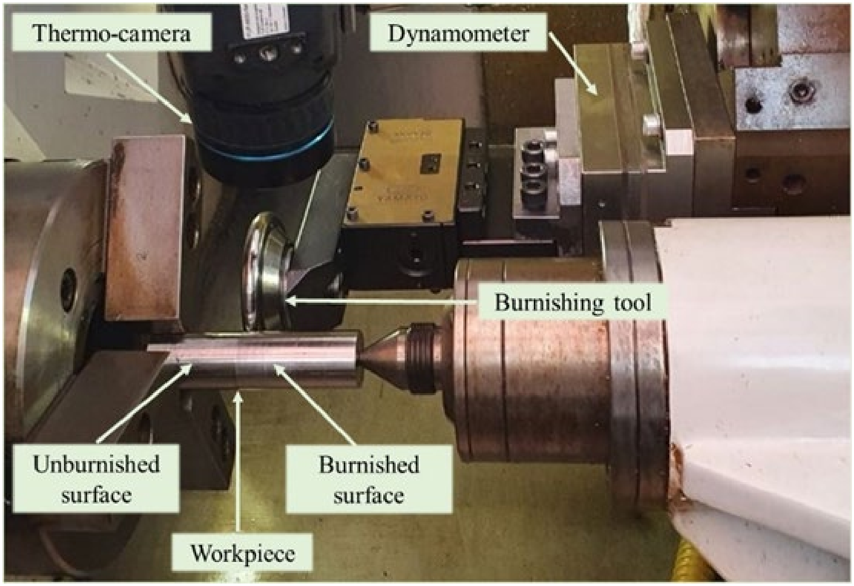

Fig. 1. Burnishing process set-up.

Results

In this preliminary analysis, the overall results were classified analyzing the influence of the burnishing force (B1000, B1500, B2000, B2500), which, according to literature [10], it is considered one of the parameters that mostly affects the surface integrity. Concerning the microstructure, Fig. 2 shows the changes between the different process conditions, in particular the As-Received (AR), As-Turned (AT), and As-Burnished (AB) samples, with 150 m/min burnishing speed, 0.05 mm/rev feed, 2500 N burnishing force, and 2.5 mm tool radius. Focusing on the AB sample, the grain distortion is visible along the working direction. Comparing the AB and AT samples, the AB one appears more deformed due to the larger amount of plastic strain induced by the burnishing process. Fig. 3 allows a better evaluation of the microstructural modifications, outlining the grain size evolution, showing that the surface grain size reduced during machining and even more during burnishing at the highest burnishing force. Although, during burnishing process significant rise in temperature was observed (temperature varied from 20°C to a maximum of 30°C), and therefore dynamic recrystallization did not occur, nevertheless the plastic deformation caused a noticeable grain refinement. This grain refinement is often the outcome of improvements in wear and corrosion resistance, generating compressive residual stresses enabling fatigue life enhancement. In terms of surface roughness, as Fig. 4 shows, an increase in the burnishing force led to a gradually decrease of the surface roughness up to 50% compare to AR sample. Burnishing process was able to give high brightness at the worked surface, also thanks to the MQL lubrication condition, which according to [4] is the optimal solution to obtain a lower roughness.

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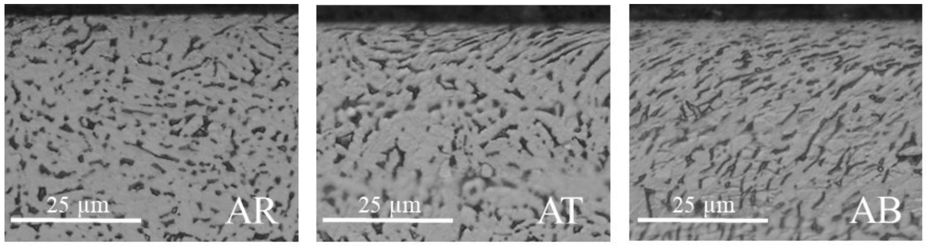

Fig. 2. Microstructure of the AR, AT and AB samples.

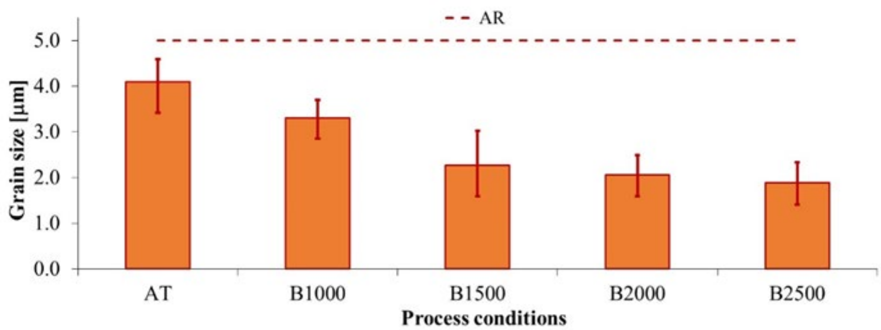

Fig. 3. Grain size evolution at varying burnishing force.

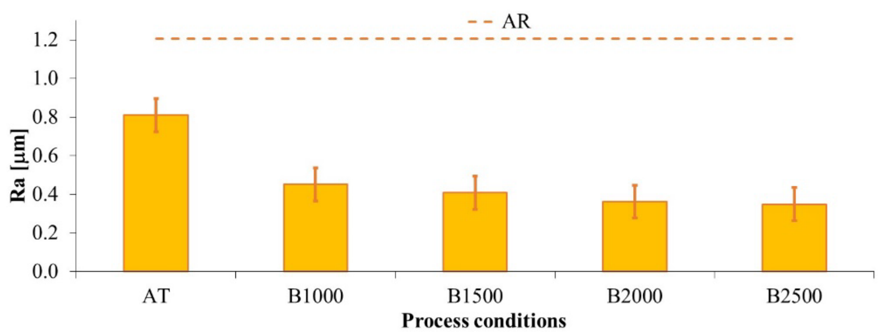

Fig. 4. Roughness at varying burnishing force.

Fig. 5 presents the hardness trend below the machined surface at varying burnishing forces. The hardness of the AR sample was measured equal to 390 HV. Thus, a slight change in the surface hardness resulted after burnishing compared to turning. Furthermore, the deformed layer was deeper after burnishing, which proves an increased work hardening, up to 400 µm from the machined surface, which increased at increasing burnishing force.

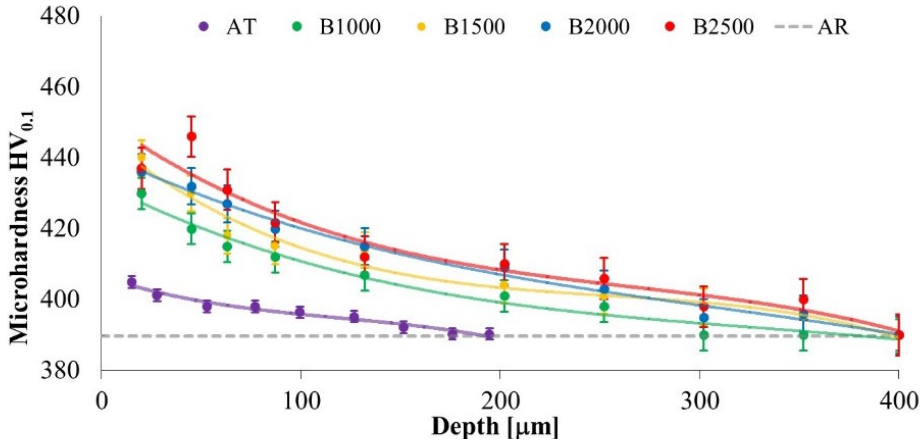

Fig. 5. Microhardness below the machined surface at varying burnishing force.

Summary

Burnishing process is shown to be viable SPD routes for achieving surface integrity enhancement in correspondence of the subsurface region of the biomedical grade *Ti6Al4V* alloy.

The burnishing process of *Ti6Al4V* highlighted enhancements in terms of grain refinement, surface roughness reduction, and hardness increase, which are fundamental characteristics required especially in the biomedical field to achieve the highest products performance.

Future studies will be devoted to investigate the influence of the different processing technologies on in-service life performances of the investigated biomaterials after being processed through burnishing. Specifically, further analysis concerning the influence of other burnishing process parameters as for instance the influence of the feed or tool radius on the *Ti6Al4V* wear resistance will be performed.

Acknowledgements

This research was carried out in the framework of the project PRIN 201742RB8R_002 “Bionic” funded by the Italian Ministry of University and Research.

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