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Cryogenic cooling effect on surface and subsurface microstructural modifications in burnishing of *Co–Cr–Mo* biomaterial

Shu Yang[a,*], Domenico Umbrello[b], Oscar W. Dillon Jr.[a], David A. Puleo[c], I.S. Jawahir[a]

[a] Institute for Sustainable Manufacturing, University of Kentucky, Lexington, KY 40506, USA
[b] Department of Mechanical, Energy and Management Engineering, University of Calabria, 87036 Rende, CS, Italy
[c] Department of Biomedical Engineering, University of Kentucky, Lexington, KY 40506, USA

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ABSTRACT

The aim of the present work is to investigate the effect of a severe plastic deformation (SPD) process, cryogenic burnishing, on the surface integrity modifications of a *Co–Cr–Mo* alloy due to the burnishing-induced surface integrity properties. A set of experiments was conducted to investigate the influence of different burnishing parameters on distribution of grain size, phase structure and hardness of the processed material. The results from this work show that the proper selection of burnishing conditions can significant improve the surface integrity of the *Co–Cr–Mo* alloy due to refined microstructure, high hardness, and favorable phase structure on the surface layer, which could potentially lead to advanced wear performance of such material.

1. Introduction

Co–Cr–Mo alloy is the most commonly used biomaterial for metal joint implants due to its good mechanical properties. However, the generation of wear debris at the contact surfaces and the resulting macrophage-mediated peri-implant osteolysis and aseptic loosening are the major complications in total hip replacements (Chan and Villar, 1996). In practical applications, the surface of a material is subjected to the influence of various external stimuli such as corrosion, wear, fatigue, *etc.*, all of which initiate at the surface. Every year, a large number of revision operations are performed to repair/replace the malfunctioned implants (Park and Kim, 2003). Often the revision operations are complex and costly. Thus, engineers and scientists continue to improve the surface properties of biomaterials. Surface modifications seem to offer solutions for improved functionality and longer service life of implants.

Burnishing is generally a cold-forming process, which improves the surface characteristics by plastic deformation of the surface layers (Loh et al., 1989). The review of published literature shows that burnishing process has been investigated by many researchers and improved properties and performance of the parts/components have been reported. Studies by Hassan and Al-Bsharat (1996) revealed that burnishing process imparted compressive residual stresses in the surface region that could mitigate fatigue cracks that usually initiate at the surface. Hassan and Al-Dhifi (1999) showed that the wear resistance of the ball-burnishing processed brass components can be significantly improved under optimized burnishing force and tool passes conditions. Seemikeri et al. (2008) studied the effect of burnishing on surface integrity and fatigue life of *AISI 1045* material in terms of evaluating the combined effects of burnishing process parameters, identifying the predominant parameter, establishing their order of significance, and setting the levels of different parameters to minimize surface roughness and maximize surface hardness and fatigue life. Rao et al. (2008) conducted a similar experimental parametric study on HSLA dual-phase steel. Their result also indicated that burnishing parameters have a significant effect on the surface hardness and wear resistance. Similar findings were reported by El-Axir and El-Khabeery (2003). It is found that the increase of burnishing passes firstly increased the microhardness until it reaches a maximum value. With a further increase in number of burnishing passes, the microhardness increasing rate gradually decreased, which is due to the over hardening and consequently flaking of the surface layers. Zhang and Lindemann (2005) have shown that the roller burnishing improved the high cycle fatigue strength of *AZ80* alloy by about 110% and an increase of 60% was demonstrated by Maximov et al. (2009). Prevéy and his co-workers (Prevéy, 2000) have shown that

* Corresponding author. Tel.: +15085795270.
E-mail address: shuyang1031@gmail.com (S. Yang).

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by using low plasticity burnishing, a compressive residual stress surface layer with sufficient depth can be created on many materials. These finally led to significant enhancements to the fatigue life of the components (Prevéy, 2000).

Moreover, it has been reported that the application of liquid nitrogen could introduce a favorable residual stress distribution in the surface layer, which may further improve the functional performance of metallic materials. Compared with conventional oil-based cooling, it is found that cryogenic cooling led to about 50% reduction of tensile residual stress in the parallel direction of the disc workpiece, and the residual stress in the perpendicular direction was reduced to nearly zero from 200 MPa tensile, which substantially improved the fatigue life of *AISI 304* steel specimens subjected to high cycle fatigue loading (Ben Fredj and Sidhom, 2006). Significantly improvements of residual stress distribution toward the favorable compressive direction in machined *AISI 52100* steel was also reported by using cryogenic cooling (Zurecki et al., 2003). Thus, control of the burnishing process conditions in such a way as to introduce desired properties in the surface layer could lead to considerable improvement in the service life of components/parts.

From the literature survey on the influence of the process parameters, it can be found that the major process parameters affecting the resulting surface conditions are: depth of penetration/burnishing force, burnishing speed, feed-rate, tool material, number of passes, and coolant/lubrication. In addition, results from the authors' previous studies have shown that the application of liquid nitrogen cooling can significantly influence the surface integrity of the processed material (Yang et al., 2013). However, due to the varying thermal softening and mechanical hardening effects under different burnishing conditions, the effectiveness of liquid nitrogen cooling on surface integrity enhancements varies. Thus, there is a need to establish better relationships among liquid nitrogen cooling, burnishing conditions and the resulting surface integrity for the purpose of finding the optimal combination of conditions to achieve the most desirable processing/product functional performance.

In this study, the effects of three burnishing parameters, namely: cooling method, depth of penetration (DoP) and burnishing speed on processing temperature, force, tool-wear and the workpiece surface integrity properties, in terms of microstructure, microhardness and phase change, are investigated.

2. Experimental work

2.1. Work material

The material used in the present investigation was BioDur *Co–Cr–Mo* alloy, which is a high nitrogen, low carbon wrought version of *ASTM F75* Cast Alloy. In order to eliminate the influence from previous manufacturing processes, and to fully investigate the effects of burnishing, the as-received material was annealed at 1100 °C for 1 h, followed by air cooling. A *Co–Cr–Mo* alloy bar (50.8 mm diameter) was used to prepare disc samples, which have a diameter of 50.8 mm and a thickness of 3 mm.

2.2. Burnishing experiments

Burnishing experiments were conducted on a Mazak Quick Turn-10 Turning Center equipped with an Air Products and Chemicals ICEFLY® liquid nitrogen delivery system. Liquid nitrogen as a cryogenic coolant was applied to the workpiece on the flank side of the tool-workpiece contact. The experiment setup and the schematic of the burnishing process with application of cryogenic cooling are shown in Fig. 1.

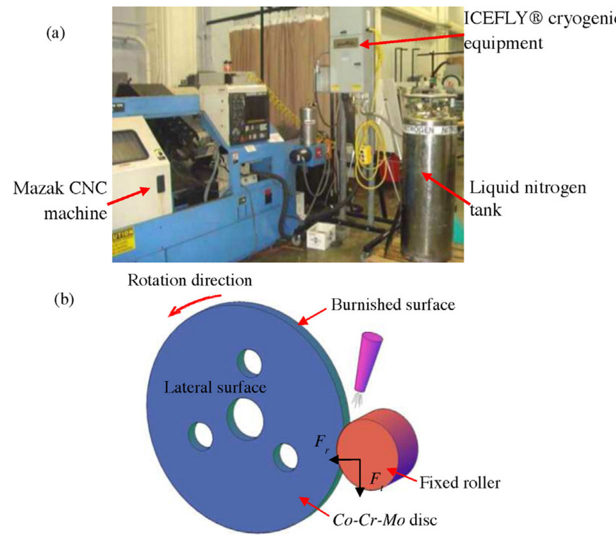

Fig. 1. (a) Mazak CNC machine equipped with ICEFLY® cryogenic equipment and (b) schematic illustration of the cryogenic burnishing process.

The burnishing conditions used are listed in Table 1. For each condition, one *Co–Cr–Mo* disc sample was used. For dry burnishing, no coolant was used; for cryogenic burnishing, liquid nitrogen was sprayed to the tool-workpiece interface at 0.6 kg/min. The fixed roller tool was pressed into the discs at a constant feed rate of 0.025 mm/rev. Simultaneously, the disc was rotating at a burnishing speed (*i.e.*, the linear speed at the contact area between the fixed roller and the disc) of 100 m/min. The feed-in process was stopped when the preselected depth of penetration (DoP) was reached. The burnishing roller then stayed at this position (*i.e.*, for the burnishing dwell time) for 10 s. The force components generated by the burnishing process were measured by a KISTLER 3-Component Tool Dynamometer through a data acquisition system with charge amplifiers. An uncoated carbide roller with a diameter of 14.3 mm was chosen as the burnishing tool for the current study. The hardness and surface roughness of the roller was measured to be 1000 HV and 0.01 μm (R_a), respectively.

2.3. Measurement and characterization methods

An FLIR ThermaCAM PM 695 infrared thermo-camera was used during the experiments to record the whole thermal field and temperature history during processing. The emissivity of *Co–Cr–Mo*

Table 1
Burnishing experimental conditions for studying the effects of cooling method and depth of penetration.

Exp. no	Depth of penetration (mm)	Surface speed (m/min)	Cooling method
1	0.08	100	Dry
2	0.08	100	Cryogenic
3	0.08	200	Dry
4	0.08	200	Cryogenic
5	0.15	100	Dry
6	0.15	100	Cryogenic
7	0.15	200	Dry
8	0.15	200	Cryogenic
9	0.15	300	Dry
10	0.15	300	Cryogenic
11	0.21	100	Dry
12	0.21	100	Cryogenic
13	0.21	200	Dry
14	0.21	200	Cryogenic
15	0.254	100	Dry
16	0.254	100	Cryogenic