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Surface integrity of magnesium-calcium implants processed by synergistic dry cutting-finish burnishing

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Abstract

Biodegradable magnesium-calcium (MgCa) alloy is a very attractive orthopedic biomaterial compared to permanent metallic alloys. However, the critical issue is that MgCa alloy corrodes too fast in the human organism. It is expected that surface integrity of an MgCa implant has significant impact on the corrosion performance. Compared to dry cutting, the synergistic dry cutting-finish burnishing of MgCa0.8 alloy is capable of producing superior surface integrity including good surface finish, high compressive hook-shaped residual stress profile, extended strain hardening in subsurface, and little change of grain size.

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1. Introduction

Current commercial, permanent, metallic implants made of stainless steel, titanium, and cobalt-chromium alloys suffer two grand challenges: stress shielding and revision surgeries [1,2], which greatly reduce the life quality of the affected individuals and impose a heavy burden on the healthcare system. Mg-Ca alloys as biodegradable implant materials have the potential to minimize stress shielding, avoid surgical interventions, and provide both biocompatibility and adequate strength [2-4]. However, the critical challenge of an Mg-Ca implant is that it has poor corrosion resistance in a saline media such as the environment of the human body. The control of the corrosion rate of Mg-Ca implants via adjusting surface integrity to match the healing rate of fractured bones is critical for the development of the next generation of biodegradable implants.

High speed dry cutting (HSM) and low plasticity burnishing (LPB) are surface treatment techniques which affect integrity. This selection utilizes different mechanics provided by material removal and forming processes. Each mechanic has distinct attributes in terms of the magnitude and depth of influence

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in the subsurface layer. The deformation penetration is at least ten times deeper in forming-based treatment like low plasticity burnishing as opposed to material removal technique and it can reach to several millimeters [5]. In this study, a synergistic dry cutting-finish burnishing is developed to combine these mechanics yielding a broad range of process parameters and physical, geometrical tool properties to explore, aimed at tailoring surface integrity of the workpiece for a specific bio-performance.

While high speed machining is a well-defined process, low plasticity burnishing is a novel technique. It includes a spherical socket to support a smooth free-rolling ball that is pressed and rolled along the surface, deforming the workpiece surface material into a state of compression. This process is characterized by a unique combination of three physical effects: (I) producing deep and stable compressive residual stresses; (II) work hardening or increasing surface/subsurface microhardness; and (III) burnishing or decreasing surface roughness and micronotches. Low plasticity burnishing can be performed on a CNC machine tool and in that sense it is affordable and compatible with modern manufacturing environment [5,6].

2. Synergistic Dry Cutting-Finish Burnishing of Mg-Ca0.8 Alloy

Dry cutting of Mg alloys produces good surface quality by the combination of high cutting speeds and low feeds [7]. Lower feeds result in lower roughness, longer exposure to thermo-mechanical loads, higher chances for microstructural changes, and ultimately harder near surface layers. Faster cutting speeds produce higher temperature, more thermal softening on the shear plane, easier cut, and smoother surface. However, higher temperatures promote adhesion between cutting tool/work material and flank built-up (FBU) formation especially when a critical cutting speed is exceeded [8-10]. FBU leads to low surface finish. Therefore, thermal conductivity of the alloy and cutting material are key parameters in determining the magnitude of cutting speed and feed effects on surface integrity. Slower cutting speeds cause higher cutting forces and consequently larger compressive residual stresses in terms of magnitude and depth of penetration [2]. In general, the effect of dry cutting on subsurface residual stresses is minor with a shallow penetration depth to the extent that it would be hard to detect considering the inherent uncertainty of X-ray diffraction technique for residual stress measurement.

Finish burnishing of Mg alloys under higher rolling forces marginally improves the surface finish [2,7,11-13]. However, surface layers will become deteriorated when excessive forces are applied. Induced residual stresses become more compressive and the maximum shifts significantly towards deeper layers under higher rolling forces. As such, subsurface layers store more energy [2]. Residual stresses on surface become less compressive applying higher rolling forces. Grains become compressed especially in maximum residual stress area and microstructure changes. The measured surface hardness was not consistentand significant microhardness change was not detected in the rolled Mg-Ca3.0 alloy [2]. The increase of microhardness of AZ31 was reported under higher rolling forces in corrosion studies [7,14].

Adjusting degradation kinetic of Mg-Ca0.8 alloy, as a new biodegradable implant material, using machining processes requires knowledge about the likely correlations between surface integrity and resulting corrosion behavior. The objective of this study is to investigate surface integrity induced by synergistic dry cutting-finish burnishing.

3. Experimental Setup and Conditions of Dry Cutting-Finish Burnishing

Binary Mg-Ca0.8 alloy was fabricated using pure Mg of the ASTM grade 9980A and Mg-30% Ca master alloy [9]. Cylindrical samples of 50 mm diameter were processed utilizing the set-up shown in Fig. 1. A broad range of cutting speeds and rolling forces in Table 1 was used to investigate the effects of process parameters on surface integrity. PCD inserts were utilized in high speed dry face milling to take advantage of low chemical affinity and friction between Mg and the tool. High pressure hydraulic unit in provides a pressurized hydro cushion for the silicon nitride ceramic ball (dia. 12.7 mm). This avoids the contact between ball and spherical housing and guarantees free rolling along the sample surface. The power carrying fluid is anti-wear, dual purpose Aries 15 oil which functions as both coolant and lubricant.

Table 1. Synergistic dry cutting-finish burnishing conditions

High speed face mill	cutting speed (m/min): 2000; 2400; 2800 feed (mm/rev): 0.2; depth-of-cut (mm): 0.2
Low plasticity burnish	rolling force (N): 400; 600; 800 rolling speed (mm/min): 1000; feed (mm): 0.1

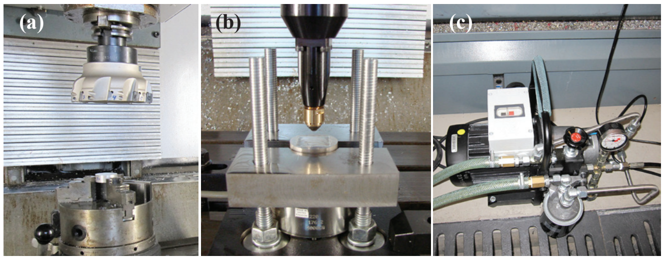

Fig. 1. Synergistic dry cutting-finish burnishing set up (a: high speed dry face milling; b: low plasticity burnishing; c: high pressure hydraulic unit)

4. Surface Integrity Characterization

4.1. Surface finish

Fig. 2 shows surface roughness obtained from dry cutting and finish burnishing. Cutting speed and rolling force have marginal effect on surface finish. This marginal effect manifests as slight decreasing trend with increasing each of parameters in Fig. 2. Higher cutting temperatures under faster cutting speeds cause material softening on shear plane, easier cuts, and smoother machined surface. Larger rolling forces act more effectively in closing surface cracks and pores. However, there is a limit on the positive effect of rolling force and beyond certain level, force acts as crack and cold weld initiating source itself and so deteriorates the surface as is shown in micrographs of Fig. 2. Comparatively, burnished surface is rougher than dry cut surface. This might be due to principal of volume conservation in plastic deformation which causes larger waviness on the surface by burnishing as opposed to milling which operates based on cutting rather than forming mechanism. Even though hammering action of the burnishing ball flattens the pre-existing cut marks and makes burnished surface look shiner than cut surface but yet increased waviness dominates in determining surface roughness.

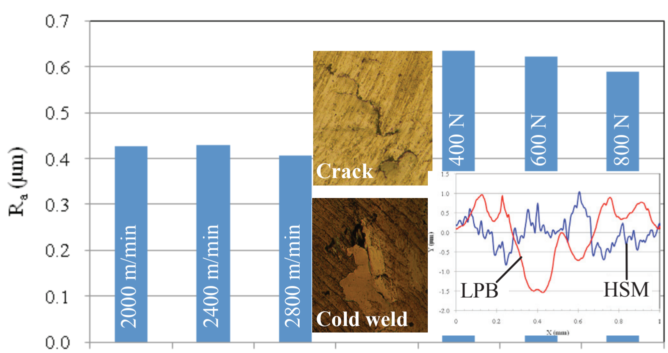

Fig. 2. Effects of process parameters on surface roughness

4.2. Residual stress

Residual stresses were measured using 4-axis Bruker D8 machine. X-rays with λ = 0.1542 nm wavelength were generated applying 35 mA and 40 kV power to X-ray tube with copper source. {1 2 3} crystallographic planes corresponding to $2\theta = 118.48^{o}$ were utilised to measure residual strains and then calculate residual stresses by $\sin^2\psi$ technique. Modulus of elasticity and Poisson's ratio for Mg-Ca0.8 alloy were 45 GPa and 0.33, respectively. Slower cutting speed in Fig. 3 produces more compressive residual stress on surface and shifts the maximum of generally hook-shaped stress profile to deeper layers in subsurface. Smaller rolling force causes larger compressive stress on the burnished surface. However, deepest residual compression happens under largest rolling force. Magnitude of the maximum compressive residual stress is not affected by cutting speed or rolling force, but its location is. *Comparatively*, in subsurface, high speed dry cutting induces -50 MPa stress at 100 μm depth while finish burnishing produces larger (-150 MPa) and deeper (600 μm) stress, i.e. three times in magnitude and six times in depth, respectively. In surface, finish burnishing makes larger compressive residual stresses as opposed to dry cutting.

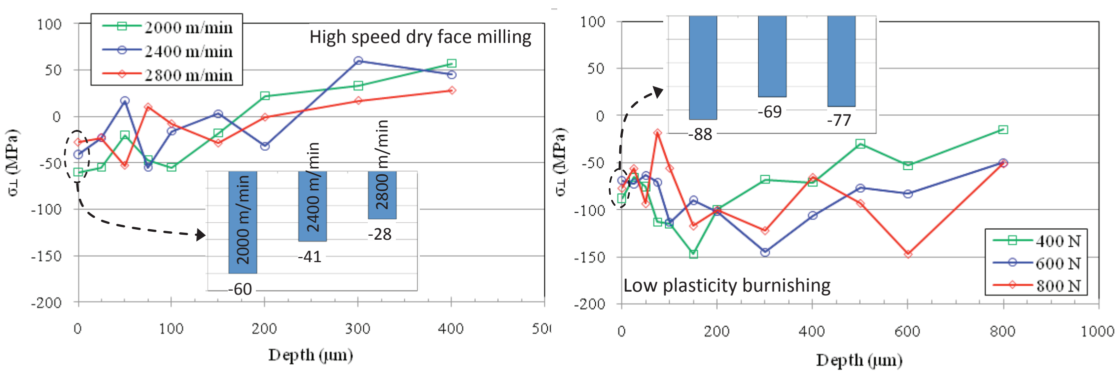

Fig. 3. Effects of process parameters on residual stresses

4.3. Microhardness

Fig. 4 shows the extent of work hardening on surface and subsurface in dry cutting and burnishing. Faster cutting speed marginally increases the amount of microhardness on surface. Microhardness on surface shows a declining trend with increasing rolling force. However, subsurface is more work-hardened under larger rolling force. The maximum work-hardened depth in dry cutting is 50 μm and beyond that microhardness profile becomes stabilized. This depth is about 300 μm in burnishing process i.e. six times deeper than dry cutting. Deep layers of compressed material produced by shallow work-hardened layers is a unique attribute of burnishing process which can be seen in contrasting residual stress and microhardness profiles in Figs. 3 and 4. This fact is determinative in stability of induced residual stresses under service loadings [5,15]. Hence, it is expected that residual stresses produced by burnishing to be more stable under typical daily loadings on a bone implant and so to have longer lasting effect on corrosion performance.

4.4. Microstructure

Subsurface microstructure of dry cut and burnished samples are shown in Fig. 5. Very coarse grain structure with no grain refinement or texture is observable. Grain refinement and texture were expected to happen through 50 μm depth work-hardened material in dry cutting and through 300 μm depth work-hardened material in burnishing. High cutting temperatures, adiabatic nature of dry cutting, and sever plastic deformation due to shear action are the ingredients which could cause dynamic recrystallization (DR) and ultimately grain refinement. FE simulations [9] have shown that high surface cutting temperatures reduce to room temperature in a shallow depth of about 25 μm. However, DR is a diffusion controlled process and strongly depends on atomic migrations which are very slow in solid state and require a stable heat source to provide the necessary temperature. Primary and secondary shear zones around the cutting edge are moving heat sources which meet each surface point for a very short amount of time. Therefore, the required time for DR is not provided. For the same reason, the observed coarse grains cannot be due to grain growth as well. Slow cooling after sand-casting seems to be the only reason for the observed coarse grain structure. Grain texture is more expected than refinement in burnishing since it is an isothermal process inherently due to presence of hydraulic oil which acts as a coolant. However, large grains clearly do not reflect the expected compression in Fig. 5.

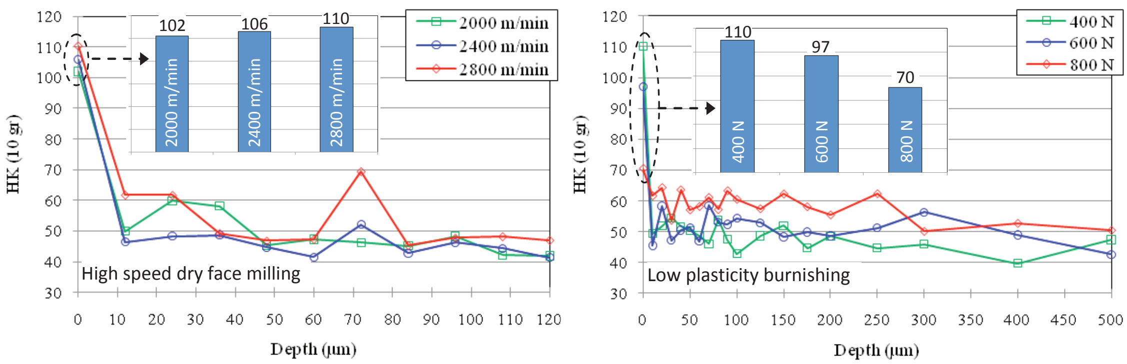

Fig. 4. Effects of process parameters on microhardness

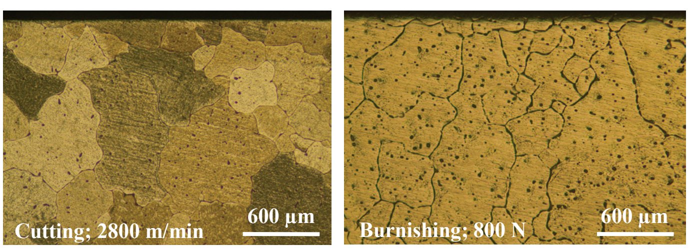

Fig. 5. Subsurface microstructures

5. Conclusions

This study focuses on surface integrity induced by synergistic dry cutting-finish burnishing process on Mg-Ca0.8 alloy. Key findings of this study are:

- Surface roughness increases by burnishing compared to the machined surfaces due to the soft nature of the Mg-Ca alloy.
- Surface hardening is apparent for both machined and burnished surfaces. In addition, burnishing produces much deep hardened layers (~ 600 µm) than those by cutting (~ 300 µm).
- Maximum compressive residual stress produced by burnishing is larger in magnitude (~ 150 MPa) and located much deeper as opposed to dry cutting.

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