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Cryogenic machining of biomedical implant materials for improved functional performance, life and sustainability

I.S. Jawahir[a]*, D.A. Puleo[b], J. Schoop[a]

[a]Institute for Sustainable Manufacturing (ISM), University of Kentucky, Lexington, KY 40506, USA
[b]Department of Biomedical Engineering, University of Kentucky, Lexington, KY 40506, USA

* Corresponding author. Tel.: +1-859-323-3239; fax: +1-589-257-1071. *E-mail address:* is.jawahir@uky.edu

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Abstract

Cryogenic cooling is known to provide a very sustainable machining process because of its environmentally benign, and economically and societally-beneficial nature. This keynote paper will focus on recent findings on producing functionally-superior engineered surfaces for improved product quality, performance and sustainability in cryogenically-processed biomedical implants. Results from cryogenic processing of *Ti* alloys, *Co-Cr-Mo* alloy, and *AZ31B Mg* alloy for achieving enhanced surface and sub-surface integrity will be summarized. Experimental results are compared with numerical/analytical simulations. Encouraging findings from this extensive study shows the tremendous potential for challenging broader applications of cryogenic machining technology for biomedical components.

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Prof. Matthias Putz

Keywords: Cryogenic cooling; Biomedical implants; Sustainable machining; Surface integrity; Functional Performance

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1. Introduction

Cryogenic cooling is a sustainable, non-toxic, and environmentally-benign means to improve the performance of both manufacturing processes and manufactured products. While cryogenic machining has been shown to offer improved tool-life across a wide range of workpiece and cutting tool materials, the ability of cryogenic coolants such as liquid nitrogen *(LN_2)* to carry away the heat generated during machining offers the unique opportunity to tailor and precisely engineer the surface/sub-surface characteristics of high value components. In the fields of automotive, aerospace, and biomedical engineering, where difficult-to-machine materials are routinely employed to manufacture high performance products, cryogenic machining is particularly relevant because it can be used as a means to attain improved functional performance and product life. Moreover, using LN_2 as a coolant is truly sustainable in the sense that it is environmentally-friendly, economically and societally beneficial, thus it further enhances the application potential of this emerging cooling strategy.

In the context of biomedical engineering, a key benefit of cryogenic machining is the elimination of secondary cleaning processes usually necessitated to wash off contamination from flood coolant (water/oil emulsion). Biomaterials are generally defined as any material that comes in intimate contact with living tissue during service [1]. For this reason, contamination has to be limited in order to prevent infection. In the context of this paper, the term *biomaterial* is used more narrowly to refer to *biocompatible metals used in biomedical implants*.

In order to be considered biocompatible, a material may not exhibit significant toxicity in the highly corrosive environment within the human body. High corrosion resistance, as well as fatigue and wear resistance, are also required characteristics of biomaterials for biomedical implants. Biocompatibility of implants is moreover not only determined by the properties of the implant material, but also by their mechanical design. Likewise, properly design implants may take advantage of a holistic design approach by considering mechanical, chemical and biological compatibility to achieve true biocompatibility. Since processing may be used to precisely engineer surface characteristics such as corrosion, wear and fatigue resistance

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by inducing compressive residual stresses and hardened surface layers, significant attention has been devoted to optimizing processes and processing parameters to achieve increased biocompatibility and functional performance in biomedical implants.

In previous work of the authors, cryogenic machining has been shown to enhance all of the relevant functional characteristics of several widely applied biomaterials such as *Ti* alloys, *Co* alloy, *Mg* alloy and *NiTi* alloys [2-4]. The key mechanism by which these improvements are attained is exceptional management of the heat generated during machining, which leads to thermal surface and sub-surface damage under conventional cooling/lubricating strategies such as flood or MQL lubrication. A summary of applications and benefits of cryogenic machining for four relevant biomedical implant materials is given in Table 1.

Table 1. Applications and benefits of cryogenic machining of metallic biomedical implant materials

	Typical applications	**Benefits of cryogenic processing**
Mg alloys	Self-absorbing implants	Enhanced corrosion resistance and hardness; compressive residual stresses; nano-structured surface layer and multi-millimeter SPD layer
Co alloys	Permanent implants	Enhanced wear resistance; nano-structured surface layer; reduced burnishing tool-wear
Ti alloys	Corrosion resistant implants and hardware	Enhanced hardness and microstructural characteristics (nano-grains likely)
NiTi alloys	Stents, clamps and staples	Significantly increased tool-life, control over phase transformation behavior

2. Experimental Results

Out of a wide range of materials used for biomedical implants, four groups of alloys were tested with cryogenic cooling and presented in the paper (see Table 1).

2.1. Cryogenic Processing of AZ31B Mg Alloy

Biocompatible *Mg* alloys are of particular interest as implant materials because of their ability to be absorbed by the body over time [5]. Essentially, no evidence of toxicity of *Mg* exists, though some alloying elements and their ions may potentially have adverse effects [6]. Moreover, *Mg* has similar density and Young's Modulus ($E \approx$ 10-60 GPa) to that of bone, largely eliminating the commonly encountered problem of stress shielding due to excessively stiff implants [5]. Denkena and Lucas [7] investigated the ability of process-induced surface and subsurface characteristics such as roughness and residual stresses to tailor the corrosion rate of $Mg_{0.7}Ca_{0.3}$ alloy. They found that by altering the burnishing force, the corrosion rate was reduced by a factor of approximately 100. Motivated by these encouraging results, cryogenic machining and burnishing of the *Mg* alloy *AZ31B* was conducted by the authors and their co-workers at the University of Kentucky for over the last several years. *AZ31B* alloy is particularly biocompatible, and therefore is an ideal candidate for self-absorbing implants [8].

2.1.1. Cryogenic Machining of AZ31B Mg Alloy

Pu et al. [9] conducted cryogenic and dry machining experiments on *AZ31B Mg* alloy at different cutting speeds and with different cutting edge radii. They reported the presence of a process-induced nano-crystalline surface layer that led to significantly improved corrosion resistance. The mechanism by which nano-grains are formed was initially hypothesized and later confirmed to be dynamic recrystallization (DRX) [9-11]. An example of the nano-structured surface layer induced by cryogenic machining can be seen in Fig. 1.

Because large cutting speeds negate the rapid cooling effect of liquid nitrogen during cryogenic machining, the cutting speed was fixed at v_c = 100 m/min following an initial investigation [8, 10]. The effects of cooling conditions and cutting edge radius were much more pronounced. With cryogenic cooling, a larger cutting edge radius led to increased compressive residual stresses, while excessive heat generated during dry machining led to the opposite trend. Pu et al. [9] subsequently reported that cryogenic finish machining with a relatively large cutting edge radius of r_β = 70 μm resulted in the largest intensity of the (0002) basal (most closely packed) plane on the machined surface, thus providing greater corrosion resistance.

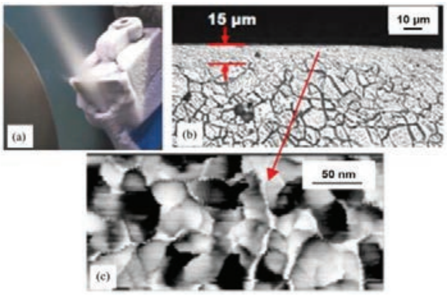

Fig. 1. Cryogenic machining of *Mg* alloy biomaterial, showing detail of cryogenic delivery (a) and sub-surface cross-sectional micrograph (b) with evidence of featureless 'white layer' and AFM image of nano-grains (c) [11].

2.1.2. Cryogenic Burnishing of AZ31B Mg Alloy

In order to further understand the nano-structured surface layer created by DRX, Pu et al. [12] also performed cryogenic burnishing experiments. Their key objective was to increase the corrosion resistance of *AZ31B Mg* alloy by severe plastic deformation (SPD), which is a common means to achieve grain refinement via DRX. Cryogenic burnishing is an alternative processing technology to other SPD techniques such as surface mechanical attrition (SMAT), which have produced contradictory results in various materials, including low carbon and stainless steels [3].

By simultaneously reducing surface roughness values and inducing compressive residual stresses, burnishing was shown to be capable of significantly increasing the corrosion resistance in *Mg* alloys [12-14]. Fig. 2 shows a comparison of the corrosion behavior between ground and cryogenically-burnished *AZ31B Mg* alloy. It can be seen that the basal texture

(0002) induced by cryogenic burnishing is directly correlated with significantly reduced corrosion rates (see Fig. 2c).

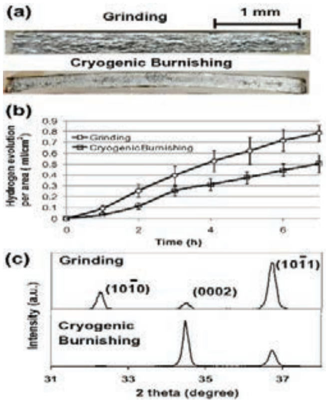

Fig. 2. Corrosion resistance of ground and cryogenically burnished samples (a,b) and XRD texture analysis (c) [14].

In addition to a favorable texture on the machine surface, Pu et al. [12] observed a deep process-induced layer in the sub-surface of cryogenically burnished samples, as seen in Fig. 3. While Denkena et al. [7] had reported layer depths of up to 1000 μm with a (dry) burnishing at a pre-load of 500 N, Pu et al. [12] demonstrated the ability to induce SPD layers in excess of 3000 μm with a radial force of approximately 1500 N using cryogenic burnishing. It should be noted that the heat generated during dry machining and burnishing with large pre-loads counteracts the grain-refining mechanism of DRX [9, 14]. Therefore, cryogenic cooling is necessary in order to produce very large process-induced layers with strong basal textures. In the context of metallic biomedical implants, control over the size of the corrosion-resistant layer in turn allows for control of the time over which biodegradation will take place. In this way, customized self-absorbing implants could be created.

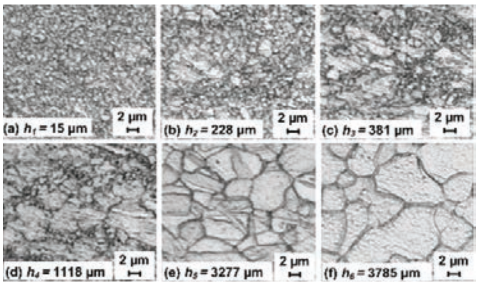

Fig. 3. Cross-sectional micrographs at various depths showing grain size throughout the process-influenced layer in *AZ31B Mg* alloy produced by cryogenic burnishing [10].

2.1.3. *Modeling*

In order to better study the microstructural changes that result in the beneficial properties of the nano-structured layer in *AZ31B Mg* alloy, Pu et al. conducted a study using finite element modeling (FEM) [2]. Based on the assumption that DRX is the key mechanism of grain refinement in *Mg* alloys, they developed a subroutine that considered the critical strain ε_{cr}, which is influenced by the Zener-Hollomon parameter Z and given by Eqs. (1) and (2), respectively.

$$\varepsilon_{cr} = 0.02039 * Z^{a} \tag{1}$$

$$Z = \dot{\varepsilon} * \exp\left(\frac{Q}{RT}\right) \tag{2}$$

where $\dot{\varepsilon}$ is the strain-rate, Q is the activation energy, R the gas constant and T the temperature. The empirical constant a was used to calibrate the critical strain in order to match the experimentally measured layer thickness. The model was subsequently calibrated using a second empirical constants b, that related the initial grain size d_{int} to the final (i.e., recrystallized) grain size d. A summary of the calibration of the user subroutine used by Pu et al. [2] is shown in Fig 4.

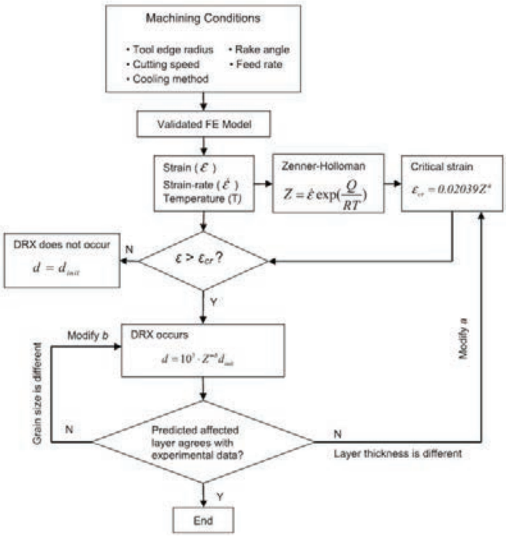

Fig. 4. Flow chart for calibration of FEM user subroutine to predict DRX in *Mg* alloy [2].

Modeling results confirm experimental observations showing a significant increase in the size of the featureless layer and reduction in grain size in cryogenic cooling [2, 11]. The effect of cutting edge radius on grain size was also accurately predicted by the model, as shown in Fig. 5.

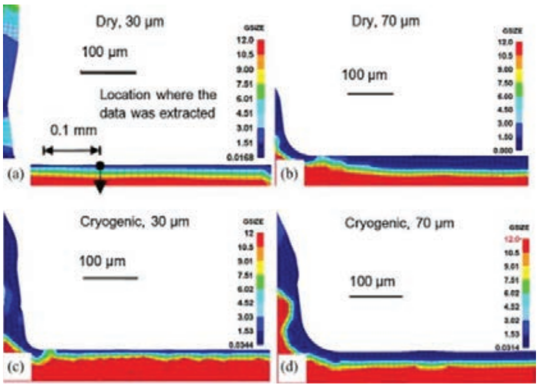

Fig. 5. FEM modelling results of recrystallized grain size distribution for both (a,b) dry, and (c,d) cryogenic machining of *AZ31B Mg* alloy [2].

As noted previously, larger cutting edge radius and cryogenic cooling, both promote increased grain refinement and process-influenced layer depth. Pu et al. [9] noted an increase in strain (and consequently DRX) as the likely reason for these observations. As a whole, the work done by Pu et al. [2, 8, 14] demonstrated the ability of cryogenic machining and burnishing processes to have a significant effect on the properties of *AZ31B Mg* alloy that are most relevant for self-absorbing biomedical implants, namely corrosion resistance and hardness. By managing the heat generated during processing, cryogenic cooling allowed for DRX-induced grain refinement, and consequently improved surface and sub-surface properties.

2.2. Cryogenic Burnishing of Co-Cr-Mo Alloy

Co-Cr-Mo alloys are a commonly used class of high-strength, high corrosion resistant biomedical alloys that are employed as permanent implants. Moreover, developing metal-on-metal bearings for complete joint replacement has become a topic of increasing interest in light of recent developments of SPD-induced nano-structured layers [15]. Such process-influenced layers exhibit improved functional performance such as wear, fatigue and corrosion resistance [12, 13]. Yang et al. [16] performed cryogenic burnishing experiments on *BioDur CCM Alloy*, which is a low-carbon, high-nitrogen (*N*<0.25%) wrought *Co-Cr-Mo* alloy with low abrasive carbide content and excellent ductility. The fixed-roller experimental set-up employed by the researchers is shown in Fig. 6.

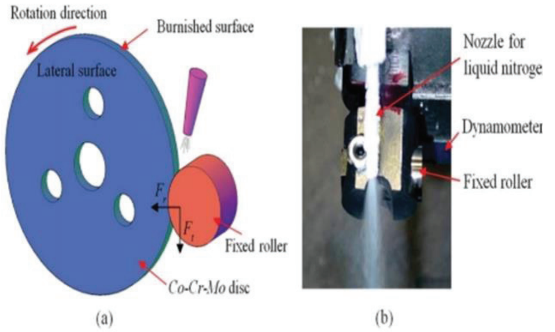

Fig. 6. Experimental setup for cryogenic burnishing of *Co-Cr-Mo* alloy [16].

Using cryogenic cooling, Yang et al. [16] were able to achieve up to three times the refined layer thickness produced by dry burnishing when a relatively large preload of 0.254 mm was used. While there was relatively little difference in process-influenced layer thickness at a lower preload of 0.127 mm, the microstructures and microhardness profiles of the burnished samples were notably different. The micrographs in Fig. 7 show that the average grain size from dry burnishing was approximately 1 μm, while cryogenic burnishing resulted in grains with an average diameter of less than 600 nm.

Yang et al. [16] cited this difference in microstructure as clear evidence of DRX being responsible for the grain refinement process, since lower temperatures with cryogenic cooling would favor develop smaller re-crystallized grains. A subsequent study by Yang et al. [17] measured the process temperature distributions in both dry and cryogenic burnishing. Interestingly, the maximum temperature during cryogenic burnishing occurred approximately 2-4 mm below the burnished surface. At a preload of 0.21 mm, they measured maximum burnishing temperatures of 630 °C (dry, surface) and 390 °C (cryogenic at 2 mm depth). The surface temperature, where the most relevant functional properties are induced, was only 250 °C in cryogenic burnishing.

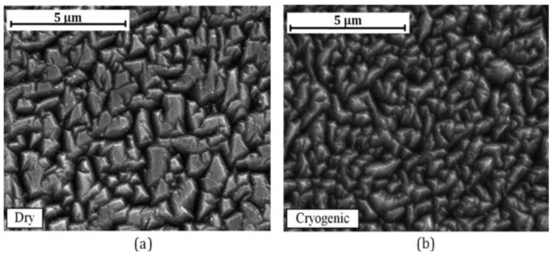

Fig.7. Scanning electron micrographs of the surface layers of dry (a) and cryogenically (b) burnished *Co-Cr-Mo* alloy [16].

In addition to DRX, strain-induced phase transformation is another mechanism that may lead to improved surface characteristics in *Co-Cr-Mo* alloy [18]. Since both of these mechanisms require relatively low temperatures in order to prevent an undesirable annealing effect, cryogenic burnishing is expected to promote improved surface and sub-surface properties compared to dry burnishing. Indeed, Yang et al. [19, 20] showed that cryogenic burnishing resulted in significantly finer surface grains, and a significantly larger fraction of hexagonal close-packed (hcp) structured grains which were hypothesized to be ε-martensite, which had been reported to nucleate exclusively along $(111)_\gamma$ planes.

The phase analysis in Fig. 8 shows the large difference in relative intensity of the $(0002)_\varepsilon$ and $(1011)_\varepsilon$ hcp planes when cryogenic burnishing was used. Hcp structured *Co-Cr-Mo* has been shown to have significantly improved wear behavior compared to the face-centered cubic (fcc) structure of virgin *Co-Cr-Mo* alloy, and therefore cryogenically-burnished samples were expected to significantly outperform other processing strategies [18, 19].

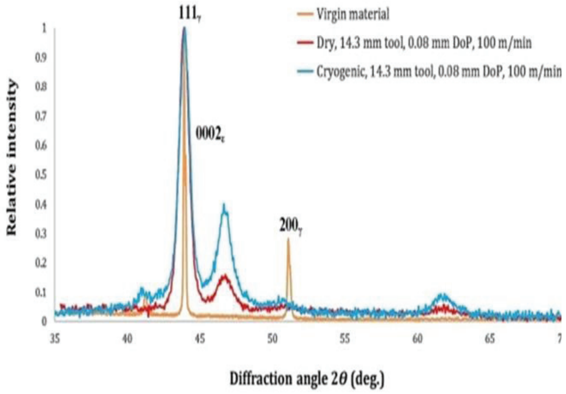

Fig. 8. XRD phase analysis of *Co-Cr-Mo* alloy [19].

2.2.1. Modeling

Yang [21] modeled the cryogenic burnishing process for *Co-Cr-Mo* alloy using a 2D FEM simulation using the Deform© software. Using the experimental data obtained under various conditions for both dry and cryogenic burnishing, the model was iteratively calibrated. The key goal of Yang's simulation was the prediction of grain size, which is compared with experimental measurement in Fig. 9.

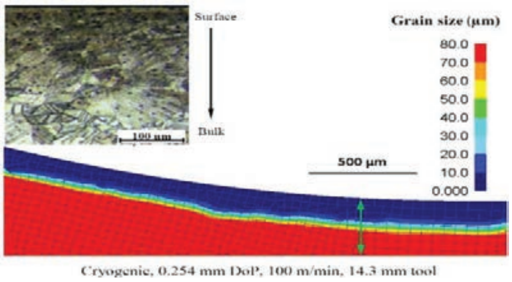

Fig. 9. Comparison between FEM grain size prediction and experimentally observed data from an optical micrograph [21].

To model the mechanical behavior of *Co-Cr-Mo* alloy more accurately, the researcher separated the flow stress into three separate stages. Before reaching the peak strain for DRX initiation, ε_p, a modified version of the Johnson-Cook constitutive model was employed. Beyond the peak strain, which was determined by finding the point of zero slope on the stress/strain curve, Yang [21] used a novel model based on the Avrami equation [22]. The latter was initially developed to model static recrystallization phenomena, but has also been applied to DRX due to the similarities between the two processes [22]. The third stage of the flow stress is reached when DRX has been completed and a steady state stress σ_{ss} is attained. Yang [21] also noted that this final condition is generally only reached at very large strains and that no experimental data on σ_{ss} was available for the particular *Co-Cr-Mo* alloy used in cryogenic burnishing experiments. Nevertheless, Yang [20] used a value of 80% of the peak stress σ_p, beyond which DRX induced softening occurs.

In order to model the variable friction that results from DRX-induced grain refinement, Yang [21] adjusted the coefficient of friction from an initial (measured) value of $\mu = 0.05$ to 0.4 for the recrystallized part of the workpiece surface in contact with the burnishing roller. Overall, Yang [21] found very good agreement between observed and predicted grain size, as can be seen in Fig. 10.

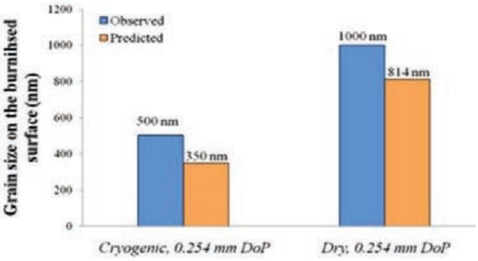

Fig. 10. Measured surface grain size from experimental data and FEM model prediction [21].

2.3. Cryogenic Processing of Ti Alloys

Titanium and its alloys are used to manufacture a variety of biomedical implants and components, including dental implants, total joint replacements, femoral hip stems, and hardware (nails, rods, screws, wires, etc.) [23]. The main reasons for using *Ti* alloys as an implant material are excellent biocompatibility due to good corrosion resistance and negligible toxicity [1]. There are concerns that certain alloying elements, particularly *V* and *Al*, may be released as part of microscopic wear particles and lead to harm in the body [24]. For example, the commonly used alloy *Ti-6Al-4V* alloy has been reported to have caused allergic reactions in a small number of patients [25]. To address this, novel *V*-free alloys such as *Ti-6Al-7Nb* been developed [26]. Overall, the major drawbacks of *Ti* alloys are poor wear characteristics (e.g., fretting and galling are common) as well and poor bending performance (fatigue resistance) [23, 27]. In light of this, the foremost motivation for cryogenically machining and burnishing of biomedical *Ti* alloys is to improve functional characteristics by inducing increased hardness and fatigue resistance while reducing grain size to improve mechanical properties.

2.3.1. Cryogenic Machining of *Ti-6Al-4V* Alloy

Hong [28] was among the first to study cryogenic machining of *Ti-6Al-4V* alloys. Subsequently, Venugupal et al. [29], Birmingham et al. [30], and Shokrani et al. [31] confirmed most of the initial observations made by Hong et al., such as improved tool-life and changes in chip morphology. However, Birmingham et al. [30] and Pusavec et al. [32] reported either an increase or very little change in tool/chip friction, while Hong [28] had reported a decrease in friction with cryogenic cooling, likely due to the unique delivery of liquid nitrogen underneath the chip by means of a special chip breaker design, which effectively reduced the tool/chip contact length.

While it has been demonstrated that cryogenic cooling leads to significant increases in tool-life when machining *Ti* alloys and other difficult-to-machine materials, little consideration was given to surface integrity or functional performance of the machined workpiece. The heat generated during machining of *Ti-6Al-4V* alloy not only increases tool-wear, but also degrades the machined surface by thermally softening it, and in some cases leaving an undesirable, brittle alpha-case. Cryogenic cooling addresses the problem of thermal softening, yielding excellent surface and sub-surface quality, as shown in Fig 11.

In a recent study on surface integrity in cryogenic machining of *Ti-6Al-4V* alloy, Rotella et al. [33] reported significantly increased surface hardness and reduced grain size with cryogenic cooling compared to flood and dry machining. They also found that cryogenic machining resulted in the lowest values of surface roughness under all cutting speed/feed conditions that were investigated. Since surface roughness has been reported to be among more relevant in determining fatigue life whenever $R_a < 0.1$ µm (i.e., under most finish turning/milling conditions), cryogenic machining may be particularly suitable for sustainable manufacturing of heavily-loaded biomedical implants such as femoral hip stems [34]. In a subsequent study, Rotella and Umbrello [35] successfully modeled their experimental results using FEM, the results of which are summarized in Fig. 11.

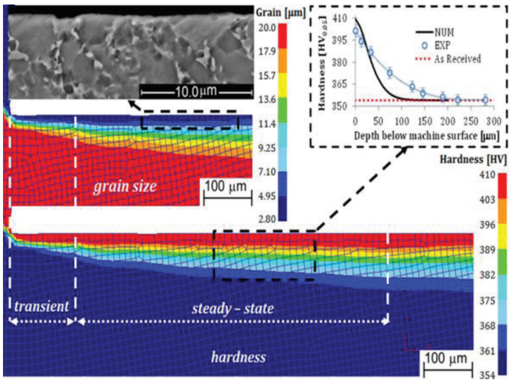

Fig. 11. Comparison between cryogenically machined microstructure from experiments and FEM simulation results for *Ti-6Al-4V* [35].

2.3.2. Cryogenic Burnishing of Ti-6Al-4V Alloy

In addition to cryogenic machining, cryogenic burnishing of *Ti* alloys has been studied by Caudill et al. [36] showing improved surface integrity in *Ti-6Al-4V* alloy. Surface roughness reduction of 56.7% was achieved with cryogenic burnishing, compared to 63.4% with dry burnishing. The authors attributed this difference to a decrease in plasticity with cryogenic cooling. Consequently, the most pronounced improvement provided by cryogenic burnishing was the creation of a 30% larger burnished layer depth compared to dry burnishing, along with a 64.2% increase in surface hardness compared to the bulk hardness of 34 HRC. The microhardness depth profiles shown in Fig. 12, in comparison with dry and flood-cooled burnishing, illustrate the increased overall sub-surface hardness in cryogenic burnishing.

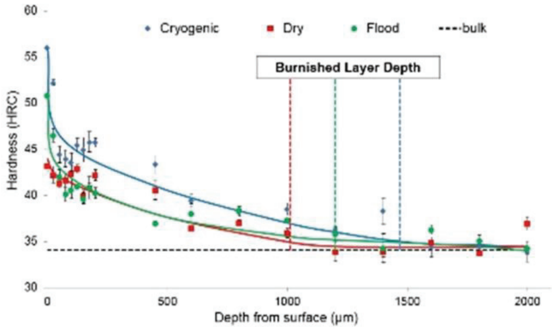

Fig. 12. Microhardness depth profiles for cryogenic and conventional (dry, flood-cooled) burnishing of *Ti-6Al-4V* alloy (adapted from [36]).

By increasing both the absolute hardness and the depth of the burnished layer, cryogenically-burnished biomedical implants may exhibit increased wear resistance across a longer life cycle. Practically, an implant with a ~1.5 mm deep burnished layer (as achieved by Caudill et al. [36], see Fig. 12) may never wear enough to expose its unaffected bulk. With a large burnishing preload of 2500 N, Caudill et al. [36] reported an increase in the average burnished layer hardness of approximately 75% when cryogenic cooling was used. They concluded that the key mechanism responsible for improved surface integrity from cryogenic burnishing was effective control over detrimental thermal softening that occurs during dry and flood-cooled burnishing.

2.3.3. Cryogenic Machining Ti-6Al-7Nb Alloy

Sun et al. [37] evaluated the applicability of cryogenic machining for biomedical alloy, *Ti-6Al-7Nb*. Cryogenic processing was found to offer improved surface roughness and overall surface morphology compared to both dry and flood-cooled machining, as can be seen in Fig. 13.

Dry machining in particular led to adhesion, which degraded the machined surface. Sun et al. [37] also noted that the increased cutting temperature during dry machining is likely to be responsible for this effect, as well as thermal softening of the machined sub-surface. While there was relatively little difference in surface and sub-surface micro-hardness between dry and flood-cooled machining, cryogenic cooling led to 35% increased surface hardness over the workpiece bulk and 20% higher hardness than flood-cooled machining.

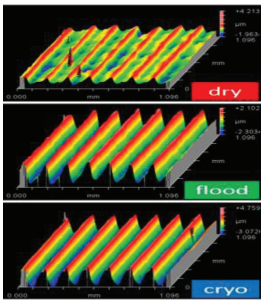

Fig. 13. Surface topography of *Ti-6Al-7Nb* alloy (adapted from [37]).

3. Discussion and Outlook

3.1. Further Applications of Cryogenic Processing of Metallic Biomaterials

In addition to the three major metallic biomaterial groups (*Mg*, *Co*, and *Ti* alloys), cryogenic processing is expected to also lead to enhanced functional characteristics in other, less commonly used implant biomaterials. A potential area for further study is cryogenic machining of implant-grade stainless steels. In this class of materials, an increase in corrosion and wear resistance may lead to a larger range of potential applications as cost-effective, long-term implants.

Both Hong and Broomer [38] and Dhananchezian et al. [39] studied cryogenic machining of *AISI 304* stainless steel. The results of both studies were in agreement that carefully applied cryogenic cooling not only improved the overall sustainability of the machining process, but also increased the surface quality of the workpiece compared to flood-cooled machining. While early work performed in Japan in 1969 by Uehara and Kumagai [40] and in the USA in 1990 by Dillon et al. [41] had reported a negative effect of cryogenic flood-cooling (i.e., submerged cryogenic machining) on tool-life and surface quality when machining *AISI 304*, these findings were later shown to have been the result of excessive (i.e., flood) use of cryogenic coolant. Hong and Broomer [38] were able to demonstrate that when a limited amount of liquid nitrogen is sprayed onto the tool/chip interface, cryogenic machining does indeed outperform conventional cooling/lubricating strategies in *AISI 304* stainless steel. Clearly, the manner in which liquid nitrogen is applied to the both the workpiece and cutting tool has a significant effect on the performance of the machining process.

Kaynak et al. [4] have studied cryogenic machining *NiTi* shape memory alloys, which are commonly used in dental implants and coronary stents as a result of their ability to undergo a predictable volumetric phase transformation. The researchers reported improvements in surface topography and roughness, as well as notable alterations of the phase transformation behavior in cryogenically machined samples, with a process-induced layer depth of 400-500 μm. As a result, cryogenically-machined and/or burnished *NiTi* material could be precisely engineered to deliver desirable mechanical properties and shape memory (i.e., phase transformation) behavior, specifically engineered to offer improved performance in biomedical applications such as stents and wires.

Fig. 14 shows TEM micrographs of *NiTi* samples with different processing histories ((a) as-received, (b) dry machined, and (c) cryogenically machined). Both dry and cryogenic machining led to an increase in dislocation density and twin boundaries, but cryogenic processing resulted in a higher density of twins, as can be seen in the diffraction pattern in Fig. 13f. Kaynak et al. [4] showed that this severe degree of plastic deformation altered the mechanical behavior of the entire workpiece by effectively suppressing the characteristic martensitic phase transformation exhibited by *NiTi* shape-memory alloys.

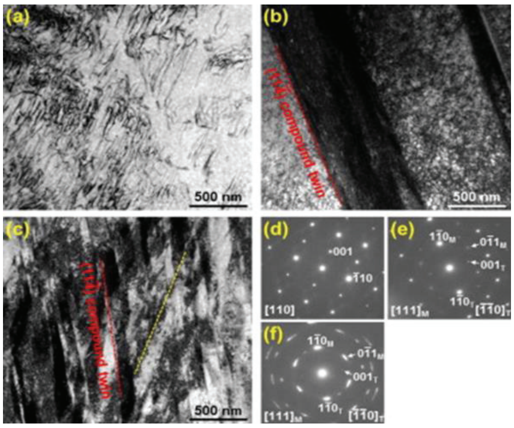

Fig. 14. Bright-field TEM micrographs of (a) as-received, (b) dry machined and (c) cryogenically machined *NiTi* specimens. (d), (e) and (f)) are selected-area diffraction patterns obtained from (a), (b) and (c), respectively. [4].

3.2. Engineered Functional Surfaces for Biomedical Applications Induced by Cryogenic Processing

A unique opportunity made available with cryogenic processing technology is the ability to create engineered surfaces with desirable functional characteristics. In metallic biomedical implants, such surfaces need to offer sustained performance in highly demanding environments (i.e., inside the body) under significant, and often repetitive, mechanical loading, as is the case of joint replacements. An issue of current interest is the development of monolithic *Ti*-alloy femoral hip stems. Presently used designs rely on a *Co-Cr-Mo* or ceramic head to articulate against the hip socket. Previous attempts to apply wear-resistant coatings have failed because of accelerated wear induced by abrasive debris that occurs during the wear process. It is now conceivable that super-hard, corrosion-resistant, and nano-structured surface layers induced by cryogenic processing may eliminate the need for coatings of multi-material assemblies. Not only would an implant with such surface properties perform better than currently available technology, but the overall environmental and society impacts the product would be meaningfully reduced. Therefore, engineered surfaces achieved with cryogenic processing are expected to lead to holistic improvements in overall sustainability of products (i.e., implants), as well manufacturing processes (machining, burnishing, etc.).

Another potentially valuable application of cryogenic cooling is the technology of cryogenic fine finishing (grinding, lapping, honing, and polishing) for highly finished surfaces of biomedical implants. Since conventional grinding generates significant heat due to large negative effective rake angles of the abrasive particles, ground surfaces often exhibit tensile residual stresses. Using a hybrid cooling approach with liquid nitrogen as the coolant medium, and a suitable (low freezing point) lubricant, cryogenic grinding may allow for very smooth surfaces without sub-surface thermal damage. In polishing, cryogenic cooling would likewise be a means to mitigate the negative effects of heat generated during the process. If compressive residual stresses and a hardened surface layers are desirable for functional performance, cryogenic grinding and polishing by be an effective means to achieve excellent surface finish and dimensional tolerances, while also ensuring engineered surface quality.

4. Conclusions

Cryogenic processing has been demonstrated to be a sustainable, non-toxic alternative to conventional flood-cooled, MQL and dry machining processes. Significant improvements in key surface integrity measures have been achieved, such as:

- Increased surface hardness and wear resistance
- Beneficial phase transformations of the processed surface layer
- Deep layers of significant grain refinement, with nano-structured surface layers
- Increased corrosion resistance of the processed surface
- Increased compressive residual stresses

By effectively managing the heat flow during machining and burnishing, significantly larger cutting edge radii and burnishing preloads can be used without inducing thermal damage. As a result, cryogenic processing is particularly conducive to DRX because very large strains can be induced without simultaneously annealing the dislocations and twins necessary for DRX to occur. Future application of cryogenic machining and burnishing may include other materials such as *NiTi* shape memory alloys and various grades of surgical stainless steels.

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