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Improved Surface Integrity from Cryogenic Machining of *Ti-6Al-7Nb* Alloy for Biomedical Applications

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Abstract

Ti-6Al-7Nb alloy is emerging as an alternative biomedical material for replacing *Ti-6Al-4V* alloy used in dental implants and femoral stem prosthesis applications. In cryogenic machining using liquid nitrogen, the surface integrity characteristics of *Ti-6Al-7Nb* alloy significantly improved compared to dry and flood-cooled machining. This study shows that surface roughness improved in cryogenic machining by 35% and 6.6% respectively, compared with dry and flood-cooled machining. Also, the hardness in the cryogenically-machined surface layer increased, by 33.6% and 14.7%, respectively, compared to dry and flood-cooled machining, with the formation of a severe plastic deformation (SPD) layer with less volume fraction of α-phase.

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Keywords: Cryogenic machining; Microhardness; Surface integrity.

1. Introduction

Due to the requirement of specific mechanical and material properties including good biocompatibility, wear resistance, excellent mechanical strength maintaining cyclic loading and low elastic modulus, stainless steels, cobalt and titanium-based alloys are used as the primary metallic biomaterials in order to endure the fatigue resistance to gradation, avoid adverse tissue reaction, minimize bone resorption and wear debris generation [1]. Titanium alloys are considered to be one of the most suitable metallic biomaterials attracting much attentions in the biomedical applications, in which *Ti-6Al-4V* alloy is widely used as the hard tissue replacements, such as dental implants, hip and knee prosthesis, artificial joins and bones etc. [2], and this is largely due to its good property combinations of high yield strength, fracture toughness and corrosion resistance.

However, recent studies show that long-term health problems, such as alzheimer, neuropathy and osteomalacia diseases, may be caused by the release of *V* ions from the *Ti-6Al-4V* alloys used as implants [3, 4]. Also, the modulus of *Ti-6Al-4V* alloy is higher than human bone tissue within the range from 10-40 GPa, and stress-shielding resulting in bone resorption and implant failure is induced because of this issue [5]. Considering these two problems, new types of titanium alloys with excellent workability, mechanical properties with non-toxic and non-allergic elements have been developed, for example, *Ti-Nb-Zr*, *Ti-Mo-Zr-Fe*, *Ti-Nb-Zr-Ta* alloys [6]. Among these newly-developed titanium alloys, *Ti-6Al-7Nb* alloy is a typical substitute to replace *Ti-6Al-4V* alloy, as the element of niobium is non-toxic and has a lower modulus closer to human bone tissue, which also has the benefit of avoiding the occurrence of stress-shielding.

Cryogenic machining with liquid nitrogen as the coolant, has emerged during the last two decades, and it continues to draw great attentions from the academic and industry communities. Machining is an indispensable process to achieve the dimensional accuracy of the manufactured components to fulfill the functional performances of these components. Recent investigations demonstrate that cryogenic machining could not only maintain the machining performance required to obtain the desired dimensional and geometrical accuracy, but also improve the surface integrity characteristics, such as reduced surface roughness, increased hardness, producing refined layers with ultra-fine or nano

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grains which result in enhanced wear/corrosion resistance, inducing compressive residual stresses in the cryogenically-machined surface layers, thus extending the fatigue life of the manufactured components.

Pu et al. [7] reported that a featureless layer with nano grains with an average size of 31 nm was produced on the machined surface of magnesium alloy *AZ31B* by cryogenic machining, while a 87% hardness increase was found in the surface layers, where the depth of compressive residual stresses was extended to approximately 200 µm below the surface. Corrosion resistance of this magnesium alloy was also improved due to the large intensity of basal plane on the machined surface [8]. In machining of *Ti-6Al-4V* alloy, the hardness in the surface layer was increased in the cryogenically-machined surface, in comparison with dry and minimum quantity lubrication (MQL) machining [9], while surface roughness R_a of lower than 0.3 µm was observed in all three machining methods where the lowest surface roughness value was produced by cryogenic machining.

Since there is very little work reported in the literature on cryogenic machining of *Ti-6Al-7Nb* alloy, the effects of cryogenic machining on the surface integrity of this biomaterial is almost unknown. The new findings presented in this paper illustrate the effects of cryogenic machining, on the surface integrity characteristics of *Ti-6Al-7Nb* alloy. The surface roughness, hardness in the surface and sub-surface and microstructure influenced by cryogenic machining are investigated and compared with those obtained from flood-cooled and dry machining in this study.

2. Experimental Work

The experimental work was conducted on *Ti-6Al-7Nb* alloy bar with 1 m length and the diameter of 17 mm used for biomedical application, and the detailed chemical composition of this material is shown in Table 1. The input parameters are cutting speed of 30 m/min, feed rate of 0.05 mm/rev and depth of cut of 0.75 mm. Dry, flood-cooled and cryogenic machining, with liquid nitrogen as the coolant are conducted. A HAAS TL-2 CNC lathe was used in the experiments, and the cutting tool inserts selected are Kennametal *TiAlN* coating CNMG 431 RP with the nose radius of 0.4 mm and 5° rake angle. The measured initial cutting edge radius was approximately 37.8 µm. Liquid nitrogen was delivered at the rake face of tool insert at a flow rate of about 10 g/s mass under the pressure of 1.5 MPa.

Fig. 1 shows the experimental setup of cryogenic machining of *Ti-6Al-7Nb* alloy. The surface roughness is measured on a Zygo NewView 5300, which is a non-contact white light interferometer system. To observe the microstructure, a Nikon EPIPHOT 300 with Leica DFC425 optical microscope is used. Hardness measurement is performed on a CSM Micro-Combi Tester, where 25 gf load and 15 seconds are selected to make the indentation. Kroll's reagent is used to study the microstructure of *Ti-6Al-7Nb* alloy after grinding and polishing processes.

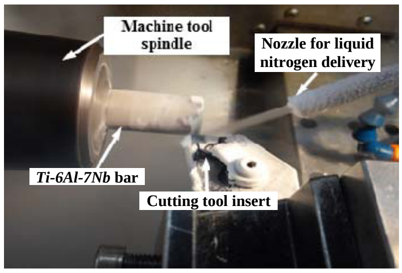

Fig. 1. Experimental setup for cryogenic machining of *Ti-6Al-7Nb* alloy.

Table 1. Chemical composition of *Ti-6Al-7Nb* alloy.

Ti-6Al-7Nb	*Al*	*Nb*	*Fe*	*C*	*N*	*H*	*O*	*Ti*
Weight (%)	6.1	6.9	0.15	0.01	0.02	0.02	0.08	Bal.

3. Results and Discussion

3.1. Surface roughness

The measured surface roughness, R_a values are shown in Fig. 2 (a). It is quite evident that a smaller surface roughness of 0.42 µm was produced by cryogenic machining, compared with dry and flood-cooled machining at 0.65 µm and 0.45 µm respectively. Surface roughness could be reduced due to less adhesion between the tool rake/flank face and newly generated machined surface under a lower cutting temperature caused by the delivery of liquid nitrogen during cryogenic machining. A similar trend was also found by Dhananchezian and Kumar when cryogenic machining was used to process *Ti-6Al-4V* alloy [10]. Lower friction at the interfaces of tool-work material and tool-chip was also shown as resulting from the lubrication and cooling effects in cryogenic coolant [11]. This effect may be causing less adhesion, thus leading to improved surface roughness in cryogenic machining.

The difference of surface roughness R_a value produced by cryogenic machining was smaller compared with flood-cooled machining, however the much smoother and more consistent surface was obtained for cryogenically machined sample showed in the detailed surface profiles as Fig. 2 (b) to (d), which support the above statement.

(a)