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The effects of Cooling Conditions on Surface Integrity in Machining of *Ti6Al4V* Alloy

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Abstract

This paper presents results from a comparative study of machining of *Ti6Al4V* alloy under dry, MQL and cryogenic cooling conditions using coated tools at varying cutting speeds and feed rates. The influence of the cooling conditions on surface integrity and the product performance was studied in terms of surface roughness, metallurgical conditions, including microstructure, hardness, grain refinement and phase transformation of the machined product. Results show that cooling conditions affect surface integrity of the product signifying the benefits of cryogenic cooling in improving the overall product performance.

Keywords: *Machining; Surface Integrity; Cryogenic Cooling; Ti6Al4V.*

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1. INTRODUCTION

Global competitive market in manufacturing demands high quality products at reduced costs and improved productivity rates. Advanced technological solutions are urged for globally-competitive sustainable manufacturing [1]. The aircraft industry is one of the most relevant example where all finished products must be produced with consistently high quality, to ensure high safety standards for performance over the lifetime. In the manufacture of aerospace components, surface integrity plays a key role due to its strong correlation with the functional performance and service-life of such engineered components. Numerous aircraft components are produced exclusively by a range of machining operations. Their use and functional performance heavily depend on being able to design and manufacture these components with high degree of reliability and predictability of their functionality and safety. Surface characteristics of machined products such as microstructure, surface roughness, hardness and residual stresses are among the most significant characteristics determining the reliability and the functional performance of a product [2]. A long-lasting product satisfying high quality standards helps to save energy and costs during its functional performance, and therefore can be considered more sustainable. A sustainable product would not only require less-frequent replacement with upgradability and maintainability, but also must demonstrate high reliability and improved safety during its service life [3]. Metalworking fluids (MWFs) have generally been considered highly-effective, and as integral part of manufacturing processes for decades, despite conflicting studies showing the actual effectiveness of their use in several operations in terms of unfavorable product and process performance results. Over the years, the MWFs have also changed dramatically, due to high demands to provide better performance, and facilitate improved health and safety conditions. In metal machining, the use of cutting fluids is regarded as an area for potential improvement because of the serious health and environmental threat associated with their use, disposal and related high costs.

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Thus, various researchers have examined the benefits, drawbacks and conditions necessary for machining a range of materials with dedicated cooling methods such as flood-cooling, dry and MQL machining [4-8].

At the onset, it appears that the most-promising idea would be to use a more sustainable and cost-effective process by eliminating the traditional MWFs, since they are not embodied in final products. However, since MWFs are often required to produce high performance products, their elimination is not always possible, especially when difficult-to-cut materials are machined [4].

Several conscious cooling approaches [4, 9, 10] have been widely investigated in the recent time, especially for difficult-to-cut materials. In particular, liquid nitrogen (LN_2) has been applied as a cryogenic coolant and, consequently, it has been widely investigated, especially for machining *Ti6Al4V* titanium alloy [11-15]. Most of the research demonstrated improvements in various aspects of *Ti6Al4V* machinability, either by cryogenically freezing the workpiece or by spraying LN_2 to the cutting zone. The main functions of cryogenic cooling in metal cutting were defined by Hong and Zhao [11] as effectively removing heat from the cutting zone. Hence, it has the potential to decrease the cutting temperatures [16], modify the frictional characteristics at the tool/chip interfaces[17], change the properties of the workpiece and the tool material [18].

Other research showed the effects of different cooling strategies, including cryogenic cooling, on surface and sub-surface hardness, founding that it generally increases when a drastic cooling is applied [14, 19]. Particularly, specimens of *Ti6Al4V* alloys machined under cryogenic cooling showed rapid increase in their strength and hardness, while their toughness and ductility showed little variation as the temperature decreases [15]. Therefore, simultaneously cooling the workpiece to enhance the chemical stability of the workpiece, and cooling the cutting tool to enhance the hardness and chemical stability of the tool, were recommended as an effective cryogenic strategy for titanium alloy [15].

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Furthermore, it was also stated that liquid nitrogen should have some sort of positive boundary lubrication effect [17]. Strong adhesion between tool rake and chip face occurs in dry cutting conditions and lower temperatures could make the material harder and less sticky by reducing adhesion between the interacting surfaces resulting in a low friction [17]. As a consequence, the reduced friction coefficient at the tool-chip interface generates lower cutting forces than those observed in dry machining.

Finally, it has been also reported that cryogenic process successfully generates thicker surface layers consisting of ultrafine/nano-grain structures on different materials such as steels, *Ni* and *Mg* alloys [20-22]. Along with the benefits on grain refinement, cryogenic under severe plastic deformation (*SPD*) is also expected to introduce compressive residual stresses on the surface and sub-surface layers [23].

In summary, the cryogenic processing-induced surface integrity modifications can be beneficial for a series of processes and products performance. However, very few studies have been devoted to quantify these simultaneous changes in surface integrity during cryogenic processing [23-25], whereas no complete investigation on surface integrity are done when *Ti* alloys are investigated, but only studies on cryogenic cooling influence on surface roughness are reported [26-27]. Therefore, the main objective of this paper is to investigate and establish the effects of different cooling/lubricating conditions on surface integrity (surface roughness, hardness modification, phase changes, grain size, etc.) in machining of *Ti6Al4V* alloy at varying cutting speeds and feed rates, to enable optimized product performance.

2. *EXPERIMENTAL PROCEDURE*

The orthogonal cutting operation was conducted on a Mazak QuickTurn10 CNC turning center, and it involved radially cutting of the *Ti6Al4V* (354 HV) disks at feed rates of 0.1 and 0.05 mm/rev at three cutting speeds (Table 1). The cutting tests were designed to avoid

undesired effects on the machined surface related to transient conditions. At the prescribed end-of-cut, the cutting tool was instantaneously retracted at maximum feed to avoid the rubbing of the tool against the machined workpiece surface. The utilized cutting tool inserts are coated carbides, Kennametal® KCU10 grade, with an advanced PVD *TiAlN* coating, and are of triangular shape - TNGG432FS series, mounted on a MTCNN-124 tool holder (providing rake and clearance angles of 7° and 11°, respectively). The measured initial cutting edge radius, prior to machining was consistent, and was in the range of 8 – 10 microns in all tested tool inserts.

The effect of variations in cutting edge radius during each test was avoided by allowing fresh cutting edge for each test of short duration. The MQL tests were performed applying vegetable oil emulsion through an external nozzle to the cutting zone properly selecting a flow rate of 60 ml/hr [28]. (with a pressure of 4 bar), while the cryogenic coolant (LN_2) was applied through a 2 mm nozzle (with a pressure of 12 bar) to the cutting region, thus creating a surface temperature of -185 °C. After machining, all samples were metallographically-processed: sectioned, mounted on a resin holder, and then polished and etched. The etchant employed is the Kroll's reagent that is recommended for etching nonferrous materials and recommended for *Ti* alloys. The composition of the reagent is 92 ml of distilled water, 6 ml of Nitric acid and 2 ml of Hydrochloric acid. A fresh etchant was used for each sample and the immersion time was around 20 second for each sample. The microstructural changes have been analyzed using a Scanning Electronic Microscopy (SEM). The surface and subsurface hardness values were also measured on a micro hardness indenter Future Tech F-7. The surface roughness was measured and analyzed using a Zygo7300® optical white light interferometry-based surface profilometer. Additionally, XRD patterns between 30 and 75 deg 2θ of the processed surfaces were also acquired for investigating the phase transformation taking place on the machined surface. The X-ray diffractometer used *Cu-Kα* radiation

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(λ=1.54184Å, $K\alpha_1/K\alpha_2$=0.5) from a source operated at 40 kV, and 40 mA. Samples were accordingly positioned at the center of plate into the X-ray goniometric in order to guarantee a correct beam radiation. The scan increment was 0.05 degree.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Surface roughness

The surface roughness of each test was measured five times at different locations along the surface. The observed trend for the mean surface roughness R_a is reported in Figure 2 (a) for a feed rate of 0.05 mm/rev, while in Figure 2 (b) the results for a feed rate of 0.1 mm/rev are reported. A decreasing trend for the mean surface roughness R_a is seen, when the cutting speed increases. The feed rate seems to have a very minor influence on the roughness trend. The R_a measurements obtained in machining with cryogenic coolant were found to be largely and consistently superior to those obtained in dry and MQL machining, and at higher cutting speed, MQL produced comparable results. The overall surface roughness for all three cooling conditions is always below 0.3 μm, which is a very good finish surface quality. It has been shown that, a smooth surface with better surface roughness would prevent the initiation of cracks under cyclic loads [29].

3.2. Surface and sub-surface hardness

Figure 3 (a) shows the surface hardness of the samples machined at 0.05 mm/rev feed rate, while the results related to the higher feed rate are reported in Figure 3 (b). The results clearly demonstrate that cryogenic cutting condition allows the material to reach a higher surface hardness in all the test conditions.

Figure 4 shows the hardness variation of machined samples at 0.1 mm/rev from the surface to the bulk material. A deeper hardness alteration is verified in all cryogenically-machined

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samples. MQL performs better than dry machining by exhibiting a higher surface hardness, and maintaining it up to a greater depth.

Dry cutting with its higher temperatures does not allow an increase in the surface and subsurface hardness, and cryogenic machining with its lower temperatures promotes the hardness increase during the cutting process. In fact, a combination of reduced thermal softening effect and greater grain refinement results in a higher surface hardness in the machined samples.

On the other hand, dry machining, due to the lack of coolant, tends to create softer and rougher surfaces. Hardness induced by the use of MQL during machining lies between the dry and the cryogenic cooling since the mix of lubricant and pressurized air slightly reduces the temperature during cutting. However, the MQL cooling effect, including the rate and intensity, is not comparable with that developed during cryogenic machining due to its significantly reduced thermal gradient and capacity.

3.3. Microstructure

The grain size and shape, and the grain boundary arrangements in *Ti* alloys have a significant influence on the induced mechanical properties of the machined component. The ability to manipulate the phase/grains present, by alloying, is responsible for achieving desirable properties in *Ti* and its alloys [30]. It is generally known that the microstructure influences the behavior of the *Ti* alloys, and a refined grain structure is more desirable from the point of view of tensile yield stress in metallic materials. In contrast, the ultimate tensile stress of *Ti* alloys is not significantly influenced by grain size, but its ductility, as represented by elongation or reduction in area, and it generally is improved with smaller grain size [30]. Also, fatigue life can strongly depend on this parameter [31-33]. Thus, the grain size was

measured on each machined surface as well as on the as received material using both an

optical and SEM microscope.

The microstructure of the as-received *Ti6Al4V* used in this study is shown in Fig. 5; the dark

region is the α phase and the light region is the β phase. The α grains were measured to be

around 20 μm.

Generally, higher α content results in higher creep resistance and high-temperature strength,

while higher β content leads to higher density and room temperature strength [30]. However,

the combination of softer α grains and harder β phase is usually preferred for achieving good

performance in an alloy for the strength and the fatigue life [30].

Figures 6 shows the SEM microstructures of the machined samples at v_c = 150 m/min, and f

= 0.05 mm/rev. These results show that both the bulk material and the machined surface

present an equiaxed microstructure of primary α grains and intergranular beta (β) grains.

Also, the structure near the machined surface presents a more dense the β phase leading to

higher room temperature strength [30].

All the examined samples present a refinement of the mean grain diameter from the bulk to

the surface although the grain refinement is more evident for MQL and cryogenic conditions,

where the microstructures are more dense and present a deeper SPD layer. Figure 7 highlights

how the lubricant/coolant and the processing parameter affect the microstructure of the

machined samples showing the grain refinement evolution from the less influencing condition

(70 m/min, 0.05 mm/rev, dry cutting) to the most effecting condition (150 m/min, 0.10

mm/rev, cutting under cryogenic cooling).

It is worth to point out that the process parameters influence a lot the microstructural changes

under dry conditions while the cooling effect of cryogenic prevails on the microstructural

behavior. This trend is better shown in Figure 8 where the grain size on the machined surface

for all the experimental tests are reported. Obtaining smaller grains when using cryogenic

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cooling conditions is related to the fact that this cooling process prevents grain growth after

the dynamic recrystallization (DRX), which in turn is the result of the severe plastic

deformation process [34]. These results also confirm the potential of the use of cryogenic

cooling to generate a stronger machined product, with a harder surface, and less prone to

crack initiation [31, 32, 34].

3.4. Phase changes – XRD analysis

Phase change is a microstructural feature that cannot be optically detected, but it strongly

influences the material properties. For example, transformed β phase products in *Ti* alloys can

affect tensile strengths, ductility, toughness, and cyclic properties [30]. Processing of *Ti6Al4V*

alloy can lead to formation of two secondary phases: *Ti3Al* and ω on the surface. *Ti3Al* is

detrimental to the resistance to stress corrosion of the material; while the ω phase is

undesirable due to its brittleness [30]. First of all, it is important to underline that X-ray

diffraction of all the investigated samples does not show any peak corresponding to *Ti3Al* or

ω phase formation.

Figure 9 shows the XRD patterns for some of the investigated cutting conditions in which the

α and β phases were identified according to Bragg's law and data reported in the materials

Handbook [35]. The results generally show that the β transus temperature was never reached

during the process since the α phase does not significantly decrease in peak intensity [36].

However, the β peak changes with the process conditions and the lubricant/coolant used. In

particular, it increases under dry condition and slightly increases with the cutting speed. In

contrast, the feed rate does not significantly affect the β peak.

Another cardinal aspect to be highlighted from the XRD analysis is related to the relative

intensity and the width, which are influenced from cutting process and cooling condition.

According to Herbert et al. [37] different intensity represents different grain size. As it is

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clearly seen in Fig. 7, primary α grains refinements are observed when higher cutting speeds and cryogenic cooling are utilized. The XRD profiles, in term of intensity and width of the α peak (Figure 9), are in accordance with the grain size trends reported in Figure 9. Also, the ratio of the two phases influences the behavior of *Ti* alloys, and therefore it is crucial to identify these differences in the processed material [38]. In fact, the α phase partially transforms to the β phase at temperatures above $\alpha / (\alpha+\beta)$ transus [38]. Thus, the volume fraction of α and β phases was calculated from the XRD results as follows [39]:

$$\frac{I_\beta}{I_\alpha} = A\frac{f_\beta}{f_\alpha} \tag{1}$$

where *I* is the peak intensity of the interested phase and *f* its volume fraction, and *A* is the ratio between the relative integrated intensities of both phases [39]. According to each XRD spectrum, the β percentage increases from the 11% in the unprocessed material to the 30% in the machined surface in dry machining at 150 m/min and 0.1 mm/rev. The peak ratios show a similar trend between cryogenic and MQL coolants, which exhibit a slightly lower β percentage than dry machining (about 22% for cryogenic and 25% for MQL). In contrast, the feed rate slightly affects the volume fraction variation, while the β percentage decreases when increasing the cutting speed. The β phase is not materially so different from the $\alpha+\beta$ phase even if, an increase of the β phase on the surface can increase the efficiency of the material since the formation of a little β permits the alloy to be strengthened [30]. However, a reduction of grain size is more effective than a decrease of primary α volume fraction for improving the fatigue life in, both the low cycle fatigue (LCF), and high cycle fatigue (HCF) ranges [30]. The effectiveness of strengthening in *Ti* alloys appears to be more influenced by the number and fineness of phase boundaries and the grain size [30].

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4. CONCLUSIONS

Experimental observations reported in this paper show the capability of cryogenic cooling to improve the product surface integrity in machining of *Ti6Al4V* alloys. In particular, the surface roughness strongly benefits from the use of cryogenic cooling as well as the hardness at the surface and sub-surface level. Furthermore, the surface microstructural changes highlight how cryogenic coolant improves the DRX mechanism containing the regrowth phase. Thus, cryogenically-machined samples generally show a superior surface finishing (combination of mean surface roughness, microhardness and grain size), which is partially reached by MQL machined specimens only under certain conditions. In contrast, dry machining permits to achieve a higher β volume fraction, which is beneficial for increased material strength at room temperature.

From a sustainability perspective, cryogenic machining is more environmentally-friendly when compared with the traditional flood cooling methods and MQL machining. It also contributes to make products having better surface integrity and quality by generating smaller grains.

Overall, this study demonstrates that the different cooling/lubrication methods affect the surface characteristics of *Ti6Al4V* alloy. In particular, cryogenic cooling can significantly improve the product surface characteristics having a great impact on its quality and potentially improve its reliability.

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measurements. The authors should also like to acknowledge Mr. Steve Chen of Kennametal Tools for the donation of cutting tools.

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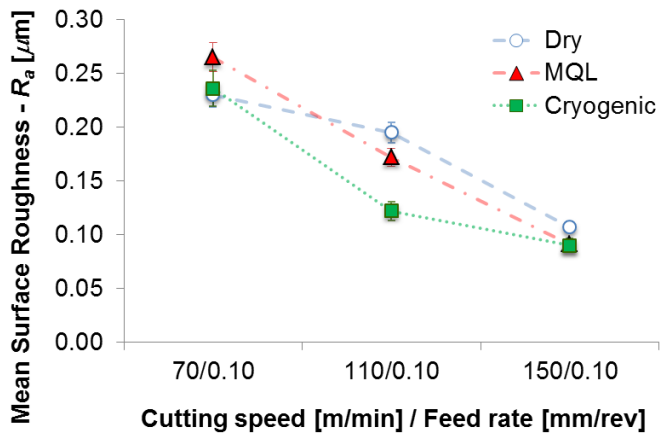
15

FIGURES

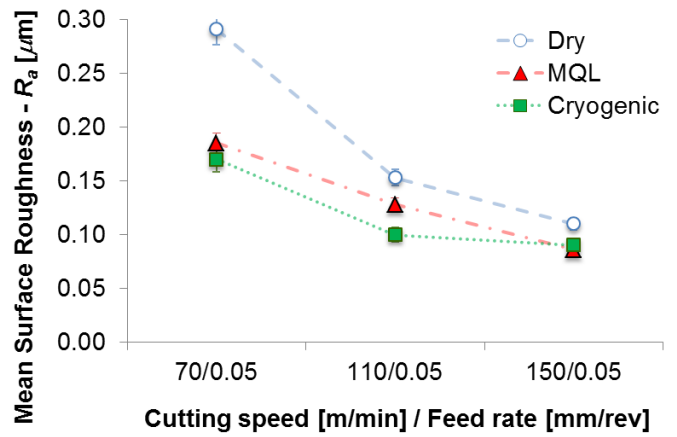(a)   (b)
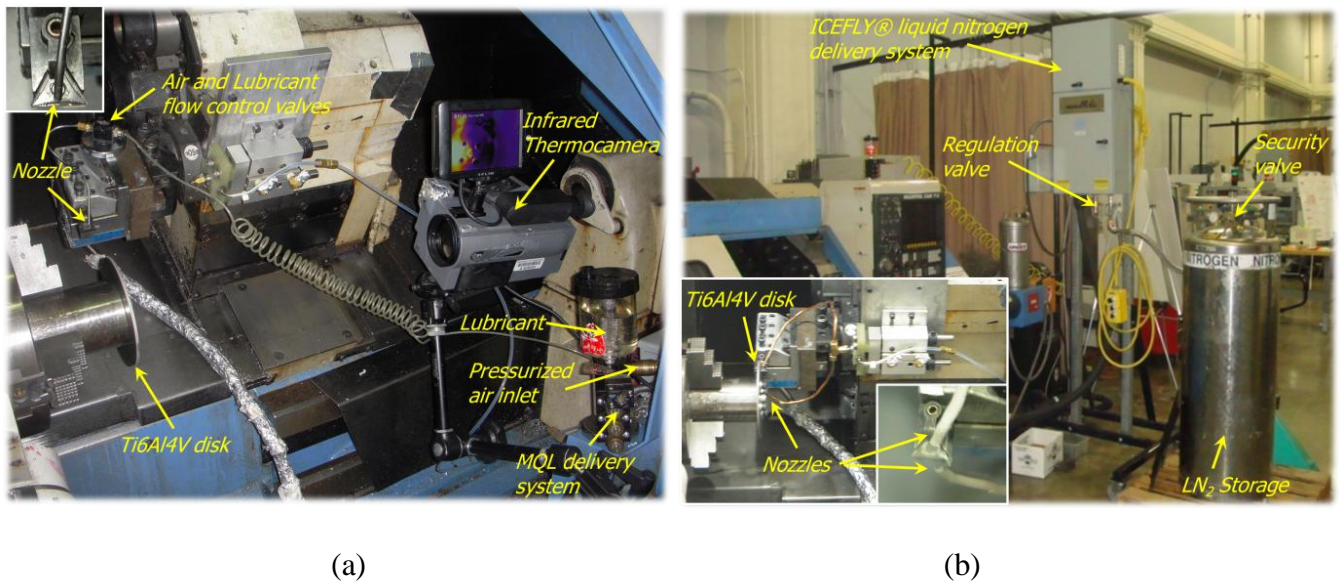
Figure 1. Experimental set-up for orthogonal cutting tests with (a) MQL and (b) cryogenic cooling

systems.
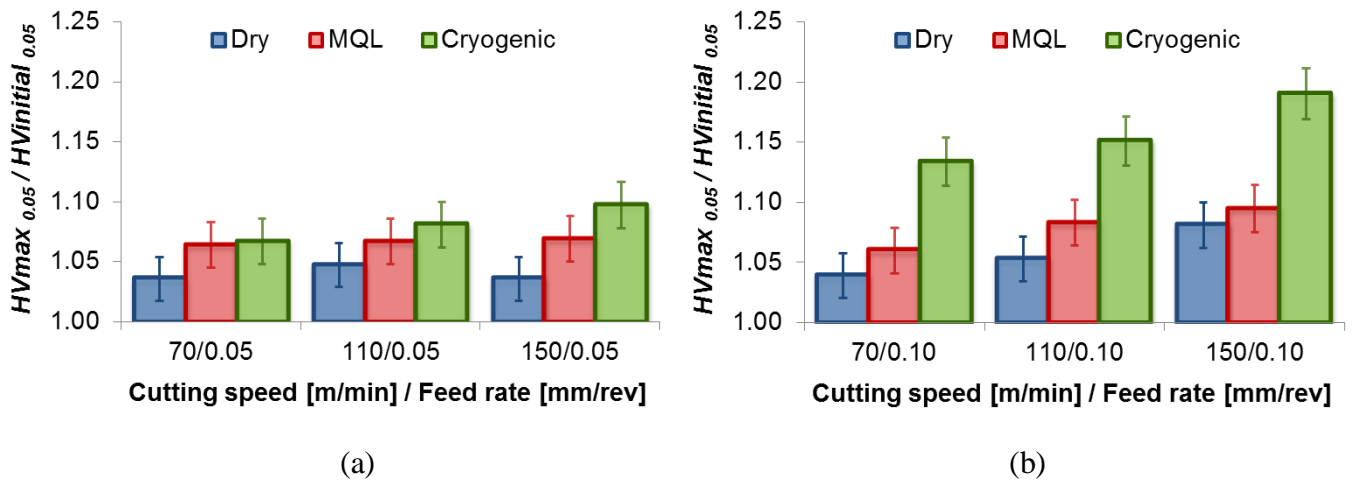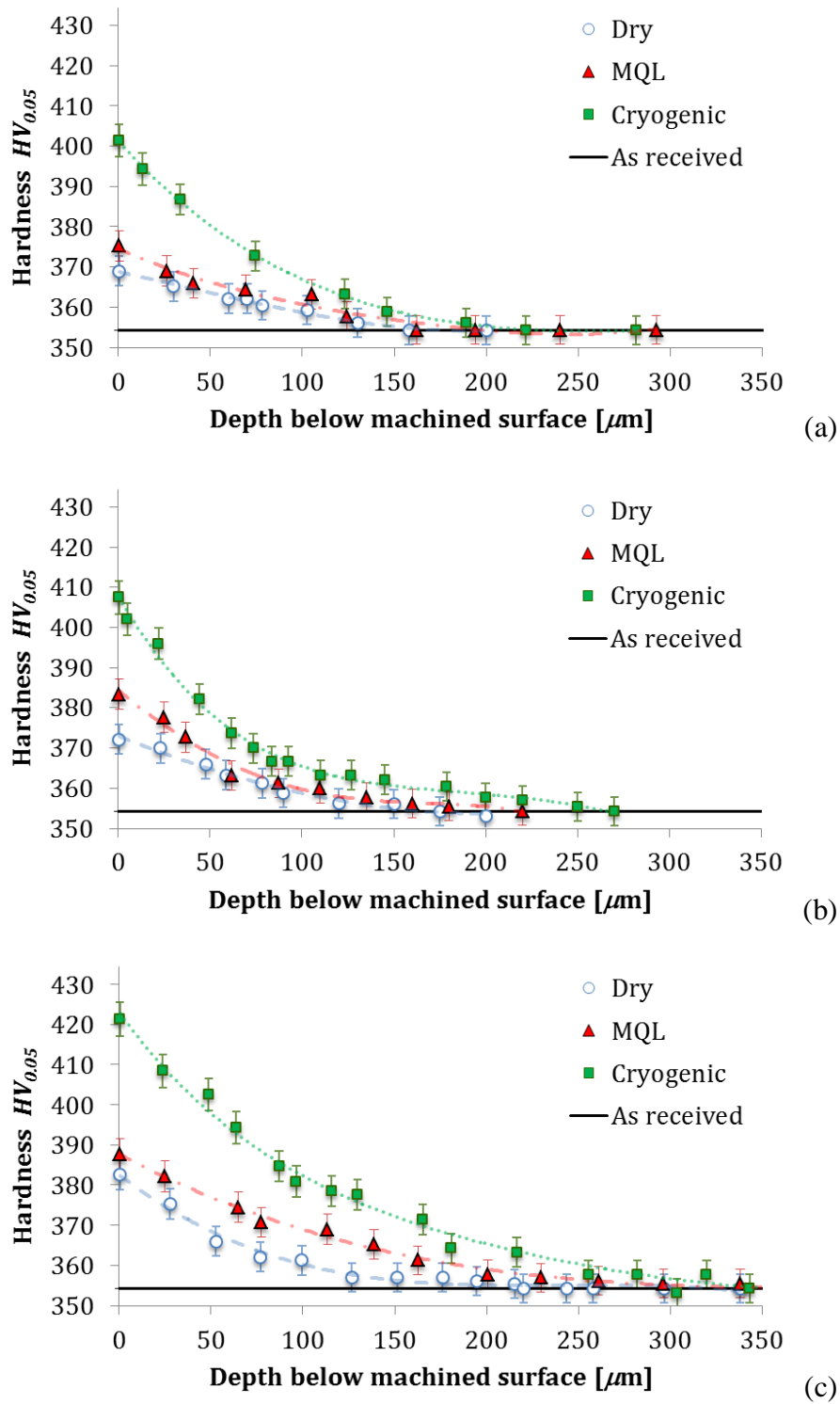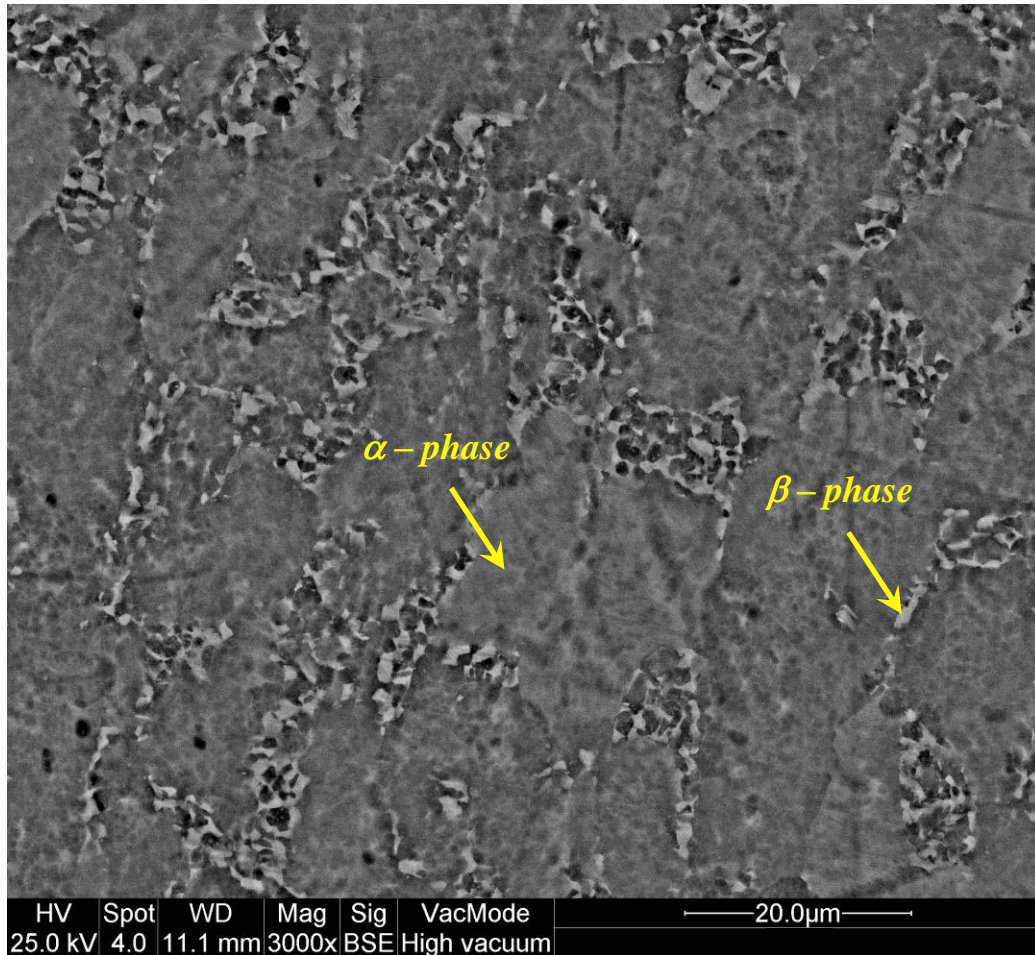
**Figure 2.** Mean surface roughness on machined samples under dry, MQL and cryogenic cooling conditions.

Figure 3. The measured surface hardness at varying cutting speeds for (a) 0.05 mm/rev and (b) 0.10 mm/rev feedrate.

Figure 4. Surface and sub-surface hardness profiles for experimental conditions at $f = 0.1$ mm/rev and cutting speed of (a) 70 m/min, (b) 110 m/min and (c) 150 m/min.

Figure 5. SEM micrograph of an etched microstructure of the as-received *Ti6Al4V* with dark

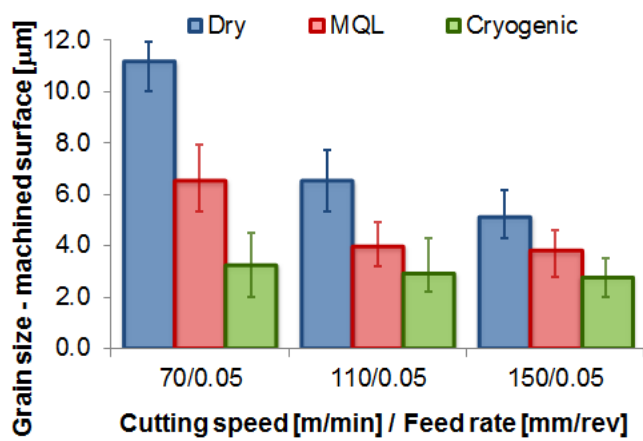region for HCP α phase and light region for BCC β phase.
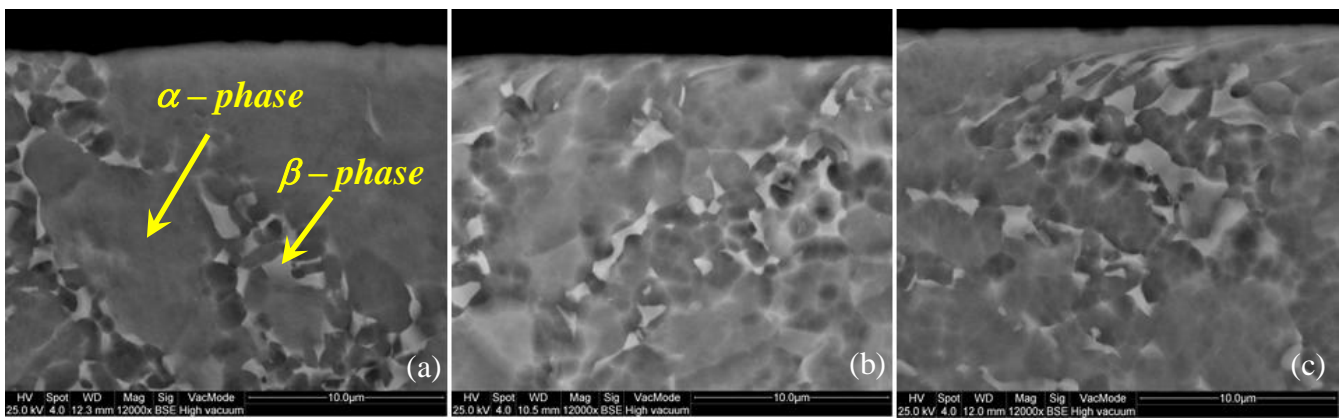
Figure 6. SEM images of the machined samples under (b) dry, (c) MQL, and (d) cryogenic conditions at v_c = 150 m/min, and f = 0.05 mm/rev. (α – dark grains; β – light grains).
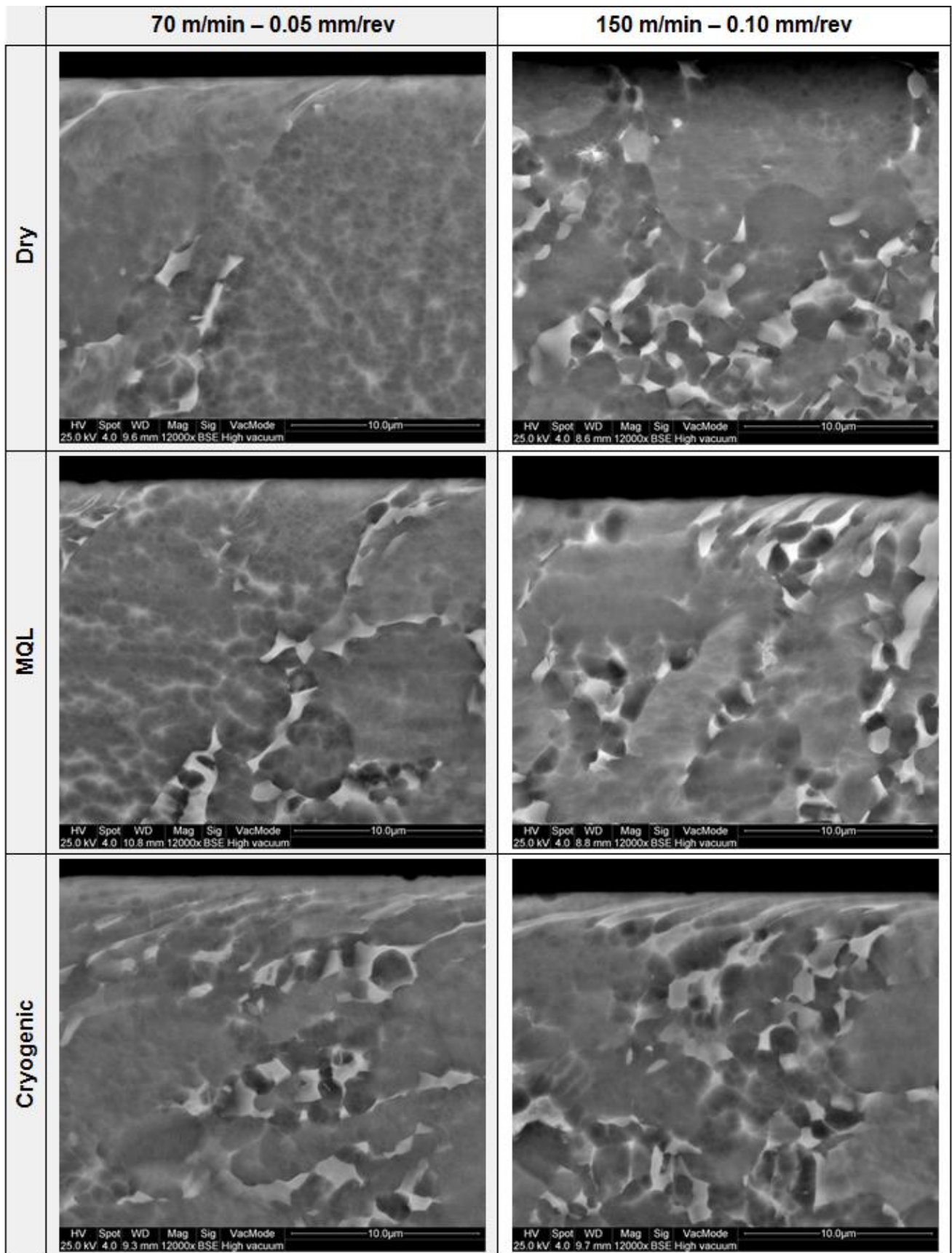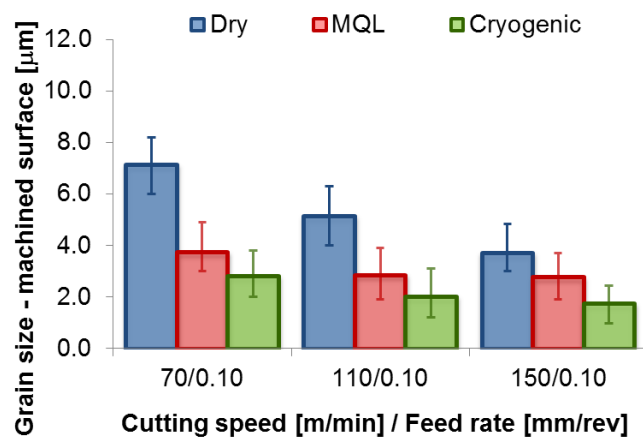
Figure 7. SEM images of the machined samples under dry, MQL, and cryogenic conditions at different cutting speeds and feed rates (α – dark grains; β – light grains).
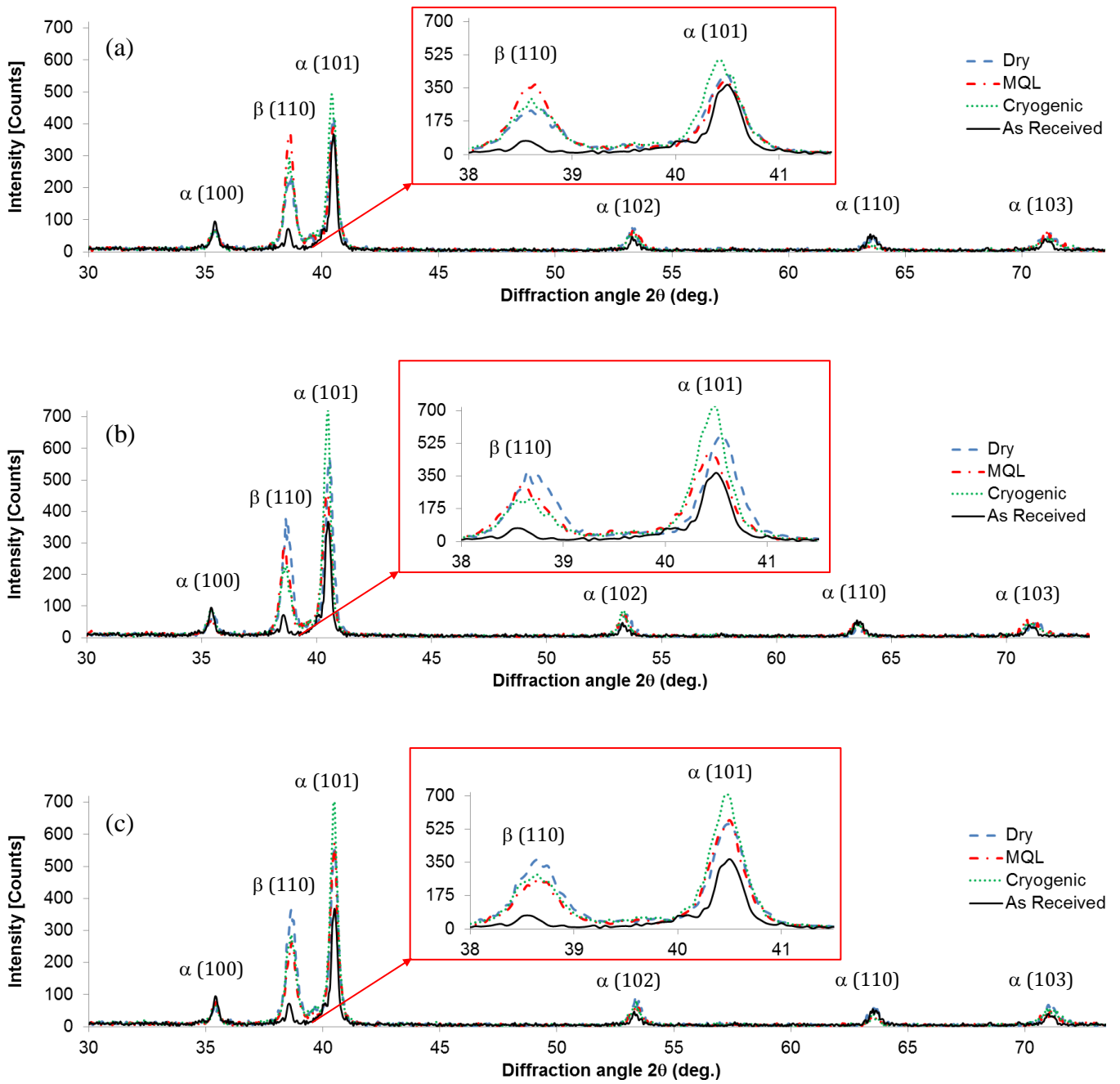
(a)

(b)

Figure 8. Comparison of measured grain size variation at varying the cutting speed: (a) 0.05 mm/rev; (b) 0.10 mm/rev.

Figure 9. XRD results obtained for machined samples at (a) v_c = 70 m/min, and f = 0.05 mm/rev; (b) v_c = 150 m/min, and f = 0.05 mm/rev; (c) v_c = 150 m/min, and f = 0.10 mm/rev.

TABLES

Table 1

Experimental test conditions.

v_c [m/min]	70	110	150	70	110	150
f [mm/rev]	0.05			0.10		
Cooling	Dry, Cryogenic, MQL			Dry, Cryogenic, MQL		