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Effect of cryogenic cooling and tool wear on surface integrity of turned Ti-6Al-4V

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Abstract

The aim of this work is to investigate the influence of flank wear and cutting fluid (emulsion vs. liquid nitrogen) on surface integrity in turning of titanium alloy Ti-6Al-4V. Longitudinal turning tests with pre-worn uncoated cemented carbide inserts are performed, after which the surface and subsurface layer of machined workpieces is studied. Results for residual stresses on the surface as well as in depth profiles, obtained by X-ray diffraction, are also presented. Scanning electron microscopy (SEM) is used to investigate the microstructure of the workpieces. The same tool holder was used for both cooling conditions, with the same nozzle configuration. The flow rate of liquid nitrogen was therefore limited and as a result, tool wear development was observed to be faster for cryogenic cooling than emulsion-based flood cooling. However, the results show limited differences in terms of achievable residual stresses when comparing cryogenic and conventional cooling at similar levels of tool wear. Despite an increase in tool wear rate, the cryogenic cooling conditions thus provide similar surface integrity results as emulsion cooling. The results suggest that the consumption of the cryogenic coolant can be reduced or optimized without a significant impact on surface quality.

Selection and peer-review under responsibility of the scientific committee of the 4th CIRP Conference on Surface Integrity (CSI 2018).

Keywords: Cryogenic machining, Titanium, Surface Integrity

1. Introduction

The use of cutting fluids can account for a significant share of the total production costs. It is estimated that the cost of the metal working fluids and associated systems may amount to as much as 15 % of the total production costs [1]. In addition, there are both health and environmental issues related to their use. Skin exposure as well as inhalation of cutting fluid mist can represent serious health hazards for the machine operators [2]. The reduction of cutting fluids and lubricating oils is thus a key sustainability issue for the metalworking industry.

The use of cryogenic coolants has emerged as a promising strategy with the potential to eliminate many of these issues. Some researchers reported experiments where they replaced traditional cooling fluids with liquid carbon dioxide (CO_2) or liquid nitrogen (LN_2) as early as the 1950s [3,4]. In the past decade, the number of publications concerned with cryogenic machining has risen considerably, showing technological advantages both in terms of improved tool life and quality of the manufactured component [5].

There is a strong relationship between the machining process, the quality and properties of the generated surface, and the functional performance of the machined part. The term *surface integrity*, which was first coined in 1964 by Field and Kahles [6], highlights this link. It refers to topography (surface roughness), metallurgy (microstructure), mechanical properties (hardness, residual stresses, fatigue) and chemistry (corrosion resistance). The requirements for improved surface integrity and functional performance have led to intense research efforts to develop experimental methods for evaluating surface integrity as well as predictive models [7]. There have been a few reviews published giving an overview of the topic, including the case of machining of titanium alloys [8–10]. More recently Kaynak et al. published a review focused on the surface integrity in cryogenic machining of different work materials [11].

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Surface integrity parameters in cryogenic machining of Ti-6Al-4V have been studied in a variety of conditions. The surface roughness is commonly quantified by R_a, the arithmetic mean of the surface profile. In cryogenic turning of Ti-6Al-4V, available literature most often reports lower values of R_a compared to dry or wet machining. This is the case both when using CO_2 and LN_2 [12], and for different cryogen-delivery methods e.g. through internal channels in the tool holder, directed to the rake and flank faces of the tool [13] or using a system designed to cool the tool, without the cryogen flowing directly towards the cutting zone [14]. It has been shown that cryogenic machining produces a surface layer with higher hardness than both dry and MQL (minimum quantity lubrication) cutting [15].

While the residual stresses that occur in machining of titanium alloys including Ti-6Al-4V have been widely studied [10,16], there is still a lack of publications focused on the residual stresses induced in Ti-6Al-4V after cryogenic machining. The potential of cryogenic cooling to improve tool life is well established when using specially adapted tool holders and nozzle configurations [17,18]. It is also known that the flow rate of the cryogenic coolant has a significant influence on the machining performance in terms of tool life and residual stresses [19,20]. The aim of this work is to investigate the influence of cryogenic cooling and tool wear on surface integrity of Ti-6Al-4V while using the same setup (same tool holder and nozzle size, comparable coolant supply pressure) for both cryogenic and flood emulsion cooling.

2. Experimental work

Turning experiments were conducted using cryogenic cooling (liquid nitrogen) and flood-cooling (emulsion) on a SMT Swedturn 12 lathe. A set of workpieces was manufactured from a single batch of the α+β titanium alloy Ti-6Al-4V. The material composition of the workpiece material is given in table 1 and its microstructure is shown in figure 1. The shape and dimensions of the workpieces is given in figure 2. Figure 3 shows the setup for the turning experiments.

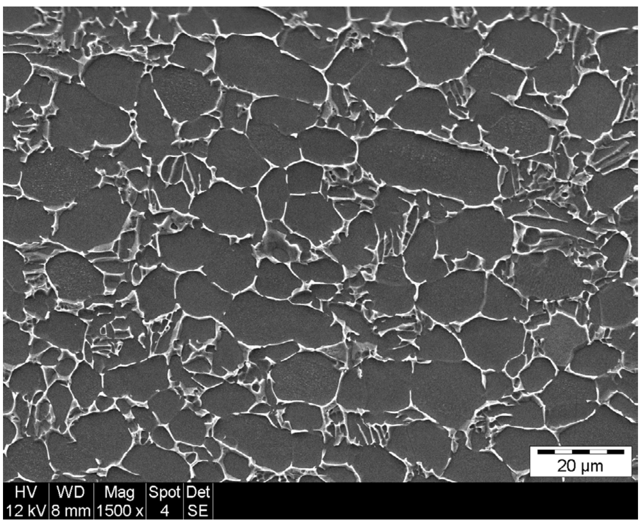


Figure 1: Microstructure of the workpiece material Ti-6Al-4V observed in SEM (Secondary electron detector, 12 kV, 8 mm working distance.)

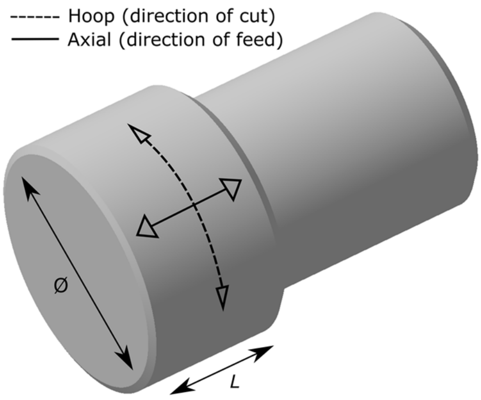


Figure 2: Shape of the manufactured workpieces. The diameter is 35 mm and the length L of the surface to be machined is 20 mm. The figure also shows the axial and hoop directions of measured residual stresses.

Table 1: Nominal chemical composition of the workpiece material Ti-6Al-4V

N	C	H	Fe	O	Al	V	Ti
≤ 0.05	≤ 0.08	≤ 0.012	≤ 0.25	≤ 0.13	5.5-6.50	3.5-4.5	Bal.

For each cooling condition, a test was performed with a new insert and with pre-worn inserts at three different levels of flank wear, according to table 2. The pre-worn inserts were "made" by turning a large bar of the same workpiece material until the desired level of flank wear VB was obtained. The flank wear was evaluated at regular intervals by using an optical microscope (Nikon SMZ1000) equipped with software for tool wear measurement.

Table 2: Test conditions

Experiment	Cooling	Nominal $VB_{,max}$ [mm]
1	Cryo	New insert
2	Cryo	0.1
3	Cryo	0.2
4	Cryo	0.4
5	Wet	New insert
6	Wet	0.1
7	Wet	0.2
8	Wet	0.4

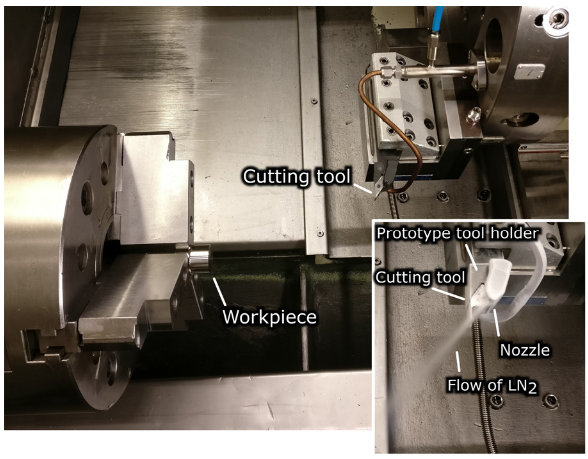


Figure 3: Setup for the turning experiments and view of the tool holder with cryogenic cooling activated.

The machining times required to obtain the different levels of flank wear used in this experiment are given in table 3.

Table 3: Machining times to obtain the desired levels of flank wear.

Nominal $VB_{,max}$ [mm]	Cryogenic LN_2	Flood emulsion
0.1	3 min	10 min
0.2	9 min	19 min
0.4	12 min	27.5 min

The cutting data for all experimental work was set to: v_c=70 m/min, f=0.15 mm/rev and a_p= 1.5 mm respectively. The tools used were commercially available uncoated cemented carbide inserts from Sandvik Coromant (VNMG 16 04 08-SM H13A). The edge radius of the inserts was 29±2 µm.

The coolant was in all cases delivered to the cutting zone through internal channels in a prototype tool holder with a nozzle diameter of 0.4 mm. The flow was directed to the rake face of the tool. For emulsion, a concentration of 6 % and a pressure of 6 bar was used. The cryogenic coolant (liquid nitrogen) was delivered at a pressure of 6.8 bar.

The residual stresses at the surface and in the sub-surface layer were determined by X-ray diffraction using an Xstress 3000 G2R diffractometer with Ti-Kα radiation. The psi method was used with 5 tilts from 0° to ±40° with equal intervals in ψ^2. Additionally, a tilt oscillation of ±5° was used. The diffraction peak for the {110} family of planes was used (Bragg angle 2θ = 137.4°). An elastic modulus of 120 GPa and a Poisson's ratio of 0.36 were used for stress calculations. The position and intensity of peaks in the diffraction patterns were determined by fitting of the Pearson VII function and parabolic background in the XTronic V1.9 software.

3. Results

3.1. Residual stresses

Residual stresses were first measured at the surface. For each workpiece, six measurements were made at regular intervals around the machined surface. The two components, i.e. hoop stress in the direction of cut, and axial stress in the direction of feed were measured, as illustrated in figure 2. Stresses in the radial direction, perpendicular to the machined surface, were assumed to be 0. The results are presented in figure 4.

The results show that at the surface, the residual stresses are compressive for all experimental conditions. In most conditions, there is an insignificant influence of the coolant nature on the magnitude of the residual stresses. The difference is most pronounced in the axial direction for moderately worn inserts. In the hoop direction with a new insert and at VB=0.1 mm, there is a small difference in the mean value of the measurements. However, there is an overlap in the values obtained. In both components of residual stress, the difference in the magnitude of measured stress is eliminated at the highest level of flank wear.

A residual stress profile was measured for each workpiece, as shown in figure 5 for the residual stress in the axial direction.

The results clearly show that the residual stresses remain compressive in the sub-surface layer even after changing from emulsion to liquid nitrogen cooling, despite a relatively limited delivery of liquid nitrogen. A maximum compressive stress value is observed slightly below the surface. This dip is most clearly seen in the axial stress direction, where a maximum compressive stress is seen at approximately 10-12 µm depth. The compressive residual stresses then decrease with increased depth, before stabilizing at around 75 µm depth. Little difference can be observed between the residual stresses in cryogenic and wet cooling conditions. However, for the axial stress, there seems to be a trend with increasing maximum compressive stress with increasing levels of flank wear.

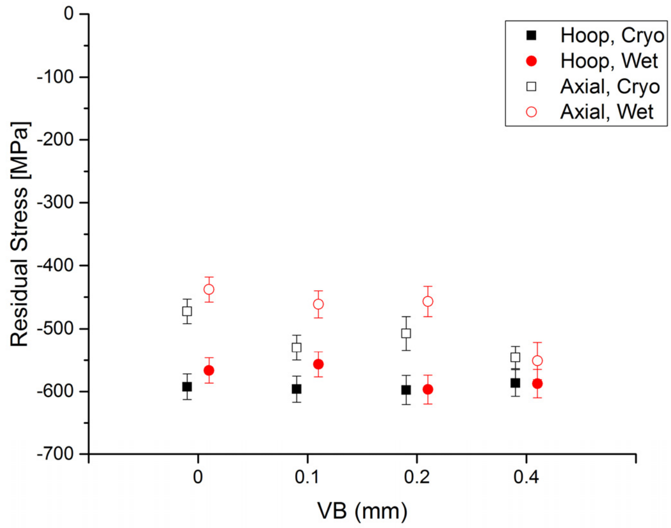


Figure 4: Surface residual stresses in the hoop and axial directions.

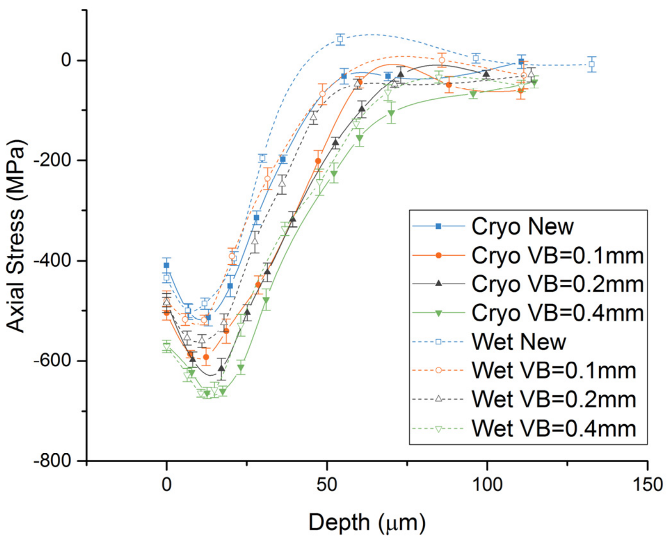
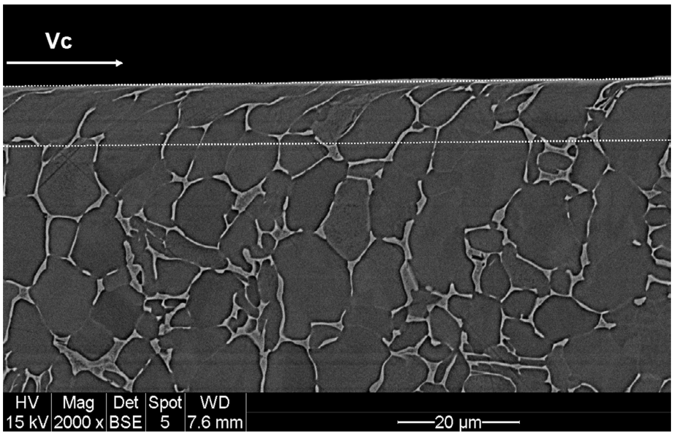


Figure 5: Residual stress profile in the axial direction (direction of feed).

3.2. Microstructure

Analysis of the microstructure of the machined workpieces in the SEM reveals a deformed layer that is in the order of 10 micrometer in depth. This corresponds approximately to the size of the observed α grains: it can be seen that the deformed layer is about one grain in depth. Figures 6 shows the deformed layer for cryogenic and wet cooling with a flank wear of VB=0.4 mm. It should be noted that the depth of the observed deformed layer corresponds well with the depth at which the maximum compressive residual stresses are recorded, see figure 5. This pattern is similar at all levels of flank wear.

The cross sections observed in the SEM revealed no defects on the surfaces in the form of fracture or cracks, in either cooling condition.



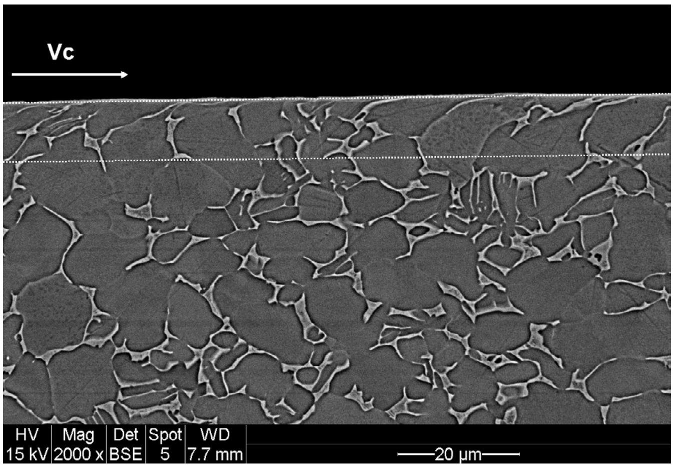


Figure 6: SEM images of cross sections of the machined samples with cryogenic (top) and emulsion (bottom) cooling. The flank wear was VB=0.4 mm in both cases. The highlighted deformed layer is approximately 10 µm in depth. (Back-scattered electron detector, 15 kV, 7.6-7.7 mm working distance.)

3.3. Surface roughness

For each workpiece, five surface roughness measurements were done parallel to the feed direction and at regular intervals around the machined surface. All the results are shown in figure 7, where each marker represents one measurement and the horizontal bar represents the mean value of the measurements for each condition. No clear trend is revealed in terms of the influence of the flank wear on the surface roughness. It can however be observed that the R_a value is lower in case of cryogenic cooling, except for when the flank wear was VB=0.2 mm where emulsion cooling produced lower values of R_a.

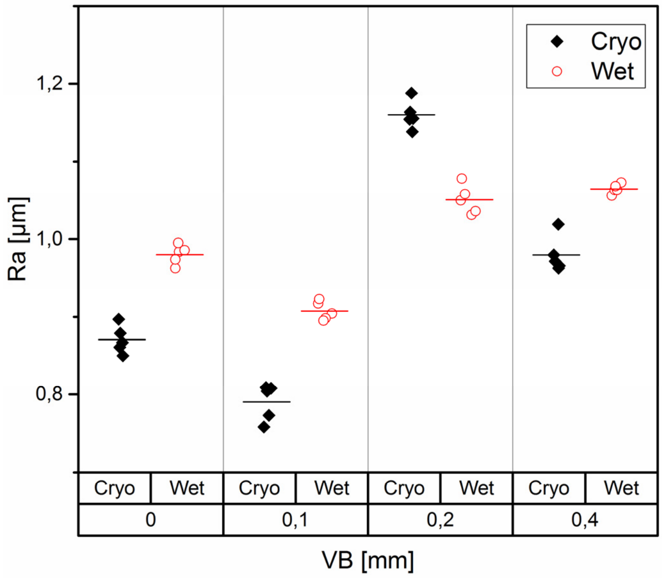


Figure 7: Surface roughness measurements (Ra) for all experimental conditions.

3.4. Cutting forces

The cutting forces measured during all experiments are presented in table 4.

Table 4: Cutting forces measured for all experimental conditions.

		LN_2	Emulsion
New insert	Fc [N]	450	421
	Ff [N]	243	219
	Fp [N]	183	175
VB=0.1 mm	Fc [N]	443	443
	Ff [N]	257	212
	Fp [N]	208	177
VB=0.2 mm	Fc [N]	505	498
	Ff [N]	327	367
	Fp [N]	230	201
VB=0.4 mm	Fc [N]	555	552
	Ff [N]	815	713
	Fp [N]	331	264

For both cryogenic and emulsion cooling, the cutting forces display a similar pattern. For new inserts, the passive and feed forces are roughly 40 % to 50 % smaller than the main cutting force. With increasing flank wear, starting at VB=0.2 mm, the relative magnitude of the feed force increases sharply, and becomes much higher than the main cutting force when the insert is severely worn (VB=0.4 mm). Changing from emulsion cooling to cryogenic cooling had limited effect on the main cutting force. With a new insert, an increase of less than 7 % was observed, whereas the differences with the worn inserts were insignificant. There was more variation in the feed and passive force components, with higher forces generally associated with cryogenic cooling. However, the feed force was almost 11 % lower with cryogenic cooling for VB=0.2 mm compared to emulsion cooling. The case of VB=0.2 mm thus produced outlying results both in terms of cutting forces (feed force) and in terms of surface roughness.

4. Discussion

The results presented in figure 4 and 5 revealed an insignificant difference in measured residual stresses between flood and cryogenic cooling. As mentioned in section 3.2, no signs of surface defects in the form of fracture or cracks were observed for any cooling condition, even when machining with the highest level of investigated flank wear (i.e. VB=0.4 mm, see figure 6). These results indicate a minor influence of cryogenic cooling on the surface integrity while using the same setup – i.e. the same tool holder/nozzle size and comparable pressure – as the one used for flood cooling. However, the machining times required to generate pre-worn tools (see table 3) clearly suggest that the supply of liquid nitrogen was insufficient when using the same tooling/coolant supply setup to obtain the expected cryogenic cooling effects as commonly reported in the literature.

The flow rate, pressure and nozzle size were proven to have a strong influence on tool performance when machining Ti-6Al-4V with cryogenic coolant [19,20]. For instance, Bermingham et al. [18] used two 1 mm nozzles on the rake and/or one 1.77 mm nozzle on the flank side of the tool with a pressure of 8 bar to achieve appropriate cooling capacity. Ayed et al. [20] used various combinations of nozzle diameters and supply pressures ranging from 1.6 to 3 mm and 4 to 10 bar, respectively. Rotella et al. [15] reported an improved surface integrity (surface roughness, microhardness and grain size) when supplying liquid nitrogen through a 2 mm nozzle with p=12 bar compared to MQL. Lequien et al. [21] developed a hybrid experimental/numerical method for assessing the cooling efficiency of liquid nitrogen. They found that the heat transfer coefficient varied with all parameters studied (nozzle diameter, supply pressure, jet angle, and distance between nozzle and plate) – but the nozzle diameter had the most dominant effect of the response.

In the current study, however, liquid nitrogen was solely supplied to the rake face of the tool at a pressure of 6.8 bar with a nozzle diameter of 0.4 mm, which seems to be insufficient to achieve the proper cooling capacity required for an improved tool performance. Yet, our investigations indicate that the effect on the surface integrity (residual stress, deformed layer and surface roughness) is marginal when machining Ti-6Al-4V. Ayed et al. [20] have recently reported similar observations for machining this alloy under dry, emulsion and cryogenic condition. They observed no significant improvements in surface roughness and only about 50 MPa increase in compressive residual stresses when using 1.6 mm nozzle size (which is 4 times larger than the one used in this study). In view of these observations, the supply of cryogenic coolant needs to be carefully set to obtain an optimum balance between flow rate (consumption), tool life and obtainable surface integrity. A more detailed investigation using advanced characterization techniques would be needed to provide further understanding of the underlying mechanisms.

5. Conclusions

The conclusions drawn from this research are as follows:

- Changing the cooling method from flood cooling (emulsion) to cryogenic cooling (liquid nitrogen) is possible without significantly affecting the surface integrity in terms of residual stresses, microstructure and surface roughness.
- The residual stresses in the axial direction (direction of feed) increase with growing flank wear.
- The depth of the deformed layer in the material microstructure corresponds to the depth of the maximum compressive residual stresses.
- Given the small size of the nozzle used for coolant delivery in this study (0.4 mm), the flow rate of cryogen can be reduced while maintaining the same level of surface integrity as with flood cooling when turning Ti-6Al-4V.
- The use of cryogenic cooling with limited (reduced) flow rate when turning Ti-6Al-4V, suggests that both economic and environmental benefits can be achieved without detrimental effects on surface integrity.

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