J Adv Manuf Eng, Vol. 2, Issue. 2, pp. 42–48, December, 2021

Journal of Advances in Manufacturing Engineering
Web page info: https://jame.yildiz.edu.tr
DOI: 10.14744/ytu.jame.2021.00007

Original Article

An investigation of the effects of cryogen application direction on Ti6Al4V alloy milling

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ARTICLE INFO

Article history
Received: 29 September 2021
Accepted: 09 November 2021

Key words:
Burr formation, chip, cryogenic cooling, titanium alloy.

ABSTRACT

Titanium and its alloys are materials with high hardness and strength. Because of these properties, titanium and its alloys are usually machined with carbide or diamond tools. However, the occurrence of high temperatures during processing elongates the processing time and hence reduces efficiency. The use of coolants is a viable technique to reduce the temperature in the processing of such hard materials. Because of the negative environmental impacts of conventional cutting fluids, cryogenic processing has become an alternative approach. The effects of cryogen usage in the milling of Ti6Al4V alloy with carbide tool were evaluated in this work together with dry machining. Cryogen was applied in two different directions, in the front and back of the tool. The effects of the cooling technique on surface roughness and burr formation were evaluated at the end of the experiment. When the cryogen was applied from the back of the tool, the surface quality was the best. Burr formation was observed to occur more frequently during dry machining.

Cite this article as: Bahçe E, Sarıgül E. An investigation of the effects of cryogen application direction on Ti6Al4V alloy milling. J Adv Manuf Eng 2021;2(2)42–48.

INTRODUCTION

Titanium is a metal which is light in weight and has high corrosion and heat resistance. These characteristics have contributed to the rapid development of the titanium industry for the last four decades. Titanium is widely used in engine parts, applications in electronics and biomedical sectors and especially in vehicles used in the medical, aviation and aerospace industries [1]. Machining methods such as milling and lathing are also widely used in the shaping of titanium alloys [2]. These alloys are coefficient as they have low heat transmission and the heat that is constantly generated as a result of their processing causes many problems both the tool and the workpiece. Rapid tool wear, tool breakage, decreased surface precision, and burr forming are all common problems. One of these problems is burr, which produces chip buildup on the edge of the machined surface as a result of the heat generated in the cutting zone. Burrs that occur during milling can affect the geometrical and dimensional accuracy of the part, complicate assembly and also cause injuries. However, the deburring procedure raises manufacturing costs and time, and it can also result in irreversible faults owing to manual application.

Niknam and Songmene [3] investigated the effects on burr formation in milling, cutting parameters and exit burrs. As a result of the experiment, they have developed an algorithm for the cutting speed, feed per tooth and un-

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Published by Yıldız Technical University Press, İstanbul, Turkey

deformed chip thickness that estimates the friction angle associated with burr formation. They stated that the large friction angle reduces the burr in the upper region at the exit of the workpiece and increases it in the lower part. Hanson et al. [4] machined polycarbonates in another research to evaluate the impact of altering machining parameters on burr development and tool wear. Furthermore, they estimated the burr height from experimental tests with 10.8 percent accuracy by modeling the milling process with finite element analysis. Another study on titanium alloy milling found that the width and length of the milling were effective on the burr, and burr sizes were reduced when tools with sharper cutting edges were used [5]. According to Bahce and Ozel, the changing temperature depending on the cutting parameters has a major influence on the development of burrs in the processing of aluminum alloys [6]. Hashimura et al. [7] observed that cutting parameters, tool geometry, mechanical properties of the material removed, and workpiece geometry all had an impact on burr development. They also systematically explained the burr formation step by step for brittle materials. Similar to this study, Jones and Furness also stated that the wear of the tool, the hardness of the workpiece, the feed and the cutting speed are important on the exit burrs in the milling of aluminum alloys [8]. Lekkala introduced an algorithm for milling aluminum and stainless steel to predict the height of the exit zone burr. They also emphasized that tool diameter and feed have a significant impact on burr height [9]. Ucun et al. [10] examined the impact of using the minimum amount of lubrication and using cryogen on cutting performance in milling Inconel 718 material. They found that cryogen increased tool wear while improving surface quality and decreasing burr formation. Also, they observed that using the minimum amount of lubrication decreases tool wear.

In addition to these problems, the thermal shock that occurs in the processing of titanium alloys can affect the phase structure of the material and shorten its life. As a reason, researchers are trying to devise alternative techniques for dealing with the negative effects of heat [8–11]. Studies on optimizing processing parameters and cooling techniques are particularly important for this aim. When researching this topic, Fernandez et al. [12] performed cryogenic cooling (CO_2) over the tool holder in milling with the aim of sending the material to the cutting edge of the tool in the most efficient method possible while ensuring that the phase structure of the material was not altered by cryogen. Huang et al. [13] investigated the effect of cryogenic machining (LN_2) on vibration and cutting forces in milling. In the experiment, cutting operations were performed at different speeds and passes over 10,000rpm in A17075-T6 alloys. It was determined that cryogenic cooling facilitates the removal of chips and reduces cutting forces. Kaynak et al. [14] used dry, cutting fluid, and cryogenic cooling techniques to process the stainless-steel material at different cutting speeds and feed rates. In the experiments, they found that when cryogenic cooling is used at a low cutting speed, the microhardness value rises, but when cutting fluid is used, the hardness reduces owing to the high temperature in the cutting zone. Shokrani et al. [15] proposed a new method consisting of cryogenic, MQL and hybrid (MQL+cryogenic) for milling Ti6Al4V alloy with carbide coated tool. In the test results, tool wear, tool life and surface roughness were examined. Jamil et al. [16] investigated the effects of nanofluids and cryogenic cooling in the turning of Ti6Al4V alloy at different speeds and feed rates. It was determined that the surface roughness of nanofluids decreased by 8.72%, the cutting power decreased by 11.8% and the tool life increased by 23% compared to cryogenic cooling. Hegap et al. [17] investigated the effects of multiple carbon nanotubes impregnated in vegetable oil on tool wear in the machining of Ti6Al4V material. As a result, the use of 2% nanofluid reduced energy consumption by 11.5% and tool flank wear by 45% compared to dry machining. At the end of the experiment, a mathematical model according to the experimental results was developed. In drilling Ti6Al4V alloy, Shah et al. [18] compared machining with cryogenic LCO2 and LN2 with machining to the coolant. Surface roughness, active cutting energy, active energy consumed by machine tool, and energy efficiency were all examined for all three cutting situations. They observed that machining is more efficient when LCO2 and LN2 are used as sustainable coolant approaches rather of mineral-based coolants.

Because traditional coolants are not ecologically friendly, most studies on the issue have concentrated on alternate cooling and lubricating solutions. In this context, it has been noticed that cryonic processing research has increased, particularly in the processing of high-hardness materials like Ti and its alloys. The majority of the research, in this context have focused on optimizing machining parameters, cooling, hybrid cooling and tool design. There has been few research on the impact of cryogen application direction on processing. The effects of cryogen application on the front and back of the tool on burrs and surface roughness were investigated and compared to dry machining in this study.

MATERIAL AND METHODS

The milling experiment was performed on a CNC milling machine (Chevalier QP2040-L type) under cryogenic and dry cutting conditions. In the experiment, a Ti6Al4V alloy with a diameter of 20 mm and a length of 240 mm was used for the workpiece, and the chemical component and physical properties of this material are given in Table 1. A precision vice is used to clamp the workpiece to the workbench, and the operation is controlled by a comparator.

In the milling process, carbide coated tools with a diameter of 8 mm were preferred as the tool in the machining of

Table 1. Chemical compound and physical properties of the Ti6Al4V alloy

Chemical compound					
Element (%)	Ti	Al	V	H (max.)	Fe (max)
Weight	88.74–91	5.5–6.75	3.5–4.5	0.015	0.25
Physical characteristics					
Ultimate Tensile Strength (Mpa)	Elongation (%)	Hardness (Rc)	Poisson's ratio		
950	14	36	0.342		

a Ti6Al4V alloy, taking into account the literature [14]. The cutting tool has four cutting edges and the cutting length is 8 cm. The new tool was used to clearly observe the effect of machining parameters in each experiment.

The milling operation was applied along four axes, as illustrated in Figure 1, with a cutting depth of 0.5 mm. The lengths of the areas indicated on the shaft in Figure 1 b were created by splitting the whole length into three equal portions, each of which was 80 mm long. The parameters of this process are given in Table 2.

After machining, the effects of the tool on the machined surface, chip types, and burr development were investigated using a Euromex microscope.

During the experiment, cryogenic coolant (LN_2, -196 °C) was applied separately at the front and back positions of the tool's cutting direction (Fig. 2). In addition, dry machining was performed to determine the effects of cryogen. A nozzle with a diameter of 1.5 mm and a constant pressure of 1.5 bars were transmitted to the cutting zone of the cooler. Pressure gauge, safety and solenoid valve were used to keep the LN2 flow constant and control the pressure during milling. The nozzle was fixed at an angle of 45°, providing simultaneous movement of the nozzle and cutting tool.

In order to determine the effects of machining methods on the surface, measurements were taken using a Time Tr-200 brand surface roughness measuring device with a sample length of 0.8x5 (Fig. 3). The surface roughness was determined by taking measurements from three different regions and averaging them.

Table 2. Machining parameters used in the experiment

Spindle speed (rev/min)	Feed rate (mm/rev)	Cutting depth (mm)
1400	0.2	0.5
2000	0.2	0.5

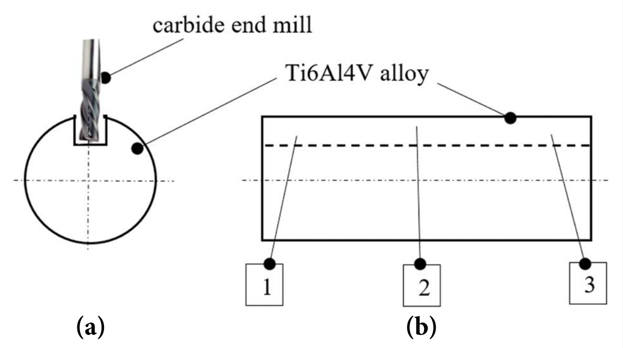

Figure 1. Image of the milling process of the workpiece **(a)** Front view **(b)** Left view.

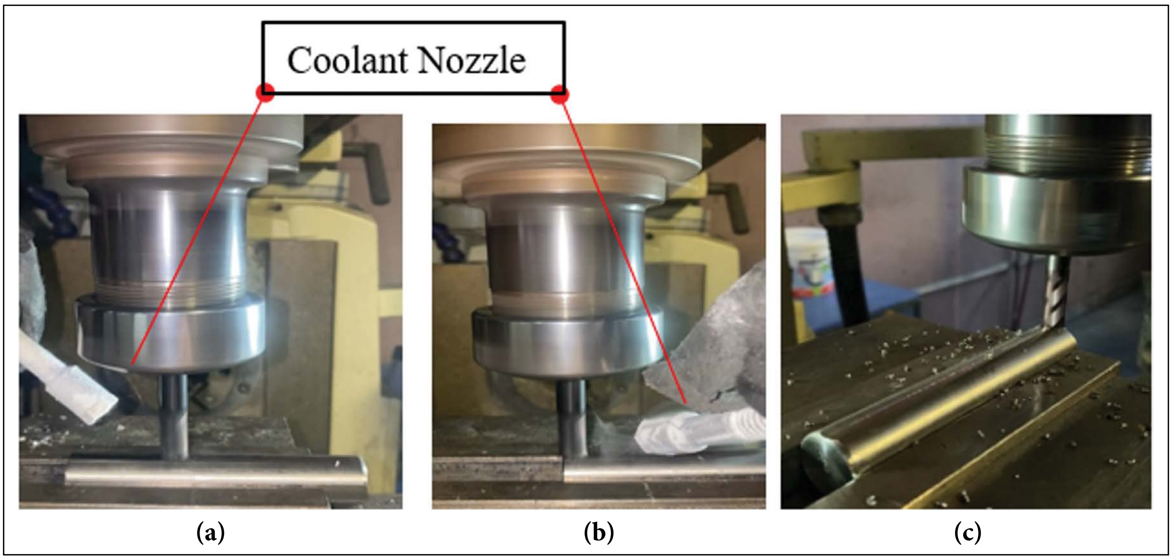

Figure 2. Application of cryogenic cooling **(a)** Cryogen at the back of the tool **(b)** Cryogen at the front of the tool **(c)** dry machining.

Figure 3. Roughness measurement from test sample.

RESULTS AND DISCUSSION

Evaluation of Surface Roughness

The change in the average roughness values (Ra) on the machined surface after the milling of the Ti6Al4V alloy according to different machining parameters is given in Figure 4.

As can be seen from the graph, the highest roughness value was obtained in the milling process performed in dry machining. The surface roughness value was obtained close to dry machining in the application of cryogen on the machining axis in front of the cutting tool. This is because the cryogen coolant (LN2) touches the workpiece more than the cutting zone in the cryogen front region application. Because of this, the Ti6Al4V alloy reaches harder values than the hardness values at room temperature. In particular, the hardness values obtained after the cryogen application were 41.7 Rc, while the hardness value of the non-cryogenic area was 33.4 Rc. In this case, the titanium alloy processing is difficult, resulting in poor surface quality. In fact, in their investigation on the impacts of A cryogen on the material, they underlined that cryogen improves strength, hardness, and toughness while decreasing toughness [19]. This means that the forces increase in the cutting plane therefore, this increase in forces is an important parameter in the deterioration of surface quality. Dry machining, on the other hand, resulted in a lower roughness value than the front application of cryogen, since frictional heat lowers the brittleness of the material, albeit only partially. The deviation between the front application of cryogen and dry processing is 11.7% on average.

The roughness value was determined to be more advantageous than the other two ways in the application of cryogen from the back of the tool. Surface roughness values in machining with cryogen applied from the back position of the tool were 47.9% lower than in dry machining and 52.8% lower than in machining with cryogen applied from the front position of the tool. The major reason for this is that if the cryogen is applied from the back of the tool, the tool does not lose its hardness at the high temperatures observed while machining titanium alloy. Furthermore, it is thought that the cryogen used in the back section of the tool reaches the cutting region more readily, lowering the chip's breaking stress and therefore simplifying chip evacuation. This reduces the contact length between the tool and the chip. Furthermore, the surface roughness at the tool's entrance to the workpiece is higher than at the tool's exit, although the difference is not significant. The cause for this is considered to be the rapid rise in forces with tool-to-workpiece contact, after which the forces are thought to return to a stable position with the stability of the machining process and the surface roughness progressively diminishes.

Figure 4. Variation of surface roughness according to measuring zones (1400 rev/min- 0.2 mm/rev).

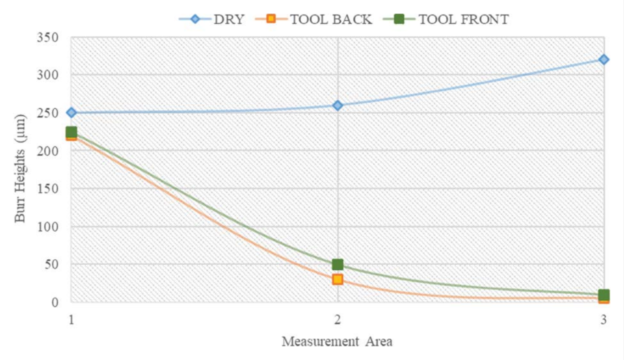

Figure 5. Burr heights that occur in the cutting zone after milling (1400 rev/min- 0.2 mm/rev).

It was showed from the experimental results; the roughness values decreased with the increased spindle speed in both dry and cryogenic conditions. Ra value showed with cryogenic cooling provided 20% improved in roughness value compared to dry milling. Cryogenic cooling at the back of the tool was found in a 12% drop and better surface roughness values when compared to cryogenic cooling in front of the tool. This is due to cryogenic cooling lowering the cutting temperature in the cutting zone, resulting in decreased cutting forces and no chip weld adhesion [20].

Effect of Cryogenic Application on Burr Formation

Burrs that form after manufacturing are an issue that is just as important as surface roughness in milling. Figure 5 shows the variations in burr heights that occur in the cutting zone after milling. The burr images obtained were taken by dividing the spindle into three equal parts, at the beginning, middle and exit region of the milling.

In general, it was determined that the burr formation was similar according to the methods in the images obtained after milling, only the size of them varied. The burr formation was divided into three equal parts of the total

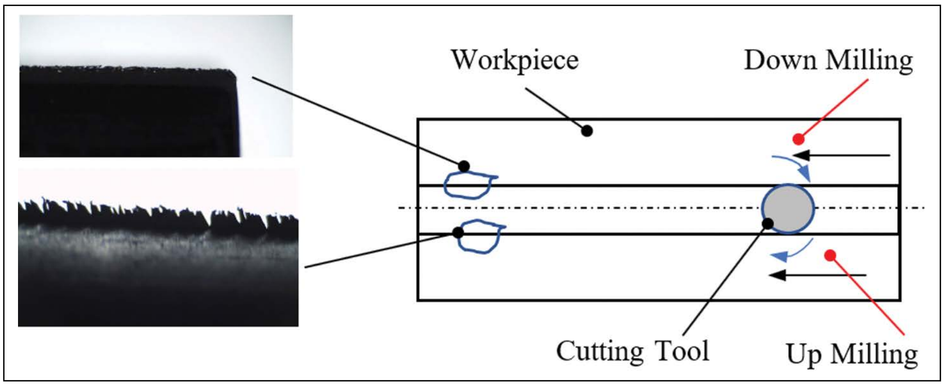

Figure 6. An investigation of the effects of cryogen application direction on Ti6Al4V alloy milling.

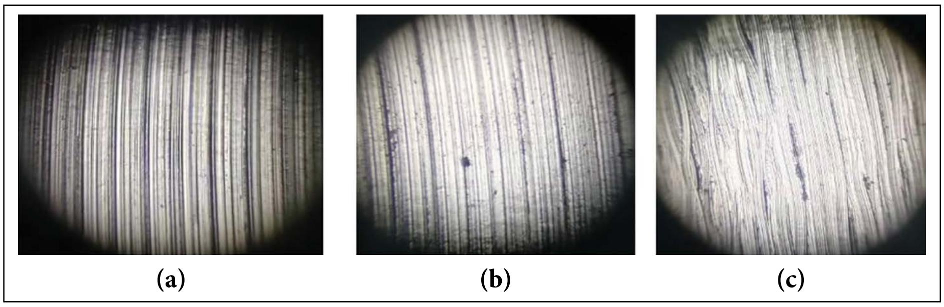

Figure 7. Tool marks from the machining surface **(a)** cryogen from the front of the tool **(b)** cryogen from the back of the tool **(c)** dry machining.

length of the workpiece and evaluated as three regions: the entrance, middle and exit regions. The application of cryogen in front of the cutting tool resulted in the smallest burr size in the starting region, whereas dry machining resulted in the highest burr size. Because the Ti6Al4V alloy used as a workpiece has alpha and beta phases, which improve the material's deformation resistance. This situation causes a sudden rise in the forces in the tool's entrance region to the workpiece, as well as an increase in temperature [21]. As a result of this, burr formation on the edges has occurred as the material's plastic deformation is aided.

Furthermore, less burr formation was seen on the edge where the cutting tool initially began to remove chips vs the edge where the chip was thrown last (Fig. 6). In other words, burr sizes remained smaller in the region where up milling was performed than in the region where down milling was performed.

Because the stable condition of the cutting was formed in the middle and exit area of the cutting tool-workpiece, no burr formation was seen in the application cryogen of the tool front and back, but burr sizes increased in dry machining, particularly in the exit region. The wear in the cutting tool is considered to be the cause of the rise of burrs in dry machining. Indeed, Weule et al. [22] reported that in their investigation of materials of varying hardnesses, greater burr development occurred in hard materials. They thought that the observed condition was caused by the rapid wear exhibited during hard material machining. Figure 7 indicates that the deformation in the processing traces images obtained from the machined surface is high in the dry machining method. Because of the use of cryogen in front of the tool in Figure 7a, the spacing of the tool marks is greater than with other methods. This is due to the fact that, as previously stated, both the workpiece and the tool are exposed to cryogen, which increases the hardness of both. In Figure 7b, the application of cryogen behind the tool increased the tool's hardness, and the tool scar on the surface was decreased as a result of the tool's increased wear resistance against cutting. Figure 7c shows that the traces were not in a regular structure due to plastic deformation caused by temperature.

It was found that changing the spindle speed in cryogenic cooling had no significant influence on burr height and also dry machining caused higher burrs in the majority of cases. This can be explained by the thermomechanical stresses generated during milling. Dry machining produces the highest temperatures in milling when compared to cryogenic cooling. Due to the generally increased temperatures during milling, the ductility of the material rises, resulting in increased burr heights.

Chip Formation

Cryogenic cooling can alter the mechanical characteristics of a material as a result, the chip breaking effect in the cutting process can change. Figure 8 shows comparisons of chip formations from dry and cryogenic machining.

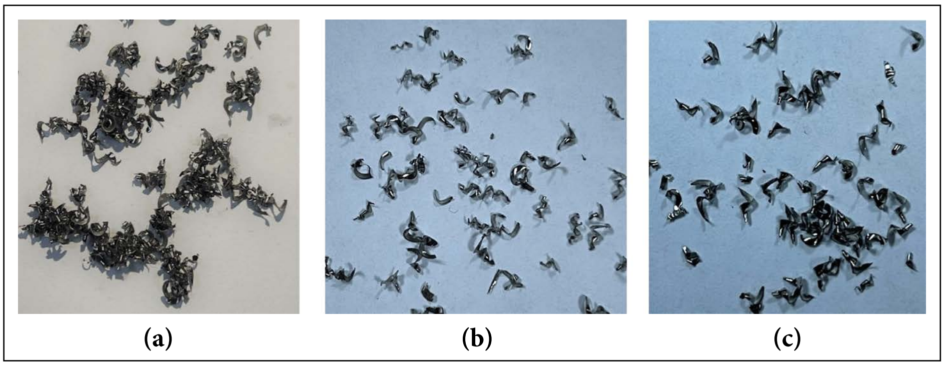

Figure 8. Chip formation from **(a)** dry machining **(b)** cryogen from the back of the tool **(c)** cryogen from the front of the tool.

Figure 8a depicts a chip generated during dry cutting of Ti6Al4V. The chip formed by dry cutting is a lengthy chip that is difficult to break. The long, curved chip is simple to wrap around the tool. It has the potential to damage the machined surface and compromise surface integrity during cutting. It can be seen that short helical chips were produced when using cryogenic machining while snarled chips were generated from dry machining. In the machining process, helical chips are preferred because they are easier to control. The length of the helical chips obtained in the cryogenic application at the back of the tool was shorter than in the cryogenic application from the front of the tool. The reason for the difference in chip forms might be because the cryogenic coolant was placed directly on the tool rake face and was able to permeate between tool-chip contacts.

CONCLUSION

As a result of the experiment, it was determined that the cryogen's application direction had an influence on the processing characteristics. The application of cryogen behind the tool, in particular, resulted in an about 50% improvement in surface quality. The roughness values decreased with the increased spindle speed in both dry and cryogenic conditions. When compared to dry milling, cryogenic cooling offered an average 20% improvement in roughness value. In the increase the spindle speed, when compared to cryogenic cooling in front of the tool cryogenic cooling at the back of the tool resulted in a 12% drop and superior surface roughness values. Burr formation, on the other hand, occurred more commonly in dry machining because to the high temperature involved in burr development in dry machining. After obtaining steady cutting in cryogenic machining, it was determined that the direction of cryogen application had no influence on burr formation. The chip generated by dry cutting is a long, difficult-to-break chip. Cryogenic machining resulted in short helical chips, whereas dry machining resulted in snarled chips. The length of the helical chips obtained in the cryogenic application from the back of the tool was less than the length of the helical chips obtained in the cryogenic application from the front of the tool.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author’s Contributions

Erkan Bahçe: Conceptualization, methodology, writing, investigation, original draft preparation.

Eray Sarıgül: Investigation, writing- griginal draft preparation.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

Financial Disclosure

This research was supported by İnonu University BAP [project number: FYL-2020-2038].

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