WWW.ATMIA.PUT.POZNAN.PL AMTM VOL. 36 (2016) 12-17

ARCHIVES OF MECHANICAL TECHNOLOGY AND MATERIALS

The influence of cooling techniques on cutting forces and surface roughness during cryogenic machining of titanium alloys

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A B S T R A C T

Titanium alloys are one of the materials extensively used in the aerospace industry due to its excellent properties of high specific strength and corrosion resistance. On the other hand, they also present problems wherein titanium alloys are extremely difficult materials to machine. In addition, the cost associated with titanium machining is also high due to lower cutting velocities and shorter tool life. The main objective of this work is a comparison of different cooling techniques during cryogenic machining of titanium alloys. The analysis revealed that applied cooling technique has a significant influence on cutting force and surface roughness (*Ra* parameter) values. Furthermore, in all cases observed a positive influence of cryogenic machining on selected aspects after turning and milling of titanium alloys. This work can be also the starting point to the further research, related to the analysis of cutting forces and surface roughness during cryogenic machining of titanium alloys.

Key words: cryogenic machining, forces, surface roughness, titanium alloys, cooling techniques

1. INTRODUCTION

Cryogenic machining allows to improve the machinability by increasing tool life, decreasing the temperature value in the cutting zone and decreasing surface roughness parameters values [7, 17, 30]. The influence of cryogenic cooling on machining is strictly dependent on OUPN system's properties.

The majority of studies in cryogenic machining of special alloys have concentrated on titanium [2, 5, 6, 9, 10, 12, 21, 22, 24] and nickel alloys [11, 16, 18, 23, 25, 27]. These alloys exhibit distinctive characteristics making the machining of these materials relatively difficult [19]. Thus, the machining methods require new strategies and tools with appropriate coatings implementation. High cutting temperature values during machining of titanium and nickel alloys impose the need of very intensive cooling, which means that dry machining may have only minimal character. Even intensive cooling the liquid under high pressure is not able to prevent rapid tool wear. The only effective way to reduce cutting temperature during machining and to reduce the effects of thermal tool wear is cryogenic cooling using liquid nitrogen (LN_2) at a temperature of -190°C.

The application of titanium and its alloys has increased in recent years due to its excellent properties and improved machinability. The main advantages of titanium and its alloys include: low density (twice lower than nickel-based alloys), high strength at increased temperatures, high creep and corrosion resistance and high hardness [8, 15, 29]. The most important problem during machining of titanium alloys is to obtain surface with required dimensional and shape accuracy and low surface roughness parameters values [3, 4, 13, 14]. This issue, including tool life, is the greatest challenge during machining [26].

Titanium materials find the application in dental prosthetics, cardiac surgery, interventional cardiology and orthopedic surgery. The application scope of titanium alloys in medicine extends from implantation pumps and components of artificial heart to spine, hip or knee implants. Titanium alloys also find the application in production of elements which are used for bones integration. It should be noted that titanium alloys are also used in the manufacture of surgical instruments, successfully replacing the stainless steel, showing at the greater durability after repeated use and sterilization. Titanium alloys are also used in aeronautic industry (engine parts, upper wings girders and chassis components).

2. CUTTING FORCES ANALYSIS OF TITANIUM ALLOYS AFTER CRYOGENIC MACHINING

In [6] investigated cryogenic turning of the *Ti-6Al-4V* alloy with modified cutting tool inserts. The turning experiments were carried out on a *Ti–6Al–4V* alloy (*Ti*-89.6%, *Al*-6.11%, *Fe*-0.127%, *Sn*-0.4%, *V*-3.63%) with PVD *TiAlN* coated tungsten carbide tool inserts under wet and cryogenic cutting conditions. The tool holder used for machining was ISO PCLNR 2020 K12 (Kennametal). In wet machining, a cutting fluid was applied on the machining zone, using a nozzle. The emulsion cutting fluid was obtained by mixing the concentrate with water at a ratio of 1:20 soluble oil. The influence of wet and cryogenic machining on forces values is presented in Figure 1. The cutting force decreases with an increase in the cutting velocity due to a decrease in the shearing area.It was also observed that a reduction in the main cutting force and feed force due to cryogenic cooling was 38% and 39% respectively over wet machining [6]. This is because of better lubrication effect produced by liquid nitrogen at the chip–tool rake surface and newly machined work surface–tool auxiliary flank surface due to the formation of a fluid cushion.

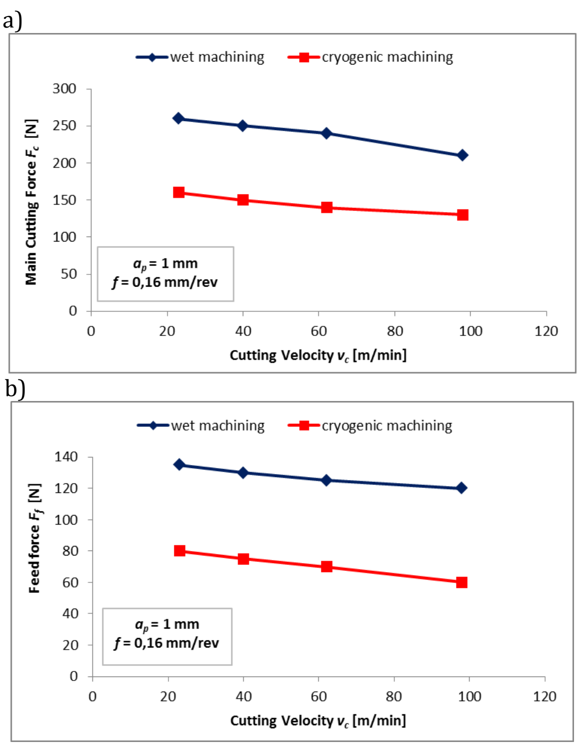


Fig. 1. Main cutting force (a) and feed force (b) values in a function of cutting velocity. Elaborated on the basis of [6]

In [2] investigated cutting forces during cryogenic machining of *Ti-6Al-4V*. The workpiece material used in this study was β-annealed *Ti-6Al-4V*. The variations of cutting forces values are presented in Figure 2. Cutting forces change their values when feed rate and depth of cut values change. Feed and main cutting force values decrease with the increase of the feed rate and decrease of the depth of cut. Under the same conditions, the thrust force increases. Figure 3 also shows that the most effective way to obtain the low cutting force values is to spray the coolant on both rake and flank face of the cutting tool. Compared to dry cutting, the main cutting force increases when cryogenic coolant is only applied to the rake [2].

Cutting forces during cryogenic machining (turning) of *Ti-6Al-4V* were also investigated in [9]. Their values are compared in Figure 4. The studies revealed that all cryogenic techniques generate higher main cutting force and thrust force. It is interesting to note that the feed force during cryogenic machining which is closely related to the frictional force of the chip acting on the tool, decreases.

In [21] machining (turning) of *Ti-6Al-4V* with cryogenic compressed air cooling was presented. The cutting forces were measured and compared with those measured during machining with compressed air cooling and dry cutting conditions.

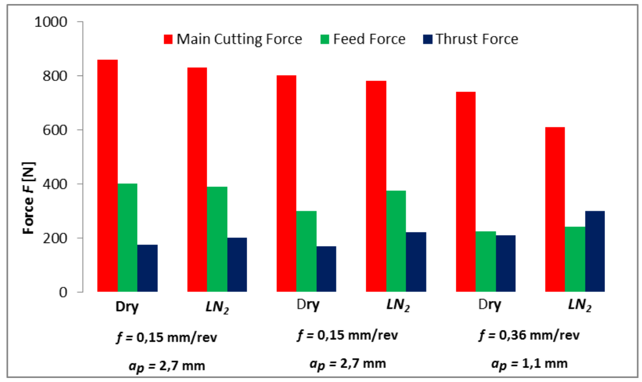


Fig. 2. Cutting forces values for variable feed rate and depth of cut values after dry and cryogenic machining. Elaborated on the basis of [2]

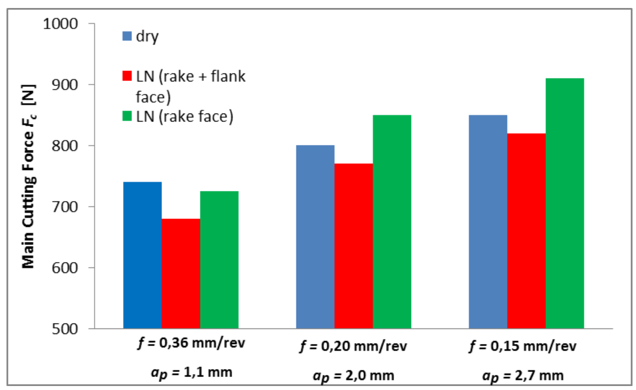


Fig. 3. Main cutting force for different cooling conditions. Elaborated on the basis of [2]

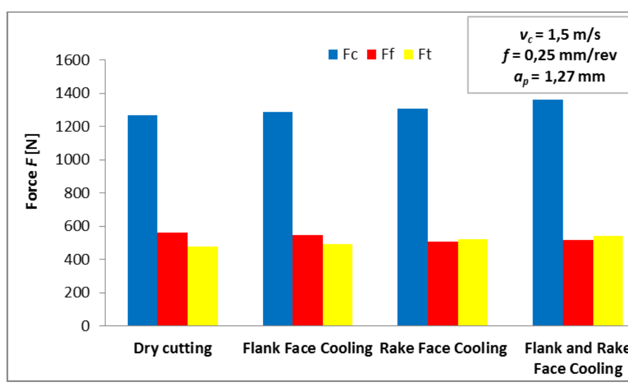


Fig. 4. The influence of cooling technique on cutting forces values. Elaborated on the basis of [9]

The forces during dry machining are smaller than those obtained during air cooling and increase rapidly after machining compared to the cutting forces with both compressed air and cryogenic compressed air cooling. Increase in cutting forces with cutting time is believed to be due to the evolution of tool wear and the development of a built-up edge. Therefore, increase in cutting forces (especially the feed force) with cryogenic compressed air cooling with respect to cutting length is significantly lower than that when dry machining.

The effects of cooling air temperature on cryogenic machining (milling) of *Ti–6Al–4V* alloy were investigated in [30]. The cooling techniques were namely dry, wet, minimum quantity lubrication (*MQL*) and *MQL* with cooling air. The average cutting forces values are presented in Figure 5. It was observed that the highest cutting force values are obtained under dry cutting environments. This may be attributed to the lower coefficient of friction at the chip–tool interface provided by the lubrication [30]. However, the influence of *MQL* on cutting force is not noticeable, which may be due to the lower cooling capability of air (17°C) compared to cooling air and flood coolant. With the application of *MQL* and cooling air (0°C, −15°C, −30°C, −45°C) in the cutting zone, there is a substantial reduction in the cutting force.

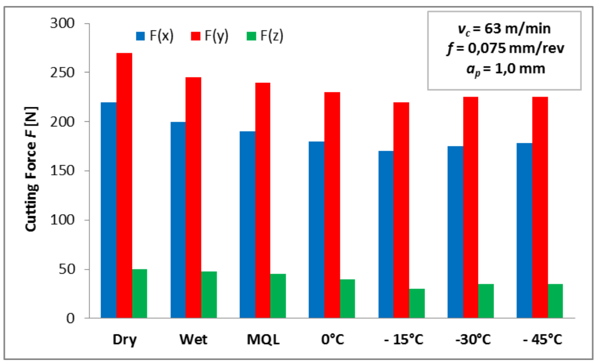


Fig. 5. The influence of cooling technique on cutting forces values during milling of titanium alloy. Elaborated on the basis of [31]

Turning of titanium alloy with *TiB₂*-coated carbides under cryogenic cooling was investigated in [24]. In this, *TiB₂*-coated carbide inserts were used to machine titanium alloy (*Ti-5Al-5Mo-2Sn-V*) under dry and cryogenic cooling conditions. Figure 6 shows force ratio with cutting velocity under dry and cryogenic conditions and Figure 7 presents the main cutting forces values. Under dry machining, the force ratio varied from 1.25 to 0.75 with an increase in cutting velocity from 56 to 123 m/min, indicating a higher rate and amount of tool wear with increasing cutting velocity [24]. However, under cryogenic cooling the force ratio was found to vary from 1.6 to 0.75 with the same increase in cutting velocity. It could be noted, that as long as the tool wear is low, the cutting forces are lower under cryogenic cooling than under dry machining.

In [10] nitrogen gas was used during milling of *Ti-6Al-4V*. Cutting force values obtained during milling with nitrogen gas were different from those obtained during cutting without the gas. Studies have shown that the cutting force values were greater during cutting without nitrogen gas (the maximum of 162 N) than those during cutting with nitrogen gas (the maximum of 109 N). It could be explained by the fact, that without nitrogen gas, the chips congregated around the cutting edge and the condition of chip drainage was very poor. The amount of machining heat was generated greatly and the chips were melted and adhered to the cutting edge. Then, the cutting force values increased consequently [24].

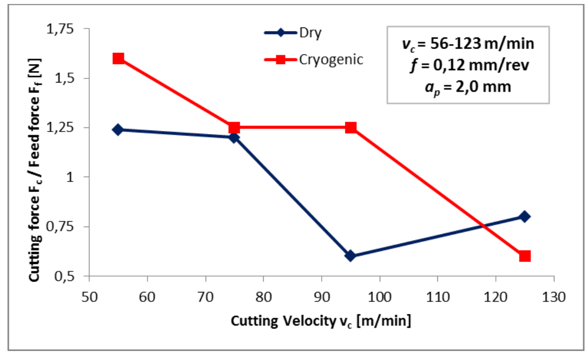


Fig. 6. Force ratio values in function of cutting velocity during dry and cryogenic machining. Elaborated on the basis of [24]

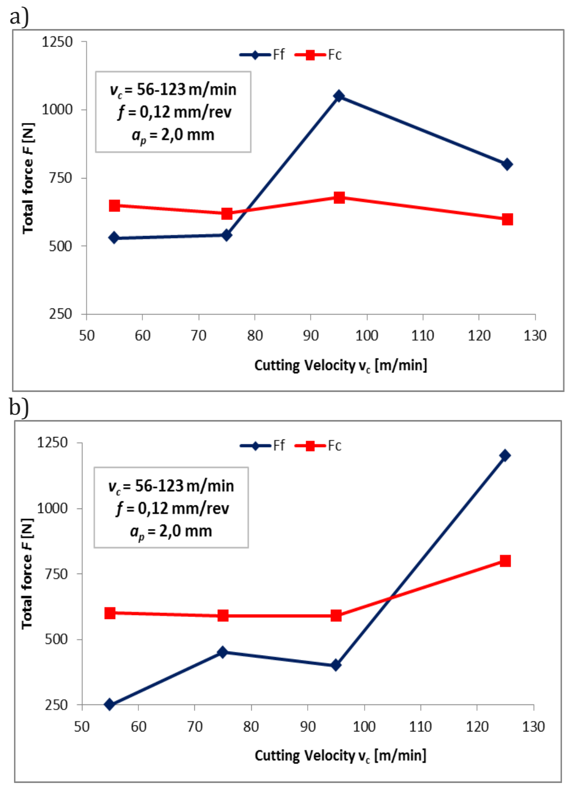


Fig. 7. Cutting forces values in function of cutting velocity during: a) dry and b) cryogenic machining. Elaborated on the basis of [24]

3. SURFACE TEXTURE ANALYSIS OF TITANIUM ALLOYS AFTER CRYOGENIC MACHINING

In [10] investigated surface roughness parameters values after conventional and cryogenic machining of titanium alloy *Ti64*. The roughness of the machined surface was measured after the milling process. The roughness value after cryogenic machining was 15-fold lower than after machining without coolant. This is because that when nitrogen gas was not able to arrive at the machining zone, lots of chips that absorbed a large amount of heat and could not be removed immediately would burn. Then the burning chips adhered to cutting edges and machined surface.

In [6] investigated surface texture after conventional and cryogenic turning of titanium alloy *Ti-6Al-4V*. Figure 8 shows the average surface roughness parameters values *Ra* obtained after wet and cryogenic machining. The reduction of *Ra* due to cryogenic cooling was about 25-35% compared to wet machining due to less adhesion between the newly generated workpiece surface and tool auxiliary flank surface and lower tool wear rate [6]. Cryogenic cooling showed a substantial improvement in the surface roughness parameters values.

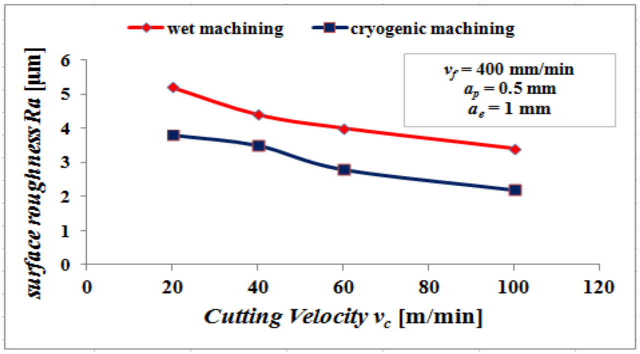


Fig. 8. The influence of machining method on surface roughness parameter Ra value for Ti-6Al-4V alloy. Elaborated on the basis of [6]

It was also observed that, in terms of surface roughness, *MQL* with -15 and -30 ºC results in better surfaces, probably due to better lubrication and cooling effect which result in lower friction at the tool-chip and tool-workpiece interfaces (Fig. 9). The roughest surfaces are obtained with dry cutting due to more intensive temperature and friction between tool flank and workpiece [31].

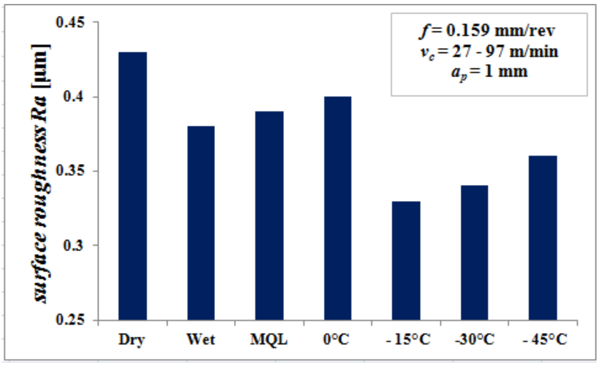


Fig. 9. Influence of the machining technique on surface roughness. Elaborated on the basis of [31]

In [24] investigated surface roughness parameters values after turning of titanium alloy *Ti-5Al-5Mo-2Sn-V* with TiB_2-coated carbides under cryogenic cooling. It was found that the surface roughness profiles obtained under dry and cryogenic environments at cutting velocities of v_c=56 m/min and v_c=72 m/min show that the feed marks are clearly visible under cryogenic cooling and indicate a better surface quality without any plastic deformation or glazing by the worn tool nose, whereas under dry machining the surface undergoes glazing, leading to an irregular surface profile [24].

In [1] experimental study on turning of *TC9* titanium alloy with cold water mist jet cooling was conducted. Figure 10 presents the surface roughness parameters values obtained after different cooling techniques. Surface roughness values under different cooling conditions all decrease with the increasing of cutting velocity value. Regardless of the cutting velocity, both CWMJ and flood cooling techniques can lead to low surface roughness values during *TC9* turning process comparing with cold air jet. It can be attributed to the lubricative performance of cooling medium. The soluble oil can provide a higher level of lubrication than the other two cooling mediums [28].

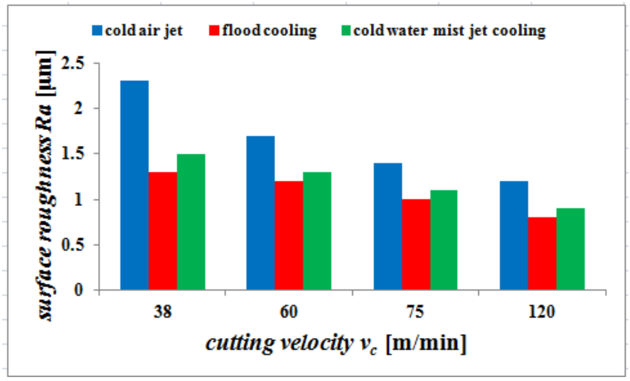
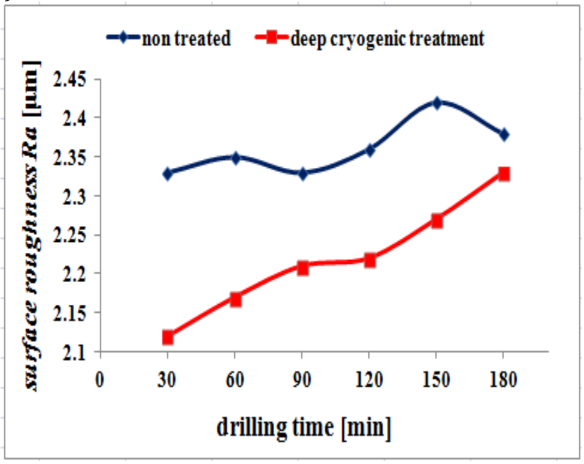


Fig. 10. Influence of cooling technique on surface roughness Ra. Elaborated on the basis of [1]

In [21] investigated the effect of deep cryogenic treatment of titanium alloy (*Ti-6Al-2Sn-4Zr-6Mo*) on surface roughness parameters values after electric discharge drilling. The arithmetic surface roughness value (*Ra*) was adopted for current research and measurements were carried out at the base and at the side wall of the blind holes. The *Ra* values of the electrical discharge machining surface were obtained by averaging the surface roughness values of 6mm measurement length. A cut off length of 0.8mm was used for the surface roughness measurement (Fig.11).

a)



b)

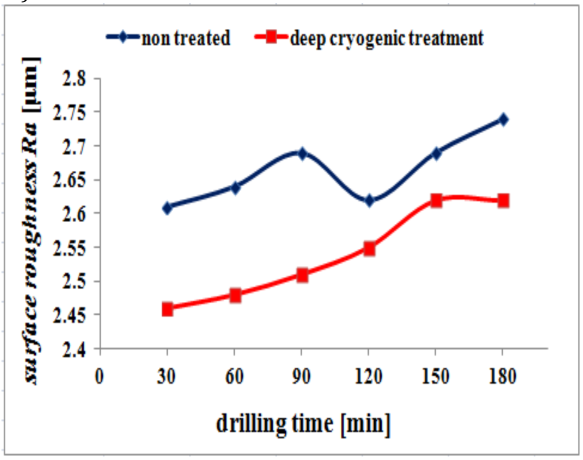


Fig. 11. Surface roughness parameter Ra values measured: a) on base of blind hole with drilling time, b) on side wall of blind hole with drilling time. Elaborated on the basis of [21]

It can be seen in Figure 11, that the *Ra* values for deep cryogenic treatment of titanium alloy workpiece are less as compared with the non-treated workpiece on both the base of the blind hole as well as side walls, irrespective of the drilling time. So the surface finish produced on the deep cryogenic treatment is better than the non-treated surface of titanium alloy [21].

4. CONCLUSIONS

In the paper, the literature survey, related to the analysis of cutting forces after different techniques of cryogenic machining of titanium alloys was presented.

The main problem of machining of titanium is high tool wear and chatter due to variation of chip thickness, high heat stress and high pressure loads. They limit the material removal rate and increase the machining costs. In addition to these, residual stress affects the quality of finished products if proper measures are not taken. Titanium alloys have different machinability. Application of high-pressure coolant is the most commonly used method to improve productivity of titanium alloys machining. However, cryogenic cooling is found to be more efficient than that of high pressure cooling method though it is not frequently used in the machining industries. Thermally enhanced machining, hybrid machining and use of high conductive cutting tool and tool holder are still in the primary stage of research. Application of these methods is not proven to contribute significantly to improve the productivity of titanium alloys machining in the industrial environment. Most of the cutting tool materials are chemically reactive to titanium alloys under machining condition. Only the carbide, binderless CBN, sintered diamond and natural diamond cutting tools are found reasonably suitable for machining of titanium alloys.

It was found that cooling methods have significant influence on the cutting force values. It has been found that the cooling approach is one of the most important phenomena that affects the cutting forces. Similar cooling techniques could yield different results in machining of titanium alloys.

Despite the advantages of cryogenic cooling in machining of titanium alloys, there is very limited research on different cryogenic cutting operations. For instance, while 22.4% of the research in cryogenic machining has focused on titanium alloys, only 18% of the studies in cryogenic milling and 13% of the investigations in cryogenic machining of titanium alloys are related to cryogenic milling of titanium [18]. In addition, there is no report or few literature survey on the cryogenic drilling of this material.

Cryogenic machining tends to increase the cutting force because the work material becomes harder and stronger at lower temperature. However, the lower temperature makes the material less sticky, reducing the frictional force inherent in the cutting process.

In cryogenic machining of titanium alloys, it can be found that, regardless of the cooling technique, cryogenic coolant exhibits promising improvements in tool life. However, in order to enhance the surface finish in the machining zone, the best approach is to penetrate the cryogen into the cutting zone.

Cryogenic machining is an efficient way of maintaining the temperature at the cutting interface well below the softening temperature of the cutting tool material. When compared with dry cutting and conventional cooling, for machining titanium and alloys the most considerable characteristics could be determined as enabling substantial improvement of machined part surface quality. Cryogenic machining allows to obtain surface roughness parameters values smaller than during conventional machining.

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