STUDY THE EFFECT OF CRYOGENIC COOLING WITH MODIFIED CUTTING TOOL INSERT IN THE TURNING OF TI-6AL-4V ALLOY

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Abstract

The present study involves modification of the cutting tool insert for supplying liquid nitrogen to the heat generation zones in the turning process. In this research work, an attempt has been made to investigate the effect of liquid nitrogen when it was applied to heat generation zones through holes made in the cutting tool insert during the turning of Ti-6Al- 4V alloy with PVD TiAlN coated tungsten carbide cutting tool inserts of ISO CNMG 120408 MP1 – KC5010. The cryogenic results of the cutting temperature, cutting force, and surface roughness for the modified cutting tool insert have been compared with wet machining. The cutting temperature was reduced by 64 – 67% in cryogenic cooling over wet machining. The cutting force was decreased by 43 - 53% in cryogenic cooling with modified cutting tool insert over wet machining. It was also observed that in the cryogenic cooling method, the surface roughness was reduced to a maximum of 33% over wet machining. Cryogenic cooling provided the substantial benefit in reducing the cutting forces and improving surface roughness through control of the cutting temperature and reduction in adhesion between the interactingsurfaces.

Keywords: *Cryogenic turning, Ti-6Al-4Valloy, Cutting temperature, Cutting force, Surface roughness*

1. Introduction

Ti-6Al-4V is the most commonly used titanium alloy. It has many applications in the aerospace and medical device industries due to its high strength-to-weight ratio, good corrosion resistance and excellent biocompatibility. It is a difficult material to machine. The main problems in machining Ti-6Al-4V alloy are the high cutting temperature and rapid tool wear. Currently, a cutting fluid is used to cool and lubricate the cutting process, which could reduce the cutting temperature and improve the tool life to some extent. But the conventional cutting is an environmental contaminant and the government has strict regulations limiting the cutting fluid waste. Cryogenic cooling is an environment-friendly clean technology for the desirable control of cutting temperature and enhancement of the tool

2. Literature review

Hong and Zhao (1999) defined the main functions of cryogenic cooling in the metal cutting process. It was reported that liquid nitrogen as a coolant removed the heat effectively from the cutting zone, lowering the cutting forces and modifying the frictional characteristics at the chip-tool interfaces. Dhar et al (2000) have investigated the role of cryogenic cooling by liquid nitrogen jet in the cutting temperature in the turning of plain carbon steel (C-40) under varying cutting velocity and feed rates. The experimental and computational results indicated that the cryogenic cooling enabled a substantial reduction in the cutting temperature, depending upon the levels of the cutting velocity and feed, and cutting tool geometry. It was also reported that the chip formation and chip-tool interaction become more favourable, and the cutting forces decreased to some extent, when the liquid nitrogen jet was employed. The liquid nitrogen jets were supplied at the cutting zone along the main and auxiliary cutting edge at a pressure of 2 bars. The reduction in the temperature is attributed to a reduction in the chip contact length, favourable chip-tool interaction, better chip breaking, reduced forces and enhanced heat transfer situation under cryogenic cooling.

Hong (2001) developed a new economical and practical approach to cryogenic machining technology. The micro nozzle jets to the cutting point locally; this approach minimizes the amount of liquid nitrogen consumption to levels at which nitrogen costs less than the conventional cutting fluid. It was reported that the cryogenic cooling reduces tool wear, and increases tool life up to five times, thereby allowing for high-speed cutting, improving productivity and reducing the overall production cost. In addition, this approach reduces the frictional forces, improves chip breaking, eliminates build-up edge, and improves surface quality. Hong and Ding (2001) studied the influence of various cryogenic cooling approaches in the turning of the Ti-6Al-4V alloy. A small amount of liquid nitrogen applied locally to the cutting edge is superior to emulsion cutting, in lowering the cutting temperature. Liquid nitrogen applied in close proximity to the tool cutting edge, can significantly reduce the tool temperature, depending on the target location. It was reported that approaches in the order of effectiveness (worst to best) are: dry cutting, cryogenic tool back cooling, emulsion cooling, pre-cooling the workpiece, cryogenic flank cooling, cryogenic rake cooling, and simultaneous rake and flankcooling.

Hong et al (2001) studied how the temperature affects the titanium properties, and compared the different cryogenic cooling approaches. The authors introduced an innovative cryogenic cooling approach in the cryogenic machining of the Ti-6Al-4V alloy. In this innovative approach, liquid nitrogen was supplied through a micro-nozzle located between the tool face and the chip breaker. An improvement in tool life under cryogenic cooling over the state-of-the-art emulsion cooling was reported. Paul et al (2001) have carried out an experimental investigation about the role of cryogenic cooling by a liquid nitrogen jet on tool wear and surface finish in the plain turning of AISI 1060 steel at industrial speed-feed combination, by two types of carbide inserts of different geometric configurations. The results have been compared with dry machining and machining with soluble oil as a coolant. A substantial benefit of cryogenic cooling on tool life and surface finish was reported. It was also reported that the application of the liquid nitrogen jets along the main and auxiliary cutting edges substantially changes the chip formation, reduces the cutting forces and effectively controls the cutting temperature.

Hong et al (2002) studied the effect of cryogenic cooling on sliding friction. The results indicated that the liquid nitrogen cooled condition has a significantly lower coefficient of friction than the dry condition. Dhar et al (2002) have studied the role of cryogenic cooling by a liquid nitrogen jet in the average chip-tool interface temperature, tool wear, dimensional accuracy and surface finish in the turning of the AISI 4140 steel. Cryogenic cooling enabled a substantial reduction in the cutting zone temperature, and favorable chip-tool and work-tool interactions. Cryogenic cooling provided a reduction in flank wear, and an improvement in tool life was reported over dry machining. It was also reported that the surface finish and dimensional accuracy significantly improved under cryogenic cooling. Hong (2006) investigated the lubrication mechanism of liquid nitrogen in the cutting process. It was found that the injection of liquid nitrogen into the contact zone created a lubricating film. The test results showed that the liquid nitrogen jet was very effective in reducing friction. Liquid nitrogen injection to form a physical barrier or hydrodynamic effect between two bodies, is always effective in reducing friction force.

Dhar and Kamruzzaman (2007) studied the effect of cryogenic cooling on the cutting temperature, tool wear, surface roughness and dimensional deviation in the turning of AISI 4037 steel at industrial speed-feed combinations by coated carbide insert, and compared the effectiveness of cryogenic cooling vis-à-vis dry and wet machining. The results indicated substantial benefit of cryogenic cooling on tool life, surface finish and dimensional deviation. This may be attributed mainly due to the reduction in the cutting zone temperature and the favourable change in the chip-tool interaction. Further, it was reported that machining with soluble oil cooling failed to provide any significant improvement in tool life; rather the surface finish deteriorated. Venugopal et al (2007) studied the effect of cryogenic cooling on the growth and nature of tool wear in the turning of the Ti-6Al-4V alloy bars with microcrystalline uncoated carbide inserts. The influence of cryogenic cooling with liquid nitrogen jets enabled a substantial reduction in the tool wear, both on the crater and flank surfaces in the turning of the Ti-6Al-4V alloy. It was also reported that there was a substantial improvement in tool life by a reduction in adhesion-dissolution-diffusion tool wear through the control of machining temperature desirably at the cuttingzone.

Mirghani et al (2007) have studied the effectiveness of cryogenic machining with a modified tool holder. The two different flow outlets were tested with the modified tool holder for use with the cryogenic cooling system. In design I, when the gas is directed towards the cutting edge to cool the newly generated chips, the hardness of the work material is not affected appreciably with cooling. This will enhance the chip brittleness for easy chip breaking. In design II, the discharging gas is directed away from the workpiece materials whose ductility has to be maintained, as it will be reduced by excessive cooling. The experimental results proved that the two designs have a significant effect on tool life and wear resistance when compared to the dry cutting process. Design II showed a better overall performance, longer tool life and morewear resistance than design
I. It is found that the modified tool holder for cryogenic cooling is more effective when the coolant outflow is directed away from the cutting edge of the carbide insert. Ahsan and Mirghani (2008) investigated the effect of cryogenic cooling with a modified tool holder on tool wear and tool life during the machining of stainless steel. In this method, liquid nitrogen cooled just at the bottom of the insert. It was reported that the tool life increased by applying liquid nitrogen with the modified tool holder. The application of cryogenic cooling was found to be more effective at higher cutting speeds as compared to wet machining. It was also observed that cryogenic cooling is efficient at a higher feed rate rather than at a higher depth ofcut.

Kalyan Kumar and Choudhury (2008) studied the effect of cryogenic cooling on tool wear and high frequency dynamic cutting forces generated during the high speed machining of stainless steel. Liquid nitrogen was supplied to the tool tip using a specially designed nozzle. It was found from the experimental results that cryogenic cooling was effective in bringing down the cutting temperatures, which accounted for the substantial reduction of the flank wear. The cutting force in cryogenic machining was observed to be less than that of dry cutting, but the reduction in the cutting force is less than anticipated. About 37.89% reduction in the flank wear has been observed with cryogenic machining over dry cutting. Cryogenic machining is a possible answer for high speed eco-friendly machining. Yakup and Muammer (2008) reviewed the use of liquid nitrogen as a coolant, and investigated in detail the terms of application methods in material removal operations, and their effects on cutting tool and workpiece material properties, cutting temperature, tool wear and tool life, surface roughness and dimensional deviation, friction and cutting forces. It was reported that cryogenic cooling has been resulted as one of the most favorable methodsfor metal cutting operations due to its capability of producing considerable improvement in tool life and surface finish through the reduction in tool wear by a desirable control of machining temperature at the cutting zone.

The review of the literature suggests that cryogenic cooling provides several benefits in machining. Based on the existing literature studies, it has been concluded that cryogenic is a different approach in which the temperature at the cutting zone is reduced to a very low range (Mirghani et al 2007). It was also concluded from the recent work that, cryogenic cooling is a possible answer for high speed eco-friendly machining (Kalyan Kumar and Choudhury 2008). Cryogenic cooling is an environment-friendly clean technology for achieving desirable control of cutting temperature and enhancement of tool life. Substantial benefit of cryogenic cooling on cutting temperature, cutting force, chip breaking, surface roughness and tool wear was reported. However, more work is needed to explore the potential advantage of cryogenic cooling. Many of the researchers have developed cryogenic cooling methods to reduce the cutting temperature in the cutting zone, and thereby improving the other machinability indices**.** In the existing cryogenic cooling methods, many researchers have attempted to supply the liquid nitrogen on the workpiece pre- cooling, tool back cooling, main and auxiliary cutting edges and tool rake and flank face. In this research work, the commercial cutting tool insert was modified at the rake, main and auxiliary flank surfaces for supply of liquid nitrogen to the heat generation zones in the turningprocess.

3. Experimental conditions andprocedure

The turning experiments were carried out on a Ti-6Al-4V alloy with PVD TiAlN coated tungsten carbide cutting tool inserts of ISO CNMG 120408 MP1 – KC5010 (Kennametal) under wet machining and cryogenic cooling. The tool holder used for machining is ISO PCLNR 2020 K12 (Kennametal). The turning experiments were performed at a depth of cut 1 mm, feed rate 0.102 mm/rev and cutting velocities of 40, 63 and 97 m/min. In wet machining, a commercial emulsion coolant was applied on the machining zone by using a nozzle. The emulsion cutting fluid was obtained by mixing the concentrate with water at a ratio of 1:20 solubleoil.

New cryogenic coolingmethodology

To supply of liquid nitrogen in the heat generation zones, the cutting tool insert was modified under cryogenic cooling methods. The standard cutting tool insert was modified by making a hole of dimensions of Ø 2 mm × 2.5 mm at the rake surface of the cutting tool insert using Electrical Discharge Machining (EDM) for cryogenic cooling requirements. The rake surface hole is interconnected with the main and auxiliary flank surface holes (Ø1mm×2mm). Figure 1 (a) shows the detail drawings of the modified cutting tool insert. Figure 2
(b) shows the sectional view of the modified cutting tool insert.

The evaporated gas from the main flank surface hole is directed away from the workpiece, so that the possibility of excessive cooling is avoided. Figure 3 shows a photographic view of the flow of liquid nitrogen from the modified cutting tool insert. In the turning of the Ti-6Al-4V alloy, liquid nitrogen was supplied to rake surface under constant pressure of 3 bar using a nozzle. The experimental set up is shown in Figure 4.

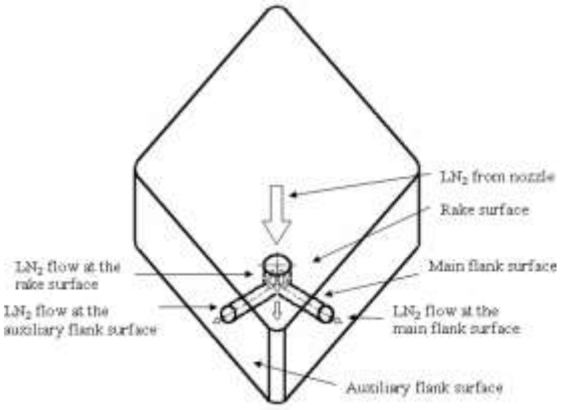
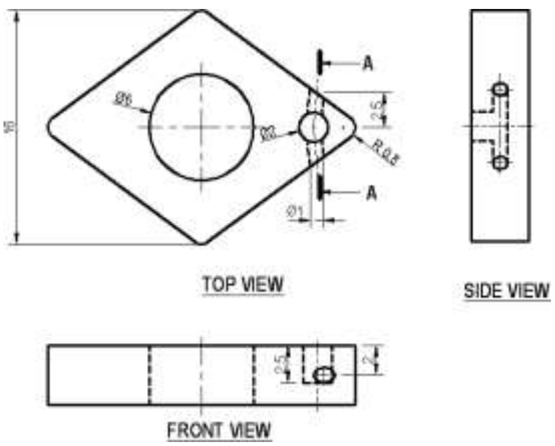
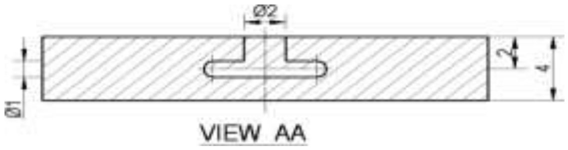


Figure 2 Schematic diagram of modified cutting tool insert.





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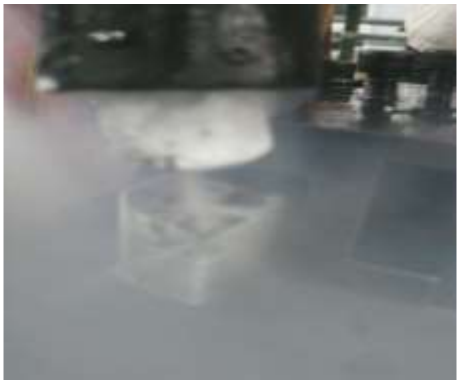


Figure 4 Experimental setup

Figure 3 Flow of liquid nitrogen in the modified cutting tool insert.

The schematic diagram of the modified cutting tool insert is shown in Figure 2. The holes are inspected for its dimensional accuracy. In this cryogenic cooling method, the liquid nitrogen was directly supplied to the hole in the rake surface of the cutting tool insert, so that a major portion of the liquid nitrogen can be splashed on to the chip-tool interface. A small amount of liquid nitrogen will reach the major and minor cutting edges of the cutting tool insert with the help of the two sideholes.

The temperature was measured using a non- contact Infrared Thermometer with an accuracyof ±1.0% reading. The cutting force was measured by an online force measurement system including a Kistler type 9257B piezo-electric three component dynamometer, a kistler type 5070A12100multi-

channel charge amplifier and a PC-based data acquisition system (Dynaware). The surface roughness was measured using a contact type stylus - Surtronic 3+ Roughness Checker.

4. Results anddiscussions

The present experimental study involving the turning of a Ti-6Al-4V alloy bar (Ø 40 × 300 mm) with ISO K10 CNMG 120408MP1-KC5010

PVD TiAlN coated tungsten carbide tool insert was carried out under wet machining and cryogenic cooling. The experimental results of the cryogenic cutting temperature, cutting forces and surface roughness have been compared with those of wet machining.

Influence of cryogenic cooling on cutting temperature

Figure 5 shows the reduction in the cutting temperature due to cryogenic cooling over wet machining. The cutting temperature increased with an increase in the cutting velocity. The cutting temperature at a cutting velocity of 97 m/min and feed rate of 0.102 mm/rev was 402°C and 141°C for wet machining and cryogenic cooling respectively. It was observed that the reduction in the cutting temperature due to cryogenic cooling was 64.93% over wet machining. This is because liquid nitrogen was supplied through holes made in the cutting tool so that the liquid nitrogen can be directly reach the sources of heat generation, which results in reduced cutting temperature at the cutting zone. The cryogenic cooling using liquid nitrogen enabled the reduction in the cutting temperature by 64 - 67% over wet machining. The reduction in thecutting temperature has significant influence on the cutting forces and surface roughness.

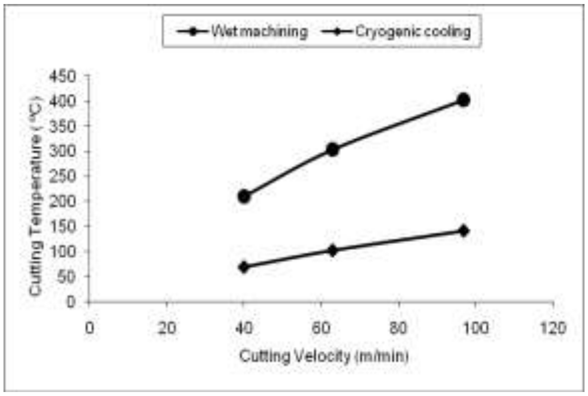


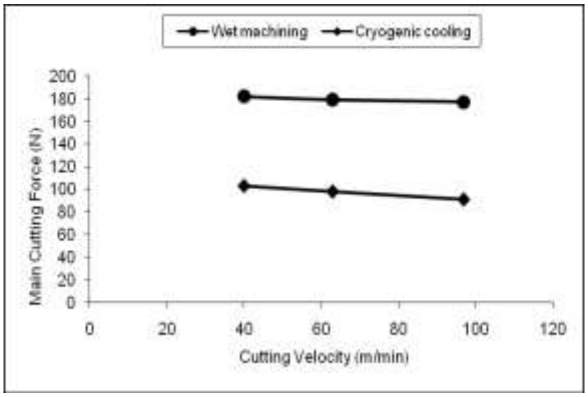
Figure 5 Variation in cutting temperature.

When the cutting velocity (40 m/min) was increased to 63 and 97 m/min under the constant feed rate of 0.102 mm/rev, the variation of percentage reduction in cutting temperature due to cryogenic cooling was found to be 0.8% and 2.21% respectively**.** This result indicates that with an increase in the cutting velocity, the cryogenic cooling effect is decreased. This is because the cutting temperature increased with an increase in the cutting parameters, thereby changing the chip-tool contact nature.

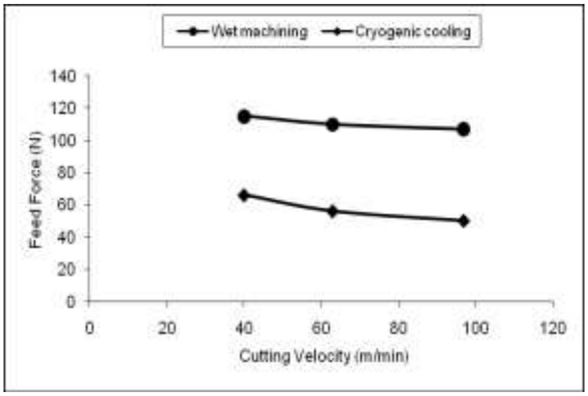
Comparison of cuttingforce

The comparison of cutting forces with cutting velocities in the turning of Ti-6Al-4V alloy under conventional and cryogenic cooling are shown in Figure 6 (a-b). The cutting forces decreased with an increase in the cutting speed due to a decrease in the shearing area in all cutting environments. The main cutting force and feed force at a cutting velocity of 63 m/min and feed rate of 0.102 mm/rev was 179 N and 110 N for wet machining. The value of main cutting force and feed force was 98 N and 56 N, when the liquid nitrogen was applied through modified cutting tool. The main cutting force and feed force was decreased by 45% and 49% respectively in cryogenic cooling method over conventional cooling. This is because the application of liquid nitrogen reduced the adhesion at the chip- tool interface due to the formation of a fluidcushion.

It was observed from Figure 6 (a-b), that the cutting force was reduced in cryogenic cooling over wet machining. The reasons for the decreased cutting force in cryogenic cooling were that the lower cutting temperature at the cutting zone, reducing the adhesion at the chip-tool and work-tool interactions, reducing the tool wear and maintaining the strength and hardness of tool material. The cryogenic cooling decreased the cutting force by 21 – 39% over wet machining.



(a)



(b)

Figure 6 Comparison of cutting forces under wet and cryogenic cooling: (a) Main cutting force (b) Feed force

4.3. Effect of cryogenic cooling on surface roughness

The variation in surface roughness with different cutting velocities under wet and cryogenic cutting conditions is shown in Figure 8. The surface roughness decreased with an increase in cutting velocity. The value of surface roughness at a cutting speed of 63 m/min and feed rate of 0.102 mm/rev was 3.1 µm and 2.2 µm for wet machiningand cryogenic cooling respectively. The reduction in the surface roughness over wet machining was observed to be 29% for cryogenic cooling. In cryogenic cooling, liquid nitrogen was applied to the rake and flank surfaces of the tool simultaneously, which results in reducing the adhesion between the newly generated workpiece surface and the tool flank surface, in controlling the cutting temperature and reducing the geometry of tool wear, thereby decreasing the surface roughness. The cryogenic cooling reduced the surface roughness by 29 – 33% over wet machining.

Figure 7 Variation in surface roughness with cutting velocity.

5. Conclusions

The experiments on the turning of Ti-6Al- 4V alloy with PVD TiAlN coated tungsten carbide tool inserts of ISO CNMG 120408 MP1 – KC5010 were carried out in wet machining and cryogenic cooling with modified cutting tool inserts. In cryogenic cooling, the cutting insert was modified for the efficient use of liquid nitrogen in the turning operation. Cryogenic cooling using liquid nitrogen reduced the cutting temperature by 64–67% over wet machining. Cryogenic cooling provided the benefits mainly by substantially reducing the cutting temperature. Cryogenic machining decreased the cutting force to 43 - 53% over wet machining. Cryogenic cooling by liquid nitrogen reduced the surface roughness by 29-33% over wet machining. Experimental investigations proved that cryogenic cooling with a modified cutting tool insert have shown better results on the cutting temperature, cutting force and surface roughness over wet machining. This may be attributed due to control of cutting zone temperature and favorable chip-tool interaction.

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