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An experimental investigation on cryogenic milling of Inconel 718 and its sustainability assessment

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Abstract

Machining of Inconel 718 is a challenge due to its mechanical, thermal and chemical properties and thus results in poor machinability. The use of conventional oil-based coolant could be ineffective and non-sustainable for cutting this material. This paper presents the experimental investigations on the influence of cryogenic cooling on milling of Inconel 718 as compared to dry and conventional oil-based coolant. Cutting force, machining temperature, tool wear, machined surface quality, chip formation and energy consumption were studied. The results demonstrated that the cryogenic cooling is promising for machinability and sustainability improvement as compared to the conventional oil-based coolant and dry cutting in term of tool wear reduction, less friction at secondary deformation zone, lower energy consumption and contamination-free on machined part.

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Keywords: Cryogemic machining; milling; Inconel 718; sustainability

1. Introduction

In metal cutting, a chip is produced by shearing of material along the shear plan. This shearing is major energy consumption in cutting process. Energy used for deforming the chip and overcoming friction is converted into heat. The process can be associated with high temperature due to the heat generation in the deformation zone and surrounding areas of cutting tool, workpiece and chip. This thermal aspect significantly influences machinability and productivity. Fig. 1 shows the heat generation in orthogonal cutting process. Heat generation in primary zone is due to the work done along the shear plane. In secondary zone, work done in deforming the chip and sliding friction between tool-chip interfaces causes heat generation in this region. While tertiary zone is influenced by rubbing contact between flank face and newly machined surface.

The most common advanced and difficult-to-cut materials such as nickel-based and titanium-based alloys are used in aerospace, engine, gas turbine, nuclear and medical industrials. When machining these materials, there will be an excessive heat generation at cutting zone. High temperature at cutting zone together with high hardness, high strength at elevated temperature, high cutting forces and poor thermal conductivity of the materials results in challenges of machining and difficulties in heat dissipation. These influence cutting mechanism and chip formation consequently of excessive tool wear, shorter tool life, poor surface quality, limitation of cutting speed, high machining cost and low productivity.

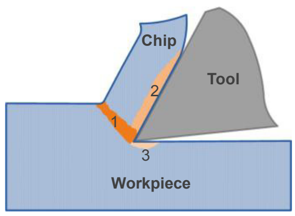

Fig. 1. Schematic of chip formation and heat generation in metal cutting.

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Different techniques have been implemented in industries to increase productivity for instance the use of cutting fluid, advanced cutting tool materials and coatings. The cooling application of cutting fluid supplied to cutting zone plays a significant role in metal cutting. Its functions are to reduce heat reduction at cutting zone, to lubricate and decrease friction between tool, chip and workpiece interfaces. However conventional cutting fluids that commonly used in machining processes are still oil-based coolant. This coolant causes environmental and health hazards.

When machining workpiece materials with high shear strength and low thermal conductivity such as nickel based alloys, conventional coolant has been claimed not effective enough to lower the temperature generation at the cutting zone. This was due to the difficulty of cutting fluid penetration through high temperature between tool-chip and tool-workpiece interfaces [1-3]. Thus the machining nickel based alloy will be associated with low cutting speeds, low productivity and high machining cost.

The implementation of cryogenic cooling has been introduced in order to reduce the cutting temperature in machining of difficult-to-cut materials. Cryogenic machining is the process to implement non-oil-based cooling supplied to cutting region. The cryogenic cooling will help in heat removal and hence reduce cutting temperature [4]. The cooling system also change material characteristics and improve machining performance [1]. Liquid nitrogen (LN2) is mostly used as a cooling medium in cryogenic system since it is colorless, odorless, tasteless, non-toxic, non-combustible and non-corrosive. LN2 has a boiling temperature at -196˚C in the atmosphere pressure. When LN2 is applied into the cutting zone, it will evaporate and return back to the atmosphere and hence no residue and contamination on cutting tool, workpiece, chip and machining area. Therefore there is no need of coolant disposal, cleaning process due to the contamination and thus the process is good for health and environment compared to conventional cooling fluids.

Shokrani et al [3] investigated the cryogenic milling of Inconel 718 compared to dry machining. The surface finish was improved and tool life reduced while no noticeable increase power consumption. The effective approach of cryogenic cooling for cutting Titanium and Nickel based alloys was to penetrate a small amount into cutting zone which was suggested by Hong and Zhao [4]. By apply LN2 to the area close to cutting edge of tool when machining Ti-6Al-4V, there was a significantly tool temperature reduction [5].

Pušavec and Kopač reported that using cryogenic machining helps in machining reliability while maintain dimensional tolerance and improved machined surface integrity [1]. Additional work studied by Pusavec et al [6] on the surface integrity of Inconel 718 when cryogenic turning showed that cryogenic machining improves machined surface integrity in term of increase hardness and compressive residual stress. The benefit of cryogenic cooling on the tool life has a direct effect on surface finish especially at the beginning cut as compared to dry machining [3]. Substantial reduction of cutting temperature in cutting zone reduces tool wear and hence increases tool life wear. Kumar and Choudhury [7] showed that flank wear reduce by 37% with cryogenic condition compared to dry machining. Additionally cutting speed can be doubled from cutting using conventional cutting fluid while maintaining similar tool life when machining Ti-6Al-4V [5]. Thus there is a potential of higher productivity due to shorter production time when applying cryogenic cooling.

Kumar and Choudhury [7] presented the influence of cryogenic on the cutting when machining stainless steel. Cutting force was lower when cutting under cryogenic compared to dry machining. It was explained to be due to the reduction of coefficient of friction at tool-chip interface. The effective lubricant from cryogenic in machining of Ti-6Al-4V was studied by Hong et al [8]. Feed force and friction coefficient between chip and tool face were considerably reduced under cryogenic condition. At lower temperature, it made materials less sticky. This reduced friction force and therefore friction coefficient became lower. However the use of cryogenic did not show how does it help in cutting force reduction which could be explained by the lower temperature resulting in material become harder and stronger [7].

Cryogenic cooling system helps in heat reduction, temperature distribution and leads to enhance more efficient and more economical in machining especially for advanced and difficult-to-cut materials. The lower cooling temperature from cryogenic media is not only capable to tackle heat generation issue but it is also capable to increase cutting speed and hence higher productivity [3, 9]. In high speed machining (HSM), the technology is a key for aerospace, engine, mould/die and automotive industries. This associates with high cutting speed which is a main influence on the cutting temperature, heat generation and heat transfer. Cryogenic cooling shows a potential for HSM and is an attractive process but there is a lack of implementation on the shop floor for industrial applications. Additionally, cryogenic machining has been considered as a clean process since it is free from coolant and/or oil mist [10, 11]. Thus the technology will promote sustainability and high speed eco-friendly machining and manufacturing.

Despite the studies of cryogenic machining have been conducted for turning process, there are hardly if any dedicated to the milling process. This paper presents the influence of cryogenic cooling using liquid nitrogen compared to dry and conventional oil-based coolant on machinability and sustainability when milling process of Inconel 718.

2. Experimental details

2.1. Machine tool and cryogenic system

The experiments were carried out on a CNC milling machine centre, a Hitachi Seikei VG45. Customized designed cryogenic cooling system, nozzles and orifice were installed on to the machine centre. Cryogenic media used in the cutting experiment is liquid nitrogen. The liquid nitrogen (LN2) was supplied through nozzle in order to deliver the cooling to the cutting zone (tool-chip interface). Fig. 2 shows a schematic view of cryogenic cooling system retrofitted on the machine center. Nozzle with insulated hose was customize designed and connected to liquid nitrogen dewar. The nozzle was attached with spindle and hence provides simultaneously movement with cutter.

2.2. Workpiece material and cutting tool

In this study, workpiece material used in the cutting experiments was Inconel 718. This material is widely used in high valued components for aerospace, engine, gas turbine and nuclear applications. Two-flute end mills of TiN coated tungsten carbide were used in the milling experiments. Tool diameter of 10 mm was selected.

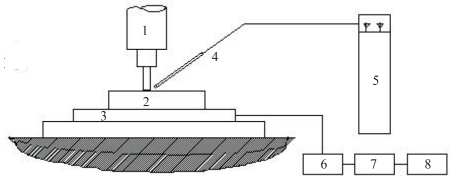


Fig. 2. Schematic view of cryogenic retrofitted on machine centre (1) spindle, (2) workpiece, (3) dynamometer (4) nozzle and insulated hose, (5) liquid nitrogen, (6) charge amplifier, (7) DAQ and (8) computer

2.3. Cutting condition and measurements

The end milling experiments were performed under dry, conventional oil-based flood coolant and cryogenic machining conditions. The cutting conditions selected for this paper based from the preliminary testes and are summarized in Table 1.

Table 1. Cutting condition.

Cutting speed	Feed rate	Depth of cut	Width of cut
90 m/min	573 m/min	0.5 mm	2.5 mm

During milling, cutting temperature was measured using thermocouple and thermal infrared imaging camera. The thermal couple method was used to identify the difference of temperature when using cryogenic cooling compared to the conventional and dry machining, while NEC TH9100 infrared thermal imaging camera was used to capture the cutting temperature for dry and cryogenic machining.

Cutting force was measured using a Kistler three-axis component dynamometer (9257BA). The signals were amplified in a load amplifier connected to a computer which was used for the acquisition of forces. DEWESoft software was used for data acquisition. Energy consumption was monitored using ELITEpro SP power meter.

After machining process, the workpieces were cut at the cross section for machined surface integrity analysis. Chips were collected, mount and etched for this study. The cutting tool wear, machined integrity and chip formation were observed under optical microscope.

3. Results and discussions

3.1. Cutting temperature

Fig. 3 (a) shows the different of cutting temperature measured by thermocouple when cutting at dry, flood coolant and cryogenic cooling conditions. The graph demonstrates the trend and the distinction when machining at different cutting conditions. The measurement depends on the embedded position of thermocouple and heat conduction into the workpiece. The cutting temperature reduced when using cooling methods. There was more temperature reduction on the application of cryogenic machining compared to the application of conventional oil-based coolant. There was a temperature reduction of almost 353 K and 473 K for conventional oil-based coolant and LN2 cryogenic machining respectively. Cryogenic cooling provides the lowest range cutting temperature compared to dry and conventional oil-based coolant.

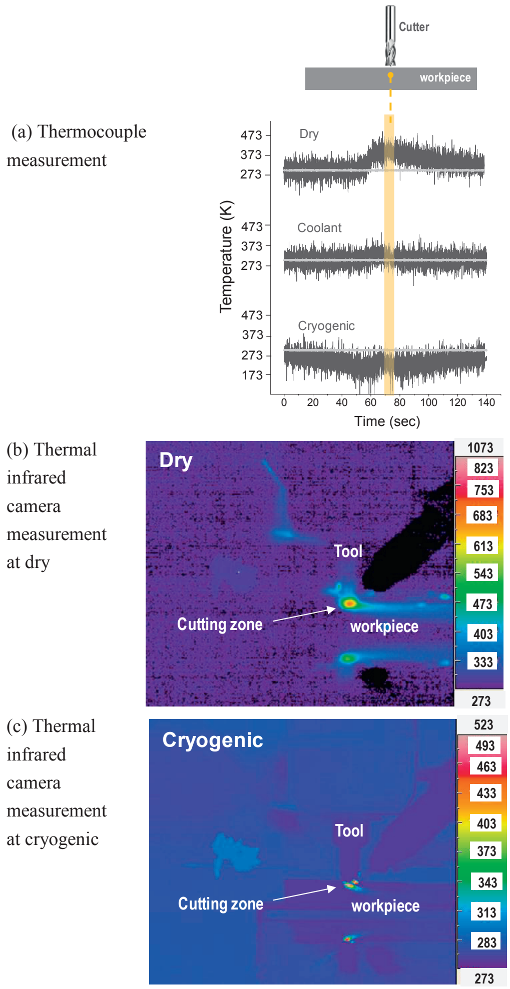


Fig. 3. Cutting temperature measurements (a) and (b)-(c) thermal infrared imaging camera measurement.

The benefit of temperature reduction when using cryogenic cooling was confirmed by thermal infrared imaging camera measurement. Fig. 3(b) and (c) illustrate the absolute value of cutting temperature for dry and cryogenic conditions respectively. The maximum cutting temperature at dry condition had reached to 843 K while the maximum temperature when using cryogenic cooling was at around 473 K. It shows that cryogenic can penetrate into the cutting zone more effectively to lower cutting temperature. Not only the cutting temperature at the tool tip area reduced when using cryogenic cooling, but the area of heat conduction through the surrounding area also reduced. The effective of cooling penetration and temperature reduction from cryogenic machining can be confirmed by both temperature measuring methods.

3.2. Cutting force

Cutting force measurement is an indirect method used for monitoring the cutting tool conditions. During machining, cutting forces were measured and the data were evaluated by the root mean square (RMS) instantaneous force. Fig. 4 shows the cutting forces (Y and Z directions) versus cutting time during dry, conventional oil-based coolant and cryogenic machining. The sharpness of cutting edge at the initial stage was showing the similar level of cutting forces and the lower range of cutting force for all cutting conditions. It can be seen that the cutting forces are sensitive with the tool wear especially under dry condition (tool wear is shown in section 3.5). With the cutting time increase, the cutting tool edge becomes dull due to tool wear or edge chipping. There is a higher friction coefficient and more contact area at the tool-chip interface. As a result the more wear progression of cutting tool predominates; the more energy is required during the cutting.

Although, cutting force at cryogenic cooling was higher than that at conventional oil-based coolant (while the tool wear at cryogenic cooling is lower as showed in section 3.5), it could be due to a higher material strength at lower temperature when using cryogenic in the primary shear zone [8, 11]. On the other hand at conventional oil-based coolant, when heat in shear zone cannot be quickly passed out and thus elevated temperature results in workpiece plastic deformation, material softening and thereby decrease the cutting force.

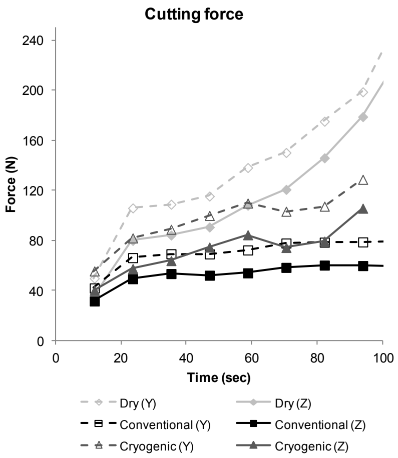


Fig. 4. Cutting force.

3.3. Chip formation

Chip formation is also important in metal cutting. The forms of chip influence the machinability. Table 2 demonstrates the chips obtained from dry, conventional oil-based coolant and cryogenic machining.

Longer chips were formed during machining under dry and conventional coolant conditions. In dry cutting, more serrated teeth chips were obtained. This subjected to intense heat thus resulting in higher shearing mechanism and large plastic deformation in the cutting zone.

When cryogenic cooling was used, the chip breakability was improved and shorter and shiner chips were obtained compared to those generated from dry and conventional coolant cuttings. This could be due to the benefit of cooling and lower cutting temperature as well as the reduction of friction and the change of workpiece material to be less ductility.

The color of chips obtained from three cutting conditions is different. Chips from dry machining are golden brown especially during the longer cutting period where the higher wear progression predominated. This indicates high cutting temperature during machining and heat remains on the chip together with oxidation (and burnt chip). When cryogenic system was used, the heat was taken away by LN2. The chip was oxidation discoloration, loose and became brittle.

Table 2. Chip formation.

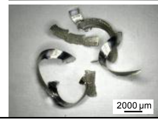
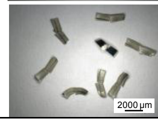
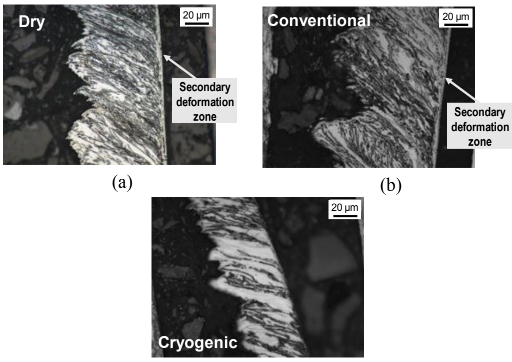
Time (sec)	Dry	Conventional	Cryogenic
60			
120			

Fig. 5 shows the images of chip morphology obtained from dry, conventional oil-based coolant and cryogenic machining. There are two surfaces of chip morphology, one is the contact with the tool rake face and the other is form the original of the workpiece (referred to Fig. 1). In dry and conventional coolant machining, white band along the side where contacts with the tool rake face was observed. This area indicates the secondary deformation zone which is attributable to the heat and friction on the tool-chip interface. Although the conventional coolant was supplied during the cutting into the cutting zone in order to reduce cutting temperature, the accessibility of conventional coolant was limited. This can be attributed to the fact that conventional coolant is not sufficient and ineffective cooling to access and lubricate through the deformation zone especially at tool-chip interface. Therefore cryogenic cooling provides better temperature reduction as well as accessibility through cutting zone.

Better lubricity was obtained when cryogenic coolant was implemented. Fig. 5 (c) demonstrates chip morphology collected from cryogenic machining. An absence of secondary deformation zone confirms that LN2 cryogenic cooling can penetrate through the cutting zone especially at tool-chip interface more effectively than conventional coolant. This accessibility of LN2 into cutting zone will act as the cushion to reduce adhesion and friction between tool-chip interface [12, 13]. The lower cooling media increases the thermal gradient between cutting zone and cutting tool with heat removal and reduction of thermal load on the cutting edge [14, 15].



(a) (b)

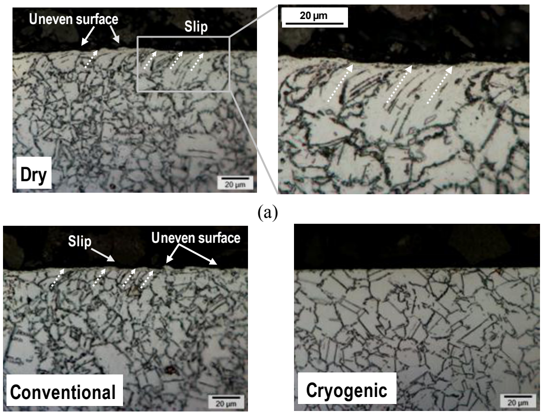
(c)

Fig. 5. Chip morphology from (a) dry (b) conventional coolant and (c) cryogenic conditions.

3.4. Machined surface quality

The workpieces were cut, mounted, ground, polished and etched for the cross-section analysis. Fig. 6 shows images of cross sectional of machined workpieces from machining under dry, conventional oil-based coolant and cryogenic cooling conditions.

Plastic deformation of the material occurred near the machined surface can be clearly seen in Fig. 6 (a) and (b) where obtained from cutting under dry and conventional coolant respectively. These phenomena are because of the sliding of cutting tool over the machined surface. When machining performed under dry condition, the machined surface could remain at high temperature together with high cutting force acting on the workpiece and cause deformation of grain structure [16].



(a)

(b) (c)

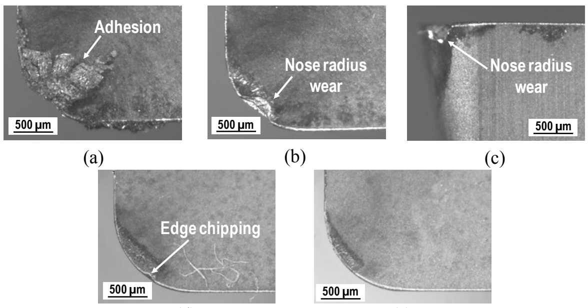
Fig. 6. Machined surface (a) dry (b) conventional coolant and (c) cryogenic conditions.

The reduction of the plastic deformation when machining with cryogenic cooling as shown in Fig. 6(c) may be attributed to more efficiency of LN2 penetration into the cutting zone. Surface defect such as uneven surface and tearing were not observed from the samples machined by cryogenic cooling.

3.5. Tool wear

Tool wear mechanisms found on cutting tools when machining Inconel 718 are nose radius wear, edge chipping diffusion and thermal softening. These were due to the combination of heat and shear stress in primary and secondary zones resulting in high temperature and stress generation in cutting zone. This phenomenon occurred especially when cutting at dry condition.

Fig. 7 (a)-(c) shows the tool wear when cutting at dry condition. When machining Inconel 718 at high speed machining, high temperature was generated as well as high pressure. These influenced the hardness of workpiece to become softer and develop the adhesive wear. Adhesion of chip on the tool rake face can be observed in Fig. 7 (a). Plastic deformation under high pressure and high cutting temperature influenced adhesive force between tool-chip interfaces with high friction. The dominant failure modes found on cutting tools were chipping on the nose radius and severe flank wear in Fig. 7(b)-(c). This is due to the abrasion and oxidation mechanism. High temperature as reported in the previous resulted in diffusion between tool-chip interfaces.



(a) (b) (c)

(d) (e)

Fig. 7: Tool wear (a)-(c) dry, (d) conventional oil-based coolant and (e) cryogenic machining at 90 m/min.

The reduction of cutting temperature, cutting force and better performance of cooling penetration on the cutting tool when using cryogenic cooling (as reported in the previous) influences the wear mechanism during milling of Inconel 718. The growth of tool wear under cryogenic cooling condition was similar to that under conventional oil-based coolant as shown in Fig. 7(d)-(e). The coating was removed, worn out and tool substrate was exposed in the air which causing oxidation wears. However, the use of cryogenic cooling increased the accessibility of cooling media through the cutting zone especially at the tool-chip interface and decreased contact area on the rake face. Therefore the contact zone of chips over the rake face when using cryogenic cooling became lesser compared to conventional oil-based coolant. Higher temperature under conventional coolant compared to LN2 also caused edge chipping. It can be confirmed that cryogenic cooling media enhances the lubrication effect close to the cutting edge and reduction friction coefficient leading to a decrease of friction heat of tool-chip contact and less sticking area which result in less secondary shear deformation zone.

Although dry cutting condition is greener and more environmental friendly aspect, the result shows in Fig. 7(a)-(c) can be confirm that dry machining is not suitable for milling of Inconel 718 due to the rapid wear progression.

4. Sustainability assessment

Sustainability composes of three pillars which are economical, environment and social. In machining, sustainability is to improve machinability and productivity, reduce waste and environmental impact and increase energy efficiency while providing health and safety for operator.

The result from tool wear revealed that the cryogenic machining process provides better tool wear reduction. This will help to increase productivity in term of shorter the production time (reduce tool change and set-up time) and potential to increase cutting condition to be faster. The cryogenic process also supports the waste reduction in term of cutting tools and scrap pieces reduction.

Since the cryogenic process can be considered as dry process due to the fact that cryogenic media evaporates back to the atmosphere, the working environment and machined component are free from contamination such as oil-free and toxicity due to the oil-based lubrication. Cryogenic machining will also create a healthy environment to operators while the oil composed in coolant causes carcinogenic.

The power consumption of cutting process reveled that the conventional oil-based coolant consumed the highest energy consumption followed by dry and cryogenic conditions. This was due to the fact that coolant system of machine tool requires power to pump the coolant. In practice, in order to complete machining for a job, the energy consumption for cutting as a whole process will include machining set-up, tool change and measurement. This attributes to the end of tool life. Hence the energy consumption for dry machining will turn to the highest. This depends on the amount of material removal and tool wear resistance. To minimize the amount of energy consumption, cryogenic machining still becomes the lowest because the system helps to promotes longer tool life (less tool wear) and reduce the energy require for coolant pump. All together, it can be claimed that cryogenic machining is more sustainable than dry and flood coolant.

5. Conclusions

This paper presented the experimental investigation of cryogenic milling of Inconel 718 compared to dry and conventional oil-based coolant. The study showed that the cryogenic cooling significantly reduced the temperature in the cutting zone and improved the cooling accessibility through the tool-chip interface compared to conventional cooling method. Contact friction between cutting tool-chip interfaces reduced and efficiency of lubricating action has been enhanced by using cryogenic cooling. Thus cryogenic machining has provided benefits on machinability enhancement in term of tool wear reduction, machined surface quality improvement and higher cutting speed enhancement. Additionally, cryogenic cooling helps to foster environmental friendly and sustainability in the cutting process.

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