

## EFFECT OF CUTTING PARAMETERS ON CUTTING ZONE IN CRYOGENIC HIGH SPEED MILLING OF INCONEL 718 ALLOY

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### Graphical abstract



### Abstract

In tribology phenomenon, surface roughness has become one of the most important factors that contributed to the evaluation of part quality during machining operation. In order to understand the behavior of cryogenic cooling assistance in machining Inconel 718, this paper aims to provide better understanding of tribological characterization of liquid nitrogen near the cutting zone of this material in ball end milling process. Experiments were performed using a multi-layer TiAlN/AlCrN-coated carbide inserts under cryogenic and dry cutting condition. A transient milling simulation model using Third Wave Advantedge has been done in order to gain in-depth understanding of the thermomechanical aspects of machining and their influence on resulted part quality. The cryogenic results of the cutting temperature, cutting forces and surface roughness of the ball nose cutting tool have been compared with those of dry machining. Finally, experimental results proved that cryogenic implementation can decrease the amount of heat transferred to the tool up to almost 70% and improve the surface roughness to a maximum of 31% when compared with dry machining. Furthermore, the microstructure of machined workpiece revealed that cryogenic cooling also can reduce a plastic deformation at the cutting surface as compared with the dry machining.

**Keywords:** Cryogenic cooling; dry cutting; inconel 718; high speed milling

### Abstrak

Dalam fenomena tribologi, kekasaran permukaan telah menjadi salah satu faktor yang penting yang menyumbang kepada penilaian kualiti sesuatu bahagian semasa operasi pemesian. Dalam usaha untuk memahami tingkah laku bantuan penyejukan kriogenik dalam pemesian Inconel 718, kajian ini bertujuan untuk memberi kefahaman yang lebih baik tentang pencirian tribologi bagi cecair nitrogen berhampiran zon pemotongan bahan semasa proses pengisaran hujung mata bulat. Kajian ini telah dilakukan dengan menggunakan mata alat karbida bersalut TiAlN / AlCrN di bawah keadaan pemotongan kriogenik dan kering. Model simulasi bagi proses pengisaran menggunakan perisian Third Wave Advantedge telah dilakukan dalam usaha untuk mendapatkan pemahaman yang mendalam mengenai aspek termomekanikal pemesian dan pengaruh mereka ke atas kualiti bahagian yang dimesin. Keputusan kriogenik ke atas suhu pemotongan, daya pemotongan dan kekasaran permukaan bagi pemotongan hujung mata bulat telah dibandingkan dengan pemesian kering. Akhir sekali, keputusan eksperimen membuktikan bahawa pelaksanaan kriogenik boleh mengurangkan jumlah haba yang dipindahkan ke atas mata alat sehingga hampir 70% dan memperbaiki kekasaran permukaan sebanyak 31% secara maksimum berbanding dengan

pemesinan kering. Tambahan pula, mikrostruktur bahan kerja yang dimesin membuktikan bahawa penyejukan kriogenik juga boleh mengurangkan ubah bentuk plastik pada permukaan pemotongan berbanding pemesinan kering.

Kata kunci: Penyejukan kriogenik; pemotongan kering, inconel 718; pengisaran halaju tinggi

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## 1.0 INTRODUCTION

Nickel based alloy is also known as a group of superalloy which is widely used for various parts of components and structures for aerospace, marine, chemical process, automobiles industries, etc. The superior of specific properties such as high resistance to creep, high toughness and strength at elevated temperature, and good resistance to chemical degradation and wear have made this alloy well suited for service in extreme environments especially for high temperature application. However, its small thermal conductivity and specific heat volume lead to high cutting temperature and its superior mechanical properties also have result to high cutting force. In addition, chips are easy to stick at the tool tip and tend to generate build up edge (BUE) where this phenomena result a rapid tool wear [1]. Thus, nickel based alloy normally refer to a difficult-to-cut material in machining context [2].

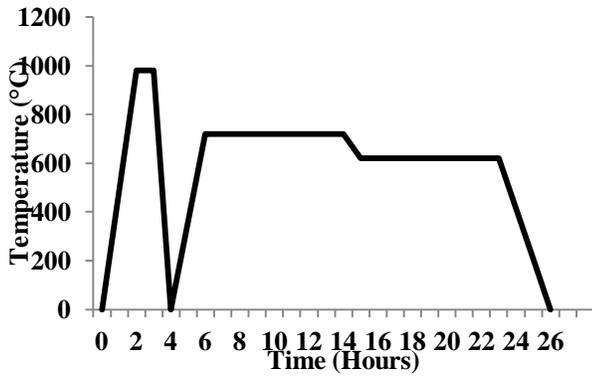
In the case of milling process, it is also known as an interrupted cutting process where the direction of the cutting force is changing due to the tool rotation, and as the tooth enters and leaves the workpiece for every cutting pass [3, 4]. This nature resulted in various wear mechanism, cutting temperature and dynamic stability compared to the continuous cutting process. It is claimed that in cutting superalloys material, due to their low thermal conductivity and adhesion with tool materials [5], temperature at the tool tip area seriously increases, and drastically affects tool wear [6, 7]. Thus, an effective high speed cutting application for these types of alloys cannot be optimized due to the extremely high thermal loads applied on the tool material. Based on this issue, most of the superalloys material still been machined under flooding conditions where this technique has a limited in terms of decreasing high cutting temperature, increasing tool life, reducing machining cost and improving environmental sustainability.

In order to increase the machining performance of superalloys material, variety of cooling/ lubrication methods are being promoted and one of the latest technique is using cryogenic method. However, they still a lot of uncertainty about the action of cryogenic fluid and especially regarding its cooling and/or lubrication capabilities on tool performance. The

performance of the cutting tool is normally respected to the tool wear and their tool life, while the quality of machining performance is normally refer to the surface integrity of machined surface. In those contexts, it is very important to understand the tribological action of the cutting tool during machining process, especially when cryogenic cooling is applied. The tribology behavior of cryogenic media is considerably important because liquid nitrogen that been used as a coolant should be supplied to the cutting zone in a small amount with the aid of atmospheric carrier gases. In the last ten years, cryogenic machining has been largely developed to improve the cutting tool life and has been mostly applied in machining especially for heat resistant superalloys [8, 9]. However, it seems that very few scientific paper have reported the influence of cryogenic in term of tribological behavior on the cutting zone between Inconel 718 and ball nose cutting tool.

## 2.0 EXPERIMENTAL PROCEDURE

The experiments for cryogenic and dry cutting processes were conducted using a CNC milling machining (DMC 635 V eco) which has maximum speed of 8000 RPM. The workpiece material used was the aged-hardened and solution-treated of Inconel 718 alloy with a dimension of 150 x 100 x 50 mm rectangular block. The block underwent a double aging process as shown in Fig. 1, where the raw Inconel was heated up to 980°C for 1 hour and then rapidly quenched in water, then reheated for 8 hours at 720°C, where then slowly cooled in the furnace until it reached 620°C, then held at that temperature for another 8 hours. Finally, the block was cooled in room temperature at open air. After the aging treatment process, the hardness of the prepared workpiece was increased from 92+ 2 HRB (Grade AMS5662) to 42 ± 2 HRC (Grade AMS5663) and the chemical composition of Inconel 718 is shown in Table 1.



**Figure 1** Double aging treatment schedule of Inconel 718 [10, 11]

**Table 1** Nominal chemical composition of Inconel 718

Elements	% wt.
Al	0.49
B	0.004
C	0.051
Nb.Ta	5.05
Co	0.3
Cr	18.3
Cu	0.04
Fe	18.7
Mn	0.23
Mo	3.05
Ni	53
P	<0.005
S	<0.002
Si	0.08
Ti	1.05

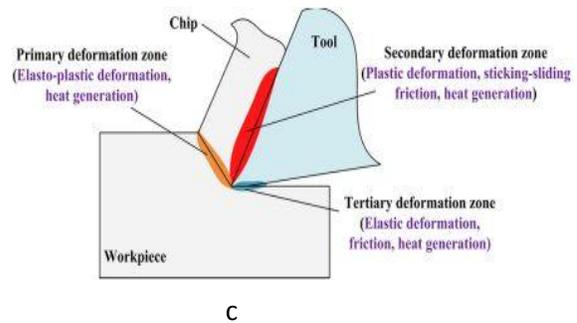
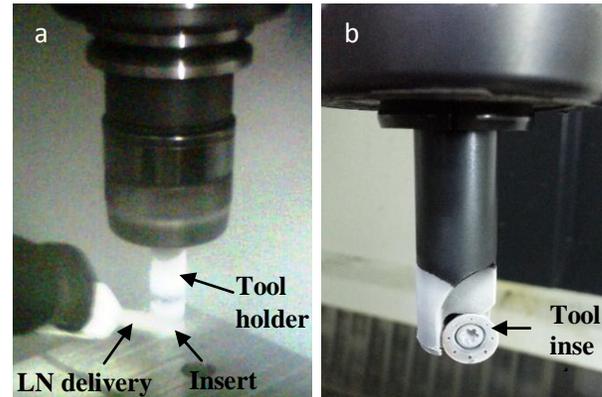
The cutting tool used in machining test was a Sumitomo ball nose type milling cutter with a nominal diameter of 16 mm attached to a BIG Hi-Power Milling Chuck DV40-HMC20-85 for powerful and precise clamping, and the overhang length was 60 mm. The insert was tungsten carbide with multi-layer PVD TiAlN/AlCrN grade ACK 300. For the experiment, the used of cutting parameter, cutting tool and tool holder specification are shown in Table 2. The experiments were conducted with sharp cutting edges, and all the data were measured at the beginning of the cut.

**Table 2** Cutting parameters and cutting tool geometry

Items	Value
Cutting speed ( $V_c$ )	170, 140 m/min
Feed rate ( $F_z$ )	0.1 mm/tooth
Axial depth of cut ( $a_p$ )	0.5 mm
Radial depth of cut ( $a_e$ )	0.25 mm
Insert diameter, $\varnothing$	10 mm
Thickness of cutting tool	3.97 $\mu$ m
Radial rake angle	0°

Axial rake angle	-3°
Approach angle	90°
Number of inserts, n	1

In the case of cryogenic machining, the liquid nitrogen was delivered direct near the cutting zone during the machining process via a nozzle as shown in Fig. 2a.



**Figure 2** (a) Liquid nitrogen delivery (b) Tool insert (c) schematic of heat source during cutting.

The workpiece was clamped on the dynamometer which was mounted on the table of a CNC vertical machining center. The dynamometer will measure the force signals in the three directions which are tangential/ cutting force ( $F_x$ ), radial force ( $F_y$ ) and axial force ( $F_z$ ). These three signals of forces were then connected to the charge amplifier and the output of dynamic cutting force signals were real-time captured and stored by Neo-MoMac software.

Cutting temperature ( $^{\circ}$ C) was measured using an infrared Thermography camera where the temperature was determined by knowing the amount of infrared energy emitted by the object and its emissivity. In this case, the emissivity of Inconel was set to 0.19 according to Cole-Parmer [12]. The verification of the emissivity is done by comparing the temperature of infrared thermography camera with infrared thermometer (Figure 3). The

measurement was taken within 1 meter as per suggestion of the instrument procedure. The reading is almost the same where show that emissivity rate is correct. The range of the temperature that can be measure is between  $-40^{\circ}\text{C} \sim 1500^{\circ}\text{C}$ . During the experiment, the highest temperature will be taken for every cutting pass and this value will be compare with the highest temperature generated by software simulation.



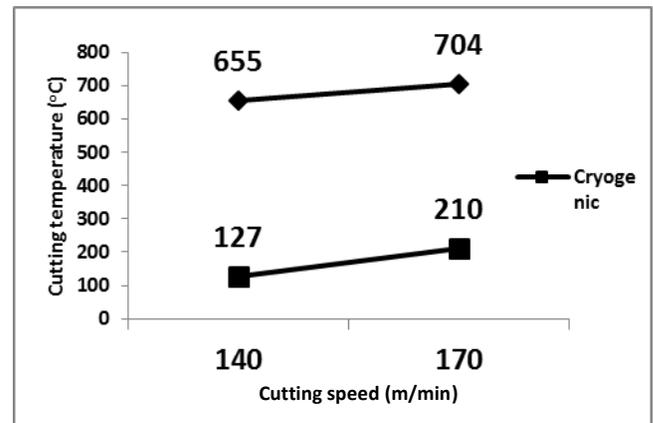
**Figure 3** Verification by comparing the emissivity value of 0.19 with infra-red thermometer

Last but not least, surface roughness ( $R_a$ ) was measured using a Mitutoyo Surf Test. The measurement of the surface roughness was repeated three times for each run and the average values of these three measurements were taken into consideration in order to make further analysis.

### 3.0 RESULTS AND DISCUSSION

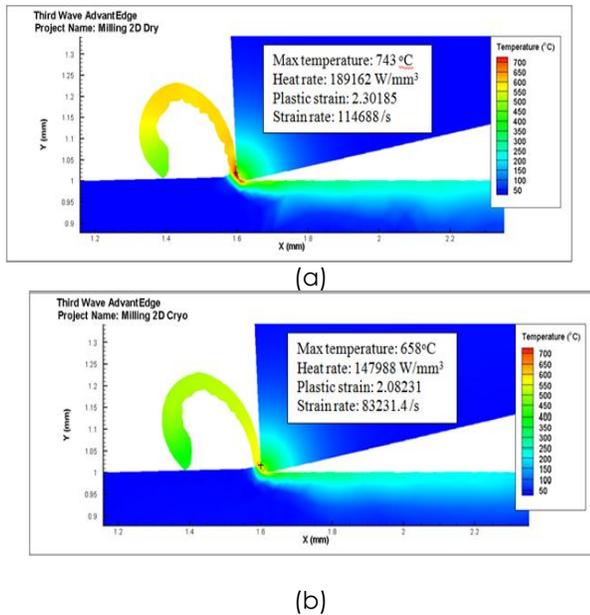
#### 3.1 Interface temperature analysis

Figure 4 show the results of cutting temperature under dry and cryogenic processes using an infrared thermal imager. The results measured by indicated that cryogenic implementation can decrease the amount of heat transferred to the tool up to almost 70%. The results show that cryogenic process not only works as a coolant but at the same time it also works as a lubricant by reducing the friction between cutting tool and workpiece. This was proved by Courbon et al. [13], where in their studies show that liquid nitrogen has the ability to decrease the friction coefficient and material transfer on Inconel 718 during machining process.



**Figure 4** Experimental results of cutting temperature

A thermal numerical simulation was performed using a Third Wave Advantedge software in order to ascertain the experimental results obtained. Fig. 5 shows the simulation of isothermal contours of temperature distribution for dry and cryogenic cooling conditions at the machined surface. In these finite element analyses, the flank face coefficient of friction has been set to 0.6 for a fresh tool cutting edge [14]. For both cooling conditions, the highest cutting temperature always occurs at the middle of tool-chip contact area. For the dry cutting (5a), the maximum heat generated is closed to  $700^{\circ}\text{C}$  which is agreed with the result obtained from experimental. However, the maximum cutting temperature for the simulation result for cryogenic cutting (5b) was less than the experimental result although the heat transfer coefficient had been set to  $32 \text{ W/m}^2\text{K}$  where this value has been established by Defence Metallurgical Research Laboratory (DMRL) [15]. This is due to limitation of the software used, which is unable to simulate the penetration of liquid nitrogen at the contact zone between cutting tool and workpiece. Hence, the simulation result for cryogenic cutting is similar with dry cutting condition at the interface of workpiece-cutting tool. On the other hand, although the simulation did not show the actual maximum cutting temperature at the interface, but the distribution of heat generated is lower compared to dry cutting in secondary deformation zone due to the cold cryogenic environment cutting condition. Therefore, cryogenic cutting still show the ability to lower down the heat transfer and was predicted to enhance the cutting tool life as observed by Wang et al. during their research [16].



**Figure 5** (a) Dry and (b) Cryogenic machining results with modelling of temperature distribution

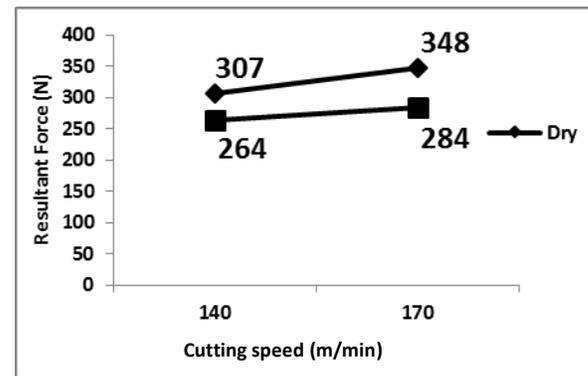
### 3.2 Cutting Force Analysis

Figure 6 shows the resultant cutting forces calculated using Equation 1 [17] at the beginning of the cut for each condition, therefore it can be assumed that tool wear is negligible and based on that the observed cutting forces area are a function of the workpiece shear strength, chip shear angle and friction between the workpiece and tool [18].

$$Fr = \sqrt{(\sum Fx)^2 + (\sum Fy)^2} \quad (1)$$

As shown in Figure 6, force during dry cutting process is higher compared to cryogenic cutting process. This is due to the fact that by applying the liquid nitrogen at the cutting zone, the liquid nitrogen will evaporates and tend to form a nitrogen cushion between the tool-chip and tool-workpiece interfaces [19]. This situation will lead to a lower coefficient of the friction at the cutting zone. Hence, due to low cutting force obtained during cryogenic machining, the hardness and the strength of the tool material will correspond increased. At the same time the tool wear and adhesion will reduced between the tool-chip and tool-workpiece interface throughout the reduction of the cutting temperature. During cryogenic cutting process, the resultant force is decrease up to 19% compared to dry cutting process. This result is in line with the study done by Ravi and Kumar [20] on end milling of hardened steel.

It is also clearly show that resultant cutting force is decreasing when the cutting speed is increasing. The same result was obtained by Hasan [21] in his research during machining AA2014 (T4) Alloy. This is due to low friction forces on the tool rake face at high cutting speed and also low shear forces required to produce the stress for deformation when shear angle increase at high cutting speed [22].



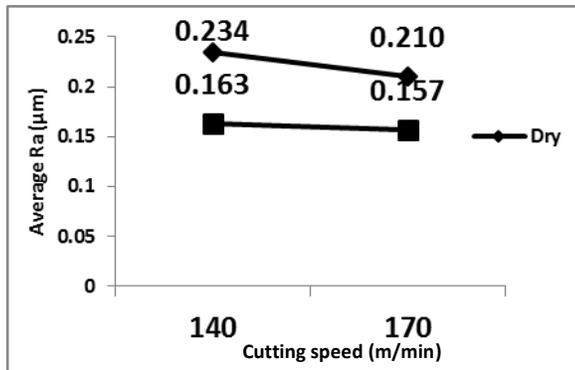
**Figure 6** Resultant cutting force during dry and cryogenic condition at the beginning of the cut

### 3.3 Surface Roughness And Microstructure Examination On The Machined Interface

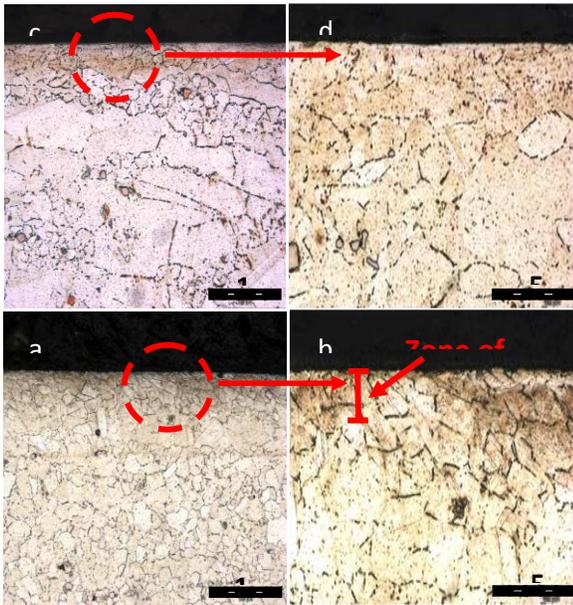
Figure 7 shows the average of surface roughness ( $R_a$ ) of the workpiece during dry and cryogenic cutting process. From the results below, it can be seen that cryogenic cutting produced better  $R_a$  value, which is almost 31% lower compared to dry cutting. A similar trend has been observed during the study done by Shokrani *et al.* [23], where they get 33% reduction in surface roughness. In general, this is due to the lower cutting force and less adhesion through a reduction of cutting temperature at the contact zone interface.

The microstructure near the machined surface is shown in Fig. 8 under 20X magnification and 50X magnification. The grain boundaries observed near the machined surface show a clearly visible with some plastic deformation during dry cutting (Fig. 8a and b), while less plastic deformation was formed under cryogenic cutting (Fig. 8c and d) during the vertical milling process. This might be due to the fact that more plastic deformation occurred on machined surface during dry machining that cause by stronger adhesion of the workpiece material to the cutting tool at higher temperature [24], as compared to low cutting temperature during cryogenic machining. A similar finding acquired by Kenda *et al.* [25] proved that less shear deformation occurred on the machined surface under cryogenic cutting conditions compared with dry machining. This recent finding also show that cryogenic cooling

allowed the build-up stress and heat generated during vertical machining to completely resist before it reach its yield strength and allowing the workpiece to assume a new equilibrium state and return to its original state when the tool is removed.



**Figure 7** Average surface roughness during dry and cryogenic cutting processes



**Figure 8** Microstructure of machined surface under different condition and magnification: (a) dry machining (20X); (b) dry machining (50X); (c) cryogenic machining (20X); (d) cryogenic machining (50X)

## 4.0 CONCLUSION

This paper focused on the tribological behavior of Inconel 718 alloy at the cutting zone during dry and cryogenic ball nose milling process. In general, the tribological phenomenon of dry and cryogenic machining cause a consequent temperature rise at the tool-chip interface. A high cutting force generated during dry machining caused

thermoplastic shear localization since the build-up stress exhibited the yield strength of the workpiece material. The high cooling capabilities of liquid nitrogen during cryogenic process have been proved with a drastic reduction of the heat generated at the cutting zone and a better surface roughness can be obtained during machining process. On top of that, cryogenic process also dissipates the high heat generation at machining zone without polluting the environment. Overall, this study demonstrates that machining superalloys like Inconel 718 under cryogenic cooling will lead to the enhancement of surface integrity and at the same time will improve machining performance.

## Acknowledgements

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