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Effect of Cryogenic Machining for Titanium Alloy Based on Indirect, Internal and External Spray System

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Abstract

Due to the excellent properties of Ti-6Al-4V titanium alloy such as lightweight, high wear and corrosion resistance and able to maintain high strength at high elevated temperature, this material has been used mostly in aerospace and biomedical industries. However, titanium alloy being considered as a hard-to-cut material with poor machinability due to its low thermal conductivity which leads to the excessive tool wear during machining and requires high machining cost. To overcome these problems, cryogenic machining has been taken place as a promising method for machinability improvement in terms of tool wear reduction, lower energy consumption and low machining cost. Even though this method has been implemented for titanium alloy machining, it is difficult to handle the excessive extremely low-temperature coolant (up to -150 ℃) that exposed directly to the workpiece. As a result, the workpiece hardness will be increased, hence will increase the required cutting force for the machining process. In concern with the problem, this paper presents a novel cryogenic cooling mechanism (indirect cryogenic cooling) that will be used as one of the cooling and lubrication strategy. The performance of the indirect cryogenic cooling will be compared with flood cooling, Minimum Quantity Lubrication (MQL) and conventional cryogenic cooling method by using the external and internal spray system. Liquid nitrogen (LN2) being selected as the cooling medium in this work since its temperature can reach lower -196 ℃, odorless and more environmentally friendly. A specially designed tooling kit that able to supply the liquid nitrogen to the cutting tool internally is used in this method. The developed indirect cryogenic supply method able to improve the machinability of Ti-6Al-4V. The cutting force is reduced by 54% and the tool life is improved by 90% compared to the conventional flood coolant strategy.

Keywords: Tool wear; tool life; cryogenic cooling; high speed milling; Ti-6Al-4V

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1. Introduction

Titanium is one of the common materials that is used in transportation, energy, and biomedical industries due to its excellent properties such as high strength, low density, biocompatibility, resistance to high temperature, also high fracture and corrosion resistance. Despite these advantages, titanium alloys are known as “difficult-to-cut” material based on its performance in machining which contributed to some drawbacks such as generate high temperatures and rapid tool wear. Poor machinability of this alloy which mainly caused by low thermal conductivity has led to high machining cost, especially when using high speed machining (HSM) process.

As its name, HSM is an advanced machining method which uses cutting speed more than material’s standard, in this case, the typical cutting speed for titanium alloy is less than 60 m/min [1]. Nowadays, HSM had gained popularity as it can improve production and increase product quality, as well as minimizing the manufacturing costs. Moreover, the implementation of this method also improves effectiveness, accuracy, and quality of the workpiece. However, as mentioned earlier, increasing cutting speed during machining process will result in increased cutting temperature which reduces the tool life immediately. According to Nandy et al. [2], almost 80% of the generated heat produced during machining remains in the tool, while the remaining heat taken away by the chip. Krishnaraj et al. [3] stated that due to the low thermal conductivity of titanium alloys, the increased heat concentration affects the surface integrity of the workpiece which causes the rapid tool wear.

Due to that, it is important to understand and overcome the heat generation problem while machining because essentially, this was the key factor that determines the tool life [4]. Recently, cryogenic machining had taken place as the best solution for high temperature problem. Originally, cryogenic was referred to the technology of producing low temperature environments but until now, there are many discrepancies in defining the term “cryogenic”. As mentioned by Jawahir et al. [5], most research and standards organizations stated that cryogenic temperature starts at or below -150 ℃ (123 K; -238 ℉). According to The Cryogenic Society of America and National Institute of Standards and Technology (NIST), the cryogenic temperature was defined at -153 ℃ (120 K; -244 ℉) and -180 ℃ (93.15 K; -292 ℉), respectively [6]. Since technically, the cryogenic temperature depends on the boiling point of coolant types, various researchers have used the term cryogenics to refer to temperatures below 0 ℃ [7,8,9,10].

Ravi and Chandran [11] explained that cryogenic cooling is a material removing process where the cryogenic is used as the replacement for conventional cutting fluids. Usually, carbon dioxide (CO2) and liquid nitrogen (LN2) being selected as a way to dissipate the produced heat during machining and improve the machinability through the modifications in cutting tool/workpiece material properties [12]. These two types of cryogenic cooling medium widely used due to their extremely low temperature, environmentally friendly and can increase tool life. Pereira et al. [13] stated that CO2 cooling is cheaper and more suitable in machining hard alloys when compared with other cryogenic gases and Lee et al. [14] mentioned that CO2 aid in removing the bur and chips during machining. CO2 cooling also can improve the lifetime of cutting tools as it being proved through studied done by Senthil Kumar [15] during turning process. Wang and Rajurkar [16] conducted an investigation of cryogenic machining of hard-to-cut materials using LN2 coolant and they found out that the cutting responses; cutting temperature, tool wear and surface roughness had been greatly improved. Same results also achieved by Umbrello et al. [17] and Kaynak et al. [18].

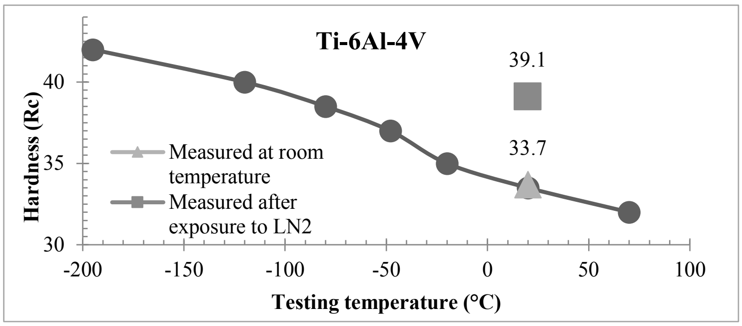
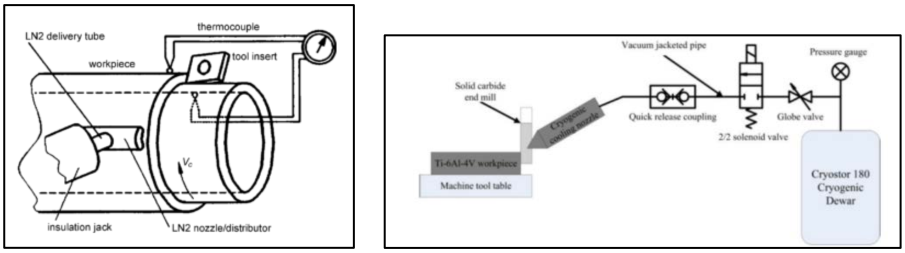


Fig. 1 The effect of excessive LN2 on Ti-6Al-4V due to the conventional external spray system [1].

Even though cryogenic cooling had shown better performance throughout the years of implementation, still there is a major drawback of using this particular method. Due to the excessively low temperature coolant, the workpiece hardness increased and hence produces higher cutting force. Shokrani et al. [19] carried out an experimental work on titanium alloy (Ti-6Al-4V) and found out that the hardness increases from 32 HRc at ambient temperature to 42HRc at the LN2 temperature. Ahmed et al. [20] also obtained the same results where the surface of the holes was damaged due to the extreme cooling when drilling titanium alloy. This problem also identified through the work done by Ko et al. [21] and Park et al. [1] while machining titanium alloy. Fig. 1 shows the effect of excessive LN2 on the workpiece which the hardness was increased up to 16% compared with normal condition. Although, ever since LN2 was introduced, the method of supplying the LN2 to the cutting zone remains the same until now. Fig. 2 shows the similarity of the LN2 supply method by using an external nozzle spray system since the year of 2001 (Fig. 2a) and recent year of 2015 (Fig. 2b).

In particular with the work done previously on the effect of internal and external cryogenic spray methods in [1], this paper presents the effect of cryogenic machining on titanium alloy through an improved spray system called 'indirect cryogenic cooling'. The term 'indirect' is being used because the liquid nitrogen will be supplied only to cooled down the tool without to be exposed to the workpiece. This approach able to keep the normal temperature of the workpiece, hence prevents hardening from occurs. In this study, the tool performance consists of cutting force, tool wear and tool performance are being analysed and the results were compared with the conventional flood coolant, MQL added with nano-particle (nano-MQL), external and internal cryogenic cooling and also the combination of nano-MQL with internal cryogenic cooling.



a) Hong & Ding, 2001 [23]   b) Shokrani et al., 2015 [24]

Fig. 2 The conventional application of the LN2 supply method by using an external nozzle spray system since the year of 2001 and recent year of 2015.

2. Experimental Setup

The experiments were performed on a Mori Seiki NVD-4000-DCG-HSC three-axis vertical milling centre. All cutting tools used for machining process is a solid end-mill cutter with six (6) cutting edges and 16mm diameter. As for indirect spray system, the tooling kit and tool itself was specially designed for supplying the liquid nitrogen to the cutting tool internally as shown in Fig. 3 and Fig. 4, respectively.

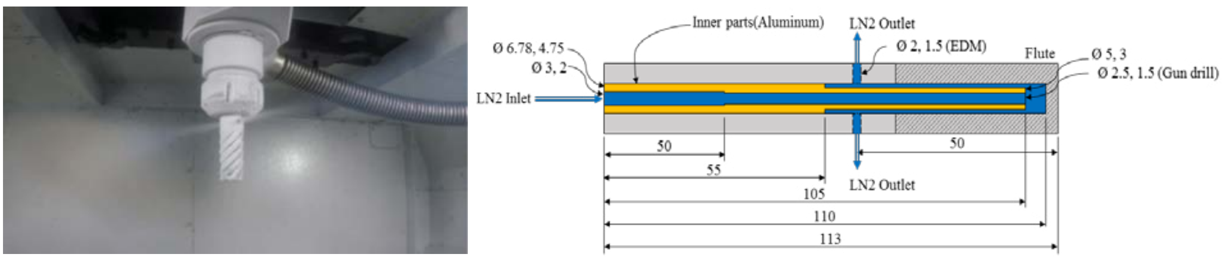


Fig. 3 Custom designed of indirect cryogenic tool

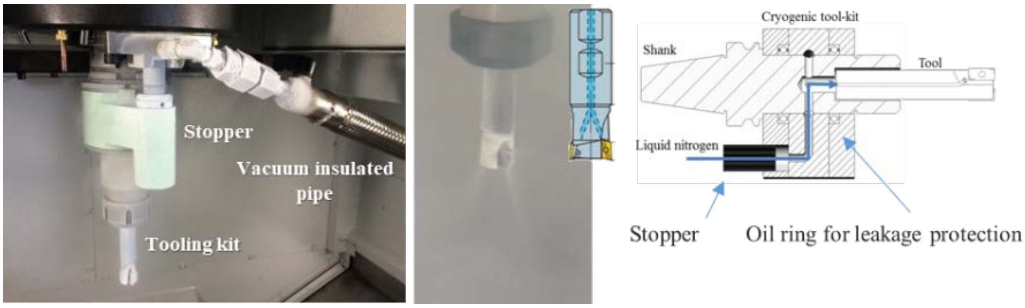


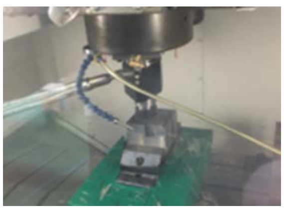
Fig. 4 Custom designed of internal cryogenic tooling kit.

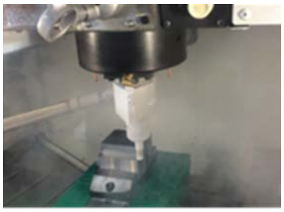
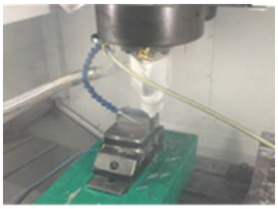
The tools used in this work were coated with Aluminium Chromium Nitride (AlCrN) made by YG-1 Korea. The workpiece material used is a commercially available titanium alloy Ti-6Al-4V with size 100 x 100 x 100 mm. The machining conditions used are shown in Table 1and the descriptions of all different cooling and lubrication methods shown in Table 2. In every experiment, the cutting force was measured using a 3-axis dynamometer (Kistler 9265B) while the tool wear evolutions are measured using a confocal laser scanning microscope (Keyence VK-X200) with 10x magnification.

Table 1. Machining conditions

Cutting Parameter	Conditions
Cutting speed (m/min)	86
Feed rate (mm/min)	1,026
Depth of cut (mm)	24.5
Width of cut (mm)	1.2
Cutting length (mm)	1,200 (12 passes)

Table 2. Cooling and lubrication methods and descriptions

Cooling and lubrication method	Description
 Flood coolant	Castrol ALUSOL AZ 10% water soluble
 MQL with added nano-particle (nano-MQL)	Oil: Mist oil 210 Pressure: 5 bar Spray rate: 3 ml/min Nano-particle: hBN-70

 External cryogenic	Liquid: Nitrogen Pressure: 3 bar Nozzle diameter: 1 mm
 Internal cryogenic	Liquid: Nitrogen Pressure: 2 bar
 Nano-MQL + internal cryogenic	Liquid: Nitrogen Pressure: 2 bar MQL spray rate: 3 ml/min
 Nano-MQL + Indirect cryogenic	Liquid: Nitrogen Pressure: 2.5 ~ 3 bar MQL spray rate: 3 ml/min

3. Results and Discussions

The work was carried out through the selected cutting conditions and the results were recorded as intended. Fig. 5 shows the cutting force values for various lubrication strategies over a number of cutting passes using 3-axis dynamometer. It can be observed that cutting force increase as the number of passes increase and all conditions show the similar trend. By comparing with flood coolant strategy, nano-MQL, nano-MQL with internal cryogenic and nano-MQL with indirect cryogenic consumed less cutting force by 7%, 4% and 54%, respectively. However, tool failure was recorded through external cryogenic and internal cryogenic process at 10th and 8th passes, respectively where catastrophic failure experienced in external cryogenic and strong adhesion occurred in internal cryogenic. This result was further discussed previously in Park et al. [1]. Subsequently, the suggested approach of using indirect tool along with nano-MQL lubricant strategy shows a great solution in excessive and hardening workpiece problem. The cutting force is significantly reduced and helps in maintaining the smooth cutting process. With the aid of additional lubrication, the cutting chip which is trapped on the tool helix was removed, hence low cutting force was used during the process.

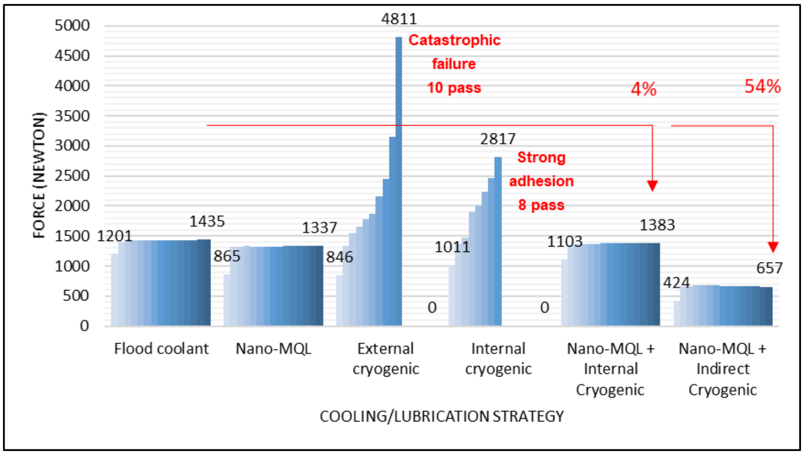


Fig.5 Cutting force for all lubrication strategy

Fig. 6 presents the average tool wear for all lubricant strategies which is measured using a confocal laser scanning microscope. Through this figure, the smallest wear size was recorded at 10 µm by the application of nano-MQL with the indirect cryogenic process. Almost 90% wear was reduced, compared to flood coolant process. Meanwhile, nano-MQL with internal cryogenic application also reduced around 32% of the wear size which is at 55.7 µm. These wear size results were further visualized and listed in Table 3 where the measurement was taken at 250 µm in size on all 6 flutes on the tool. It can be observed that the tool wear was greatly enhanced in the application of indirect cryogenic with nano-MQL. The wear almost unseen in indirect tool and it looks as good as new. While the other two approaches clearly visualize the wear on the tool tip. This increasing wear size of all approach closely relates with increasing cutting force across the passes. As agreed by Park et al. [1], the cutting force could be used to monitor the condition of the tool where high cutting force indicates that the tool experience relatively high wear and the possibility of tool break also increase.

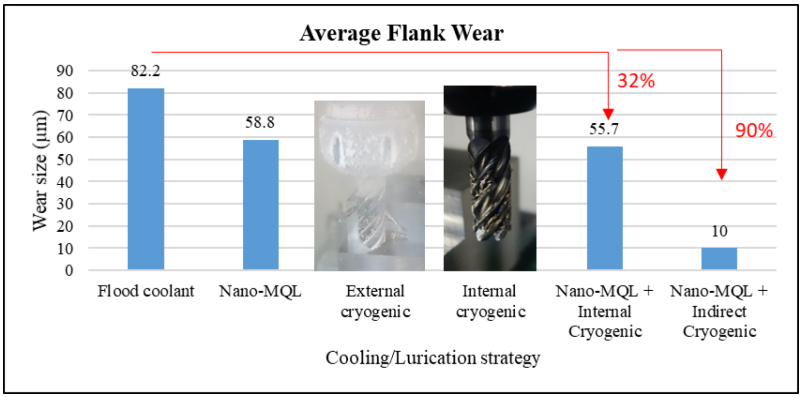
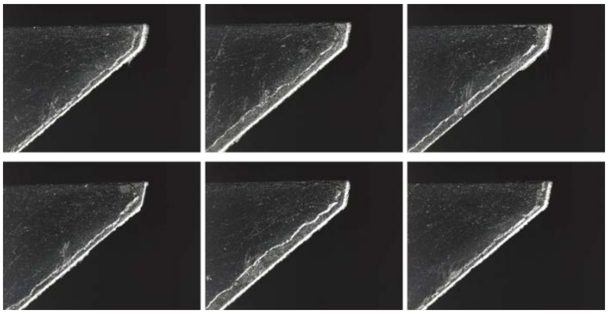
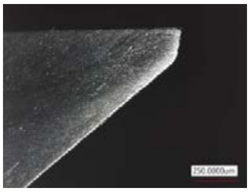
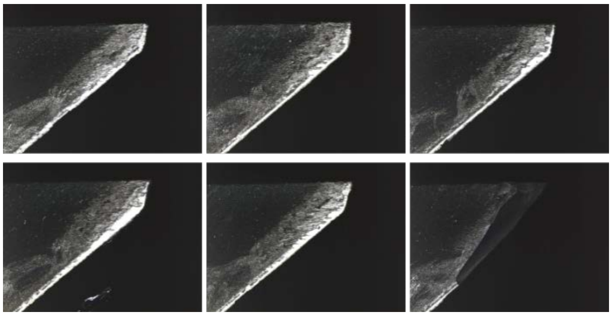
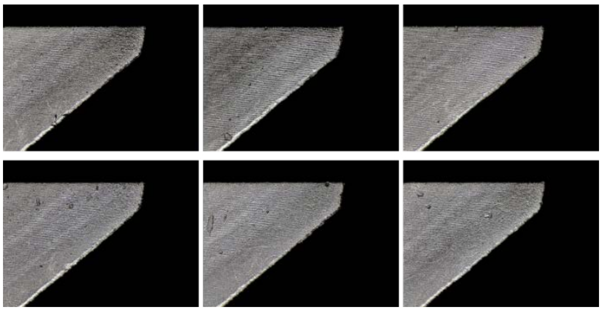


Fig. 6 Average flank wear for all lubricant strategies

Table 3. Tool wear on each lubrication strategy

New tool	Lubricant strategy	Tool wear
	Wet	
	Nano MQL + internal cryogenic	
	Nano MQL + indirect cryogenic	

4. Conclusions

The possible solutions for avoiding workpiece hardening during the cryogenic process has been carried out and the results that collected fulfill the main objective of this work. As for conclusion that can be drawn:

i) The combination of indirect cryogenic cooling with nano-MQL lubricant strategy able to improve the machinability of Ti-6Al-4V. The cutting force is reduced to 54 % and tool wear improved to 90% compared to the conventional flood coolant strategy.
ii) The novel idea of ‘indirect’ cryogenic cooling able to prevent the workpiece from hardening due the excessive used of liquid nitrogen as in the external and internal cryogenic spray method.

Acknowledgements

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