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The effect of cryogenic cooling and minimum quantity lubrication on end milling of titanium alloy Ti-6Al-4V †

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Abstract

The cooling down of cutting temperature in machining is very important for the improvement of tool life, especially when dealing with work materials that have low thermal conductivity such as titanium alloy. In this study designed to investigate the machining performance of a variety of cooling methods, cryogenic, Minimum quantity lubrication (MQL), and flood cooling are performed on solid end milling of titanium alloy, Ti-6Al-4V. In particular, the effect of internal and external spray methods on cryogenic machining is analyzed with a specially designed liquid nitrogen spraying system by evaluating tool wear and cutting force at cutting conditions. The cutting force is also analyzed for tool breakage detection. As a result, the combination of MQL and internal cryogenic cooling improves tool life by up to 32% compared to conventional cooling methods. The cutting force is also reduced significantly by this combination of cooling and lubrication strategy of side end milling.

Keywords: Titanium; Cryogenic cooling; Liquid nitrogen; Tool wear; MQL; Cutting force monitoring

1. Introduction

Materials that have superior mechanical properties such as high strength, light weight, high wear and corrosion resistance are recommended for use in the aerospace and automotive industries. However, these materials, including titanium, nickel based super alloy, etc., are well known as difficult-to-cut materials due to their low machinability compared to carbon steel and aluminum. This is mainly because of excessive tool wear caused by the high cutting temperature generated during the machining process, which is due to the low thermal conductivity of the materials [1-4], thus contributing to poor machinability and accelerated tool wear [5]. Therefore, in the machining industry, the cutting speed of these difficult-to-machine materials is very limited. For example, typical cutting speeds of titanium alloy are less than 60 m/min and 100 m/min using High speed steel (HSS) and tungsten carbide tools respectively. In this regard, many machining technologies that improve the machinability of the materials by focusing on reduction of cutting zone temperature have been studied (refer to Ref. [6] for more detail).

Particularly, cryogenic machining and Minimum quantity lubrication (MQL) have been applied for the machining of hard-to-cut materials due to their ability to suppressing high heat generation and providing lubricity on the cutting surface during the cutting, respectively, in which the machinability of the materials can be enhanced. Consequently, cryogenic and MQL are considered as a viable solution for machining of difficult-to-cut materials.

In this study, cryogenic machining is performed for titanium alloy, Ti-6Al-4V, using a specially designed liquid nitrogen spraying system. For cryogenic fluid dispensing on the cutting tool, external nozzle and internal channeled tool spray systems are used. In addition, MQL machining with and without nanoparticle additive is carried out using an MQL oil dispense system that can control spray conditions precisely, as in Park et al. [7]. In addition, a machining condition that sprays cryogenic and MQL fluids simultaneously is also tested. In the experiment, the machining performance of MQL and cryogenic machining are evaluated in terms of tool wear and cutting force by comparing them to flood cooling machining. For tool breakage detection in titanium machining, the cutting force is analyzed.

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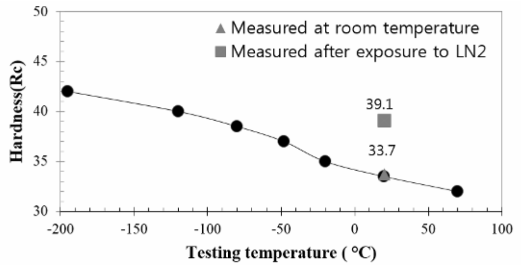


Fig. 1. The effect of excessive LN2 due to the conventional external spray on Ti-6Al-4V.

2. Background and rationale

The effect of cooling and lubrication in metal cutting play an important role in increasing productivity without sacrificing tool life. Machining hard-to-cut materials such as titanium alloys are more challenging compared to carbon steel and aluminum due to its poor thermal conductivity. Consequently, the effect of cooling and lubrication on removing the elevated temperature between the tool and workpiece engagement region is vital for improving the tool life and increasing the machining performance. Traditionally, flood cooling is used in machining industries for this purpose and is a preferable strategy due to its ease of application. Typically, however, flood cooling works effectively when dealing with the materials that have medium or high machinability and in a low cutting speed. Due to the low thermal conductivity of titanium alloys, the heat generation at the engagement region of the tool and workpiece will easily increase up to 1000°C, which will soften the tool and accelerate tool wear [8]. To deal with this issue, several studies have been carried out to enhance the cooling effect by replacing conventional flood cooling with cryogenic cooling. It has been proven that a cryogenic cooling strategy using liquid nitrogen (LN2) spray is able to control the cutting tool temperature effectively, thereby increasing the tool life [9-13]. However, there is no specific approach on the application of delivering the cryogenic spray, although several techniques of the application are discussed by Hong et al. [10]. While cryogenic cooling is able to lower the tool temperature, at the same time, however, the hardness of the workpiece material will increase due to the excessive amount of LN2 [14]. Fig. 1 shows the effect of excessive LN2 on the hardness of titanium alloy Ti-6Al-4V with respect to temperature due to the conventional external spray system. This figure shows that hardness can easily increase up to 16% compared to the normal condition at room temperature.

Thus, in this study, to overcome the effect of excessive LN2 on the workpiece material, a specially designed internal cryogenic tooling kit as shown in Fig. 2 is used. This tooling kit is capable of supplying the LN2 directly to the internal body of the cutting tool, hence the temperature of the cutting tool remains low without increasing the hardness of the workpiece. The performance of both the conventional spray system and the specially designed tooling kit are discussed in this paper.

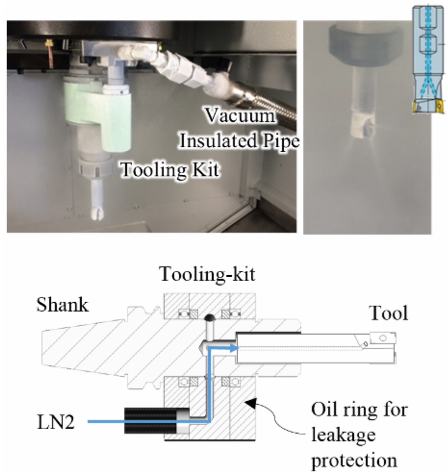


Fig. 2. Custom designed internal cryogenic cooling tooling kit.

Minimum quantity lubrication (MQL) is a strategy that uses a minimum amount of lubrication and at the same time reduces friction between the tool and the workpiece. MQL can be a better choice to replace conventional flood coolants due to its ability to improve tool life, consume less lubrication (thereby keeping costs down) and is more environmentally friendly, as reported by Refs. [15-19]. MQL works effectively with low cutting speeds because the oil simply evaporates as soon as it strikes high temperature tools at high cutting speeds [20], especially in the machining of titanium alloys. Hence, in this study, nano-particles enhanced MQL with is studied for titanium machining, as in the method used by Park et al. [7]. This strategy is sounder than conventional MQL due to the characteristics of the nano-particle scheme which is arranged in a multiple-layer order, so as the oil droplets strike the high temperature tool, the nano-particle still provides additional lubrication even though the oil droplets have evaporated. Meanwhile, using the same strategy, Nguyen et al. [20] study the performance of added Hexagonal Boron Nitride (hBN) nano-particles and compare its effect on tool wear against the exfoliated nano-graphene (xGnP) nano-particle used in Park et al. [7]. They reported that a mixture of hBN particles reduces the flank wear and central wear of a ball-milling process better than the xGnP mixture.

To investigate further the effect of added nano-particle mixture to MQL (Nano-MQL), this study considers the application of hBN Nano-MQL in machining titanium Ti-6l-4V. In addition, the combination of both internal cryogenic cooling and Nano-MQL is conducted to examine the performance on tool wear. The cutting force will be monitored for all cooling/lubrication strategies for a better understanding of the tool wear behavior.

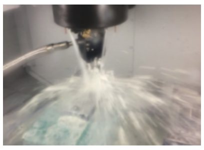
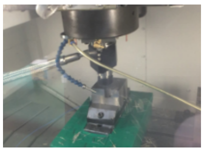
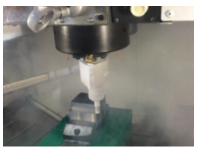
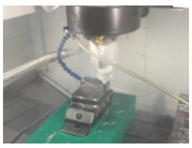
3. Experimental procedure

The experiments were performed on a Mori Seiki NVD-4000-DCG-HSC three-axis vertical milling center. The cutting

Table 1. Machining conditions.

Cutting parameter	Conditions	
	Flood coolant	Nano-MQL, external cryogenic, internal cryogenic, Nano-MQL + internal cryogenic
Cutting speed (m/min)	72	86
Spindle speed (rpm)	1430	1711
Table speed (mm/min)	860	1026
Feed per tooth (mm/tooth)	0.1	
Axial depth of cut (mm)	24.5	
Radial depth of cut (mm)	1.2	
Cutting length (mm)	1200 (12 passes, 100 mm length/pass)	

Table 2. Cooling and lubrication methods and descriptions.

Cooling and lubrication method	Descriptions
Flood coolant 	Coolant type: ALUSOL AZ manufactured by Castrol Corp. Mixture rate: 10% water soluble
MQL with nano particle (nano-MQL) 	MQL oil: Ester based vegetable oil Nano-particle: hBN-70, diameter 70nm, thickness 2nm, manufactured by M K Impex Corp., Canada. Mixture rate: 5 wt % Nano-particle mixture method: ultrasonic dispersion MQL spray device: Unist Korea Corp. UNIMAX F210 MQL spray rate: 3ml/min
External cryogenic 	External spray system with vacuum insulated pipe. Liquid nitrogen supply pressure: 3 Bar Nozzle diameter: 1 mm.
Internal cryogenic 	Internal cooling supply from tool holder. Liquid nitrogen supply pressure: 2 bar
Nano-MQL + internal cryogenic 	Liquid nitrogen supply pressure: 2 bar MQL spray rate: 3ml/min

tool used in the machining test is a solid end-mill cutter with six cutting edges. The tool diameter is 16 mm. The tool is coated with Aluminium Chromium Nitride (AlCrN) made by YG-1 Korea. The workpiece material used is a commercially

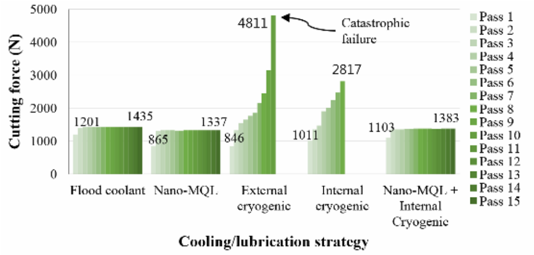


Fig. 3. The cutting force for all cooling/lubrication strategies.

Fig. 4. Strong adhesion on solid end milling in cryogenic cooling.

available titanium alloy Ti-6Al-4V with a size of 100 x 100 x 100-mm. The machining conditions used are as shown in Table 1. For every experiment, the cutting force was measured by using a 3-axis dynamometer (Kistler 9265B). The tool wear evolutions are measured by a confocal laser scanning microscope (Keyence VK-X200) with a magnification of 10X. The descriptions of all different cooling and lubrication methods are shown in Table 2.

4. Results and discussion

Fig. 3 shows the cutting forces for the various cooling/lubrication strategies over the number of passes. The cutting forces gradually increase as the number of passes increased. This increase of cutting forces is mainly due to tool wear. As shown in Table 1, the cutting speed for the flood coolant method is lower than the other cooling/lubrication methods, which are 72 and 86 m/min, respectively. However, the forces consumed by the flood cooling at the end of the experiment are relatively high compared to Nano-MQL and Nano-MQL + internal cryogenic. The cutting force for the flood coolant is 3% and 7% higher compared to Nano-MQL + internal cryogenic and Nano-MQL, respectively. For the cryogenic cooling, both external and internal cryogenic cooling has a similar trend of increasing cutting forces. The cutting force for external cryogenic was increased almost 5 times higher at the end of the tool life. For external cryogenic, the tool was totally broken by the 10th pass; meanwhile, for the internal cryogenic, the tool suffered from strong adhesion that lead to Build-up-edge (BUE) formation (Fig. 4), and the machining had to stop at the 8th pass. The cutting force in the internal spray of LN2 is slightly lowered compared to that in the external spray method due to a reduction of titanium hardening by LN2 spray with internal channel. The strong adhesion on the tool occurred in both cryogenic with internal and external sprays is mainly due to the deep axial depth-of-cut with the

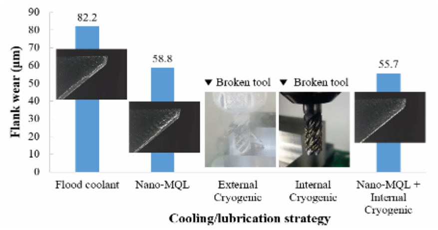


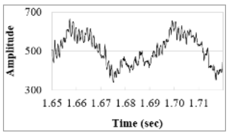
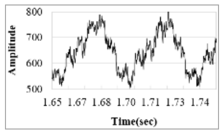
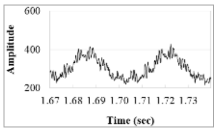
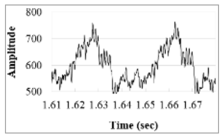
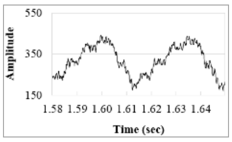
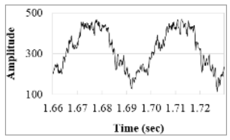
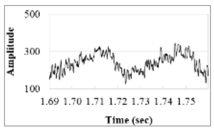
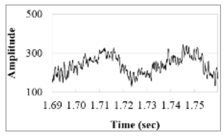
Fig. 5. Flank wear in various cooling/lubrication strategies.

large contact area through the helix of the solid end mill. The large contact can increase the friction forces without any lubrication. Therefore, the cutting chip is trapped on the tool helix caused by lack of lubrication at large tool/workpiece engagement region. Because of this, the cutting force increased tremendously as the tool passes increased, as in Fig. 3. In the previous research done by Park et al. [19], the cryogenic cooling with internal and external sprays in the application of the indexable end-mill with a smaller depth-of-cut showed high machining performance without the strong adhesion. As a result, it can be said that even though cryogenic is able to cool down the tool with the liquid nitrogen that has extremely low temperature, in the case of the machining that has deep axial depth-of-cut the tool can be suffered from strong adhesion and catastrophic failure for both external and internal cryogenic cooling due to the lack of lubrication, as shown in Figs. 3 and 4. However, if the enough lubrication can be supplied as the case of Nano-MQL + internal cryogenic strategy, the cutting force remained at a low level until the end of the 15 passes. This indicates that the solid end mill needs more lubrication on the cutting interface in order to suppress the friction force increase.

Fig. 5 presents the tool wear measurement for the flood coolant, Nano-MQL and Nano MQL + internal cryogenic strategies by using a confocal laser scanning microscope. Based on this figure, the smallest tool wear size is by the application of Nano-MQL + internal cryogenic, which are improved up to 32% compared to the wear size of the flood coolant machining. The cutting force data shown in Fig. 3 agrees with this result that cutting force has a direct relationship to influence tool wear. Higher cutting force consumption is mainly due to the increase of the wear size. Hence, the cutting force could be used to monitor the condition of the tool. In this study, the thrust force that caused the tool to break in the external cryogenic machining is used for tool breakage detection. In orthogonal cutting, the thrust force is in the direction of feed motion, and it can be used to obtain the power of feed motion. Hence, Table 3 shows that the feed forces in one rotation of the spindle at first and last passes of the cutting for the various cooling/lubrication conditions. Fig. 6 illustrates the thrust forces of the fresh tool versus the worn/broken tool in detail.

From Table 3, the broken tool behavior can be identified from the thrust force value. For the fresh tool, the thrust force maintains positive value, above 0 N, while for the broken tool thrust forces shows negative value, below 0 N [22]. Fig. 7 shows the thrust forces in cryogenic and Nano-MQL machining. Fig. 7(a) indicates the average thrust force in terms of the cutting passes. This data just shows that the average peak thrust force increases during the cutting but it do not provide any clues for the tool condition. However, in Fig. 7(b), it can be observed that the thrust force gradually decreases to -750 N, starting from the 2nd pass. And at the 5th pass the thrust force reaches as low as 0 N. This may indicate the cutting tool starts to engage in rubbing action of the tool with the work material, instead of the cutting due to tool wear or breakage. In this manner, the tool conditions such as tool breakage can be detected during the cutting process.

Table 3. The feed forces of the various cooling/lubrication conditions.

Fresh tool (First pass)		Worn/broken tool (Last pass)	
Cooling/ Lubrication strategy	Force (N)	Cooling/ Lubrication strategy	Force (N)
(a) Flood coolant 	690.08	(a) Flood coolant 	784.32
(b) Nano-MQL coolant 	424.52	(b) Nano-MQL coolant 	752
(c) External cryogenic 	459.84	(c) External cryogenic 	1685.33
(d) Internal cryogenic 	475.97	(d) Internal cryogenic 	1525.7
(e) Nano-MQL + Internal cryogenic 	347.05	(e) Nano-MQL + Internal cryogenic 	749.18

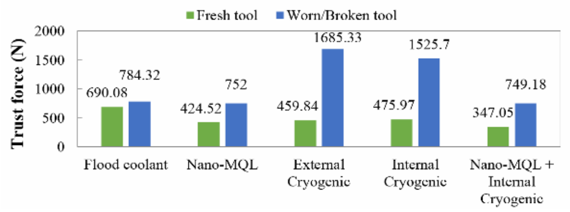
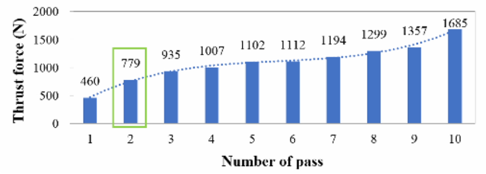
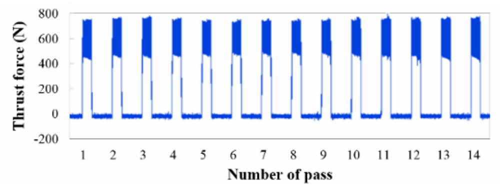


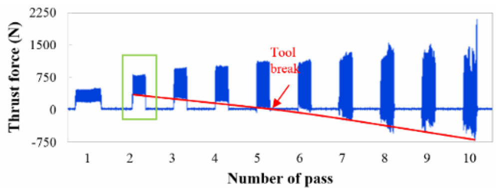
Fig. 6. Thrust forces of the fresh tool compared to worn/broken tool.



(a) Average peak force of the external cryogenic



(b) Thrust forces of the external cryogenic



(c) Thrust forces of the Nano-MQL

Fig. 7. The comparison of thrust forces between the external cryogenic and Nano-MQL conditions.

5. Conclusions

In this work, the effect of the various cooling/lubricating methods on machining of titanium, Ti-6Al-4V is investigated. The following conclusions can be drawn from this work:

(1) The combination of enhanced MQL with added hBN nano-particle with custom designed internal cryogenic cooling performs better than the conventional flood cooling in terms of cutting force and tool life. This combination of cooling and lubrication strategy improves tool life by up to 32% compared to the conventional flood cooling condition in the deep axial depth-of-cut machining of Ti-6AL-4V.

(2) In deep axial depth-of-cut machining, the cutting tool with only cryogenic cooling can be suffered from strong adhesion due to the lack of lubrication. Therefore, the lubrication method such as MQL should be added in deep axial depth-of-cut machining.

(3) Thrust forces can be used to detect the tool condition such as breakage with the point where the thrust force is reduced to 0 N due to the rubbing action between the tool and the workpiece.

Acknowledgment

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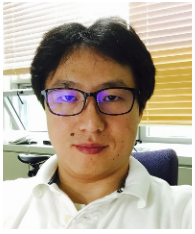

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