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CUTTING AND THRUST FORCES IN FACE TURNING OF TI6AL4V UNDER VARIOUS CUTTING ENVIRONMENTS

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ABSTRACT

Ti6Al4V alloys are widely applicable in aerospace, military, automotive, medical etc. industries due to their inherent properties such as high temperature resistance, high strength to weight ratio, dimensional stability, great corrosion endurance etc. However, there are some challenges on machining of Ti6Al4V because of their high hardness, elevated cutting temperature at cutting zone, chemical reaction between cutting tool and workpiece. For these reasons, the studies related to machining of these alloys have been conducting. In the presented experimental study, face turning tests were performed on Ti6Al4V alloy under dry, minimum quantity lubrication (MQL) and cryogenic (liquid nitrogen, LN_2) conditions at various cutting speeds. During machining experiments, cutting and thrust forces were measured. Based on the force results, the cutting forces reduced with increase of the cutting speed in three cutting environments. Additionally, the minimum cutting forces were achieved under MQL condition whereas the maximum cutting forces were obtained under dry cutting.

Keywords: *Ti6Al4V, face turning, cutting forces, cryogenic, MQL.*

INTRODUCTION

In recent years, the costs of purchasing, recycling, chip drying etc. for cutting fluids and some environmental legislations have been increasing the demand for sustainable machining processes such as dry cutting, minimum quantity lubrication (MQL) method and cryogenic (LN_2) cooling. Therefore, researchers have performed some studies on this issue especially cutting of hard-to-cut materials such as Ti6Al4V alloys, Ni-based alloys, stainless steels etc. Yuan et al. [1] presented experimental investigations on the effects of various coolant strategies in milling of the Ti6Al4V alloy with uncoated carbide inserts. The experimental results showed that MQL with cooling air significantly reduced cutting force, surface roughness and tool wear. Machai et al. [2] performed an experimental work to understand the influences of cutting speed and carbon dioxide snow (CO_2-snow) in machining of high-strength β-titanium alloy (Ti-10V-2Fe-6Al). Based on the results, performing of CO_2-snow cooling caused lower tool wear as compared to the flood cutting. In addition, it was noticed that MQL application at rake face along with CO_2-snow at flank face was slightly better than CO_2-snow application at both faces. Sales et al. [3] worked on tool wear in machining of Ti6Al4V alloy using Polycrystalline Compact Diamond (PCD) tools under cryogenic cooling, hybrid (cryogenic + MQL) and flood cutting conditions. The results showed that flank and crater wears were dominant wear types and also abrasive wear was observed in flood cutting. Benjamin et al. [4] carried out milling experiments on Ti6Al4V alloy under MQL and minimum quantity cooling lubrication (MQCL) which consists of sub-zero air in the MQL aerosol. Researchers compared the surface roughness, cutting temperatures, and chips. Based on the researchers' work, MQCL showed significant improving over MQL. Umbrello and Rotella [5] presented a work on the effects of cutting parameters and cooling/lubrication conditions on the fatigue life of Ti6Al4V alloy. The cooling/lubrication conditions were selected as dry, MQL, cryogenic and high-pressure air jet (HPAJ). The experimental results highlighted the fatigue endurance was improved in cryogenic cooling. The MQL and HPAJ also improved fatigue strength as comparing to dry cutting. Damir et al. [6] combined cryogenic cooling and MQL method to take advantage of their cooling and lubrication properties in machining of Ti6Al4V. Based on the results, an improving in tool life was achieved with the optimized hybrid cooling technique rather than cryogenic cooling, high pressure, and flood. Gross et al. [7] examined the potential of cooling and lubrication conditions in turning of Ti6Al4V, X5CrNi18-10 and 42CrMo4 materials by examining tool wear, surface roughness, and cutting forces. According to the experimental results, researchers indicated that the cryogenic minimum quantity lubrication might be replaced by the flood cutting. Rubio et al. [8] presented a study on the surface roughness of Ti6Al4V alloy under low-performance turning conditions. The results showed that spindle speed, feed rate and measurement location had effects on the surface roughness whereas the cooling system type and tool were not independently factors. According to the researchers, their effects on the surface roughness only occurred through their interactive relations with the

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spindle speed. Shokrani et al. [9] proposed a hybrid cryogenic MQL cooling/lubrication method for end milling of Ti6Al4V. The influence of this method on machinability of Ti6Al4V was investigated at different cutting speeds and the results were made comparison with cryogenic cooling, MQL, and flood in terms of surface roughness and tool life. The analyses showed that the hybrid method increased the tool life approximately 30 times and achieved 50% improvement in productivity as comparing the flood cooling. Al-Ghamdi et al. [10] presented a study to compare the machinability of Ti6Al4V and AISI 4340 materials in regards to tool wear, specific cutting energy consumption, and cutting forces under various CO_2-snow and hybrid (CO_2-snow and MQL) cooling types. Researchers also optimized the machining operation by utilizing fuzzy logic system. Sun et al. [11] developed cooling approach using LN2 cooling to cool off both the flank face and rake face of the cutting tool. The effects of this technique on the chip temperature, cutting force, and chip formation were examined. Bermingham et al. [12] studied the effects of cryogenic coolant in turning of Ti6Al4V at a constant cutting speed and material removal rate with various combinations of depth of cut and feed rate. It was observed that the combinations of low depth of cut and high feed rate caused the greatest improving in tool life. Dhananchezian and Kumar [13] investigated the effects of LN2 cooling in turning of Ti6Al4V. The LN_2 cooling was applied to the rake and flank surfaces through holes made in the insert. The cutting forces, tool wear, cutting temperature, and surface roughness were measured and the results were compared with flood cutting. It was observed that the sending of LN_2 cooling the cutting zone through holes was more effective over flood cutting. Bermingham et al. [14] investigated the chip morphology and tool life in turning of Ti6Al4V under cryogenic cooling and high pressure water based emulsion at constant cutting parameters and coolant nozzle position. It was found that the most effective parameter was the coolant nozzle position. Shokrani et al. [15] performed a research work to investigate the feasibility of LN_2 cooling during end milling Ti6Al4V and the results were compared with the results of dry and flood cuttings. The analysis revealed that cryogenic machining significantly improved the machinability of Ti6Al4V. In addition, LN_2 cooling also increased the tool life in almost three times and reduced the surface roughness by 40% as comparing to flood cutting. Ayed at al. [16] investigated the impact of the flow rate and coolant jet pressure surface integrity and tool wear during cryogenic machining of Ti6Al4V. In order to change the flow rate and the pressure, different nozzle diameters were employed. The reduced tool life and the proved surface integrity were obtained by increasing the flow rate and pressure. Mia and Dhar [17] investigated the surface roughness, specific cutting energy, tool wear, chip morphology, and chip-tool interface temperature in cryogenic turning of Ti6Al4V through single and duplex jets. The LN_2 cooling was applied to the rake face through single jet whereas it was sent to the rake and flank surfaces through duplex jets. Results showed that the duplex LN_2 cooling increased tool life, reduced cutting temperature and improved surface quality. Jamil et al. [18] performed an experimental work to investigate the effects of cryogenic CO_2 and hybrid nanofluid-based MQL techniques in turning of Ti6Al4V. The used hybrid nanofluid was prepared by mixing alumina (Al_2O_3) and multi-walled carbon nanotubes (MWCNTs) in vegetable oil. Results showed that the hybrid nanofluid-based MQL method reduced the average surface roughness and cutting force and improved the tool life as against the cryogenic cooling. However, the cryogenic cooling decreased the cutting temperature at high and low cutting speeds and feed rates. Sartori et al. [19] investigated the influences of LN_2 cooling and gaseous nitrogen (N_2) cooled at -100°C on the tool wear in turning of Ti6Al4V with uncoated and coated carbide tools. Based on the tool wear observations, the best results concerning the tool life improvement were obtained during cooled N_2 turning.

Based on the researchers' works and some sanctions, sustainable machining have increased its importance in manufacturing industries, especially hard-to-cut materials. In addition, knowledge of the cutting forces has become important because power required to cut material, machinability of the materials, frictional forces on the material, optimum parameters on machining the material, cutting tool life etc. are closely related to the cutting forces. Therefore, in this paper, an experimental study was performed on face turning of Ti6Al4V alloy to measure the cutting and thrust forces under dry, MQL and cryogenic (LN_2) environments at three different cutting speeds.

EXPERIMENTAL WORKS

Face turning experiments were conducted on Ti6Al4V alloy under dry, MQL and cryogenic (LN_2) environments by using experimental set-up given in Figure 1. In the experiments, Ti6Al4V alloy having diameter of 76 mm was used as workpiece material and cutting length of 10 mm was orthogonally machined at constant spindle revolution. All experiments were performed with the uncoated carbide tools and a new cutting edge was used in each experiment to avoid the tool wear effect. The cutting parameters were chosen according to previous works in literature [5,8,10] and given in Table 1. As seen in Table 1, the experiments were performed under various lubricating/cooling conditions and three different cutting speeds to investigate their effects on the cutting and thrust forces.

Figure 1. Experimental set-up.

Table 1. Face turning parameters for Ti6Al4V alloy.

Exp. Nu.	Lubricating/Cooling Condition	Cutting Speed, V (m/min)	Undeformed chip thickness, a_p (mm)
1	Dry	50	
2	Dry	80	
3	Dry	110	
4	MQL	50	
5	MQL	80	0.1
6	MQL	110	
7	Cryogenic	50	
8	Cryogenic	80	
9	Cryogenic	110	

In MQL process, the cutting fluid was applied through a MQL system to the rake face at flow rate of 25 ml/h and air pressure of 0.4 MPa. In cryogenic cooling, the liquid nitrogen (LN_2 at -196°C) was applied to the tool rake face by a nozzle at a pressure of 0.4 MPa. The cutting and thrust forces were measured by a Kistler 9121 3-component tool dynamometer during the experiments.

RESULTS AND DISCUSSION

The experimental cutting and thrust forces in face turning of Ti6Al4V alloy under dry cutting, MQL and cryogenic cooling were given in Figures 2-4, respectively. In MQL method and cryogenic cooling, the oil mist and the LN_2 were applied to the rake face of the cutting insert. As seen in Figures 2-4, the cutting and thrust forces decreased with increase of the cutting speed in all cooling/lubricating conditions. For those reductions, there may be two factors. One of them could be due to thermal softening of work material. The other factor could be the effect of contact area between cutting tool and chip. As increasing the cutting speed, the contact areas could be shorter and the forces are reduced.

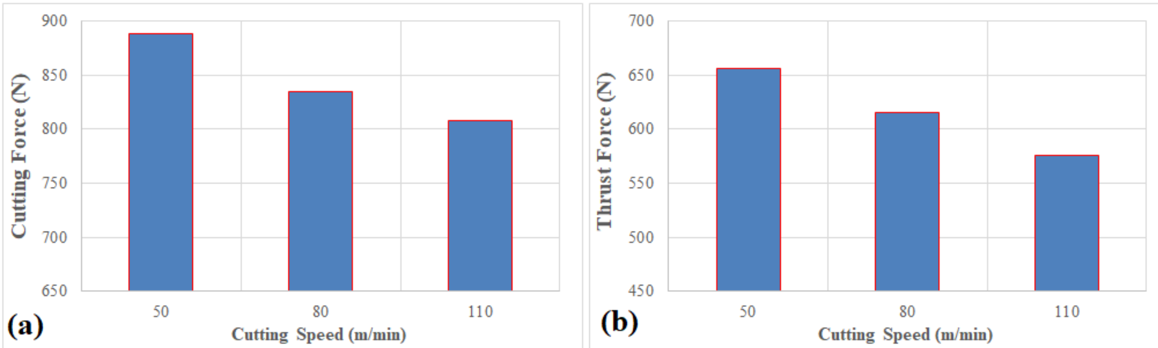

Figure 2. a) Cutting forces and b) thrust forces in dry face turning.

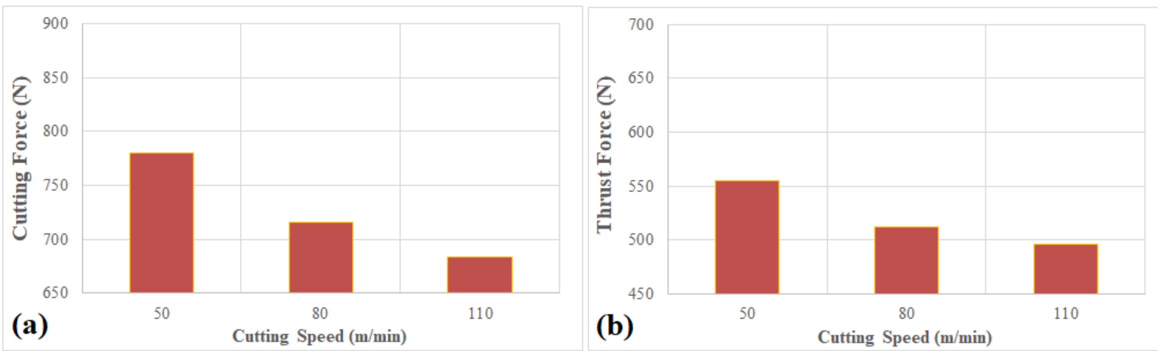

Figure 3. a) Cutting forces and b) thrust forces in MQL face turning.

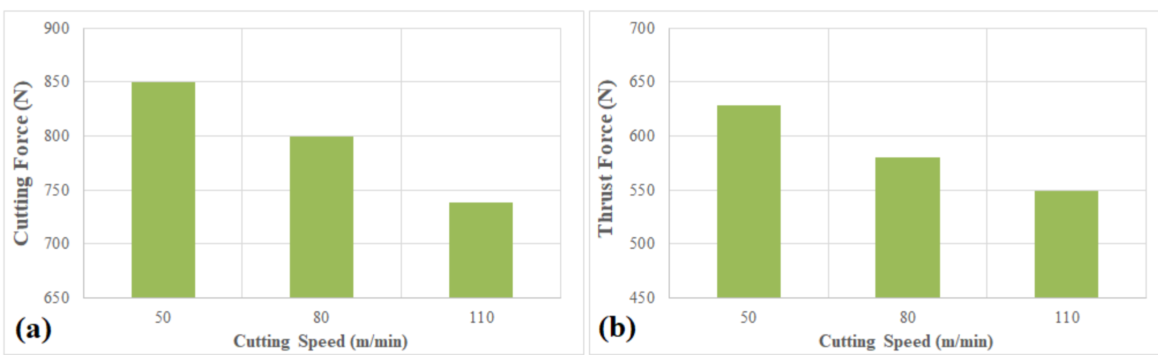

Figure 4. a) Cutting forces and b) thrust forces in cryogenic face turning.

When the cooling/lubricating conditions were compared each other, the minimum cutting and thrust forces were obtained under MQL condition due to the better lubrication effect provided by the MQL mist at the cutting zone as the maximum values for the both were measured under dry cutting (Figure 5). This may be attributed to the lower coefficient of friction at the tool-chip interface provided by the lubrication [1]. At the cutting speed of 80 m/min, the cutting force reduced 14.24% and 4.16% for MQL condition and cryogenic cutting, respectively as compared to dry cutting. In addition, at the same cutting speed, the thrust force decreased 16.73% and 5.78% for MQL condition and cryogenic cutting, respectively as compared to dry cutting. In cryogenic cooling, the cutting and thrust forces were measured higher than MQL method due to the fact that the effect of sub-zero temperature (around -196°C) on cutting force is the result of a reduction in friction but an increase in the hardness and the yield strength of the workpiece as specifying in the study of Sun et al. [11].

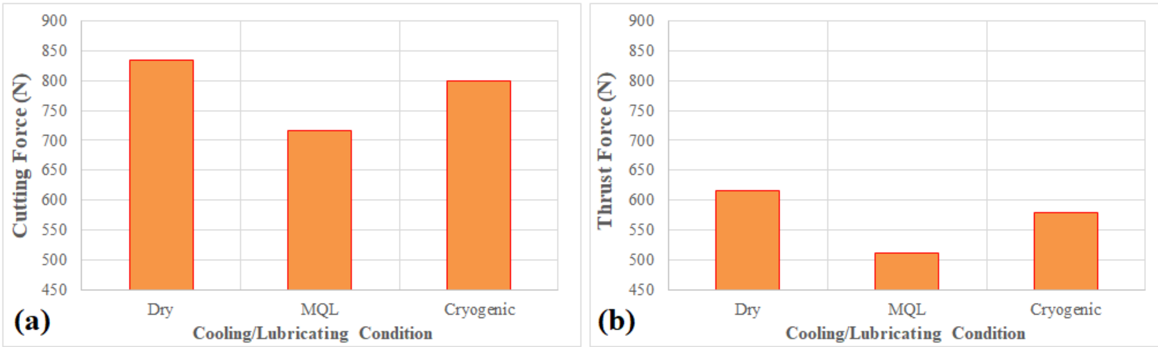

Figure 5. Comparison of cooling/lubricating conditions at the cutting speed of 80 m/min, a) cutting forces and b) thrust forces.

CONCLUSION

The sanctions and legislations have promoted the usage of sustainable alternatives in machining operations due to environmental effects and cost of the cutting fluids. For this reason, in this study, face turning experiments were performed on Ti6Al4V alloy to investigate the effects of cutting speed and cooling/lubricating condition on the cutting and thrust forces. Dry cutting, MQL method and cryogenic (LN_2) cooling were selected as sustainable environments. Based on the results, lower cutting and thrust forces were obtained as increasing the cutting speed for all cooling/lubricating conditions due to thermal softening of workpiece and shortening of cutting tool-chip contact area. In addition, MQL method caused the lowest cutting and thrust forces whereas the highest values were obtained under dry cutting. The cutting forces were measured higher in cryogenic machining than those in MQL turning due to increasing the hardness and yield strength of workpiece. From an environmental point of view, MQL cutting meet the increasing demands for cleaner manufacturing of Ti6Al4V, and may be an alternative of dry and flood cuttings.

REFERENCES

[1] Yuan S. M., Yan L. T., Liu W. D., Liu Q., Effects of cooling air temperature on cryogenic machining of Ti–6Al–4V alloy. *J Mater Process Tech* 2011;211:356-62.

[2] Machai C., Iqbal A., Biermann D., Upmeier T., Schumann S., On the effects of cutting speed and cooling methodologies in grooving operation of various tempers of β-titanium alloy. *J Mater Process Tech* 2013;213:1027-37.

[3] Sales W. F., Schoop J., Jawahir I. S., Tribological behavior of PCD tools during superfinishing turning of the Ti6Al4V alloy using cryogenic, hybrid and flood as lubri-coolant environments. *Tribol Int* 2017;114:109-20.

[4] Benjamin D. M., Sabarish V. N., Hariharan M. V., Raj D. S., On the benefits of sub-zero air supplemented minimum quantity lubrication systems: An experimental and mechanistic investigation on end milling of Ti-6-Al-4-V alloy. *Tribol Int* 2018;119:464-73.

[5] Umbrello D., Rotella G., Fatigue life of machined Ti6Al4V alloy under different cooling conditions. *CIRP Ann - Manuf Techn* 2018;67:99-102.

[6] Damir A., Shi B., Attia M. H., Flow characteristics of optimized hybrid cryogenic-minimum quantity lubrication cooling in machining of aerospace materials. *CIRP Ann - Manuf Techn* 2019;68:77-80.

[7] Gross D., Bigelmaier M., Meier T., Amon S., Ostrowicki N., Hanenkamp N., Investigation of the influence of lubricating oils on the turning of metallic materials with cryogenic minimum quantity lubrication. *Proc CIRP* 2019;80:95-100.

[8] Rubio E. M., Bericua A., de Agustina B., Marin M. M., Analysis of the surface roughness of titanium pieces obtained by turning using different cooling systems. *Proc CIRP* 2019;79:79-84.

[9] Shokrani A., Al-Samarrai I., Newman S. T., Hybrid cryogenic MQL for improving tool life in machining of Ti-6Al-4V titanium alloy. *J Manuf Process* 2019;43:229-43.

[10] Al-Ghamdi K. A., Iqbal A., Hussain G., Machinability comparison of AISI 4340 and Ti-6Al-4V under cryogenic and hybrid cooling environments: A knowledge engineering approach. *P I Mech Eng B - J Eng* 2015;229(12):2144-64.

[11] Sun S., Brandt M., Dargusch M. S., Machining Ti-6Al-4V alloy with cryogenic compressed air cooling. *Int J Mach Tool Manu* 2010;50(11):933-42.

[12] Bermingham M. J., Kirsch J., Sun S., Palanisamy S., Dargusch M. S., New observations on tool life, cutting forces and chip morphology in cryogenic machining Ti-6Al-4V. *Int J Mach Tool Manu* 2011;51(6):500-11.

[13] Dhananchezian M,, Kumar M, P., Cryogenic turning of the Ti-6Al-4V alloy with modified cutting tool inserts. Cryogenics 2011;51(1):34-40.

[14] Bermingham M. J., Palanisamy S., Kent D., Dargusch M. S., A comparison of cryogenic and high pressure emulsion cooling technologies on tool life and chip morphology in Ti-6Al-4V cutting. *J Mater Process Tech* 2012;212(4):752-65.

[15] Shokrani A., Dhokia V., Newman S. T., Comparative investigation on using cryogenic machining in CNC milling of Ti-6Al-4V titanium alloy. *Mach Sci Technol* 2016;20(3):475-94.

[16] Ayed Y., Germain G., Melsio A. P., Kowalewski P., Locufier D,. Impact of supply conditions of liquid nitrogen on tool wear and surface integrity when machining the Ti-6Al-4V titanium alloy. *Int J Adv Manuf Tech* 2017;93:1199-206.

[17] Mia M., Dhar N.R., Influence of single and dual cryogenic jets on machinability characteristics in turning of Ti-6Al-4V. *P I Mech Eng B - J Eng* 2019;233(3):711-26.

[18] Jamil M, Khan AM, Hegab H, Hong L, Mia M, Gupta MK, He N. Effects of hybrid Al_2O_3-CNT nanofluids and cryogenic cooling on machining of Ti-6Al-4V. *Int J Adv Manuf Tech* 2019;102:3895-909.

[19] Sartori S., Taccin M., Pavese G., Ghiotti G., Bruschi S., Wear mechanisms of uncoated and coated carbide tools when machining Ti6Al4V using LN_2 and cooled N_2. *Int J Adv Manuf Tech* 2018;95:1255-64.