Effect of metal cutting fluid (MCF) conditions on tool wear and thrust force in drilling Ti-6Al-4V using coated carbide tools

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Abstract. Titanium alloy (Ti-6Al-4V) is well known as difficult to cut material due to their low machinability rating. Machining Ti-6Al-4V generate high cutting temperature close to the cutting edge of the tool. The high cutting temperature, mostly during the deformation process and friction at the tool–chip and tool–workpiece interfaces. This circumstances will lead to the rapid tool wear. This study focuses on the growth of tool wear and development of the thrust force. Drilling tests were conducted using coated (TiAlN) carbide tool with diameter of 6 mm under two different condition of metal cutting fluid (MCF). The MCF used were minimum quantity lubrication (MQL) and minimum quantity cooling lubrication (MQCL). The outcomes of this study indicates MQL performed better coolant-lubricant effect during drilling Ti-6Al-4V as the results of thrust force development are consistent with the trends of tool wear growth.

1. Introduction
Ti-6Al-4V offer better strength than pure titanium and has been extensively used in aerospace industry due to their outstanding resistance to corrosion at high operating temperature. Also, their bio-compatibility, low elasticity and increased resistance to corrosion make this alloy desirable for bio-medical industry [1-3]. High cutting temperature were generated during machining Ti-6Al-4V close to the cutting edge of the tool. Low thermal conductivity of the material play a critical role toward the heat dissipation process, thus result to rapid tool wear and shorter tool life.

MCF are employed to reduce the friction or wear between tool-workpiece interfaces and carried away the heat generated in the cutting zone. MCF used also enhanced machining performance during drilling process. However, the application of MCF received a lot of question regarding to disposal, environmental and health issues, also lead to economical overhead [4-5]. As an alternative, MQL techniques and an extension of the MQL system, MQCL has been introduced to tackle issues associated with conventional flood cooling. Both technique used extremely low quantity of oil flow rates to reduce friction at the tool-chip and tool workpiece contacting regions. In addition, MQCL system used lubricant combined with compressed air to enhance the cooling action.

Other than environmental aspect, MQCL and MQL conditions improves machinability as well as prolong tool life, reduce cutting force, improves heat dissipation and surface roughness. MQCL condition has shown to be effective in reducing the temperatures and facilitate chip breaking. With the aid of cold air combine with MQL system, the condition lowered temperature rise during drilling process [6-7].

2. Experimental Details
A three axis CNC milling machine (Tong Tai EZ-5) were used to conduct drilling test under two MCF conditions as shown in Figure 1. Ti-6Al-4V size 94 x 70 x 14 mm was selected to perform the test. The plate was secure tightly on a special design jig to avoid chatter. Drilling tests were carried out using 6 mm diameter of coated (TiAlN) carbide tools with varying cutting speeds of 65, 75, 85 and 95 m/min. The feed rate were remain constant at 0.02 mm/rev. Table 1 shows the machining parameter in details.

Thrust force was measured using Kistler (Type 9129) dynamometer with charge amplifier. Xoptron stereomicroscope XST60 with IMT Mini 3 software was used to measure the growth of tool wear. The measurement of flank wear was made for every hole and stopped when any of the following criteria had reach.

i. Maximum flank wear, Vmax ≥ 0.2 mm
ii. Chipping ≥ 0.2
iii. Fracture or catastrophic failure

![Diagram of drilling setup with MQL and MQCL](image)

**Figure 1.** (a) Drilling with MQL; (b) Drilling with MQCL.

| Items                          | Descriptions                                      |
|-------------------------------|---------------------------------------------------|
| Machine Tools/Equipment       | 3-axis CNC Milling Machine (Tong Tai – EZ 5)      |
| Workpiece Material            | Titanium alloys (Ti-6Al-4V)                       |
| Cutting Tool                  | WC-Co (TiAlN coated)                              |
| Point Angle (PA) & Helix Angle (HA) | 140° & 30°                                    |
| Cutting speed (m/min)          | 65, 75, 85, 95 m/min                              |
| Feed rate (mm/rev)            | 0.02 mm/rev                                      |
| Tool diameter                 | 6 mm                                              |
| Type of Cutting               | Through hole (peck drilling)                      |
| MCF conditions                | i. MQL**                                          |
|                               | ii. MQCL**                                        |
|                               | ** Both method using Karanja oils as medium lubrication |

3. Results and Discussion

3.1. Tool Wear

The effect of MQL and MQCL on the tool wear at four employed cutting speed is shown in Figure 2 and Figure 3 respectively. Tool wear, $V_{min}$, was measured along the main cutting edge of the carbide tool after every drilled hole for both MQL and MQCL conditions. According to Asyraf [8], flank wear has direct influence on the machining cost and product quality. Once tool life has reach the criterion as stated earlier, the number of hole can be drilled at cutting speed of 65 m/min, 75 m/min, 85 m/min and 95 m/min under MQL condition are 9, 8, 7 and 4 holes while under MQCL are 10, 6, 5 and 4 holes respectively. The results show, cutting speed of 65 m/min achieved the highest number of holes compared to other cutting speed under both MQL and MQCL condition. The longest tool life is obtained under MQL at cutting speed 75 m/min, 85 m/min and 95 m/min as compared to MQCL. It can be said that MQL performed better than MQCL at cutting speed 75 m/min and above. The result was in line with Raza [9] on tool wear pattern when machining Ti-6Al-4V, MQCL gave better performance in term of tool wear at lower cutting speed.

Figure 4, shows typical tool failure mode of cutting tool for both MQL and MQCL condition. The result show cutting tool experienced maximum flank wear, chipping, fracture and catastrophic failure during drilling experiment. Chipping was common phenomenon during drilling at higher cutting speed due to the immediate loss of sharp cutting edge. Also, adhesion wear has been observed to be the dominant mechanisms for tool failure at all cutting speeds due to the ability of the Ti-6Al-4V to retain its strength at elevated temperature.
Figure 2. Maximum flank wear under MQL condition using coated (TiAlN) carbide drill

Figure 3. Maximum flank wear under MQCL condition using coated (TiAlN) carbide drill

| Cutting Speed | MQL | MQCL |
|---------------|-----|------|
| 65 m/min      | Hole 9 | Hole 10 |
| 75 m/min      | Hole 8 | Hole 6 (Fracture) |
| 85 m/min      | Hole 7 (Fracture) | Hole 5 (break) |
| 95 m/min      | Hole 4 | Hole 4 (break) |

Figure 4. Typical pattern of tool wear under various cutting speed and feed 0.02 mm/rev under MQL and MQCL condition using coated (TiAlN) carbide drill

3.2 Thrust force
Figure 5 shows the progression of thrust force against number of drilled hole for both conditions, MQL and MQCL. It can be seen that thrust force increase with the increase of number of hole. This situation is due to the effect of flank wear. Thrust force increase as the tool wear increase as reported by Lin [10] on tool wear monitoring
in drilling using force signals. The thrust force range from 100N to 450N. At first stage, under MQCL condition with cutting speed 95 m/min resulted lower thrust force of 104N compared to MQL condition 116N.

The result for thrust force versus cutting speed is shown in Figure 6. From the result, it indicates that cutting speed have significant effect on thrust force. The trend of thrust force is seen to be higher at lower cutting speed, and decrease as cutting speed increase. Thrust force increased as cutting speed decrease due to the difficulty to cut material, especially Ti-6Al-4V. According to Caliskan [11], at higher cutting speed, cutting temperature increase and soften the material, thus resulted to lower thrust force during machining process. Overall, during drilling process under MQCL condition, temperature increase due to high cutting speed. Higher temperature facilitate material to be cut, thus lower the thrust force. Under MQCL condition, cold air lowered the temperature during drilling process.

![Figure 5. The progression of thrust force for MQL and MQCL conditions under various cutting speeds using coated (TiAlN) carbide drill.](image)

![Figure 6. Thrust force comparison under MQL and MQCL conditions under various cutting speeds using coated (TiAlN) carbide drill.](image)

4. Conclusion

MCF conditions of MQL and MQCL were tested in drilling Ti-6AL-4V. The results of this study indicated MQL and MQCL have significant influence on tool wear as well as the development of thrust force. At higher cutting speed, 75m/min and above, MQCL provide longer tool life and tool wear compared to MQCL during drilling Ti-6AL-4V. As for thrust force, similar decreasing trend were display as cutting speed increase. The difference thrust force was observed for both condition. Lower thrust force was obtained under MQCL condition.

References

[1] Guo Y B, Li W and Jawahir I S 2009 Surface integrity characterization and prediction in machining of hardened and difficult-to-machine alloys: A state-of-art research review and analysis Machining Science and Technology 13 (4) 437–470.
[2] Zhu Z, Sui S, Sun J, Li J and Li Y 2017 Investigation on performance characteristics in drilling of Ti6Al4V alloy The International Journal of Advanced Manufacturing Technology 93 (1–4) 651–660.
[3] Sharif S, Abd E and Sasahar H 2012 Machinability of Titanium Alloys in Drilling Titanium Alloys-Towards Achieving Enhanced Properties for Diversified Applications (Croatia : InTech)
[4] Ginting Y R, Boswell B, Biswas W K and Islam M N 2016 Environmental Generation of Cold Air for Machining Procedia CIRP 40 648–652.
[5] Shokrani A, Dhokia V and Newman S T 2012 International Journal of Machine Tools & Manufacture Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids International Journal of Machine Tools and Manufacture 57 83–101.
[6] Maruda R W, Legutko S, Krolczyk G M and Raos P 2015 Influence of Cooling Conditions on the Machining Process under MQCL and MQL Conditions Tehnički vjesnik 22 (4) 965–970.
[7] Pervaiz S, Rashid A, Deib J and Niculescu C M 2016 An experimental investigation on effect of minimum quantity cooling lubrication (MQCL) in machining titanium alloy (Ti6Al4V) International Journal of Advanced Manufacturing Technology 87 (5–8) 1371–1386.
[8] Asyraf M, Ali M, Azmi A I, Nabil A, Khalil M and Leong K W 2017 Experimental study on minimal nanolubrication with surfactant in the turning of titanium alloys The International Journal of Advanced Manufacturing Technology 92 (1–4) 117–127.
[9] Raza S W, Pervaiz S and Deiab I 2014 Tool Wear Patterns When Turning of Titanium Alloy Using Sustainable Lubrication Strategies International Journal of Precision Engineering and Manufacturing 15 (9) 1979–1985.

[10] Lin S C and Ting C J 1995 Tool wear monitoring in drilling using force signals Wear 180 (1–2) 53–60.

[11] Caliskan H and Altas E 2015 The Effect of Cutting Conditions on Cutting Forces In Milling of Ti6Al4V Alloy International Journal of Engineering, Technology and Natural Sciences 1 (1) 13-22