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Cost evaluation on PVD coating during end milling of Inconel 71 under MQL condition

M.S. Kasim[1,3,*], C.H. Che Haron[2], J.A. Ghani[2], M.A. Hadi[2], M.A. Ali[1], R.Izamshah[1,3], M. Minhat[1], T.J.S. Anand[1], T. Ito[3]

[1)] Advance Manufacturing Center, Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.
[2)] Advanced Manufacturing Research Group, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.
[3)] Tokushima-UTeM Academic Centre, The University of Tokushima, Institute of Technology and Science, Minami-Josanjima 2-1, Tokushima-shi, Tokushima, 770-8506 Japan.

[*]Corresponding e-mail: shahir@utem.edu.my

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ABSTRACT – This paper aims to promote environmentally friendly manufacturing areas without sacrificing productivity, by the application of biodegradable minimum quantity lubricant (MQL) coolant in end-milling Inconel 718. This study is carried out by comparing a machining cost and method of lubrication applied in the end-milling process. High-speed cutting of Inconel 718 was performed, according to response surface methodology (RSM). Later, the optimum condition of the PVD TiAlN/AlCrN coated carbide tool consumption and minimum quantity lubrication (MQL) are evaluated, based on the tool performance; i.e. machining time and material removed. In addition, the number of cutting tool edges is taken into consideration in the machining cost calculation. Machining performance at maximum tool life, minimum surface roughness and force are compared with the optimum condition, and the results show that the application of MQL and using ball-nose end mill under optimum condition is competitive. Since this type of tool has a high index number which reduces the number of cutting tools required drastically. The multi-objective optimization of cutting parameters, with regard to the criteria of the maximum material removed (9.029 cm^3) and the lowest total cost (\$11/100 cm^3), gives the combination parameter that meets the requirement for green manufacturing; i.e. by reducing the usage of cutting tools and the amount of lubrication consumption.

1. INTRODUCTION

Nowadays, many manufacturers are implementing Minimum Quantity Lubrication (MQL) with biodegradable lubricant as a move toward green manufacturing. MQL is one of the cooling and lubricating strategies during material removing process. MQL differs from traditional metalworking coolant by applying small amounts of high-quality mist-form lubricant directly onto the cutting tool-workpiece interface [1]. Chalmers [2] outlined pertain to health and environment issues. More than 100 million gallons of coolant are used in the US every year, with 1.2 million employees exposed to health risk. The long term exposure to metalworking fluid may contribute to bad health effects and other safety issues, including toxicity, respiratory problem, dermatitis and cancer. With respect to occupational safety, MQL offers numerous advantages over water-mixed metalworking fluids, such as better compatibility concerning skin care. In addition, the implementation of minimum quantity lubrication savings significantly cutting fluid and other related handling costs.

The necessity for machines to apply less risky cutting fluids has encouraged many researchers to investigate the use of MQL in many applications, such as machining performances and parameter optimization in drilling, turning, milling and grinding. However, little attention is placed on the economic cost analyses of adopting the MQL technique. This work presents the cost evaluation associated with the machining time and removed material, using biodegradable MQL coolant in the end milling of Inconel 718.

2. EXPERIMENT SETUP

The work piece material used was a rectangular block of Inconel 718 that had been age-hardened (42±2 HRC). The chemical composition of the work piece material confirms the following attribute (wt.%): 0.49 Al; 0.004 B; 0.051 C; 5.0Cb; 18.30 Cr; 0.04 Cu; 0.23 Mn; 3.05 Mo; 53.0 Ni; < 0.005 P; < 0.002 S; 0.08 Si; 1.05 Ti and balance Fe. Figure 1 shows the assembly of the cutting tool and tool holder used in the experiment. The insert was a 16 mm-diameter ball-nose end mill with the following features: WC-10% Co with PVD coating of multilayer TiAlN/AlCrN; relief angle 11°; radial rake angle 0°; axial rake angle -3°. All the milling experiments were conducted on the DMC 635 V Eco CNC milling machine. The cutting parameters were set as the finishing process, as shown in Table 1. The tests were stopped when uniform tool wear (VB_1) reached 0.3 mm or localized flank wear reached 0.5 mm (VB_3), in accordance with ISO 8688-2 (1989).

As shown in Figure 2, the MQL nozzles were positioned so that the mist could be jetted out to the rake and flank face of the cutting tool. The distance between the nozzle and the tool was 30 mm. The flowrate of MQL was set at 50 ml/hr. The medium of lubrication was biodegradable Coolube® 2210EP, an advanced metal-cutting lubricant based on a composition of natural esters, which are formulated from renewable plant-based oils [1].

Figure 1 Assembly of ball-nose end mill and tool holder.

Figure 2 MQL experiment setup.

Response surface methodology was used to design experiments, model and optimize three response variables; namely, tool life, t_l, surface roughness, Ra, and resultant force, Fr. Each independent variable was coded at three levels between -1 and +1 in the matrix. The variables investigated were cutting speed, feed rate, axial depth of cut and width of cut, and varied in the range, as shown in Table 1.

Table 1 Cutting condition.

Cutting speed, Vc	100–140 m/min
Feed rate, fz	0.1–0.2 mm/tooth
Axial depth of cut (DOC), ap	0.5–1.0 mm
Width of cut (WOC), ae	0.2–1.8 mm
Run out	10 µm (radial) and 5 µm (axial)
Overhang length	30 mm
Cutting configuration	Down milling
Lubricant	MQL with flow rate of 50 ml/h

3. EXPERIMENTAL RESULTS AND DISCUSSION

The effect of machining parameter on t_l, Ra, and Fr were recorded under MQL conditions. Test no. 1 (Vc 100 m/min, fz 0.15 mm/tooth, ap 0.75, ae 0.2 mm) was found to have the longest tool life among the other cutting parameters, while the lowest Ra can be obtained by a combination of test no. 22 (Vc 140 m/min, fz 0.15 mm/tooth, ap 1 mm, ae 1 mm) and test no. 6 (Vc 120 m/min, fz 0.15 mm/tooth, ap 0.5 mm, ae 0.2 mm), which gives the lowest resultant force generated during machining.

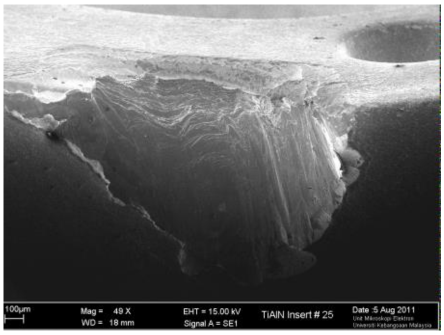

Figure 3 SEM image of notch wear of TiAlN/AlCrN cutting tool under MQL cutting condition.

Table 2 shows the cost comparison with various experiment result conditions. The maximum tool life, min surface roughness and minimum force do not guarantee cost effective. The optimum cutting parameter offers cost effective with the total cost incurred $11.03 per 100 cm^3.

Table 2 Comparison of estimation machining cost for removal of every 100 cm^3 of Inconel 718.

Result condition	**Cutting tool cost ($)**	**Lubrication cost ($)**	**Total cost ($)**
Max tool life	10.48	8.7	19.22
Min surface roughness	39.59	1.0	40.58
Min cutting force	22.10	10.1	32.21
Optimum cutting parameter	7.38	3.7	11.03

* Not include tool holder and initial cost.

4. CONCLUSION

Multi objective optimization of maximum tool life, minimum surface roughness and low cutting force offers better total machining cost than single objective.

5. REFERENCES

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