Journal of Emerging Technologies and Industrial Applications
Vol. 3 No. 2 (2024) pp. 1-5
e-ISSN: 2948-507X
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Journal homepage: https://jetia.mbot.org.my/index.php/jetia/index

Flank wear and cutting temperature in half-immersion up-milling of 6061 Aluminium Alloy

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Abstract: Research findings indicate that flank wear is closely related to cutting temperature, but the relationship of varying cutting distance on flank wear and cutting temperature is rarely defined, as well as determining the ideal cutting distance. Dry machining provides rhythm as the manufacturing industry profits from cutting fluid drawback. However, with the absence of this fluid, it will lead to catastrophic flank wear and cutting temperature especially on long cutting distance. This manuscript presents the comparative assessment of flank wear and cutting temperature under dry and wet condition, when varying the cutting distance in half-immersion up-milling of 6061 Aluminium Alloy. The results show that flank wear and cutting temperature are directly proportional to cutting distance under both conditions. Dry condition is the ideal approach as compared to wet condition when half-immersion up-milling is performed at cutting distance up to 270 mm, while wet condition is the ideal approach as compared to dry condition when the cutting distance is beyond 270 mm.

Received 10 June 2024; Accepted 18 September 2024; Available online 28 December 2024

Keywords: Flank wear, cutting temperature, half-immersion up-milling, 6061 Aluminium Alloy, cutting distance

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1. Introduction

Metal cutting process is generally viewed as the core in the manufacturing sector [1]. Milling process, especially end-milling process, always plays a major role among various metal cutting processes in the aircraft and automotive sector [1, 2] due to its versatility in manufacturing a product with complex profile from various types of materials [2]. 6061 Aluminium Alloy is one of the 6XXX series of Aluminium Alloys and it possesses excellent corrosion resistance and high strength [3]. This is why this type of Aluminium Alloy is widely used in various sectors, mainly aircraft and automotive [4]. Based on the research conducted by Mohd Nor et al. [5], dry end-milling of 6061 Aluminium Alloy is practical to be performed in various sectors, because there is a positive result to cutting temperature, surface hardness, and surface roughness. Furthermore, the exclusion of cutting fluids in end-milling of 6061 Aluminium Alloy is an ideal technique, as the usage of this fluid is hazardous to human health [6] and uneconomical due to its disposal costs, which double the cutting fluid price itself [6]. However, it may accelerate the wear rate of the cutting tool.

Cutting tool wear is often associated with the cutting tool life [2]. Basically, cutting tool wear can be described as a gradual loss of cutting tool material at the cutting tool and machined material interface [7]. Moreover, dry machining has negative impact on cutting tool life [6]. As mentioned by Özbek and Saruhan [6], this impact is due to the hardness of the cutting tool decrease when the cutting temperature at the cutting zone increases during chip removal, as there is no cooling agent. Besides, catastrophic heat phenomenon occurs when machining is performed with the absence of cutting fluid because heat will accumulate at the cutting tool and machined material interface, subsequently causing a rapid cutting tool wear [8]. As cutting tool wear is closely related to cutting tool life, increase in cutting tool wear rate indirectly increases the number of fresh cutting tool usage, and subsequently increase the manufacturing cost [2, 9]. In addition, low carbon manufacturing has garnered attention due to growing concerns on global warming issues resulted from the high carbon emissions. As stated by Tian et al. [10], manufacturing sectors contribute 36 % of carbon emissions. Meanwhile, the percentage can increase up to 44 % when a cutting tool with wear condition is used during production [10]. From this percentage, it is clearly shown that research in cutting tool wear is crucial as its contribution in carbon emissions is almost at 10 %. This is due to worn cutting tool can cause high cutting force thus resulting in high machine tool power consumption.

Cutting tool wear can be divided into several types such as flank wear, chemical wear, fatigue wear, diffusion wear and adhesion wear [7]. In flank wear, it occurs due to the friction between the machined material and the cutting tool [2]. According to Cui et al. [11], when this type of cutting tool wear occurs, the heat generated by friction between machined material surface and cutting tool flank face is the main cause for the rise of cutting temperature. Meanwhile, cutting distance is very important element in end-milling as it is closely related to the dimension of the material to be end-milled, also it plays a major role on flank wear [12] and cutting temperature [11] generated. However, the relationship of varying cutting distance on flank wear and cutting temperature simultaneously is rarely defined, as well as determining the ideal cutting distance. Apart from this, this research aims to compare flank wear and cutting temperature under dry and wet condition, when varying the cutting distance in half-immersion up-milling of 6061 Aluminium Alloy. Therefore, the behaviour of flank wear and cutting temperature under both conditions with increment in cutting distance are systematically analysed. The ideal approach in terms of ideal cutting distance under both conditions is also determined in this manuscript.

2. Experimental Procedure

Table 1 shows the cutting conditions used in this experimental test. It was setup based on the optimum cutting conditions for half-immersion dry up-milling of 6061 Aluminium Alloy leading to the minimum cutting temperature and surface roughness and maximum surface hardness as suggested by Mohd Nor et al. [5]. Therefore, this experimental test is intended to compare the flank wear and cutting temperature under dry and wet condition, when varying the cutting distance in half-immersion up-milling of 6061 Aluminium Alloy, as well as determining the ideal cutting distance based on the optimum cutting conditions proposed by Mohd Nor et al. [5].

Table 1 - Cutting conditions used in experimental test

Cutting condition	Value
Cutting speed (m/min)	68
Feed rate (mm/min)	100
Axial depth of cut (mm)	1
Radial depth of cut (mm)	3

In this experimental test, half-immersion up-milling on 6061 Aluminium Alloy was performed using the Lagun FTV-2F vertical knee mill. The machined material used in this research was untreated 6061 Aluminium Alloy with dimension of 630 × 106 × 45 mm and with original hardness of 104 HV. Half-immersion up-milling was performed under both conditions using Sutton Tools carbide end-mill with 6 mm diameter and 2 flutes. Additionally, the wet condition was performed using HOCUT 5759 AL-S cutting fluid with a flow rate of 2.7 l/min.

The total cutting distance was 630 mm, while the cutting distance increment was 90 mm, thus there were seven intervals. At each interval, flank wear and cutting temperature were recorded using the AM4115ZTL Dino-lite edge microscope and FLIR E50 thermal imaging camera, respectively. The range of magnification and working distance for AM4115ZTL Dino-lite edge microscope are 10 to 140× and up to 23 cm, respectively. Meanwhile, the temperature measurement range and detector resolution for FLIR E50 thermal imaging camera are -20 to +650 ^{o}C and 240 × 180 pixel. Fig. 1 shows the instruments used in flank wear measurement and cutting temperature measurement as well as the selected recorded data. In addition, the cutting temperature was measured 1 m from the cutting zone and the ambient temperature was approximately 30.5 ^{o}C, where each of the recorded cutting temperature included the ambient temperature.

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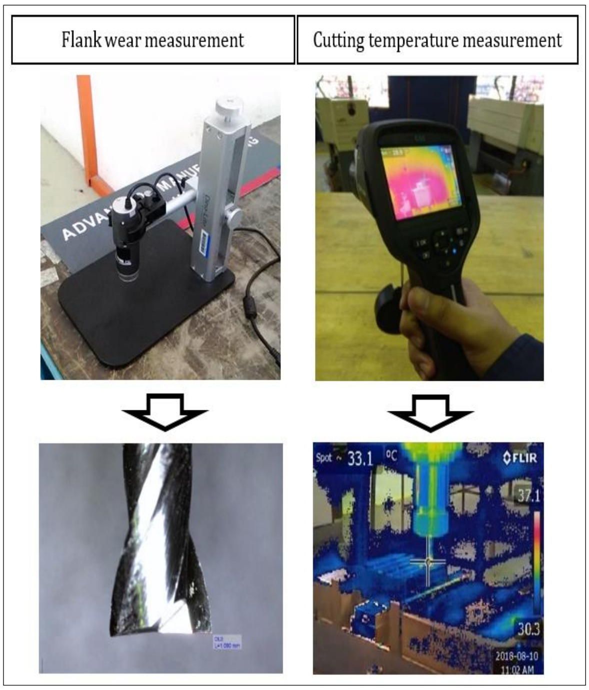
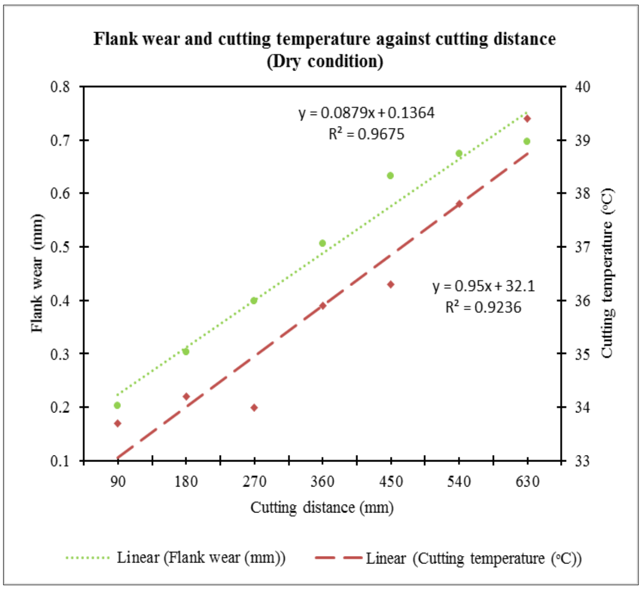


Fig. 1 - Instruments used in experimental test

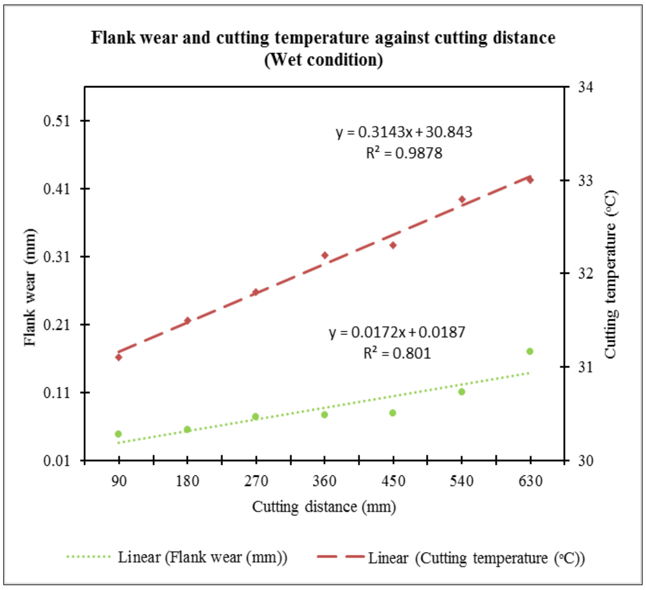
Apart from this, the values of flank wear and cutting temperature under both conditions were plotted in X-Y plot in Microsoft Excel software. The analysis was carried out by determining the behaviour of flank wear and cutting temperature under both conditions based on the obtained trend-line and R^2 value. Minitab software was used to perform desirability function analysis (DFA), then line plot was used to compare the DFA results of dry and wet condition for determining the ideal cutting distance under both conditions.

3. Results and Discussion

X-Y plot in Fig. 2 illustrates flank wear and cutting temperature against cutting distance under dry and wet condition. It can be seen clearly that both trend-lines for both conditions had a similar trend. This proves that flank wear is closely related to cutting temperature, where an increase in cutting temperature will cause an increase in the flank wear, while an increase in the flank wear will also increase cutting temperature [13]. Further, all the trend-lines had R^2 value greater than 0.8 and very close to 1, which indicates a better representation of the relation between flank wear and cutting distance as well as cutting temperature and cutting distance [14]. It shows that cutting distance is closely related to flank wear and cutting temperature. This phenomenon can be related with the findings mentioned by Zhang et al. [12] and Cui et al. [11], where the flank wear [12] and cutting temperature [11] are greatly influenced by cutting distance. In addition, the equations and the R^2 values were obtained by extracting from Microsoft Excel software.



(a)



(b)

Fig. 2 - Flank wear and cutting temperature against cutting distance; (a) dry condition and (b) wet condition

From this X-Y plot, it also shows that the behaviour of flank wear and cutting temperature under both conditions with increment in cutting distance was of linear behaviour. When increasing the cutting distance during half-immersion up-milling of 6061 Aluminium Alloy under both conditions, the behaviour of both flank wear and cutting temperature increased simultaneously. This phenomenon can be associated with the flank wear increasing in line with the increase in cutting distance [15]. Apart from this, as both flank wear and cutting temperature have a direct relationship, thus increase in cutting distance will also increase cutting temperature. From this findings, it can be deduced that flank wear and cutting temperature increased with the increase in cutting distance. By comparing the slope of flank wear and cutting temperature between dry and wet condition, dry condition produced a higher steepness than wet condition. This is believed to be due to the heat concentrating and accumulating at the cutting zone, leading to cutting temperature rise, as there is no cutting fluid to cool down the cutting temperature [8]. Besides, rapid flank wear occurs at high cutting temperature [1].

Based on the DFA results in Fig. 3, the optimisation plot shows that cutting distance 90 mm was the optimum cutting distance leading to minimisation of flank wear and cutting temperature under both conditions. This is because the value of composite desirability or D value for the cutting distance 90 mm under both conditions was 1.0000. In addition, the value of individual desirability or d value for flank wear and cutting temperature at cutting distance 90 mm under both conditions was also 1.0000. However, this optimum cutting distance is impractical to be performed due to low cutting distance will increase cutting tool changing time and cutting tool cost per fresh cutting tool.

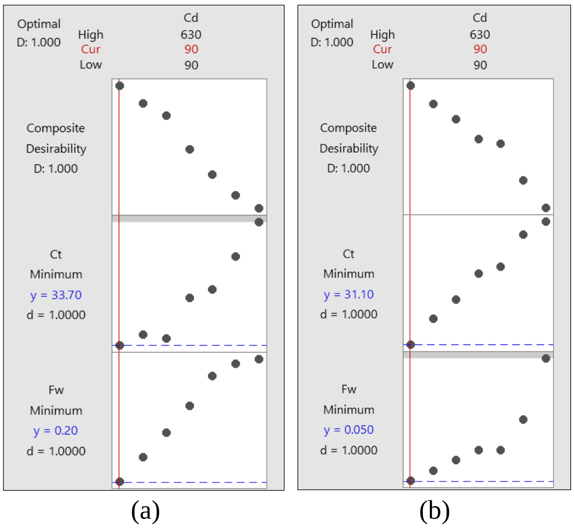


Fig. 3 - Optimisation plot; (a) dry condition and (b) wet condition

Apart from this, Table 2 shows the overall D and d values after being extracted from optimisation plot. From this table, it can be noticed that the D values under both conditions decreased when the cutting distance increased. Therefore, it can be said that increasing cutting distance is undesirable for flank wear and cutting temperature.

Table 2 - Overall composite desirability with individual desirability; (a) dry condition and (b) wet condition

(a)

Dry condition			
Cutting distance (mm)	Individual desirability, d		Composite desirability, D
	Flank wear	Cutting temperature	
90	1.0000	1.0000	1.0000
180	0.8000	0.9123	0.8543
270	0.6000	0.9474	0.7539
360	0.3800	0.6140	0.4830
450	0.1400	0.5439	0.2759
540	0.0400	0.2807	0.1060
630	0.0000	0.0000	0.0000

(b)

Wet condition			
Cutting distance (mm)	Individual desirability, d		Composite desirability, D
	Flank wear	Cutting temperature	
90	1.0000	1.0000	1.0000
180	0.9167	0.7895	0.8507
270	0.8333	0.6316	0.7255
360	0.7500	0.4210	0.5620
450	0.7500	0.3684	0.5257
540	0.5000	0.1053	0.2294
630	0.0000	0.0000	0.0000

In terms of DFA results comparison between dry and wet condition, D values as tabulated in Table 2 was plotted into line plot as depicted in Fig. 4.

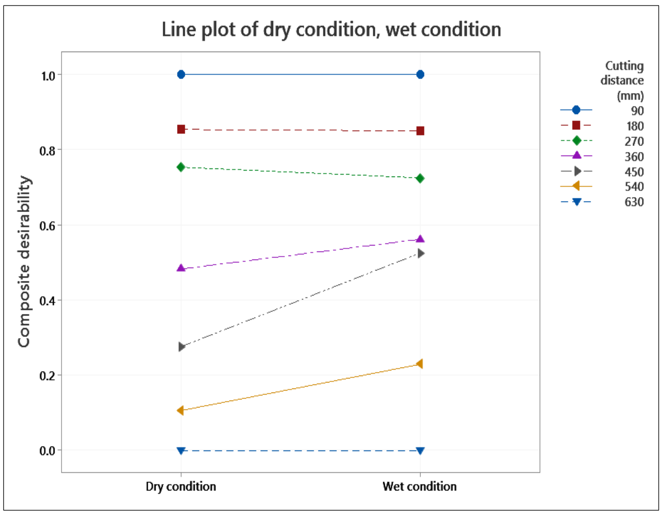


Fig. 4 - Line plot of dry condition, wet condition

Without comparing the D value at cutting distance 90 and 630 mm as both cutting distance has the same value under both conditions, it can be proposed that performing half-immersion up-milling under dry condition at cutting distance up to 270 mm is the ideal approach as compared to under wet condition. Whereas, performing half-immersion up-milling under wet condition at cutting distance beyond 270 mm is the ideal approach as compared to under dry condition. By neglecting cutting fluid cost, this analysis shows that wet condition is more worthy in terms of cutting tool changing time and cutting tool cost as compared to dry condition, when the size of large-scale aircraft and automotive components are being brought into half-immersion up-milling of 6061 Aluminium Alloy. Nevertheless, dry condition is the great choice due to its positive impact to human health as well as environment when dealing with the size of small-scale aircraft and automotive components.

4. Conclusion

Flank wear and cutting temperature under dry and wet condition, when varying the cutting distance in half-immersion up-milling of 6061 Aluminium Alloy were compared and analysed. The findings showed that cutting distance is closely related to flank wear and cutting temperature, as the R^2 values for both conditions are very close to 1. Under both conditions, increase in cutting distance indirectly increases flank wear and cutting temperature. Further, dry condition is the ideal approach as compared to wet condition when half-immersion up-milling is performed at cutting distance up to 270 mm, while wet condition is the ideal approach as compared to dry condition when the cutting distance is beyond 270 mm. Future research should be carried out to elucidate surface integrity of the 6061 Aluminium Alloy based on these research findings.

Acknowledgement

The authors would like to acknowledge technical support from the Malaysia Board of Technologists as well as Mr. Nor Iman Ziqri bin Nor Aznan, Mr. Mohd Nor bin Puteh and Mdm. Hatijah binti Kassim for encouragement.

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