Journal of Mechanical Engineering *Vol 16(3), 17-27, 2019*

Effect and Optimization of Cutting Speed and Depth of Cut in Half-immersion Up-milling of 6061 Aluminium Alloy

Nor Aznan Mohd Nor, Syibli Syaddad Mohd Alisjabana, Ghirran Seloraji, Tee Yean Men, Teh Jun Xian, Baharudin, B.T.H.T., Arifin, M.K.M. and Leman, Z*
Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Malaysia.
**Email: noraznan.namn@gmail.com*

ABSTRACT

Cutting fluids are instrumental as manufacturing sectors achieved a variety of aims. As human rights and environmental protection have become a matter of global concern, end milling under dry conditions is becoming an important approach. However, cutting speed and depth of cut have different correlations on cutting temperature and surface roughness. Thus, end milling without using cutting fluids will result in catastrophes to cutting temperature, surface hardness, and surface roughness when cutting speed and depth of cut changes are not considered precisely. Consequently, optimising these two factors during end milling under dry conditions is an important aspect for manufacturing sectors. In this manuscript, 3^2 factorial experimental design were applied, whereas the significance of cutting speed and depth of cut, as well as their optimal combinations was analysed by analysis of variance (ANOVA) and desirability function analysis (DFA). The results indicated that cutting speed is the most significant factor on surface roughness, whereas depth of cut is the most dominant factor affecting cutting temperature and surface hardness. Furthermore, optimal combinations that minimise cutting temperature and surface roughness, and maximise surface hardness are obtained at the highest cutting speed and the lowest depth of cut.

Keywords: *Cutting speed, depth of cut, cutting temperature, surface hardness, surface roughness*

ISSN 1823- 5514, eISSN 2550-164X
Received for review: 2018-03-11
Accepted for publication: 2019-10-15
Published: 2019-12-31

Introduction

The use of cutting fluids is generally viewed as a required addition for a variety of reasons, such as decreasing friction between cutting tool and machined materials [1], flushing away chips from the cutting zone [2, 3], reducing cutting temperature [1, 4, 5], improving surface quality [1, 3, 5, 6], and extending tool life [1]-[3]. Despite the fact that cutting fluids have contributed remarkable influence in manufacturing sectors, this liquid can cause extensive burden to the environment due to the rise of natural resource consumption in cutting fluid productions and the disposal of waste cutting fluids [1, 2, 5, 6]. Another prominent drawback of cutting fluids is health hazards because it can be harmful to machinists' lungs and can cause skin irritation following prolonged or frequent contact [1, 2, 4, 6, 7]. Furthermore, it contributes significantly to additional cost following the purchase of cutting fluids and has indirectly increased manufacturing costs [1, 3, 4].

End milling under dry conditions is an option to preserve natural resources and human well-being while performing metal cutting process, as well as reducing manufacturing costs [2, 7], but it is not an ultimate solution. Research has recently indicated that surface roughness increases with increasing feed rate [8]-[10] and depth of cut [11], whereas the increase in cutting speed reduces surface roughness [10, 12, 13]. On the other hand, increasing feed rate [14]-[16], depth of cut [12, 14, 16], and cutting speed [15]-[19] increases cutting temperature, which further affects surface hardness. It can be said that there is a different correlation between cutting speed and depth of cut on cutting temperature and surface roughness. Consequently, end milling without using cutting fluids will result in catastrophes to cutting temperature, surface hardness, and surface roughness when changes in cutting speed and depth of cut are not considered precisely. On the other hand, surface hardness changes will reduce surface hardening treatment costs as altering surface properties may become unnecessary. Therefore, optimising cutting speed and depth of cut during end milling under dry conditions is an important aspect for manufacturing sectors.

The aim of this research is to identify the effect of cutting speed and depth of cut on cutting temperature, surface hardness, and surface roughness during half-immersion up-milling of 6061 aluminium alloy under dry conditions, and also their optimal combinations of both factors leading to minimum cutting temperature and surface roughness, and also maximum surface hardness using design of experiment and incorporating ANOVA and DFA. Furthermore, up-milling or conventional milling is focused in this research because many small machine shops use conventional machines as the capital for advanced machine tools is not available. Besides, 6061 aluminium alloy is extensively used in manufacturing sectors [20]-[23].

Experimental Setup

Experimental works in this research were conducted on 150 mm × 106 mm × 45 mm of 6061 aluminium alloy with original hardness of 104 HV using Lagun FTV-2F vertical knee mill. E100 high speed steel (HSS) with end-mill diameter of 6 mm and two flutes from Sutton Tools was employed to perform half-immersion up-milling under dry conditions.

The 3^2 factorial experimental design was setup based on recommended parameters by the cutting tool manufacturer. As depicted in Table 1, the selected cutting speed and depth of cut values are 56.5487 m/min, 62.2035 m/min, and 67.8584 m/min, and 1 mm, 2 mm, and 3 mm, respectively. Furthermore, the feed rates were kept constant at low values and equal to 100 mm/min.

Table 1: Variable parameters used in experiment

Cutting speed (m/min)	: 56.5487, 62.2035, 67.8584
Depth of cut (mm)	: 1, 2, 3
Feed rate (mm/min)	: 100

The cutting temperature was measured in degree Celsius (°C) by Flir E50 compact thermal imaging camera. Surface hardness and surface roughness of 6061 aluminium alloy were measured in Vickers hardness (HV) and Ra by Wolpert UH930 universal hardness tester and Mahr Perthometer S2. Furthermore, changes in cutting temperature, surface hardness, and surface roughness were analysed by response surface plots. The effect and optimal combinations of cutting speed and depth of cut were determined by ANOVA and DFA. In addition, the optimisation of cutting conditions was aimed towards minimising cutting temperature and surface roughness, as well as maximising surface hardness. Finally, the maximum mean of composite desirability (D) gives the optimal combinations.

Results and Discussions

Figure 1 to Figure 3 illustrate the response surface plots of cutting temperature, surface hardness, and surface roughness for various cutting speed and depth of cut, and the feed rate was fixed during half-immersion up-milling of 6061 aluminium alloy under dry conditions. Figure 1 obviously shows that increasing cutting speed [15]-[19] and depth of cut [12, 14, 16] increases cutting temperature. Meanwhile, decreasing cutting speed and depth of cut decreases cutting temperature. Furthermore, Figure 2 shows that the highest values of surface hardness for half-immersion up-milling of 6061 aluminium alloy are on the middle right side of the plot, which corresponds to high cutting speed and medium depth of cut. Meanwhile, the lowest values of surface hardness are on the bottom left side of the plot, which corresponds to the low values of both factors. Referring to Figure 3, it is observed that during half-immersion up-milling, higher cutting speed [10, 12, 13] and lower depth of cut [11] produce the lowest surface roughness. Meanwhile, medium values of both factors lead to greater surface roughness values.

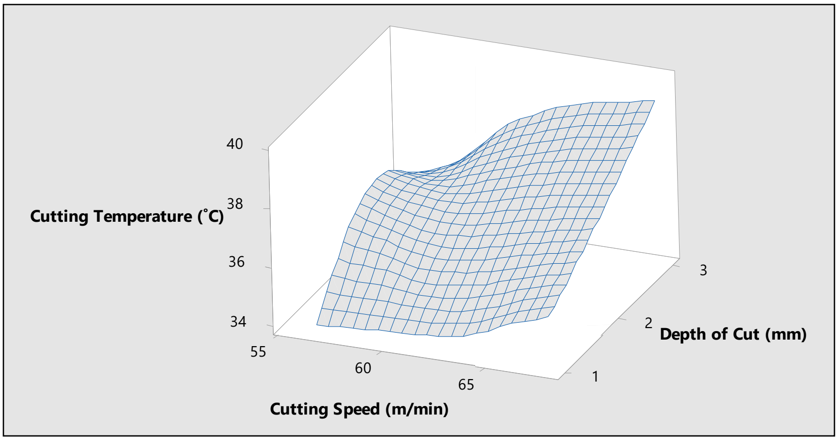

Figure 1: Effect of cutting speed and depth of cut on cutting temperature

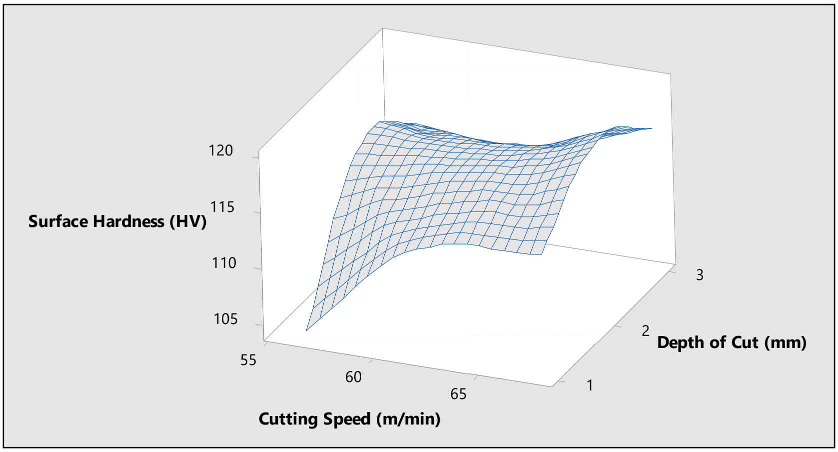

Figure 2: Effect of cutting speed and depth of cut on surface hardness

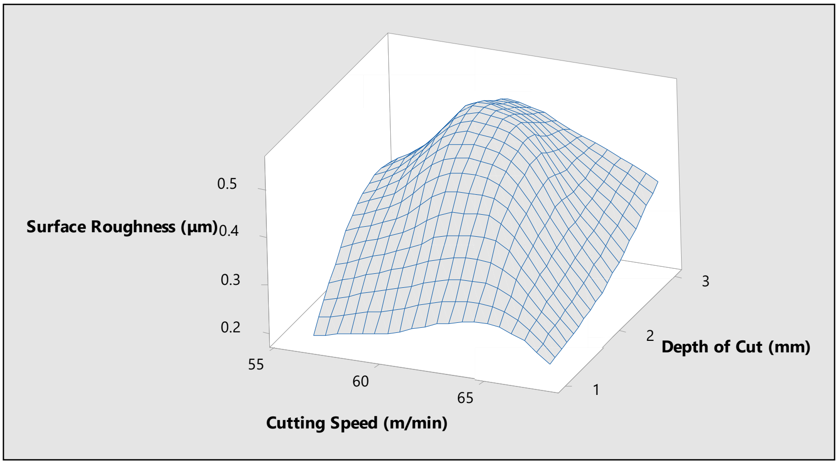

Figure 3: Effect of cutting speed and depth of cut on surface roughness

The main effect plots for cutting temperature, surface hardness, and surface roughness are presented in Figure 4 to Figure 6. From Figure 4 and Figure 5, the line slopes indicating the magnitude of depth of cut are greater than cutting speed. It can be said that depth of cut is the most significant factor affecting cutting temperature and surface hardness. Conversely, Figure 6 clearly shows the significance of increasing cutting speed on surface roughness [8, 24, 25] and this is in line with the study conducted by Airao et al. [9] such that as cutting speed increased, the value of surface roughness first increased and then decreased, but depth of cut has less significant effect [8, 24, 25]. This is because the surface roughness means increased slightly after further increase in the values of depth of cut.

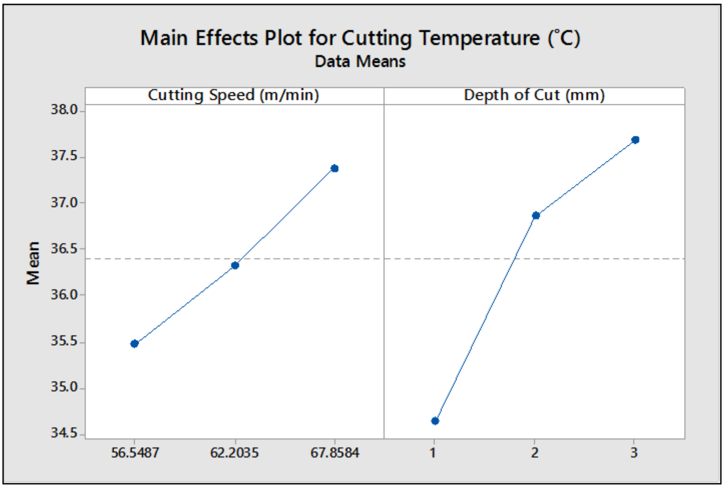

Figure 4: Main effects plot for cutting temperature

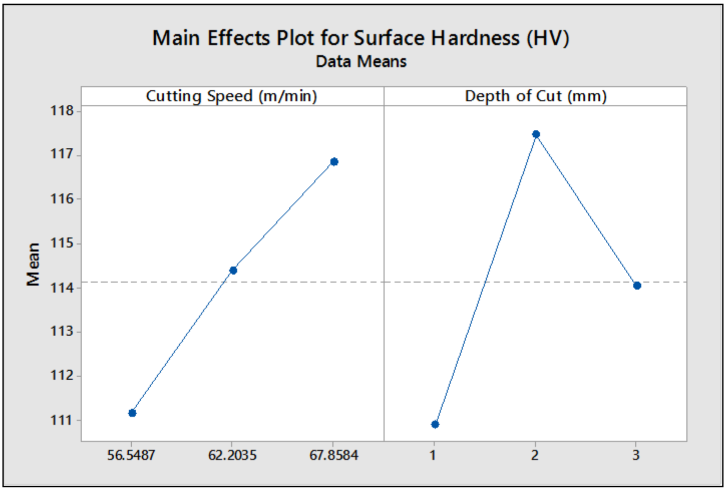

Figure 5: Main effects plot for surface hardness

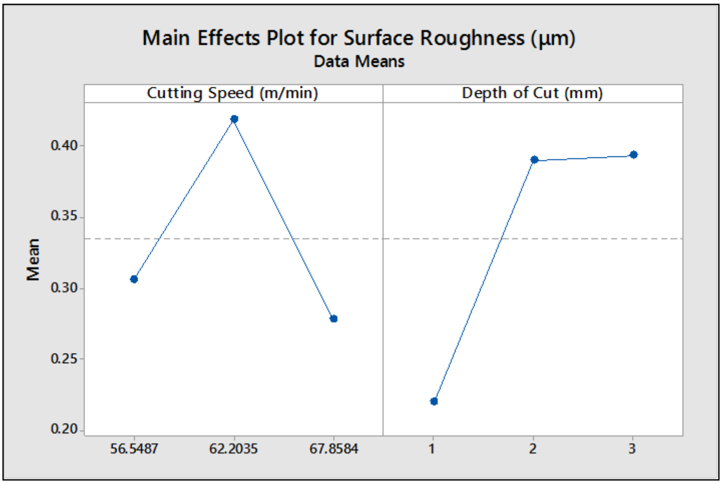

Figure 6: Main effects plot for surface roughness.

As depicted in Figure 7, the optimisation plot shows the maximum D value of 0.74880, which indicates that the predicted response for cutting temperature, surface hardness, and surface roughness is about 75%. Furthermore, optimum cutting conditions that minimise cutting temperature and surface roughness, and maximise surface hardness during half-immersion up-milling of 6061 aluminium alloy under dry conditions are obtained at cutting speed of 67.8584 m/min and depth of cut of 1 mm, which is at the highest cutting speed and the lowest depth of cut. Moreover, the individual desirability values for cutting temperature, surface hardness, and surface roughness are 0.69915, 0.60063, and 1.00000, respectively, in composite desirability. Lastly, the predicted responses for cutting temperature, surface hardness, and surface roughness are 35.6244 °C, 113.6156 HV, and 0.1642 µm, respectively. Meanwhile, the experimental results obtained for cutting temperature, surface hardness, and surface roughness are 35.5600 °C, 114.7200 HV, and 0.2120 µm, respectively. It is found that the percentage difference between the predicted responses and the experimental results are 0.1% (cutting temperature), 1% (surface hardness), and 25% (surface roughness).

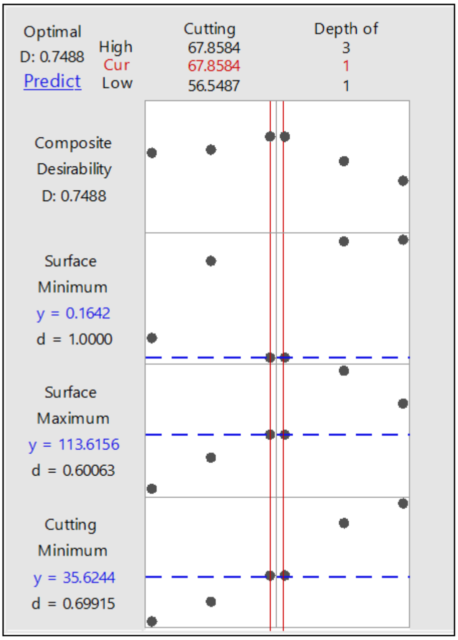

Figure 7: Optimization of cutting temperature, surface hardness and surface roughness by DFA

Conclusions

The experimental tests carried out have shown that depth of cut is the most significant factor influencing cutting temperature and surface hardness. Meanwhile, cutting speed is the most significant factor influencing surface roughness. Furthermore, the combinations of cutting conditions leading to optimum cutting temperature, surface roughness, and surface hardness during end milling under dry conditions of 6061 aluminium alloy are 67.8584 m/min (cutting speed) and 1 mm (depth of cut). The findings are not only for economic reasons but also for eliminating any possibility of health risks to machinists and preserving natural resources and human well-being. In addition, future studies should be carried out to analyse cutting tool life based on the optimal combinations.

Acknowledgements

The authors would like to acknowledge technical support from the Universiti Putra Malaysia as well as Mr. Mohd Nor Bin Puteh, Mdm. Hatijah Binti Kassim, Mdm. Dyg. Siti Quraisyah Bt. Abg. Adenan and Mr. Nor Iman Ziqri Bin Nor Aznan for encouragement.

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