Interaction Effect of Machining Parameters on Material Removal Rate in the Machining of AA6061–T6 Using Minimum Quantity Lubrication Conditions

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Abstract. The objectives of this study are to investigate the interaction effect of machining parameters on material removal rate in end milling of aluminium alloy AA6061–T6 with conventional MQL techniques. Uncoated tungsten carbide (WC-Co 6.0%) and PVD TiAlN and TiAlN+TiN coated carbide cutting tools are considered using 23.4-54.0 ml/hr flow rate of commercial mineral oil for MQL machining with different combinations of input cutting parameters. Response surface methodology with central composite design approach is used for the design of experiments. Second-order mathematical models are developed for machining performance measures with different cooling conditions and validated statistically. The developed models show good agreement (< 5 % error) with the experimental results. The metal cutting performance of the TiAlN coated tools relative to uncoated and TiN coated inserts is better at all combinations of input cutting parameters. Hence the superior performance of TiAlN coating makes it more suitable for use with MQL. In case of material removal rate, all the tools show similar behaviour in all the measurements with the depth of cut as the most significant parameter followed by feed rate. Interaction of feed rate and depth of cut is most effective.

1. Introduction

As the manufacturing world is in continuous pursuit of investigating the methods in order to increase the process performance and to reduce the production costs, in addition to the growing environmental concerns [1], minimum quantity lubrication process can offer the near-term solution to the problem. Minimum quantity lubrication (MQL) has demonstrated as a successful near-dry machining technique as well as a globally-acknowledged option compared to completely dry and wet cutting conditions from the perspective of cost, ecological, human health issues and machining process performance [2]. The significant challenges faced by the manufacturing industry are the improved quality, enhanced productivity as well as economic production [3-4]. These challenges are addressed by increasing the material removal rate for enhanced productivity, surface quality and surface integrity as well as longer tool life with consistence performance [5]. Cutting fluids are considered essential for machining operations in order to perform lubrication, cooling and chip flushing. These functions of cutting fluids in machining processes are continually being reviewed due to cost pressures together with growing global concerns related to occupational and environmental consciousness [6-8] and the want for increased employee satisfaction through healthier environment and cleaner work areas [5]. The
conventional method of application of cooling and lubrication in machining processes involve excessive use of cutting fluids. In MQL, the cutting fluid flow rate varies from a minimum of 10 ml/hr to a maximum of 100 ml/hr [8]. Some researchers have given different ranges of lubricant flow rate in MQL, such as 2 to 500 ml/hr [9]. However, most industrial applications consume MQL in the range of 10 to 100 ml/hr [9]. High pressure of the fluid penetrates through the rake face of the tool hence lowering the temperature of the critical zone. It was observed that oil-water MQL had better cooling characteristics while pure oil MQL had better lubrication capacity. Navid [10] analysed the results from dry and MQL machining of Monel K-500 in order to investigate the influence of cutting speed, depth of cut and feed rate on surface roughness and cutting forces. MQL yielded a reduction in surface roughness by 38 % and cutting force by 59 %. The vegetable-based lubricant used to conduct wear analysis experiments during end milling AISI 1018 steel with varying feed rate and cutting speed at a fixed depth of cut [11]. Solid carbide cutting tool was used with varying cutting speed and feed rate has a constant depth of cut. The proper selection of the cutting parameters might result in possible to obtain higher tool life. The objective of this study to investigate the interaction effect of machining parameters on the material removal rate in the machining of aluminium alloy AA6062-T6 for minimum quantity lubrication technique.

2. Materials and Methods
Aluminium alloy AA6061-T6 is selected as a workpiece material due to excellent mechanical and corrosion resistance [12]. Conflicting views about the cooling conditions for the alloy are observed in the literature [13]. Workpiece dimensions are 100 × 100 × 30 mm. Alloy composition is recorded using a spectrometer (Foundary-Master type, Oxford Instruments, Inc.) for three random samples at three different places each and weight % obtained is an average of the nine samples. The conventional (oil-based) MQL cutting environments are considered in the study. Vegetable oil-based coolant (Coolube 2210, UNIST, Inc.) is used for conventional MQL machining. A two-flute end mill of diameter 12 mm MaxiMill shoulder design cutter (CERATIZIT: C211.12.R.02-07-A-20) is used. Three types of different milling inserts including uncoated WC-Co 6.0%, TiAIN coating and TiAlN+TiN coating by PVD process are selected. The facet corner radius for uncoated tungsten carbide insert is 0.8 µm while for coated inserts facet corner radius is 0.4 µm. Cutting edge width of uncoated tungsten carbide insert is 0.1 mm more than coated ones. All other dimensions are similar. Two-flute end mill cutter is selected to minimise the clogging of adhered material and chips into the end mill flutes. Length of the end mill flute is 8.0 mm. MQL is delivered to the cutting zone through the UNIST Uni-MAX Coolubricator system. The pulse generator produces repetitive cycles of the metering pump. A 1-drop meter output 6-nozzles configuration is used. The system is provided with six positive displacement oil metering pumps (0.2-1.00 ml/stroke) with adjustable stroke and output. MQL flow rate is adjusted by setting the stroke length as 10 while the flow rate is adjusted by indexing the flow rate according to counter-clockwise turnings. Material removal rate (MRR) is a critical machining control factor from the viewpoint of productivity. The material removal rate is calculated in mm³/min. Schimadzu (4-decimal places resolution) digital balance is used to measure the mass of workpiece before and after the machining for material removal rate. Mass of the workpiece is measured after machining a slot over the entire length of a workpiece according to the design of an experiment. Machining time for each sample has been calculated accordingly. The machining is performed with machine doors closed. Response surface methodology is used to determine the optimum operating conditions. Theoretical formulae can be used to estimate material removal rate in end milling however in order to estimate actual material removal rate with material density included in analysis along with the machining conditions effects, reduction in volume per unit time is used for more actual results. Hence, empirical relationships are necessary to relate to the material removal rate and input machining parameters. Levels of independent cutting parameters in the experimental design for material removal rate under conventional MQL is presented in Table 1. Total 78 (26 × 3) experiments result for conventional MQL conditions with two experiments repeated to increase the model accuracy and repeatability.
Table 1. Levels assigned to the input cutting parameters for conventional MQL cooling conditions.

| Input cutting parameter          | Levels of input cutting parameters | Conventional MQL conditions |
|----------------------------------|------------------------------------|----------------------------|
|                                  | Lowest    | Low       | Centre     | High       | Highest   |
| Cutting speed (RPM)              | 5252.0    | 5300.0    | 5400.0     | 5500.0     | 5548.0    |
| Feed rate (mm/min)               | 288.0     | 318.0     | 379.0      | 440.0      | 469.0     |
| Depth of cut (mm)                | 0.37      | 1.00      | 2.00       | 3.00       | 3.63      |
| MQL flow rate (ml/min)           | 0.39      | 0.48      | 0.65       | 0.83       | 1.00      |

3. Results and Discussion

3.1 Mathematical Modeling

The mathematical models in terms of material removal rate are developed using response surface method. Second-order mathematical models for different tools with various cooling environments are developed using RSM. Analysis of variance (ANOVA) is utilized to verify the adequacy of the experimental data. The estimated regression coefficients for the material removal rate with various cutting inserts are determined using experimental data. The ANOVA for MRR with uncoated tungsten carbide, TiAlN coated and TiAlN+TiN coated carbide tools are presented in Table 2. For conventional MQL machining, four squared terms (speed and speed, feed rate and feed rate, depth of cut and depth of cut and squared term of MQL flow rate), six interaction terms (speed and feed rate, speed and depth of cut, speed and MQL flow rate, feed rate and depth of cut, feed rate and MQL flow rate and interaction of depth of cut and MQL flow rate) and four linear terms are included in regression analysis. The regression $p$-value for different inserts is 0.000. Hence, regression analysis is significant. The interaction term of feed rate with the depth of cut shows a $p$-value of 0.000 <0.05; hence, the term is the most significant term in the analysis for all the inserts. For TiAlN coated insert in MQL machining, quadratic terms of depth of cut are also significant. It is observed that $R^2$ value for all the inserts is more than 98 % for various cooling conditions. Lack-of-fit for all the conditions is also insignificant i.e. greater than 0.05 for all cases. Therefore, it is concluded that the experimental data for all inserts with various cooling conditions are adequate and suitable for further analysis.

Table 2. ANOVA analysis for different uncoated- tungsten carbide and coated carbide insert.

| $p$-value        | uncoated tungsten carbide | Coated TiAlN | Coated TiAlN+TiN |
|------------------|---------------------------|--------------|------------------|
| Regression       | 0.000                     | 0.000        | 0.000            |
| Linear           | 0.142                     | 0.181        | 0.243            |
| Square           | 0.109                     | 0.093        | 0.001            |
| Interaction      | 0.007                     | 0.000        | 0.000            |
| Lack-of-fit      | 0.219                     | 0.088        | 0.054            |
| R-Sq (%)         | 99.09                     | 99.64        | 99.84            |

3.2 Effects of Input Parameters on Response Variables

Effects of input process parameters and different phenomena arising during machining on performance parameters against the experimental design are presented in the following section. Significance of input parameter is determined based on the difference in the mean of two groups of experimental design at high and low levels. The relative importance and rankings of main parameters and their interactions with respect to response variables are evaluated by determining the parameters effect size using DOE. Significance of input cutting parameters for material removal rate with conventional MQL is presented in Figure 1. Depth of cut is the most significant factor affecting material removal rate (61.06 -71.61 %) followed by feed rate (26.06 - 31.99 %). Theoretical formulæ for material removal rate show that the response variable increases with increasing depth of cut and feed rate. This is due to more volume of
chips generated with increasing depth of cut and increased material removed per revolution [14]. Depth of cut with larger intervals between the levels selected for the machining results in more significant effects of depth of cut on material removal rate in this study. Effects of speed on material removal rate are very insignificant. The reason is that the selected speed range is set at levels with very narrow intervals, hence the effects of speed are not so pronounced.

Figure 1. Significance of input parameters for the material removal rate for different cutting tools with conventional MQL conditions
Figure 2 presents three-dimensional surface plots on the basis of response model of material removal rate against the depth of cut and feed rate for various inserts at a cutting speed of 5400 rpm and MQL flow rate of 0.65 ml/min. A linearly increasing relationship is observed for material removal rate with the depth of cut and feed rate. For all inserts used with different cooling conditions, the most significant parameters for the material removal rate are feed rate and depth of cut. Material removal rate increases with increasing depth of cut and feed rate but the effect of depth of cut is more significant. The maximum material removal rate is obtained at a maximum depth of cut and maximum feed rate due to the resulting maximum volume of chips and material removed. It is observed that variations in depth of cut more significantly affect the material removal rate as compared to feed rate. This is attributed to the larger volume of material removed on account of the higher depth of cut selected. All the tools in different cooling conditions show an average increasing rate of material removal rate per mm of the depth of cut when the feed rate is at its maximum. Hence a combination of higher depth of cut and higher feed rate is more effective for material removal rate for machining of AA6061 because of the higher material volume of chips produced with increasing depth of cut and feed rate. This conclusion is in complete accordance with the findings of Kuttolamadom et al. [15] for end milling of aluminium alloy 6061 T6. In order to increase the material removal rate, depth of cut and feed rate should be increased however the real challenge is to keep the surface roughness within the recommended range.

4. Conclusions
End milling experiments for aluminium alloy 6061 T6 are conducted in order to assess the performance of minimum quantity lubrication technique using uncoated and PVD coated cemented carbide tools. The PVD coatings used are single layer TiAlN and dual-layered TiAlN+TiN (TiN is the outer layer) coating on cemented carbide substrate. MQL machining was performed with uncoated carbide insert in order to assess the improvement in the insert performance. The central composite design approach of response surface methodology is used to design experiments. Second-order polynomials in terms of input cutting parameters including cutting speed, feed rate, depth of cut, MQL flow rate result as regression models from the experimental data to predict the machining performance measures in terms material removal rate. The models are validated statistically as well as experimentally. Regression models show good agreement with the experimental data. The metal cutting performance of the TiAlN coated tools relative to uncoated and TiN coated inserts is better at all combinations of input cutting parameters. In the case of TiAlN coated tools, not only the hot hardness of the tool plays a significant role in better performance at higher temperatures but the formation of the layer of Al₂O₃ also serves to increase the stability. Hence the superior performance of TiAlN coating makes it more suitable for use with MQL. All the tools show similar behaviour in all the measurements with the depth of cut as the most significant parameter followed by feed rate. Interaction of feed rate and depth of cut is also effective.
5. References

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