Influence of cutting fluid conditions on tool wear and surface roughness in hard turning AISI-D2 Steel using mixed ceramic tools

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Abstract. In the present work, the effects of machining factors and cutting fluid flow conditions on tool wear and surface roughness were studied. Response surface methodology technique with Face centered composite design was employed to minimize the number of experiments. The experiments were performed on a hardened AISI D2 rod using mixed ceramic (\textit{Al}_2\textit{O}_3/TiC) inserts in turning process. The effect of machining time was found to be the most influential parameter affecting tool wear, followed by cutting speed. However, machining time followed by feed rate were the most significant parameters on surface roughness. Moreover, cutting fluid condition showed substantial contribution towards decreasing tool wear rate and increasing surface finish.

1. Introduction

Hard turning is rapidly becoming the most suitable finishing process to obtain finished products directly from hardened parts. Hard turning is substituting traditional and costly finish machining process i.e. grinding process, because of the ability to machine intricate work-piece geometries in single step with greater process flexibility, increased MRR and decreased set up times [1,2]. Hard turning process is almost cited in literature using dry conditions, for the reason that the increases of temperature make chip deformation and shearing of the hardened materials easier. Conversely, the high temperature causes increase in friction and heat generation at the tool-work piece interface, which in turn leads to rapid tool wear, affects tribological properties, dimensional accuracy and surface integrity of the machined parts [3]. Conventionally, cutting fluid (CFs) has been used to cool down and lubricate the cutting process, therefore addressing these issues [4]. CFs also favour chip transportation and reducing heat produced during cutting. Despite the constant attempts to totally eliminate CFs from cutting process, cooling and lubrication is still necessary in many places where higher machining efficiency, tight tolerances, higher dimensional accuracies and machining of difficult to cut materials is involved [5,6]. Moreover, CFs is used in a machining operation to enhance the tribological properties of the tool-work piece and tool-chip interfaces. This is achieved only when CFs is able to provide good lubrication and cooling in the metal cutting process, particularly at the cutting edge and tool tip [7,8]. The effectiveness of CFs depends upon the ability to access or penetrate the interface between the chip and the tool, and build a thin intermediate film between the surfaces. This intermediate layer or film emerges either by physical absorption or by a chemical reaction and must have low shear resistance than that of the materials at the interface [9]. In this manner, it will reduce the friction and hence the heat generation by acting indirectly as a coolant. Moreover, at higher cutting speeds, the conditions for fluid penetration at the interface are not favourable. In these conditions, water based fluids must be used, as cooling becomes more important. Recent studies of applying high pressure coolant (HPC) supplies in machining operations have reported noteworthy...
increase in productivity relative to conventional technique of coolant delivery. Research studies in HPC for machining of steels by Pigot and Colwell [10], Naves et al. [11], and Kaminski and Alvelid, [12] reported significant improvements in tool life, dimensional accuracy, surface finish and elimination of BUE formation. The technique was also successful in reducing the cutting zone temperature and cutting forces. In recent years, researchers have also focused their attention on issues related to environmental problems and have tried to discover new ways of improving the current methods of cooling during turning, such as Cryogenic cooling, using vegetable oils, viscosity modifiers and directing fluid flow to contact regions [13,14]. The purpose of present study aims at evaluating the turning performance of mixed alumina ceramic insert while hard turning of AISI D2 steel. The influence of the cutting fluid velocity and cutting fluid flow rate targeted at the chip-tool interface is investigated for surface roughness and tool wear. The investigations were carried out using an environment-friendly Blasocut 2000 universal cutting fluid. The parameters including cutting speed, feed rate, machining time and cutting fluid conditions were considered for the present study.

2. Methodology

2.1. Materials
Horizontal-turning experiments were carried on steel shafts of 55 mm diameter and 300 mm length on a 5.2 kW centre lathe. The Length/diameter ratio of the test material was maintained as per ISO 3685 standards i.e. less than 10. The chemical composition of test material CRP for AISI D2 sample and is recorded in Table 1. The cutting inserts used in present is a mixed ceramic tool with chemical composition of Al₂O₃ (70%) and TiC (30%). These cutting inserts with ISO code-CNGA 120408 T01020 were placed in a right-hand tool holder with ISO designation PCLNR 2525 M12. A water based emulsion was made by adding Blasocut 2000 concentrate (7-10%) to water. The flow rate (Q) of emulsion was measured by using a stop-watch and measuring beaker. In order to calculate the Q of emulsion, the valve was initially opened to 45 º and then in the second step the value was fully opened, the emulsion was allowed to flow for 15s in both the cases. In the last step, a small tube of dia. 6 mm was used instead of previously used 9.6 mm diameter tube and the valve was also kept opened completely for another 15s. The recorded relative velocity and flow rates of cutting fluid are recorded in Table 2.

Hommel Etamic, Jenoptiik, Germany, (Model W5) contact stylus profilometer with a stylus tip radius of 2 µm was used for Ra measurement. The transverse length was 3.2 mm with basic span of 0.8 mm over five sampling lengths. Average of these Ra values were used to determine the surface roughness achieved on the machined surfaces. Leica DM 6000 microscope with magnification 50 X to 1000 X and with image characterization software was used for measurement of wear on the flank surface of the tool.

| Table 1. Work-piece description. |
|---------------------------------|
| C | Si | Mg | Cr | W | V | Mo | Fe |
| 1.70 | 0.30 | 0.30 | 12 | 0.50 | 0.10 | 0.60 | balance |

| Table 2. Cutting fluid flow specifications. |
|--------------------------------------------|
| Flow rate, Q (ml/s) | Dia. of tube, D (mm) | Velocity of cutting fluid (m/s) | Lubricating or Cutting fluid condition, Qc |
|---------------------|---------------------|-------------------------------|------------------------------------------|
| 74                  | 9.6                 | 1.022                         | Low flow rate low velocity (LFLV)        |
| 140                 | 9.6                 | 1.92                          | High flow rate low velocity (HFLV)       |
| 97                  | 6                   | 3.43                          | Low flow rate high velocity (LFHV)       |

2.2. Design of experiments
A total of 81 experiments are needed when we consider a full factorial design with four parameters at three levels each. However, this experimental study is time-consuming and expensive. Consequently, Response surface methodology (RSM) with FCCD was used to design the experiments for each parameter i.e., cutting speed (Vc), machining time (T), feed rate (f), and cutting fluid conditions (Qc).
Accordingly, only 30 experiments are required on the work material to study the effect of parameters on the desired outputs (flank wear and Ra). The designed levels are shown in Table 3.

### 3. Results and discussion
The influence of cutting factors on the performance of Al_2O_3/TiC ceramic tool is discussed herein. Tool flank wear and Ra were plotted for individual (main) and interaction effects. Three dimensional (3D) plots were generated based on the four independent factors. The relationship(s) between input factors and desired outputs can be inferred from Table 4.

| Run | A: Cutting speed (m/min) | B: Feed rate (mm/rev) | C: Machining time (min) | D: Cutting fluid condition | Tool flank wear (µm) | Ra (µm) |
|-----|-------------------------|----------------------|------------------------|---------------------------|---------------------|---------|
| 1   | 190                     | 0.1                  | 2                      | LFHV                      | 85                  | 0.66    |
| 2   | 150                     | 0.1                  | 4                      | HFLV                      | 112                 | 1.125   |
| 3   | 110                     | 0.05                 | 6                      | LFHV                      | 101.08              | 0.75    |
| 4   | 150                     | 0.075                | 4                      | HFLV                      | 106.19              | 0.89    |
| 5   | 150                     | 0.075                | 4                      | HFLV                      | 101.3               | 0.87    |
| 6   | 150                     | 0.075                | 4                      | HFLV                      | 99.8                | 0.82    |
| 7   | 150                     | 0.075                | 4                      | HFLV                      | 102.9               | 0.81    |
| 8   | 190                     | 0.1                  | 6                      | LFHV                      | 161                 | 1.31    |
| 9   | 190                     | 0.1                  | 2                      | LFLV                      | 89.6                | 0.76    |
| 10  | 110                     | 0.1                  | 2                      | LFLV                      | 69.59               | 0.69    |
| 11  | 190                     | 0.05                 | 2                      | LFHV                      | 77.0                | 0.63    |
| 12  | 190                     | 0.05                 | 6                      | LFHV                      | 143                 | 0.91    |
| 13  | 150                     | 0.075                | 4                      | LFHV                      | 98.6                | 0.75    |
| 14  | 150                     | 0.075                | 4                      | HFLV                      | 111.2               | 0.79    |
| 15  | 150                     | 0.05                 | 4                      | HFLV                      | 96.4                | 0.77    |
| 16  | 150                     | 0.075                | 2                      | HFLV                      | 65.3                | 0.62    |
| 17  | 110                     | 0.1                  | 6                      | LFLV                      | 130                 | 1.21    |
| 18  | 110                     | 0.05                 | 2                      | LFHV                      | 54.5                | 0.54    |
| 19  | 190                     | 0.075                | 4                      | HFLV                      | 135.84              | 1.01    |
| 20  | 110                     | 0.1                  | 6                      | LFHV                      | 119.7               | 1.23    |
| 21  | 110                     | 0.075                | 4                      | HFLV                      | 87.5                | 0.79    |
| 22  | 110                     | 0.1                  | 6                      | LFHV                      | 58.65               | 0.6     |
| 23  | 190                     | 0.05                 | 2                      | LFHV                      | 138                 | 1.09    |
| 24  | 190                     | 0.05                 | 2                      | LFHV                      | 58.5                | 0.41    |
| 25  | 150                     | 0.075                | 4                      | HFLV                      | 99.9                | 0.84    |
| 26  | 110                     | 0.05                 | 2                      | LFLV                      | 59.5                | 0.6     |
| 27  | 150                     | 0.075                | 6                      | HFLV                      | 151                 | 1.2     |
| 28  | 190                     | 0.1                  | 6                      | LFHV                      | 194.23              | 1.34    |
| 29  | 150                     | 0.075                | 4                      | LFLV                      | 119.7               | 0.93    |
| 30  | 110                     | 0.05                 | 6                      | LFHV                      | 123.465             | 0.91    |
machining time. A-VC has the most significant factor relationship contributed by less important factors. Among the main input parameters, machining time (Figure 1c) has the most significant factor relationships, followed by Vc (Figure 1a), f (Figure 1b) and at last by Qc (Figure 1d). Cutting speed is the second largest parameter influencing tool flank wear after machining time. The higher temperature generated at contact zone with increased cutting speed cause

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### Table 5. ANOVA table for tool wear of mixed ceramic tools

| Source       | Sum of Squares | df  | Mean Square | F   | p-value | PC % |
|--------------|----------------|-----|-------------|-----|---------|------|
| Model        | 30873.28       | 14  | 2205.23     | 33.04 | < 0.0001 | Significant | 13.48 |
| A-Vc         | 4299.15        | 1   | 4299.15     | 64.42 | < 0.0001 | significant | 4.93  |
| B-f          | 1574.15        | 1   | 1574.15     | 23.59 | 0.0002  | significant | 72.24 |
| C-T          | 2205.23        | 1   | 2205.23     | 345.07 | < 0.0001 | significant | 2.55  |
| D-Qc         | 814.26         | 1   | 814.26      | 12.20 | 0.0033  | significant | 1.07  |
| Vc x f       | 341.56         | 1   | 341.56      | 5.12  | 0.0390  | significant | 1.73  |
| Vc x T       | 553.77         | 1   | 553.77      | 8.30  | 0.0114  | Significant | 0.00  |
| Residual     | 902.66         | 15  | 66.73       | 4.59  | 0.0532  | not significant |
| Lack of Fit  | 98.36          | 5   | 19.67       |       |         |      |
| Pure Error   | 1001.02        | 15  | 66.73       |       |         |      |
| Cor Total    | 31874.30       | 29  |             |       |         |      |

### Table 6. ANOVA for surface roughness (Ra) of mixed ceramic tools

| Model Source | Sum of Squares | df  | Mean Square | F   | p-value | PC % |
|--------------|----------------|-----|-------------|-----|---------|------|
| Model        | 1.55           | 14  | 0.11        | 27.57 | < 0.0001 | significant |
| A-Vc         | 0.030          | 1   | 0.030       | 7.57  | 0.0149  | significant | 1.86  |
| B-f          | 0.28           | 1   | 0.28        | 70.26 | < 0.0001 | significant | 17.3  |
| C-T          | 1.07           | 1   | 1.07        | 265.08 | < 0.0001 | significant | 66.4  |
| D-Qc         | 0.062          | 1   | 0.062       | 15.53 | 0.0013  | significant | 3.85  |
| Vc x T       | 0.021          | 1   | 0.021       | 5.23  | 0.0372  | Significant | 1.30  |
| f x T        | 0.058          | 1   | 0.058       | 14.33 | 0.0018  | Significant | 3.60  |
| f x Qc       | 0.014          | 1   | 0.014       | 3.58  | 0.0779  | significant | 0.86  |
| Residual     | 0.053          | 10  | 0.053       | 3.73  | 0.0797  | not significant |
| Lack of Fit  | 7.133E-003     | 5   | 1.427E-003  |       |         |      |
| Pure Error   | 1.61           | 29  |             |       |         |      |

### 3.1 Statistical analysis

Analysis of variance was carried out with an objective to analyze the effect of cutting speed (Vc), machining time (T), feed rate (f) and cutting fluid conditions (Qc) on tool flank wear and surface roughness. Table 5 and 6 displays the ANOVA results for tool flank wear and surface roughness. The analysis was carried out for a 5% significance level. ANOVA Tables 5 and 6 displays the values under different columns viz., sum of squares, degree of freedom, mean square, F-value and p-value and percentage contribution (PC%). PC % column shows the contribution of each factor relative to the total sum of squares, subsequently signifying the degree of control on the result. The Wellness of the Fit to the suggested model is expressed as the coefficient of determination (R²).

The ANOVA results of the tool flank wear is presented in Table 5. From Table 6, the model F-value of 33.04 implied that the model is significant. The ANOVA indicated that Vc, f, T and Qc, the interactions (f*Vc) and (Vc*T), factors were significant on the basis of their P-values. However, the effect of T contributed largely to the process and accounted for approx. 72.24 % of the total contribution. The next factor affecting tool flank wear is Vc and contributed approximately 13.48% to the model followed by f (4.93%).

Figure 2 shows the individual influence of cutting parameters on tool wear. In these plots, the larger effect is represented by a line with a steep slope for long-range change in comparison to the effects contributed by less important factors. Among the main input parameters, machining time (Figure 1c) has the most significant factor relationships, followed by Vc (Figure 1a), f (Figure 1b) and at last by Qc (Figure 1d). Cutting speed is the second largest parameter influencing tool flank wear after machining time. The higher temperature generated at contact zone with increased cutting speed causes...
the cutting tool material to lose its strength and wear occur rapidly. Similar results were reported by other researchers in this area. Bensouilah et al. [15] and Raja et al. [16] found that the cutting speed was the important factor affecting tool wear. Alternatively, feed rate and cutting fluid conditions also have shown considerable effect on tool wear. The plot for tool wear against Qc showed (Figure 1d) that the tool wear considerably decreased from 113.2 to 99.8 (µm) i.e., negatively significant effects. This negatively significant effect is good for increasing the tool life and reducing the wear on cutting inserts.

Table 6 shows the ANOVA data for Ra. The model F-value of 27.57 implied that the model is significant. Feed rate (f), Machining time (T), Vc ,cutting fluid condition (Qc), interaction - (Vc×T), (f×T)and (f×Qc) were significant model terms. The main effect of T dominated the process and contributed nearly 66.4% of the whole followed by f (17.3 %) and Qc (3.85%). Figure 2 shows the main effect plots for Ra. Machining time and feed rate were the most considerable factors influencing surface roughness (Ra) while hard turning of AISI D2. The slope of surface roughness line versus machining time showed that Ra value increases continuously with increase in machining time (Figure 2c). Similarly, the slope of Ra line versus feed rate (Figure 2b) demonstrates that Ra significantly increased when feed rate increased from 0.05 mm/rev to 0.1 mm/rev. The increase in feed rate generates helicoids furrows, which are broader and deeper as feed rate increases [17]. Feed rate is found to be important parameter affecting Ra. Similar results were obtained by other researchers in this area [18]. For this reason, weak or small feed rates should be or have to be applied during machining operations. Similarly, the Ra value was a considerably influenced by cutting fluid conditions. Ra valve decreased when the cutting fluid condition was changed from LFLV-LFHV (-1 to +1 level). Cutting speed has less statistical significance as regards to Ra.

3.2 Regression equations
The relationship between the input parameters (Vc, f, T and Qc) and performance measures (Tool flank wear and average surface roughness) was modelled by quadratic regression equations. The different quadratic models attained from statistical analysis can be helpful to predict the tool flank wear and Ra according to the studied parameters. The models are presented in equations (1-2) respectively. The tool wear (VB) model for mixed ceramic inserts is given below in Eq. (1). Its coefficient of determination (R²) is 96.6% and R² is 93.3%

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\text{Tool wear, (Mixed Ceramic)= } 59.17 -0.79 * Vc + 547.36 * f + 3.7 * T + 0.050 * Qc + 4.6 * Vc * f + 0.073 * Vc * T \]

The Ra model for mixed ceramic inserts is given below in Eq. (2). Its coefficient of determination (R²) is 96.2% and R² is 92.7%

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\text{Ra, (Mixed Ceramic) = 1.0216 -0.00123 * Vc -12.3099 * f -0.053 * T -0.129 * Qc + 0.00045 * Vc * T + 1.2 * f * T + 1.2 * f * Qc} \]

Figure 3(a) shows the normal probability plot for tool wear. The plot 3(a) indicates that the deviations of residuals from the line were minor, which specifies that the model prediction is accurate. Figure 3(b) shows the actual versus predicted plot. The plot depicts that minor deviation occurred between the actual and predicted values, this implies that the model is accurate.

Figure 4(a) shows the probability plot for surface roughness. From this plot it can be observed that the distribution of residuals is approximating a straight line, which shows the model prediction is accurate. Similarly pot 4(b) shows the actual vs predicted plot for surface roughness. The plot indicates that the points are falling or approximating a straight line, which reveals that the accuracy of experimental values and predicted values are acceptable.
Figure 1. Tool wear versus (a) Vc (b) f (c) T (d) Qc.

Figure 2. Ra versus(a) Vc (b) f (c) T (d) Qc.

3.3 Effect of machining parameters on responses
Figure 5 illustrates the effect on tool flank wear with respect to machining time (T), cutting speed (Vc), feed rate (f) and cutting fluid conditions (Qc). Figure 5(a) and (b), shows that flank wear increases continuously with increase in both T and Vc. Moreover, it can be deduced from the plots also that T exhibits maximum influence on tool flank wear. Cutting speed has the second largest effect on tool flank wear, because with the increase in Vc (110-190 m/min), the temperature at the cutting edge of the insert increases. The increased temperature generated at contact region with increased Vc causes the cutting tool material to lose its strength and thus wear occurs rapidly [19, 20]. However, it can also be seen from figure that f has less effect on tool wear; similar results were also obtained some researchers in this fields [21]. However, the combination of highest cutting speeds and highest feed rate produces higher tool flank wear, because with simultaneous increase of both feed rate and cutting speed, the forces, heat generation and speed of MRR increases, which subsequently increase
temperature at the interface[19]. This increased temperature at the flank face softens the cutting tool edge and wear occurs rapidly. Highest level of machining time along with highest level of cutting speed gives maximum value of tool flank wear and vice versa.

Figure 3. Comparison between (a) normal probability plot (b) measured and predicted values for tool wear.

Figure 4. Comparison between (a) normal probability plot (b) measured and predicted values for tool wear.

Figure 5(c) presents the interaction among cutting fluid conditions and cutting speed keeping feed rate and machining time at middle levels on tool flank wear. It can be observed from the 3D graphs that tool wear increases with increase in cutting speed, whereas it decrease with increase in cutting fluid conditions. It can also be observed from Figure 5(c) that highest level of cutting fluid condition is capable of reducing tool flank wear at the highest levels of cutting speeds. The decrease in flank wear in combination with LFHV condition can be attributed to the high speed of cutting fluid which possibly penetrates the tool workpiece interface and removes heat from interface and hence reduces the tool wear.

Figure 6 presents the interaction effects of machining time-cutting speed, machining time- feed rate and feed rate - cutting fluid conditions on surface roughness while hard turning of AISI D2 steel. According to Figure 6(a) and (b), surface roughness shows an increasing trend with respect to increase in machining time. At the lowest machining time, the Ra value is at a lesser level and is attributed to less tool wear on the tool edge. However, at a higher machining time, the Ra values increases severely with increase in both feed rate and cutting speed. This can be explained by the gradual increase in tool wear with time [17]. Similarly, from Figure 6(b), it can be noticed that increase in feed rate increases surface roughness considerably. The finest surface finish is obtained with the arrangement of lowest feed rate and lowest machining time.
According to figure 6(c), it can be recognized that the Ra values increases considerably with increasing in feed rate, and decreases with increase in cutting fluid condition. Moreover, it can be observed from figure 6(c) that an improvement in Ra value is achieved with highest level of cutting fluid conditions. This improvement can be explained by the penetration of lubricant into the workpiece and tool interface, which reduces the friction and hence improves surface finish.

4. Confirmation test

In this section, confirmations tests were performed for mixed ceramic cutting to confirm the accuracy of the model. The test condition was so chosen, that they have not been used previously but fall within the range of the levels selected for the present study. The predicted values and the actual experimental values were compared and the error percentage was calculated. The comparisons of experimental results and the predicted values from the model (RSM method) are shown in Table 7. The confirmation tests show that the measured and predicted values are close to each other and the error percentage is within the permissible limits. So, the mathematical model can be successfully used to predict the tool wear and surface roughness for any combination of cutting conditions, cutting speed, feed rate and machining time within the range of performed experimentations.
Table 7 Confirmation experiments for tool Wear and Ra parameters of mixed ceramic tools.

| Trial no. | Cutting condition | Vc (m/min) | f (mm/rev) | T (min) | Expt. result (VB) | Ra (µm) | RSM predicted (VB) | RSM predicted (Ra) | Error % (VB) | Error % (Ra) |
|-----------|-------------------|------------|------------|---------|--------------------|---------|--------------------|--------------------|--------------|--------------|
| 1.        | LFLV              | 110        | 0.1        | 5       | 112.01             | 0.95    | 118.107            | 1.07               | 5.13         | 9.53         |
| 2.        | LFHV              | 190        | 0.1        | 5       | 162.35             | 1.21    | 147.69             | 1.16               | 10.00        | 4.16         |

5. Conclusion:-

Hard turning of AISI D2 steel has been performed using Al₂O₃ + TiC mixed ceramic inserts under different cutting conditions. The key results drawn from the presents study are:

1. Quadratic model was selected as regression model of both desired outputs, namely tool flank wear and surface roughness. It was found that there was a good conformity between experimental and predicted values by quadratic models.

2. Machining time is the largest dominant parameter (72.2%) on tool wear followed by cutting speed (13.4%). While as machining time (66.4%) followed by feed rate (17.3%) contributed the most towards surface roughness.

3. Cutting fluid conditions showed a negatively significant effect to tool wear (2.5%) as well as to surface roughness (3.8%). LFHV condition was the most efficient cutting fluid condition in reducing tool wear rate and decreasing surface roughness.

4. Confirmation experiments showed that the developed mathematical models through RSM can be used for turning of AISI D2 steel.

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