Investigation on cutting tool wear in turning Al 7075/SiC\textsubscript{p} metal matrix composite

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\textbf{Abstract.} Influence of machining process parameters on the tool flank wear (VB\textsubscript{c}) was investigated and optimized during turning silicon carbide particulate (SiC\textsubscript{p}) reinforced Al 7075 (Al 7075/SiC\textsubscript{p}) metal matrix composite (MMC) in heat treated condition. Metal removal was carried out by multilayer TiN coated tungsten carbide inserts in dry environment. Mechanism of tool failure was also studied. ANOVA revealed that the most significant machining parameter for VB\textsubscript{c} was cutting speed, followed by feed. Depth of cut was not significant. Quadratic response surface model was developed and its adequacy was verified.

1. Introduction

Ceramic particulate reinforced Al based MMCs have the potential to replace the conventional monolithic materials in aircraft, marine and automobiles industries. This is because of their improved properties; such as light density, high specific strength, high fatigue strength, high temperature resistance and outstanding wear resistance behaviour [1-4]. But it is not easy to machine these materials conventionally due to existence of hard and brittle reinforcements, which micro-cut and damage the cutting edge. It also induces high rate of tool wear at the flank surface, leading to poor machinability [5].

While turning SiC\textsubscript{p} reinforced Al 359 MMCs in dry environment using cutting tools of different materials, Hung et al. [6] reported an increase of flank wear on increasing the time of machining, tool life increased on increasing the cutting speed and it was maximum for polycrystalline diamond (PCD) inserts. During turning SiC\textsubscript{p} reinforced Al 359 MMCs with PCD inserts, flank wear increases with cutting speed or feed [7]. PCD tools perform better than polycrystalline cubic boron nitride (PCBN) tools while turning SiC\textsubscript{p} reinforced Al MMCs in both dry and wet environments [8]. While turning Al based MMCs with TiN coated tungsten carbide inserts, the wear on flank surface increases on increasing speed of cutting, feed rate, or reinforcement content [9]. TiN coated carbide inserts are more wear resistant than uncoated tools while turning Al 6063/SiC\textsubscript{p} MMCs in dry condition; and influence of cutting speed on flank wear is more than the feed [10]. Cutting time or cutting speed increases flank wear; and the PCD inserts performs better than chemical vapour deposited diamond coated inserts during turning Al 356/SiC MMCs in wet condition [11]. While turning Al 6063 alloy in dry condition, TiN coated carbide tools suffer less flank wear as compared to uncoated carbide tools; and life of the coated tools is about 8.75 times more than that of the uncoated tools [12]. During
turning Al 6061/SiC MMC with TiN coated inserts in dry condition, Sahoo et al. [13] reported that flank wear was more for higher levels of cutting speed and feed, but cutting speed was more influential than feed for flank wear.

Although Al based MMCs have the potential to replace the conventional materials in various engineering applications, they possess poor machinability due to presence of hard reinforcements, leading to machined surface imperfections and high rate of tool wear. Attempts are being taken worldwide to improve surface quality and to reduce tool wear during machining the MMCs. Accordingly this paper presents an investigation on cutting tool flank wear (VBc) while turning Al 7075/SiCₚ MMC in dry cutting environment.

2. Materials and methods

Al 7075 alloy was used as matrix and 5 wt.% SiC particulates (of mean particle size 6.18 µm) were used as reinforcement for fabrication of the MMC. Chemical composition of the alloy was tested by optical emission spectrometer (Leco GDS500A) and elemental constituents (by wt.%) in the alloy was Si: 0.143, Fe: 0.313, Cu: 1.39, Mn: 0.137, Mg: 2.46, Zn: 5.60, Ti: 0.044, Cr: 0.198, Al: 88.9 and others: rest. Mean size of the SiC particulates was determined by Malvern Mastersizer 2000 particle size analyzer following ISO 13320 standards; and it was observed to be 6.18 µm. Vortex method of stirring process was employed to fabricate the MMC. During the fabrication process, the sliced alloy bars were melted at superheated temperature of 820°C in an electrical resistance furnace (Jay Crucible) fitted with a motorized stirring system. The SiC particles were heated at 900°C for two hours in Carbolite make STF 10/75 22 high temperature Single-zone Tube Furnace. The preheated SiC particles were added to vortex of the molten alloy by a spatula at very slow rate (about 5 g/min). The vortex was created by stirring the liquid alloy at 160 rpm. The stirrer speed was increased to 220 rpm after the reinforcement addition and the mixing was continued for 10 minutes more. Then the composite slurry was degassed by solid hexachloroethane tablet and poured into a mild steel mold at about 800°C.

The cast Al 7075/SiCₚ MMC sample was then heat treated to T6 condition, which essentially consisted of two steps. First of all the MMC sample was solution annealed at 483°C for two hours, followed by water quenching. It was then precipitation hardened (aged) at 122°C for twenty four hours, followed by air cooling. A Labotech make BDI 73 muffle furnace with maximum working temperature 1150°C and temperature control accuracy of ± 3°C was used for heat treatment. Hardness of the composite sample was 81.2 and 91.5 HRB before and after the heat treatment, respectively.

To investigate the cutting tool wear, turning experiments of the heat treated MMC sample were conducted by HMT-NH 22 high precession engine lathe at dry cutting environment. TiN-TiCN-Al₂O₃-TiN coated CNMG 120408 carbide inserts were used for metal removal and the inserts were held rigidly by PCLNR 2525 M12 turning tool holder. To prevent vibration, the MMC workpiece was supported by a revolving center in the tailstock. The MMC workpiece was 50 mm of diameter and 120 mm of length; however, the machining length was 80 mm. Table 1 presents the machining process parameters and their levels. Experimental runs were conducted following Taguchi L₁₆ standard orthogonal array and each run was conducted by a fresh cutting edge. Figure 1 shows the experimental setup during turning the MMC.

Table 1. Machining process parameters and their levels.

| Parameters            | Level of parameters |
|----------------------|---------------------|
| Cutting speed, V (m/min) | 40 | 106 | 169 | 206 |
| Feed, f (mm/rev)     | 0.05 | 0.1 | 0.16 | 0.2 |
| Depth of cut, d (mm)  | 0.2 | 0.3 | 0.4 | 0.5 |

VBc was measured on the flank surface below the corner, as depth of cut for every experimental runs was lower than the tool nose radius (0.8 mm). Nikon-V10AD profile projector was used for the measurement of VBc and image of worn cutting edges were captured by Radical Instrument-RSM 8.
stereo zoom microscope. Schematic of the flank wear measurement process is presented in Figure 2. All the measurements were taken on the basis of four-point average method, i.e. any measurement was taken four times and their average was considered for data analysis.

![Figure 1. Experimental setup during turning.](image1)

![Figure 2. Schematic of flank wear measurement process.](image2)

3. Results and discussion

3.1 Influence of machining parameters

Experimental results of \( \text{VB}_c \) during turning the Al 7075/SiC\(_p\) MMC by multilayer TiN coated carbide inserts in dry cutting environment is presented in Table 2. Minimum (0.04 mm) value of \( \text{VB}_c \) is observed for the lowest levels of cutting parameters, i.e. at 40 m/min of cutting speed, 0.05 mm/rev of feed and 0.2 mm of depth of cut (run no. 1). \( \text{VB}_c \) is maximum (0.179 mm) for run no. 16, i.e. at 206 m/min, 0.2 mm/rev and 0.2 mm of cutting speed, feed and depth of cut, respectively. In all the runs \( \text{VB}_c \) is within the limiting criterion of 0.3 mm (ISO 3685:1993). It may be due to formation of stable built-up-edge on the cutting edge of the tool that protected it from rapid wear.
Table 2. Experimental results of tool flank wear and their SN ratios.

| Run No. | V  | f   | d   | VBC (mm) | SNR VBC (dB) |
|---------|----|-----|-----|----------|--------------|
| 1       | 40 | 0.05| 0.2 | 0.04     | 27.9588      |
| 2       | 40 | 0.1 | 0.3 | 0.06     | 24.4370      |
| 3       | 40 | 0.16| 0.4 | 0.112    | 19.0156      |
| 4       | 40 | 0.2 | 0.5 | 0.154    | 16.2496      |
| 5       | 106| 0.05| 0.3 | 0.098    | 20.1755      |
| 6       | 106| 0.1 | 0.2 | 0.119    | 18.4891      |
| 7       | 106| 0.16| 0.5 | 0.134    | 17.4579      |
| 8       | 106| 0.2 | 0.4 | 0.168    | 15.4938      |
| 9       | 169| 0.05| 0.4 | 0.127    | 17.9239      |
| 10      | 169| 0.1 | 0.5 | 0.134    | 17.4579      |
| 11      | 169| 0.16| 0.2 | 0.145    | 16.7726      |
| 12      | 169| 0.2 | 0.3 | 0.17     | 15.3910      |
| 13      | 206| 0.05| 0.5 | 0.151    | 16.4205      |
| 14      | 206| 0.1 | 0.4 | 0.156    | 16.1375      |
| 15      | 206| 0.16| 0.3 | 0.167    | 15.5457      |
| 16      | 206| 0.2 | 0.2 | 0.179    | 14.9429      |

From the response table for means of VBc (Table 3) and main effects plots for means of VBc (Figure 3), it is observed that the mean VBc increases with increase of either of the cutting parameters, i.e. cutting speed or feed or depth of cut. Moreover, cutting speed is the highest influencing factor for VBc, as it posses the highest delta value (0.07175) and is ranked 1 in Table 3. Similarly, the least influencing factor for VBc is depth of cut, as it posses the smallest delta value (0.0225) and is ranked 3. Increase of VBc at higher parametric levels is due to the increased tool temperature and increased friction between the flank surface and reinforced abrasive particles in the MMC. Image of some worn cutting edges are shown in Figure 5 (i-iv), as illustration. Principal mechanism of tool wear was abrasion; however, at low cutting speeds adhesion was observed on the tool face leading to built-up-edge formation. Due to abrasive action of the hard SiC particulates, deep scratch marks were observed in the wear region of the tools at higher cutting speeds.

Table 3. Response table for means of VBc.

| Level | V     | f    | d    |
|-------|-------|------|------|
| 1     | 0.0915| 0.104| 0.12075|
| 2     | 0.12975| 0.11725| 0.12375|
| 3     | 0.144 | 0.1395| 0.14075|
| 4     | 0.16325| 0.16775| 0.14325|
| Delta | 0.07175| 0.06375| 0.0225|
| Rank  | 1     | 2    | 3    |

Table 4. Response table for SN ratios of VBc.

| Level | V     | f    | d    |
|-------|-------|------|------|
| 1     | 21.92 | 20.62| 19.54|
| 2     | 17.9  | 19.13| 18.89|
| 3     | 16.89 | 17.2 | 17.14|
| 4     | 15.76| 15.52| 16.9 |
| Delta | 6.15  | 5.1  | 2.64 |
| Rank  | 1     | 2    | 3    |
3.2 Optimization of process parameters

Machining process parameters are optimized for VBc using Taguchi method. Signal to Noise (SN) ratios are determined considering "smaller is better" criteria; and presented in Table 2. Response table for SN ratios of VBc (Table 4) and main effects plot for SN ratios of VBc (Figure 4) reveal that the mean SN ratio of VBc reduced on increasing either spindle speed or feed or depth of cut. Mean SN ratios are maximum for first levels of all the machining parameters ($V_1$- $f_1$- $d_1$), i.e. 40 m/min of cutting
speed, 0.05 mm/rev of feed and 0.2 mm of depth of cut. This was the optimal combination of machining process parameters for VBc, while turning the T6 conditioned Al 7075/SiCp MMC with multilayer TiN coated tungsten carbide inserts in dry environment.

Some confirmatory experiments were conducted to verify the improvement of the response (VBc) and the results are presented in Table 5. Closeness between the predicted and experimental values was observed; and the improvement of SN ratio for optimal parameters was 8.472 dB.

Table 5. Results of confirmation experiments.

| Level | Initial machining parameters | Optimal machining parameters | Prediction | Experiment |
|-------|------------------------------|------------------------------|------------|------------|
| VBc   | V2-f2-d2                     | V1-f1-d1                     | 0.122      | 0.046      |
| SN Ratio (dB) | 18.2728                     | 25.0564                     | 26.7448    |
| Improvement of SN ratio | 8.472 dB                      |

3.3 Analysis of Variance (ANOVA)

Significance of process parameters on the flank wear is verified through ANOVA at 95% confidence level. Table 6 represents results of ANOVA for VBc. Results reveal that the most significant parameter is cutting speed, followed by feed, as for these parameters the probability of significance (P) is sufficiently lower than 5% (0.05); and the statistical F-values (18.87 for V and 15.94 for f) are sufficiently higher than the tabulated F-value (4.76 for both V and f) [14] at 95% confidence level. Influence of depth of cut is not significant for VBc. Contribution of cutting speed and feed are 47.749% and 40.325%, respectively.

Table 6. ANOVA results for VBc.

| Parameters | Degree of freedom | Sum of squares | Mean square | F     | P     | % of contribution |
|------------|------------------|----------------|-------------|-------|-------|------------------|
| V          | 3                | 0.0111         | 0.0037      | 18.87 | 0.002 | 47.749           |
| f          | 3                | 0.0093         | 0.0031      | 15.94 | 0.003 | 40.325           |
| d          | 3                | 0.0016         | 0.0005      | 2.71  | 0.138 | 6.865            |
| Error      | 6                | 0.0012         | 0.0002      |       |       | 5.060            |
| Total      | 15               | 0.0232         |             |       |       | 100.00           |

3.4 Response surface model

Quadratic response surface model is developed to predict VBc during turning Al 7075/SiCp MMC with multilayer TiN coated inserts in dry environment, using the relevant experimental data from Table 2 and by computing the values of various parameters through MINITAB software. Eq. (1) represents the quadratic response surface model for VBc. The determination coefficient (R^2) of the model is close to 100% and in reasonable agreement with the adjusted R^2 value, which proves adequacy of the model and fitness to the sample data. Figure 6 represents normal probability plots of residuals, which depicts reasonable closeness of the residuals to the normal probability line. It indicates normal distribution of the residuals and the terms mentioned in the quadratic models are significant as well as adequate [15]. Adequacy of the predicted model is also confirmed from the plot for residuals versus fitted values (Figure 7), where the points representing the residuals are randomly scattered [15].
\[ VBc = 0.123925 + 0.040405V + 0.032557f - 0.003864d - 0.004646V^2 + 0.110808f^2 - 0.000113d^2 - 0.025729V * f - 0.001305V * d + 0.009264f * d \]

\[ R^2 = 98.56\%, R^2(\text{adj}) = 96.40\% \]

4. Conclusions

While turning T6 conditioned Al 7075/SiC<sub>p</sub> MMC with multilayer TiN coated tungsten carbide inserts in dry machining environment, VBc was within the limiting criterion for all the experimental runs, which may be due to formation of stable built-up-edge on the cutting edge of the tool that protected it from rapid wear. VBc increased with increase of cutting speed or feed or depth of cut. Abrasion was the dominant mechanism of tool wear; however, at low cutting speeds adhesion was observed on the tool face leading to built-up-edge formation. 40 m/min of cutting speed, 0.05 mm/rev of feed and 0.2 mm of depth of cut was the optimal combination of machining process parameters for VBc.

Results of ANOVA revealed that the most significant parameter for VBc was cutting speed, followed by feed; and depth of cut was not significant. Quadratic response surface model was developed for VBc. Its significance and adequacy were verified through determination coefficients, normal probability plot of residuals and plot for residuals versus fits.

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