ASSESSMENT AND MODELLING OF CUTTING FORCES IN TURNING OF ALUMINIUM METAL MATRIX COMPOSITE USING RESPONSE SURFACE METHODOLOGY

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Abstract: - The conventional materials are nowadays replaced by Metal matrix composites owing to their excellent Mechanical and machining phenomena. The growing/ up-trending growth in Automobile and aerospace sector paves / necessitates the need for accuracy / closer tolerance in machining parameters. The constraints while machining MMC’s are surface roughness and cutting force parameters. The present study focuses on the cutting parameters, condition influencing the surface roughness in terms of material composition, tool wear, speed feed, during the machining of LM6/SiC composites. The mathematical model has been established using Taguchi technique (L16 orthogonal array). By using the RSM approach empirical relation for various machining attributes has been generated to assess the output parameters namely, Feed force (Ff), Cutting force (Fc), Radial force (Fd) and surface roughness (Ra). Desirability function approach is used to find the optimal machining condition. The influence of various parameters in machining of LM6/SiC composite have been analyzed in detail. The study showed that the optimized outputs for the machining of LM6/SiC composite for the input parameters 0% Reinforcement, new tool flank wear(0mm), speed in the range of 684 rpm and 0.1mm feed rate respectively are 7.827 N, 11.196N, 7.890 N and 10.786μm

Keywords: LM6/SiC Composites, Response Surface Methodology, Surface Roughness

1. Introduction

A composite material is a heterogeneous combination of matrix and reinforcing phase yielding the desired properties. Aluminium composites have become an apparent material in the industrial sector owing to superior properties such as resistance to corrosion, enhanced strength to weight ratio and improved resistance to wear.

Most of the engineering services/applications in the present scenario demands materials that exhibits varied composition and proportion of properties which cannot be substituted by conventional existing alloys/ceramic materials. The reason is obvious in the case of materials employed in aerospace sectors requiring low density and impact resistance characteristics. In order to meet the demand and surpass the shortcomings faced by industry composites have emerged as a promising candidate of interest. MMC exhibits high strength, moduli, good damping and improved resistance to wear compared to unreinforced.

MMCs machining and conventional alloys machining will be significantly different in many aspects of machining. During the machining of MMCs behaviour of the MMCs will be non-homogeneous. Machining mainly depends on the matrix, reinforcement material & its volume fraction. Proper mechanisms should be implemented for selection of proper tool based on the behaviour of the work material, geometry and tool wear. Hence proper cutting force data to be
generated to check the behavior of the cutting tool for different working conditions. Since machinability cannot be changed for the given work material, however to increase the tool life, Machining parameters like speed, feed and depth of cut to be selected appropriately [1,2].

Santosh Kumar Tripathy et al [3] carried out an investigation related to the influence of process attributes like Tool wear, Tool life, Power utilization and Surface roughness in Turning of Aluminium Metal Matrix reinforced with waste derived from industrial sectors. The investigated study concluded that surface roughness and power consumption projected a declining and rising trend respectively with the spike in cutting speed and feed rate. Also decrement in performance of tool (Tool life) with increase in addition reinforcement is also reported.

Ireneusz Zagorski et al [4] observed the influence of technology bound factors on assessing the roughness characteristics on assessing the roughness characteristics of aluminium alloys post machining (Turning). The observation arrived at the fact that feed rate exhibits significant influence on quality of machined surface and cutting speed factor is insignificant.

Diptikanta Das and Vivek Chakraborty [5] performed machining on T6-AMMC’s under Dry environment for different levels of attributes like speed, feed rate and depth of cut (DOC). The performance study showed that flank wear maximized with rising attribute levels and reduction in surface roughness was observed with increase in cutting speed and elevated with rising feed/DOC.

Joardar [6] adapted Response Surface Methodology (RSM) to optimize the process parameters in turning of cast AMMC reinforced by Titanium diboride. The influence of attributes like speed, feed, DOC on surface roughness were examined with the establishment of Numerical model through ANOVA analysis. The analysis unveiled that reduction of feed rate results in improved surface finish.

Philip Hoier et al [7] studied the microstructural characteristics of superalloys 718 and waspaloy and impact on flank wear of uncoated tungsten carbide tools on turning. The study concluded that significant progression of flank wear is noticed when machining alloy 718 in comparison to the later. The study also confines to the fact that mechanism contributing to flank wear is abrasion by the presence of inclusions.

Shubhajit Das et al [8] studied the machinability characteristics of Al 2024 reinforced with B4C in terms of surface roughness and Metal Removal Rate. The study revealed that feed rate is the prominent factor affecting surface roughness and Depth of Cut being the influential attribute affecting the MRR.

Ram Singh et al [9] studied the turning characteristics of Al 5083 reinforced with B4C under dry condition. The effect of addition/ dispersion of B4C in Al 5083 was analyzed and optimized to arrive at effective and efficient machining using algorithm. The study revealed that cutting and DOC has an substantial effect/influence on MRR. It also exposed that surface roughness is effected by DOC and feed rate.

The studies pertaining to the machining of Al 2024, Al 5083, super alloys 718, have been adequately carried out to assess the cutting forces using experimental and numerical methods. The present study concerning the machining of LM6 composites, subsequent analysis of impact of input process parameters like feed, speed, artificially induced tool wear on the output responses like surface roughness, cutting forces, followed by optimization of cutting parameters is scarcely reported. The scope of the present study is oriented to characterize the machinability nature of the LM6 composite aided with the analysis of the contributing factors, assessment of cutting forces and surface finish of the machined composite.
2. Materials and Methods

For the fabrication of the composite base/ matrix material used is LM6 as per BS1490:1988 standard [16]. Fabrication of the composite is carried out by using stir casting technique. In this process SiC is dispersed in the molten aluminium matrix by means of stirring. Graphite crucible is used to melt the aluminium alloy LM6 by using the coke fired crucible. Preheating is carried out for the reinforcement material SiC to a temperature of about 250°C for 1/2 hr to take away the volatile impurities on the particle surface. Preheating also oxidize the surface artificially to improves the wettability by formation of SiO2 layer. Preheated SiC partials are added to the molten metal, which is kept at a temperature of 720-740°C. Molten metal is stirred at a speed of 250rpm, and SiC particles are slowly added to the vertex to distribute inside the matrix. The mechanical properties of base metal aluminium alloy and MMC (LM6/SiC) such as Ultimate tensile strength and hardness are measured and tabulated in Table 1.

| Table 1. Mechanical properties of LM6 and MMC |
|-----------------------------------------------|
| LM6/SiC composite material | 0 wt% SiC | 4 wt% SiC | 8 wt% SiC | 12 wt% SiC |
| Tensile strength (N/mm²) | 173 | 208 | 216 | 230 |
| Hardness (BHN) | 55.0 | 65.87 | 76.25 | 78.95 |

| Table 2. Levels of various control factors |
|--------------------------------------------|
| Code | Control Factors | Level |
| A | Composite Material (LM6/SiC) (%) | -2 | -1 | 1 | 2 |
| B | Tool wear (Flank wear) (mm) | 0 | 0.1 | 0.2 | 0.3 |
| C | Cutting speed (rpm) | 250 | 500 | 750 | 1000 |
| D | Feed rate (mm/rev) | 0.1 | 0.2 | 0.3 | 0.4 |

| Table 3. Measured values of Cutting force components and surface roughness. |
|---------------------------------------------------------------|
| Run | Composite Material (LM6/SiC) (%) | Tool wear (Flank wear) (mm) | Cutting Speed (rpm) | Feed (mm/rev) | Feed force (FF) N | Cutting force (FC) N | Radial force (Fd) N | Surface roughness (Ra) μm |
|-----|-------------------------------|-----------------------------|------------------|---------------|------------------|------------------|------------------|-------------------------|
| 1   | 0                             | 0                           | 250              | 0.1           | 15.14            | 30.18            | 12.48            | 10.5                   |
| 2   | 0                             | 0.1                         | 500              | 0.2           | 11.25            | 20.46            | 10.56            | 11.2                   |
| 3   | 0                             | 0.2                         | 750              | 0.3           | 11.89            | 21.48            | 10.89            | 11.6                   |
| 4   | 0                             | 0.3                         | 1000             | 0.4           | 24.48            | 28.14            | 18.17            | 12.4                   |
| 5   | 4                             | 0                           | 500              | 0.3           | 28.47            | 47.28            | 26.54            | 12.8                   |
| 6   | 4                             | 0.1                         | 250              | 0.4           | 55.18            | 80.17            | 52.18            | 11.4                   |
| 7   | 4                             | 0.2                         | 1000             | 0.1           | 6.14             | 15.48            | 4.15             | 13.8                   |
| 8   | 4                             | 0.3                         | 750              | 0.2           | 20.48            | 40.15            | 18.45            | 12.6                   |
| 9   | 8                             | 0                           | 750              | 0.4           | 45.15            | 44.58            | 44.89            | 12.3                   |
| 10  | 8                             | 0.1                         | 1000             | 0.3           | 40.15            | 72.13            | 32.47            | 13.2                   |
| 11  | 8                             | 0.2                         | 250              | 0.2           | 52.89            | 84.78            | 42.18            | 11.4                   |
| 12  | 8                             | 0.3                         | 500              | 0.1           | 44.16            | 76.87            | 34.58            | 12.2                   |
| 13  | 12                            | 0                           | 1000             | 0.2           | 69.48            | 98.48            | 57.47            | 14.2                   |
| 14  | 12                            | 0.1                         | 750              | 0.1           | 70.58            | 96.18            | 60.48            | 13.8                   |
| 15  | 12                            | 0.2                         | 500              | 0.4           | 150.49           | 178.54           | 135.87           | 11.3                   |
| 16  | 12                            | 0.3                         | 250              | 0.3           | 140.58           | 158.47           | 118.47           | 11.8                   |
Composite samples are machined in the conventional lathe using the tungsten carbide tool bit, which is ground to induce the artificial tool wear. Experiment is carried out using the Taguchi’s L16 orthogonal array, levels of various control factors are as shown in the table 2. The force components feed force (Ff), Cutting force (Fc) and Radial force (Fd) are measured using the lathe tool dynamometer. Surface roughness values are measured for all the 16 experimental run using the Mitutoyo SJ-210 surface roughness tester. The results are tabulated in the table 3.

2.1 Response surface methodology.

By using Design-expert trail version 12 software [22], Machining variables and the RSM responses are correlated by quadratic polynomial regression model. By regression approach second order polynomial mathematical models shows the correlation between the force component (Ff, Fc, Fd) and surface roughness (Ra), with the input variables such as composite material (A), flank wear (B), cutting speed(C), and flank wear (D)

From the ANOVA table the R2 value (the coefficient of regression) obtained is 0.9532 (95.3%), 0.9324 (93.24%), 0.9399 (93.99%), 0.8437 (84.37%) for Ff, Fc, Fd, and Ra respectively. These R2 value indicated that model developed through experimental study is reasonably good and hence relationships are satisfactory.

**Feed force (Ff) =** $+27.80+37.17A-8.71B+0.4120C +2.92D-15.85AB-7.78AC16.88AD +13.32BC-4.23BD-9.08CD+38.14A2+2.47B2-10.02C2+8.05D2$ (1)

The variation of feed force with respect to speed and flank wear on the machining characteristics of the metal matrix composites with varying reinforcement shows a positive effect. On the other hand, the interaction of composite of different reinforcement ratio with flank wear and speed over the output feed force showed a minimal effect.

**Cutting force  (Fc) =** $+45.11+38.87A-7.91B+0.9374C+11.55D-20.17A B-9.05AC-19.22AD +10.00BC-4.94BD-7.58CD+48.26A2-0.3736B2-9.63C2+3.60D2$ (2)

The variation of the cutting force with respect to flank wear, cutting speed and feed on the machining characteristics of MMC with varying reinforcement shows the significant effect. On the other hand minimal effect is exhibited in the interaction of flank wear and speed.

**Radial force (Fd) =** $+25.11+33.55A-7.39B+0.2869C +2.92D-12.86AB-6.92AC12.76AD+12.16BC-10.66BD-10.22CD+30.95A2+3.64B2-10.22C2+6.13D2$ (3)

The variation of radial force with respect to flank wear and speed shows the positive effect on the machining characteristics of the MMC with varying reinforcement. On the other hand meagre effect is observed in the interaction of composite of varying reinforcement with cutting speed and feed.

**Surface roughness (Ra) =** $+12.55+0.5901A+0.3592B-0.0485C+0.3982D+0.6165AB+0.4270AC-0.2530AD-0.1749BC+0.1188BD+0.0628CD-0.1882A2-0.4607B2+0.6402C2 -0.2183D2$ (4)

The variation of surface roughness with respect to tool wear, cutting speed and feed on the machining characteristics of the MMC with varying reinforcement shows a positive effect. On the other hand, the interaction of composite of different reinforcement ratio with flank wear and speed over the output surface roughness showed a minimal effect
3. Results and Discussions

3.1 Evaluation of Mechanical and microstructural characteristics

From the mechanical properties Table 1, Tensile strength of the composite were increased by 33% and hardness increased to 43% with the increase in SiC reinforcement content, compared to base material LM 6. The properties of the MMC’s has been changed due to addition of the SiC reinforcement. Figure 1 shows the EDS analysis report for LM6/12% SiC, proves that with the addition of the reinforcement SiC particulate will tend to increase the silicon element peak in the composite. Apart from the major element aluminium, silicon, traces of Fe, Mn, Ni, Cu, Zn, Cu and Mg were identified [10]. The SEM image in figure 2 reveals that there is a uniform distribution of the SiC particles in the LM6/SiC MMC. In the micrograph some porosity regions are identified. This is principally due to the precipitation of the dissolved gas in the melt, incomplete evacuation leads to the formation of the gas entrapment, solidification shrinkage occurs because of inability to feed the voids due to insufficient pressure gradient to overcome the resistant offered by dendritic networks and incomplete infiltration. The micro porosity observed in composite was ascribed to poor nucleation at the SiC particulate sites and due to the particle clustering will hinder the flow of metal. Thereby the presence of porosity in the casting, could be attributed to the fact that, ceramic reinforcement have lower thermal conductivity it needs to be pushed to the solidifying front of a freezing melt. [10, 11].

![Figure 1. LM6/ 12wt% SiC-EDS analysis](image1)

![Figure 2. SEM micrograph of LM6+12%SiC](image2)

3.2 Effect of process parameters on composite machining

The interaction effect of the process parameters, associated output in terms of graphical representations/3D surface plot derived from DOE using Response Surface Methodology (RSM) approach have been presented below.
3.2.1 Effect of reinforcement on force components

The variation of the force components respectively Feed force, Cutting force and Radial force with the Reinforcement and Flank wear is depicted in Figure 3 (a-c).

![Figure 3 (a-c). Variation of the force component with the reinforcement and flank wear](image)

From the surface plots, it is evidenced that the force components showed a increasing trend with the increase in the addition of reinforcement or in other terms upsurge in the volume fraction of the particulates. When the reinforcing percentage ascends from 0% to 12% the feed force varies from 25-75N, cutting force shifts from 50 N to 100N and radial component of force sways from 25-70 N. The addition of reinforcements/particulate matter to the aluminium matrix can lead to possible increase in yield strength of the composite which is attributable to the entangling/pinning/restrainment of the reinforcement particle in the matrix boundary. These observations are in conformance with the findings of the previous researchers [12,13].

The influence of flank wear on force components is shown in figure 3 (a, b, c). The increasing trend of the flank wear results in significant increase in the force components which could be ascribed to the aggravated ploughing of the tool on the matrix composites with subsequent increase in the size of the wear land. With further progress in the size of the wear land cutting force increases resulting from the effective secondary rubbing action between the wear land and work piece.

3.2.2 Effect of feed on force components

The influence of feed rate on force components is shown in figure 4 (a-c).
Figure 4. (a-c). Variation of the force component with the reinforcement and feed

It is inferred from the plot that, increase in feed rate is directly associated to enhance metal removal rate within the same time period. As MRR peaks up, the cutting force required to cut the material subsequently increasing the plastic deformation and heat generation. Moreover, increased feed rate promotes the friction between the cutting edge of the tool and workpiece which shoots up the cutting force.

With rise in feed, high forces were essential to deform the material within the short period of time elevating the temperature at tool tip-work material interface. The heat created at the tool interface was dissipated through chips rather than work material retaining the heat. Material removal takes place within a short time requiring high cutting forces

3.2.3 Effect of Speed on force components

The influence of cutting speed on force components is shown in figure 5 (a-c).

The increase in cutting force with increase in cutting speed could be ascribed to the existence of elevated temperature at the tool tip zone/cutting segment leading to increased wear in the flank portion of the tool and thereby peak in cutting force component [12] Further the presence of silicon carbide which can withstand higher/increased thermal gradient does not get softened and so the softening effect is not more pronounced which aids in the reduction of cutting force.
3.2.4 Effect of Surface roughness (Ra) on force components

The variation of surface roughness with feed rate is shown in the figure 6.

Figure 5 (a-c). Variation of the force component with the reinforcement and speed

Figure 6. Variation of the surface roughness (Ra) with the feed and speed
With rising trend in feed rate the surface roughness of the machined surface increases. MRR is also high at increased feed rate creating friction at the tool-work interface resulting in pitting marks. With increase in feed rate higher heat is accumulated at the zone of cutting which can be ascribed to higher thermal loading/thermal gradient. Rise in temperature lowers the bonding affinity thereby strength between the matrix and Silicon carbide is reduced. Hence increase in feed rate leads to the generation of pits resulting from pulling out of the SiC particles from MMC that counteracts at the tool-work interface. Similar trend is observed by Dwivedi et al [14]

The variation of surface roughness with cutting speed is shown in figure 6. At lower speed, temperature gradient is more pronounced at the tool-work interfaces promoting the formation of unstable larger Built-Up-Edge (BUE) as shown in the figure 7, accompanied by fracturing of chips creating rough surface and adhesive wear on the tool. As the cutting speed peaks up the time consumed in machining is reduced drastically, decreasing the tool-chip contact length and friction impeding the formation of BUE, occurrence of chip fracture leading to improved surface finish [13,15]

The variation of surface roughness with percentage addition of reinforcement could be attributed to the presence of harder Silicon carbide particles in the matrix. Also presence of pores, shearing /pull out of the surface during machining can deteriorate the surface leading to increased surface roughness.

Figure 7 (a-b). Formation of Built up edge and tool wear

3.3 Numerical optimization of machining variables

Desirability chart for solution as shown in the figure 8 is generated thorough numerical optimization, represents the factors and the responses individually in the desirability graph. Overall desirability of the parameters and responses are indicated in the bottom of the histogram bar. The desirability value of responses lies in the range of 0.92 to 1. The value of the complete desirability is 0.970 and it indicates that the regression equation offers better performance under optimal conditions.

Figure 8. Desirability solution chart
3.4 Validation of model

Figure 9. Predicted vs Actual value for Ff

Predicted and actual values shown in the figure 9. The values of predicted and actual experimental data shows the good correlation.

4. Conclusions

The machining characteristics of LM6 aluminum alloy was investigated experimentally. Tungsten Carbide tool tips used in the process were artificially grounded to induce the flank wear. The resulting process responses are optimized using RSM technique for minimizing the component factors. The regression model have been arrived at to predict the output response. The following conclusion are drawn.

- LM6/SiC MMC with varying 0, 4, 8 and 12wt% SiC reinforcement percentage are fabricated for sound casting by using the stir casting method. SEM analysis of the casting shows fairly uniform distribution of SiC Particulates, agglomerates and micro porous sites. EDAX confirms the validation of the fabricated composite. It shows the predominance of aluminium and silicon in the composite.
- Response surface methodology established using the functional relationship between the cutting forces and cutting parameters showed the 95% confident interval for the mathematical model and predicted values of the cutting forces responses. The force components showed an increasing trend with increasing flank wear, feed and addition of reinforcement. Decrement in the feed rate results in better surface finish of the machined component.
- Optimized force components for the given set of input attributes are 7.827 N, 11.196N, 7.890 N and 10.786μm

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