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# MACHINABILITY STUDY ON Al7075/$Al_2O_3$-SiC HYBRID COMPOSITES

*Ravikumar M* [1]*, *Reddappa H N*[2], *Suresh R*[3], *Rammohan Y S*[4], *Babu E R*[2], *Nagaraja C R*[2]

[1]*Department of Mechanical Engineering, B M S Evening College of Engineering, India*

[2]*Faculty of Mechanical Engineering, Bangalore Institute of Technology, 560004, Bangalore, India*

[3]*Faculty of Mechanical and Manufacturing Engineering, M S Ramaiah University of Applied Sciences, 560058, Bangalore, India*

[4]*Faculty of Aerospace Engineering, B M S College of Engineering, 560019, Bangalore, India*

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## Abstract

In the present research, the effects of volume fraction of SiC+$Al_2O_3$ particles and aging temperature on the machinability of stir-casted Al7075 metal matrix composites (MMC) have been investigated. The hybrid composites were fabricated using the liquid metallurgy route. Al7075 was reinforced with different wt. % of SiC (3%, 6%, and 9%) and $Al_2O_3$ (2%, 4%, and 6%) which were used to fabricate the hybrid metal matrix composites. The samples were aged at different temperatures (140 ºC, 160 ºC, and 180 ºC) for 4 h and cooled at furnace temperature (27 ºC). The machinability of hybrid metal matrix composites was studied by carrying out L27 orthogonal array experiments. Three process parameters were selected, such as 0.2 mm/min of the depth of cut, 0.1 mm/min of feed rate, and 1500 rpm of spindle speed. The obtained results indicate that the surface roughness and machining force of MMCs increase with an increase in weight percentage of $Al_2O_3$/SiC and decrease with the increase in aging temperature. Optimum machining force and surface roughness were obtained at 2% $Al_2O_3$ + 3 % SiC and 180°C of aging temperature.

**Keywords:** hybrid composite; stir casting; machining force; surface roughness.

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*Corresponding author: Ravikumar M, *ravikumar.muk@gmail.com*

## Introduction

Aluminum (Al) composites are extensively used to substitute conventional materials for various applications due to cumulative enactment necessities. In metal composites (MMCs), matrix materials are aluminum, titanium, and magnesium alloys. Whereas, reinforcements in MMC are alumina ($Al_2O_3$), silicon carbide (SiC), graphite (Gr) and boron carbide ($B_4C$), etc. in the form of particulates or fibers. Generally, aluminum matrix composites (AMCs) are known as low-cost composites. These composites offer better strength, improved stiffness, and high fatigue resistance including optimal increases in density over the base alloy. Owing to their higher strength and stiffness, aluminum composites have high utilization in the application of aerospace and automotive industries. Machining of these aluminum composites is very challenging owing to the presence of the abrasive nature of the reinforcing particulates [1-3].

The mechanical behavior and machinability of the composites are influenced by reinforcing particulates in composites. The word which defines the operative features of a cutting tool during machining a composite material is relatively defined and is generally arbitrated in terms of material removal rate (MRR), tool life, and surface finish. However, MMCs are produced to required accurate shape, essential equipment often is desired for machining. The characteristics of machining depend on the reinforcing material, reinforcement type (particulates/whisker), uniform dispersal of reinforcements within the matrix, and wt. % of the reinforcements. Generally, the machining of MMCs is different compared to the machining of metal due to the presence of brittle and hard reinforced particulates. During machining of composites, the cutting tool meets reinforcement and base matrix materials alternatively, where the reaction to machining process is completely different. The foremost problem during the machining of MMC is high tool wear and which leads to an inefficient manufacturing process. Here, machining of MMCs calls for exceptional demands on wear resistance and geometry of the cutting tool/s [3].

Best mechanical properties obtained by reinforcement in composites also significantly affect the characteristics of the machinability. Though, being anisotropic, non-homogeneous, and hard abrasive particulates, the composites are very hard to machine. Generally, the machining of MMCs is influenced by the properties and comparative content of the matrix and the reinforcements as well as the machining condition. The machinability of composite materials usually depends on their structure, properties, and cutting tool material.

Due to the poor machinability, in industries, composites are not widely used. Due to the existence of hard reinforcing materials like silicon carbide (SiC) and alumina ($Al_2O_3$), machining is very tedious. Although metal matrix composites have frequently been produced with near-net shape (very close to the final) processing methods, the secondary or finishing machining processes are essential in order to attain the required dimensional precision with good surface texture. The machinability analysis aims at the assessment of machining performance based on the work material, cutting fluids, cutting tools, and machining circumstances to produce acceptable components which conform to the required dimensional surface finish. The word machinability describes the characteristics of the cutting tool and is generally judged based on the resultant force, tool life, surface finish, work-tool temperature, and material removal rate. Meanwhile, in the manufacturing process, machining is very essential in industries for manufacturing purposes. Machinability feature is a substantial requirement for manufacturing purposes to identify the characteristics of machinability so that the process can be scheduled in an efficient way. It is beneficial to identify the machining features of composites to be treated in addition to their material properties for process planning. Thereafter, the enhanced application of machining by automation has been attentive to the accessibility of dependable machinability which confirms the optimal production by using modern equipment. Even in conventional manufacturing methods, more work should be done to deliver consistent statistics for production causes to permit them to set accurate standards for different processes of machining concepts [4-7].

The presence of hard ceramic reinforcements affects the machinability of MMCs considerably. These hard ceramic particulates present in composites cause a problem of increased tool wear. Particles size and wt. % of the reinforcements play an important role in the machining of MMCs. The surface-finish of machined workpiece mainly depends on the size and wt. % of particulates. *Tamer Ozben et al.* [1] studied the effect of reinforced ratios of 5-15 % of SiCp on machinability properties and surface roughness (Ra) was studied. It was noted that by increasing the wt. % of reinforcements, tool wear was reduced at lower cutting speed when the feed rate and the depth of cut were kept constant. The effect of reinforcement ratio is assessed under varying feed rates at 0.1, 0.2, and 0.3 mm per rev. By increasing the feed rate, Ra value was determined by maintaining the constant depth of cut and cutting speed. When the feed rate was constant, it was found that flank wear within the cutting tool increased as the wt. % of reinforcements were increased. During machining, the presence of small gaps on machined surfaces due to the removal of SiC particles was observed. It is predicted that this circumstance caused an increase in the Ra value of MMCs. It was revealed that the Ra value of composite samples with high reinforcement content was higher than composite samples which have low reinforcement content.

*Kannan et al.* [9], in their research, noted an increase in wt. % of particulates showed high tool wear and consequently affected the Ra value of the composite samples. High tool wear was caused due to the hard ceramic particulates. The surface-roughness worsened during wet cutting due to operative reddening away of the moderately un-bonded particulates creating microvoids. *Ibrahim et al.* [10] in their investigation, SiC reinforced MMCs with different particle sizes were produced by stirring-squeeze casting method. It was revealed that the particle size and wt. % of reinforcement, together with cutting speed were the main parameters that affected the life of the cutting tool. *Krishnamurthy et al.* [4] in their research, studied the machinability features of SiC reinforced AMMCs. Experimentations were conducted by applying DOE (Design of Experiments) method & concept of regression analysis models. It was observed that the most significant factor was the wt. % of reinforcement. In SiC reinforced AMMCs, the maximum wt. % of reinforcement resulted in higher resultant force as the presence of SiCp increased the hardness in the composite. *Rabindra Behera et al.* [5] in their research, LM6 was reinforced by 5% and 10% of SiC particulates with a mesh size of 400 µm. It was observed that the machinability of aluminum composites differed from traditional materials due to the existence of hard reinforcement particulates. During the machining process, it was observed that the cutting forces increased by an increase in wt. % of SiC. *Rabindra Behera et al.* [11] investigates the effect of machining parameters of LM6 reinforced by SiCp at varying wt. % (7.5%, 10%, and 12.5%) of SiCp. The outcomes revealed that higher wt. % of SiC reinforcements reported a high surface-roughness on the composite samples and required high machining forces. In order to maximize production rate and to minimize cost simultaneously; Taguchi's optimization approach was applied. In this research work, surface roughness and machining force have been reported to demonstrate some aspects of the process parameters of the investigation. In the present paper the effect of wt. % of reinforcement and aging temperature on surface roughness and cutting forces in machining of $Al_2O_3$-SiC reinforced Al7075 hybrid composites were investigated.

## Experimental work

### *Materials and method*

In order to attain better mechanical properties of MMCs, a virtuous bonding between the matrix and reinforcements has to be attained. Stir casting is one of the simplest and low-cost techniques followed to fabricate MMCs which have been effectively implemented by many investigators. This technique is the most cost-effective method used to produce MMCs with particulates and this process is considered in this work to obtain the cast samples. In the present investigation, hybrid MMCs were produced using Al-7075 reinforced with particulates such as $Al_2O_3$ - SiCp by stir-casting technique. $Al_2O_3$ particulates size of 20-30 microns with pH value between 6.5-7.5 and SiC particulates size of 30-35 microns were used as reinforcements in this work. During the preparation of cast samples, required precautions have been taken to maintain optimal casting parameters like 150 rpm of stirring speed, 2 min of stirring time, and finally pouring temperature of 700°C. Here, hard ceramic reinforcements were pre-heated and then mixed in the molten melt. To reduce the porosities, degassing agents were used. The molten melt was poured into the mold box made up of cast iron. After the solidification, cast samples (composites) were removed from the mold box. Cast samples were machined according to ASTM standards using CNC turning. The test samples specimens are depicted in Fig. 1. The hardening of cast specimens was carried out at 490 °C for 2 h and then they were quenched in oil. Finally, age hardening was carried out at different temperatures of 120 °C, 140 °C, 160 °C, 180 °C, and 200 °C for the duration of 4 h and cooled at room temperature (27 °C).

Composites samples for the metallographic study were prepared by polishing through grit papers of different sizes by using diamond to get a fine finish on the sample surfaces. Thereafter the samples were etched by using Keller"s reagent which is known as the etching agent. Subsequently, etched samples (both as cast and composites) were dried in air. Uniform dispersal of ceramic particulates in the matrix was detected by optical microscope equipment (Nikon E-200). Fig. 2 (a and b) depict the microstructure of composites with a uniform dispersion of ceramic particles in the matrix. The changes in material properties are affected by the variation in microstructure and material composition at the obligatory direction [8 and 12]. In the current research work, machinability characteristics for $Al_2O_3$/SiCp reinforced composites were studied using ϕ8 mm flat end-mill of carbide tool in CNC milling machine. A machinability study was performed on the basis of fixed factors such as 0.2 mm/min of the depth of cut, 0.1 mm/min of feed rate, and 1500 rpm of spindle speed. Specifications of the CNC milling machine equipped in this study are maximum speed 600rpm, maximum feed rate: 3000 mm/min, cutting tool working directions: X, Y & Z, maximum workpiece size: 360 x 360 mm, bed size: 800 x 400 mm, make: FANUC Series (OJ MADE MD). CNC machine used for machinability study is depicted in Fig. 3. Surface roughness (Ra value) of machined surface was assessed and the results were evaluated. The apparatus specifications are: measuring range: 350 µm (Z-axis stroke), measurement of speed: 0.25 mm/sec to 0.5 mm/sec and tip radius 5 µm (200 µinch). The testing equipment setup is as shown in Fig. 4.

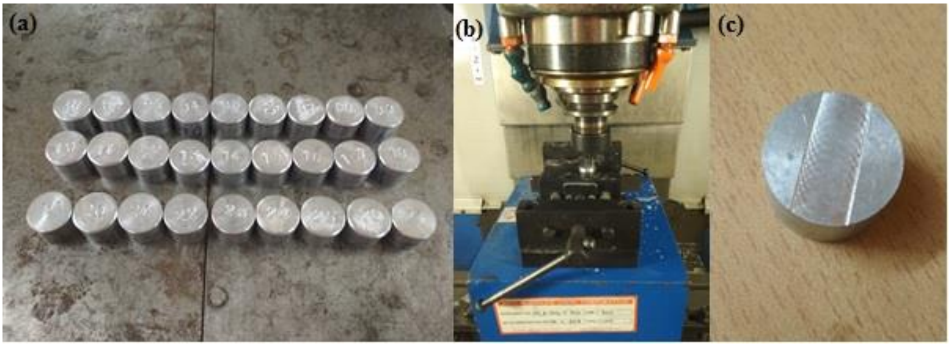


*Fig. 1. Specimens for machinability test.*

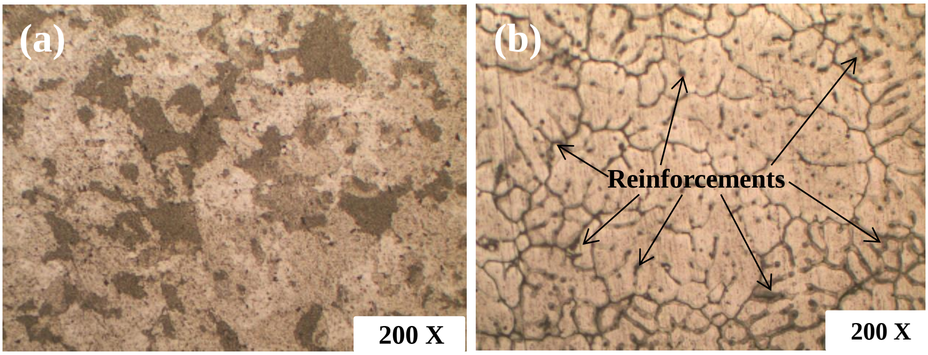


*Fig. 2. Optical Micrograph of (a) Pure Al alloy in as-cast condition (b) Al 7075 reinforced with $Al_2O_3$-SiCp with uniform dispersal.*

*Fig. 3. CNC milling machine.*

*Fig. 4. Surface roughness testing equipment.*

### *Design of experiments*

DOE method was implemented to evaluate the effect of reinforcements on machining force and Ra values of composites. Based on the Taguchi technique, L27 OA (orthogonal array) was considered for minimizing the number of experimental trials. The process parameters (factors) considered for the current investigation are vol. % of $Al_2O_3$ / SiC and temperature of heat treatment. Levels for each parameter were designated as shown in Table 1. Pilot experiments were conducted and selected the levels of each parameter. The reinforcement's levels of $Al_2O_3$: 1% - 6%, SiC: 2% - 10% and aging temperature 120°C - 200°C were selected. We observed that the best physical and mechanical properties were obtained at 6% $Al_2O_3$, 9% SiC and an aging temperature of 180°C. Further increasing the reinforcement, the properties of the composite are decreased. Finally, $Al_2O_3$ reinforcement with three levels 2, 4, and 6 wt.%, SiC reinforcements with three levels 3, 6, and 9 wt.%, and aging temperature with 140°C, 160°C, and 180°C were used for the Taguchi optimization process.

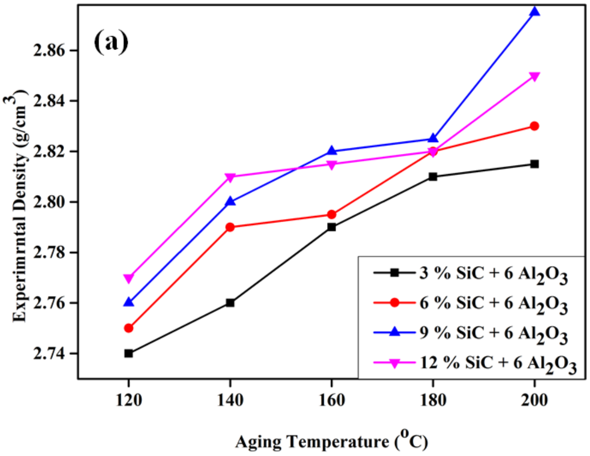
*Table 1. Levels of parameters.*

| Process parameters | Level-1 | Level-2 | Level-3 |
|---|---|---|---|
| $Al_2O_3$ (wt. %) | 2 | 4 | 6 |
| SiC (wt. %) | 3 | 6 | 9 |
| Heat-treatment (°C) | 140 | 160 | 180 |

## Results and discussion

### *Density and porosity*

The density and porosity of SiC and $Al_2O_3$ reinforced hybrid Al composites are as shown in Fig. 5. The results of density measurement on the hybrid composites are shown in Fig. 5(a). Densities of all the hybrid composites were higher than that of as-cast which may be due to higher density of combined (SiC + $Al_2O_3$) particles than that of pure Al7075 metal matrix.



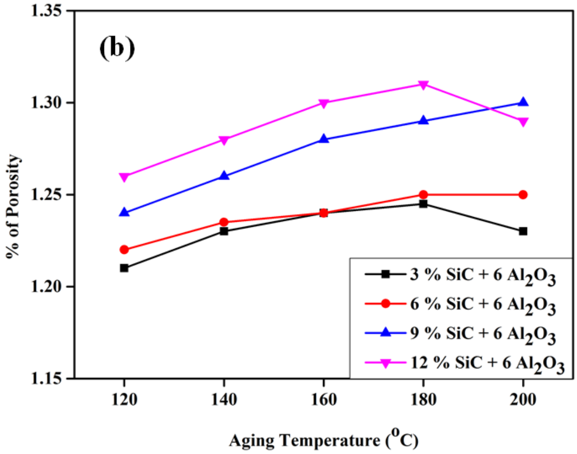


*Fig. 5. Density and porosity of hybrid composites.*

The apparent porosity value of reinforced hybrid composites increased with combined (SiC + $Al_2O_3$) particles addition (Fig. 5(b)). This increase in porosity may be due to the presence of impurities in the metal matrix and combined (SiC + $Al_2O_3$) particles. From the outcomes, it is also observed that density and porosity increased by the increase in aging temperature.

*Tensile strength*

Fig. 6 depicts the variation of tensile strength versus aging temperature of MMCs. It is noted that the tensile strength of composites increased with the increase in aging temperature up to 180 °C and on further increase in aging temperature to 200 °C the tensile strength decreased. It is inferred that for temperature up to 180 °C there is a possibility of formation of coherent precipitates.

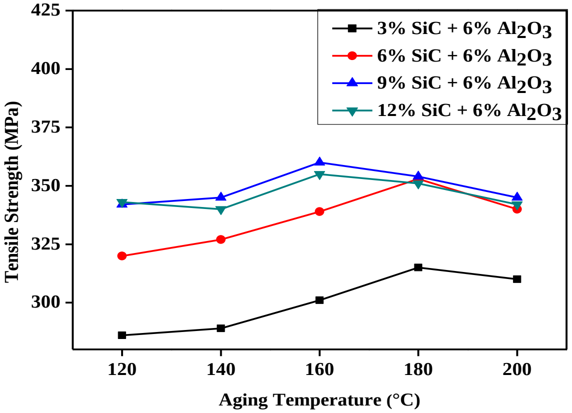


*Fig. 6. Tensile strength of hybrid composites.*

Lattice coherence between the matrix and the precipitates exists up to a certain temperature above which the lattice vibrations produce non-coherent precipitates with the matrix. It is also noted that aging at higher temperatures, in turn, has a coarsening effect on the precipitates which causes poor mechanical properties of MMCs.

Energy dispersive spectroscopy (EDS) study of Al matrix with the $Al_2O_3$ and SiC particles is shown in Fig. 7. The major constituent elements like aluminum, silicon, and oxygen peaks are observed in the EDS analysis and confirm the incorporation of SiC and $Al_2O_3$ particles in Al composites. From the observation, it is said that the small amount of oxygen detected by EDS is probably coming from an oxide ($Al_2O_3$) present during sample preparation.

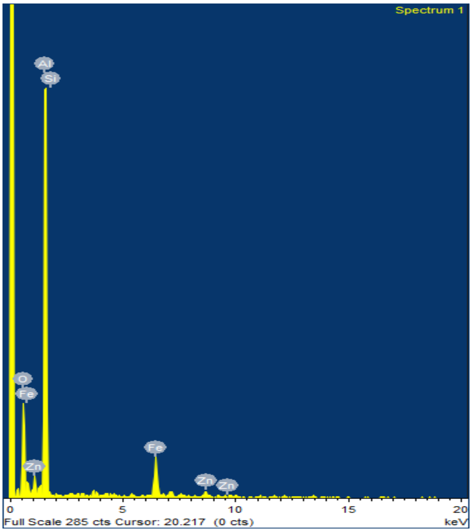


*Fig. 7. EDS spectrum of hybrid composites.*

*Machining force and surface roughness*

Machinability is designated as ‘ease’ by which materials can be machined. The efficiency of a cutting process is influenced by a large amount of the machinability of the material. The machinability cannot be accurately determined; generally, it depends on the principles for evaluation such as surface finish, machining forces, power consumption, and chip formation. Comprehensive experimental work on machinability of $Al_2O_3$and SiC reinforced with Al7075 has been carried out. The output to be investigated is the machining force (Fm). During the trials, the values for Thrust force (Ft), Feed force (Ff), and Cutting force (Fc) data were recorded [6]. A mean force is taken as the mean machining force calculated from the theoretical equation shown in Eq. (1).

$$F_m = \sqrt{(F_t^2 + F_f^2 + F_c^2)} \qquad 1$$

Determination of the optimization is to authenticate the optimal levels of process parameters. The experimental values of machining force and surface roughness for Al 7075 composites under varying process parameters and their outcomes for all trials are tabulated in Table 2.

*Table 2. Experimental results of machining force and surface roughness for L27 OA.*

| Sl. No. | $Al_2O_3$ (wt. %) | SiC (wt. %) | Aging Temperature (°C) | Machining force, Fm (N) | Surface roughness, Ra (μm) |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 140 | 5.77 | 0.506 |
| 2 | 2 | 3 | 160 | 6.38 | 0.698 |
| 3 | 2 | 3 | 180 | 7.26 | 0.751 |
| 4 | 2 | 6 | 140 | 11.59 | 1.684 |
| 5 | 2 | 6 | 160 | 12.01 | 1.439 |
| 6 | 2 | 6 | 180 | 9.95 | 1.575 |
| 7 | 2 | 9 | 140 | 18.10 | 2.458 |
| 8 | 2 | 9 | 160 | 15.45 | 2.645 |
| 9 | 2 | 9 | 180 | 15.96 | 2.148 |
| 10 | 4 | 3 | 140 | 8.91 | 2.481 |
| 11 | 4 | 3 | 160 | 9.68 | 2.568 |
| 12 | 4 | 3 | 180 | 9.97 | 2.231 |
| 13 | 4 | 6 | 140 | 13.56 | 2.473 |
| 14 | 4 | 6 | 160 | 13.88 | 2.589 |
| 15 | 4 | 6 | 180 | 9.29 | 2.689 |
| 16 | 4 | 9 | 140 | 16.32 | 3.354 |
| 17 | 4 | 9 | 160 | 16.88 | 2.994 |
| 18 | 4 | 9 | 180 | 17.45 | 3.012 |
| 19 | 6 | 3 | 140 | 12.25 | 3.536 |
| 20 | 6 | 3 | 160 | 10.84 | 3.225 |
| 21 | 6 | 3 | 180 | 9.74 | 2.895 |
| 22 | 6 | 6 | 140 | 17.69 | 3.653 |
| 23 | 6 | 6 | 160 | 15.30 | 3.654 |
| 24 | 6 | 6 | 180 | 15.20 | 3.684 |
| 25 | 6 | 9 | 140 | 18.59 | 3.846 |
| 26 | 6 | 9 | 160 | 17.92 | 3.758 |
| 27 | 6 | 9 | 180 | 15.68 | 3.845 |

ANOVA models were considered to determine the machining force and Ra value which are given by regression equations. The effect of significance was verified by the predictable regression analysis method. The effect of machining force and surface roughness are explained by ANOVA results.

*Table 3. ANOVA results of machining force.*

| Source | DOF | Seq. SS | Adj. SS | Adj. MS | F-value | P-value | Cont. % | Remarks |
|---|---|---|---|---|---|---|---|---|
| $Al_2O_3$ | 1 | 52.497 | 9.172 | 9.1716 | 5.8196 | 0.025573 | 13.44 | Significant |
| SiC | 1 | 284.411 | 12.346 | 12.3456 | 7.8335 | 0.011085 | 72.85 | Significant |
| Aging Temperature | 1 | 8.378 | 1.152 | 1.1578 | 0.7347 | 0.401529 | 2.14 | Insignificant |
| $Al_2O_3$ * SiC | 1 | 9.612 | 9.612 | 9.6123 | 6.0992 | 0.022652 | 2.46 | Significant |
| SiC * Aging Temperature | 1 | 1.307 | 1.307 | 1.3068 | 0.8292 | 0.373351 | 0.33 | Insignificant |
| Aging Temperature * $Al_2O_3$ | 1 | 2.632 | 2.632 | 2.6320 | 1.6701 | 0.210980 | 0.67 | Insignificant |
| Error | 20 | 31.520 | 31.520 | 1.5760 | | | 8.07 | |
| Total | 26 | 390.357 | | | | | 100 | |

Table 3 depicts the ANOVA outcomes of machining force for the composites. It is seen that the SiC has maximum significance due to the highest percentage contribution (72.85%) among all process parameters. $Al_2O_3$ (13.44%) and aging temperature were the least significant individual factors (2.14%). Two-factor interaction has 2.46 % ($Al_2O_3$ * SiCp) contributions, while the contributions of the other two combination parameters are less. The combined error due to all factors is 8.07%. The machinability of hybrid composite varies from that of traditional material due to the existence of hard reinforcing particulates. In milling processes, the material cutting forces gradually increased due to an increase in wt. % of SiC content [13].

*Table 4. ANOVA results of surface roughness (Ra).*

| Source | DOF | Seq. SS | Adj. SS | Adj. MS | F-value | P-value | Cont. % | Remarks |
|---|---|---|---|---|---|---|---|---|
| $Al_2O_3$ | 1 | 18.3860 | 0.6215 | 0.62150 | 12.7486 | 0.001915 | 73.11 | Significant |
| SiC | 1 | 4.6706 | 0.2106 | 0.21065 | 4.3209 | 0.050732 | 18.57 | Significant |
| Aging Temperature | 1 | 0.0749 | 0.0001 | 0.00012 | 0.0026 | 0.960123 | 0.29 | Insignificant |
| $Al_2O_3$ * SiC | 1 | 1.0226 | 1.0226 | 1.02258 | 20.9759 | 0.000182 | 4.06 | Significant |
| SiC * Aging Temperature | 1 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.992789 | 0.001 | Insignificant |
| Aging Temperature * $Al_2O_3$ | 1 | 0.0159 | 0.0159 | 0.01591 | 0.3264 | 0.574128 | 0.06 | Insignificant |
| Error | 20 | 0.9750 | 0.9750 | 0.04875 | | | 3.87 | |
| Total | 26 | 25.1450 | | | | | 100 | |

Results of this investigation were analyzed using ANOVA for identifying the level of significance of factors affecting the surface roughness (Ra). From Table 4, it is observed that $Al_2O_3$ has high significance having a maximum percentage contribution of

73.11% among all other parameters. SiC (18.57%) and aging temperature are of least significance of individual factors (0.29%). Two-factor interaction has 4.06 % ($Al_2O_3$ * SiC) contributions, while the contributions of the other two combination parameters are less. The combined error due to all factors is 3.87%. After the test trials according to Taguchi's technique, the main effects Plots (MEP) for machining force and surface roughness of the MMCs have been graphically represented. The MEP of process parameters w.r.t machining force and Ra values for MMCs is depicted in Fig. 8 and 9.

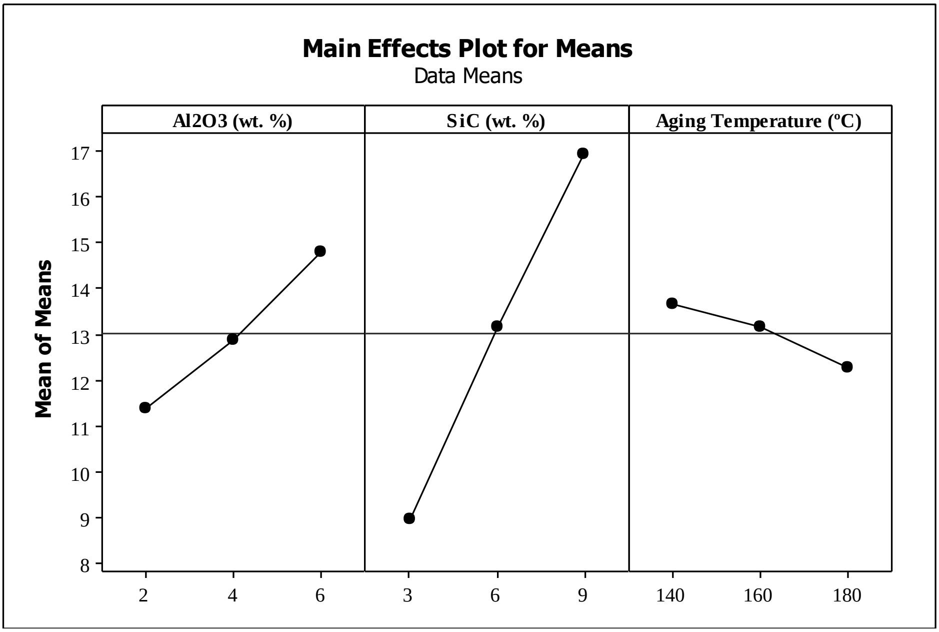


*Fig. 8. Main effect plot for machining force.*

Fig. 8 depicts the MEP for machining force and the "smaller the better" criteria are considered for analysis. The graph clearly indicates that level-1 of $Al_2O_3$, level-1 of SiCp, and level-3 of aging temperature are the optimum points of machining force of hybrid MMCs in this study. The machining force increased with the increase of wt. % of particulates. When machining ceramic reinforced hybrid MMCs, instead of generating a single crack within the shear region for homogeneous materials, fracture crack at first initiated above the SiCp and then extended underneath the particulates. Particle rotation feature is present, which is the basic reason for the presence of high surface roughness which causes an increase in machining forces. It is also observed that machining force decreased by the increase of aging temperature due to the formation of brittleness. A MEP for Ra values was drawn as depicted in Fig. 9 to find the optimum parameters for machining by which a better surface finish can be obtained. The graph clearly indicates that level-1 of $Al_2O_3$, level-1 of SiCp, and level-3 of aging temperature are the optimum points that correspond to the better surface finish of composites in this study [14, 15]. It is observed that the surface roughness decreased by increasing aging temperature. This is owing to fact that the tendency towards BUE formation deteriorates due to increasing aging temperature which results in the decrease of frictional stress on MMCs [15]. Better surface roughness was obtained for the heat-treated samples when compared to the un-heat treated samples. This is similar to the observation made by other researchers [16]. The effect of all the three factors i.e. $Al_2O_3$, SiCp & temperature of heat-treatment and the interactions among the factors were assessed using ANOVA. If the plots indicate parallelism between interaction lines and other parameter lines it is inferred that no interaction exists among the parameters. Whereas, if the plots are not parallel to each other then it shows the presence of interaction among the parameters [17]. Fig. 10 and 11clearly show the interaction plots of the considered factors on machining force and Ra values. This graphical representation indicates the effects of interaction for all the three varying parameters i.e., wt. % of $Al_2O_3$, SiCp, and temperature of heat-treatment together for better visualization.

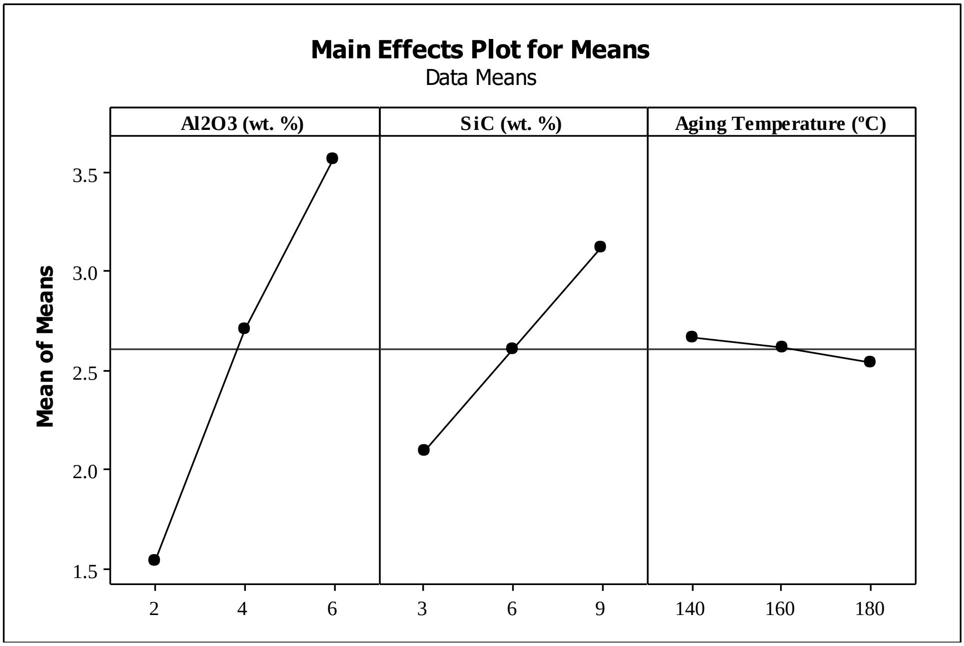


*Fig. 9. Main effect plot for surface roughness.*

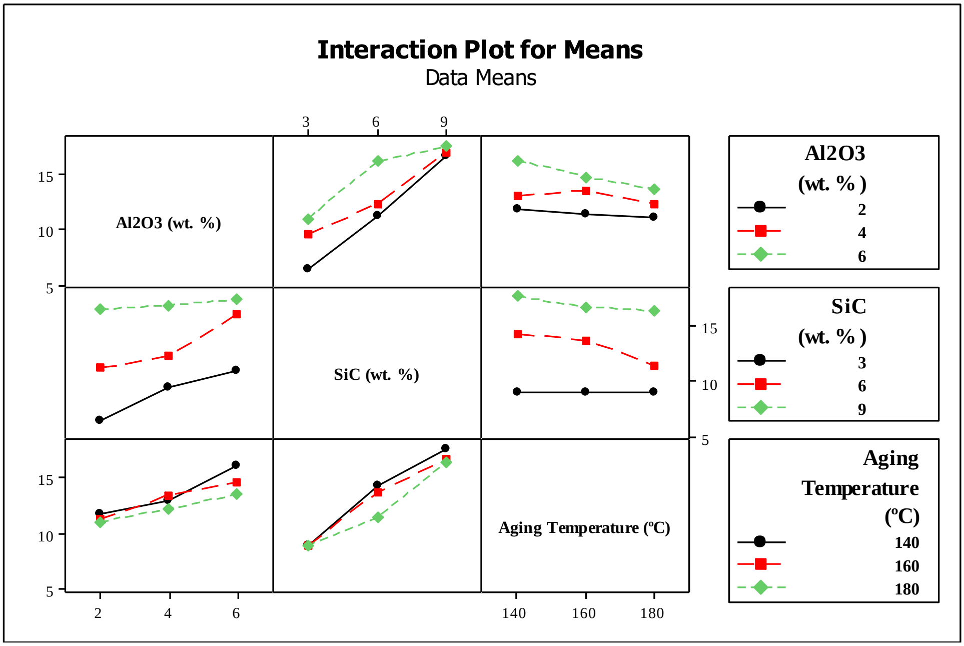


*Fig. 10. Interaction Plot for machining force.*

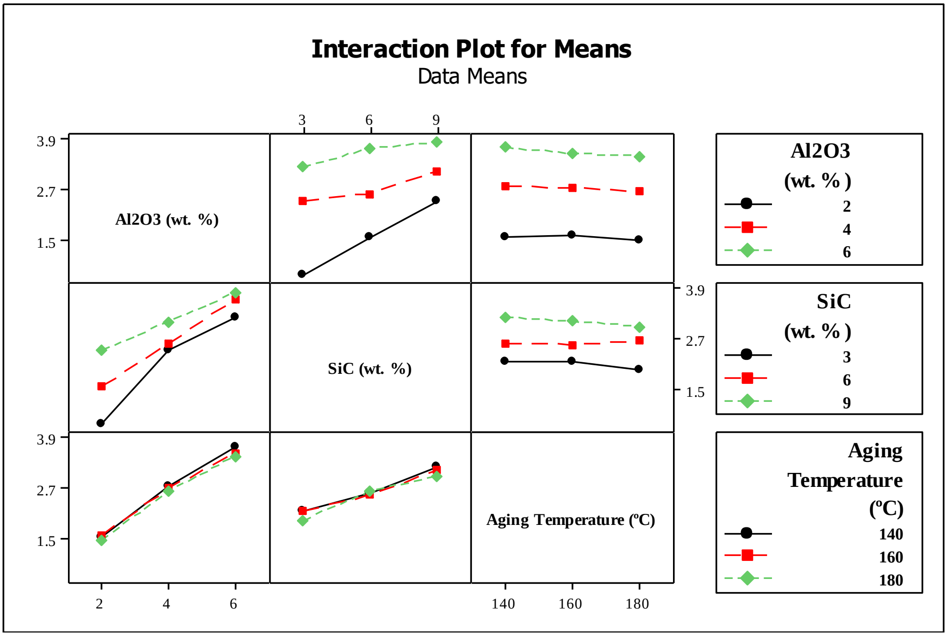


*Fig. 11. Interaction plot for surface roughness.*

The machinability of hybrid MMCs varies from that of traditional materials due to the existence of hard-reinforcing particulates. In milling processes, the material cutting forces gradually increased due to an increase in wt. % of SiC content [5, 18, 19, 20]. Fig. 10 shows the interaction plots among the process parameters of machinability. The machining force shows better interaction plots due to the appreciable effect of interaction between the parameters. The interaction plots for parameters like $Al_2O_3$, SiC, and aging temperature for surface roughness are shown in Fig. 11. In these plots, the significance of every process parameter can be gauged by the inclination of lines. Differing values of surface roughness are seen owing to a robust effect of interaction between all the parameters. To forecast the properties of hybrid MMCs, regression analysis has been used. Regression equations have been used to predict the machining force and surface roughness among the parameters used. These equations generally used are in the form of Y = f (A, B, and C). Where Y indicates the performance characteristics (machining force/surface roughness). A, B, and C are the varying parameters such as $Al_2O_3$ / SiC (wt. %) and temperature of Heat-Treatment (HT) in the present investigation. The equations (regression equation) for machining force and surface roughness are as follows:

Machining force = -9.23815 + 3.62222 $Al_2O_3$ + 2.80167 SiC + 0.0457222 Aging Temperature - 0.149167 $Al_2O_3$ * SiC - 0.0055 SiC * Aging Temperature - 0.0117083 Aging Temperature * $Al_2O_3$(2)

Surface Roughness = -1.6767 + 0.942917 $Al_2O_3$ + 0.365963 SiC + 0.000475 Aging Temperature - 0.0486528 $Al_2O_3$ * SiC - 9.72222e-006 SiC * Aging Temperature - 0.000910417 Aging Temperature * $Al_2O_3$ (3)

To check the accuracy of the test trials, experimental trials were executed and the comparison between the experimental results with predicted results is witnessed through graphical representations. The outcomes of experimental versus predicted values for machining force and surface roughness are plotted graphically for all the levels of factors are depicted in the Figs. 12 and 13.

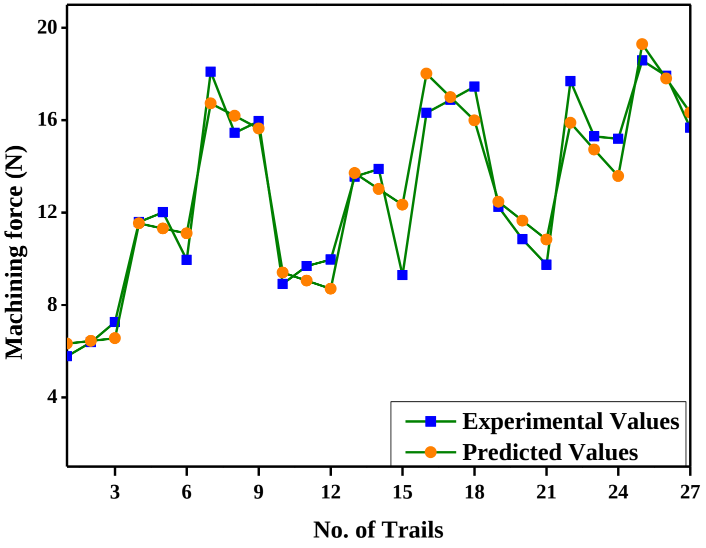


Fig. 12. Comparison plot of experiment values vs. predicted values for machining force.

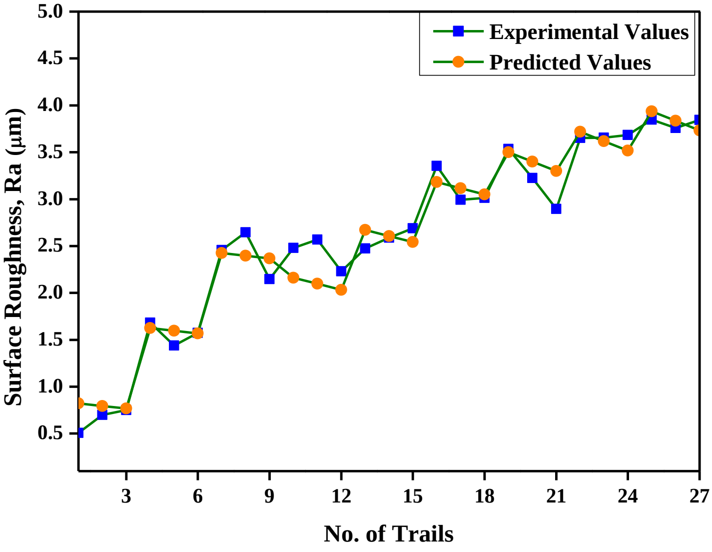


*Fig. 13. Comparison plot of experiment values vs. predicted values for surface roughness.*

Based on the results of machining force and surface roughness, the ranks of the parameters in the response table depicts the SiC in machining force, $Al_2O_3$ in surface roughness as a high significant parameter since delta of means have been ranked it 1 based on the three parameters which were considered within the study, a distinctive response has been tabulated in the Tables 5 and 6.

*Table 5. Response table for machining force.*

| Level | $Al_2O_3$ | SiC | Aging Temperature |
|---|---|---|---|
| 1 | 11.386 | 8.978 | 13.642 |
| 2 | 12.882 | 13.163 | 13.149 |
| 3 | 14.801 | 16.928 | 12.278 |
| Delta | 3.416 | 7.950 | 1.364 |
| Rank | 2 | 1 | 3 |

*Table 6. Response table for surface roughness (Ra).*

| Level | $Al_2O_3$ | SiC | Aging Temperature |
|---|---|---|---|
| 1 | 1.545 | 2.099 | 2.666 |
| 2 | 2.710 | 2.604 | 2.619 |
| 3 | 3.566 | 3.118 | 2.537 |
| Delta | 2.021 | 1.019 | 0.129 |
| Rank | 1 | 2 | 3 |

The main reason for the confirmation test is the optimization of process parameters levels [21]. The confirmation test depicts the best combinations among the process parameters and their levels. Composite samples were prepared based on the parameters optimized from the Taguchi technique and the samples were subjected to machining force and surface roughness tests. From the study of Taguchi analysis, the optimized process parameter and confirmatory outcomes for machining force and surface roughness values are tabulated in Table 7.

*Table 7. Optimized process parameters and confirmatory outcomes for machining force and surface roughness.*

| Process Parameters | Optimized Values | | Confirmatory outcomes | |
|---|---|---|---|---|
| | For machining force | For Surface roughness | Machining force, Fm (N) | Surface roughness, Ra (µm) |
| $Al_2O_3$(wt. %) | 2 | 2 | 6.89 | 0.705 |
| SiC(wt. %) | 3 | 3 | | |
| Aging Temperature (°C) | 180 | 180 | | |

## Conclusions

In the research, the Al 7075-SiC-$Al_2O_3$ hybrid MMCs were successfully produced by the stir casting technique. The machining force and Ra values were evaluated. The outcomes are summarized as follows:

- Machining force and surface roughness varied almost linearly with an increase in wt. % of reinforcements and aging temperature.
- The addition of $Al_2O_3$and SiC particles increased the machining force and surface roughness in MMCs. It was caused by the rubbing of hard particles on the soft matrix.
- Cutting forces such as Ft, Ff and Fc decreased on an increase of aging temperature. Ra values of composites increased by increasing the wt. % of $Al_2O_3$ and SiC and decreased on an increase of the aging temperature.
- Machining parameters were optimized by using Taguchi's method for reducing the machining force and surface roughness.
- Optimum parameters for minimization of machining force and surface roughness are obtained at 2 wt. % of $Al_2O_3$, 3 wt. % of SiC and 180 °C of aging temperature.

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