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Role of Silicon Carbide on Mechanical Characterization and Machinability Optimization of Aluminium Alloyed With Copper

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ABSTRACT: *Aluminium copper alloy with reinforcement of silicon carbide possess improved strengths over conventional metals. Machining of these composites occupies a key role while their fabrication suitable for different applications. This is due to acquired hardness of the alloy upon addition of silicon carbide which creates difficulty of machining of the composite. Aluminium copper alloy with particulates of silicon carbide is studied for mechanical strength and turning behaviour using HSS tool with reinforcement varied as per design of experiments. Tensile strength and hardness have improved with increase in percentage addition of silicon carbide. Increase in feed results in corresponding increase of cutting force, tool wear and surface roughness. Whereas, addition of silicon carbide though reduces cutting force but affects surface roughness.*

KEYWORDS: *Copper Alloy, Design of experiments, Feed, Machinability, Silicon Carbide*

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I. INTRODUCTION

Enhanced characteristics of aluminium are observed in its alloy form in contrast to its purity. Copper is the preferred alloying element because of improved thermal resistance and strength. Addition of copper by 6 wt. % has resulted in linearity of increased hardness, reduction in corrosion rate, impact energy and grain size than by 3 and 9 wt. % [1]. Separate addition of 6% Zn and 8% Cu has exhibited higher tensile strengths than their equal inclusion of 10% in Al-Sic-Zn-Cu composites [2]. High strength and low weight is evidenced by the maximum tensile strength at 15% for 5% -20% SiC addition to aluminium [3]. Vickers hardness values are found to be best at 70% weight fraction when 40% - 70% reinforcement of SiC is added to aluminium fabricated by powder technology using X-ray diffraction [4]. Decrease of wear rate as a result of increase in hardness is due to 4 - 10% addition of SiC [5]. First pass of SiC particles in stir zone has resulted in higher micro hardness than third pass in friction stir processing of aluminium [6]. Fatigue strength increases with 0.5 to 1.5 % addition of SiC and is higher than for identical addition of Al2O3 in 4% Cu alloyed Aluminium [7]. The surface composite layer of SiC has a lower specific wear rate of 27% than AA2024 aluminium alloy [8].

Improved tensile strength and hardness but with low ductility caused due to hardness is the result of 3-15% SiC reinforcement to Al-Si alloy [9]. High ratio of strength to weight and reduced impact strength are noticed with 5 to 20 % SiC in Al 6063 alloy [10]. Tungsten carbide, molybdenum carbide, titanium carbide and iron carbide when added individually to aluminium also provide similar characteristics [11]. SiC as reinforcement also influences aluminium alloy when it is machined both conventionally and non-conventionally. Tool life of MCD and PCD tools are better than WC tool in turning AA2124 alloy with 25 % SiC [12]. But, similar trend is not observed for PCD tools while turning A356 alloy reinforced by 20% SiC [13]. Depth of cut and feed affect cutting force while surface roughness is influenced by feed when Al/SiC/10p/ composites are turned [14]. Cutting speed of 100 to 200 m/min, 0.4 to 0.6 mm depth of cut and a feed of 0.4 mm/rev provide optimal surface finish during turning of LM 13 alloy reinforced with 15% SiC using carbide insert [15].

It is observed that machining of aluminium composites is as important as their applications. A parametric study of turning characteristics of aluminium-copper-silicon carbide composites is considered in this investigation.

II. MATERIALS

Al2419, an alloy of aluminium with copper, is the base material the spectrum analysis details of which are provided in Table-1. Silicon carbide particulates of 25 microns are reinforced to aluminium in the range 0-8%. Cutting speed, depth of cut and feed are the machinability parameters considered. Values of SiC and machinability parameters are based on Central Composite Design (CCD), an experimental technique of Response Surface Methodology (RSM). Values at five levels of all the factors for machinability of Al-SiC composites are given in Table-2. Large information in less number of trials can be obtained as CCD is a comprehensive experimental technique. Conventional experiments require $L^K = 5^4 = 625$ trials for each of the four factors of Table-2 varied at 5 levels (L). Whereas, CCD experimental plan requires only 25 trials providing sufficient information compared to conventional experiments. Specimen required for tensile, hardness and machinability characteristics of Al-SiC composites are fabricated with SiC reinforcement as per Table-2.

Table-1: Metallurgical details of Al2149

Cu	Mn	Zr	V	Fe	Ti	Zn	Si	Ni	Mg	Cr	Balance
5.92	0.539	0.197	0.148	0.130	0.109	0.105	0.049	0.033	0.008	<0.001	92.42

Table-2: Machinability parameters of Al-Cu-SiC composites

Coded Levels of Parameters	- 2	- 1	0	+ 1	+ 2
Parameters					
Speed (A), m/s	1	1.75	2.5	3.25	4
Depth of cut (B), mm	0.1	0.2	0.3	0.4	0.5
Feed (C), mm/rev	0.05	0.16	0.28	0.40	0.50
% SiC (D)	0.0	2.0	4.0	6.0	8.0

Stir casting is used for fabrication of composites [2, 10]. Fig-1 shows melting of ingots of Aluminium Alloy in crucible. Ribbons of magnesium are added to improve wettability of SiC particulates which are added and stirred prior to pouring of melt in to metal moulds. Tension specimen is 15 mm diameter and 110 mm length and machinability specimen is 240 mm length with 50 mm diameter after casting. Tension specimen is turned for a gauge length of 36 mm with 9 mm diameter and for gripping length of 25 mm with 12 mm diameter on either end as per ASTM E8-09. Ends are knurled for better gripping. Specimen with thickness 10 mm and diameter 12 mm are machined and polished for hardness testing. Specimen of tension and hardness test are respectively shown in Fig-2 and Fig-3. SEM image is considered to ascertain the distribution of SiC particulates in composites. Fig-4 represents SEM image of composite with 8% SiC. It can be seen that distribution of SiC particulates is uniform.

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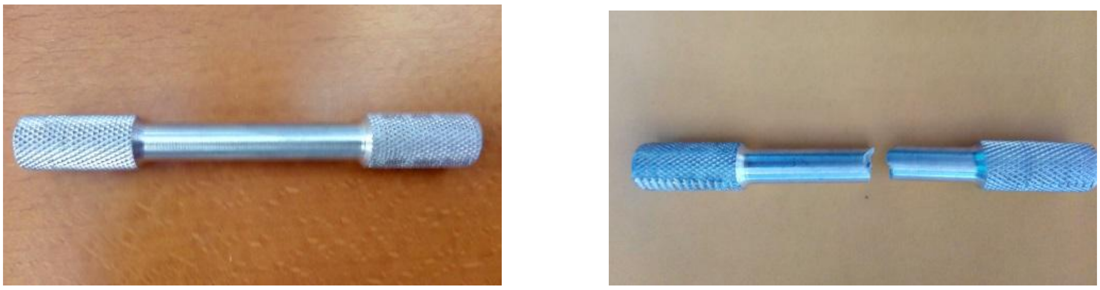
(a)

(b)

Fig-1: (a) Melting of Aluminium Alloy Ingots (b) Crucible with Stirrer



(a) **(b)**

Fig-2: (a) Tension Test Specimen (b) Specimen after Tension Test

Fig-3: Hardness Test Specimen

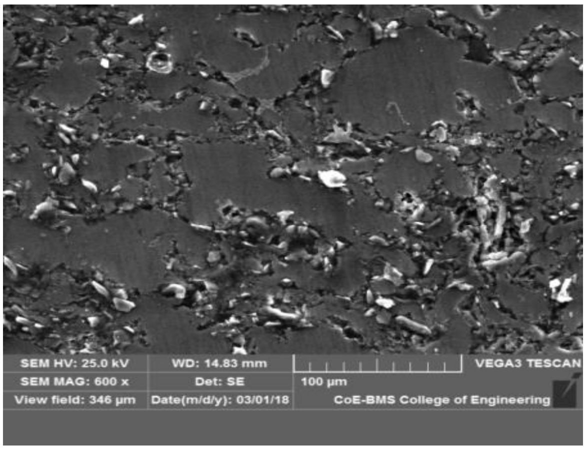


Fig-4: SEM image of Composite with 8% SiC

III. EXPERIMENTS AND RESULTS

Tests for tensile characteristics are carried out on 60 ton UTM. Three sample specimens are considered for each reinforcement of SiC as detailed in Table-2 and values are averaged for tensile yield strength, ultimate tensile strength and % elongation. Table-3 provides these values. Hardness tests are carried out with three indentations for each sample specimen of SiC reinforcement as in Table-2 and average values are given in Table-3.

Table-3: Tensile and Hardness Characteristics of Al-Cu-SiC Composites

%SiC	Tensile Yield Strength ,MPa	Ultimate Tensile Strength ,MPa	% Elongation	BHN
0	165.23	208.53	13.07	66.33
2	171.13	222.13	11.75	73.06
4	180.06	239.10	10.77	82.33
6	207.36	262.63	8.71	95.03
8	217.00	280.87	7.99	104.16

Machinability of Al-Cu-SiC Composites is carried out by turning operation using HSS tool considering the parameters of Table-2 keeping 100 mm as length for turning. These parameters are varied as per the experimental plan and corresponding Cutting Forces, Tool Wear and Surface Roughness are measured as responses. The coded and actual values of parameters for different test combinations (tc) of experimental plan are given in Table-4 for Al-Cu-SiC Composites. Cutting force (F) during each experiment is measured in three mutually perpendicular directions at the tool tip and their resultant is considered. Tool wear (W) and Surface roughness (R) are measured after each experiment and these values are provided in Table-4.

Table–4: Coded and Actual Values of Parameters and Test Results for Al-Cu-SiC Composites.

tc	Parameters										
	Coded Value				Actual Value				Test Results		
	A	B	C	D	A Speed m/s	B Depth of Cut mm	C Feed mm/rev	D % SiC	Cutting Force (F) N	Tool Wear (W) mm	Surface Roughness (Ra)
1	-1	-1	-1	-1	1.75	0.2	0.16	2	67	0.002	2.98
a	+1	-1	-1	-1	3.25	0.2	0.16	2	54	0.000	2.17
b	-1	+1	-1	-1	1.75	0.4	0.16	2	66	0.003	2.10
ab	+1	+1	-1	-1	3.25	0.4	0.16	2	37	0.002	1.16
c	-1	-1	+1	-1	1.75	0.2	0.40	2	62	0.006	3.04
ac	+1	-1	+1	-1	3.25	0.2	0.40	2	57	0.004	2.34
bc	-1	+1	+1	-1	1.75	0.4	0.40	2	70	0.004	1.70
abc	+1	+1	+1	-1	3.25	0.4	0.40	2	73	0.006	2.40
d	-1	-1	-1	+1	1.75	0.2	0.16	6	33	0.003	2.39
ad	+1	-1	-1	+1	3.25	0.2	0.16	6	25	0.004	1.42
bd	-1	+1	-1	+1	1.75	0.4	0.16	6	25	0.005	4.57
abd	+1	+1	-1	+1	3.25	0.4	0.16	6	37	0.004	1.89
cd	-1	-1	+1	+1	1.75	0.2	0.40	6	57	0.006	6.38
acd	+1	-1	+1	+1	3.25	0.2	0.40	6	25	0.004	2.16
bcd	-1	+1	+1	+1	1.75	0.4	0.40	6	62	0.006	6.28
abcd	+1	+1	+1	+1	3.25	0.4	0.40	6	54	0.006	6.23
$-\alpha_a$	-2	0	0	0	1	0.3	0.28	4	74	0.003	1.32
$+\alpha_a$	+2	0	0	0	4	0.3	0.28	4	33	0.003	1.70
$-\alpha_b$	0	-2	0	0	2.5	0.1	0.28	4	47	0.001	1.47
$+\alpha_b$	0	+2	0	0	2.5	0.5	0.28	4	46	0.009	2.01
$-\alpha_c$	0	0	-2	0	2.5	0.3	0.05	4	37	0.002	0.63
$+\alpha_c$	0	0	+2	0	2.5	0.3	0.50	4	65	0.004	3.37
$-\alpha_d$	0	0	0	-2	2.5	0.3	0.28	0.0	46	0.004	2.39
$+\alpha_d$	0	0	0	+2	2.5	0.3	0.28	8	46	0.005	2.87
Zero	0	0	0	0	2.5	0.3	0.28	4	37	0.002	1.79
Zero	0	0	0	0	2.5	0.3	0.28	4	33	0.003	1.67
Zero	0	0	0	0	2.5	0.3	0.28	4	46	0.002	1.58

IV. DISCUSSION OF RESULTS

4.1 Tensile Strength and Hardness

Values of tensile properties as provided in Table-3 are plotted. Fig- 5 represents plot of tensile yield strength with % reinforcement. It can be observed that the strength increases marginally up to 4% SiC but is considerable for 6% SiC and is again marginally increased for 8% SiC addition at which tensile yield strength is 217 MPa. Improvement of this strength can be attributed to formation of aluminium carbide to which transfer of load takes place. On the other hand, ultimate tensile strength of the composite increases continuously on addition of SiC with the maximum value being 280 MPa at 8% SiC as reflected in Fig-5. Improvement of both tensile yield strength and ultimate tensile strength can also be attributed to uniform distribution of SiC particulates as observed in SEM image of Fig-4. Addition of SiC has reduced % elongation continuously except for 4% SiC as shown in Fig-6. This is due to composites being harder on addition of SiC particulates as evidenced by the hardness values provided in Table-3. Addition of SiC has influence on hardness of composites similar to tensile yield strength and ultimate tensile strength as shown in Fig-6. This is due to SiC particulates which are naturally hard contributing for increased hardness of composites, the values of which increased continuously with SiC addition up to 8%.

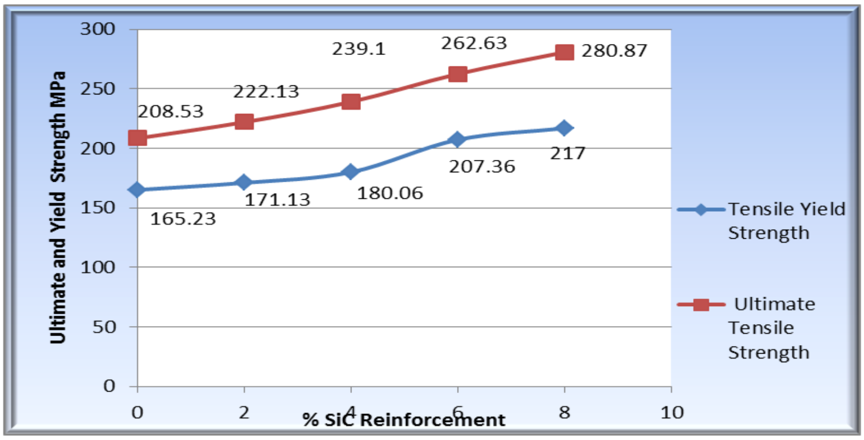


Fig-5: Plot of Tensile Yield Strength and Ultimate Tensile Strength with % SiC

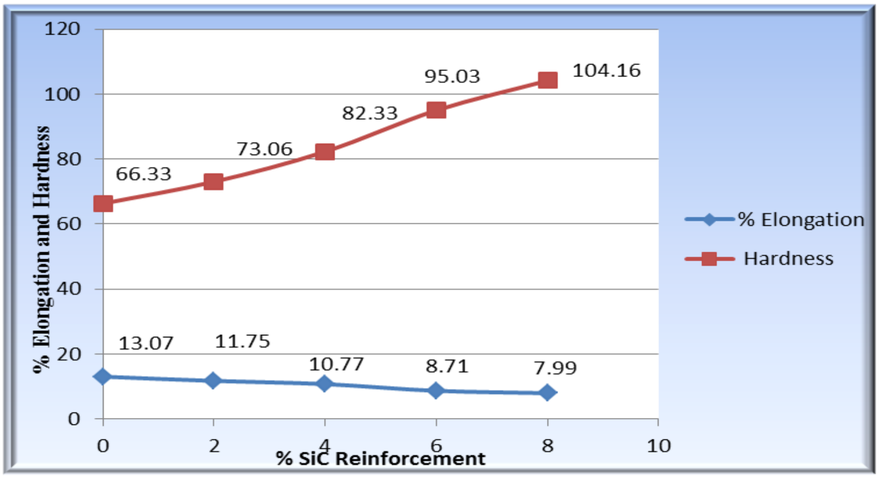


Fig-6: Plot of % Elongation and Brinell Hardness with % SiC

The values of cutting force (F), tool wear (W) and roughness of turned surface (Ra) which are measured as responses provided in Table-4 are analyzed using a software, MINITAB. Analysis of variance (ANOVA) is carried out for these measured responses considering the coded values of each test combinations of Table-4. Factors with p-value less than 0.05 are significant with a confidence limit of 95%. Results of analysis are separately discussed for each of the responses.

4.2 Cutting Force

Turning of a particular composite is shown in Fig-7 during which the three components of cutting forces are measured. Table-5 provides the results of ANOVA for cutting force. As can be seen, Speed, Feed and % SiC are significant influencing the cutting force during turning of Al-Cu-SiC Composites. Increase of Speed and % SiC reduce cutting force the value of which increases with increase of feed. But, Speed does not have any influence on cutting force and feed affects cutting force similar to the present work while turning Al/SiC/10p/220 and Al/SiC/10p/600 composites with PVD coated carbide inserts. On the other hand, increase of depth of cut results in corresponding increase in cutting force which is not the observation in the present work where it is not affecting the cutting force [14]. Normal probability plot for cutting force is shown in Fig-8. It can be observed that all the experimental values are normally distributed as their values are very close to the normal probability line. Surface plots and corresponding contour plots for different combinations of the significant factors provide more insight in to their effect on the cutting force by way of optimal combinations. Actual values of factors are considered with contour plots for different % SiC and corresponding depth of cut as per Table-2 are used for combination of Speed and Feed. Such plots are shown in Fig-9 to Fig-13 and the values of cutting forces are summarized in Table-6. These plots are advantageous wherein any combination of both %SiC and depth of cut in the range can be considered and corresponding speed and feed is known which result in the least cutting force.

Fig-7: Turning of Composite

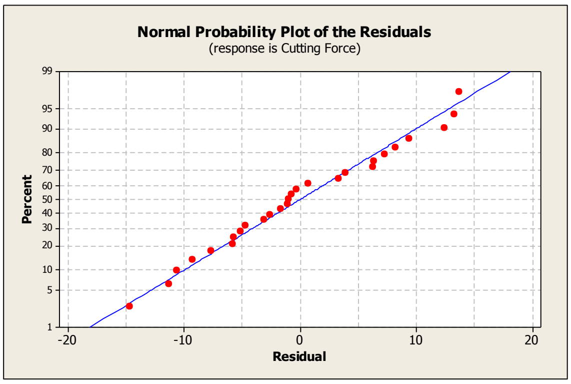


Fig-8: Normal Probability Plot

Table-5: ANOVA Results for Cutting Force of Al-Cu-SiC Composites

Term	Coefficient	P
Constant	38.6667	0.000
Speed	-6.7500	0.014
Depth of cut	1.7500	0.468
Feed	7.1667	0.010
% SiC	-7.0000	0.011
Speed*Speed	3.8750	0.144
Depth of cut*Depth of cut	2.1250	0.408
Feed*Feed	3.2500	0.214
%SiC*%SiC	2.0000	0.435
Speed*Depth of cut	2.2500	0.447
Speed*Feed	-0.2500	0.932
Speed*SiC	0.5000	0.864
Depth of cut * Feed	4.5000	0.142
Depth of cut *%SiC	2.0000	0.498
Feed*%SiC	2.5000	0.399
Estimated Regression Coefficients for Cutting Force with R-Sq = 74.4%		

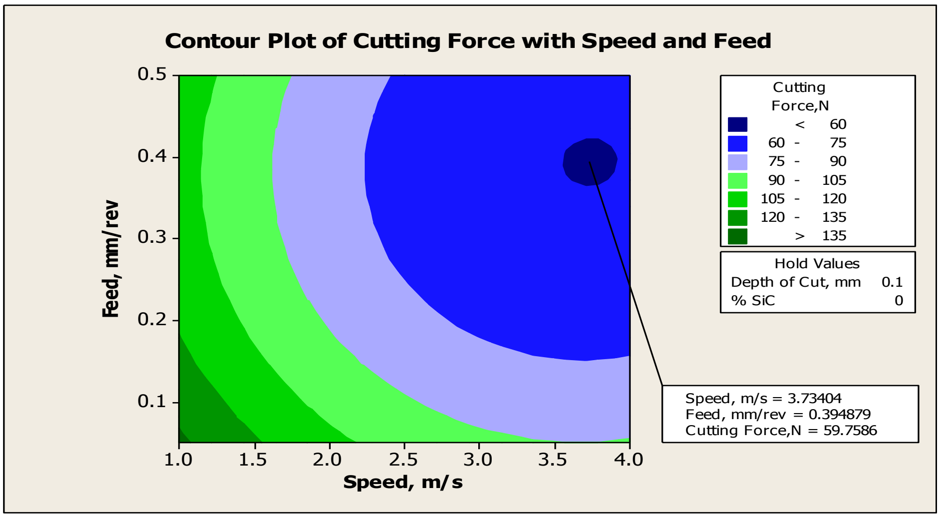


Fig-9: Contour Plot of Cutting Force with 0% SiC and 0.1 mm Depth of Cut

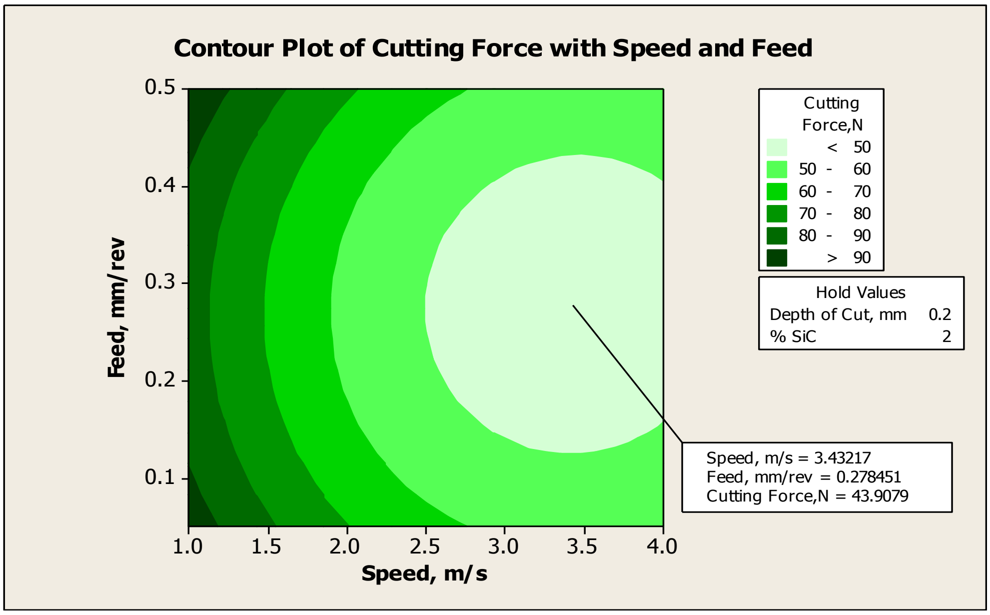


Fig-10: Contour Plot of Cutting Force with 2% SiC and 0.2 mm Depth of Cut

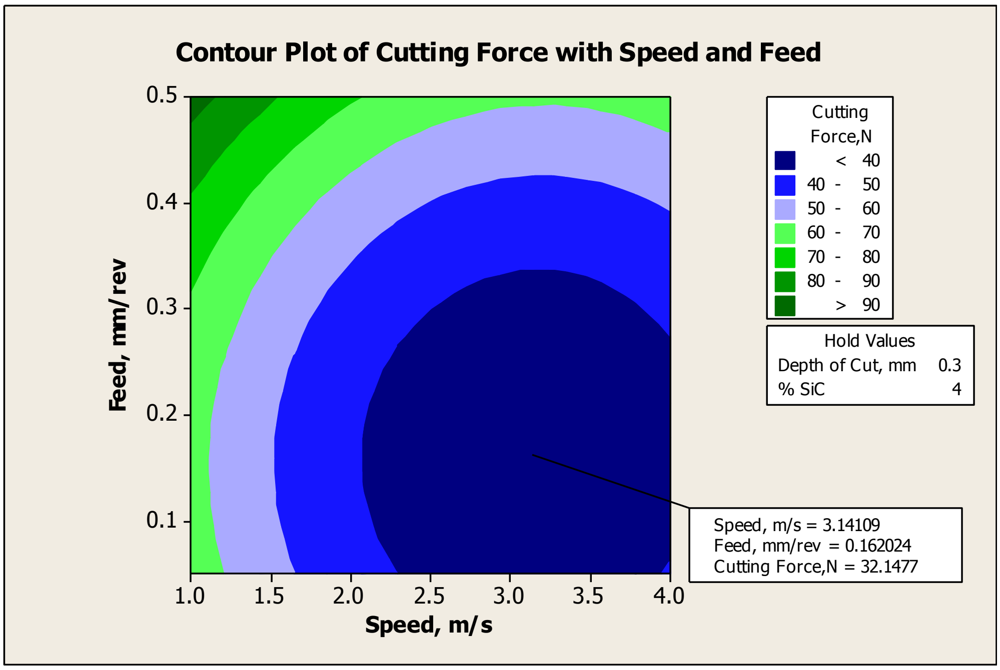


Fig-11: Contour Plot of Cutting Force with 4% SiC and 0.3 mm Depth of Cut

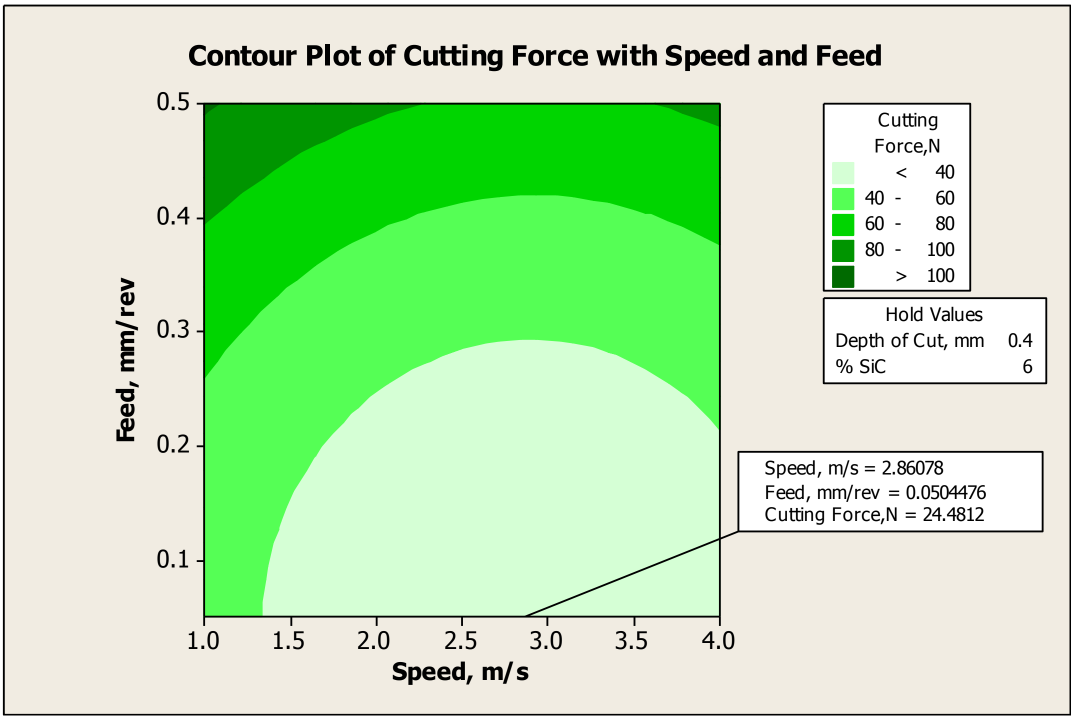


Fig-12: Contour Plot of Cutting Force with 6% SiC and 0.4 mm Depth of Cut

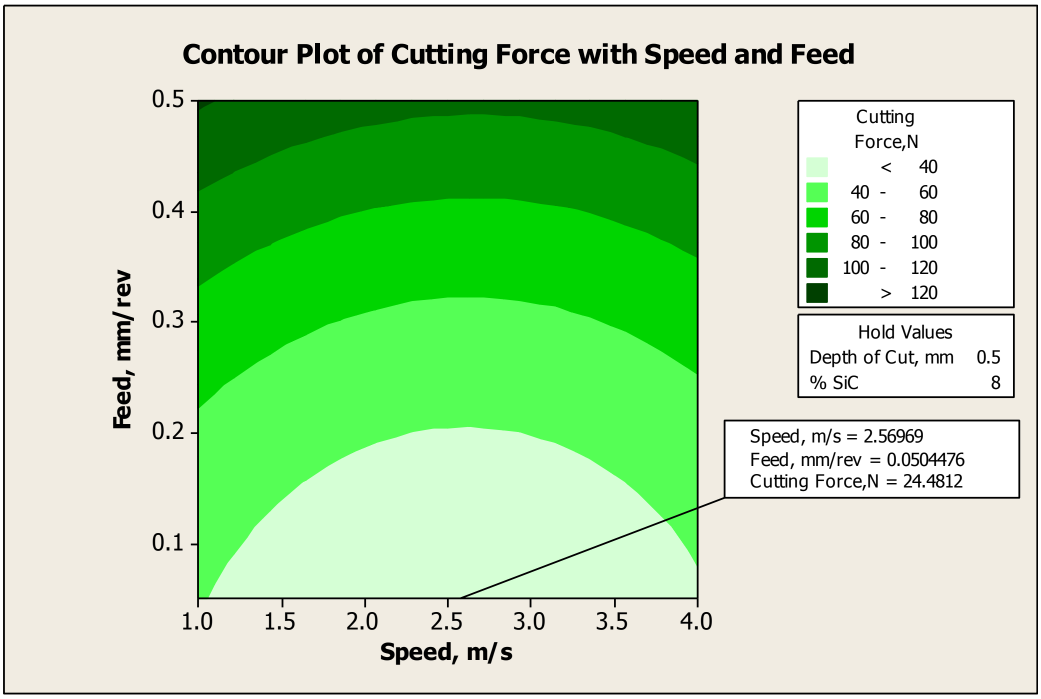


Fig-13: Contour Plot of Cutting Force with 8% SiC and 0.5 mm Depth of Cut

Table-6: Optimal Combinations of Depth of Cut, Speed and Feed for minimum Cutting Force during Turning of Al-Cu-SiC Composites

% SiC	Depth of Cut, mm	Speed, m/s	Feed, mm/rev	Cutting Force, N
0	0.1	3.73	0.39	59.75
2	0.2	3.43	0.37	43.90
4	0.3	3.14	0.16	32.14
6	0.4	2.86	0.05	24.48
8	0.5	2.56	0.05	24.48

4.3 Tool Wear

Tool wear is measured using Nikon Measure Scope 10 and Fig-14 represents tool tip under the scope. ANOVA results for tool wear are given in Table-7. Both depth of cut and feed are affecting tool wear so that increase of either of the two or both results in increase of tool wear. Fig-15 is the normal probability plot for tool wear and normal distribution of all the experimental values is noticed due to the fact that the values are very close to the normal probability line. Speed and % SiC as per Table-2 are used for combinations of Feed and Depth of cut and contour plots are drawn as shown in Fig-16 to Fig-20. Table-8 provides the optimal values of depth of cut and feed for five levels of % SiC and speed of Table-2. Similar to contour plots for cutting force, these plots also have advantage so that any combination of both speed and %SiC in the considered range can be used to know the corresponding feed and depth of cut so that the tool wear is least.

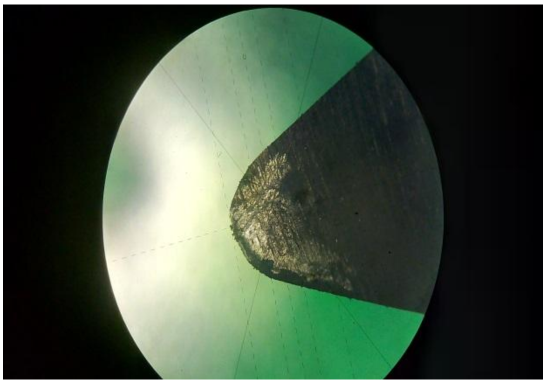


Fig-14: Tool Tip under Microscope

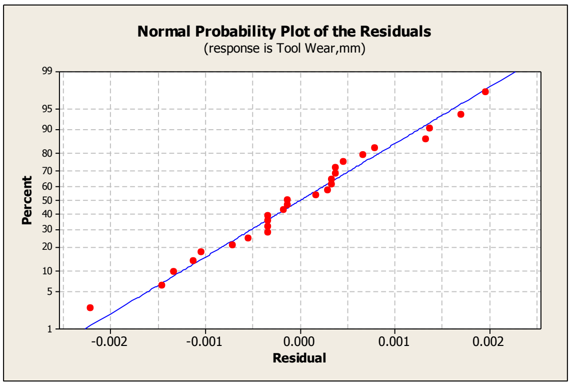


Fig-15: Normal Probability Plot

Table-7: ANOVA Results for Tool Wear of Al-Cu-SiC Composites

Term	Coefficient	P
Constant	0.002333	0.016
Speed	-0.000208	0.491
Depth of cut	0.000958	0.007
Feed	0.000958	0.007
% SiC	0.000542	0.089
Speed*Speed	0.000198	0.536
Depth of cut*Depth of cut	0.000698	0.044
Feed*Feed	0.000198	0.536
%SiC*%SiC	0.000573	0.090
Speed*Depth of cut	0.000312	0.401
Speed*Feed	0.000062	0.865
Speed*SiC	0.000062	0.865
Depth of cut * Feed	-0.000188	0.611
Depth of cut *%SiC	0.000062	0.865
Feed*%SiC	-0.000438	0.246
Estimated Regression Coefficients for Tool Wear with R-Sq = 74.2%		

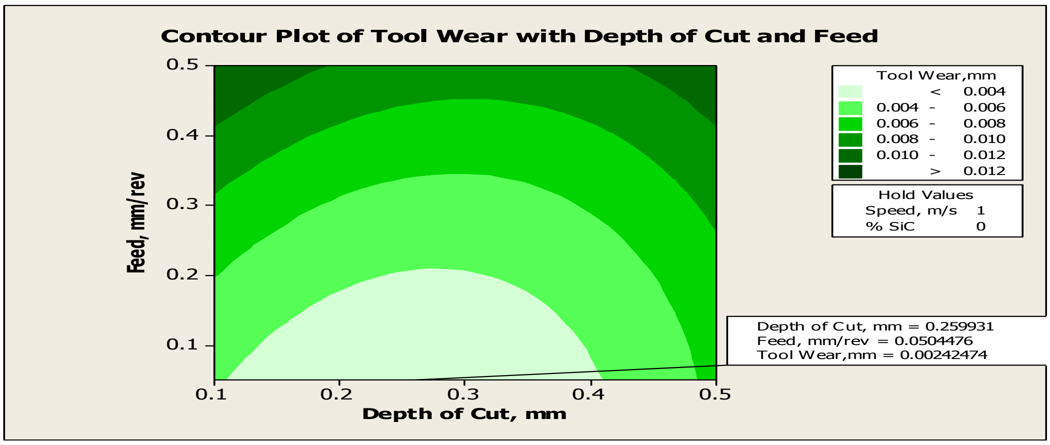


Fig-16: Contour Plot of Tool Wear with 0% SiC and 1 m/s Speed

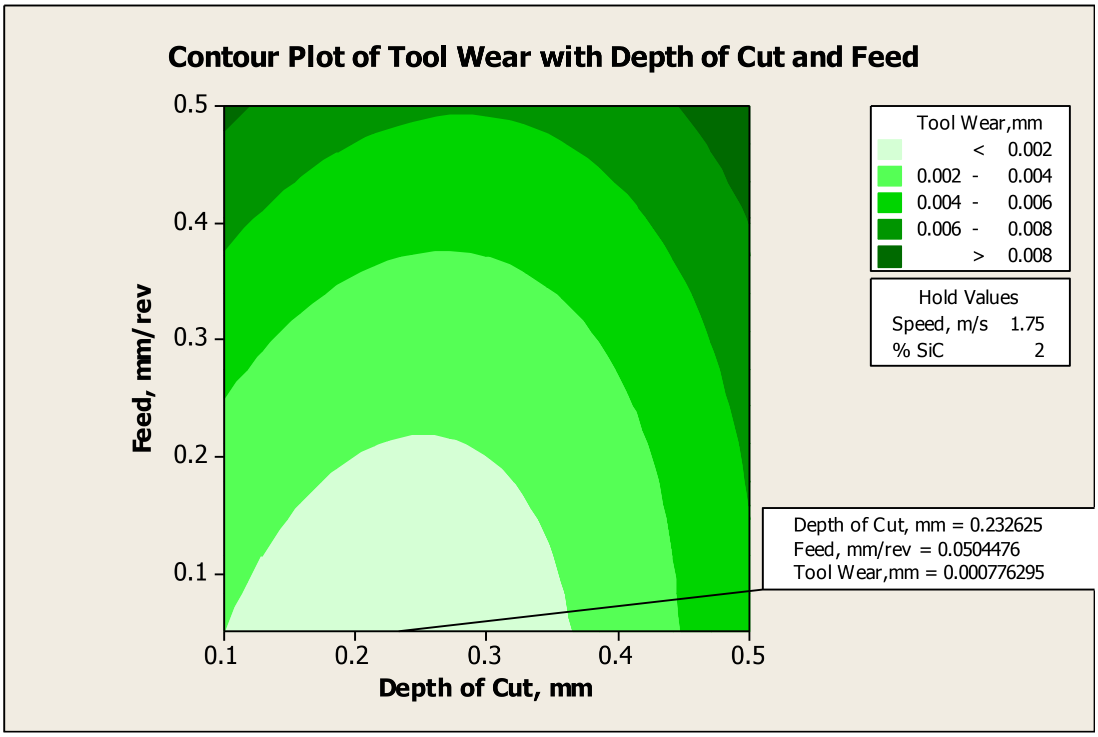


Fig-17: Contour Plot of Tool Wear with 2% SiC and 1.75 m/s Speed

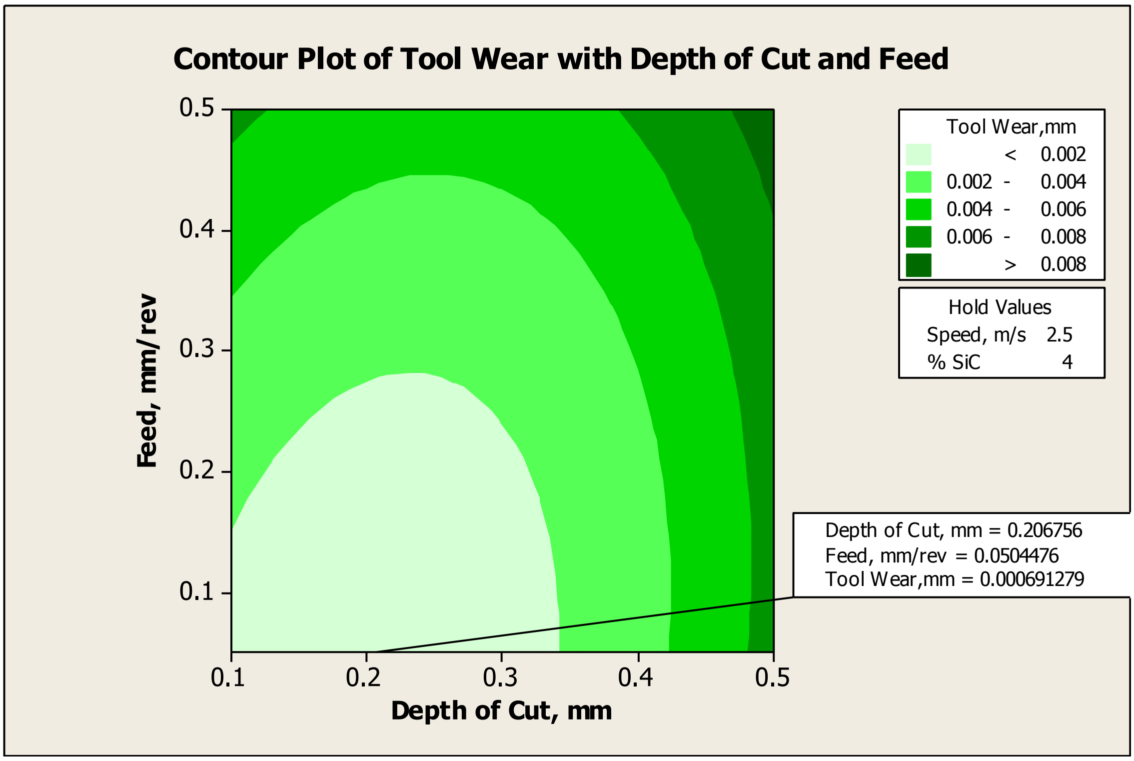


Fig-18: Contour Plot of Tool Wear with 4% SiC and 2.5 m/s Speed

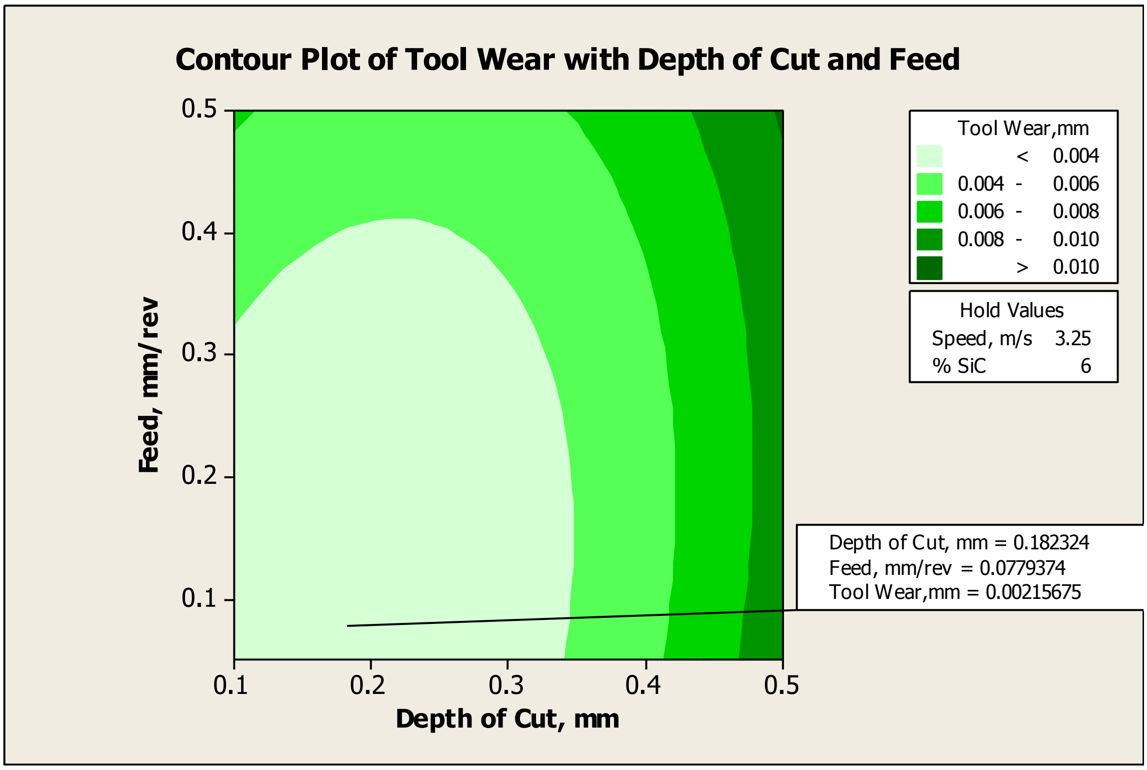


Fig-19: Contour Plot of Tool Wear with 6% SiC and 3.25 m/s Speed

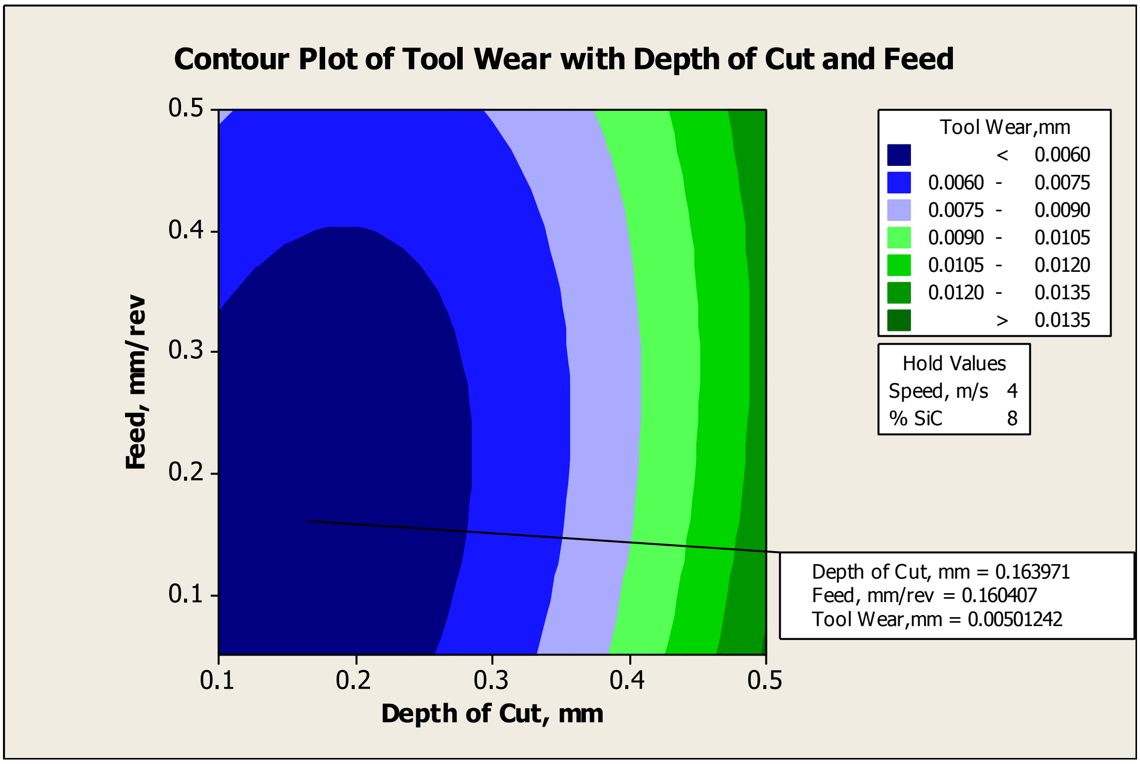


Fig-20: Contour Plot of Tool Wear with 8% SiC and 4 m/s Speed

Table-8: Optimal Combinations of Depth of Cut, Speed and Feed for minimum Tool Wear during Turning of Al-Cu-SiC Composites

% SiC	Depth of Cut, mm	Speed, m/s	Feed, mm/rev	Tool Wear, mm
0	0.25	1	0.05	0.0024
2	0.23	1.75	0.05	0.0007
4	0.20	2.5	0.05	0.0006
6	0.18	3.25	0.07	0.0021
8	0.16	4	0.16	0.0050

4.4 Surface Roughness

Roughness of turned surface is measured by equipment, SURFCOM FLEX as shown in Fig-21. Table-9 gives the details of ANOVA for surface roughness. As can be observed feed and % SiC are influencing the roughness of turned surface of composites. Increase of feed results in increase of surface roughness of composites. Similar observation is made during turning of Al composite (LM13/SiCp 15%) using cemented carbide tool [15]. Values of Feed and % SiC as per Table-2 are used to prepare contour plots as shown in Fig-23 to Fig-27. Combination of speed, feed and depth of cut which result in least surface roughness for different % SiC can be ascertain from these plots and values are summarized in Table-10. However, for % SiC other than those in Table-2 also the optimal values of speed, feed and depth of cut can be known from these plots.

Table-9: ANOVA Results for Surface Roughness of Al-Cu-SiC Composites

Term	Coefficient	P
Constant	1.68333	0.031
Speed	-0.37125	0.153
Depth of cut	0.18875	0.453
Feed	0.72208	0.012
% SiC	0.59958	0.030
Speed*Speed	0.14094	0.595
Depth of cut*Depth of cut	0.19844	0.457
Feed*Feed	0.26344	0.327
%SiC*%SiC	0.42094	0.129
Speed*Depth of cut	0.23312	0.449
Speed*Feed	0.07062	0.817
Speed*SiC	-0.38563	0.220
Depth of cut * Feed	0.12062	0.693
Depth of cut *%SiC	0.61188	0.062
Feed*%SiC	0.60687	0.064
Estimated Regression Coefficients for Surface Roughness with R-Sq = 72.5%		

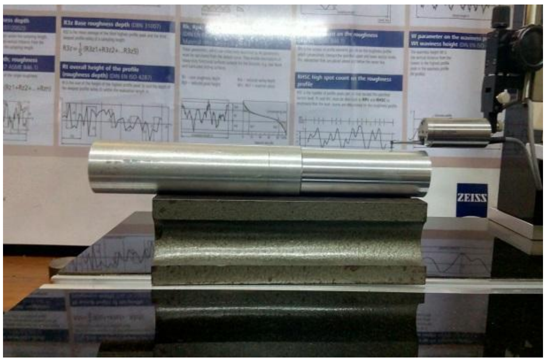


Fig-21: Roughness Measurement of Composite

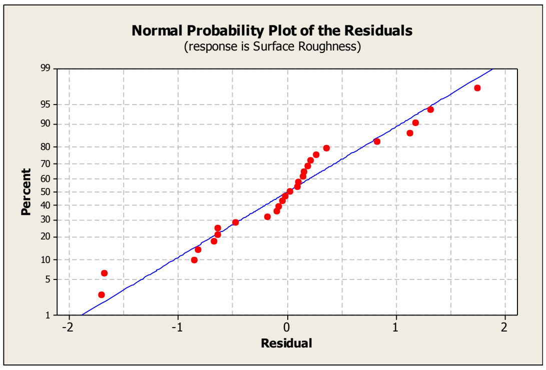


Fig-22: Normal Probability Plot

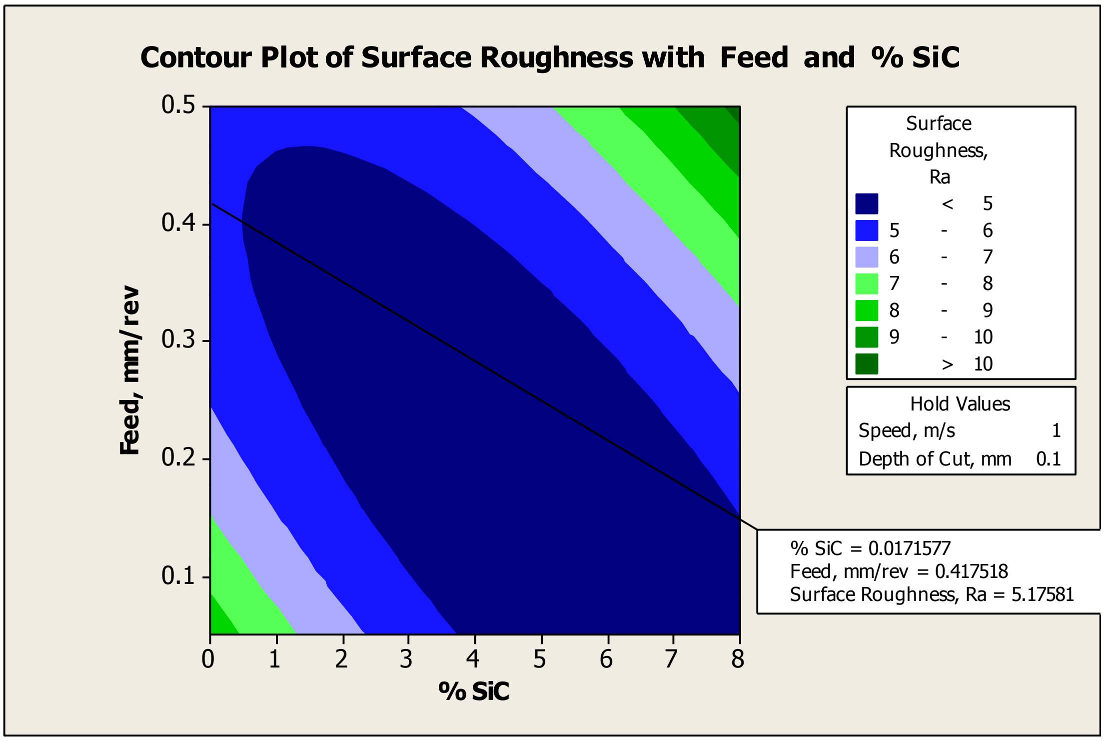


Fig-23: Contour Plot of Surface Roughness with 1 m/s Speed and 0.1 mm depth of Cut

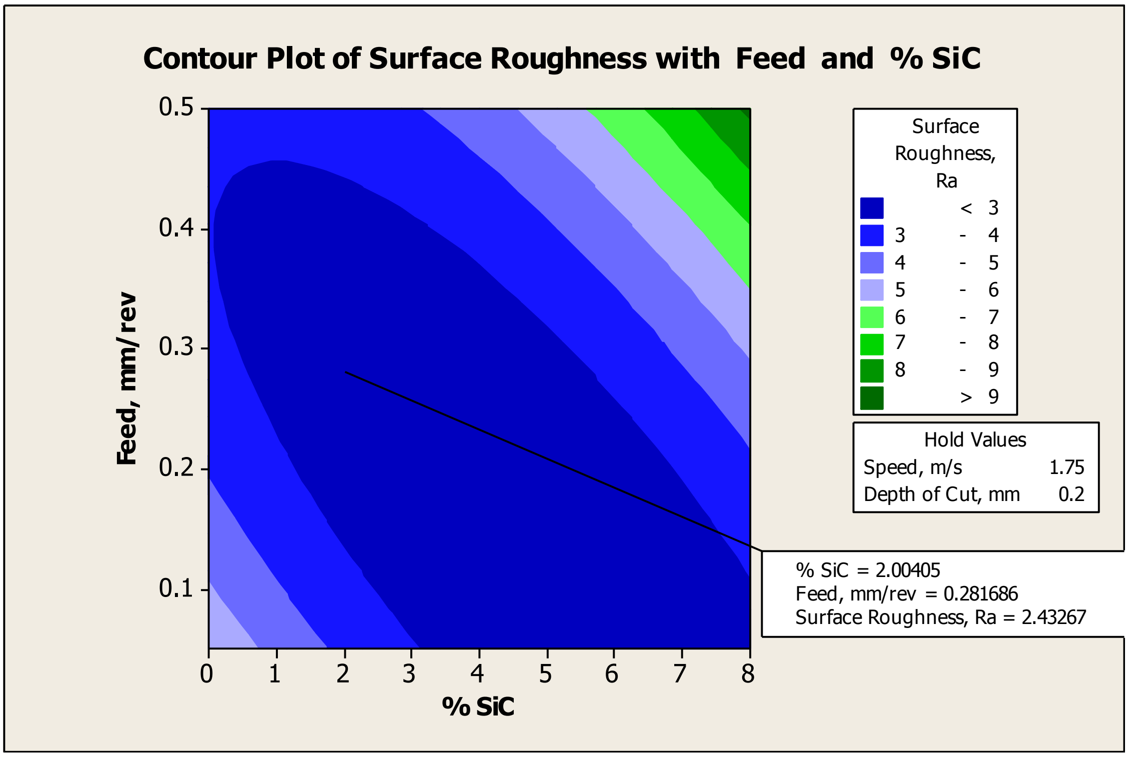


Fig-24: Contour Plot of Surface Roughness with 1.75 m/s Speed and 0.2 mm depth of Cut

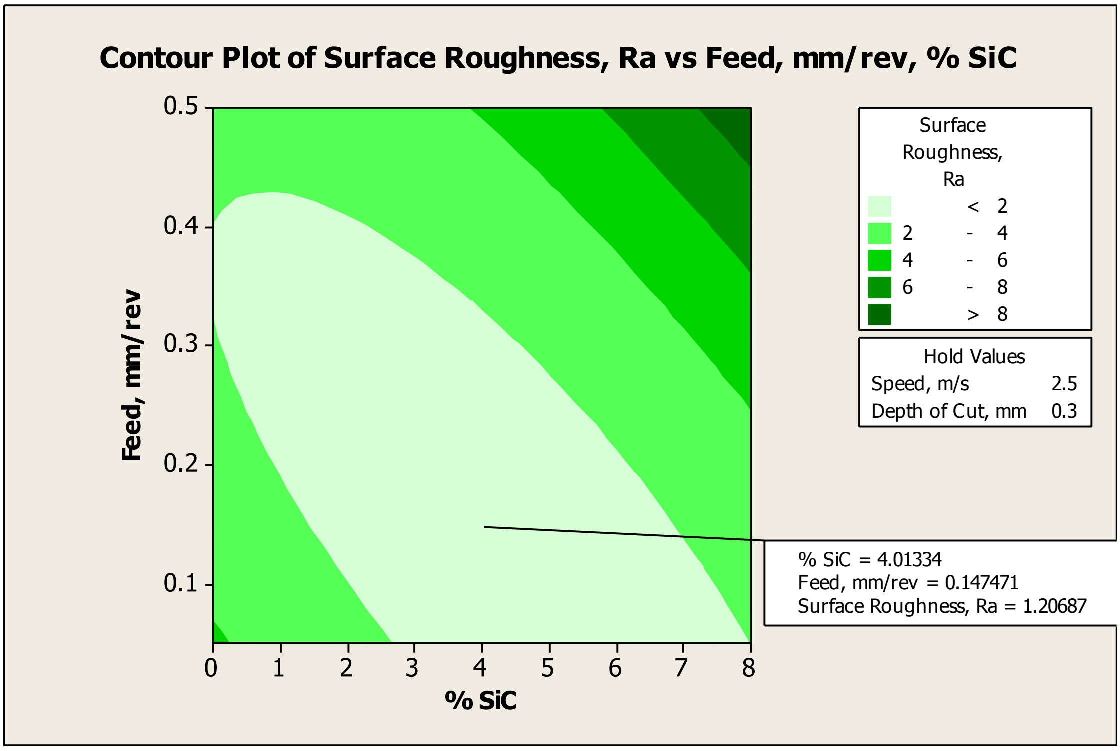


Fig-25: Contour Plot of Surface Roughness with 2.5 m/s Speed and 0.3 mm depth of Cut

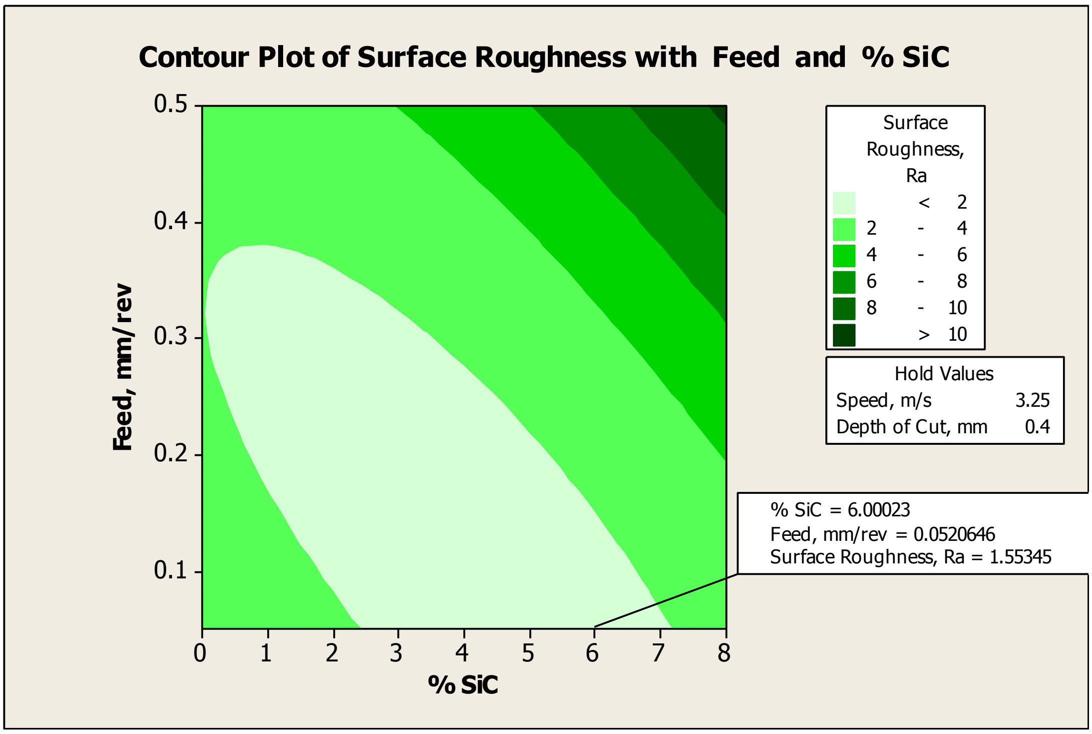


Fig-26: Contour Plot of Surface Roughness with 3.25 m/s Speed and 0.4 mm depth of Cut

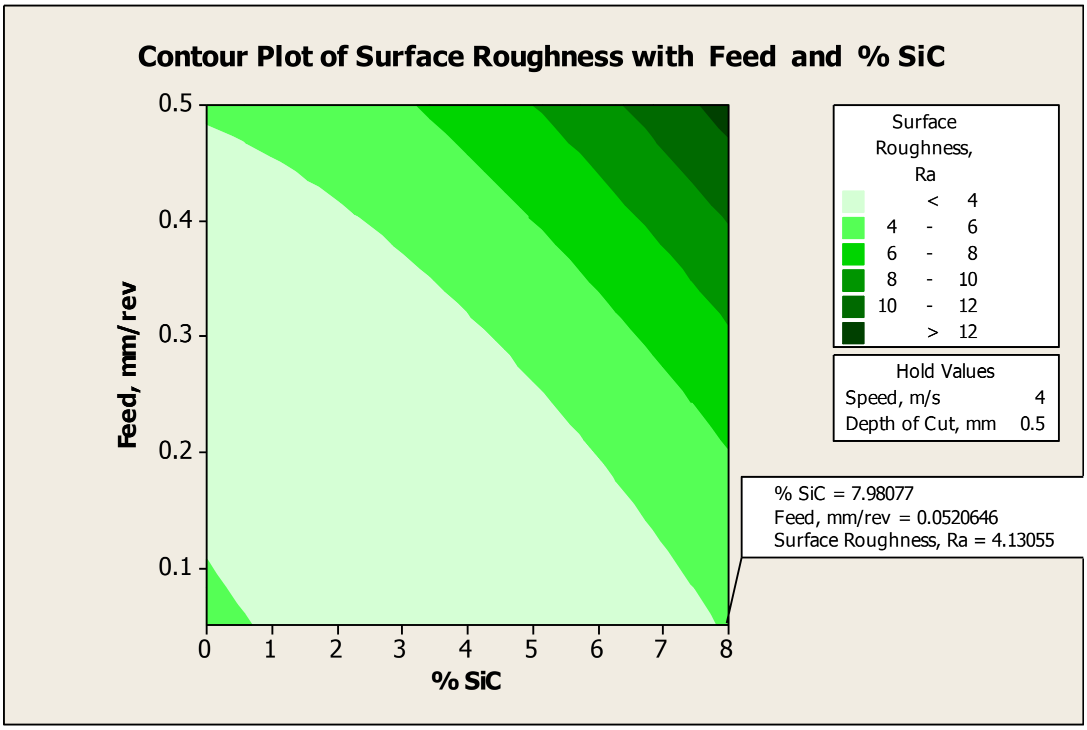


Fig-27: Contour Plot of Surface Roughness with 4 m/s Speed and 0.5 mm depth of Cut

Table-10: Optimal Combinations of Depth of Cut, Speed and Feed for minimum Surface Roughness during Turning of Al-Cu-SiC Composites

% SiC	Depth of Cut, mm	Speed, m/s	Feed, mm/rev	Surface Roughness Ra
0	0.1	1	0.41	5.17
2	0.2	1.75	0.28	2.43
4	0.3	2.5	0.14	1.20
6	0.4	3.25	0.05	1.55
8	0.5	4	0.05	4.13

Table-6 and Table-8 respectively provide combinations of speed, feed and depth of cut in order to minimize cutting force and tool wear while turning Al-Cu-SiC composites with 2, 4, 6 and 8 % SiC. But, the information of Table-10 is more useful than that of the previous two because of the reason that it is essential to know the combinations speed, feed and depth of cut which provide the least surface roughness in turning a composite with a particular % SiC reinforcement from application point of view. This is because of the fact that the quality of turned surface of a component made of a particular composite decides its suitability. Therefore, contour plots of Fig-23 to Fig-27 can be advantageously used to turn composites of Al 2419 alloy with reinforcement of 2, 4, 6 and 8 % SiC.

V.CONCLUSIONS

Composites of Al 2419 alloy with 2, 4, 6 and 8 % SiC reinforcement are fabricated by stir casting, tested for tensile, hardness and turning characteristics. Following are the conclusions.

- Reinforcement percentage of SiC, Speed, Feed and Depth of cut for investigation are arrived at with the help of Central Composite Design of Experimental Technique.
- SEM image has ensured the uniform distribution of SiC particulates.
- Tensile Yield Strength, Ultimate Tensile Strength and Hardness of composites have improved for all % SiC addition of 2, 4, 6 and 8.
- Percentage elongation has decreased for 2, 4, 6 and 8% SiC addition to the alloy.
- Cutting Force is influenced by Feed, Speed and % SiC so that increase of Feed results in increase of cutting force.
- Depth of Cut and Feed affect the tool wear in such a way that increase of either any one or both result in increased tool wear.

  Feed influences Surface roughness during turning because of which quality of surface reduces with increase of feed due to increased value of Ra

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