

# Statistical Optimization by Response Surface Methodology of Process Parameters During the CNC Turning Operation of Hybrid Metal Matrix Composite

Ashish Kumar Srivastava  
G. L. Bajaj Institute of Technology and Management

Manish Maurya  
Accurate Institute of Management and Technology

Ambuj Saxena  
G. L. Bajaj Institute of Technology and Management

Nagendra Kumar  
G. L. Bajaj Institute of Technology and Management

他

<https://doi.org/10.5109/4372260>

---

出版情報 : Evergreen. 8 (1), pp.51-62, 2021-03. Transdisciplinary Research and Education Center for Green Technologies, Kyushu University

バージョン :

権利関係 : Creative Commons Attribution-NonCommercial 4.0 International



# Statistical Optimization by Response Surface Methodology of Process Parameters During the CNC Turning Operation of Hybrid Metal Matrix Composite

Ashish Kumar Srivastava<sup>1</sup>, Manish Maurya<sup>\*2</sup>, Ambuj Saxena<sup>1</sup>, Nagendra Kumar Maurya<sup>1</sup>, Shashi Prakash Dwivedi<sup>1</sup>,

<sup>1</sup>G. L. Bajaj Institute of Technology and Management, Greater Noida -201308, India

<sup>2</sup>Accurate Institute of Management and Technology, Greater Noida -201308, India

\*Author to whom correspondence should be addressed:

E-mail: manishmaurya33@gmail.com

(Received October 14, 2020; Revised January 14, 2021; accepted February 16, 2021).

**Abstract:** The demand for new class of specific materials is rising day by day. In this context machining plays an vital role to finish the final product according to required geometry. Lightweight material such as aluminum based metal matrix composites is one of the most suitable material for most of the engineering and structural works. In this research work, an effort is made to optimize the process parameters of 16-TC Botliboi CNC machine to get desired output responses of MRR, surface roughness (SR) and tool flank wear during the processing of previously developed aluminum hybrid composite A359/B4C/Al<sub>2</sub>O<sub>3</sub>. Response surface methodology (RSM) has been applied to get the mathematical model of input parameters to get the desired response. The results reveal the optimized value of feed rate, rotational speed and depth of cut to experimentally find the outputs. Further confirmation experiments are performed at optimum level of process parameter.

**Keywords:** Hybrid MMC, Conventional machining, Botliboi CNC, Material removal rate, Tool wear rate, Surface Roughness

## 1. Introduction

The development of new class of composite materials continuously changes the market of engineering materials and extend its use in most of the engineering applications<sup>1-4</sup>. Nowadays, metal matrix composites (MMCs) are attracting attention of the researchers due to light weight and high strength to weight ratio<sup>5-6</sup>. The light weighted characteristics, improved mechanical and thermal properties makes it more preferable over lots of existing materials<sup>7-11</sup>. However, the challenges are still open in its machining area<sup>12-14</sup>. The presence of hard ceramic reinforcements increases the tool wear and overall machining cost<sup>15-16</sup>. Still the research is going on in this field, while lot of work carried out in this field. Processing of Al/SiC composites by CNC machining has been done by Manna and Bhattacharyya<sup>17</sup>. Taguchi's orthogonal array was used to find the desired surface finish. The effect of process parameters was analyzed during machining of aluminium MMCs reported by Ozbenet al<sup>18</sup>. The uncoated HX carbide and coated TiN (K10) tools were used by Kok et al.<sup>19</sup> during machining of Al 2024/Al<sub>2</sub>O<sub>3</sub> composite to investigate the life of tool. While increasing the cutting speed, tool life was reduced. The processing of Al6061/SiC/Al<sub>2</sub>O<sub>3</sub> hybrid composite

on lathe has been done by Sasimurugan and Palani kumar<sup>20</sup>. The performance measurement like surface quality regarding process parameters of lathe machine such as depth, cutting speed and feed was carried out. They reported the decreasing trend of surface roughness with the increased cutting speed. Srinivasan et al.<sup>21</sup> studied the machining behavior of stir cast in-situ LM25/Al<sub>2</sub>O<sub>3</sub> MMC. Response surface methodology (RSM) technique with desirability approach was implemented to find the optimized set of process parameters like depth, feed and cutting speed to evaluate the effect of surface roughness, cutting forces and tool life.

Stir casting is preferred in conducting the experiment due to its simplicity and low cost<sup>22-24</sup>. Natural fibre is used as reinforcement by few researchers<sup>25-26</sup>. Other technique like FSP is also available to prepare the composite<sup>27-29</sup>. Draw backs of FSP is given by various researcher<sup>30-31</sup>. Sticking of tool is a common problem found in FSP technique. The optimization of machine variables in CNC turning of composites is performed by Butola et al.<sup>32</sup>.

This research article deals with the effect of process parameters of 16-TC Botliboi CNC machine to get desired output responses such as MRR, tool flank wear

and surface finish during the processing of previously developed A359/B<sub>4</sub>C/Al<sub>2</sub>O<sub>3</sub> hybrid MMCs. To minimize the number of experiments response surface methodology was used to design the experiments. The influence of selected process parameters on machining is observed. The novelty of this research work, lie in the fact that only few studies have been performed related to machining of hybrid metal matrix composite using these process parameters.

## 2. Experimental Procedure

In the present work, CNC lathe SPRINT 16TC made by BATLIBOI is used for the conventional turning operation. Fig. 1 shows the SPRINT 16TC-CNC lathe machine. The coated carbide tool inserts made of TNMG standards from Kyocera are used for turning purpose. The standard specification of the tool and its mechanical

properties are shown in Table 1. Three parameters namely depth of cut (DC), spindle speed (SS) and feed rate (FR) are selected as primary process parameters in the present work. All other technological parameters are kept constant (Table 2). There are three significant outputs, been selected which are measured for study purpose as well as to analyze the turning process for the machining of hybrid MMCs. These output responses are (a) surface roughness (SR) (b) material removal rate (MRR), and (c) wear of cutting tool. To measure surface roughness, Mitutoyomake (SJ-210) roughness tester was used as shown in Fig 2. Four independent readings are taken from equally offset lines parallel to the axis of rotation. The measurements are done as per ISO 1997 standard while taking the sampling length 0.4 mm with cut-off value 2.5  $\mu\text{m}$ . Mean value of all four readings is taken for further analysis

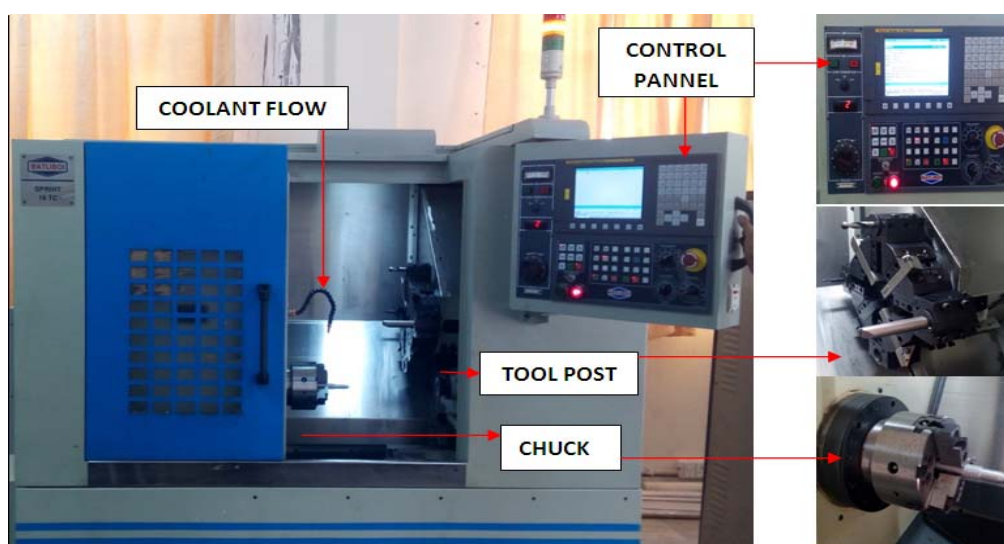
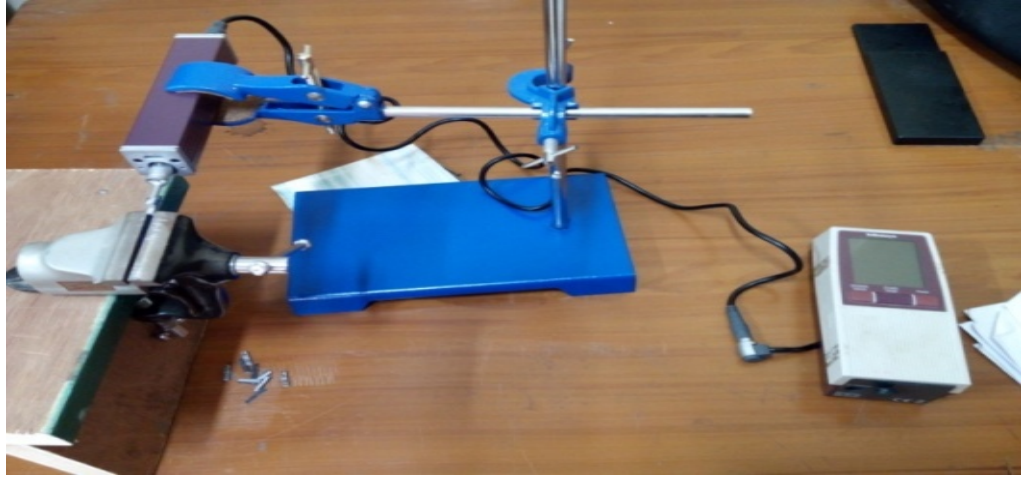


Fig. 1: Sprint 16-TC CNC lathe machine

Table 1. Tool specification

S. No.	Tool Specification	Range/Value	S. No.	Properties	Range/Value
1.	Nose angle	60°	1.	Young Modulus	530-700 GPa
2.	Nose radius	0.80 mm	2.	Shear Modulus	274 GPa
3.	Width (S)	4.76 mm	3.	Ultimate compressive strength	2.7 GPa
4.	Flank (I)	16.50 mm	4.	Ultimate tensile strength	344 MPa
5.	Diameter (Di)	9.52 mm	5.	Bulk modulus	630-655 GPa
6.	Melting point	2,785–2,830 °C	6.	Poisson's ratio	0.31



**Fig. 2:** Mitutoyomake (SJ-210) roughness tester

In turning operation, MRR was calculated by the following Eqs. (1 and 2):

$$MRR = \frac{\pi \times (D^2 - d^2) \times l}{4 \times t} \text{ mm}^3/\text{min} \quad (1)$$

or

$$MRR = \frac{\text{Initial weight} - \text{final weight}}{\text{machining time}} \text{ gm/min} \quad (2)$$

In Eq.1, MRR is the material removal rate in mm<sup>3</sup>/min, d is the final diameter in mm, D is the initial diameter in mm, l is the machining length in mm, and t is the

machining time in a minute. In the present work, MRR is intended by recording the machining time during each experiment and then applying Eqs. (1 and 2). Tool wear is an undesirable phenomenon. In this work, an optical microscope is used to analyse the flank wear after each experiment. Table 3 shows the process parameter ranges and their level of design considered during turning operation. Three levels of machining parameters are selected to cover the full range of machining. A cylindrical rotating work piece of selected hybrid MMC (A359 + 2% B<sub>4</sub>C + 2% Al<sub>2</sub>O<sub>3</sub>) of diameter 20 mm is used for turning purpose. In this experiment, turning length (10 mm) is kept same, and 2 mm gap is provided between each machining to distinguish and identify different experiments. Fig 3 shows the turning operation.

Table 2. Parameters of CNC lathe turning

Parameters	Values
Workpiece diameter (mm)	20
Coolant type	Bizolgrenvo (German lubricants)
Tool insert	carbide
Tool type	TNMG (Kyocera)

Table 3. Process parameters used in CNC turning and their level of design

S. No.	Parameters	Symbol	Level of design		
			-1	0	+1
1	Rotational speed (N) (rpm)	A	200	400	600
2	Feed rate (f) (mm/rev)	B	0.025	0.05	0.075
3	Depth of Cut (d) (mm)	C	0.2	0.4	0.6

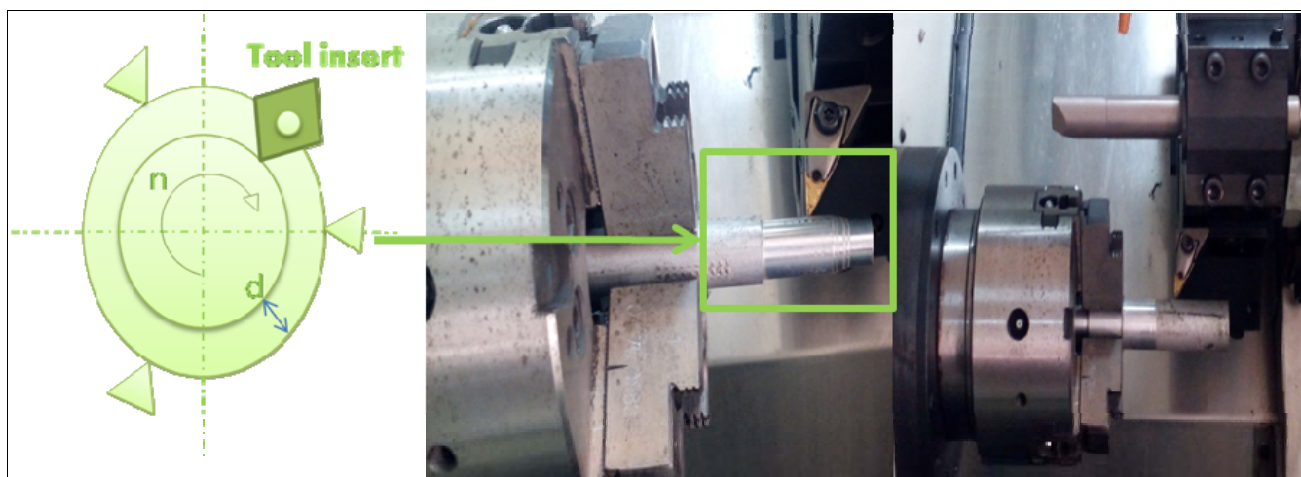


Fig. 3: Turning mechanism and machining zone

The experimental work is based on RSM Box-Behnken design performed by Minitab 17 software. All three process parameters were analyzed separately to evaluate the effect of process parameters.

### 3. Result and Discussion

Table 4 illustrates the experimental plan and the value of observed responses. Analysis of variance (ANOVA) was employed to get the effect of individual process parameters, their percentage contribution and their interaction effects. Through ANOVA results (Table 5), it is clear that the p-values for all desired outputs namely surface roughness, MRR and tool flank wear are less than 0.05 and there is an insignificant lack of fit for each response. ANOVA results depicted that the given set of

process parameters and their range are significantly affected the out-put responses. While comparing the calculated F-values with the standard table (F-table, 0.05), it is found that at the given set of degree of freedom the standard F-values (6.61) is lower for that process parameters which have p-values less than 0.05. It is desirable for significant process parameters. From the table, the  $R^2$  value for surface roughness, MRR and tool flank wear are 99.73%, 97.87% and 99.89% respectively which are nearly equal to 1. It leads to an error-proof regression equations. The developed regression equation for the response variables viz., in terms of actual value of the input variables for surface roughness, MRR and tool flank wear are shown in the Eq. 3 to 5. Similar results were obtained by other researchers<sup>33-35</sup>.

Table 4. Experimental design in CNC turning and output responses

Run Order	Rotational speed (N) (rpm)	Feed rate (Fr) (mm/rev)	Depth of cut (DC) (mm)	Surface roughness (Ra) ( $\mu\text{m}$ )	MRR ( $\text{mm}^3/\text{min}$ )	Tool flank wear ( $\mu\text{m}$ )
1	400	0.05	0.4	1.548	476.71	318.25
2	600	0.025	0.4	1.158	164.88	312.25
3	200	0.05	0.2	2.125	122.37	105.42
4	400	0.075	0.6	1.946	843.88	465.36
5	200	0.025	0.4	2.374	122.13	285.74
6	600	0.05	0.2	1.181	311.02	108.25
7	400	0.05	0.4	1.554	461.81	316.42
8	400	0.075	0.2	1.612	373.22	102.24
9	600	0.075	0.4	1.223	985.20	337.64
10	400	0.025	0.2	1.487	118.48	108.25
11	400	0.05	0.4	1.542	434.65	298.83

12	400	0.025	0.6	1.754	219.60	422.25
13	600	0.05	0.6	1.229	1044.80	466.22
14	200	0.075	0.4	2.424	343.68	297.21
15	200	0.05	0.6	2.579	337.55	412.54

Table 5. ANOVA results in CNC lathe turning

				F-Value		
Source	SS	DOF	MS	F Value	(std)	p-value
Surface Roughness (SR)						
Model	3.118140	9	0.346460	208.994	4.77	< 0.0001
Rotational speed	2.774190	1	2.774190	1673.46	6.61	< 0.0001
Feed Rate	0.023328	1	0.023328	14.072	6.61	0.0133
Depth of cut	0.152076	1	0.152076	91.736	6.61	0.0002
Rotational speed x Fr	0.000056	1	0.000056	0.034	6.61	0.8611
Rotational speed x DC	0.041209	1	0.041209	24.858	6.61	0.0042
Fr x DC	0.001122	1	0.001122	0.677	6.61	0.4481
Residual	0.008289	5	0.001658			
Lack of Fit	0.008217	3	0.002739	0.076	5.41	0.0130
Pure Error	0.000070	2	0.000036			
Cor Total	3.126429	14				
R-Sqr. = 99.73%		Adj R-Sqr. = 99.26%		Pred R-Sqr. 95.79%		
Material Removal Rate (MRR)						
Model	1266997.32	9	140777.48	25.497	4.77	0.0012
Rotational speed	312121.10	1	312121.10	56.529	6.61	0.0007
Feed Rate	461223.43	1	461223.43	83.533	6.61	0.0003
DC	289083.82	1	289083.82	52.357	6.61	0.0008
Rotational speed x Fr	89633.66	1	89633.66	16.234	6.61	0.0100
Rotational speed x DC	67236.97	1	67236.97	12.177	6.61	0.0175
Feed Rate x DC	34140.29	1	34140.29	6.183	6.61	0.0554
Residual	27607.11	5	5521.42			
Lack of Fit	26697.39	3	8899.13	0.020	5.41	0.0490
Pure Error	909.72	2	454.86			
Cor Total	1294604.43	14				
R-Sqr. = 97.87%		Adj R-Sqr. = 94.03%		Pred R-Sqr. 91.85%		
Tool Flank Wear						
Model	233844.46	9	25982.72	496.498	4.77	< 0.0001
Rotational speed	1904.99	1	1904.99	36.402	6.61	0.0018
Fr	683.76	1	683.76	13.066	6.61	0.0153

DC	225190.96	1	225190.96	4303.123	6.61	< 0.0001
Rotational speed x Fr	48.44	1	48.44	0.926	6.61	0.3802
Rotational speed x DC	646.43	1	646.43	12.352	6.61	0.0170
Fr x DC	603.19	1	603.19	11.526	6.61	0.0194
Residual	261.66	5	52.33			
Lack of Fit	31.70	3	10.57	0.092	5.41	0.9578
Pure Error	229.96	2	114.98			
Cor Total	234106.12	14				
R-Sqr. = 99.89%			Adj R-Sqr. = 99.69%		Pred R-Sqr. 99.56%	

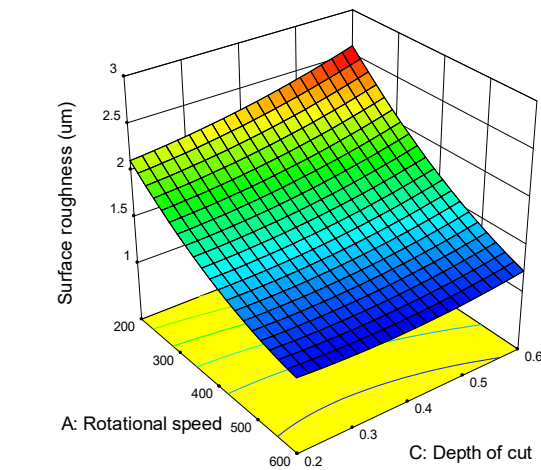
$$\text{Surface roughness (Ra)} = 3.276 - 0.005222 \text{ Rotational speed} - 12.92 \text{ Feed rate} + 0.182 \text{ Depth of cut} + 0.000004 \text{ Rotational speed}^2 + 134.4 \text{ Feed rate}^2 + 1.694 \text{ Depth of cut}^2 + 0.00075 \text{ Rotational speed} \times \text{Fr} + 0.002537 \text{ Rotational speed} \times \text{DC} + 3.35 \text{ Fr} \times \text{Depth of cut} \quad (3)$$

$$\text{MRR (mm}^3/\text{min)} = 436 - 1.920 \text{ Rotational speed} - 251 \text{ Feed rate} - 1080 \text{ Depth of cut} + 0.000142 \text{ Rotational speed}^2 - 95112 \text{ Feed rate}^2 - 237 \text{ Depth of cut}^2 + 29.94 \text{ Rotational speed} \times \text{Feed rate} + 3.241 \text{ Rotational speed} \times \text{Depth of cut} + 18477 \text{ Feed rate} \times \text{Depth of cut} \quad (4)$$

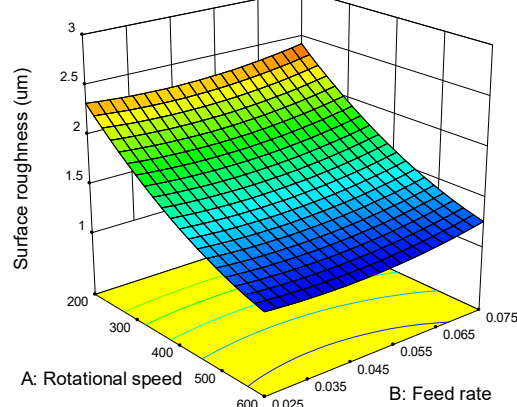
$$\text{TWR (}\mu\text{m)} = -115.2 - 0.0410 \text{ Rotational speed} - 768 \text{ Feed rate} + 1306.4 \text{ Depth of cut} - 0.000055 \text{ Rotational speed}^2 - 1231 \text{ Feed rate}^2 - 896.8 \text{ Depth of cut}^2 + 0.696 \text{ Rotational speed} \times \text{Feed rate} + 0.3178 \text{ Rotational speed} \times \text{Depth of cut} + 2456 \text{ Feed rate} \times \text{Depth of cut} \quad (5)$$

In Eq.4, MRR is the material removal rate in mm<sup>3</sup>/min, in Eq. 5, TWR is the tool wear rate in micro-meter. It is shown in ANOVA results that all three process parameters had significantly influenced the SR. Through response table, the minimum roughness of 1.158  $\mu\text{m}$  is found at rotational speed 600 rpm, Fr 0.025 mm/rev and DC 0.4 mm. The maximum value of roughness is 2.579  $\mu\text{m}$  at rotational speed 200 rpm, DC 0.6 mm and Fr 0.05 mm/rev. Fig 4 shows the 3D response graph of the surface roughness with respect to process parameters. Regarding individual process parameters, it was revealed that while increasing the rotational speed (Fig 4 a), surface roughness decreases. Usually, the increase of rotational speed up to a critical value leads to better surface finishing. It is due to the reduction in the size of the built-up edge at higher rotational speed <sup>33)</sup>. A larger depth of cut (Fig 4 a) also leads to the reduced surface finish because of the increment in the chip cross-sectional area and increased cutting forces over the machined surface. The Higher depth of cut may also be accountable for chattering, which is undesirable and increases the roughness value <sup>34)</sup>. Feed rate is also a significant parameter. Increasing the feed rate makes helicoids on machined surface and hence increases the roughness value <sup>35)</sup>. Variation in feed rate shows (Fig 4b) that a small increment in the feed rate up to a critical value decreases the roughness.

However, the increasing trend of roughness is observed with a further increment of the Fr but at a slower rate <sup>36)</sup>. The interaction plot between process parameters shows the combined effect of roughness. Fig 4 (a) indicates the combined effect of rotational speed and depth of cut while keeping feed rate at a constant value of 0.05 mm/rev. The response surface seems like flat, which avoids any unusual change of reaction. Both rotational speed and depth of cut significantly affected the rotational speed, while increasing the rotational speed, surface roughness decreases. It seems from the response surface that rotational speed changes the roughness value drastically compared to the depth of cut. Fig 4 (b) illustrates the 3D interaction plot of DC and Fr on the roughness value at the constant rotational speed of 400 rpm. It is shown from the response curve that at constant rotational speed with the increase of DC, roughness value also increases. The response surface also indicates that the middle range of feed rate provides the better surface finishing. Fig 4 (c) depicts that the interaction graph of rotational speed and feed rate at a constant depth of cut of 0.4 mm. It appears from the response surface that SR is influenced by both feed and rotational speed. Similar type of results were observed by the researchers <sup>33-36)</sup> working in this area.

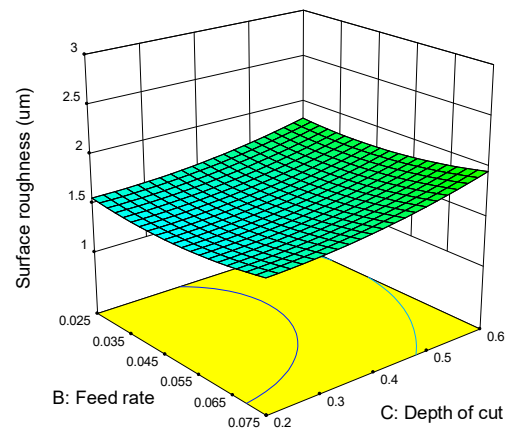


**Fig.4 (a)**

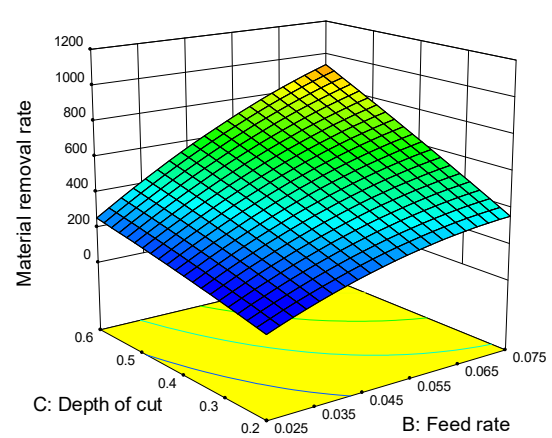


**Fig. 4 (c)**

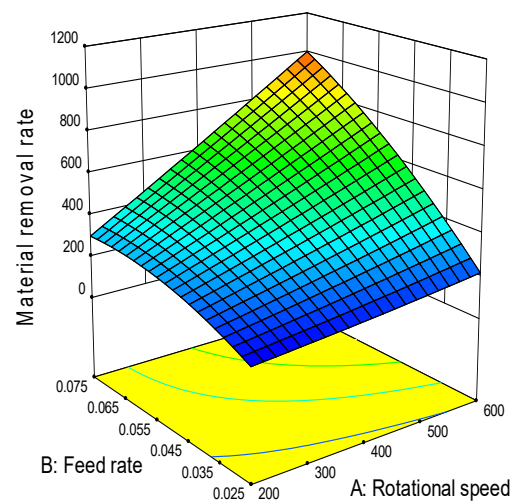
**Fig. 4:** Response graph for Surface roughness V/s process parameters in CNC lathe turning



**Fig.4 (b)**



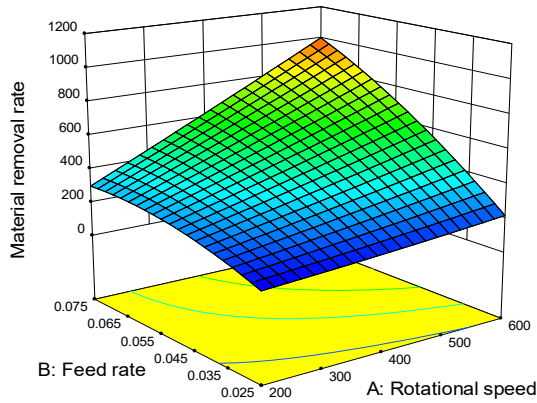
**Fig. 5 (a)**



**Fig. 5 (b)**

In all the experimental run, the maximum MRR of 1044.80 mm<sup>3</sup>/min is observed at rotational speed 600 rpm, DC 0.6 mm and Fr 0.05 mm/rev. On the other hand, minimum MRR of 118.48 mm<sup>3</sup>/min is reported at rotational speed 400 rpm, DC 0.2 mm and Fr 0.025 mm/rev. Fig 5 illustrates the effect of all process parameters on the MRR. It is indicated from the graphs 5 (a, b, c) that while increasing the rotational speed, Fr and DC, MRR is increased. It is attributed to the fact that at higher rotational speed the machining time decreases. Fig 5 (a) illustrates the influence of depth of cut and rotational speed, while feed rate is fixed at medium range. MMR increases with increasing depth of cut while the impact of rotational speed also pursues the similar trend but at the lower range of MRR. Fig 5 (b) demonstrates the influence of depth of cut and feed rate, while keeping the rotational speed at medium range 400 rpm. It is observed a slightly curved surface of response between the parameters. An increasing trend of MRR is seen at increasing range of parameters. Fig 5 (c) illustrates the effect of rotational speed and feed rate at a fixed depth of cut 0.4 mm. The response surface shows the peak value

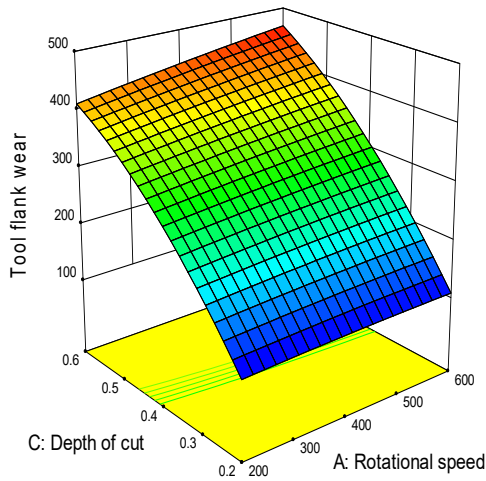
at a higher feed rate and rotational speed. The response surface also shows that the rotational speed is more significant than the feed rate and depth of cut.



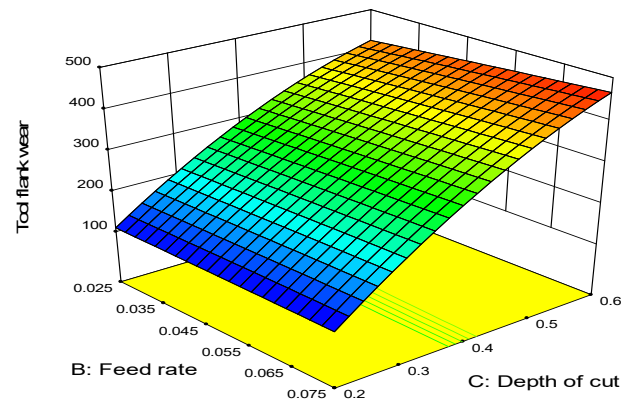
**Fig. 5 (c)**

**Fig. 5:** Response graph for MRR V/s process parameters in CNC lathe turning

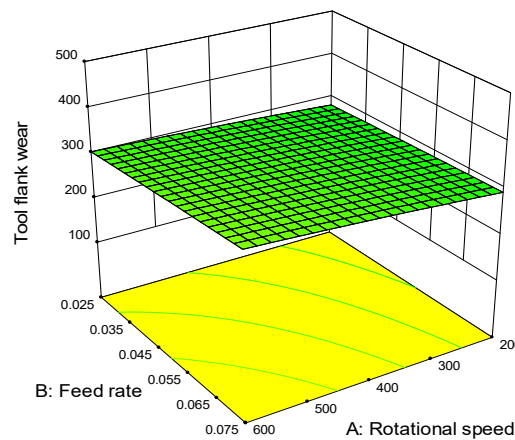
The lowest tool flank wear of 102.24  $\mu\text{m}$  is found at a rotational speed of 400 rpm, depth of cut 0.2 mm and feed rate 0.075 mm/rev. Whereas, maximum flank wear of 466.22  $\mu\text{m}$  is found at a rotational speed of 600 rpm, depth of cut 0.6 mm and feed rate 0.05 mm/rev. Fig 6 illustrates the 3D surface plots of the response variables i.e. tool flank wear on process parameters. The influence of individual process variables on tool flank wear revealed that while increasing the rotational speed, depth of cut and feed rate, flank wear also increases. It is attributed because at high rotational speed, the tool is subjected high contact stress and high temperature. Another reason for tool flank wear is the presence of hard reinforcement content in the MMC work piece which increase the abrasive wear of tool. In the case of MMCs, the combined effect of thermal, mechanical and abrasive wear of tool leads to the more substantial flank wear.



**Fig. 6 (a)**



**Fig. 6 (b)**



**Fig. 6 (c)**

**Fig. 6:** Response graph for tool flank wear Vs process parameters in CNC lathe turning

Fig. 6 (a) shows the response surface plots between DC and rotational speed at fixed value 0.05 mm/rev of feed rate. It was noted from the graph that flank wear increases by the increasing the DC. Fig. 6 (b) shows the interaction response between Fr and DC at a fixed rotational speed of 400 rpm. The response surfaces shows that at fixed rotational speed, depth of cut and feed rate both have a significant effect on tool flank wear. Fig. 6 (c) shows the response surface between feed rate and rotational speed at a fixed depth of cut. It can be stated from the graph that rotational speed and feed rate both have increasing trends of flank wear. However, From the F values in ANOVA table, it can be states that the contribution of rotational speed is more than feed rate. Hence, the tool flank wear is profoundly affected by rotational speed as well as DC and Fr. Fig. 7 (a, b) shows the images of tool wear before and after turning operation.

The combined optimum response of the machining is still a difficult task. Here an attempt is applied to

investigate the suitable value of process variables to get an overall optimized response using composite desirability approach. In the present investigation, the objective is to minimize SR, tool flank wear and maximize the MRR. The optimum responses outcomes regarding a set of process parameters are shown in Fig 8. The graph shows that the composite attraction to get optimized responses is model. The SR, MRR and tool flank wear values were measured as 1.324  $\mu\text{m}$ , 619.018  $\text{mm}^3/\text{min}$  and 176.73  $\mu\text{m}$ , 76.77%, and it can be found at rotational speed 600 rpm, DC 0.2444 mm, and Fr 0.075 mm/rev. At this composite desirability value, the minimum SR, maximum MRR and minimum tool flank wear is predicted as 1.2633  $\mu\text{m}$ , 665.018  $\text{mm}^3/\text{min}$  and 164.73  $\mu\text{m}$ , respectively. The individual desirability of surface roughness, MRR and tool flank wear are 92.59 %, 59.01% and 82.83%. The confirmation test was done to ensure the validity of the forecasted values respectively. Therefore, it can be stated that the results are almost close enough to the desired values.

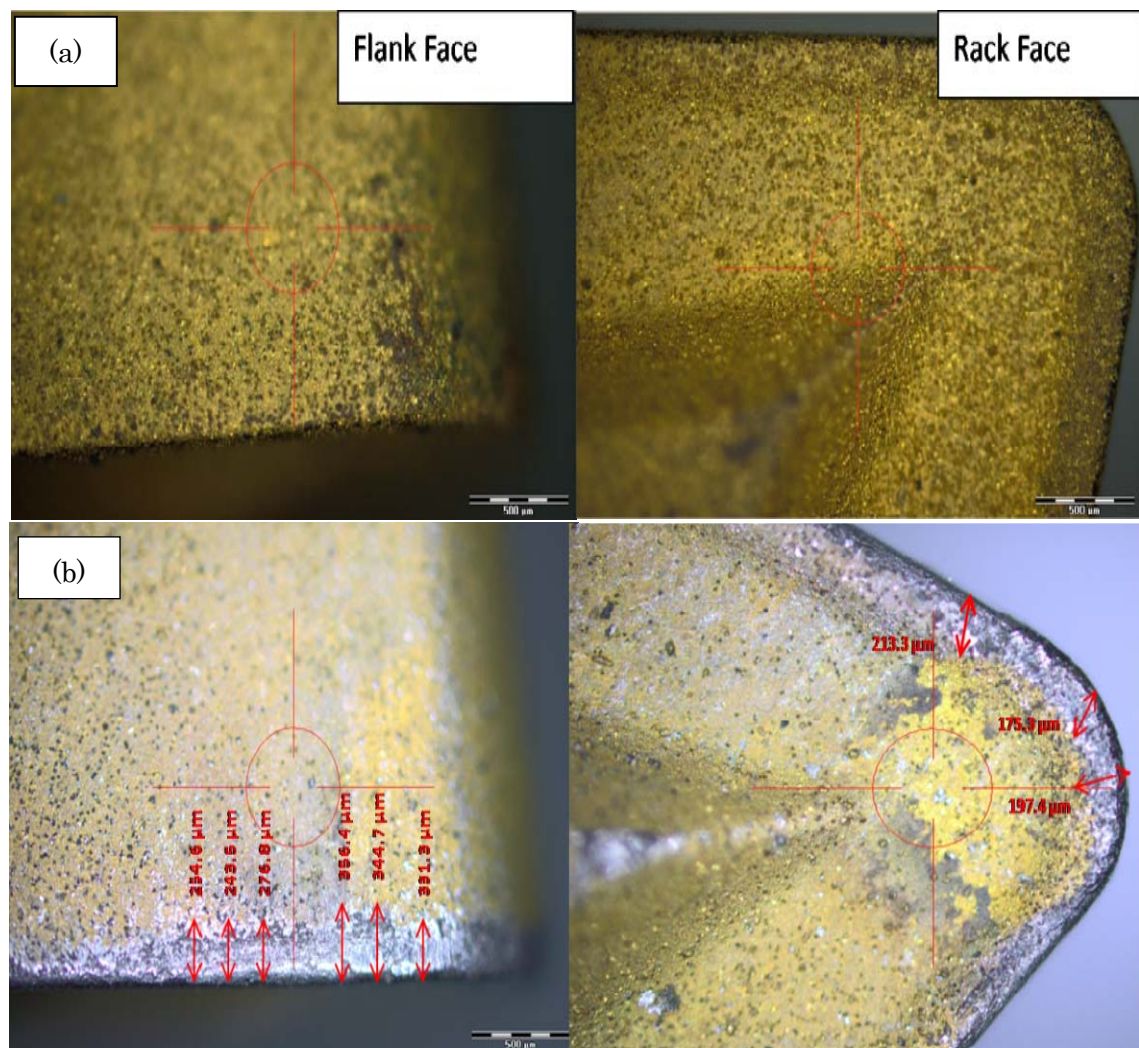


Fig. 7: Tool insert (a) before turning (b) after turning

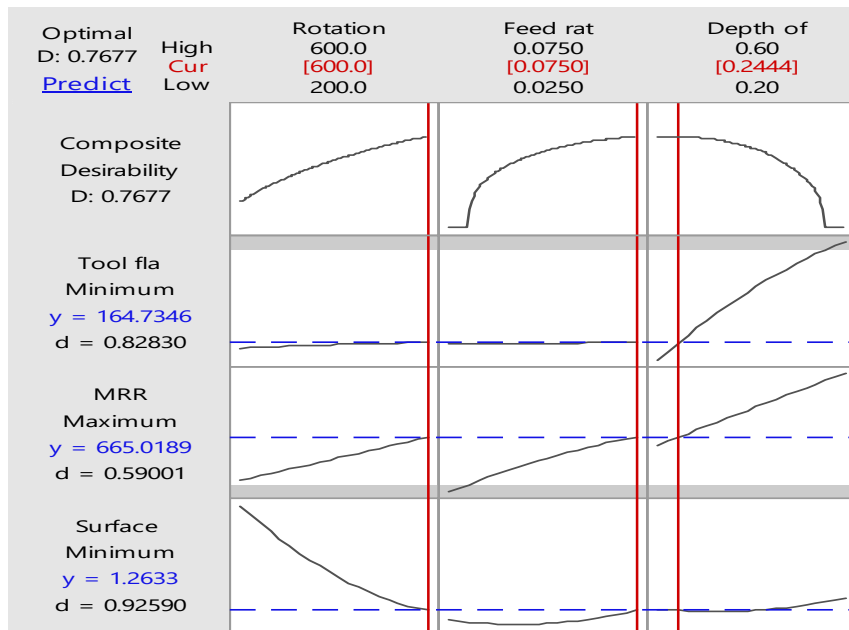


Fig. 8: Composite desirability for optimized responses in CNC lathe turning

### 3. Conclusion

It has been concluded that the machining of hybrid MMCs through CNC machined was successfully done. The experimental results found that the values of optimized SR and MRR are depends on the process parameters and their suitable range of machining. The lowest range of surface roughness lies between 1.15  $\mu\text{m}$  to 2.58  $\mu\text{m}$  and is observed for CNC lathe turning. However, it was required to change the tool insert in each experiment to get the similar surface finish. It may be noted that the depth of cut was kept low. At a higher depth of cut (approx. 1 mm), tool insert is subject to high cutting forces with high thermal and mechanical loading which leads to the breakage or rapid flank wear of the tool insert. The maximum and minimum MRR in the case of CNC lathe turning is found 118.48  $\text{mm}^3/\text{min}$  and 1044.8  $\text{mm}^3/\text{min}$ , respectively. It is observed that CNC lathe provides better surface finishing but at high tool wear. The tool flank wear of 466.22  $\mu\text{m}$  is observed at maximum MMR (1044.8  $\text{mm}^3/\text{min}$ ) and corresponding surface roughness of 1.22  $\mu\text{m}$ .

### References

- 1) S. P. Dwivedi, N.K. Maurya, M. Maurya, Assessment of Hardness on AA 2014/Eggshell composite Produced Via Electromagnetic Stir Casting Method, EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 06, 285 (2019).
- 2) N. K. Maurya, M. Maurya, A. K. Srivastava, S. P. Dwivedi, A. kumar, S. Chauhan, Investigation of mechanical properties of Al 6061/SiC composite prepared through stir casting technique, Materials Today: Proceedings, (2019), doi: 10.1016/j.matpr.2019.09.003.
- 3) M. Maurya, N. K. Maurya, V. Bajpai, Effect of SiC Reinforced Particle Parameters in the Development of Aluminium Based Metal Matrix Composite, EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 06, 200 (2019).
- 4) H. Sosiati, Y. A. Shofie, A. W. Nugroho, Tensile Properties of Kenaf/E-glass Reinforced Hybrid Polypropylene (PP) Composites with Different Fiber Loading, EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 05, 1 (2018).
- 5) T. Tiwari, S. Sourabh, A. Nag, A. R. Dixit, A. Mandal, A. K. Das, N. Mandal, A. K. Srivastava, Parametric investigation on abrasive water jet machining of alumina ceramic using response surface methodology, IOP Conf. Series: Materials Science and Engineering 377 (2018) 012005. doi:10.1088/1757-899X/377/1/012005
- 6) A.K. Srivastava, Y. Gupta, S. Patel, S. K. Tiwari, S. Pandey, Metal matrix composites- a review on synthesis and characterization, IOP Conf. Series: Materials Science and Engineering 691 (2019) 012077, doi:10.1088/1757-899X/691/1/012077
- 7) S. P. Dwivedi, M. Maurya, N. K. Maurya, A. K. Srivastava, S. Sharma, A. Saxena, Utilization of

- Groundnut Shell as Reinforcement in Development of Aluminum Based Composite to Reduce Environment Pollution: a review, EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 07,15(2020).
- 8) A. K. Srivastava, S. P. Dwivedi, N. K. Maurya, Manish Maurya, 3D visualization and topographical analysis in turning of hybrid MMC by CNC lathe SPRINT 16TC made of BATLIBOI, EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 07, Issue 02, pp202-208, June, 2020
- 9) A.K. Srivastava, A. Nag, A.R. Dixit, S. Tiwari, J. Scucka, M. Zelenak, S. Hloch, P. Hlavacek, Surface integrity in tangential turning of hybrid MMC A359/B4C/Al<sub>2</sub>O<sub>3</sub> by abrasive water jet, J. Manuf. Process. 28, 11(2017).
- 10) A. Nag, A. K. Srivastava, A. R. Dixit, A. Mandal, A. K. Das, T. Tiwari, Surface Integrity analysis of Wire-EDM on in-situ hybrid composite A359/Al<sub>2</sub>O<sub>3</sub>/B4C ,Materials Today: Proceedings, 5, 11, 24632 (2018),doi:10.1016/j.matpr.2018.10.261.
- 11) A. Nag, J. Ščučka, P. Hlavacek, D. Klichová, A.K. Srivastava, S. Hloch, A.R. Dixit, J. Foldyna, M. Zelenak, Hybrid aluminium matrix composite AWJ turning using olivine and Barton garnet”, Int. J. Adv. Manuf. Technol. (94),2293(2017).DOI 10.1007/s00170-017-1036-0
- 12) A. K. Srivastava, A. Nag, A. R. Dixit, Jiri Scucka, SergejHloch, Dagmar Klichová, PetrHlaváček, Sandeep Tiwari, Hardness measurement of surfaces on hybrid metal matrix composite created by turning using an abrasive water jet and WED, Measurement, 131, 628(2019).
- 13) M. Maurya, Sudhir Kumar, and Vivek Bajpai, Assessment of the mechanical properties of aluminium metal matrix composite: A review, Journal of Reinforced Plastics and Composites, 38, 267 (2019).
- 14) M. Maurya, S. Kumar, V. Bajpai and N. K. Maurya, Process parameters, development and applications of stir cast composite: A review, Materials Testing, 62 (2020) 2, DOI 10.3139/120.111472
- 15) A. K. Srivastava, A. Nag, A. R. Dixit, S. Tiwari, V.S. Srivastava, Parametric Study During Abrasive Water Jet Turning of Hybrid Metal Matrix Composite.” In: Hloch S., Klichová D., Krolczyk G., Chattopadhyaya S., Ruppenthalová L. (eds) Advances in Manufacturing Engineering and Materials. Lecture Notes in Mechanical Engineering. Springer, Cham, (2019) doi: 10.1007/978-3-319-99353-9\_9
- 16) A.K. Srivastava, A. Nag, A.R. Dixit, S. Hloch, S. Tiwari, J. Scucka, P. Pachauri, Surface integrity in wire-EDM tangential turning of in-situ hybrid metal matrix composite A359/B4C/Al<sub>2</sub>O<sub>3</sub>”,Sci. Eng. Compos. Mater. (2018). Doi: 10.1515/secm-2017-0391.
- 17) A. Manna, B. Bhattacharyya, Investigation for optimal parametric combination for achieving better surface finish during turning of Al/SiC-MMCs, International Journal of Advanced Manufacturing Technology, 23, 658 (2004).
- 18) Ozben Tamer, Kilickap Erol, Cakır Orhan, Investigation of mechanical and machinability properties of SiC particle reinforced Al-MMCs, Journal of Materials Processing Technology, 198, 220(2008).
- 19) K. Metin, A Study on the machinability of Al<sub>2</sub>O<sub>3</sub> particle reinforced aluminium alloy composite, Practical Metallography, 46, 580 (2009).
- 20) Sasimurugan T., Palanikumar K., Analysis of the machining characteristics on surface roughness of a hybrid aluminium metal matrix composite (Al6061-SiC-Al<sub>2</sub>O<sub>3</sub>), Journal of Minerals & Materials Characterization & Engineering, 10,1213(2011).
- 21) Srinivasan, A., Arunachalam R.M., Ramesh S. and Senthil kumaar J.S, Machining performance study on metal matrix composites-a response surface methodology approach, American Journal of Applied Sciences, 9 (4), 478(2012).
- 22) A. Goyal, N. Yuvaraj, R. Butola, L.Tyagi, An experimental analysis of tensile, hardness and wear properties of aluminium metal matrix composite through stir casting process, SN Applied Sciences 2,892(2020).
- 23) R. Butola, C. Pratap, A. Shukla, R. S. Walia, Effect on the mechanical properties of aluminum-based hybrid metal matrix composite using stir casting method, Mater Sci Forum 969, 253(2019).
- 24) A. Coyal, N. Yuvraj, R. Butola, K. Dev Pandey, T. S. Kalra, Microstructure and Mechanical Properties of Synthesized Aluminium Composite using Stir Casting Process, IJAPIE-2019-04-237,2,35(2019).
- 25) R. Butola, A.Malhotra, M.Yadav, R.Singari, Q.Murtaza, P.Chandra, Experimental Studies on Mechanical Properties of Metal Matrix Composites Reinforced with Natural Fibres Ashes, SAE Technical Paper 2019-01-1123, (2019).
- 26) L. Tyagi, R. Butola, A. K. Jha, Mechanical and tribological properties of AA7075-T6 metal matrix composite reinforced with ceramic particles and aloe vera ash via Friction stir processing, Material Research Express, 7, 1 (2020).
- 27) R. Butola, Q. Murtaza, R.M. Singari, An experimental and simulation validation of residual stress measurement for manufacturing of friction stir processing tool, Indian Journal of Engineering & Materials Sciences, 27(4) 826 (2020).
- 28) R. Butola, R. M. Singari, A. Bandhu, R. S. Walia, Characteristics and Properties of different reinforcements in hybrid aluminium composites: a review, Int. J. Adv. Product Ind. Eng.-SI-MM, 511,71 (2017).
- 29) R. Butola, M. S. Rangnath, Q. Murtaza, Fabrication

and optimization of AA7075 matrix surface composites using Taguchi technique via friction stir processing (FSP), Engineering Research Express. 1(2), 025015 (2019).

- 30) A. Chaudhary, A. K. Dev, A. Goel, R. Butola, M.S. Ranganath, The Mechanical properties of different alloys in friction stir processing: a review, Mater Today 5(2):5553 (2018).
- 31) R. Butola, Q. Murtaza, M. S. Rangnath, Formation of Self-Assembled Monolayer and Characterization of AA7075-T6/B4C Nano-ceramic surface composite using Friction Stir Processing, Surface Topography: Metrology and Properties 8 (2) 025030 (2020).
- 32) R. Butola, S. Kanwar, L. Tyagi. R. M. Singari, M. Tyagi, Optimizing the machining variables in CNC turning of aluminium based hybrid metal matrix composites, SN Applied Sciences 2, 1356 (2020).
- 33) Astakhov Viktor P., Cutting tool wear, tool life and cutting tool physical resource, Tribology and Interface Engineering Series, Book chapter, Elsevier, 52,220 (2006).
- 34) Shaw Milton C., Metal Cutting Principles, Second Edition, Oxford University Press.(2005)
- 35) Hamdi, Aouici, Bouchelaghem, H, Yallese, Mohamed, Mohamed, Elbah, Fnides, Brahim, Machinability investigation in hard turning of AISI D3 cold work steel with ceramic tool using response surface methodology, The
- 36) Abdullah A.B., Chia L.Y., Samad Z., The Effect of Feed Rate and Cutting Speed to Surface Roughness. Asian Journal of Scientific Research, (1) 12, 21(2008).