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Effect of Turning Parameters and Reinforcement on the Surface Roughness of Hybrid Aluminium Metal Matrix Composite

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***Abstract:** Since last two decades, technology has changed rapidly in each industry from consumer goods to aerospace. To quench the thrust of technology advancement of industries, the research community has to develop the novel materials. As a part of the ongoing process of material development and machinability study, present work was carried out to find out the effect of various cutting parameters on surface roughness and machining time of aluminium Hybrid Metal Matrix Composites (AHMMCs). In this study, pure aluminium was used as a matrix material while; B4C, Mg, Ti and Graphite were used as reinforcement. It was observed that 2202 RPM spindle speed, 0.18 mm/rev feed rate and 1.1 mm depth of cut are the optimum turning parameters with PCD insert. While machining of same composites using carbide insert, optimum spindle speed, feed rate and depth of cut are 2091 RPM, 0.19 mm/rev and 1.1 mm respectively. Moreover, PCD insert provides better surface finish compared to carbide coated insert for same cutting conditions. Moreover, the effect of reinforcement particles presence on the surface finish was also investigated and it was concluded that reinforcement presence reduces the surface roughness considerably. Particularly presence of Mg and graphite reduces surface finish significantly.*

***Keywords:** Hybrid Metal Matrix Composite, Surface finish, Machining time, Box- Behnken design*

I. INTRODUCTION

Since the last three decades, industries and research community have strived for the development of composite materials for varies applications in an automobile to aerospace industries. There are various fabrication processes available that can produce a component with high dimension tolerance. Still, it is not possible to eliminate the machining need because of part design, aesthetics and tolerance required [1]. Machining of MMCs (Metal Matrix Composites) is diverse compared to conventional materials and their alloys. The presence of abrasive reinforcement particles like B_4C, Ti, TiB_2 etc. make the machining of such material difficult [2-4]. Turning is the most frequently used machining operation for the development of circular objects. Therefore, optimization of turning parameter is necessary for the production of a component with good surface integrity [3, 5], low machining time and low tool wear [6]. Optimization of cutting parameters is also essential for machining economics and quality [7]. Surface roughness is considered a significant response as it affects the wear, corrosion and fatigue resistance of machined part [8]. As surface roughness increases the fatigue resistance of the machined part reduces significantly [9]. Suresh, Basavarajappa and Samuel [8] recommended surface roughness study of the machined part along with the tool wear study to get a better idea about the important phenomenons that affect the machining process. They emphasise on surface quality along with tool wear study because machining of the materials produce various flaws on the surface. Thus, it is difficult to substantially conclude much from tool wear study [10]. Dabade et al. [11] and El-Gallab and Sklad [12] conducted a study to find out the effect of machining parameters and tool properties on the surface finish of Al/SiC/10p metal matrix composite. They observed that cutting speed and feed rate are the significant parameters for surface finish, whereas the depth of cut found insignificant parameter. The surface finish of the machined part improves as cutting speed increases and feed rate reduces. [13]. Moreover, the surface finish also depends on the quantity and quality of reinforcement in metal matrix composite [14]. Type of reinforcement also influences the surface quality of the composite. Kumar and Chauhan [15] performed machining on Al-SiC-graphite and Al-SiC composite and concluded that the hybrid metal matrix composite produces better surface quality compared to the ceramic reinforced metal matrix composite. The graphite acts as a solid lubricant is responsible for the good surface quality of hybrid metal matrix composite [15]. In the machining of metal matrix composites cemented carbide or PCD inserts are generally used because of their distinct advantages. However, many conflicting studies suggested that the use of carbide inserts is only advantageous if used under certain conditions [16, 17]. Researchers concluded that carbide inserts are effective in short run machining operations or roughing operations. Low cutting speed (20 to 30 m/min) and high feed rate suggested for the effective tool life of carbide coated tools. Chen and Hoshi [18] conducted from the machining study on Al-SiC with carbide insert that tool life reduces up to 40 min only with cutting speed of 250 m/min. Moreover, they observed significant damage to the machined surface due to carbide insert used at high cutting speed.

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However, carbide tools coated with ceramic material improves the tool life by 200 % to 300 % compared to uncoated carbide insert [19]. Furthermore, researchers suggested the use of carbide insert because it reduces the cost of machining considerably compared to PCD insert [20]. Conversely, PCDs are considered the best tool materials for the machining of the composite material. This is attributed to the fact that the hardness of the PCD is much higher than any of the reinforcement used in the development of metal matrix composites [21] and hence provides higher tool life compared to carbide tool. Besides, PCD tools are excellent for better surface integrity of the work materials at higher cutting speed and low feed rate [22]. Therefore, in the present study PCD and carbide insert were used to check the effect on surface integrity of newly developed aluminium metal matrix composite during turning operation.

II. MATERIALS AND METHODOLOGY

The composite material was fabricated using stir casting method. Pure aluminium was used as a matrix material while B_4C, Mg, Ti and graphite were the reinforcement. Particularly, B_4C was added to improve the mechanical properties while graphite was added to improve the wear resistance properties of the matrix material. Ti and Mg were added as wetting agents for B_4C and graphite respectively. Information about the fabrication process and trial experiments were mentioned in a paper that is published somewhere else. Moreover, authors have reviewed the work carried out by various researchers and explicitly mentioned the problems encountered during the fabrication of aluminium matrix composite using stir casting process [23]. Therefore, the experimental design and fabrication process during current work were designed using such knowledgebase.

Specimens were prepared in a shape of circular bar having a diameter of 30 mm form for the convenience of machining using permanent graphite mould. Carbide coated and PCD (Polycrystalline Diamond) inserts were used in single pass machining operation to find out the effect of types of tools on surface finish. Experiments were carried out using Box-Behnken design and the results were analysed using statistical software Minitab 17. Table 1 shows the factors, levels, responses and other machining conditions while Table 2 shows the design matrix. Machining was performed on GREENFIELD CNC turning centre (Turn master GF 165). Cutting parameters were selected based on the literature available [23] while parameter levels of the same were selected based on trial experiments and suggested for carbide and PCD inserts used in the finishing of aluminium metal matrix. Surface finish and machining time were selected as the responses. The surface finish was measured with the help of Mitutoyo SJ-210 surface roughness tester while machining time was calculated with the help of Eq. (1). In this equation *v*, *f*, *d* and *l* represent cutting speed, feed, the diameter of the specimen and machining length respectively. Separate experiments were performed using carbide and PCD inserts and each experimental run was performed thrice. Therefore, 108 total experiments were performed. To validate the results Microscopic and Scanning Electron Microscopic (SEM) techniques were used.

Table 1 List of factors, responses and other machining conditions

Factors	Levels	Response	Type of tool	Coolant (used)	Reinforcement Amount
Spindle Speed (RPM)	1000-2250	Surface Finish & Machining Time	Carbide coated (CNMG) and PCD (CNMA) insert	Yes	B_4C-10%, Mg-5%, Ti-1, Graphite-5%
Depth of cut(mm)	0.2-2.0				
Feed (mm/rev)	0.18-0.25				

Table 2 Box-Behnken design matrix for turning parameter optimization

Sr. No	Speed	Cut	Feed	Sr. No	Speed	Cut	Feed
1	1000	0.2	0.21	9	1625	0.2	0.18
2	2250	0.2	0.21	10	1625	2	0.18
3	1000	2	0.21	11	1625	0.2	0.25
4	2250	2	0.21	12	1625	2	0.25
5	1000	1.1	0.18	13	1625	1.1	0.21
6	2250	1.1	0.18	14	1625	1.1	0.21
7	1000	1.1	0.25	15	1625	1.1	0.21
8	2250	1.1	0.25				

III. RESULTS AND DISCUSSION

Effect of machining parameters on surface finish and machining time

Experiments were performed as per Box-Behnken design as shown in table 2. The carbide insert was used on 80 cm length of the hybrid composite bar having a diameter of 30 mm and the results are shown in the fig. 1(a) and fig. 1(b). It is evident from the fig. 1(a) that lowest surface finish value was obtained at spindle speed 2250 RPM, feed 0.18 mm/rev and depth of cut 1.1 mm (i.e. in run no. 6). However, as shown in fig. 1(b), machining time found lowest when spindle speed 2250 RPM, feed 0.25 mm/rev and depth of cut 1.1 mm (i.e. in run no. 8). Fig. 2 & 4 show the individual and response surface plots of surface roughness and machining time respectively when composite was machined with a carbide coated insert. It is evident from the individual plot that spindle speed and feed are the significant parameters for machining time but the depth of cut is an insignificant parameter.

However, in case of surface finish, depth of cut along with spindle speed and feed found significant parameters. These results are in agreement with the result observed by Nataraj and Balasubramanian [24]. Researchers performed a turning parameters optimization for surface roughness, vibration and work-tool interface of hybrid metal matrix composite and concluded that depth of cut along with speed and feed has a significant effect on the hybrid metal matrix composite. However, this contradicts the result observed by Palanikumar, Karunamoorthy and Karthikeyan [25]. Researchers observed that the depth of cut is insignificant parameter compared to the speed and feed while machining a monolithic materials and metal matrix composite [20, 26, 27]. Subsequently, the microscopic examination of the composite was performed to find out the reason for such contrary results. Fig. 3 shows the microscopic image of a cross-section of the composite. It is evident from the image that reinforcements are present at the outer layer of the composite and increases as the depth increases (up to 1.2 mm). Then it decreases subsequently after certain depth and this reduction in reinforcement amount due to non-uniform distribution of reinforcements was considered the reason behind such contradictory result. It was observed by the authors that mechanical force applied by impeller during the stirring process stimulates the reinforcement particles and concentrate them around the periphery of the cast specimen. Optical emission spectrometry was also performed to validate the presence of the reinforcement and the result is shown in Table 3. Therefore, further analysis was performed by considering the depth of cut 1.1 mm constant from individual plots. Hence, response surface plots shown in fig. 4 were plotted by taking the depth of cut constant (i.e. 1.1 mm). It is evident from the plots that surface finish value reduces as speed increases and feed decreases. While in the case of machining time, time reduces as speed and feed increases. Fig. 5 shows contour plots and overlaid contour plot for surface finish and machining time. These plots were also plotted by maintaining the depth of cut constant (i.e. 1.1 mm). It is evident from the fig. 5 (a) that surface finish value lower than 1.7μm is achievable if spindle speed and feed maintain at 2200 RPM and 0.18 mm/rev respectively. While it is apparent from the fig. 5 (b) that machining time reduces up to 0.15 min, if spindle speed and feed maintain at 2200 RPM and 0.25 mm/rev respectively. Therefore, to get the optimum value of speed and feed for lower machining time and lower surface finish value, the overlaid contour plot was plotted as shown in fig. 5(c). It is evident from the figure that speed and feed range between 1600 to 2200 RPM and 0.18 to 0.22 mm/rev provides the optimum value of speed and feed for lower surface finish and machining time. Therefore, one of the data points was selected from the overlaid plot as shown in fig. 5(c). That data point suggests that speed 2091 RPM, feed 0.19 mm/rev and depth of cut 1.1 mm could provide the surface finish value and machining time 1.67 μm and 0.19 min respectively. To confirm and validate the prediction made by the software, confirmation test was performed and results are shown in table 4. It is apparent from the table that predicted and actual results are under a 95% confidence interval as %error between predicted and actual results is less than 5%. This also proves the stability of systems used for the machining of specimens and measurement of responses.

Table 3 Chemical composition of composite

Si	Fe	Cu	Mn	Mg	Zn	Ti
0.45	0.44	0.009	0.04	2.01	0.02	0.421
Cr	**Ni**	**Pb**	**Sn**	**C**	**B**	**Al**
0.007	0.007	0.03	0.002	1.7	4.7	90

Table 4. Confirmation test result when the carbide insert was used.

Speed	Feed	Depth of cut	Predicted Value		Actual Value		(%)error	
			Ra (μm)	TC (min)	Ra (μm)	TC (min)	Ra (μm)	TC (min)
2091	0.19	1.1	1.678	0.193	1.737	0.190	3.39	1.57
2091	0.19	1.1	1.678	0.193	1.701	0.190	1.35	1.57
2091	0.19	1.1	1.678	0.193	1.722	0.190	2.55	1.57

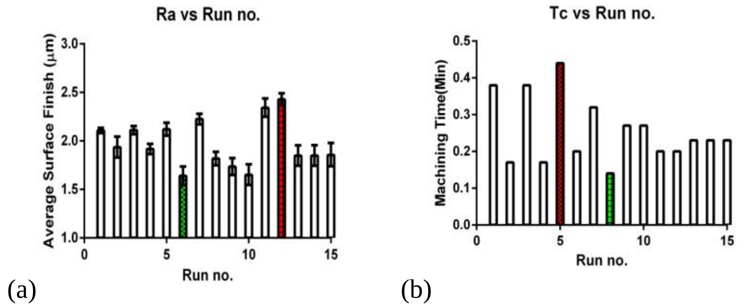


Figure 1 Graphs of surface finish and machining time when machining carried out using carbide insert.

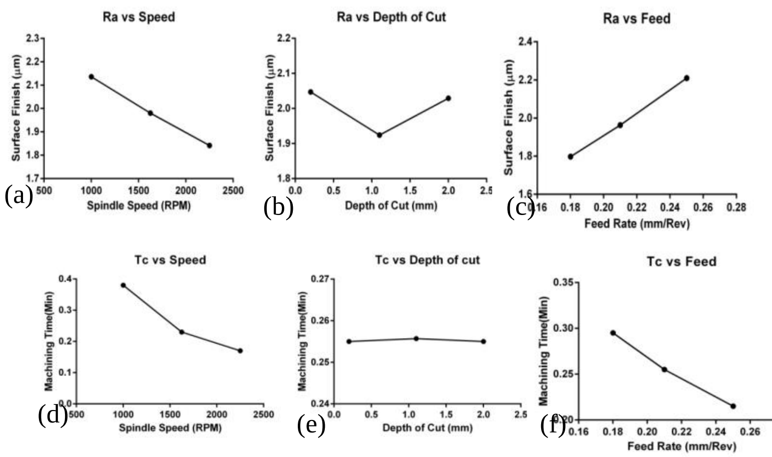


Figure 2 Individual plots of a mean of surface roughness and machining time when machining carried out using carbide insert.

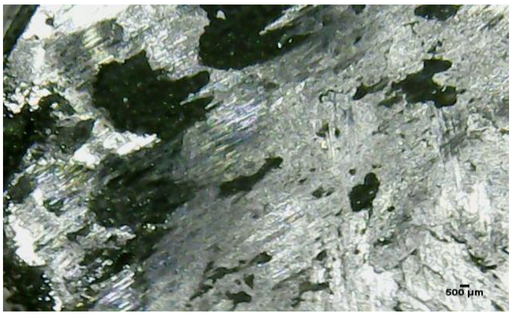


Figure 3 Microscopic image of the cross-section of the composite.

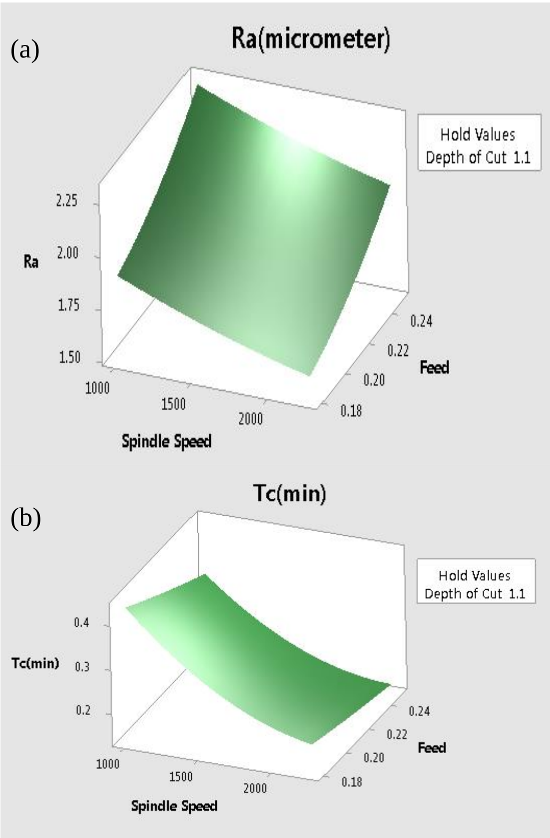
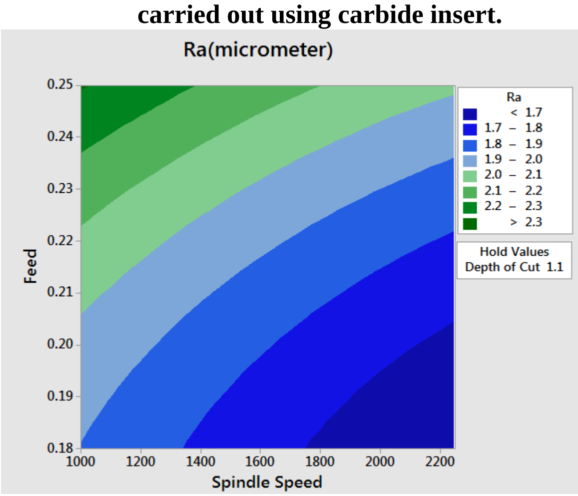


Figure 4 Response surface plots of surface roughness and machining time when machining carried out using carbide insert.



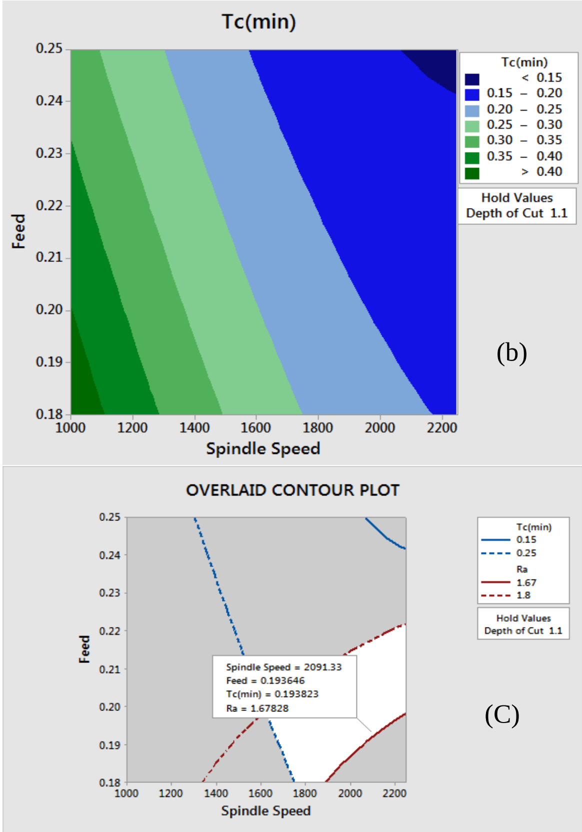


Figure 5 Contour plots of surface roughness and machining time when machining carried out using carbide insert.

The PCD insert was used on 80 cm length of the hybrid composite bar and the results are shown in the fig. 6(a) and fig. 6(b). It is evident from the fig. 6(a) that lowest surface finish value was obtained at spindle speed 2250 RPM, feed 0.18 mm/rev and depth of cut 1.1 mm (i.e. in run no. 6). However, as shown in fig. 1(b), machining time found lowest when spindle speed 2250 RPM, feed 0.25 mm/rev and depth of cut 1.1 mm (i.e. in run no. 8). Moreover, comparison of results of surface finish with PCD (i.e. in fig. 6(a)) and carbide insert (i.e. in fig. 1(a)) suggest that PCD insert produces good surface finish compared to the carbide at the same cutting condition. These results are in agreement with results obtained by Schrock, Kang, Bieler and Kwon [28]. This is also evident from the comparison of individual plots of surface finish and machining time shown in fig. 2 and fig. 7. It is evident from the fig. 7(a) and fig. 7(b) that spindle speed and feed are the significant parameters for machining time but the depth of cut is an insignificant parameter. However, in case of surface finish, depth of cut along with spindle speed and feed found significant parameters. These are the similar results as obtained using a carbide insert. The response surface plots are shown in fig. 8 (a) and 8(b) which were plotted by taking the depth of cut constant (i.e. 1.1 mm). Response surface plots show similar results as observed from individual plots. It is evident from the plots that surface finish value reduces as speed increases and feed decreases. While in the case of machining time, time reduces as speed and feed increases. Fig. 9 shows contour plots and overlaid contour plot for surface finish and machining time. These plots were also plotted by maintaining the depth of cut constant (i.e. 1.1 mm).

It is evident from the fig. 9 (a) that surface finish value lower than 1.3 µm is feasible if spindle speed and feed maintain at 2200 RPM and 0.18 mm/rev respectively. While it is evident from the fig. 9 (b) that machining time reduces up to 0.15 min, if spindle speed and feed maintain at 2200 RPM and 0.25 mm/rev respectively. Therefore, to get the optimum value of speed and feed for lower machining time and lower surface finish value, the overlaid contour plot was plotted as shown in fig. 9(c). It is evident from the figure that speed and feed range between 1800 to 2200 RPM and 0.18 to 0.22 mm/rev respectively provide the optimum value of spindle speed and feed for lower surface finish and machining time. Therefore, one of the data points was selected from the overlaid plot as shown in fig. 9(c). That data point suggests that spindle speed 2202 RPM, feed 0.18 mm/rev and depth of cut 1.1 mm would provide the surface finish value and machining time 1.2 µm and 0.19 min respectively. To confirm and validate the forecast made by the software, confirmation test was performed and results are shown in table 5. It is apparent from the table that predicted and actual results are under a 95% confidence interval as %error between predicted and actual results is less than 5%.

Table 5 Confirmation test result when a PCD insert was used

Speed	Feed	Depth of cut	Predicted Value Ra (µm)	Predicted Value TC (min)	Actual Value Ra (µm)	Actual Value TC (min)	(%)error Ra (µm)	(%)error TC (min)
2202	0.18	1.1	1.261	0.196	1.315	0.2	4.10	2
2202	0.18	1.1	1.261	0.196	1.321	0.2	4.54	2
2202	0.18	1.1	1.261	0.196	1.302	0.2	3.14	2

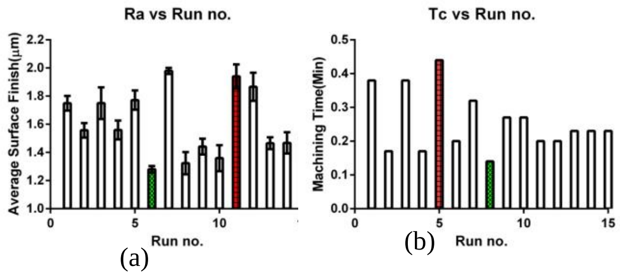
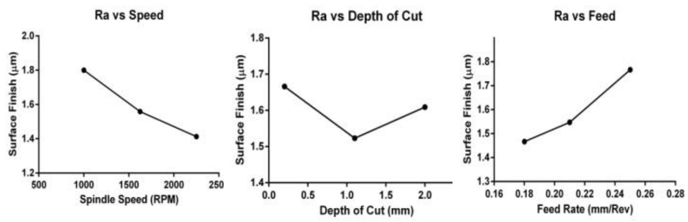
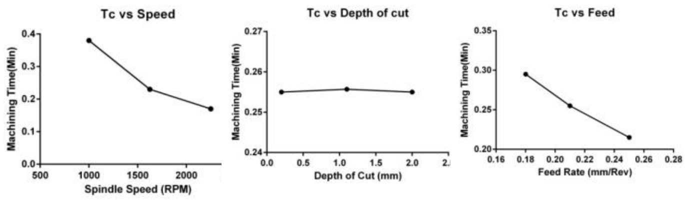


Figure 6 Graphs of surface finish and machining time when machining carried out using PCD insert.



(a) (b) (c)



(d) (e) (f)

Figure 7 Individual plots of a mean of surface roughness and machining time when machining carried out using PCD insert.

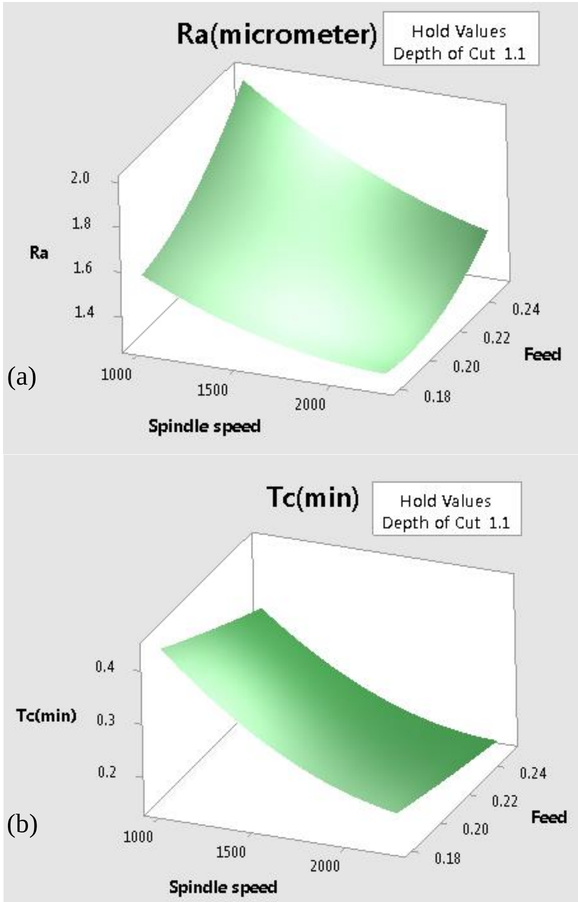
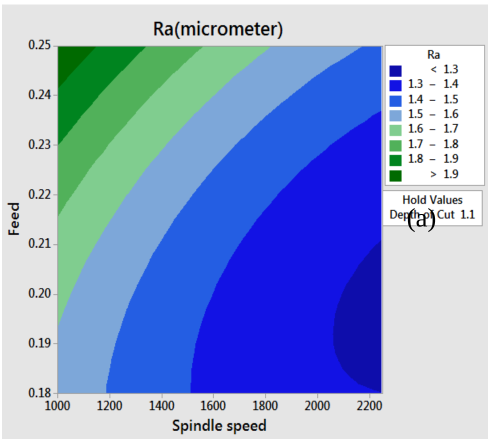


Figure 8 Response surface plots of surface roughness and machining time when machining carried out using PCD insert.



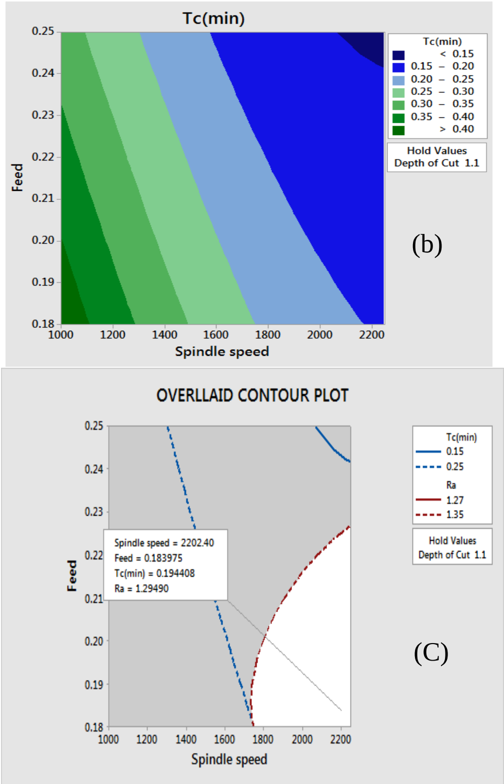


Figure 9 Contour plots of machining time and surface roughness when machining carried out using PCD insert.

Effect of reinforcement on the surface finish of the composite

It was observed from the individual, response surface and contour plots that surface roughness increases as feed increases. It is evident from the fig. 10 (a) that feed marks produce big hills and valleys where reinforcements are not present. However, when reinforcement material comes in a path of the cutting tool during the machining operation, it produces small hills and valleys and therefore it generates smooth surface compared to a matrix metal. Furthermore, it was noted by authors during initial experiments [29] and also observed by other researchers [30] that graphite plays a significant role as a lubricating agent which reduces the friction coefficient between tool and workpiece by generating a lubricating film between the two. This phenomenon was also validated by the results (i.e. under publication somewhere else) and Suthar and Patel [29] that shows a significant reduction in wear of tool material due to the presence of Mg and Graphite. Mg acts as a bonding agent for graphite that increases the wettability between graphite and matrix material. Graphite without Mg is not able to sustain for a longer period of time under machining conditions. Mg provides necessary bonding strength between matrix and graphite which allows graphite to sustain for a longer period of time on the work material. Therefore, overall surface roughness reduces with increase in % reinforcement in the composite material. A similar conclusion was made by Karabulut [31] during machining of AA7039/Al_2O_3 metal matrix composite. The researcher observed that presence and uniform distribution of Al_2O_3 particles provided a better surface finish compared to the matrix martial. Therefore, it was concluded that not only the optimized machining parameters but the presence of reinforcement also affect the surface roughness immensely. A microscopic and SEM image of the composite material after machining is shown in fig. 10 (b) and (c). It is evident from the fig. 10 (b) that the reinforcement clusters along the tool path are present while fig. 10 (c) shows scatter reinforcement particles that pulled out from the workpiece material after machining.

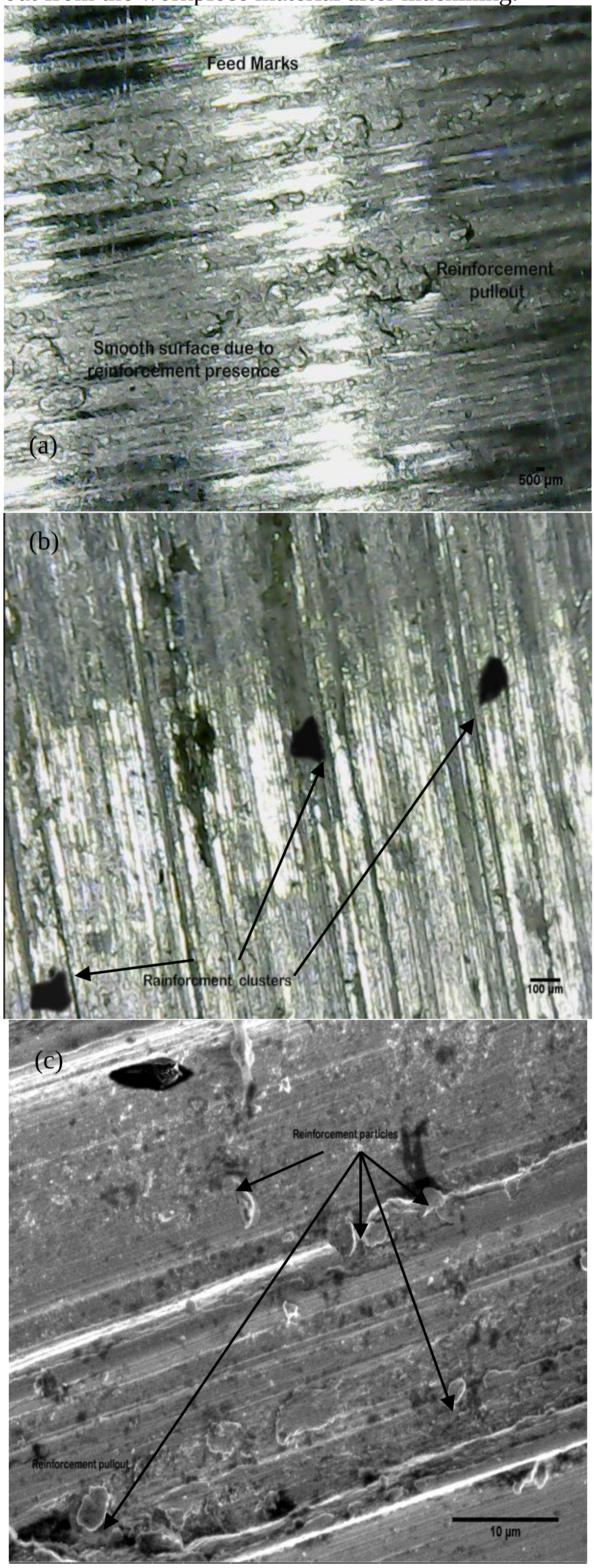


Figure 10 Microscopic and SEM images of the machined composite.

IV. CONCLUSION

It was observed that 2202 RPM spindle speed, 0.18 mm/rev feed rate and 1.1 mm depth of cut are the optimum turning parameters with PCD insert. While machining of same composites using carbide insert, optimum spindle speed, feed rate and depth of cut are 2091 RPM, 0.19 mm/rev and 1.1 mm respectively. Moreover, PCD insert provides better surface finish compared to carbide coated insert for the same cutting conditions. Amount of reinforcement, types of reinforcement and reinforcement distribution also significantly affect the surface finish of the machined specimen. As the number of reinforcement decreases and distribution becomes non-uniform, the quality of the surface deteriorates. Lubricating material like graphite reduces surface roughness significantly. Presence of wetting agent (Mg) along with lubricating agent (Graphite) further enhances the surface quality of the machined part.

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