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Effect of Machining Parameters on MRR and Surface Roughness in Machining of ZA43/ SiCp Composite by WEDM

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Abstract: The present work emphasis on behavior of zinc-aluminium alloy reinforced with silicon carbide particles when machined with wire electric discharge machining process (WEDM). The difficulty faced by conventional machining is severe tool damage while machining metal matrix composites. Electrical discharge machining can be successfully employed for machining MMC in the place of conventional machining to reduce the tool damage and to produce complicated contours with superior finish. In the present study ZA43 reinforced with SiCp is machined by wire EDM process. Machining is carried-out by varying applied current of (2, 4 and 6amp.), pulse on time (4, 8 and 16µs) and pulse off time (5, 7 and 9µs) while other parameters such as voltage, dielectric flushing pressure, wire tension etc. are maintained constant. It is observed that reduction in the material removal rate and increase in surface roughness for increasing reinforcement percentage in the composite. It is also observed that applied current and pulse on time increases the material removal rate where as pulse off time has less effect on it.

Keywords: WEDM; MMC; pulse-on time; pulse-off time; dielectric liquid; surface roughness; material removal rate.

1. Introduction

Conventional monolithic materials fail to compete in the market because of their limitations. The properties like strength, stiffness, toughness and density are the barriers for wide usage of the materials under different working conditions. To overcome these limitations and to meet the requirements, composites are most widely used materials. Metal matrix composites (MMC) are a relatively new class of materials characterized by lighter weight, greater strength and wear resistance than those of conventional materials. Due to their superior strength and stiffness, MMCs have good potential for application in the automotive and aerospace industries. One of the factors that prevent most of the manufacturers from embracing MMC technology is the difficulty of machining these materials. The machining of MMC is very difficult due to the highly abrasive and intermittent nature of the reinforcements. MMC components are mostly

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produced using near net shape manufacturing methods and are subsequently finish machined to the final dimensions and surface finishes. Conventional tool materials such as high-speed steel and uncoated-carbides cannot be used for machining MMCs as the cutting tool undergoes very severe damage [1-4].

To overcome the tool damage caused in the conventional machining process, non conventional machining techniques are employed for effective machining of MMCs. Improved surface finish and low tool wear is observed as there is no contact between tool and work piece material. WEDM is slightly modified version of the conventional EDM process, which uses an electrode to initialize the sparking process. WEDM utilizes a continuously traveling wire electrode made of copper, brass, tungsten or molybdenum of diameter 0.05-0.30mm. The wire is kept in tension using a mechanical tensioning device which increases the precision of machining. The wire is passed through the work piece where sparking takes place. The spark temperature is so high that the material is removed by vaporization. There is a very small gap between wire and work piece hence no contact between the work piece and the wire which eliminates the mechanical stresses during machining [4-7].

Many researchers have done work on machining of metal matrix composite materials by electrical discharge machining. By observing previous work material removal rate, surface roughness, effect of contents on machining and tool wear are determined by varying the parameters such as current, pulse on time, pulse off time, gap voltage, wire tension, type of dielectric medium, pressure of dielectric etc. R.N. Ahmad [12] et.al. have worked on wire EDM machining of 5% alumina reinforced aluminium matrix composite. Machining was carried out by considering the variables like pulse off time, servo voltage and wire tension. Current, pulse on time, dielectric flow rate and other parameters are kept constant. Regression analysis was done on the results obtained and it was found that servo voltage has significant effect on material removal rate. Pulse off time and wire tension must be set to maximum value to get maximum material removal rate [12].

Patil [1, 2] et. al. have worked on determination of material removal rate in wire electro-discharge machining of metal matrix composites using dimensional analysis. Aluminium based silicon carbide composite was machined using wire EDM process. The results reveal that material removal rate not only depends upon pulse on time but also material properties like coefficient of thermal expansion, thermal diffusivity and melting point temperature etc. and also the material removal rate decreases with increase in reinforcement percentage in the composite material [1, 2].

Sornakumar [5] et.al. have worked on EDM studies on aluminum alloy-silicon carbide composites developed by vortex technique and pressure die casting. The results revel that material removal rate and surface finish are greatly affected by current and reinforcement percentage. Material removal rate increases with increase in current and decreases with increase in reinforcement percentage. For better surface finish lower current and higher reinforcement content was suggested [5].

Singh [6] et.al. have reported the effect of process parameters on material removal rate in wire EDM process on steel with brass wire. According to their findings wire tension and wire feed rate has no effect on material removal rate but pulse on time has direct effect on it. Increase in material removal rate is observed for increasing pulse on time while with pulse off time it shows negative effect i.e. material removal rate decreases with increasing pulse off time [6].

Kanthababu [16] et.al. have worked on wire electrical discharge machining characteristics of Al6063/SiCp composites. In their work they reported effect of various machining parameters like pulse on time, pulse off time, current and applied voltage on material removal rate and surface roughness. Three compositions i.e. 5%, 10% and 15% SiC is considered for the study. The result shows that material removal rate decreases and Ra value increases with increasing reinforcement percentage. Statistical analysis was also carried out on results obtained to find out the optimum machining parameters. Form statistical analysis it is found that gap voltage is the significant parameter which affects the material removal rate [16].

Ramulu and Taya [14] reported machining of on aluminium matrix reinforced with SiC whiskers by EDM process. Aluminium 2124 as matrix and SiC whiskers of 15% and 25% by weight are used for fabrication of composite material. The results shows that, machining time for 25% reinforced composite is more than that of 15% reinforced composite. Hardness of machined surface is less for slow machining speeds and high for higher machining speeds. Higher machining speeds damage the material at surface and subsurface levels [14].

Narender Singh [8] et.al. have worked on Electric discharge machining of Al-10% SiCp as-cast metal matrix composites. Taguchi design of experiment technique is used for designing the experiments and ANOVA is used for analyzing the results and the significant factor affecting the machining. For experimentation variable machining parameters considered are applied current, pulse on time and dielectric. The results reveal that higher material removal rate can be obtained by higher current and higher pulse on time. Flushing pressure has considerable effect on material removal rate and tool wear rate. It is also observed that tool wear is more for high current values [8].

From above observations it is clear that there is a lot of scope for non traditional machining of metal matrix composites. By observing the previous work done in the area of WEDM of metal matrix composites, there is a lot of scope for present work. In the present work, wire electric discharge machining of ZA43 alloy reinforced with SiCp particles have been studied. The effect of parameters like current, pulse on time and pulse off time on machinability characteristics of ZA43+SiCp MMC is studied. Identical testing conditions are employed for testing the specimen with varying reinforcement percentage.

2. Materials and experimentation

2.1. Materials

In the present investigation ZA43 matrix was used. The chemical composition of matrix is given in the Table 1. All the elements are taken in their weight percentage. SiCp with 120 µm particle size was used for the preparation of the composite [17].

Table 1. Composition of metal base of MMC

Element	Al	Cu	Mg	Fe	Zn
Percentage (wt)	43	2.5	0.02	0.012	rest

2.2. Fabrication of MMC

Liquid metallurgy technique is used for fabrication of MMC. The cylindrical specimen of 20mm diameter and approximately 100mm in length is fabricated for test. The matrix was heated above its melting temperature and stirred with zircon coated impeller. Zircon coating was done to prevent diffusion of ferrous material in to the matrix during stirring. When the molten metal whirl is formed, to improve the wettability property pre heated SiC particles to about 400^0C were introduced in to molten matrix. Magnesium is added in the small percentage which also improves the wettability [17, 18]. Continuous stirring of the mixture is enforced to facilitate the proper distribution and wetting of the particles in to the matrix. The stirred mixture is poured in to the permanent cast iron mould and required castings are obtained. Three compositions of SiCp are fabricated for current study and it includes 5%, 10% and 15% by weight. Microscopic study of composite was carried out by scanning electron microscopy. The MMC specimen is polished for metallographic inspection. Polishing was carried out with different grades of emery papers and finally polished with Al_2O_3 paste and abrasive cloth. Suitable etching agent was applied to the surface for clear visualization of particle distribution. The typical SEM micrograph shows distribution of SiCp in the matrix and distribution was found to be uniform and at some portion clustering of SiCp was observed which is given in Figure 1.

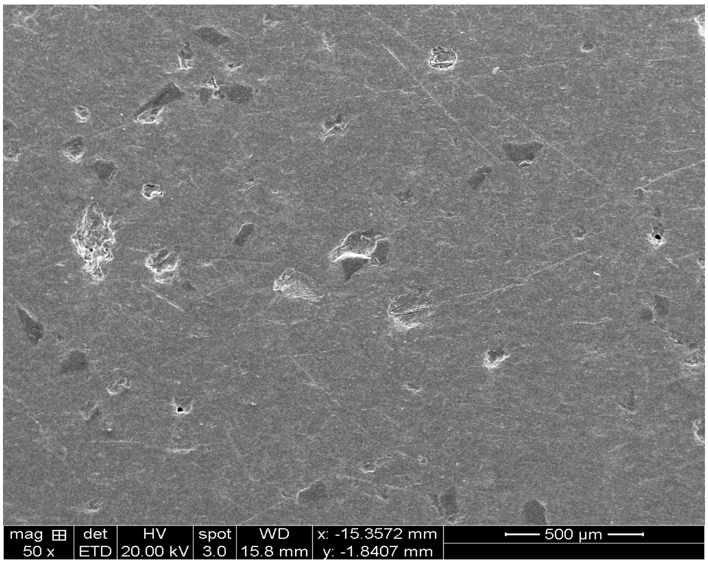

Figure 1. SEM micrograph showing SiC particle distribution in MMC

3. Machining of MMC

Concord DK7720C 4 axes CNC controlled wire EDM machine was used to carryout the experiments. Non consumable molybdenum wire with diameter 0.18mm was used for machining. The machining parameters such as wire tension, dielectric fluid pressure and applied voltage were kept constant and current, bed speed rate, and pulse on time and pulse off time were considered variable parameters for present investigation. Soap dissolved in deionized water was used as dielectric liquid during machining process.

The fabricated cylindrical composite specimen is fixed on the machine and circular pieces are sliced from it. The time duration for machining each slice was recorded. The material removal rate can be determined by [8].

$$\text{Material removal rate (MRR)} = \frac{I_{wt} - F_{wt}}{t} \text{ g/min}$$

Where I_{wt} (g) is the initial weight of the specimen, F_{wt} (g) is the final weight of the specimen after machining and t is the machining time in min.

Slices of composite were collected and surface roughness is checked by Talysurf make Mitutoyo and values were recorded. SEM micrographs of machined surface were taken to study the nature of material failure during machining. The parameters considered for machining MMC are given in the Table 2 below along with the Figure 2 showing the principle of WEDM.

Table 2. Machining parameters for WEDM

Sl. No	Parameter	Values			Unit
1	Current	2	4	6	Amp
2	Pulse on time	4	8	16	µs
3	Pulse off time	5	7	9	µs
4	Bed speed	20	30	40	µm/sec
5	Voltage	110			Volts
6	Dielectric	Soap + Deionized water			
7	Flush rate	1.2			lit / min

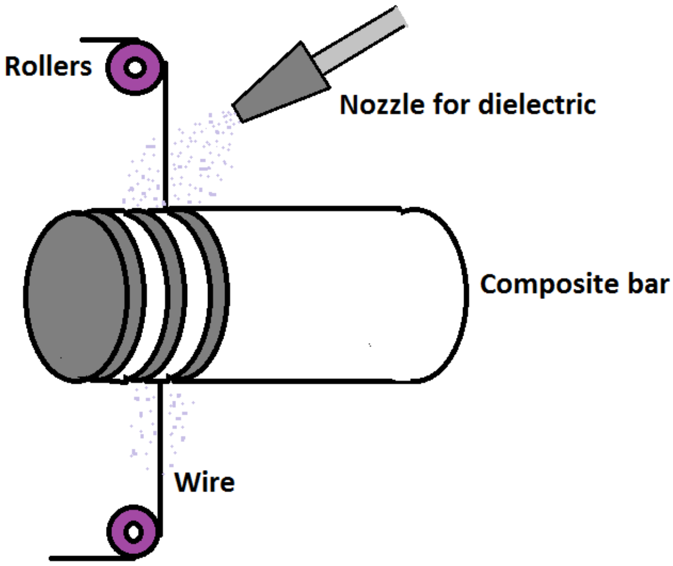

Figure 2. Principle of MMC machining using WEDM process

4. Results and discussion

4.1. Effect of machining parameters on MRR

Material removal rate in WEDM is very important as it is influencing the productivity of the industry. Higher MRR during the machining results in improved economy of the industry. In the present investigation machining was carried-out on the MMC cylindrical specimen with three reinforcement percentages by varying machining parameters to study the effect on material removal rate. Applied current has highest influence on the material removal rate. It is clear from the graphs that, material removal rate increases with increasing current. Figure 3 represents the material removal rate for MMC with 5% SiC. Machining was carried-out by varying the applied current by retaining constant bed speed of 20m/min and pulse on time as 4µs and it was observed that for 2 A, the MRR was observed to be 6.802g/min. For the same set of machining condition current was increased to 6 A and MRR observed to be 7.297g/min. The reason for increased MMR was due to increased applied current where energy contained per spark increases with increase in applied current. The approximate temperature of the spark was around 8000ºC. When such a high energy spark hits the surface of the work piece, large amount of material was removed by evaporation or melting leaving a pit on the surface which is the evidence for material removal. Similar trend was observed for other compositions of the MMC. The findings of the experiment were plotted in Figure 3.

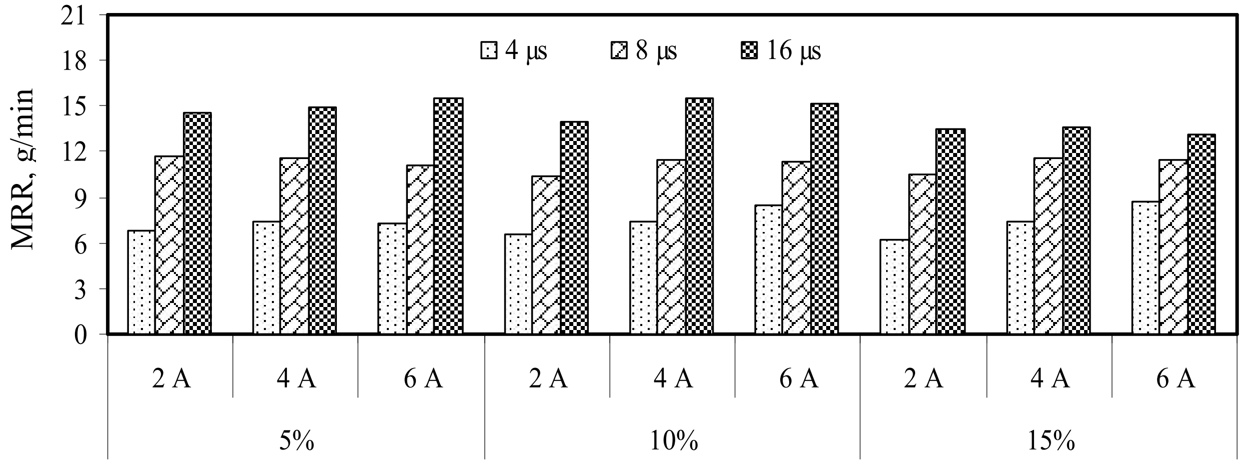

Figure 3. Variation of MRR with current and pulse on time

Material removal rate also increases with increase in pulse on time. Pulse on time is the duration of time the current is allowed to flow per cycle. Material removal is directly proportional to the amount of energy applied during pulse on-time. This energy is really controlled by the peak current and the length of the pulse on-time [6-9]. MMC specimen with 5% SiC was machined by keeping constant applied current of 6 A and pulse-on time was varied. For pulse-on time of 4µs MRR was observed to be 7.297g/min where as for 16µs it was around 15.515g/min. Increasing trend was observed for increasing pulse on time. Similar trend was observed for applied current of 4 A and 6 A and also for MMC with 10% and 15% reinforcement. Figure 4 indicates variation in the MRR with pulse-on time.

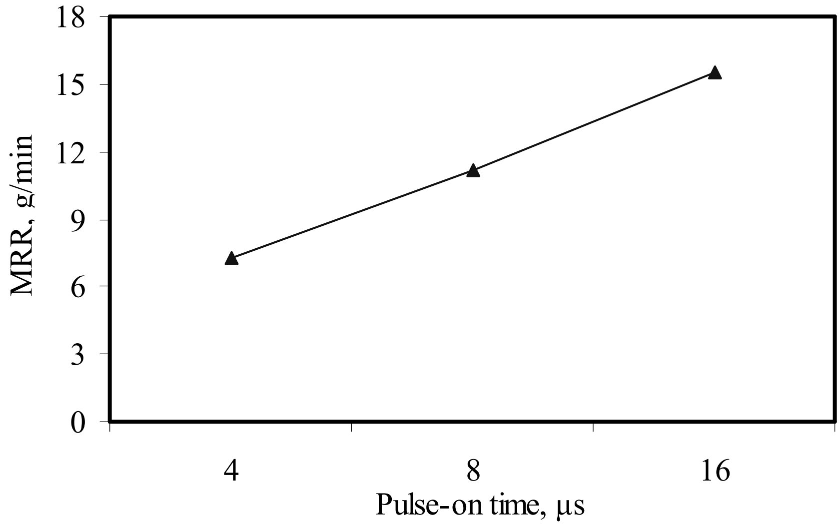

Figure 4. Variation of MRR with pulse-on time, SiC 5%, applied current 6 A

The increase in the volume fraction of SiC in MMC causes reduction in the material removal rate. Machining was carried-out on MMC containing all the three compositions of SiC with applied current of 2 A, pulse on time of 4μs. The results of the experiment were plotted in the Figure 5. The graph clearly indicates that there was a negative effect of reinforcement on rate of material removed during the experiment. Reason for reduction in the MRR during the experiment was due to the presence of silicon carbide particles which shields and protects the matrix from being removed. SiC being insulating material will decrease the electrical and thermal conductivity. As thermal conductivity decreases, the spark energy transferred to the material also decreases. SiC particles act as barriers for the penetration of the spark in to the material. Hence increase in the volume fraction in the MMC reduces the material removal rate.

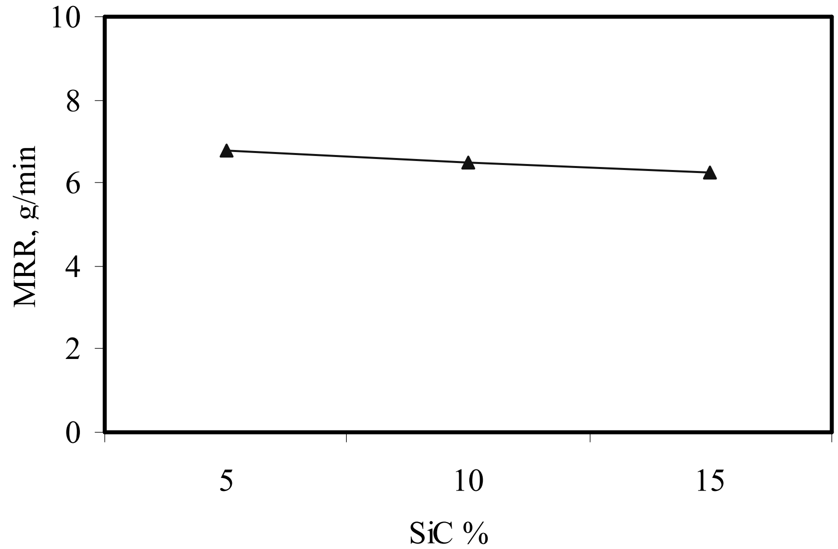

Figure 5. Variation of MRR with SiC concentration applied current 2 A, pulse-on time 4μs

Pulse off time is the duration of time (μs) between the sparks. It is the waiting interval time period between two pulses on time periods. During pulse off time no machining takes place (idle time period) and it allows the melt material to vaporize and to remove the debris from machining area. This parameter is affecting the machining speed and the stability of the cut. If the time gap between the pulses is short then material removal increases [12].

The experimental results were analyzed using analysis of variance (ANOVA), for identifying the factors significantly affecting the MRR. The results of the ANOVA with the MRR are given in Table 3. The analysis was carried out for a significance level of $\alpha=0.05$, i.e. for a confidence level of 95%. The P-value less than 0.05 are considered to have a statistically significant contribution to the material removed during machining. From the results it is clear that applied current significantly affecting the material removal with 64.29%, which is highest among the contributions of the other parameters. Bed speed is significantly affecting the MRR with 31.33%. Reinforcement content in the MMC significantly affects the MMR with 1.87%. Pulse on time is also affecting the MRR with less contribution of 0.86% where as pulse off time has least contribution for MRR. The effect of machining parameters and SiC content on MRR will be better understand by SN ratio plots which is given in Figure 6.

Table 3. ANOVA table for material removal rate

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage contribution
Current	2	149.827	149.827	74.913	560.02	0.000	64.29
Bed speed	2	73.015	73.015	36.507	272.91	0.000	31.33
Pulse-on time	2	2.025	2.025	1.013	7.57	0.005	0.86
Pulse off time	2	1.636	1.636	0.818	6.12	0.011	0.7
SiC %	2	4.375	4.375	2.188	16.35	0.000	1.87
Error	16	2.140	2.140	0.134			
Total	26	233.018					
S= 0.365745		R-Sq = 99.08 %				R-Sq(adj) = 98.51 %	

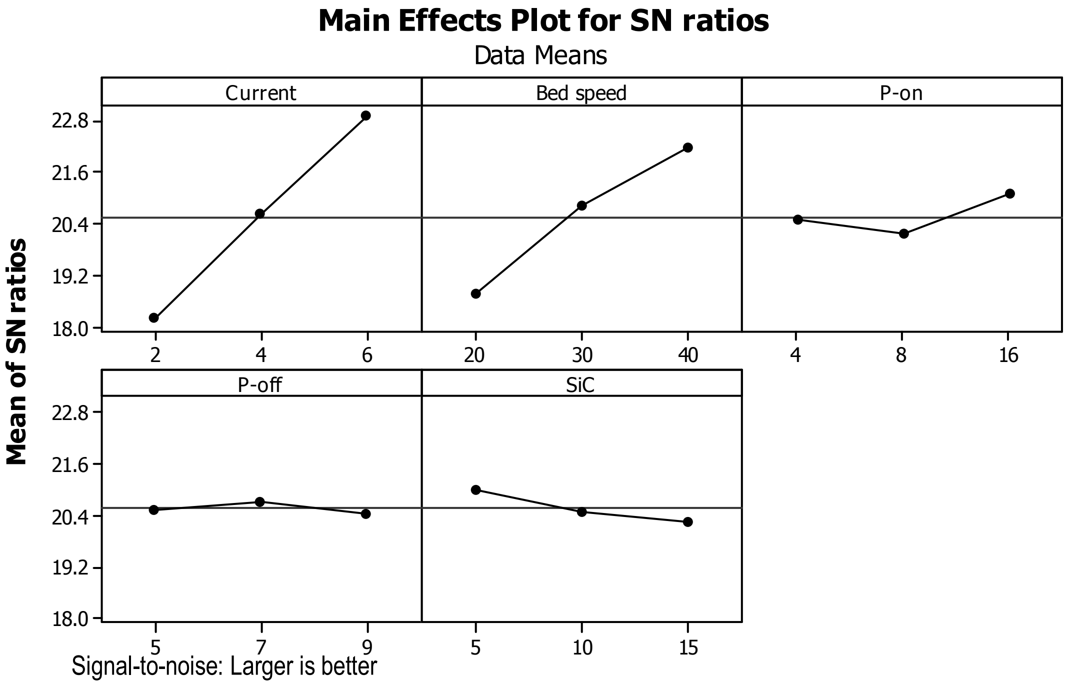

Figure 6. SN ratio for MRR with applied current, bed speed, P-on time, P-off time, SiC percentage

To have higher MRR during machining process preferred parameters such as applied current of 6 A, bed speed of 40 mm/min, P-on of 16µs should be used. Pulse off time has least effect on MRR. MMC with 5% SiC yields higher MRR compared to other reinforcement concentrations.

4.2. Effect of machining parameters on surface roughness

Machined surface was checked for its roughness value. Figure 7 shows the variation of surface roughness with current and bed speed. The sliced piece from MMC bar is fixed on fixture and surface roughness is measured by Talysurf. From the graph it is clear that surface roughness increases with increasing current. Figure 7(a) indicates the roughness value for the MMC with 5% reinforcement. For the applied current of 2 A the surface roughness observed was 2.85µm and for 6 A the observed value was 3µm. This indicates surface roughness increases with increasing applied current. Similar trend was observed for MMC with 10% and 15% SiC and which is shown in Figure 6(b) and 6(c). As discussed in previous section that pit formation takes place due to the spark on the surface of the specimen. The depth of the pit depends upon the energy content in the spark. Higher the current, higher will be the energy content per spark. When such high energy spark hits the material deeper pits will be formed. These pits were responsible for surface roughness. Many times the melted material due to high temperature gets re-deposited on the machined surface leaving behind rough surface. This material deposition on the surface can be minimized by increasing the flushing pressure [9, 10]. Pulse-on time has influencing effect on Ra. Pulse-on time of 4µs will give lower roughness value where as 16µs gives higher roughness value. As pulse on time increases, the period of spark hitting the MMC increases due to which deep pits were formed on the surface. These pits are responsible for increased surface roughness.

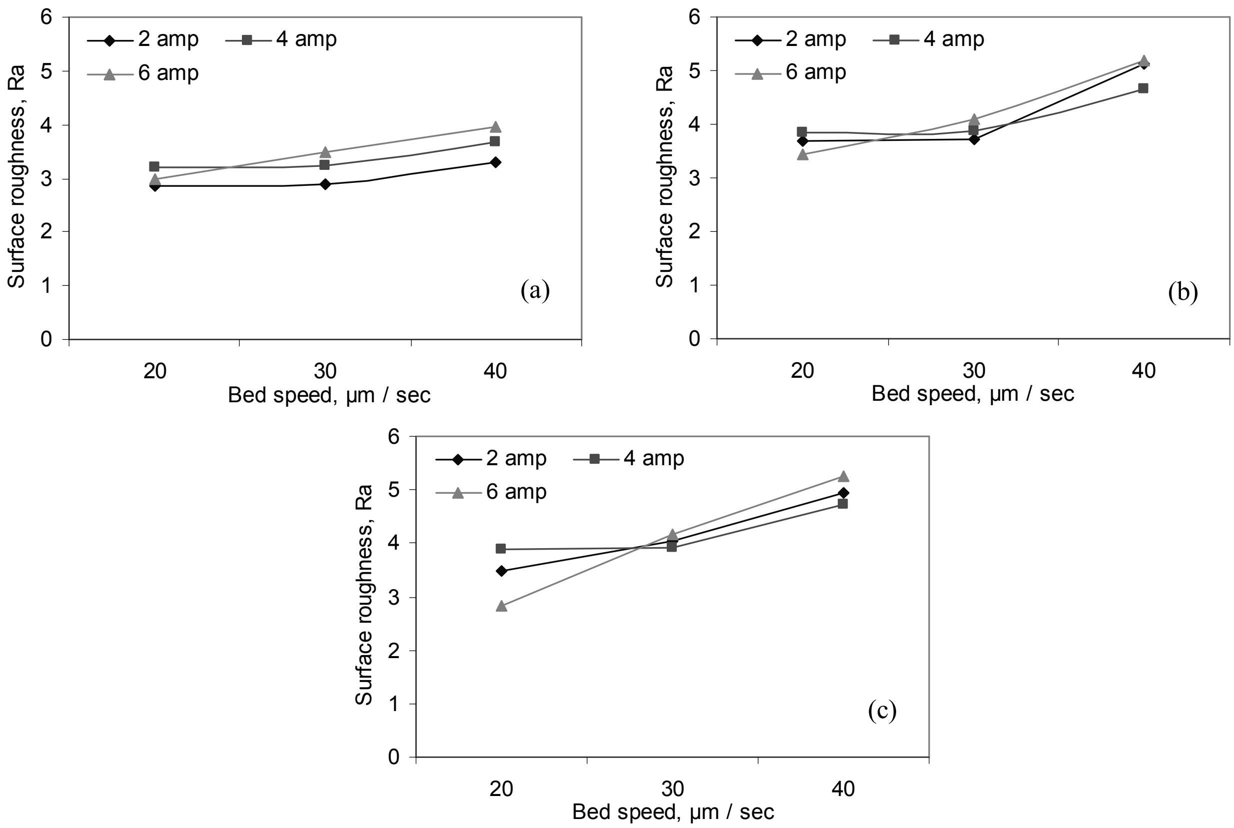

Figure 7. Variation of surface roughness with current and bed speed rate (a) 5% SiC; (b) 10% SiC; (c) 15% SiC

Roughness also increases with increase in reinforcement percentage which is shown in Figure 8. Under constant machining condition of applied current of 6 A, pulse on time of 16µs, MMC with 5% SiC show roughness of 3.96µm where as 15% SiC shows 5.25µm. This indicates that increase in reinforcement content in MMC responsible for increase in the Ra value. At very high temperature of the spark, bond between reinforcement and matrix breaks. Due to this particles embedded in matrix become free and pockets are formed at the place. As the concentration of SiC in MMC increases, the number of pockets on unit area also increases. The presence of these pockets on the machined surface is responsible for surface roughness. The released free SiC particles are washed away by the flow of dielectric fluid.

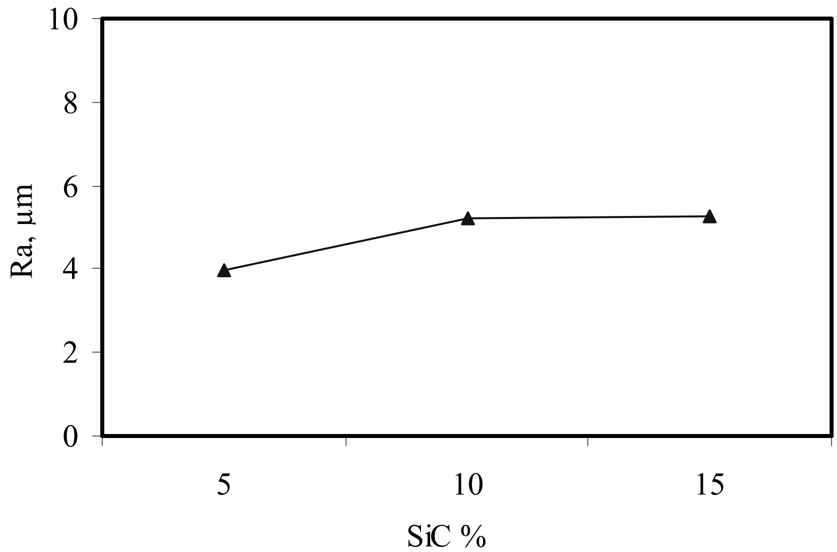

Figure 8. Variation of surface roughness with varying reinforcement concentration

One more reason for increased surface roughness is increasing bed speed. Increasing bed speed against wire increases wire shifting marks or feed marks on the machined surface. These marks on the machined surface led to increase in surface roughness. With increase in bed speed rapid cutting of the material takes place along with severe damage takes place to the MMC. Formation of micro cracks on the surface of the component was observed. The feed marks and micro cracks are responsible for increased surface roughness [15] which is shown in Figure 9.

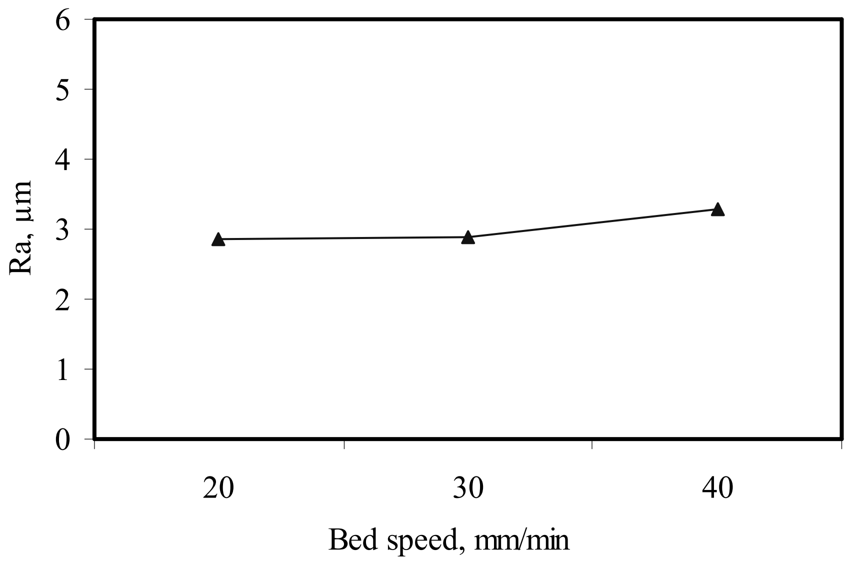

Figure 9. Variation of surface roughness with bed speed, applied current 2 A, 5% SiC

ANOVA analysis was also done on the results of surface roughness to know the significant parameter which is affecting it. The results of the anova are given in the Table 4. From the results it is clear that contribution of bed speed with 36.37% which is significantly affecting the surface roughness. SiC concentration in MMC is the second deciding factor with 20.77% on surface roughness. Increase in the SiC in MMC leads to increased surface roughness. Applied current is also contributing major share with 11.75% to roughness value. Pulse on time with 10.86% where as pulse off time has least contribution to surface roughness with 2.31%. The variation of these parameters on surface roughness can be better understood by SN ratio plots which are given in Figure 10.

Table 4. ANOVA table for surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage contribution
Current	2	1.3039	1.3039	0.6520	5.25	0.018	11.75
Bed speed	2	4.0337	4.0337	2.0168	16.24	0.000	36.37
Pulse-on time	2	1.2048	1.2048	0.6024	4.85	0.023	10.86
Pulse off time	2	0.2573	0.2573	0.1286	1.04	0.378	2.31
SiC %	2	2.3040	2.3040	0.1520	9.28	0.002	20.77
Error	16	1.9870	1.9870	0.1242			
Total	26	11.0907					
S= 0.352402		R-Sq = 82.08 %				R-Sq(adj) = 70.89 %	

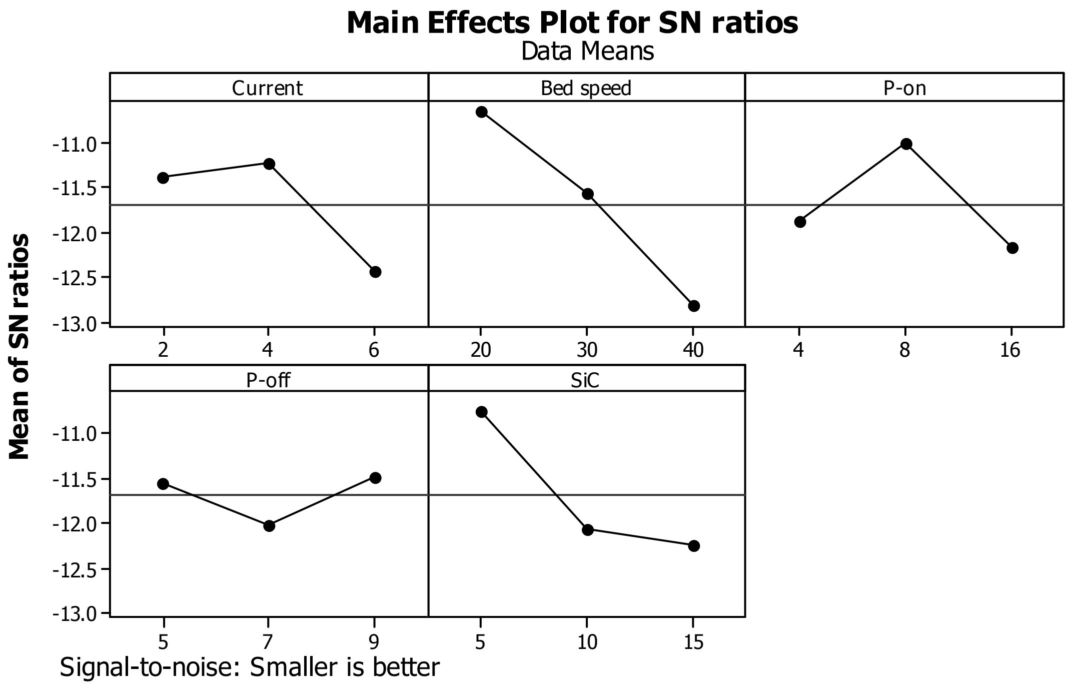

Figure 10. SN ratio for surface roughness with applied current, bed speed, P-on time, P-off time, SiC percentage

To achieve better surface finish the preferred parameters adopted for machining were applied current 2 A, bed speed 20mm/min, pulse on time of 8µs and MMC with 5% SiC. Pulse off time has least contribution for surface roughness.

SEM micrographs of machined surface were taken to study the surface and it is shown in Figure 5. It is observed from the micrograph that, pit formation takes place at machined surface due to spark. In Figure 11(a) it is observed that formation of micro cracks on the surface. Wire shifting marks or feed marks is also observed on the surface leading to increased surface finish. In Figure 11(b) (c) surface level pits and deeper pits are observed at different magnification.

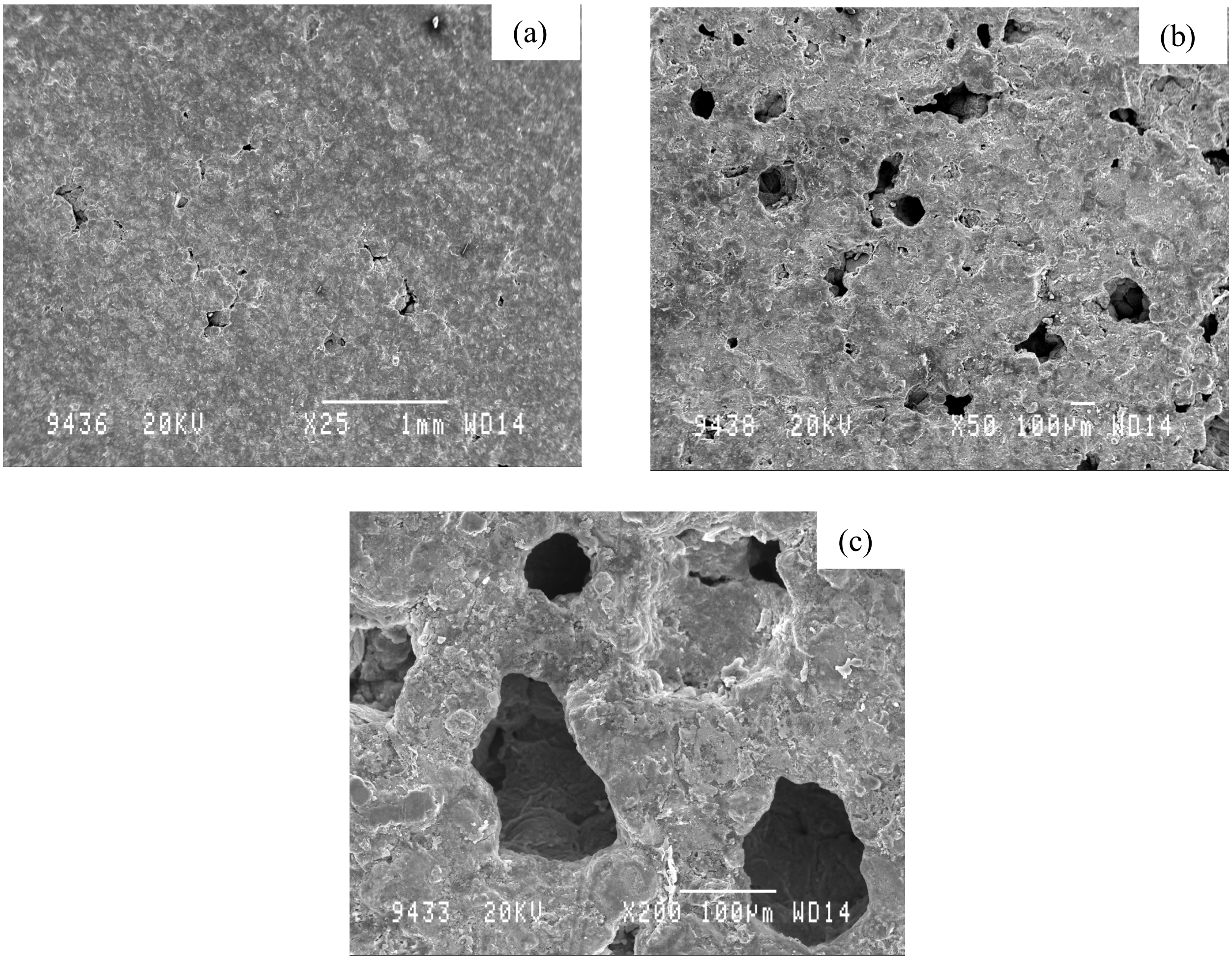

Figure 11. SEM micrographs of machined surface at different magnification (a) 25X; (b) 50X; (c) 100X

5. Conclusion

In the present investigation ZA43 + SiCp metal matrix composite was machined by wire EDM process. MMC was fabricated by liquid metallurgy technique. MMC with three different reinforcement percentages 5%, 10% and 15% were casted in the form of cylindrical specimen. The fabricated cylindrical specimens were machined i.e. sliced in transverse direction by varying the machining parameters like current, voltage, pulse on time, pulse off time, dielectric flushing pressure etc. Some of these parameters are considered as variable parameters and some are kept constant. Machining time was recorded for each composition of MMC and material removal rate was determined. Machined surface was checked for its roughness.

From the results obtained the following conclusions can be drawn:

a) Material removal rate increases with increase in current and pulse on time. Material removal rate decreases with increase in pulse off time.
b) Material removal rate decreases with increase in reinforcement content in MMC. For same value of current and pulse on time, MMC with 5% SiC take less time and with 15% SiC take more time to slice the bar. This implies that there is a restriction for smooth movement of wire through MMC bar by SiC particles. To get higher material removal rate, higher currents and higher value of pulse on time should be used for machining.

c) Surface roughness of machined surface increases with increase in current. Higher the current, more will be the energy per spark. Due to this craters with higher depth are formed on the surface leading to surface roughness.
d) The quantity of SiC in MMC is also influencing parameter on surface roughness. Higher the quantity of SiC, higher will be the surface roughness.
e) One more parameter which influences the surface roughness is bed speed. Higher the bed speed, higher will be the surface roughness. This happens due to the formation of wire feed marks on the machined surface. To achieve better surface finish, lower current and lower bed speed should be employed.

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