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ORIGINAL PAPER

Experimental Investigation for Performance Study of Wire Electrochemical Spark Cutting of Silica Epoxy Nanocomposites

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Abstract

Purpose Polymer Nanocomposites are advanced engineering composites with enhanced properties. These materials play a central role in various industrial sectors. The growing awareness of the key parameters (which influence the physical properties) with different combination of matrix-reinforcement, are making them more attractive in various applications. Machining of these materials is a challenging task for engineers with their properties (hardness and brittleness) due to various combinations of matrix-reinforcement. Therefore, the aim of present work is to investigate the machining behaviour of Silicon Dioxide (silica) Epoxy Nanocomposite due to straight cutting by using Wire Electrochemical Spark Cutting (WECSC) process.

Method A specific number of experiments were conducted based on one parameter at-a-time approach to study the effect of influencing input parameters.

Result The effect of various process parameters namely voltage supply, electrolyte concentration, wire velocity, pulse-on time and silica particle concentration (Cp) such as 3%, 4% and 5% (weight percent) on performance measures such as material removal rate (MRR) and surface roughness were demonstrated experimentally.

Conclusion WECSC has been found effective technique for cutting of Silicon Dioxide Epoxy Nanocomposite. It is reported that MRR increases with decrease in silica particle concentration in Silicon Dioxide Epoxy Nanocomposite.

Keywords Polymer nanocomposite · Silicon dioxide epoxy nanocomposite · MRR · Wire electrochemical spark cutting (WECSC) process

1 Introduction

Silicon dioxide epoxy nanocomposite is a polymer based nanocomposite material, having well dispersed nanosized SiO_2 ceramic fillers as a reinforcing agent for improving the engineering properties of resin such as stiffness and hardness [1]. Nano-silica is extensively used filler, in polymers due to their excellent properties namely high elastic modulus, low density, high thermal stability and good abrasion resistance [2]. Researchers have attempted to fabricate silicon dioxide epoxy nanocomposite and analysed the improvement in various properties of nanocomposite [2, 3]. The polymer composites based products are generally manufactured by moulding methods but these materials sometimes needs machining processes namely cutting and drilling for final products [4]. During machining of polymer nanocomposite the release of nano-filler is major disadvantage of conventional machining methods and also these techniques are sometimes not appropriate due to material damage [5]. The researchers are urgently looking for development of such kind of new generation materials to open up a wide range of potential applications. The main challenging task for researches is the effective machining of these materials. Non-traditional processes are very effective for machining of composite materials with the objectives of improving machining rates, enhancing surface quality of parts, where traditional methods are ineffective [6]. But some non-traditional processes are not effective to produce complex shapes in composites because of tool wear, air borne dust and thermal damage [7]. Therefore, a new hybrid approach is developed to overcome all these difficulties with nonconductive, hard and brittle materials known as electrochemical spark machining (ECSM) process. Traveling wire electrochemical spark machining (TW-ECSM) process is a successful configuration of ECSM, which can be effectively

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used for the machining of such type of electrically non-conductive nanocomposite [8]. Researchers suggested that TW-ECSM process is capable of machining large volumes, complex shapes in nonconducting materials and also slicing at micron level [9, 10]. Jain et al. [7] examined the machining behaviour of composites namely glass epoxy and Kevlar epoxy using TW-ECSM process. Sarkar et al. [11] investigated the machining characteristics of ceramics using ECDM (electrochemical discharge machining) process. They developed a non-linear second order mathematical model for electrochemical discharge micro-drilling of silicon nitride ceramic. They analysed the effects of process parameters on MRR, radial over cut (ROC) and heat affected zone (HAZ) and reported that electrolyte concentration and inter-electrode gap were less significant parameters compared to applied voltage.

Nesarikar et al. [12] experimentally examined the machining characteristics of Kevlar epoxy composite using TW-ECSM process. They analysed the effect of specimen thickness along with voltage and electrolyte conductivity. Peng and Liao [13] investigated TW-ECSM for slicing of optical glass and quartz and discussed the appropriate operating conditions for these materials. Kuo et al. [14] experimentally investigated the quality of machined surface of quartz glass workpiece using WECDM (wire electrochemical discharge machining) process. They used deionized (DI) water and potassium hydroxide (KOH) solution as an electrolyte and wire electrode of brass (CuZn73) wire having diameter of 150 μm. They reported that titrated electrolyte flow has yielded quality of cut. They also added that titrated flow not only provides efficient machining but also cost effective and environmental friendly machining. Bhuyan and Yadava [15] developed TW-ECSM setup and verified the feasibility of developed setup by machining of borosilicate glass materials. They concluded that MRR and Kerf width increases with increase in voltage and pulse on-time. Singh et al. [16] fabricated a TW-ECSM setup and performed experiments on partially electrically conductive material PZT ceramic and carbon fibre epoxy composite and examined that MRR enhanced with increase in applied voltage and electrolyte concentration up to 20% by wt. They observed the non uniformity in edges of slots due to undesirable spark and arc. Bhattacharyya et al. [17] studied the machining characteristics of ceramic materials using ECDM process and found the effective range of parametric combinations for achieving higher machining rate and dimensional accuracy. Rattan and Mulik [18] examined the effect of magnetic field during TW-ECSM process for MRR and surface roughness. They applied utility function approach and converted the multi-objective optimization into a single objective problem. They used quartz material as a workpiece and reported that the lower values of R_a and improved MRR obtained with magnetic field assisted technique when compared to the TW-ECSM process. In this study, an attempt has been made to analyse the influence of various process parameters during straight cutting of fabricated silica epoxy nanocomposites by using WECSC process. The silica epoxy nanocomposites were fabricated by homogeneous dispersion of the nano silica in epoxy resin with different particle concentration such as 3%, 4% and 5% (weight percent). The influence of various parameters namely voltage supply, electrolyte concentration, wire velocity and pulse-on time along with silica particle concentration on various performance parameters have been examined experimentally.

2 Experimentation

This section describes the description of set up, material fabrication and experimental planning for cutting of Silica Epoxy Nanocomposite.

2.1 Description of WECSC Setup

A photographic view of WECSC setup, used for experimentation is shown in Fig. 1. WECSC setup comprises of various units namely wire-drawing unit, workpiece feeding unit, machining chamber unit and power supply unit. A controller with display panel was used to provide automatic feed motion to stepper motor which regulates the wire velocity by which wire can travels appropriately. An automatic feed control system for providing constant feed rate to workpiece was used for machining. The minimum feed motion achieved with compound gear arrangement in the range of 0.001 mm/s to 0.01 mm/s in upward and downward direction. A rectangular acrylic chamber of size 400 mm × 250 mm ×110 mm was used as a machining chamber which also acts as a reservoir for electrolyte solution. A brass wire employed as cathode and a graphite rod (auxiliary electrode) was taken as an anode.

2.2 Materials

The rectangular cross-section specimen of size 30 mm × 25 mm × 3 mm, made of SiO_2 epoxy nanocomposite was used as workpiece. Initially, the Silicon Dioxide Epoxy Nanocomposite sheet of 3 mm thickness was fabricated using particulate dispersion technique follows molding. The mold of acrylic material was used for casting of composite sheet. The commercially available epoxy resin (Araldite LY5052) which was cured by a hardener (Aradur 5052) was taken as a matrix for the nano-composite material. The density of epoxy resin and hardener are 1.17 and 0.94 g/cm^3 respectively. SiO_2 nanoparticles with 15 nm average size purchased from Sisco Research Laboratories (SRL) Maharashtra India, was taken as a reinforcing agent. The Particle sizes have measured for the confirmation with Particle Size Analyzer (Nanotrac Wave). It is an analytical technique by which the distribution of sizes in a sample of solid or liquid particulate material can be analysed. Here nano-particles with different concentration have been taken for the fabrication purpose. SiO_2 nano-

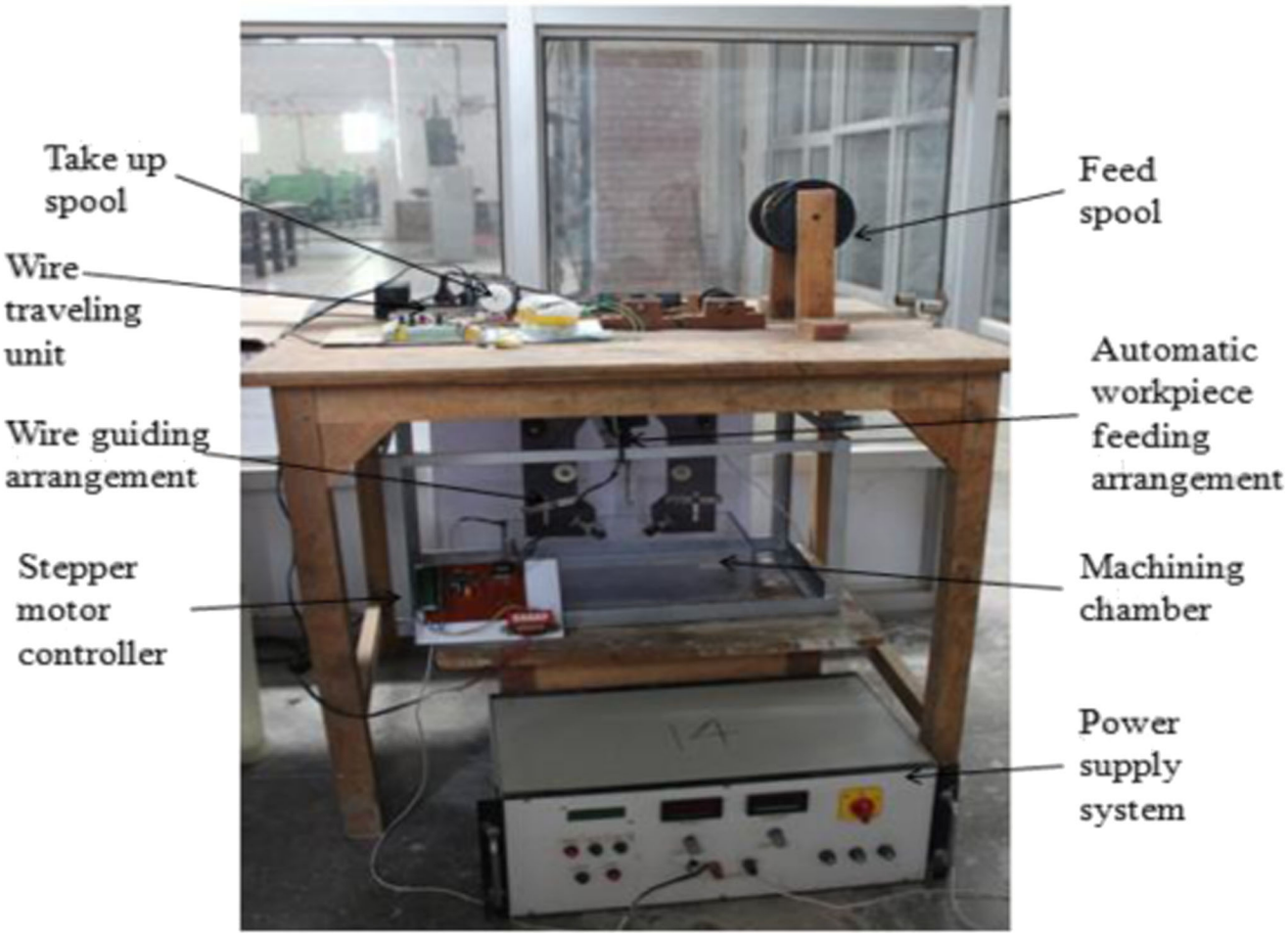


Fig. 1 Photographic view of WECSC setup

particles of 3%–5% by wt. were added to the epoxy resin. The steps involved in fabrication of SiO_2 epoxy nanocomposite are the mentioned below.

- Step 1: Reduce moisture of nano-particles (hot air oven)
- Step 2: Mixing of nano-particles (ultrasonic bath and magnetic stirrer)
- Step 3: Degassing (vacuum oven)
- Step 4: Moulding (acrylic mould)
- Step 5: Curing (at room temperature)

The SiO_2 nanoparticles were mixed with epoxy resin (araldite) using magnetic stirrer at 700 rpm at 65^0 C for 60 min. After mixing, hardener was added to the mixture, using magnetic stirring operation, followed by the continuous stirring. The ratio of epoxy resin and hardener was 10:4. Degassing of mixture was done to remove the effect of entrapped air bubbles during the procedure. The mixture was poured into acrylic molds and kept at room temperature for 24 h for the curing purpose.

2.3 Experimental Planning

A WECSC setup has been utilized for conducting the experiments. Based on one parameter at-a-time (OPAT) approach a specific number of experiments were conducted to study the effect of influencing input parameters on MRR and R_a. The range of input parameters was decided after performing a number of exhaustive experiments. In the present work, a rectangular silica epoxy nanocomposite of size 30 mm × 25 mm × 3 mm was taken as a workpiece specimen. A brass wire having 0.2 mm diameter was taken as cathode and graphite rod was employed as anode. The brass wire was constantly in contact with workpiece sample dipped in electrolyte during machining process. The inter-electrode gap was taken as 60 mm. NaOH solution is used as the electrolyte for the experiments. The time of machining is taken as 7–10 min for each experiment. MRR is calculated by measuring difference of weight of workpiece sample per unit machining time. The weight of workpiece sample (before and after machining) was measured using digital microbalance (accuracy of 10 μg, CAS

Table 1 Detail of experimental conditions

Workpiece	Silica Epoxy Nanocomposite
Cathode (tool)	brass wire
Anode	graphite rod
Electrolyte type	sodium hydroxide (NaOH)
Machining time	7–10 min
Workpiece feed rate	0.01 mm/s
Workpiece thickness	3 mm

India Private Ltd.). The average surface roughness (R_a) measured using surface roughness tester (Taylor Hobson, UK).

Details of experimental conditions are shown in Table 1. The macrograph of machined samples is shown in Fig. 2. The micrograph of machined surface were analysed using a scanning electron microscope (Carl ZEISS SUPRA 40VP, Germany) at 20 kV acceleration voltage shown in Fig. 7.

3 Results and Discussion

Experiments were conducted and the effects of process parameters namely applied voltage, electrolyte concentration, pulse on-time, wire velocity and silica particle concentrations on MRR and R_a have been studied.

3.1 Effect of Applied Voltage on MRR and R_a with Variation in Silica Particle Concentration

Figure 3a illustrates the variation of voltage on MRR for cutting of Silica Epoxy Nanocomposite at different particle concentrations. It is observed from figure that MRR increases with applied voltage and decreases with increase in silica particle concentration. The reason is that an increase in applied voltage increases the energy (VIt_{on}) at the machining zone which increases the material removal rate. The value of MRR increases by 64% from 40 V to 45 V and 19% from 45 V to 50 V at 3% particle concentration. It may be due to higher voltage values. Initially large amount of material removal takes place from the workpiece but it drops later due to improper flushing of debris by flowing electrolyte. Jain and Priyadarshini [19] reported that MRR increases with increase in voltage value. They explained that due to an increase in energy content (VIt_{on}) of a spark more material removal obtained.

MRR decreases with increase in Cp in the Fig. 3a. The reason behind it that the glass transition temperature of 5% Cp is more compared to 4% and 3% Cp workpiece therefore, more energy required for removing material from large % of Cp and hence MRR decreases.

Figure 3b shows the effect of applied voltage on surface roughness. The value of surface roughness increases with increase in applied voltage because more

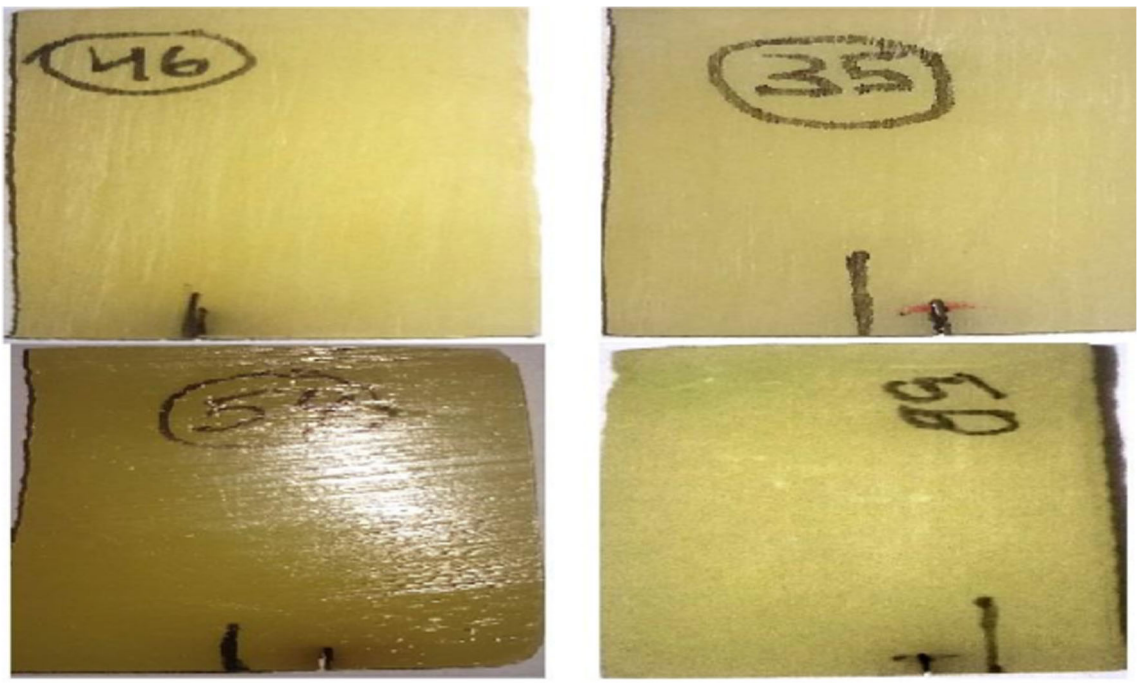
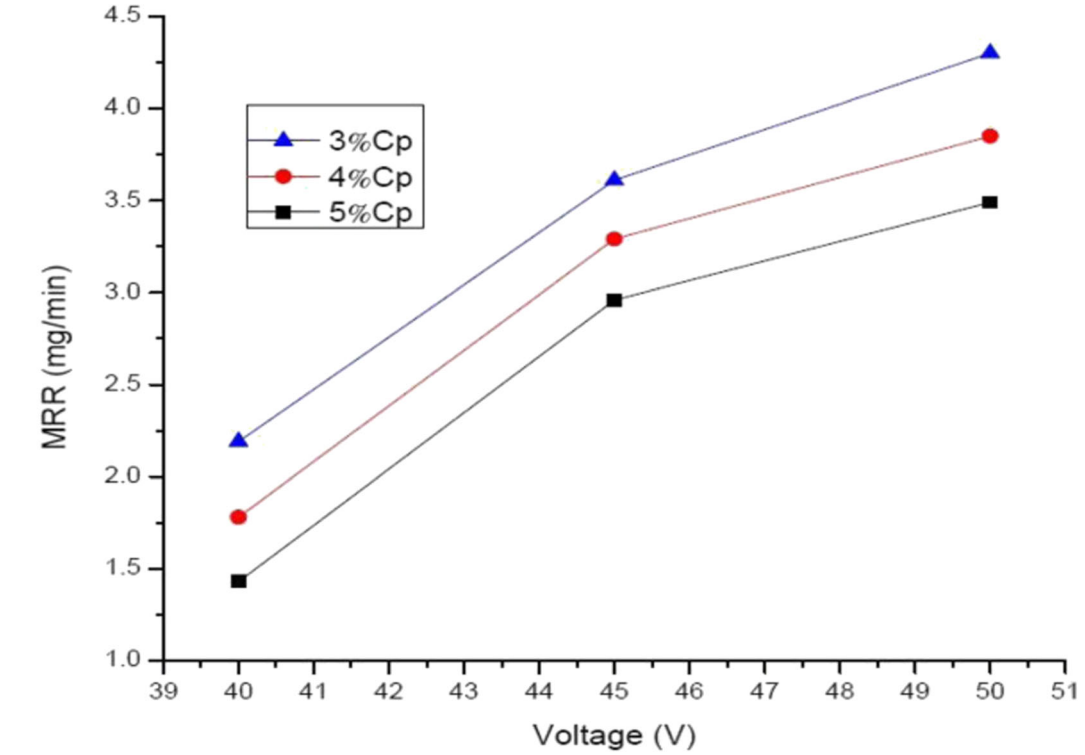


Fig. 2 Macrograph of machined samples



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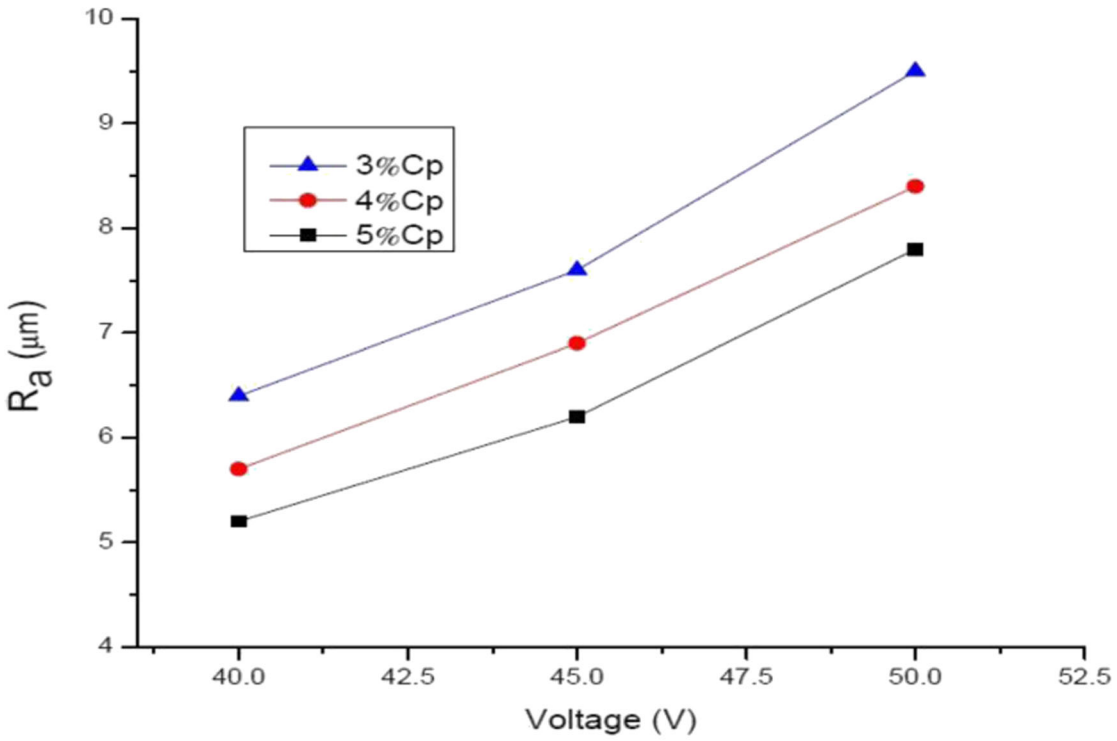
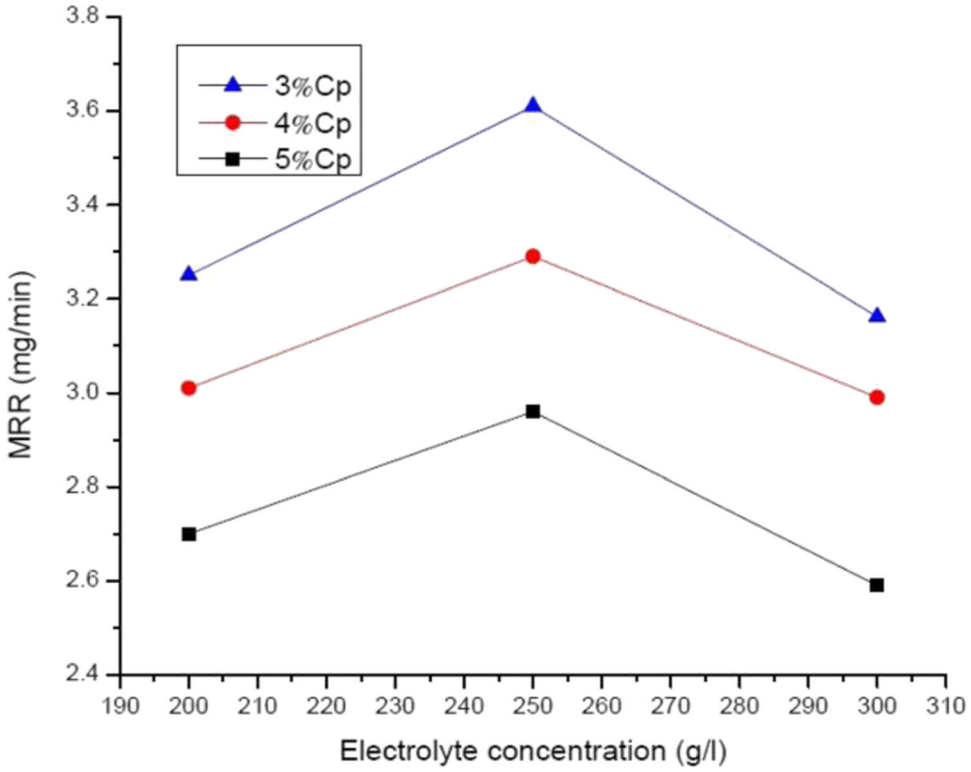


(b)

Fig. 3 Effect of applied voltage on (**a**) MRR and (**b**) R_a with pulse on-time = 350 μs, wire velocity = 2.1 m/min and electrolyte concentration = 250 g/l



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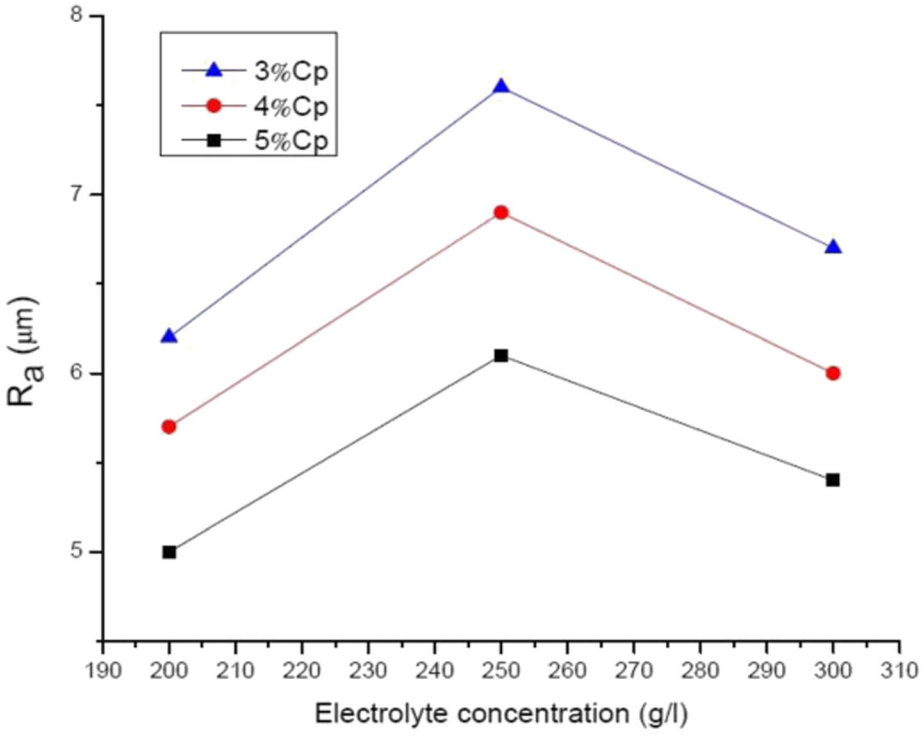
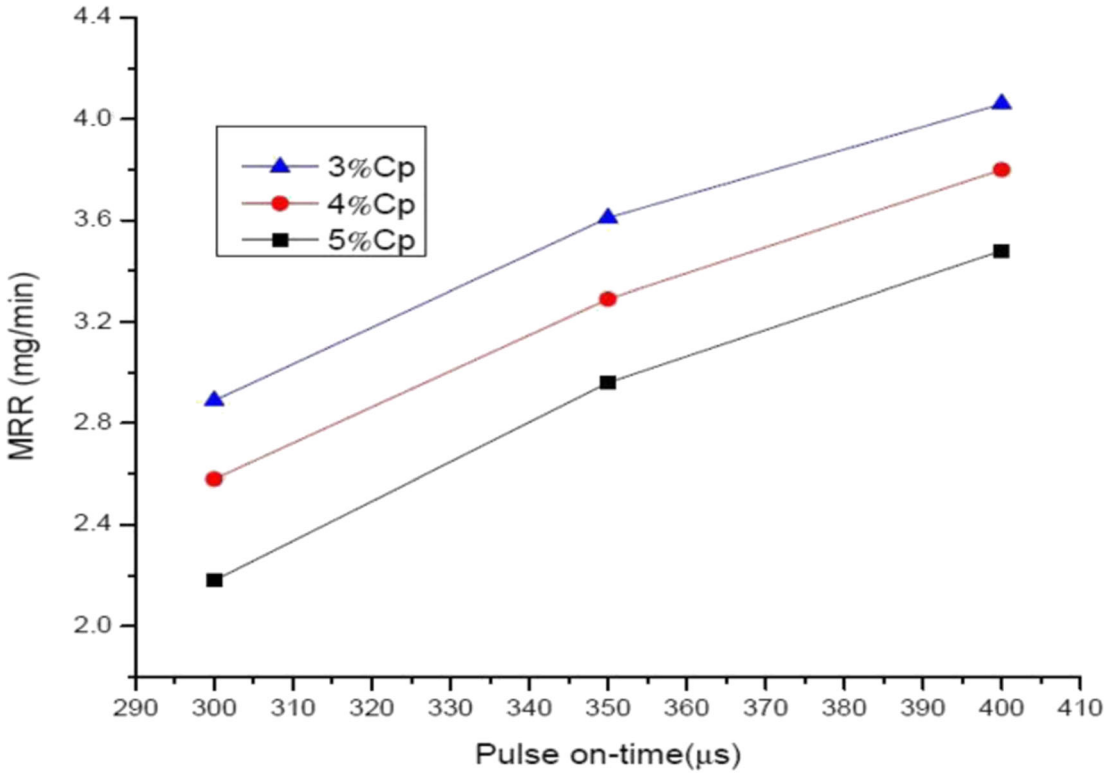


(b)

Fig. 4 Effect of electrolyte concentration on (**a**) MRR and (**b**) R_a with pulse on-time = 350 µs, wire velocity = 2.1 m/min and applied voltage = 45 V



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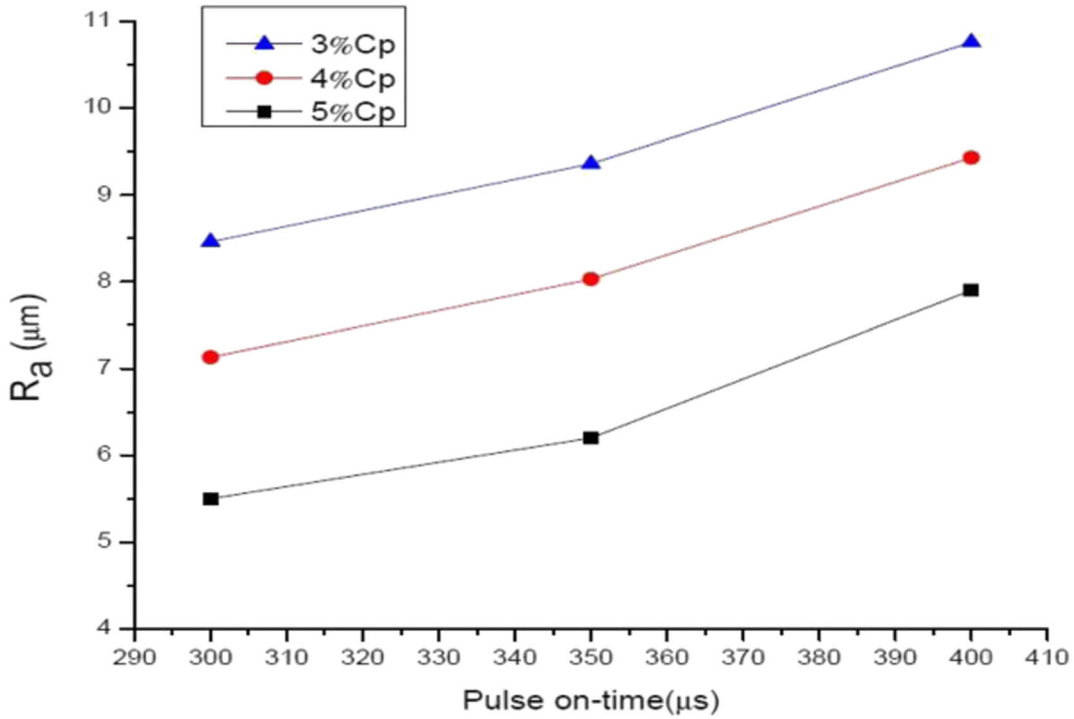
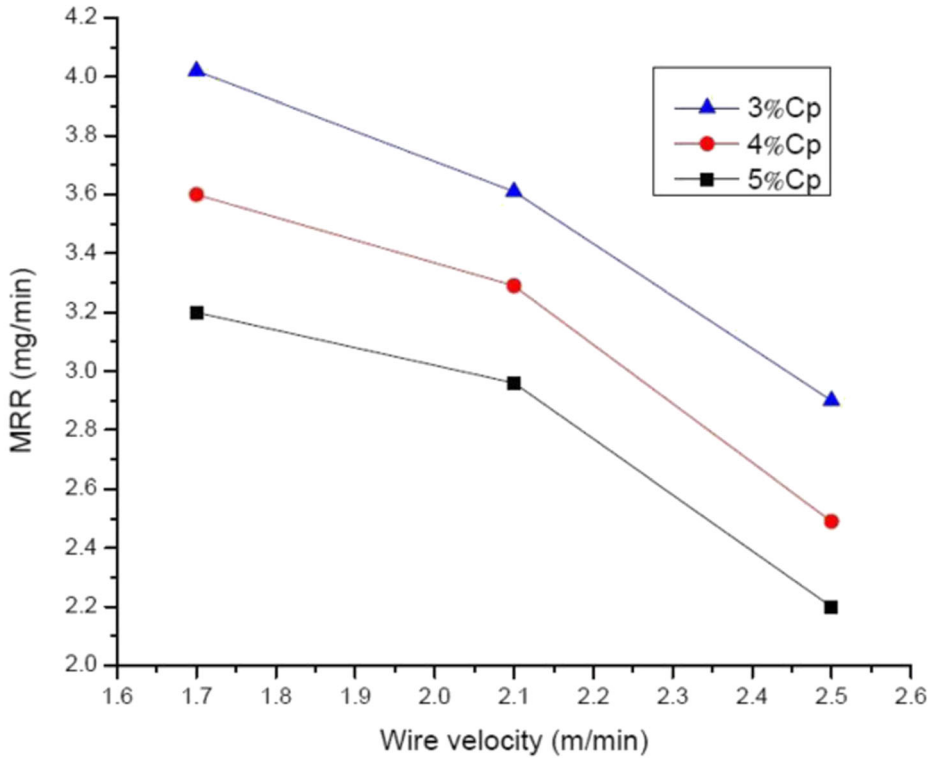


(b)

Fig. 5 Effect of pulse on-time on (**a**) MRR and (**b**) R_a with electrolyte concentration = 250 g/l, wire velocity = 2.1 m/min and applied voltage = 45 V



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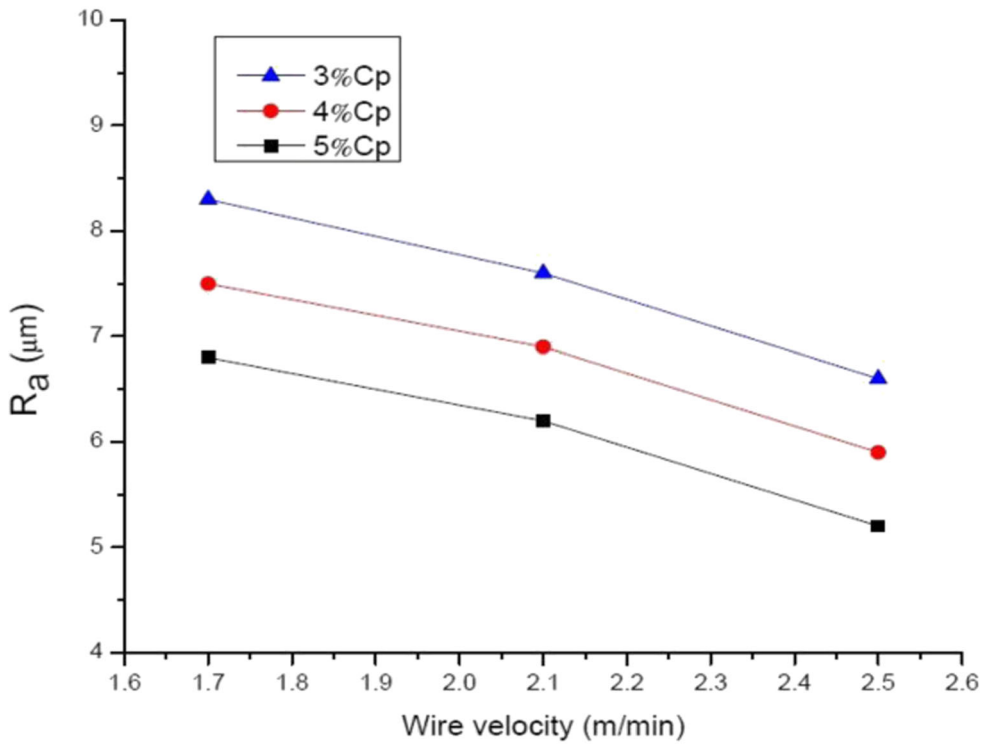


(b)

Fig. 6 Effect of wire velocity on (**a**) MRR and (**b**) R_a with electrolyte concentration = 250 g/l, pulse on- time = 350 µs and applied voltage = 45 V

amount of energy generated therefore, more material removed from workpiece sample in the form of large craters during the machining. The R_a increases 19.2% from 40 V to 45 V and 25.8% from 45 V to 50 V at 5% Cp. Approximately same percentage variation is observed for 3% Cp and 4% Cp.

3.2 Effect of Electrolyte Concentration on MRR and R_a with Variation in Silica Particle Concentration

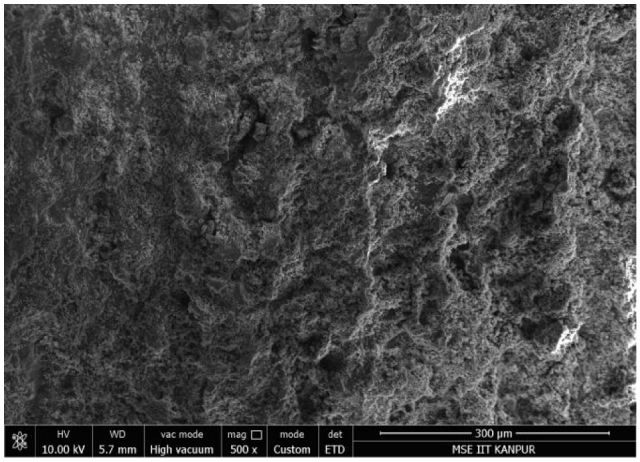
Figure 4a shows the variation of MRR with variation of electrolyte concentration for different values of particle concentration. From Figure, it is clearly observed that MRR increases by 9.6% from 200 g/l to 250 g/l and decreases by 10% from 250 g/l to 300 g/l at 5% Cp. It happens because at higher electrolyte concentration, more electrochemical reactions occurs between the wire and the graphite electrode and produces more gas bubbles at the sparking zone, therefore greater number of sparks generated. Bhuyan and Yadava [15] also explained that the specific conductance of NaOH solution is high at 250 g/L, due to this the conductivity of solution increases and additional energy is obtained which further used for melting a material.

Figure 4b shows the variation of surface roughness with varying electrolyte concentration. The rate of electrochemical reaction increases with increase in electrolyte concentration upto 250 g/l. As the concentration percentage of particle increases the valve of surface roughness decreases at similar experimental conditions. After the value of 250 g/l concentration of electrolyte, the value of surface roughness starts to decrease because at this value of electrolyte, specific conductance of used solution is higher and beyond this it decreases.

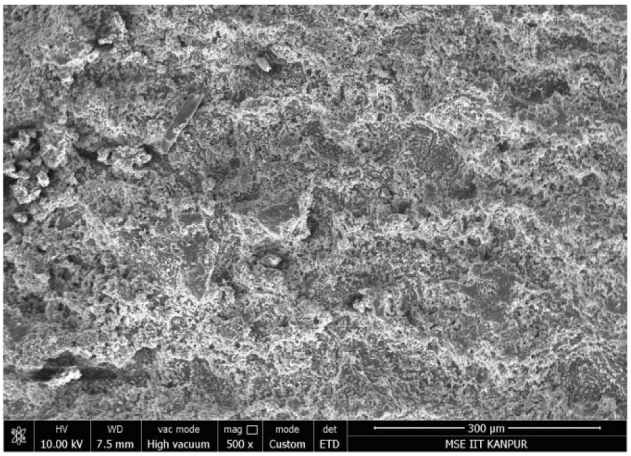
3.3 Effect of Pulse on-Time on MRR and R_a with Variation in Silica Particle Concentration

The effects of pulse on-time on MRR have been observed in Fig. 5a. As pulse on-time increases the MRR also increased because longer pulse on-time provides higher thermal energy which is responsible for removing large amount of material from workpiece. MRR increases by 35% from 300 to 350 μs and 17.5% from 350 to 400 μs at 5% Cp. The percentage variation of MRR values is observed 27.5% from 300 to 350 μs and 15.5% from 350 to 400 μs at 4% Cp. Almost similar percentage variation in MRR values is observed for 3% Cp.

Figure 5b shows the effects of pulse on-time on the R_a for different values of particle concentration. As the pulse on-time increases from 300 μs to 350 μs, the surface roughness of workpiece increases. The roughness of machined workpiece at the pulse on-time of 300 μs was very small, because the less interaction time available between spark and workpiece



(a)



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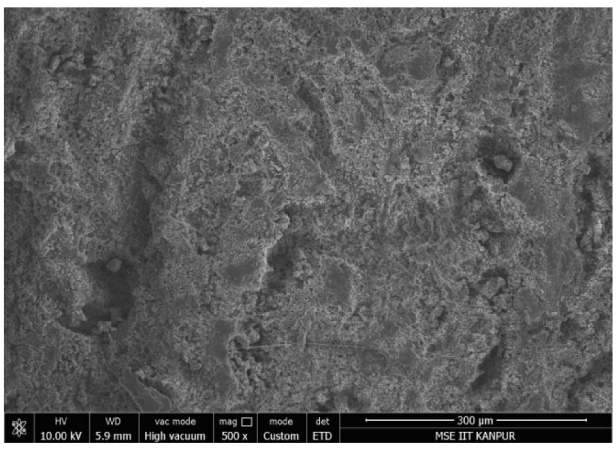

(c)

Fig. 7 SEM micrographs of machined surface of (**a**) 3%Cp (**b**) 4% Cp and (**c**) 5% Cp of SiO_2 epoxy nanocomposite

material. As value of pulse on-time increases, the total discharge time is longer over the machining time hence roughness increases with increase in material removal in form of craters.

The value of R_a increases by 12.72% from 300 μs to 350 μs and 27.4% from 350 μs to 400 μs at 5% Cp. It can clearly be observed that the machined edges became more uneven at longer pulses, may be due to the high thermal energy released during the larger machining time.

3.4 Effect of Wire Velocity on MRR and R_a with Variation in Silica Particle Concentration

Figure 6a shows the effect of wire velocity on MRR for different particle concentration. As the wire velocity increases the MRR reduces. This is because, with increasing wire velocity there is unstable gas film formed, leads to discontinuous sparking at the machining zone, therefore less amount of energy generated which causes less melting of workpiece material. The MRR reduces by 10% from 1.7 m/min to 2.1 m/min and 19.6% from 2.1 m/min to 2.5 m/min at 3% Cp. It follows approximately same percentage variation for 1.7 m/min to 2.1 m/min at 5% and 4% particle concentrations.

Figure 6b shows the variation of surface roughness (R_a) with wire velocity for different particle concentration. The surface roughness decreases as the wire velocity increases. This may be because of the higher velocity of wire which swept away most of the bubbles so insufficient spark generated and less material removed from workpiece. Similar trends are observed for different particle concentration.

The SEM micrographs of machined samples at different particle concentration (3%, 4% and 5%) have been shown in Fig. 7a, b and c. Here, the machining condition applied during cutting was voltage = 45 V, electrolyte concentration = 250 g/l, wire velocity = 1.7 m/min and pulse on-time = 350 μs. The images of specimens show the quality of cutting by using WECSC process. It can be clearly observed from Fig. 7c that the more clear surfaces are developed at particle concentration of 5%. It may be due to less material removal obtained from surface of workpiece. The reason behind is it that the glass transition temperature at 5% Cp is more compared to 4% and 3% Cp. Therefore, more energy required for material removal in the form of crater from workpiece.

4 Conclusions

Based on the experimental investigation, machining characteristics of silicon dioxide epoxy nanocomposite using WECSC process have been reported. WECSC process for cutting of silicon dioxide epoxy nanocomposite has been found to be effective machining process. It can be analysed from the experimental results that at higher value of voltage material removal rate is high and more uneven surface obtained. It may happen due to higher energy content produced at higher value of voltage. MRR and surface roughness both increases with decrease in silica particle concentration. It is because of lower T_g value at lower particle concentration. The MRR is less at lower pulses and higher wire velocity due to the less discharge energy availability at higher wire velocity. From SEM images it is clear that at higher particle concentration (5%), fewer crater developed on the machined surface therefore, surface quality was better than 3% and 4% particle concentration.

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