Analysis, predictive modelling and multi-response optimization in electrical discharge machining of Al-22%SiC metal matrix composite for minimization of surface roughness and hole overcut

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Received: 27 March 2020 / Accepted: 23 May 2020

Abstract. Due to the widespread engineering applications of metal matrix composites especially in automotive, aerospace, military, and electricity industries; the achievement of desired shape and contour of the machined end product with intricate geometry and dimensions that are very challenging task. This experimental investigation deals with electrical discharge machining of newly engineered metal matrix composite of aluminum reinforced with 22 wt.% of silicon carbide particles (Al-22%SiC MMC) using a brass electrode to analyze the machined part quality concerning surface roughness and overcut. Forty-six sets of experimental trials are conducted by considering five machining parameters (discharge current, gap voltage, pulse-on-time, pulse-off-time and flushing pressure) based on Box-Behnken’s design of experiments (BBDOEs). This article demonstrates the methodology for predictive modeling and multi-response optimization of machining accuracy and surface quality to enhance the hole quality in Al-SiC based MMC, employing response surface methodology (RSM) and desirability function approach (DFA). Finally, a novel approach has been proposed for economic analysis which estimated the total machining cost per part of rupees 211.08 during EDM of Al-SiC MMC under optimum machining conditions. Thereafter, under the influence of discharge current several observations are performed on machined surface morphology and hole characteristics by scanning electron microscope to establish the process. The result shows that discharge current has the significant contribution (38.16% for Ra, 37.12% in case of OC) in degradation of surface finish as well as the dimensional deviation of hole diameter, especially overcut. The machining data generated for the Al-SiC MMC will be useful for the industry.

Keywords: EDM / Al-SiC MMC / surface roughness / overcut / optimization / cost analysis

1 Introduction

With today’s technologies, one of the important challenges for manufacturing industry is to provide workpieces with specified quality characteristics in the required quantity and in the fastest and most cost-effective way possible. Therefore, the improvement of the machining of newer materials and alloys becomes an absolute necessity in manufacturing process. Day-by-day, metal matrix composites (MMC) have increasingly widened their use in manufacturing sectors like aerospace, defense, manufacturing, automobile, electronic, and nuclear industries. These materials are extensively employed in different industrial applications to attain high performances due to their favorable characteristics such as lightweight, more excellent resistance to wear, high specific strength and high-temperature resistance than conventional materials [1]. Lightweight materials are mechanically consistent with lesser manufacturing costs. In the viewpoint of commercial production, the traditional machining techniques are incompetent to machine metal matrix composites for achieving the required accuracy as well as precision, intricate shapes, also time-consuming and sometimes not possible (i.e., extremely difficult to be machined). Such features on a component can be achieved only through the advanced manufacturing process. Recent past, electrical discharge machining (called, EDM) process have made an attention to be an effective technology for machining several hard and difficult-to-cut materials due to the intense heating generated along with localized electric spark that almost produces negligible cutting force including minimum stress on the machined surface for the removal of material, and high flexibility with versatility of production. Hence, the EDM process deals with as a
sustainable and reasonable unconventional process for MMCs.

However, due to the complex-dynamic behavior of EDM process and its close connection with various parameters, the achievement of high responsiveness of production is essential from the techno-economical point-of-views. Several factors influencing the cutting behaviour in EDM process are such as dielectric flushing pressure \( [2,3] \), electrode materials \( [4-8] \), electric spark variables (current, discharge voltage, frequency, pulse duration) \( [9-11] \), dielectric fluids \( [12-15] \), etc. Moreover, for successful implementation of EDM technology as the substitute of conventional machining of various difficult-to-cut materials can be improved in terms of cutting efficiency, quality, cost, and productivity by considering the most appropriate and optimal process parameters, which mainly consumes precious time and effort. Under such circumstances, the effective utilization of experimental, modeling, and optimization methodology make possible a more considerable improvement in decision-making with a new technological solution that can simultaneously satisfy and control the several distinctive as well as contradictory objectives (multi-objective) in order to make the EDM process an excellent choice for machining of advanced metal matrix composite materials. Several statistical and computational approaches such as RSM \( [16-21] \), ANN \( [22-27] \) have been applied for predictive modeling and Taguchi method \( [28-31] \), GRA \( [32-36] \), desirability function approach of RSM \( [37-40] \), and PCA \( [41,42] \) have been employed for parametric as well as process optimization in electrical discharge machining. Extensive studies have been reported by employing various experimental designs, modeling techniques and optimization approaches in order to assess or investigate the machinability \( [43-46] \), to predict the various technological responses, and to control the process parameters in machining of different workpiece materials (AISI D2, D3, D6, MDN 300, AISI 316L, stainless steel, A2 tool steel, grey cast iron, Inconel 600, 601, 625, 825, 718, Ti6Al4V, Ti32Zr13Nb, nickel alloy, Al7075, Al6061, Al6063 alloy, Al-SiC MMC, Si3N4-TiN MMC, Al-Mg3Si, WC, polycrystalline diamond). Table 1 overviews the workpiece surface characteristics have not been emphasized intensively. It was most solicited from an industrial standpoint to process in EDM with the possibility of achieving the good surface quality as well as hole quality. Though the implementation of RSM and desirability function approach was existent in the literatures, until now no systematic study has been reported to predict as well as to control surface quality and dimensional accuracy of the machined hole in the absence of MRR, EWR. Moreover, to the best of the author’s knowledge, previous studies did not consider any economic analysis solution enabling cost-effective manufacturing using EDM, which finds the scope for researches from techno-economical point-of-view. In order to fill up the existing research gap, the process work addresses the workpiece surface finish and hole overcut during electrical discharge machining of newly engineered metal matrix composite (MMC) of aluminum reinforced with 22 wt.% of SiC particles with brass electrode. A methodology for predictive modelling and multi-response optimization has been developed by employing response surface methodology (RSM) and desirability function approach (DFA). Additionally, an out of the paradigm investigation of EDM on Al-SiC MMC has been made to analyze how the discharge current affects the hole quality as well as surface finish of the machined component. Finally, a unique economic analysis has been performed: (i) to rationalize the usefulness of EDM process for difficult as well as hard-to-cut materials, and (ii) to confirm the feasibility of the EDM strategy for mass production in industry. Hence, the gap between the literature and the current research is somewhat diminished. Novelty aspect, the present study will be useful as technological guidelines for practical industrial application of EDM process in automotive, aerospace, military, and electricity industries to establish a superior advantage of mechanism from the economical point of view. All of these points bring worthy investigations, contribute to the uniqueness of the current study, and make advancements towards economic manufacturing.

2 Experimental setup and procedure

In this work, conductive silicon carbide particle reinforced aluminum-based metal matrix composite (Al-SiC MMC) of a circular plate having dimensions \( \phi 65 \text{ mm} \times 5 \text{ mm} \) (diameter and thickness, respectively) is selected as workpiece material because of its excellent-unique characteristics (lightweight, strength, hardness, stiffness, wear, and corrosion resistance) as well as due to its economic production and its widespread application in aerospace, automobiles industries. For the preparation of workpiece material, the furnace was preheated at a temperature of 400 °C. Scraps of aluminum of around 1 kg were preheated
| References | Workpiece materials | Electrode materials | Dielectric medium | Process parameters | Machining characteristics | Techniques | Research findings |
|------------|---------------------|---------------------|-------------------|--------------------|------------------------|------------|-------------------|
| [1]        | Al-SiC metal matrix composite | Brass | Kerosene | Discharge current, pulse duration, speed of electrode rotation, hole diameter of the electrode, polarity of the electrode, volume percentage of SiC | Material removal rate, electrode wear rate, surface roughness | GA | • With the increase in volume percentage of SiC, MRR decreases and EWR increases.  
• With the decrease in hole diameter and increase in speed of the rotating tube electrode, MRR increases and EWR and SR decreases. |
| [2]        | WC/30%Co composite | Copper | Kerosene | Electrode rotation, pulse on time, current, flushing pressure | Material removal rate, surface roughness | RSM | • Combination of low pulse time and high peak current, rotational speed, and flushing pressure yields more MRR and less Ra.  
• Surface finish improves at higher levels of electrode rotation and flushing pressure  
• Peak current has the most significant effect on MRR, whereas the pulse-on time and gap voltage show almost the same effect, over MRR  
• Surface roughness is affected by peak current and pulse-on time while gap voltage and spindle speed have no effect. |
| [3]        | Titanium alloy (Ti-6Al-4V) | Copper | EDM oil | Pulse-on time, peak current, gap voltage, spindle speed, flushing pressure | Material removal rate, surface roughness | Taguchi method | • Overcut is significantly affected by pulse-on time and pulse current but pulse-off time and gap voltage have less effect.  
• Deep cryogenic treated brass tool with longer soaking duration has been proven to be an ideal EDM tool to machine hard materials like Inconel 718. |
| [4]        | AISI D3 tool steel | Copper | Kerosene | Pulse current, pulse-on time, pulse-off time, gap voltage | Overcut | RSM |
| [5]        | Inconel 718 | Brass | | Discharge current, open-circuit voltage, pulse-on time, duty factor, flushing pressure, cryogenic treatment soaking duration of brass tool | Electrode wear ratio, surface roughness, radial overcut | TOPSIS, TLBO |

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| References | Workpiece materials | Electrode materials | Dielectric medium | Process parameters | Machining characteristics | Techniques | Research findings |
|------------|---------------------|---------------------|-------------------|--------------------|--------------------------|------------|------------------|
| [6]        | Inconel 718         | Copper, graphite, brass | Paraffin oil      | Open circuit voltage, discharge current, pulse-on-time, duty factor, flushing pressure, electrode material | Material removal rate, tool wear rate, surface roughness, radial overcut | PSO        | • Material removal rate can be maximized with the use of graphite tool and minimized using brass electrode but better surface integrity can be obtained using brass electrode. • Tool wear decreases using graphite tool compared to copper and brass tool. • QPSO provides better result than PSO resulting. |
| [7]        | Tungsten carbide    | Copper, tungsten     | EDM 22 mineral oil | Electrode material, polarity, open-circuit voltage, peak current, pulse duration, pulse interval, flushing pressure | Material removal rate, relative wear ratio, surface roughness |           |                  |
| [8]        | Titanium Grade 6 alloy (Ti-5Al-2.5Sn) | Copper, brass, zinc | EDM 22 mineral oil | Pulse on time, peak current, gap voltage, Duty cycle | Material removal rate, tool wear rate | RSM        | • Material removal rate and the surface roughness are directly proportional to the peak current. |
| [9]        | Titanium alloy (Ti-6Al-4V) | Tungsten, copper, cryogenically treated copper | EDM 30 oil        | Peak discharge current, pulse-on time, gap voltage, duty factor, dielectric flushing pressure, spark gap, machining time | Material removal efficiency, surface roughness, surface crack density, white layer thickness | RSM        | • Cryogenically treated Copper has exhibited higher micro-hardness value, higher MRR, improved surface finish and lower tool wear as compared to normal Copper. • Lower MRR and too rough surface has obtained by using tungsten electrode. |
| [10]       | Al6061-SiC MMC      | Copper, brass, stainless steel | Kerosene oil mixed with graphene nanoparticle | Current intensity, pulse duration, duty cycle | Material removal rate, surface roughness, electrode wear ratio | RSM        | • Brass electrode yielded higher MRR and better surface finish than copper and stainless steel electrodes. |
| References | Workpiece materials | Electrode materials | Dielectric medium | Process parameters | Machining characteristics | Techniques | Research findings |
|------------|---------------------|---------------------|-------------------|-------------------|--------------------------|------------|-----------------|
| [11]       | Inconel 825         | Graphite, tungsten, brass, copper | EDM 30 oil        | Peak discharge current, gap voltage, pulse-on time, duty factor, flushing pressure | Material removal rate, surface roughness, surface crack density, white layer thickness | EDM         | Lower EWR resulted by using stainless steel electrode than copper and brass electrodes. Copper electrode yielded higher MRR. Increase in peak discharge current, increases the material removal rate, surface roughness, white layer thickness etc. |
| [12]       | Titanium alloy (Ti-6Al-4V) | Cu-TaC composite | Urea solution, distilled water | Peak current, pulse duration | Surface roughness, microhardness | Urea solution | Distilled water dielectric fluid gave better surface roughness, while use of urea solution gives higher surface roughness. |
| [13]       | AISI 8407 steel     | Steel needle        | Oxygen, air, kerosene, deionized water, water-in-oil emulsion | Pulse duration, type of dielectrics | Hole geometry, craters, recast layer thickness, material removal rate | Deionized water, kerosene | Different shape of craters formed in different dielectrics with the same experimental conditions. Higher removal has been obtained in liquid dielectrics compared to gaseous dielectrics. Kerosene resulted in higher removal efficiency; less volume of material was melted compared to other dielectrics. |
| [14]       | Aluminium alloy 6063 | Copper              | Biodiesel, transformer oil, kerosene | Peak current, pulse on time, pulse off time, different dielectrics | Material removal rate, electrode Wear, surface roughness | Taguchi method | Biodiesel gives high MRR and less EWR compared to kerosene dielectric. The material removal rate and electrode wear rate are mainly affected by peak current followed by the pulse on time with negligible effect of pulse off time.
| References | Workpiece materials | Electrode materials | Dielectric medium | Process parameters | Machining characteristics | Techniques | Research findings |
|------------|---------------------|---------------------|-------------------|-------------------|--------------------------|------------|------------------|
| [15]       | Inconel 738         | Brass               | Kerosene, deionized, water, EDM emulsion, water solution EDM fluid | Open circuit voltage, current peak, pulse duration, pulse interval | Material removal rate, electrode wear, holes generation, recast layer formation | Taguchi method | • The recast layer became thicker with the increase in electric conductivity of dielectric fluids.  
• The recast layer became thin with kerosene but due to decomposition of kerosene, the machining speed was low. |
| [16]       | Spheroidal graphite cast iron | Copper     | Kerosene          | Diameter of graphite particle, quantity of graphite particle, area fraction of graphite particle | Layer thickness, Ridge density | RSM | • Layer thickness increases with the increase of the quantity and area fraction of graphite particle but it reduces with the increase of diameter of graphite particle. |
| [17]       | Al/SiC metal matrix composite | Copper     | Kerosene          | Pulse on time, peak current, average gap voltage, volume fraction of SiC in aluminium matrix | Material removal rate, electrode wear ratio, gap size, surface finish | RSM | • MRR becomes higher with an increase of pulse on time, peak current and relatively with gap voltage and reduces with increase of SiC percentage.  
• EWR becomes higher with an increase of both pulse on time and peak current and reduces with increase of both of SiC percentage and gap voltage.  
• Surface roughness increases with the increase of pulse on time, SiC percentage, peak current, gap voltage. |
| [18]       | AISI D2 tool steel  | Graphite           | Kerosene mixed with carbon nanotube | Discharge current, discharge duration, discharge voltage | Surface roughness, morphology, micro-cracks | RSM, fuzzy logic modelling | • Micro-cracks with CNT are less than that without CNTs.  
• The maximum test errors for surface roughness and micro-cracks using response surface model are more without CNTs compared to with CNTs. |
| References | Workpiece materials | Electrode materials | Dielectric medium | Process parameters | Machining characteristics | Techniques | Research findings |
|------------|--------------------|---------------------|------------------|-------------------|--------------------------|------------|------------------|
| [19]       | Al-Mg2Si metal matrix composite | Copper | Dielectric fluid mixed with aluminium powder | Voltage, current, pulse on time, duty factor | Material removal rate, electrode wear ratio, microstructure changes | RSM        | • MRR is significantly affected by voltage, current and EWR is significantly affected by pulses ON time. |
|            |                    |                     |                  |                   |                          |            | • It was obtained from the microstructure analysis that voltage, current, and pulse ON time have a significant effect on machined surface profile. |
| [20]       | AISI D6 tool steel  | Copper              | Kerosene         | Pulse on time, pulse current, voltage | Material removal rate, tool wear ratio | RSM        | • Increased pulse on time resulted in higher material removal rate and reduced tool wear ratio. |
|            |                    |                     |                  |                   |                          |            | • Both material removal rate and tool wear ratio become maximum by increasing the pulse current and reduces at higher value of the input voltage respectively. |
| [21]       | Titanium Ti-13Nb-13Zr alloy | Graphite | Kerosene         | Current, voltage, pulse on time, pulse off time | Material removal rate, electrode wear rate, surface roughness | RSM        | • The absolute error between predictions and actual values fall within 10% for which the model can be effectively used to predict the EDM machining parameters. |
| [24]       | AISI D2 steel      | Copper              | EDM oil          | Pulse current, pulse on time, duty cycle | Surface roughness | ANN        | • The process performance with accuracy could be predicted using neural models under different machining conditions. |
|            |                    |                     |                  |                   |                          |            | • RBFN is faster than the BPNs and the BPN is reasonably more accurate. |
| References | Workpiece materials | Electrode materials | Dielectric medium | Process parameters | Machining characteristics | Techniques | Research findings |
|------------|---------------------|---------------------|-------------------|-------------------|-------------------------|------------|------------------|
| [25]       | Al/SiC MMC          | Copper, graphite,   | EDM oil, EDM oil + | Workpiece, electrode, | Residual stress          | ANN        | ● MMCs with low   |
|            |                     | copper–graphite      | copper powder, EDM oil + graphite powder | current, pulse-on time, |            |                 | coefficient of   |
|            |                     | composite           | EDM oil           | pulse-off time,      |            |                 | thermal expansion| |
|            |                     |                     |                   | dielectric fluid     |            |                 | and a high      |
|            |                     |                     |                   |                   |            |                 | density of      |
|            |                     |                     |                   |                   |            |                 | reinforced      |
|            |                     |                     |                   |                   |            |                 | particle have   |
|            |                     |                     |                   |                   |            |                 | lower residual   |
|            |                     |                     |                   |                   |            |                 | stresses.       |
| [26]       | Titanium alloy      | Copper, copper-     | Ferrolac 3M EDM    | Peak current, pulse- | Surface roughness       | Hybrid Taguchi-ANN | ● The residual    |
|            |                     | chromium, copper-   | oil               | on-time, pulse-off-  |            | ANN approach     | stresses reduced| |
|            |                     | tungsten            |                   | time, dielectric     |            |                 | by adding powder | |
|            |                     |                     |                   | fluid mixed with     |            |                 | in the dielectric.|
|            |                     |                     |                   | powder, electrode     |            |                 |                 |
|            |                     |                     |                   | material, cryogenic  |            |                 |                 |
|            |                     |                     |                   | of electrode material,|            |                 |                 |
|            |                     |                     |                   | workpiece material,  |            |                 |                 |
|            |                     |                     |                   | cryogenic workpiece   |            |                 |                 |
| [27]       | Polycrystalline     | Copper-tungsten,    | Kerosene           | Peak current, pulse- | Material removal rate,  | ANN        | ● High discharge  |
| diamond    |                     | copper-nickel       |                   | interval, pulse       | electrode wear rate     |            | energy resulted  |
|            |                     |                     |                   | duration             |            |                 | as surface      |
| [28]       | Inconel 718         | Tungsten carbide    | Kerosene           | Peak current, pulse- | Electrode wear,           | Grey-Taguchi method | ● Surface defects|
|            |                     |                     |                   | on-time, pulse-off-   | material removal rate,    |            | such as cracks,  |
|            |                     |                     |                   | time, spark gap       | working gap             |            | craters, thick   |
| [29]       | Maraging steel (MDN | Copper              | Kerosene           | Discharge current,    | Material removal rate,    | Taguchi method | ● Grey-Taguchi   |
| 300)       |                     |                     |                   | pulse on time, pulse  | tool wear rate, relative |            | method is very   |
|            |                     |                     |                   | off time              | wear ratio, surface      |            | suitable for     |
|            |                     |                     |                   |                     | roughness               |            | solving the      |
| [30]       | S-03 special stainless steel | Copper              | Kerosene           | Gap voltage, peak     | Material removal rate,    | Taguchi method, grey | ● Discharge current |
|            |                     |                     |                   | discharge current,    | surface roughness        | relational analysis | more significant  |
|            |                     |                     |                   | pulse width, pulse    |            |                 | than pulse on    |
|            |                     |                     |                   | interval              |            |                 |      time for    |
|            |                     |                     |                   |                     |            |                 | MRR and TWR.     |
|            |                     |                     |                   |                     |            |                 | Higher discharge  |
|            |                     |                     |                   |                     |            |                 | current and      |
|            |                     |                     |                   |                     |            |                 | longer pulse on  |
|            |                     |                     |                   |                     |            |                 | duration gives   |
|            |                     |                     |                   |                     |            |                 | rougher surface  |
|            |                     |                     |                   |                     |            |                 | with more craters,|
|            |                     |                     |                   |                     |            |                 | globules of debris,|
|            |                     |                     |                   |                     |            |                 | and microcracks. |
|            |                     |                     |                   |                     |            |                 |                 |
|            |                     |                     |                   |                     |            |                 |                 |
|            |                     |                     |                   |                     |            |                 |                 |

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| References | Workpiece materials | Electrode materials | Dielectric medium | Process parameters | Machining characteristics | Techniques | Research findings |
|------------|---------------------|---------------------|-------------------|--------------------|--------------------------|------------|------------------|
| [31]       | NiTi alloys         | Copper              |                   | Gap current, pulse on time, pulse off time, workpiece electrical conductivity, tool conductivity | Material removal rate | Taguchi method | • The material removal rate affected by the significant material removal rate parameters like work electrical conductivity, gap current and pulse on time. |
| [32]       | SS 304              | WC                  | Kerosene          | Voltage, capacitance, resistance, feed rate, spindle speed | Electrode wear, entrance clearance, exit clearance, machining time, number of shorts | Taguchi method, grey relational analysis | • Electrode wear and the entrance and exit clearances have a significant effect on the diameter of the micro-hole when the diameter of the electrode is identical. |
| [33]       | 6061Al/Al2O3p/20P aluminium MMC | Copper              |                   | Pulse current, pulse ON time, duty cycle, gap voltage, tool electrode lift time | Material removal rate, tool wear rate, surface roughness | Grey relational analysis | • The sequence of the process parameters to the multi-performance characteristics is in the order of pulse current, aspect ratio, tool electrode lift time, pulse ON time, gap voltage and duty cycle. |
| [34]       | Nickel-based superalloy | Copper              |                   | Gap voltage, gap current, pulse on time, duty factor, polarity, tool & workpiece materials, type of dielectrics, flow rate, flushing pressure, rotation of electrode or workpiece | Material removal rate, surface roughness, circularity | Taguchi method, RSM, PCA-GRA | • Grey system theory is designed to work with system where the available information is not sufficient to characterise the system. MRR become improves with the use of present hybrid approach in this experimental study. |
| [35]       | Al7075              | Brass               | Deionized water   | Pulse on-time, pulse off-time, flushing pressure | Material removal rate, tool wear rate | Grey relational analysis | • The optimization results showed that the MRR become maximum due to combination of higher pulse on-time and reduced pulse off-time. |
| References  | Workpiece materials          | Electrode materials | Dielectric medium | Process parameters | Machining characteristics                          | Techniques  | Research findings                                                                 |
|------------|-----------------------------|---------------------|-------------------|-------------------|-------------------------------------------------|-------------|----------------------------------------------------------------------------------|
| [36]       | Si$_3$N$_4$-TiN composites  | Copper              |                   | Current, pulse on time, pulse off time, dielectric pressure, gap voltage | MRR, electrode wear rate, surface roughness, radial overcut, taper angle, circularity, cylindricity, perpendicularity | GRA-RSM     | Tool wear rate was highly affected by pulse on-time, pulse off-time.             |
|            |                             |                     |                   |                   |                                                 |             | MRR increases with increase in discharge current and pulse on time.               |
|            |                             |                     |                   |                   |                                                 |             | EWR increases with increase in discharge current and pulse on time, and decrease in gap voltage. |
|            |                             |                     |                   |                   |                                                 |             | The surface roughness decreases with decrease in discharge current whereas increasing gap voltage reduces surface roughness. |
| [37]       | JIS SKD 61 alloy tool steel | Copper              |                   | Discharge current, gap voltage, pulse on-time, pulse off-time | Material removal rate, relative electrode wear ratio, surface finish | RSM, GA     | MRR increases due to a more powerful spark energy, at higher discharge current and pulse on time. |
|            |                             |                     |                   |                   |                                                 |             | Larger thickness of recast layer was formed on the machined surface due to the powerful spark energy. |
|            |                             |                     |                   |                   |                                                 |             | Relative electrode wear ratio reduces with increase of pulse on-time.          |
| [38]       | Al-SiC nano-composites      | Copper              |                   | Voltage, pulse current, pulse on-time, pulse off-time | Material removal rate, electrode wear rate, surface roughness | RSM         | MRR increases with an increase in pulse on time and then with further increase in pulse on time. |
|            |                             |                     |                   |                   |                                                 |             | MRR and surface roughness is mainly affected by pulse current and pulse on time. |
| References | Workpiece materials | Electrode materials | Dielectric medium | Process parameters | Machining characteristics | Techniques | Research findings |
|------------|---------------------|---------------------|-------------------|--------------------|--------------------------|------------|--------------------|
| [39]       | Aluminium-multiwall carbon Nano- tube composites (AL-CNT) | Copper              | Kerosene          | Machining-on time, discharge current, voltage, total depth of cut | Material removal rate, wear electrode ratio, surface roughness | Taguchi method, RSM | • As the number of trials increases over wider domains of process variables, the accuracy of these models is enhanced. |
| [40]       | Tool steel 55NiCrMoV7 | Graphite (EDM-3 POCO) | EDM fluid 108 MP-SE 60 |                            | Material removal rate | RSM | • Increase in the discharge current and pulse time leads to generation of craters with a larger depth and diameter. |
| [42]       | A2 tool steel       | Copper              | EDM-30            | Discharge current, pulse on time, duty cycle, discharge voltage | Material removal rate, Electrode wear rate | Principal component analysis | • Discharge current is directly proportional to both MRR and EWR. |
| [43]       | Beryllium–copper alloy | C-122 copper       | EDM-244 oil, deionized water | Dielectric medium, pulse on/off time, working current | material removal rate, electrode wear ratio, surface roughness | Taguchi method, GRA, RSM | • MRR is mostly affected by the working current, while the dielectric medium is the dominant parameter for EWR and Ra. |
| [44]       | AISI 202 steel      | Tungsten carbide    | Kerosene          | Discharge current, gap voltage, duty factor | Material removal rate, surface roughness | Taguchi method | • Better surface finish with high MRR could be produced by the modified ISO current pulse generator. |
at 450 °C for 2–3 h, and 3–4 pouches of silicon carbide (having a mesh size of about 300–400 microns) powder of 10 grams each were taken and melted along with the aluminum scraps at a temperature of 800 °C in a crucible. A higher amount of aluminum and silicon carbide was added to the crucible in order to prevent material loss. The molten material was stirred vigorously and was immediately cast into a graphite mold to obtain a tapered-cylindrical ingot of around 70 mm diameter. The diffusion of aluminum silicon carbide occurs in three stages: aluminum-aluminum (Al-Al), aluminum-silicon carbide (Al-SiC), silicon carbide-silicon carbide (SiC-SiC). The grain growth rate of SiC-SiC is much faster than the other two combinations, which, if not controlled might dominate the final grain structure of the material. In order to not let this happen, a small amount of around 0.1% NaCl powder was added just before casting. A tapered cylindrical piece of Al-SiC (22.13% SiC) of fine grain structure was thus obtained. For the present experimental purpose, the ingot was cut by a wire-EDM into six pieces with the piece having an average diameter of 65 mm, and each piece having a thickness of 5 mm. The elemental constituents and particle shape characterization of Al-SiC MMC are identified (refer, Fig. 1) in a scanning electron microscope (SEM) with an embedded energy dispersive X-ray (EDS) analyzer. Commercially available brass rod with diameter of 9 mm has been considered for electrode material in machining. Bio-degradable vegetable oil (with density: 0.917 g/cm³; dynamic viscosity 48.4 g/m·s; dielectric rigidity: 62 kV/mm; specific heat: 1.67 J/g·K) was employed as dielectric medium.

For performing a series of experiments, a high accuracy computer numerical controlled electrical discharge machine tool (make: ECOWIN, model: MIC 432CS) has been utilized with maximum working current of 60 amp manufactured by Taiwan. During electrical discharge machining of Al-SiC MMC, the measurement of surface finish of machined hole part in term of arithmetical average roughness (Ra) is measured by Surftest SJ-210 Mitutoyo roughness tester. After every successive experimental trial, the overcut (OC) of the machined hole on Al-SiC MMC material is evaluated by employing co-ordinate measuring machine (ZEISS MC850), equipped with a stylus probe accessory. For better understanding of electrical discharge machining process as well as for machinability improvement, a comprehensive investigation is performed on the morphological study of machined surface by employing scanning electron microscope (JEOL JSM-6480LV). A scheme of the experimental setup with methodologies proposed in this work, is pictorially presented in Figure 2.

In this experimental investigation, five machining parameters (discharge current, gap voltage, pulse-on-time, pulse-off-time, flushing pressure) and two major technological performance characteristics (surface roughness, and overcut) of machined part are considered as input process factors and output responses, respectively. The selection of different levels of machining parameters are considered with reference to published research work [37,46] and by inspecting the workpiece for a through-hole of acceptable quality. Moreover, preliminary trails were executed to choose the appropriate range of each input parameters.

| References | Workpiece materials | Electrode materials | Dielectric medium | Process parameters | Techniques | Machining characteristics | Research findings |
|------------|---------------------|---------------------|-------------------|-------------------|-----------|--------------------------|-----------------|
| [45]       | Inconel 600         | Graphite            | Mineral oil       | Current intensity, pulse-time, duty cycle, flushing, pressure | RSM       | Material removal rate, electrode wear, surface roughness | Positive polarity results in higher MRR and surface roughness increases with peak current. |
| [46]       | Inconel 601, 625, 718, 825 super alloys | Graphite | EDM oil | Gap voltage, peak discharge current, pulse-on-time, duty factor, flushing pressure | Satisfaction function approach integrated with Taguchi method | Material removal rate, electrode wear rate, surface roughness, surface crack density | MRR and surface roughness increases with peak current. |

Table 1. (continued).
Table 2 illustrates the detailed input factors with their corresponding levels for the experiment in actual as well as coded values setting. The proposed experimental design involves the variation of five factors (DC, GV, TON, TOFF, FP) at three levels. Machining trials are completely conducted based on Box-Behnken design of experiments associated with forty-six numbers of trial runs. The experimental design layout and results of machining trials are reported in Table 3.

3 Results and discussion

3.1 Development of predictive model using response surface methodology

In the present work, Design expert 11.0 is employed to analyze the obtained experimental results of the technological responses of machined part quality (here, surface roughness and overcut) in accordance with Box-Behnken DOEs through RSM. It is used to develop a best fitted empirical model that establishes a correlation between the machining response characteristics (surface finish of the machined component Ra, and overcut of drilled hole OC) with the given machining process parameters (DC, GV, TON, TOFF, FP). Regression equations for each response are presented by,

\[
Ra = 1.032 + 0.0548DC + 0.725GV - 0.00254TON - 0.0624TOFF - 3.996FP - 0.002427DC^2 - 0.1621GV^2 - 0.000001TON^2 + 1.875FP^2 - 0.0374DCGV - 0.000108DC * TON + 0.002565DC * TOFF + 0.022GVFP + 0.000087TON^2TOFF + 0.0051TONFP + 0.0221TOFFFP
\]

\[
R^2 = 88.92\%, \quad R^2(\text{adj.}) = 80.05\% \quad (1)
\]

\[
OC = 0.020 + 0.01255DC - 0.0877GV + 0.001718TON + 0.01002TOFF + 0.001FP + 0.001055DC^2 + 0.0393GV^2 - 0.000001TON^2 - 0.00159TOFF^2 - 0.272FP^2 - 0.01407DCGV - 0.000069DC * TON + 0.000286DC * TOFF + 0.01258DCFP + 0.000010GV * TON + 0.00197GV * TOFF + 0.0850GVFP - 0.000035TON^2TOFF + 0.00548TONFP - 0.00841TOFFFP
\]

\[
R^2 = 93.69\%, \quad R^2(\text{adj.}) = 88.64\% \quad (2)
\]
surface roughness in electric discharge machining is significant as its P-value is desirable (i.e., under 0.05). After the execution of the analysis, it is also observed that DC, GV, TOFF, FP, DC*DC, FP*FP, DC*GV, DC*TOFF, DC*FP, TON*TOFF and TON*FP are the significant terms affecting Ra. However, among all the significant process parameters, the discharge current with 38.16% contribution has the most significant effect on
Table 3. Experimental plan layout and results.

| Test. no. | DC (amp) | GV (V) | TON (μs) | TOFF (μs) | FP (kgf/cm²) | Ra (μm) | OC (mm) |
|-----------|----------|--------|----------|-----------|--------------|---------|---------|
| 1         | 5        | 1.0    | 200      | 20        | 0.4          | 0.177   | 0.3194  |
| 2         | 15       | 1.0    | 200      | 20        | 0.4          | 0.7     | 0.4622  |
| 3         | 5        | 2.0    | 200      | 20        | 0.4          | 0.205   | 0.345   |
| 4         | 15       | 2.0    | 200      | 20        | 0.4          | 0.354   | 0.3471  |
| 5         | 10       | 1.5    | 100      | 10        | 0.4          | 0.419   | 0.251   |
| 6         | 10       | 1.5    | 300      | 10        | 0.4          | 0.389   | 0.3821  |
| 7         | 10       | 1.5    | 100      | 30        | 0.4          | 0.4     | 0.3174  |
| 8         | 10       | 1.5    | 300      | 20        | 0.6          | 0.463   | 0.3532  |
| 9         | 10       | 1.5    | 100      | 20        | 0.4          | 0.187   | 0.2245  |
| 10        | 15       | 1.5    | 100      | 20        | 0.4          | 0.6242  | 0.4118  |
| 11        | 20       | 1.0    | 200      | 20        | 0.2          | 0.381   | 0.3999  |
| 12        | 10       | 1.5    | 200      | 20        | 0.6          | 0.421   | 0.3124  |
| 13        | 10       | 1.5    | 200      | 20        | 0.4          | 0.414   | 0.3003  |
| 14        | 10       | 1.5    | 200      | 20        | 0.6          | 0.5685  | 0.3138  |
| 15        | 10       | 1.5    | 200      | 20        | 0.4          | 0.759   | 0.2628  |
| 16        | 10       | 1.5    | 200      | 20        | 0.4          | 0.381   | 0.3075  |
| 17        | 10       | 1.5    | 200      | 20        | 0.4          | 0.435   | 0.2904  |
| 18        | 10       | 1.5    | 200      | 20        | 0.4          | 0.458   | 0.3698  |
| 19        | 10       | 1.5    | 200      | 20        | 0.4          | 0.386   | 0.3548  |
| 20        | 10       | 1.5    | 200      | 20        | 0.4          | 0.221   | 0.3152  |
| 21        | 10       | 1.5    | 200      | 20        | 0.4          | 0.291   | 0.3772  |
| 22        | 10       | 1.5    | 200      | 20        | 0.4          | 0.476   | 0.3136  |
| 23        | 10       | 1.5    | 200      | 20        | 0.2          | 0.39    | 0.3561  |
| 24        | 10       | 1.5    | 200      | 20        | 0.2          | 0.429   | 0.2565  |
| 25        | 10       | 1.5    | 200      | 20        | 0.2          | 0.751   | 0.3428  |
| 26        | 10       | 1.5    | 200      | 20        | 0.2          | 0.39    | 0.3116  |
| 27        | 10       | 1.5    | 200      | 20        | 0.2          | 0.432   | 0.3847  |
| 28        | 10       | 1.5    | 200      | 20        | 0.2          | 0.214   | 0.3033  |
| 29        | 10       | 1.5    | 200      | 20        | 0.2          | 0.781   | 0.4267  |
| 30        | 10       | 1.5    | 200      | 20        | 0.2          | 0.451   | 0.361   |
| 31        | 10       | 1.5    | 200      | 20        | 0.2          | 0.36    | 0.3205  |
| 32        | 10       | 1.5    | 200      | 20        | 0.2          | 0.417   | 0.3303  |
| 33        | 10       | 1.5    | 200      | 20        | 0.2          | 0.412   | 0.3293  |
| 34        | 10       | 1.5    | 200      | 20        | 0.2          | 0.383   | 0.3183  |
| 35        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 36        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 37        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 38        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 39        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 40        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 41        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 42        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 43        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 44        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 45        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
| 46        | 10       | 1.5    | 200      | 20        | 0.2          | 0.371   | 0.3585  |
Table 4. ANOVA results for predictive models.

| Source                  | DoF | SS         | Contr., % | Adj. MS     | F-value | P-value |
|--------------------------|-----|------------|-----------|-------------|---------|---------|
| (a) Surface roughness (Ra) model |     |            |           |             |         |         |
| Model                    | 20  | 0.979426   | 88.92%    | 0.048971    | 10.03   | <0.00001|
| Linear                   | 5   | 0.576319   | 52.32%    | 0.115264    | 23.60   | <0.00001|
| DC                       | 1   | 0.420293   | 38.16%    | 0.420293    | 86.06   | <0.00001|
| GV                       | 1   | 0.023639   | 2.15%     | 0.023639    | 4.84    | 0.037   |
| T_ON                     | 1   | 0.014090   | 1.28%     | 0.014090    | 2.88    | 0.102   |
| T_OFF                    | 1   | 0.056110   | 5.09%     | 0.056110    | 11.49   | 0.002   |
| FP                       | 1   | 0.062188   | 5.65%     | 0.062188    | 12.73   | 0.001   |
| Square                   | 5   | 0.139988   | 12.71%    | 0.027998    | 5.73    | 0.001   |
| DC*DC                    | 1   | 0.032140   | 4.79%     | 0.032140    | 6.58    | 0.017   |
| GV*GV                    | 1   | 0.014340   | 3.33%     | 0.014340    | 2.94    | 0.099   |
| TON*TON                  | 1   | 0.000899   | 0.11%     | 0.000899    | 0.18    | 0.672   |
| TOFF*TOFF                | 1   | 0.005421   | 0.02%     | 0.005421    | 1.11    | 0.302   |
| FP*FP                    | 1   | 0.049099   | 4.46%     | 0.049099    | 10.05   | 0.004   |
| 2-Way Interaction        | 10  | 0.263119   | 23.89%    | 0.026312    | 5.39    | <0.00001|
| DC*GV                    | 1   | 0.034969   | 3.17%     | 0.034969    | 7.16    | 0.013   |
| DC*TON                   | 1   | 0.015178   | 1.05%     | 0.015178    | 2.37    | 0.136   |
| DC*TOFF                  | 1   | 0.065792   | 5.97%     | 0.065792    | 13.47   | 0.001   |
| DC*FP                    | 1   | 0.068906   | 6.26%     | 0.068906    | 14.11   | 0.001   |
| GV*TON                   | 1   | 0.000324   | 0.03%     | 0.000324    | 0.07    | 0.799   |
| GV*TOFF                  | 1   | 0.001849   | 0.17%     | 0.001849    | 0.38    | 0.544   |
| GV*FP                    | 1   | 0.000020   | 0.00%     | 0.000020    | 0.00    | 0.949   |
| TON*TON                  | 1   | 0.030276   | 2.75%     | 0.030276    | 6.20    | 0.020   |
| LR-TON*FP                | 1   | 0.041616   | 3.78%     | 0.041616    | 8.52    | 0.007   |
| TOFF*FP                  | 1   | 0.007788   | 0.71%     | 0.007788    | 1.59    | 0.218   |
| Error                    | 25  | 0.122096   | 11.08%    | 0.004884    |         |         |
| Lack-of-Fit              | 20  | 0.106029   | 9.63%     | 0.005301    | 1.65    | 0.304   |
| Pure Error               | 5   | 0.016067   | 1.46%     | 0.003213    |         |         |
| Total                    | 45  |            | 100.00%   |             |         |         |

| Source                  | DoF | Adj. SS    | Contr., % | Adj. MS     | F-value | P-value |
|--------------------------|-----|------------|-----------|-------------|---------|---------|
| (b) Overcut (OC) model   |     |            |           |             |         |         |
| Model                    | 20  | 0.090892   | 93.69%    | 0.004545    | 18.55   | <0.00001|
| Linear                   | 5   | 0.058467   | 60.26%    | 0.011693    | 47.73   | <0.00001|
| DC                       | 1   | 0.036015   | 37.12%    | 0.036015    | 147.02  | <0.00001|
| GV                       | 1   | 0.004855   | 5.00%     | 0.004855    | 19.82   | <0.00001|
| T_ON                     | 1   | 0.016796   | 17.31%    | 0.016796    | 68.57   | <0.00001|
| T_OFF                    | 1   | 0.000486   | 0.50%     | 0.000486    | 1.98    | 0.171   |
| FP                       | 1   | 0.000315   | 0.32%     | 0.000315    | 1.29    | 0.268   |
| Square                   | 5   | 0.014488   | 14.93%    | 0.002898    | 11.83   | <0.00001|
| DC*DC                    | 1   | 0.006074   | 9.63%     | 0.006074    | 24.80   | <0.00001|
| GV*GV                    | 1   | 0.000844   | 2.60%     | 0.000844    | 3.44    | 0.075   |
| TON*TON                  | 1   | 0.000395   | 0.01%     | 0.000395    | 1.61    | 0.216   |
| TOFF*TOFF                | 1   | 0.002200   | 1.62%     | 0.002200    | 8.98    | 0.006   |
| FP*FP                    | 1   | 0.001033   | 1.06%     | 0.001033    | 4.22    | 0.051   |
| 2-Way Interaction        | 10  | 0.017938   | 18.49%    | 0.001794    | 7.32    | <0.00001|
| DC*GV                    | 1   | 0.004949   | 5.10%     | 0.004949    | 20.20   | <0.00001|
| DC*TON                   | 1   | 0.004775   | 4.92%     | 0.004775    | 19.49   | <0.00001|
| DC*TOFF                  | 1   | 0.000821   | 0.85%     | 0.000821    | 3.35    | 0.079   |
surface roughness of machined component, as supported and justified by F-statistics (86.06) and $P$-value (<0.00001). The factors such as, pulse-on-time and interactions (DC*TON, GV*TTON, GV*TOFF, GV*FP, TOFF*FP) reflect insignificant impact on Ra, as their contributions are very inconsiderable. In the same context, the ANOVA result of overcut (OC) model is presented in Table 4b, which shows the $P$-value is desirable (i.e., under 0.05), thereby resulting in excellent significance of regression model. It was observed that (see Tab. 4b) among the several process parameters that have been considered during machining of aluminum-silicon carbide metal matrix composite, the terms DC, GV, TON, DC*DC, TOFF*TOFF, DC*GV, DC*TON, TON**TOFF and TOFF*FP are found to be significant at 95% confidence level as well as are the influencing parameters of OC. The other parameters don’t present statistical significance as well as an important role on OC because of their larger $P$-value, and the calculated $F$-value is not more than $F$-value. Considering the criterion of significant level to 0.05 and the insight of the $F$-value reveals that the individual effect of discharge current (DC) has the dominant contributor on overcut of machined hole, which explains the larger calculated $F$-values than standardized $F$-distribution value.

To avoid the misleading conclusion, different diagnostic tests such as adequacy, effectiveness and goodness-of-fit were carried out for developed regression models (Ra and OC). When the regression coefficient ($R^2$-value) approaches to one, the predicted model effectively fits with the actual data. For surface roughness and overcut models, the calculated $R^2$-values (0.889 and 0.936, respectively) are very close to unity, which depicts statistical significance as well as goodness-of fit for the proposed model. Moreover, there is a very good degree of resemblance between the experimental and predicted value, as shown in Figure 3. Thus, it is concluded that the proposed model has high effectiveness with good predictability. From the normal probability plot (see Fig. 4), it is noticed that all the terms related with the regression model of Ra and OC are statistically significant as the residuals are approaching to a straight line, which concluded that associated errors were normally distributed. With lower AD-statistic (0.725 for Ra, and 0.435 in case of OC) as well as larger $P$-value (0.055 for Ra, and 0.288 in case of OC) received from Anderson-Darling test, confirmed that null-hypothesis can’t be rejected. Finally, it is concluded that, the proposed predictive models for surface roughness and overcut using RSM is efficient, statistically significant, adequate and also probabilistically validate as it has low probability value (less than 0.05), higher $R^2$-value and larger AD-test $P$-value.

### 3.2 Parametric influence on technological responses

The effect of process parameters (discharge current, gap voltage, pulse-off-time, pulse-on-time, and flushing pressure) on two major technological responses (Ra, OC) of machined part quality are graphically analyzed by three-dimensional (3D) surface plot. Figure 5a illustrates the combined effect of increasing discharge current and gap voltage on surface roughness, Ra. Higher discharge current gives rise to higher discharge spark energy as well as current density. Consequently, increasing MRR results in bigger-deeper carter marks on the machined surface and hence, poor surface finish. Almost the same effect is also observed when spark voltage is raised. Figure 6 shows the SEM micrograph of machined component having poor surface quality that explains the topographical status in terms of crater (due to the existence of different kinds of interaction among the dielectric circulations, debris, and continuous electrical discharge spark), globular modules of debris (attributed to cohesion effect in the machined surface caused by molten material, cold welding effects, and insufficient flushing of dielectric fluid in the gap), micro-voids (due to the gas produced in the discharge process), micro-crack (attributed to the overreach of induced stress over the tensile strength of the workpiece material caused by rapid heating and cooling effect), and micro-pores (due to low fracture toughness and thermal shock resistance of Al-SiC MMC). Moreover, it is observed that, with increased discharge current under machining condition (GV = 2 V; TON = 200 µs; TOFF = 20 µs; FP = 0.2 kgf/cm²) transferring more thermal energy that
develops extremely high temperature at the target surface where the spark strikes cause melting followed by vaporization of MMC material and induces undesirable deep-irregular on workpiece surface, thereby resulting poor surface finish. Figure 7 shows the SEM microphotograph of machined surface under the influence of different discharge currents. It is obvious form these images that, increase of discharge energy aids in the enlarging and deepening of the crater size, which comes with other surface defects such as micro cracks. Therefore, larger discharge energy hinders the surface integrity and to some extent compromises its application capability. Increasing pulse-on-time, at higher pulse-off-time, as shown in Figure 5b, results in increase in surface roughness. This is because the energy available for material removal during a given period is shared less by a large number of sparks; hence the corresponding crater size is increased. Moreover, shorter the pulse-on-time removes very little metal, closer to the accuracy with less thermal damage to the workpiece produces better surface finish, Ra. Apart effect of flushing pressure seems to be insignificant.
on surface finish of the machined part, as shown in Figure 5c. However, it is advisable to keep suitable flushing pressure during electrical discharge machining to prevent stagnation of dielectric fluid and short circuit.

During EDM, the role of dielectric fluid is to flush out the molten material away from the work surface, which is under melting (or partial melting) condition. While flushing, molten material is transformed into tiny particles (droplets), which are expected to be carried away; thereby, exposing a new layer. But all the particles are not flushed out, and they adhere to the top surface of the machined workpiece due to evaporation of the dielectric fluid. That part of the molten material appearing on the topmost layer is known as re-solidified layer; also called as recast layer.

![Surface plots for illustration of machining parameters effect on surface roughness.](image)

**Fig. 5.** Surface plots for illustration of machining parameters effect on surface roughness.
This layer exhibits brittleness to a large extent. Figure 8 depicted the existence of recast layer as noticed from SEM micrographs of machined Al-SiC MMC at parameters setting: GV = 2 V; TON = 200 μs; TOFF = 20 μs; FP = 0.4 kgf/cm². It is also observed that, with increased discharge current under cutting condition (GV = 1 V; TON = 200 μs; TOFF = 20 μs; FP = 0.4 kgf/cm²) results in increased overcut, presented in Figure 10. In fact, overcut increases with an increase in flushing pressure upto a certain point then decrease, as shown in Figure 9c. Similar observation has been reported on overcut in electrical discharge machining of SS316 [50]. The overcut reduces with increase in pressure upto 0.4 kgf/cm² can simply be illustrated as a consequence of less deposition of debris elements in the machining zone, which develops uniformity of sparking at the periphery of machined surface (i.e. wall-edge at the entrance of machined hole). Nevertheless, more increase in flushing pressure promotes increase in OC which can be explained due to a reduction in flushing effectiveness as the density of the debris particles are too high at certain points within the gap.

Figures 9a and 9b illustrate the influence of discharge current and pulse-on-time on overcut (OC). The effect of above-mentioned two parameters leads to the increase in discharge energy per every individual spark, as well as cutting time along with cutting velocity, and consequently transfers more thermal energy on workpiece surface that results in more evaporation of material in comparison to sub-surface and in turn it affects increase in dimensional deviation of hole, especially radial overcut caused by side spark erosion [49]. Moreover, it is observed that, hole taper gradually increases with the rise in discharge current from 5 to 15 amp may be attributed to the fact that thermal energy per unit area is more which might have resulted in high tool wear causing deterioration of tool-tip geometry and thus, resulting geometrical deviation of hole in the form of increased hole taper. Optical micrographs (see Fig. 11b) exhibiting the size of craters formed at various discharge current is evaluated quantitively using a circle to surround the crater marks. It is observed that while executing EDM of Al-SiC MMC, increase in peak discharge current, the crater size increased and resulting in the reduced hole quality in the form of poor surface finish of the hole side wall. Thereby resulting geometric shape deformation of hole as increased overcut.

During electrical discharge machining, intense heat is produced on the workpiece surface because of the spark discharge for which material removal is caused in views of melting followed by evaporation. However, the spark not only melts the workpiece but also melts the tool electrode too. The melting of the tool is called electrode wear. Tool wear rate is considerably affected by specific heat capacity, melting point and thermal conductivity of the electrode material. In addition, dielectric medium circulation flow rate and tool geometry also partly responsible for tool wear. The microscopic view of the bottom surface as well as edge of tool electrode after EDM operation on Al-SiC MMC are presented in Figure 12. Carbon deposition is noticed both at the bottom surface and around the edge of the tool electrode. It is also observed from the optical images that,
increase in discharge current results in increased tool wear (obtained at parameters setting: GV = 1 V; TON = 200 μs; TOFF = 20 μs; FP = 0.4 kgf/cm²). This is so because, during electrical discharge machining, heat is mostly transferred to both the tool electrode and work surfaces. Pyrolysis of the dielectric liquid medium produces pyrolytic carbon atoms, which gets deposit on bottom as well as edge of the tool (and at the machined surface as well), developing a blackish layer of carbides. Deposition of hard and low-conductive carbide layer lowers the thermal conductivity of tool electrode as a whole. These issues promote the electrode wear. Particularly, such carbides accumulated at the tool surface serve as a heat conductive barrier. Thus, heat can only be transferred through bulk of the electrode material after this barrier is overcome. This illustrates the mechanism of tool wear, and leads to poor electrode shape retention capability.

3.3 Optimization using response surface methodology

The present study includes multiple-response optimization based on the desirability function approach of RSM, to keep the surface roughness as well as overcut of machined hole to the minimum. Parameter design is an effective way to improve product quality as well as the process efficiency. Desirability function approach is a statistical based multiple response robust parameter design methodology, employed for solving the multi-objective optimization problems. The approach looks for correct combination of parameter levels that simultaneously takes the responsibility to fulfill the requirements placed on each response. The criterion for achievement of optimization result is evaluated based on overall desirability, which is a weighted geometric mean of respective desirability for the different performance characteristics, which are expressed within the range of 0–1. The response will be completely unaccepted or undesirable if the desirability value approaches to 0. Response will be most desirable or accepted only if the ideal desirability value is near or equal to 1.

For solving the parameter design problems by desirability function approach, the objective function, F(x) is specified as [51]:

\[ F(x) = -DF \]

Overall (i.e. composite) desirability function can be stated as:

\[ DF = \left( \prod_{i=1}^{n} d_i^{w_i} \right)^{1/n} \]

Here, DF is the composite desirability function which finds the optimal setting by minimizing the F(x) (i.e. maximizes DF as it is highly desirable for optimization), \( d_i \) is the desirability designated for the \( i^{th} \) targeted output, and \( w_i \) is the weighting of \( d_i \) (considered equally important) in this study.

For a goal to minimization of output, individual desirability can be defined as:

\[ d_i = \begin{cases} 1 & \text{if } Y_i \leq L_i \\ \frac{H_i - Y_i}{H_i - L_i} & \text{if } L_i \leq Y_i \leq H_i \\ 0 & \text{if } Y_i \geq H_i \end{cases} \]

where \( L_i \) and the \( H_i \) are the lowest and largest acceptable value of \( Y \) for the \( i^{th} \) output response respectively.

The optimal solution was obtained using Design Expert 11 software. A set of thirty-six solutions were obtained, and the solution with the highest desirability (close to 1) was selected, as shown in the ramp function graph in Figure 13a. Once the optimal level of process parameters is selected, the final step to predict and verify the improvement of the performance characteristics using the optimal level of the machining parameters. The point on the graph shows the optimal values for the responses and the height obtained for each point in the graph discloses...
how much enviable are the optimal values obtained. These values were validated by conducting confirmation experiments. The values for the optimal parameters are derived from the points on the ramp graphs. Figure 13b shows optimization plot based on desirability function approach for technological responses, showing the optimal manufacturing conditions for electrical discharge machining of Al-SiC MMC with discharge current (DC) of

Fig. 9. Surface plots for illustration of machining parameters effect on overcut.
5.12 amp, gap voltage (GV) of 1.95 V, pulse-on-time (TON) of 100.02 μs, pulse-off-time (TOFF) of 12.45 μs, and flushing pressure (FP) of 0.55 kgf/cm². Finally, the estimated optimal values of pre-cited two technological responses are 0.17032 μm for Ra, and 0.22412 mm in case of OC.

3.4 Confirmation test

With a view to avoid the misleading conclusion, the optimum machining conditions suggested by desirability function analysis of RSM technique are validated with the results of confirmation test, which could be possible by conducting one additional experiment using the same experimental setup. A comparison between the optimal and experimental values of responses (Ra, OC) under the cutting conditions proposed by RSM is presented in Table 5. The results of RSM approach presents the suitable combination of machining parameters for optimization of surface roughness and overcut because the error percentage is lower (5.8%). Hence, the optimization results obtained by RSM approach is considered for cost analysis.

3.5 Cost analysis

Cost consciousness with respect to machining process is a fundamental venture in efficient manufacturing system. In order to determine the manufacturing cost for a machining operation, important criteria are selected based on convolution of shape, product accuracy and tooling process. Nowadays, with increased pressure on profitability and cost management, manufacturers decided to standardized the total cost in machining operation to ensure consistency and set cost benchmarks for future reference. Because of the large expenditures involved, it is a prime importance to analyze machining operations in order to operate with optimum economic conditions. For components produced by machining, cost estimation is kept minimum by considering the optimum cutting condition and total machining cost per part. This means appropriate selection of machining parameters will definitely affect the
Fig. 12. Deposition of carbon layer at the bottom and edge of the tool electrode after EDM on Al-SiC MMC workpiece at $GV = 1\text{ V}$; $TON = 200\mu\text{s}$; $TOFF = 20\mu\text{s}$; $FP = 0.4\ \text{kgf/cm}^2$.

Fig. 13. Optimization plot for surface roughness and overcut using desirability function approach.
 MMC. The following conclusions are obtained.

Economic analysis is performed to estimate the total machining cost per component during EDM of Al-SiC MMC with brass electrode by the combined approach of Box Behnken design (BBD) – analysis of variance (ANOVA), response surface methodology (RSM) and desirability function analysis (DFA) to analyze the surface roughness and overcut. Also, an economic analysis is performed to estimate the total machining cost per component during EDM of Al-SiC MMC. The following conclusions are obtained.

- The contribution of discharge current is found to be the most responsible factor for the degradation of surface quality as well as finish, and achieved the roughness (Rₐ) in the range of 0.172–0.781 μm.
- ANOVA analysis followed by the 3D surface effect plot illustrated that, the discharge current followed by pulse-on-time are the influential parameters to control the dimensional deviation of hole diameter, i.e. overcut (OC) produced by electrical discharge machining.
- Result showed that discharge current has the significant contribution (38.16% for Ra, 37.12% in case of OC) in degradation of surface finish as well as dimensional deviation of hole diameter, especially overcut.
- Topological as well as morphological status of the machined Al-SiC MMC surface is observed indeed disappointing due to the presence of crater marks, uneven fusion structure, globules of debris, voids and surface microcracks. Recast layer is found at the top of the machined surface. However, intensity of surface irregularities, thickness of recast layer are observed increasing with increase in discharge current.
- Dielectric cracking also results in deposition of hard carbide layer at the bottom of the tool electrode. Formation of such carbide layer is detrimental since it promotes rapid tool wear hence adversely affecting tool shape retention capability as well as corner size machining accuracy.
- The predictive models for various technological parameters developed by RSM technique are found to be adequate, statistically significant and probabilistically valid because their higher R²-value (0.889 and 0.936, respectively for Ra and OC), model probability P-value under 0.05 and larger AD-test P-value (0.055 and 0.288, respectively for Ra and OC).
- The application of RSM’s desirability function analysis for multi-response optimization presented the optimal manufacturing conditions for electrical discharge machining of Al-SiC MMC at discharge current (DC) of 5.12 amp, gap voltage (GV) of 1.95V, pulse-on-time (TON) of 100 μs, pulse-off-time (TOFF) of 12.45 μs, and flushing pressure (FP) of 0.55 kgf/cm². The estimated optimum value of technological responses is 0.17032 μm for Ra, and 0.22412 mm in case of OC.

### Table 5. Overview of confirmatory test results.

| Optimum machining parameters | Surface roughness, Ra (μm) | Overcut, OC (mm) | Average error (%) |
|------------------------------|-----------------------------|------------------|-------------------|
| DC  | GV  | TON | TOFF | FP  | Predicted | Experimental | Predicted | Experimental |                  |
| 5   | 2   | 100 | 12.5 | 0.55 | 0.17032 | 0.182 | 0.2241 | 0.2374 | 5.8% |

### Table 6. Cost estimation in electrical discharge machining of Al-SiC MMC.

| Specific basic variables | In minutes | Costs | In Indian rupees |
|--------------------------|------------|-------|-----------------|
| Workpiece clamping and positioning time, T_{clamp} | 5 | Cost of each electrode, C_{elcd} | Rs.15 |
| Electrode positioning and zeroing time, T_{p} | 1 | Cost of machine working per minute, C_{mach/min} | Rs.8.33 |
| Electrode drawing out time, T_{edr} | 1 | Cost of machine operator per minute, C_{op/min} | Rs.5.83 |
| Single hole drilling time at optimum machining conditions, T_{d} | 11.5 | Total machining cost per component, C_{tot} \( \{ \left( C_{elcd} \right) + \left( T_{tot} C_{mach/min} \right) \} + \left( T_{clamp} + T_{edr} \right) T_{op/min} \) | Rs.211.08 |
| Total machining time per component, T_{tot} (T_{clamp} + T_{p} + T_{edr} + T_{d}) | 18.5 | | |

production rate as well as manufacturing cost. Considering the optimal cutting conditions suggested by RSM technique, cost analysis is used to perform detailed direct and indirect cost estimation in terms of total machining cost per part in electrical discharge machining process [52], as shown in Table 6. It is noticed that the total machining cost per part in electrical discharge machining is considerably lower around Rs.211.08 at optimum condition. It is interesting to note that the cost estimation of operational activities in EDM process ensures a dramatic gain in productivity and efficiency in finish machining. The cheapest solution to the total machining cost per part, longer tool life with minimized downtime calculations is obtained using brass as electrode material that justifies an economic solution to machining of Al-SiC MMC.

### 4 Conclusions

In the present experimental investigation, predictive modelling and multi-response optimization of EDM process is done for Al-SiC MMC with brass electrode by the combined approach of Box Behnken design (BBD) – analysis of variance (ANOVA), response surface methodology (RSM) and desirability function analysis (DFA) to analyze the surface roughness and overcut. Also, an economic analysis is performed to estimate the total machining cost per component during EDM of Al-SiC MMC. The following conclusions are obtained.

- The contribution of discharge current is found to be the most responsible factor for the degradation of surface quality as well as finish, and achieved the roughness (Rₐ) in the range of 0.172–0.781 μm.
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- The application of RSM’s desirability function analysis for multi-response optimization presented the optimal manufacturing conditions for electrical discharge machining of Al-SiC MMC at discharge current (DC) of 5.12 amp, gap voltage (GV) of 1.95V, pulse-on-time (TON) of 100 μs, pulse-off-time (TOFF) of 12.45 μs, and flushing pressure (FP) of 0.55 kgf/cm². The estimated optimum value of technological responses is 0.17032 μm for Ra, and 0.22412 mm in case of OC.
At optimal conditions (suggested by RSM technique), the estimated total machining cost per component of only Rs. 211.08 in Indian rupees, ensures benefit from economical point of view because of reduced machining time and machine downtime.

The proposed multiple techniques demonstrate an effective approach towards improvement in EDM process and it can be implemented in real-time process monitoring, predictive model control and optimization during machining of different workpiece materials as well as in other machining processes via. advances in computer technology.

In terms of future work, this study can be extended to analyze the influence of tool material as well as the type of dielectric fluids to improve the surface quality and reduced overcut. Further investigations can be carried out to assess the effects of EDM process parameters on tool wear rate (TWR) and material removal rate (MRR).

**Nomenclature**

| Symbol | Description |
|--------|-------------|
| $\phi$ | Diameter in mm |
| $R_d$ | Arithmetic average surface roughness in $\mu$m |
| $R^2$ | Coefficient of determination |
| $T_{clamp}$ | Workpiece clamping and positioning time in minute |
| $T_p$ | Electrode positioning and zeroing time in minute |
| $T_{edr}$ | Electrode drawing out time in minute |
| $T_d$ | Single hole drilling time at optimum machining conditions in minute |
| $T_{tot}$ | Total machining time per component in minute |
| $C_{ele}$ | Cost of each electrode in rupees |
| $C_{mach/min}$ | Cost of machine working per minute in rupees |
| $C_{op/min}$ | Cost of machine operator per minute in rupees |
| $C_{tot}$ | Total machining cost per component in rupees |
| EDM | Electrical discharge machining |
| Al-SiC | Aluminium-silicon carbide |
| MMC | Metal matrix composite |
| DC | Discharge current in ampere |
| GV | Gap voltage in volt. |
| $T_{ON}$ | Pulse-on-time in $\mu$s |
| $T_{OFF}$ | Pulse-off-time in $\mu$s |
| $FP$ | Flushing pressure in kgf/cm$^2$ |
| OC | Overcut in mm |
| BBD | Box-Behnken design |
| RSM | Response surface methodology |
| ANN | Artificial neural network |
| GA | Genetic algorithm |
| GRA | Grey relational analysis |
| ANOVA | Analysis of variance |
| SS | Sum of squares |
| MS | Mean of squares |
| SEM | Scanning electron microscope |
| PSO | Particle swarm optimization |

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Cite this article as: Subhashree Naik, Sudhansu Ranjan Das, Debabrata Dhupal, Analysis, predictive modelling and multi-response optimization in electrical discharge machining of Al-22%SiC metal matrix composite for minimization of surface roughness and hole overcut, Manufacturing Rev. 7, 20 (2020)