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PREDICTION OF SURFACE ROUGHNESS IN WIRE CUT ELECTRIC DISCHARGE MACHINING OF Al-Fe-Si ALLOY COMPOSITES USING TAGUCHI TECHNIQUE AND REGRESSION ANALYSIS

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Wire cut electric discharge machining (WCEDM) is a flexible and more essential for the precise machining of hard materials like composites and super alloys. In order to improve the surface texture as the main focus of the WCEDM process, the expansion of the fundamental procedural perceptive is very important. This paper mainly focuses on the prediction of surface quality of Al-Fe-Si alloy (AA8011) matrix composites during the WCEDM process. For the fabrication of composites, the varying proportions (0, 5, 10 and 15 wt.%) of ZrO_2 ceramic particle were incorporated with AA8011 matrix alloy by using stir casting method. In the machining studies, to investigate the effects of reinforcement (wt. %) and the WCEDM process parameters, namely pulse current (amps), pulse-on time (μs) and pulse-off time (μs) on machining performance like surface roughness (SR) of the proposed composites. Based on the selection of parameters and their levels, an L16 (4^4) orthogonal array was most suitable for conducting the WCEDM experiments.

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A Taguchi technique was employed in this study to determine the optimal conditions of machining parameters through the signal-to-noise (S/N) ratio analysis. The result shows that the minimum SR is achieved at 5 wt.% of reinforcement, 6 amps of pulse current, 110 μs of pulse-on time and 50 μs of pulse-off time, respectively. Analysis of variance (ANOVA) results revealed that the reinforcement wt.% has the primary significant factor on SR, trailed by pulse-on time and pulse current, respectively. Furthermore, the regression equation was also developed to predict the SR and that values well agree with the experimental SR.

Keywords: Al-Fe-Si alloy; ZrO_2; stir casting; WCEDM; surface roughness; Taguchi method; S/N ratio; ANOVA.

1. Introduction

Aluminum matrix composites (AMCs) are most widely acceptable material for replacing of iron and its alloys from various applications based on its enhanced properties. Notably, aluminum possesses light density thereby plummeting the component weight and henceforth can be taken as a most appropriate material in the field of aerospace, automotive and defense industries.[1,2] Machining of AMCs by traditional techniques is very difficult due to the direct contact between the tool and workpiece. By the dispersion of ceramic particulates (B_4C, Al_2O_3, TiC, TiO_2, ZrO_2, SiC, etc.) in AMCs, the strength is enhanced and hardness property causes rapid tool wear and poor surface finish, which have been encountered during the machining by the traditional methods.[3,4] Hence, there is a need of advanced machining techniques such as abrasive jet machining (AJM), electric discharge machining (EDM), electro-chemical machining (ECM) and laser beam machining (LBM).[5] Among them, WCEDM process is an extremely prominent metal cutting process due to its merits like most cost effective and flexibility. WCEDM is an electro-thermal process that can be extensively used to produce intricate or complex profiles of electrically conductive hard materials.[6] In WCEDM, metal removal takes place by a sequence of discrete electric spark producing between the workpiece and a wire which is act as an electrode. A dielectric fluid flow is continually supplied in the machining zone. Usually, the range from 0.025 to 0.05 mm gap is maintained between the workpiece and a wire electrode during machining. WCEDM's primary characteristics provide excellent surface finish and high precision with dimensional accuracy.[7,8] In order to obtain a better surface finish during WCEDM process, the effects of various factors had been studied by so many researchers. Tilekar *et al.*[9] studied the surface characteristics of aluminum and mild steel during machined in WCEDM process. They observed that the spark on time and current is considered as the primary remarkable factor on SR. Bobbili *et al.*[10] carried out the WCEDM process of AA7075 by using brass electrode and found that the utmost current and pulse on-time created more craters on the machined zone thus resulted in increased SR. Rozenek *et al.*[11] reported the influence of WEDM parameters, namely discharge current, pulse-on time, pulse-off time and voltage on the SR while machining of AlSi7Mg/SiC and AlSi7Mg/Al_2O_3 MMCs. They concluded that the SR mainly depends on the reinforcement addition. Li *et al.*[12] presented the surface integrity characteristics of Inconel 718 during WEDM process and they noticed that the SR can be significantly reduced when low discharge energy supplied. Harmesh Kumar *et al.*[13] investigated the effect of various factors on SR for the Al/SiC composite. Based on the ANOVA results, pulse-on time was the most decisive factor on SR, followed by pulse current and wire tension, respectively. Lenin *et al.*[14] determined the optimal conditions of WEDM parameters to obtain less SR for the fabricated LM25/fly ash/B_4C hybrid composites. ANOVA result reveals that the gap voltage, pulse-on time and reinforcement wt.% are the most influencing factors on machining performances. Pramanik[15] reported that pulse-on time and wire tension are the most important factors on SR and also he noticed that the shorter pulse-on time provides a better surface finish at lower wire tension. Likewise, the higher wire tension at longer pulse-on time creates a fine surface finish. Anand Sharma *et al.*[16] investigated the WEDM performance of Al6063 reinforced with 5 wt.% $ZrSiO_4$ composite fabricated through stir casting route. They stated that spark voltage has the most effective parameter on the SR, subsequently by pulse-on time, and also the machined surface characteristics were studied by using scanning electron microscopy (SEM). Ergun Ekici *et al.*[17] studied the influence of wire tension, reinforcement wt.%, wire speed, pulse-on time and pulse-off time on SR while WEDM of Al/B_4C composites. They reported that pulse-on time was the primary significant factor on SR that contributes 30.22%, trailed by pulse-off time that contributes 22.19%. Titus *et al.*[18] predicted the optimal settings of WEDM parameters on SR of Al/Sn/SiC composites using Taguchi method. They have noticed that dispersion of SiC wt.% has the main noteworthy factor on SR, trailed by pulse-on time with a contribution of 18.98%. Mustafa Ulas *et al.*[19] predicted the SR of Al7075 alloy during WEDM process and noticed that the low SR of 2.490 μm was obtained at 8 V of voltage, 8 μs of pulse-on time, 25 bar dielectric pressure and 2 mm/min wire feed, respectively. N. G. Patil[20] performed the WEDM experiments for obtaining good surface finish of the machined Al/Al_2O_3/22_p composites at different machining parameter combinations. The results found that the surface finish was affected by the dispersion of ceramic particles protruding on the machined surfaces. Raju *et al.*[21] studied the WCEDM behavior of Si_3N_4 reinforced AA7075 composites using Taguchi technique and they reported that pulse-on time was most noteworthy factor followed by the pulse current in achieving better MRR with good surface finish. Kumar *et al.*[22] presented the WCEDM process of Al-Mg-0.6Si-0.35Fe alloy composites incorporated with 15 wt.% RHA and 5 wt.% Cu as reinforcements. They observed that current has the most dominant factor for affecting the MRR and SR and also the SEM images of machined surface clearly depicts the improvement of surface quality by using the optimal parameters.

Based on the previous research work, it is necessary to determine the optimal conditions of process parameters in WCEDM for improving the surface texture. Hence, the aim of this investigation is to predict the surface quality in WCEDM of ZrO_2-reinforced AA8011 matrix composites fabricated through stir casting route. The WCEDM process of proposed composites was carried out as per L16 (4^4) orthogonal array by considering various input parameters. The optimal machining parameters to obtain the minimum SR were identified using Taguchi's S/N ratio analysis. Moreover, the significant effects of process parameters on SR were analyzed by employing ANOVA. Finally, the regression mathematical relations were formulated to get the predicted values of SR.

2. Experimental Details

2.1. *Matrix and reinforcement*

For the current investigation, Al-Fe-Si alloy (AA8011) was taken as matrix metal purchased from Metal Mart, Coimbatore, India. Table 1 shows the chemical elements of the aforementioned matrix alloy. In the AA8011, Iron (Fe) and silicon (Si) are considered one of the main elements since its presence leads to the enhancement of strength and hardness property. This alloy can be widely used in aerospace, automotive, marine and sports industries due to their unique properties such as weight to strength ratio, high stiffness, better wear resistance and low thermal expansion co-efficient.[24] Likewise, ZrO_2 particulate was taken as reinforcement with an average particle size of 10 μm have received from LOBA Chemie, Mumbai, India. The stir casting technique was employed to develop the AA8011 matrix composite by inclusion of varying weight fraction (0, 5, 10 and 15 wt.%) of ZrO_2 particle. Figure 1 illustrates the outline of this research work.

2.2. *Fabrication of AA8011-ZrO_2 composites*

Due to their merits like simplicity, cost effective and uniform distribution of reinforcements stir casting technique were chosen for this study.[24] In the

Table 1. Chemical elements of AA8011.

Elements	Fe	Si	Cu	Mn	Mg	Cr	Zn	Ti	Al
Weight (%)	0.6–1.0	0.5–0.9	0.10	0.20	0.05	0.05	0.10	0.08	Remaining

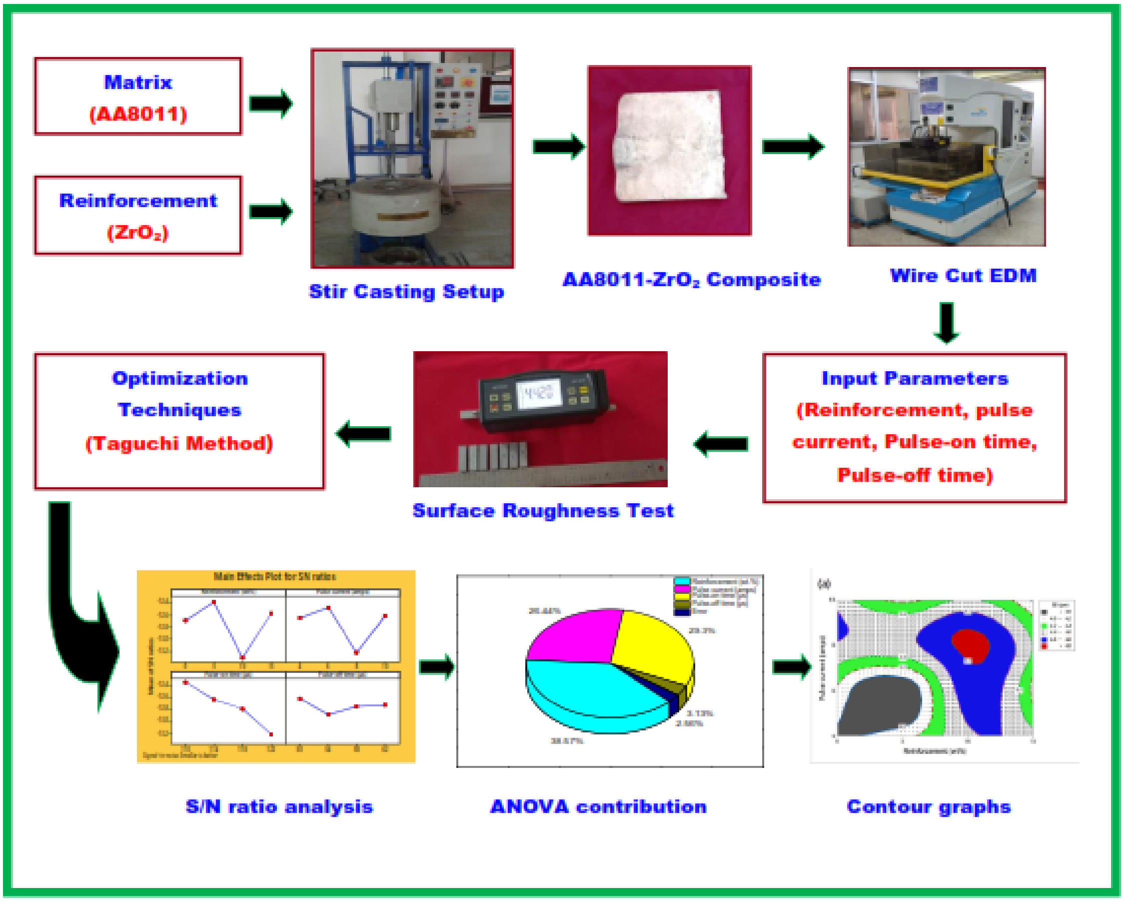

Fig. 1. (Color online) The layout of this research work.

beginning, the required quantity of AA8011 ingots was weighted and it was kept into a graphite crucible. The ingots were heated to 850°C for entire alloy was melted by using an electric furnace. Meanwhile, the selected weight percentages (5, 10 and 15 wt.%) of ZrO_2 particles were preheated at a temperature of 300°C for 1 h. After the melting of ingots, the preheated particles were constantly injected into the molten metal. For enhancing the uniform distribution of particles, the molten mixture was continuously stirred for 10 min at a speed of 300 rpm by using two-blade stainless steel stirrer.[23] Finally, the molten mixture was taken out from the furnace and then poured into the preheated metallic mold. Then, the composite slurry was permitted to solidify at normal room temperature. The same procedure is followed to fabricate the various wt.% of ZrO_2 particles-reinforced AA8011 matrix composites.

2.3. *WCEDM process of AA8011-ZrO_2 composites*

The machining of developed composites (AA8011-ZrO_2) was performed on ECOCUT wire cut EDM machine. The specifications of machining parameters are provided in Table 2. The size of workpiece is 100 mm (length) × 100 mm (breadth) × 10 mm

Table 2. Specification of WCEDM process.

Machine tool parameters	Specifications
Workpiece	AA8011-ZrO_2 (0, 5, 10 and 15 wt.%) composites
Electrode	Brass wire (0.25 mm diameter)
Polarity	Workpiece (+), Tool (−)
Dielectric fluid	De-ionized water
Pulse current	4, 6, 8 and 10 amps
Pulse-on time	110, 114, 118 and 122 μs
Pulse-off time	50, 54, 58 and 62 μs

Table 3. Experimental layout of L16 (4^4) orthogonal array.

Ex. no.	Reinforcement (wt.%)	Pulse current (amps)	Pulse-on time (μs)	Pulse-off time (μs)	SR (μm)	S/N ratio (dB)
1	0	4	110	50	3.972	−11.9802
2	0	6	114	54	4.164	−12.3902
3	0	8	118	58	4.580	−13.2173
4	0	10	122	62	4.549	−13.1583
5	5	4	114	58	4.136	−12.3316
6	5	6	110	62	3.833	−11.6708
7	5	8	122	50	4.549	−13.1583
8	5	10	118	54	4.156	−12.3735
9	10	4	118	62	4.562	−13.1831
10	10	6	122	58	4.709	−13.4586
11	10	8	110	54	4.844	−13.7041
12	10	10	114	50	4.428	−12.9242
13	15	4	122	54	4.504	−13.072
14	15	6	118	50	4.154	−12.3693
15	15	8	114	62	4.395	−12.8592
16	15	10	110	58	3.974	−11.9846

(thickness), and it was connected to the positive terminal. A brass wire having 0.25 mm diameter was chosen as the cutting tool and it was connected to the negative terminal. During machining, de-ionized water was used as a dielectric medium and it was maintained at a temperature of 20°C. In WCEDM process, there are so many variables that had affected the surface texture while machining of composite materials as well as hard materials. Based on the literature works,[25,26] we had chosen four parameters such as reinforcement wt.%, pulse current, pulse-on time and pulse-off time and its levels are depicted in Table 2. The experiments were executed as per L16 (4^4) orthogonal array and are illustrated in Table 3. After the machining, the Mextech SRT-6200 digital portable surface roughness tester was used to measure the SR at three locations on the machined surfaces and the average values are considered.

2.4. *Optimization technique — Taguchi method*

This study employed Taguchi technique as a reliable statistical methodology, which is used to determine the least number of experiments to be carried out within the permissible range of parameters and levels. The main objective of the method is to develop high-quality product at minimum cost.[27] This method uses special orthogonal array designs, it can be selected based on the number of factors and levels involved. During the Taguchi method, three mathematical relations (S/N ratio) can be applied to predict the response such as larger the better, nominal the best and smaller the better, respectively.[28] Here, the aim of this study is to predict the low SR while WCEDM process of AA8011-ZrO_2 composites. Hence, the smaller, the better the S/N ratio relation is used and the equation is given as follows:

$$\text{S/N ratio} = -10\log_{10}(1/n)\sum_{k=1}^{n} {Y_{ij}}^2, \tag{1}$$

where n is the number of trials, Y_{ij} is the response, where $i = 1, 2, 3,\ldots,n$; $j = 1, 2, 3,\ldots,k$. The raw data and their computed S/N ratio are presented in Table 3.

3. Results and Discussion

3.1. *S/N ratio and mean of SR*

Figures 2 and 3 show the S/N ratio and mean graphs for SR indicating the effect of various levels of the WCEDM parameters. From the graphs, it can clearly be noted that the different levels of the parameters are represented in x-axis, while y-axis indicates the computed S/N ratio (dB) and the mean value of SR. Notably, the peak value of S/N ratio is identified as the primary impact factor on response. As it is seen from the graphs (Figs. 2 and 3), it exactly understood that the reinforcement wt.% had the deciding factor on SR of the developed composite materials. Higher amount of ZrO_2 addition enhances the hardness property of the AA8011 matrix composites. Hence, those composites produce rough surface during machining. However, in this case, 5 wt.% ZrO_2 inclusion of AA8011 matrix composite gives low SR due to their less hardness obtained. The similar observations were reported by Ekici *et al.*[17] during WEDM of Al/B_4C composites. They stated that the SR increased with an increase in the weight.% of reinforcement particles in the composites. By considering pulse current, initially SR decreases at 6 amps, then slightly increases with an increase in current at 8 amps. Thereafter, SR value gradually decreases at 10 amps pulse current. Pulse current is one of the main sources of WCEDM process because

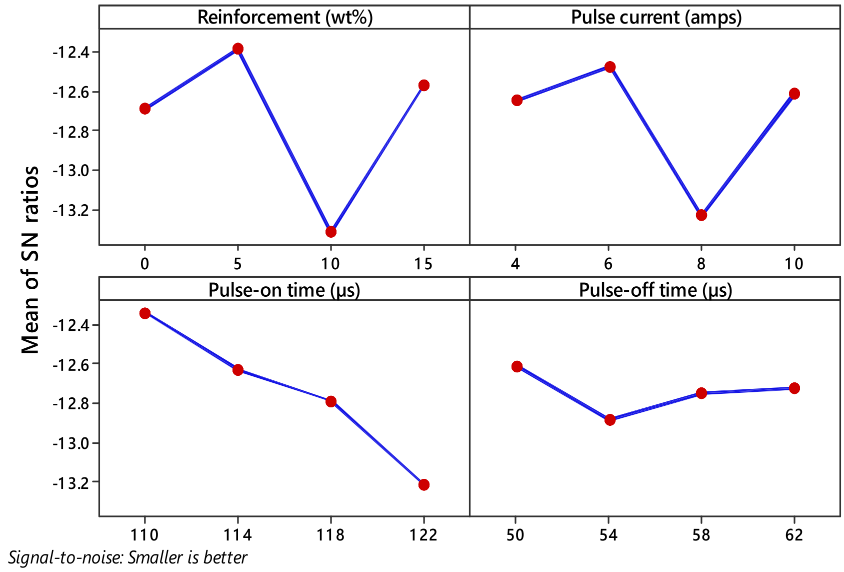

Fig. 2. (Color online) Main effect plot for S/N ratios of SR.

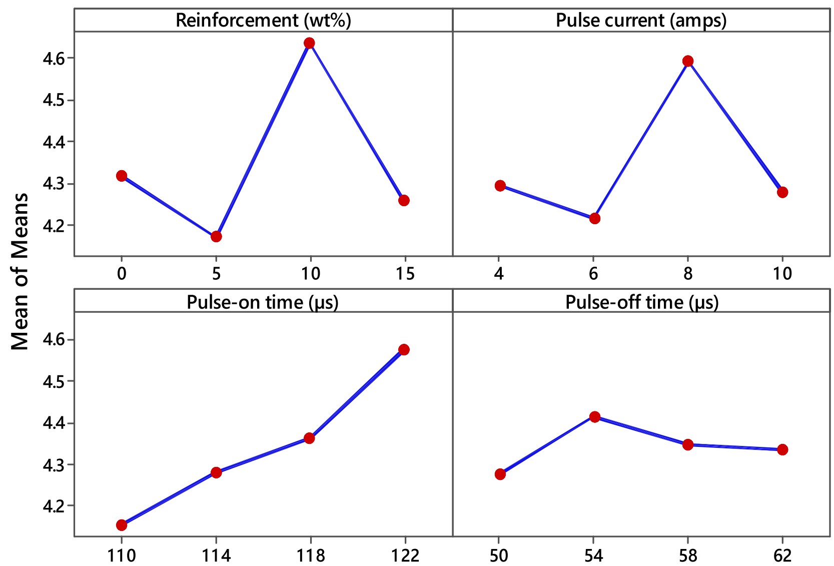

Fig. 3. (Color online) Main effect plot for means of SR.

the required amount of heat is generated depending upon it. A high discharge energy will create ripple surface, thus resulting in cracks and residual stresses on the machined surface. An increase in pulse-on time increases the SR since more spark energy is produced in the machined region. The minimum SR is achieved at 110 μs of pulse-on time. At the initial level of pulse-off time (50 μs), a low SR of the composites is obtained, further increase in pulse-off time faintly improves the SR.

Tables 4 and 5 provide the S/N ratio and mean value for SR with respect to each level of WCEDM parameters. From the tables, it can clearly be noticed that the rank of the significant factors is determined. Notably, the rank is assigned based on the delta value. Delta value is determined by the maximum value minus minimum value of S/N ratio

Table 4. Response table for S/N ratio of SR.

Level	Reinforcement (wt.%)	Pulse current (amps)	Pulse-on time (μs)	Pulse-off time (μs)
1	–12.69	–12.64	–12.33	–12.61
2	–12.38	–12.47	–12.63	–12.88
3	–13.32	–13.23	–12.79	–12.75
4	–12.57	–12.61	–13.21	–12.72
Delta	0.93	0.76	0.88	0.28
Rank	1	3	2	4

Table 5. Response table for mean of SR.

Level	Reinforcement (wt.%)	Pulse current (amps)	Pulse-on time (μs)	Pulse-off time (μs)
1	4.316	4.293	4.156	4.276
2	4.168	4.215	4.281	4.417
3	4.636	4.592	4.363	4.350
4	4.257	4.277	4.578	4.335
Delta	0.467	0.377	0.422	0.141
Rank	1	3	2	4

and mean for each level of the parameter. As per the results (Tables 4 and 5), it has been observed that the reinforcement wt.% is the most remarkable factor on SR. Since the incorporation of the hard ceramic (ZrO_2) particulate content improved the surface hardness of the fabricated composites, it resulted in an increase the SR during machining. Likewise, the pulse-on time and pulse current also indicate that the more influencing factors on SR. Pulse-off time is considered as the least significant factor on SR. Typically, the larger value of the S/N ratio for each parameter is represented as the optimum level. According to the S/N ratio result, reinforcement wt.% at level 2 (5 wt.%), pulse current at level 2 (6 amps), pulse-on time at level 1 (110 μs), and pulse-off time at level 1 (50 μs) were identified as the optimum level for obtaining the minimum SR of the produced AA8011-ZrO_2 composites.

3.2. *ANOVA*

To determine the effects of WCEDM process parameters such as reinforcement wt.%, pulse current, pulse-on time and pulse-off time on SR of the machined composites, ANOVA was applied in this study. ANOVA is a compilation of analysis tool used to find out the statistical influence that independent variables have on the dependent variables.[29] The result of ANOVA for SR is depicted in Table 6. From the table, the F-value and P-value at 95% confidence level are used to ensure the order of effects of parameters on SR. Based on the ANOVA results (Table 6), it can be found that the F-value of reinforcement wt.% (15.06), pulse-on time (11.44) and pulse current (10.32) were greater than the tabulated F-value ($F_{0.05,(3,15)} = 3.29$), then the factors are significant. Similarly, the P-values of reinforcement wt.% (0.026), pulse-on time (0.038) and pulse current (0.043) were less than 0.05, which lso ensure that these factors have a statistical influence on SR. Moreover, the predicted R^2 value 97.44% well agrees with the Adjusted R^2 value 87.20%. Figure 4 illustrates the graphical chart for the percentage of contribution of each parameter on SR. It obviously

Table 6. ANOVA for SR.

Source	DoF	Seq.SS	Adj.SS	Adj.MS	F	P
Reinforcement	3	0.49720	0.49720	0.16573	15.06	0.026
Pulse current	3	0.34087	0.34087	0.11362	10.32	0.043
Pulse-on time	3	0.37775	0.37775	0.12592	11.44	0.038
Pulse-off time	3	0.04042	0.04042	0.01347	1.22	0.436
Error	3	0.03302	0.03302	0.01101	—	—
Total	15	1.28926	—	—	—	—
$S = 0.104908$; R-Sq = 97.44%; R-Sq(adj) = 87.20%						

DoF-degrees of freedom; Seq. SS-Sequential sum of square; Adj.SS-adjusted sum of square; Adj.MS-adjusted mean square, F-Fisher ratio, P-probability value.

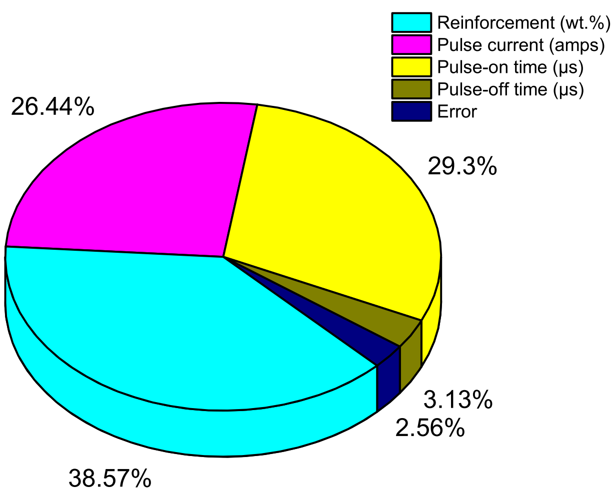

Fig. 4. (Color online) Contribution of parameters on SR.

shows that the contribution of reinforcement wt.% is 38.57%, which is the primary dominant factor, trailed by pulse-on time (29.3%) and pulse current (26.44%), respectively. The pulse-off time was considered as the insignificant factor with contribution, which is only 3.13%. The similar observations were reported by Ramraji *et al.*[26] while machining of AA6061-TiB_2 alloy in WCEDM. They concluded that the wt.% of reinforcement is identified as the most dominant factor in surface quality with a contribution of 62.04%.

3.3. *Interaction effect of parameters on SR*

The contour graphs of SR with respect to WCEDM process parameters are shown in Figs. 5(a)–5(f). From the graphs, the effect of parameters interaction on SR of the developed composite specimens during machining process can be understood. Figure 5(a) reveals the interaction of reinforcement wt.% and pulse current on SR. It was shown that the low SR (<4.0 μm) can be made at 4 amps of pulse current with 5 wt.% ZrO_2 -reinforced Al matrix composite.

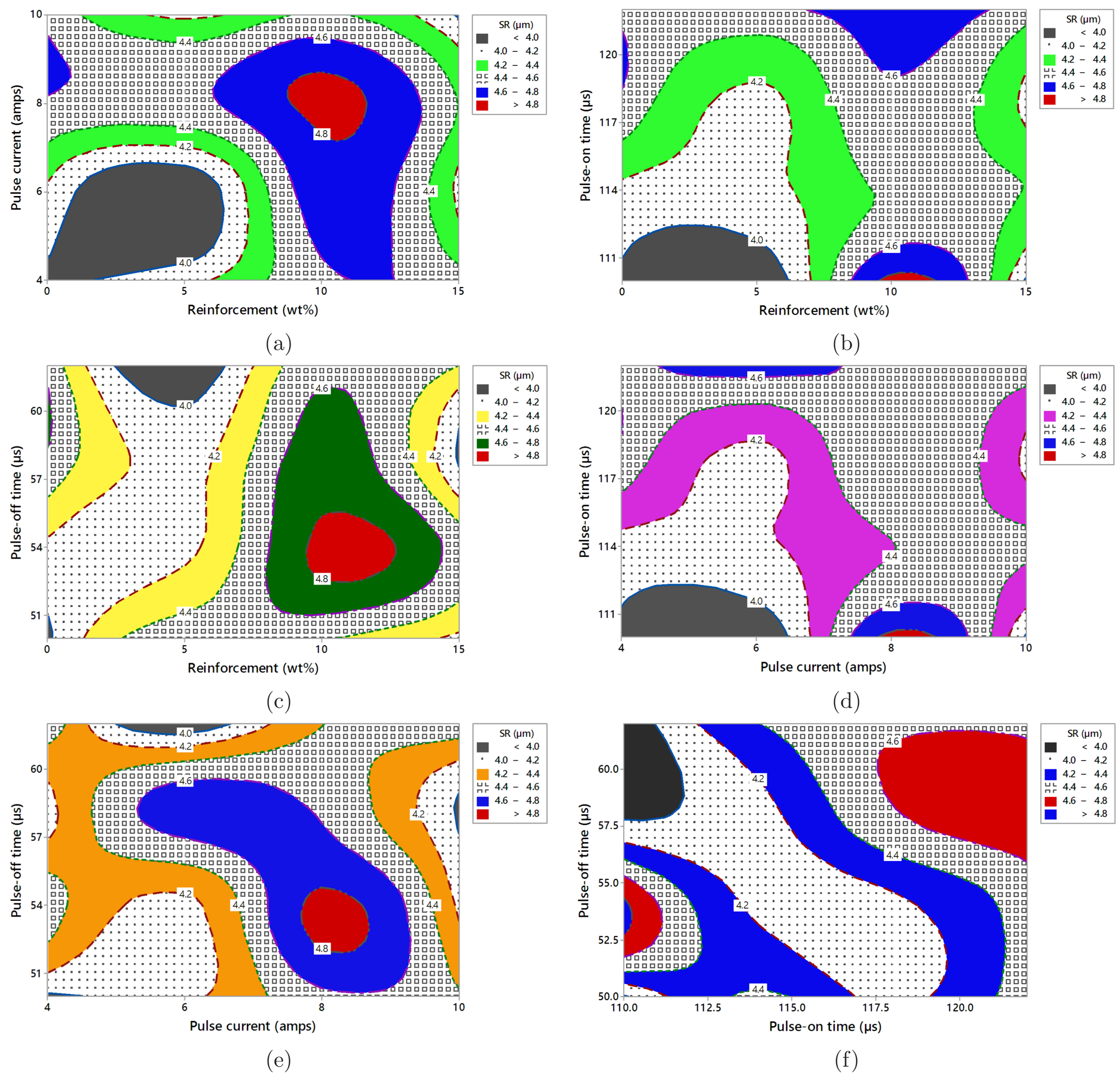

Fig. 5. (Color online) Contour plot of SR (a) reinforcement vs. pulse current, (b) reinforcement vs. pulse-on time, (c) reinforcement vs. pulse-off time, (d) pulse current vs. pulse-on time, (e) pulse current vs. pulse-off time, and (f) pulse-on time vs. pulse-off time.

However, an increase in pulse current increases the SR due to generation of more heat energy at machined region, thus producing more craters on machined surfaces. It also has been noticed that the high SR (4.8 μm) is formed in 10 wt.% inclusion of ZrO_2 composite specimen at 6 amps current. The reason for that is the addition of ceramic (ZrO_2) particulates into the soft matrix alloy enhances the hard surface of the fabricated composites. In Fig. 5(b), we explore the obtained SR with the interaction of reinforcement with.% and pulse-on time. It was clearly observed that 110 μs of pulse-on time with 5 wt.% of reinforced composite specimen provides low SR. Moreover, the average value of SR (4.2–4.4 μm) is achieved at 120 μs of pulse-on time. At the same time, the higher pulse-on time gives more SR (4.6–4.8 μm), while machining of 10 wt.% ZrO_2 filled composite specimen. Figure 5(c) displays the interaction effect of reinforcement (wt.%) and pulse-off time. From the plot, it exactly shows that the pulse-off time was insignificant factor, hence it doesn't affect the SR more. Therefore, an increase in pulse-off time decreases the SR. By addition of 10 wt.% ZrO_2 composite, SR is maximum at 52 μs of pulse-off time. The influence of pulse current with pulse-on time on SR is shown in Fig. 5(d). It has been observed that the SR gradually improved when an increase in pulse-on time. The higher SR (4.6–4.8 μm) was obtained at 6 amps of pulse current with 120 μs of pulse-on time. Furthermore, the moderate SR (4.2–4.4 μm) was found at 118 μs of pulse-on time and 10 amps of pulse current. Figure 5(e) illustrates the SR with respect to pulse current and pulse-off time. It reveals that the SR decreases with an increase in pulse-off time at 6 amps pulse current but an increase in pulse current slightly improved the SR. The maximum SR (4.8 μm) is attained at 8 amps pulse current with low level of pulse-off time (50 μs). As is seen from Fig. 5(f), it can be revealed that the high SR is observed when pulse-on time and pulse-off time are maximum, but the maximum pulse-off time with minimum pulse-on time produced low SR (4.2 μm).

3.4. *Estimation of predicted SR*

To verify the optimal levels of machining parameters, confidence interval (CI) of predicted value of the SR has been computed. The 95% CI for the confirmation experiments (CI_{CE}) and the mean of population (CI_{POP}) were established by using the following mathematical equations:[30]

$$\mathrm{CI}_{\mathrm{POP}} = \sqrt{\frac{F_\alpha(1, f_e)V_e}{\eta_{\mathrm{eff}}}}, \tag{2}$$

$$\mathrm{CI}_{\mathrm{CE}} = \sqrt{F_\alpha(1, f_e)V_e\left[\frac{1}{\eta_{\mathrm{eff}}} + \frac{1}{R}\right]}, \tag{3}$$

where $F\alpha$ (1, f_e) is the F-ratio at 95% CI, f_e is error DoF, V_e is error variance, η_{eff} is the effective no. of replications, R is the count of replications required for confirmation trials and N is the total experimental trials.

$$\eta_{\mathrm{eff}} = \frac{N}{1 + \text{DoF associated in the estimate of mean response}},$$

where
$N = 16 \times 1 = 16$ (treatment = 16, repetitions = 1),
$f_e = 15 - 12 = 3$ (refer Table 5) and $V_e = 0.01101$ (refer Table 5),
$F_{0.05}$, (1,2) = 10.13 (Tabulated F-value),
$\eta_{\mathrm{eff}} = 1.23$,
So, $CI_{POP} = \pm 0.30112$ and $CI_{CE} = \pm 0.60547$.

The predicted mean value of SR (μ_{SR}) was determined at the certain optimal conditions of machining parameters as stated above viz. reinforcement wt.% at level 2, pulse current at level 2, pulse-on time at level 1 and pulse-off time at level 1, respectively. The predicted SR (μ_{SR}) was computed from the following equations:

$$\mu_{\mathrm{SR}} = A_2 + B_2 + C_1 + D_1 - 3T_{\mathrm{SR}} = 3.782\,\mu\mathrm{m}, \tag{4}$$

where T_{SR} = overall mean of SR = 4.344 μm.

The 95% CI for the mean of population of SR is given by

$$(\mu_{\mathrm{SR}} - \mathrm{CI}_{\mathrm{POP}}) < \mu_{\mathrm{SR}} < (\mu_{\mathrm{SR}} + \mathrm{CI}_{\mathrm{POP}})(3.782 - 0.30112) < 3.782\,\mu\mathrm{m}) < (3.782 + 0.30112)$$
$$\mathrm{CI}_{\mathrm{POP}} : (3.480) < 3.782\,\mu\mathrm{m} < (4.083)$$

The predicted value of SR at 95% CI for confirmation experiment is given by

$$(\mu_{\mathrm{SR}} - \mathrm{CI}_{\mathrm{CE}}) < \mu_{\mathrm{SR}} < (\mu_{\mathrm{SR}} + \mathrm{CI}_{\mathrm{CE}})(3.782 - 0.60547) < 3.782\,\mu\mathrm{m}) < (3.782 + 0.60547)$$
$$\mathrm{CI}_{\mathrm{CE}} : (3.176) < 3.782\,\mu\mathrm{m} < (4.387).$$

3.5. *Development of regression model*

To estimate the correlations between the machining parameters and the output response, the regression mathematical equation for the response was formulated.[31] The regression analysis was employed to ensure the validity of the formulated mathematical model. By using MINITAB 18 software, the regression equation was created to predict the response like SR. Equation (5) can be directly used to predict the SR values in advance within the given range of machining parameters. Figure 6 and Table 7 show the comparison of predicted SR with experimental values of SR.

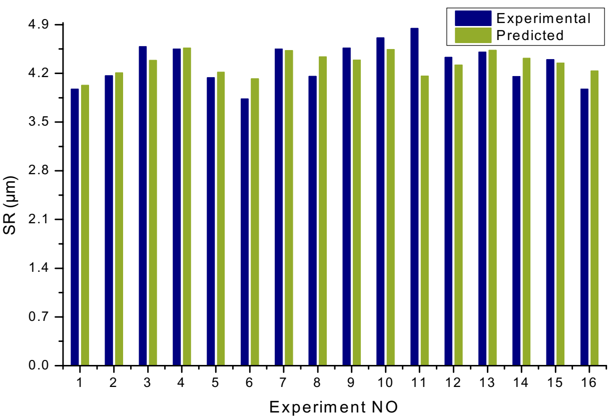

Fig. 6. (Color online) Comparable results of SR.

Table 7. Comparison table of SR.

Run. no.	Experimental SR (μm)	Predicted SR (μm)	Error (%)
1	3.972	4.027	−1.390
2	4.164	4.205	−0.994
3	4.58	4.384	4.288
4	4.549	4.562	−0.281
5	4.136	4.213	−1.852
6	3.833	4.121	−7.519
7	4.549	4.526	0.510
8	4.156	4.434	−6.699
9	4.562	4.387	3.832
10	4.709	4.544	3.508
11	4.844	4.161	14.096
12	4.428	4.318	2.489
13	4.504	4.529	−0.564
14	4.154	4.416	−6.317
15	4.395	4.347	1.101
16	3.974	4.234	−6.532

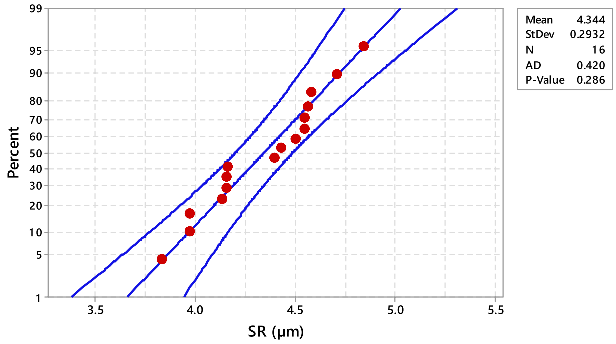

Fig. 7. (Color online) Normal probability plot of SR.

The regression equation for SR as evolved after machining is

$$\begin{aligned}\text{SR } (\mu\text{m}) = &+0.12 + 0.0058 \text{ Reinforcement (wt\%)}\\ &+ 0.0163 \text{ Pulse current (amps)}\\ &+ 0.0337 \text{ Pulse-on time } (\mu\text{s})\\ &+ 0.0027 \text{ Pulse-off time } (\mu\text{s}).\end{aligned} \quad (5)$$

Moreover, the normality assumptions are verified, if the projection of residuals is placed along a straight line. The probability plot of SR is shown in Fig. 7. It reveals that the residuals for SR lie apparently near to a straight line indicating that the errors are normally distributed, and the predicted SR values bear good agreement with the experimental SR.

4. Conclusions

This research work was investigated on the surface quality of fabricated Al-Fe-Si alloy filled with ZrO_2 composites during wire cut electric discharge machining (WCEDM) process. The following vital observations were drawn from this study:

- Stir casting method was successfully employed to fabricated the varying weight proportions (0, 5, 10 and 15 wt.%) of ZrO_2 particles reinforced AA8011 matrix composites.
- WEDM process was carried out as per L16 orthogonal array layout by choosing different process parameters, namely, reinforcement (wt.%), pulse current (amps), pulse-on time (μs) and pulse-off time (μs), respectively. The experimental result like surface roughness (SR) was recorded for each trial and statistically analyzed by using S/N ratio and ANOVA.
- From the S/N ratio results, it has been exactly noticed that the minimum SR is obtained at the

optimal conditions of WCEDM parameters are reinforcement at level 2 (5 wt.%), pulse current at level 2 (6 amps), pulse-on time at level 1 (110 μs) and pulse-off time at level 1 (50 μs), respectively.

- ANOVA results proved that the inclusion of reinforcement wt.% has the most remarkable parameter for affecting the SR of fabricated composites during the WCEDM process with a contribution of 38.57%, followed by a pulse-on time and pulse current with contributions are 29.3% and 26.44%, respectively. Likewise, pulse-off time was insignificant parameter with contribution, which is only 3.13%.
- Furthermore, the regression mathematical relations were developed to predict the SR values and these values are well agreed with the experimental results. Finally, the confirmation experiments were performed to verify the optimal conditions of WCEDM parameters.

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References

1. S. V. Alagarsamy and M. Ravichandran, *Mater. Res. Express* **6** (2019) 1.
2. A. Kumar, N. Grover and A. Manna, *Adv. Compos. Lett.* **29** (2020) 1.
3. S. V. Alagarsamy, M. Ravichandran and H. Saravanan, *J. Adv. Manuf. Syst.* **20** (2021) 1.
4. K. H. Ho and S. T. Newman, *Int. J. Mach. Tools. Manuf.* **43** (2003) 1287.
5. A. S. Gore and N. G. Patil, *Procedia Manuf.* **20** (2018) 41.
6. S. V. Alagarsamy *et al.*, *Mater. Today Proc.* **27** (2020) 853.
7. Y. S. Liao, J. T. Huang and Y. H. Chen, *J. Mater. Process. Technol.* **149** (2004) 165.
8. I. Maher, A. A. D. Sarhan and M. Hamdi, *Int. J. Adv. Manuf. Technol.* **76** (2015) 329.
9. S. Tilekar, S. S. Das and P. K. Patowari, *Procedia Mater. Sci.* **5** (2014) 2577.
10. R. Bobbili, V. Madhu and A. K. Gogia, *Eng. Sci. Technol.* **18** (2015) 720.
11. M. Rozenek, J. Kozak, L. Daibrowski and K. Ebkowski, *J. Mater. Process. Technol.* **109** (2001) 367.
12. L. Li, Y. B. Guo, X. T. Wei and W. Li, *Procedia CIRP* **6** (2013) 220.
13. H. Kumar, A. Manna and R. Kumar, *Trans. Indian Inst. Met.* **71** (2018) 231.
14. N. Lenin *et al.*, *Metals* **119** (2021) 1.
15. A. Pramanik, *Mater. Manuf. Process.* **31** (2016) 397.
16. A. Sharma, M. P. Garg, K. K. Goyal and A. Kumar, *Int. J. Mach. Mach. Mater.* **18** (2016) 1.
17. E. Ekici, A. R. Motorcu and A. Kus, *J. Compos. Mater.* **50** (2016) 2575.
18. T. Titus *et al.*, *Appl. Surf. Sci.* **472** (2019) 22.
19. M. Ulas, O. Aydur, T. Gurgenc and C. Ozel, *J. Mater. Res. Technol.* **9** (2020) 12512.
20. N. G. Patil, *Aust. J. Mech. Eng.* **21** (2023) 1259, doi: 10.1080/14484846.2021.1977454.
21. K. Raju *et al.*, *Adv. Mater. Sci. Eng.* **4438419** (2022) 1.
22. J. Kumar, S. Sharma, J. Singh, S. Singh and G. Singh, *J. Manuf. Mater. Process.* **6** (2022) 1.
23. B. Vinoth, S. V. Alagarsamy, M. Meignanamoorthy and M. Ravichandran, *Proc. Inst. Mech. Eng. E J. Process Mech. Eng.* **236** (2022) 2420.
24. P. Raveendran, S. V. Alagarsamy, M. Ravichandran and M. Meignanamoorthy, *Surf. Rev. Lett.* **28** (2021) 1.
25. S. Ozan and L. Feray Guleryuz, *AIP. Conf. Proc.* **1476** (2012) 317.
26. K. Ramraji, K. Rajkumar, G. Selvakumar and S. Ram Prakash, *Surf. Topogr. Metrol. Prop.* **9** (2021) 1.
27. S. V. Alagarsamy and M. Ravichandran, *Mater. Test.* **63** (2021) 182.
28. M. Vinoth Kumar *et al.*, *Mater. Today Proc.* **27** (2020) 1163.
29. P. Raveendran *et al.*, *Surf. Topogr. Metrol. Prop.* **9** (2021) 1.
30. S. V. Alagarsamy and M. Ravichandran, *Mater. Res. Express* **7** (2020) 1.
31. V. K. Pasam, S. B. Battula, P. Madar Valli and M. Swapna, *J. Braz. Soc. Mech. Sci. Eng.* **32** (2010) 107.