Research Article

Optimization of WEDM process parameters by RSM in machining of stir cum squeeze cast A413–B₄C composites

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Abstract

In this paper, aluminium alloy metal matrix composites were manufactured via stir cum squeeze casting technique owing to their tremendous automotive and aviation applications. The aluminium alloy with 12 weight percentage boron carbide (A413 with 12 wt% B₄C) composites was prepared with optimal stir cum squeeze casting parameters like applied squeeze pressure of 140 MPa, 225 °C preheated die temperature and 12 wt% of B₄C particles which yielded pore-free fine-grained equally distributed ceramic particles of the composite, leading to an enhanced higher hardness of 136 VHN and higher tensile value of 373 MPa due to squeezing pressure and B₄C particles. The prime intern of the wire electrical discharge machining process was adopted for investigating the machinability of stir cum squeeze cast high-strength A413 with 12 wt% B₄C composite. The stratagem of response surface methodology along through central composite rotatable design was taken towards systematic design of experiments. The experimental study results exhibited a possibility of higher amount of metal removal rate for maximum pulse on-time and peak current values, and also better surface roughness was acquired for higher values of pulse off time. The mathematical model shows excellent prediction in accordance with experimental data which seems to fall inside the bounds of acceptable average error around 6.47% and 1.52% for metal removal rate and surface roughness through additivity tests, respectively. The proposed multi-response optimization results revealed a great potential for improving machined surface quality which could be utilized according to the industrial requirements.

Keywords Stir cum squeeze cast composites · WEDM · Process parameter · Optimization · RSM

List of symbols

MMCs	Metal matrix composites	EDM	Spark electric discharge machining
B ₄ C	Boron carbide	WEDM	Wire electric discharge machining
SiC	Silicon carbide	A/Al	Aluminium
TiC	Titanium carbide	AA	Aluminium alloy
Al ₄ C ₃	Aluminium carbide	wt%	Weight percentage
Al ₂ O ₃	Aluminium oxide	Ton	Pulse on-time
SiO ₂	Silicon dioxide	Toff	Pulse off-time
TiB ₂	Titanium diboride	IP	Peak current
C ₂ Cl ₆	Hexachloroethane	MRR	Metal removal rate
K ₂ TiF ₆	Potassium hexafluorotitanate	SR	Surface roughness
°C	Degree celsius	ASTM	American Society for Testing and Materials
		SEM	Scanning electron microscopy

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DOE	Design of experiments
RSM	Response surface methodology
CCRD	Central composite rotatable design
ANOVA	Analysis of variance
VHN	Vickers hardness number
MPa	Megapascal
mho	Reciprocal of ohm
V	Voltage
Kg/cm ²	Kilogram per square centimetre
DC	Direct current
mm ³ /min	Millimetre cube per minute
µm	Micro-meter

1 Introduction

The physical, mechanical and tribological behaviour of ceramic particle-reinforced MMCs is better than their parent metals. MMCs show the combinational benefits of both the matrix and reinforcements [1]. Among the accessible MMCs, the ideal alternative is aluminium-based MMCs on account of their intrinsic properties like lightweight, higher strength and stiffness, better thermal conductivity, low thermal expansion, poor electrical conductivity, and low wear resistance [2]. Non-oxide ceramics like borides, nitrides, carbides and silicides are significant engineering materials in contrast with oxides offering improved refractoriness, higher strength and stiffness and enhanced thermal shock resistance at higher temperatures. These hard ceramic materials in particulate form are synthesized with aluminium parental matrix to form the metal matrix composites. These hard particles are in standard dissemination towards matrix which improves massive characteristics of the metal matrix composites [3]. Common ceramic particulates used to reinforce aluminium matrix alloys are B₄C, SiC, TiC, Al₄C₃, Al₂O₃, SiO₂, and TiB₂. Among these reinforced particulates, B₄C ceramic particulate reinforcements possess low density, high temperature withstand ability, high strength and more wear resistance; hence, it is often chosen. Literature reports have revealed that various fabricating procedures are viable when reinforced by B₄C particles in aluminium matrix, and the boron carbide particulate reinforcement in aluminium alloys is suitable for high-temperature applications due to its rudimentary properties [4]. Wettability of ceramic particles in the molten aluminium metal can be upgraded by the adoption of K₂TiF₆ halide salt for the duration of casting for enhanced bonding among aluminium alloy and B₄C particles and thus obtaining improved metallurgical and mechanical behaviour of the prepared composites [5].

The MMCs are prepared using different fabrication techniques. Among them, liquid-state method is more viable

and economical one. The primary factor which affects the behaviour of the composites in the liquid-state processing route (stir casting) is stirring speed, and, on the other hand, the stirring time also deliberates some effect on percentage of reinforcement addition in the matrix [6]. Among available modern liquid casting techniques, the squeeze casting gives quality surface finish with very little operating costs and excludes the micro-porosity defects making it the most effective manufacturing process to manufacture components with high precision and with enhanced properties than gravity die casting or pressure die casting [7]. The bonding, diffusion, and scattering of reinforcement elements inside the matrix play significant role in metal matrix composites casting while attaining preferred properties. High pressure is applied during the squeeze casting process leading to enhancement of bonding of reinforcement particles in molten metal and obtaining pore-free dense casting within a very short span of time [8]. In squeeze casting, the applied squeeze pressure and a nominal weight percentage of particles within the matrix provide porosity-free uniform distribution with closely bonded particles and fine grain dendritic structures, leading to enhanced strength of the composites [9].

Machining is the most important phase in manufacturing. The parts are manufactured by casting; forming and other shaping processes often require post- or secondary-processing operations before the product is ready for real-time applications. MMCs are difficult for conventional machining due to their extreme abrasive properties [10]. A few literature reports revealed that the conventional machining is impractical for machining MMCs due to their considerable requirement of power, poor machinability and surface profile, high tooling costs, serious wear of the cutting tool, and producing complex shapes becomes more tedious [11]. The major non-conventional machining methods of spark EDM followed by WEDM and magnetic field-assisted WEDM are relatively thriving for removing materials of superalloys or composites with higher surface integrity [12]. WEDM suits best for machining aluminium matrix composites since it is being used to machine the intricate and complex components for aerospace and automotive industries. Many researchers investigated on WEDM for various alloys, and MMCs are being produced through stirred gravity casting technique [13]. During machining of the stir casted specimens like AlSi7Mg with 20 wt% SiC and A413 with 9 wt% B₄C having a higher percentage of reinforcement composites, craters occur on the machined surface due to influenced WEDM process parameters of high discharge energy, voltage and pulse on time passing through it. Further, the recast layers are composed of a higher percentage of ceramic particles protruding on the surfaces leading to an uneven machining surface [14, 15]. WEDM is suitable for cutting AA6351

with 5 wt% SiC and 5 wt% B₄C hybrid metal matrix composites which shows having more pores on the machined region [16]. Al 7075 alloy reinforced with 1.5 wt% B₄C and 1.5 wt% fly ash nanoparticles hybrid composites was being considered for machining through EDM process. The surface characteristics observations revealed that high input energy melts more sufficient material with greater crater generating coarser surface texture [17]. A new combination of fabricated hybrid metal matrix composite of A359 with 2.5 wt% B₄C and 2.5 wt% Al₂O₃ is being made up in-house by electromagnetic stir casting. The machined surface had many peaks and valleys with moderate of flaws such as surface porosity [18]. Machinability study of composites is prepared using WEDM route, and after machining of AA2024 with 2.5 wt% ZrB₂ composite, it showed better surface roughness value than higher weight percentage addition of reinforcement particles in the matrix [19]. The machined surface integrity/quality directly depends on reinforcement addition, composites preparation method, and WEDM influenced process parameters like Ton, Toff, IP, etc. Similarly, the presence of higher weight percentage addition of particles in matrix results in higher hardness and strength. The machinability of these composites directly influences the WEDM process parameters [20, 21]. Experimentation has been done on stir cast A413 with 9 wt% of B₄C reinforcement which is then processed by micro-EDM to investigate the output for various input process variables such as the rate of feed on MRR, voltage, capacitance, SR, and kerf width. Several researchers acknowledged that the wire drum speed, the pulse current; the pulse on and off time are the influencing process variables in WEDM. The experimental results of the MMCs showed that the wire drum speed has a minor impact on the SR and MRR in comparison with other factors like peak current, pulse off time, and pulse on time correspondingly [22].

Experiments have been performed utilizing the design of experiments technique since it is more precise, more effective, and less expensive. Some of the design techniques are factorial designs, Taguchi methods, genetic algorithm, RSM, etc., [23]. A stir cast AA5083 with 7 wt% B₄C composites was taken for WEDM process parameters optimization by using metaheuristic techniques [24]. Grey-based Taguchi technique has been chosen as an optimum parameter combination to achieve the performance features of maximum MRR, minimum roughness value, B₄C 6 wt%, aluminium alloy 6063 [25]. Since the time consumption for arrival of results is more in the existing experimental approach, RSM is used as an effective tool for improving, optimizing, and evolving the processes by coalescing numerous input factors and assessing how their intricate interactions influence the performance of the response factors [26, 27]. RSM exhibits a statistical method

for the design of experiments. The other techniques like CCRD are adopted for analyzing the performance of the projected model and improving the model which is subsequently identified by response graphs. Further, the impact of input factors on responses can be analysed by ANOVA test. Mathematical models for the optimization of WEDM characteristics are developed by RSM technique [28, 29]. CCRD is one of the widely used experimental design methods of RSM. The key benefits of CCRD are as follows: It provides design points beyond the predetermined range of factors as axial points (α). This in turn offers good predicting ability of the developed model over the design space along with better accuracy than that of other approach [30, 31]. The RSM technique seems to be more promising in predicting the response via mathematical modelling over the other techniques [30–32].

All the available literature reports of various MMCs were mainly focusing on stirring with the gravity casting process, followed by WEDM process. There are sufficient research reports available on the fabrication of pore-free fine-grain high-strength aluminium metal matrix composites done through stir cum squeeze casting technique and performed for metallurgical and mechanical characterization study. As mentioned, very few studies have undertaken composites, that too only stirred with gravity casting processes on WEDM. But there is no report on optimizing the WEDM process parameters on aluminium metal matrix composites done through stir cum squeeze casting technique. The variation of casting/composites process parameter is not the main intent of our work. The exploration of the machinability of stir cum squeeze cast A413–B₄C composites through WEDM is the key objective of the research which is deemed vital. The manufacturers of WEDM would give the optimal range of parameters for very few material combinations which is commercially available. However, an extensive study on optimal WEDM process parameters for high-strength newly developed stir cum squeeze cast A413–B₄C composites is an essential thing for the manufacturing industries. The usage of appropriate machining parameters forms the base for optimum usage of WEDM process. This investigation is based on focusing to plot the effects of WEDM influenced by several process variables like pulse on time and off time, followed by peak current on the MRR and SR while machining stir cum squeeze cast A413–B₄C composites by using CCRD in RSM. From the systematic experiments, a mathematical model has been established to predict the responses contained in the affordable error region, in agreement with the experimental responses. Also a multi-constrained optimization model using the desirability approach for MRR and SR in WEDM parametric combination is formulated. The machined surface quality and integrity were observed through scanning electron microscopy which revealed good bonding,

Table 1 Chemical composition of A413 aluminium alloy

Elements	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Al
Standard	0.25 max	0.15 max	10.0–13.0	0.60 max	0.50 max	0.10 max	0.30max	0.10 max	0.10 max	0.20 max	Remainder
Tested	0.1	0.1	11.81	0.56	0.5	0.1	0.1	0.1	0.05	0.1	Remainder

Table 2 Chemical composition of pure boron carbide (B_4C) with 98.1 wt% of purity

Elements	B	C	Ca	Fe	Si	F	Cl
Standard %	80.0	18.1	0.3	1.0	0.5	0.025	0.075

fine structure, elimination of particle pullout/plucking and absence of surface micro-cracks due to stir cum squeezing casting processing composites was being considered.

2 Casting and machining experimental details

2.1 Material details

A soft nature of aluminium alloy A413 was chosen as the matrix material because of 2.66 g/cm^3 of density being suitable for different industrial applications in the current scenario. The advantage of this alloy is its exceptional distinctive mechanical properties, better fluidity, castability and corrosion resistance coupled with better machinability. Table 1 illustrates the chemical composition of A413 aluminium alloy.

Boron carbide (B_4C) well known as the third toughest material following to diamond and cubic boron nitride is preferred as a reinforcement particle having 2.52 g/cm^3 density, which is a very hard ceramic particle with low specific gravity, good chemical stability, high thermal, wear and impact resistance that offers advantages in applications involving neutron absorption capability. Table 2 gives the chemical composition pure boron carbide.

2.2 Stir cum squeeze casting experimental set-up

The stir casting machine consists of an electric furnace which could heat the material up to 1000°C with EN8 crucible being capable of melting an ingot weighing about 2 kg. The machine has a leak-resistant bottom pouring unit and an insulated multi-layer for reducing the skin temperature, which is coupled to the electric furnace. The purpose of the special bottom pouring arrangement is to provide a pathway for the molten metal to be directly poured into the die from the furnace output via an electrically heated pathway. The die used to prepare the composite is permanent H13 steel die of dimensions 50 mm diameter and 200 mm height. An electrically operated rotary stirrer

capable of a top rotational speed of 1500 rpm is attached to the furnace for stirring the mixture to create a whirlpool in the liquid metal. The melt temperature is measured by the aid of a *K*-type thermocouple with a digital display that is also connected to the set-up. The die was preheated before the molten material was poured onto it. The temperatures at various points of the set-up such as the bottom pouring induction furnace, metal transfer pathway along stirrer speed can be monitored and controlled in the control panel. Figure 1 shows a 50 Ton motorized hydraulic set-up with a pressure indicator and a control panel. This set-up was used for applying the pressure over the molten metal inside the die which was hinged on the basement of hydraulic arrangement.

2.3 Fabrication of composites and their properties

The previous investigation by Soundararajan et al. [33] has reported about stir cum squeeze casting of A413 with B_4C composites and the impacts of each squeeze casting parameters over the mechanical behaviour of hardness and tensile strength of the test sample. Based on the analysis, the conclusion explored that the optimal combination of the squeeze casting parameters considered was the squeeze pressure, weight% of B_4C particles and die preheating temperature of 140 MPa, 12 wt%, and 225°C , respectively. This combination of input parameters has yielded high-strength pore-free specimens.

Hence, A413 with 12 wt% B_4C composites in the present investigation was fabricated under this optimal stir cum squeeze casting process condition, and the samples were made and taken for WEDM process. The A413 alloy pure ingots of 1Kg were measured and melted (725°C) in the steel crucible. The melt was cleaned by adding the 8 g weight of coat flux, and the entrapped gases were also removed by adding C_2Cl_6 degasser. A 12 wt% of boron carbide of size 44 microns along with 12 g of K_2TiF_6 were preheated (500°C) with the help of inbuilt preheated set-up. The purpose of adding K_2TiF_6 is to achieve proper wettability with the tight bound B_4C particles to aluminium alloy melt. The preheated

Fig. 1 Stir cum squeeze casting set-up

12 wt% B_4C particle along with K_2TiF_6 was being slowly fed into the molten metal. For the avoidance of parting particles, agglomeration, thereby sustaining homogeneous distribution, the stirring was done for 5 min at 300 rpm. The colloidal graphite-coated H13 hot steel die was preheated to 225 °C, and the molten metal was transferred into it within few seconds to eliminate the heat loss and turbulence which occur due to the flow of the molten metal. A squeeze pressure of 140 MPa was applied on the melt in the preheated mould with a delay time of about five seconds and retained over the solidifying mould for 60 s to produce the sound casting.

The cylindrical (50 mm diameter x 150 mm height) cast sample is shown in Fig. 2.

Prior to machining of casted samples, few cast samples were subjected to metallurgical and mechanical testing conducted as per ASTM standards procedure for conforming the test results. By using scanning electron microscopy equipment, particle distribution was confirmed before machining. The SEM image of Fig. 3 revealed the equal dispersion with better bonding of 12 wt% B_4C particles in A413 matrix, agglomeration-free composites were observed, and this evidence directly impacts on the mechanical properties.

Fig. 2 A413 with 12 wt% B₄C cast samples made from stir cum squeeze casting process

Fig. 3 **a** SEM image of stir cum squeeze casted A413 with 12 wt% B₄C composites (100× magnification), **b** SEM image of stir cum squeeze casted A413 with 12 wt% B₄C composites (500× magnification)

Also by used Vickers hardness tester (DHR 1000), ZWICK universal testing system (2000 N capacity, microprocessor-controlled) hardness and strength were measured. The average tested results of the prepared composites obtained were higher hardness of 136 VHN, tensile and yield strength of 373 MPa and 216 MPa, respectively, as shown in Fig. 4 with error bar.

Similar results were obtained by Soundararajan et al. [33] in which the mechanisms were described in detail already and also being found under optimal processing conditions of the composite samples that were being prepared prior to machining. A squeeze pressure of 140 MPa resulted in the increase in heat transfer rate leading to progressive solidification, thereby eliminating the cluster formation, uniform distribution of the B₄C particles in the composites and leading to a strong bond between the matrix and reinforcement, which results in improved load transference ability from the matrix to the reinforcement. Also applied squeeze pressure increases densification,

thereby increasing grain boundary of particles within the matrix resulting in strengthening of the composites. It was noted that the addition of B₄C particles of harder and stiffer material in the soft A413 alloy, leads to an obstacle for the dislocation motion, thereby increasing both yield strength and UTS as the 12 wt% of B₄C increases the barrier to dislocation. The improvement in hardness of the composite was due to B₄C particles with a hard surface that resists the localized plastic deformation. The negative effects of particle settling/cluster formation form agglomeration and porosity which acts as a stress concentration zone in the composite under loading. These factors are eliminated at 225 °C of die preheating temperature, thereby producing the maximum results of the composites.

Followed by the remaining casted samples that exhibited higher strength and pore-free A413 with 12 wt% B₄C composites were being taken for WEDM machining process in the present investigation.

Fig. 4 **a** Vickers hardness for stir cum squeeze casted A413 with 12 wt% B_4C composites, **b** yield and ultimate tensile strength for stir cum squeeze casted A413 with 12 wt% B_4C composites

2.4 Design of experiments in WEDM process

ELEKTRA SPRINTCUT 734 machine was used to conduct experiments. The brass wire coated with zinc of 0.25 mm diameter, dielectric medium of dielectric conductivity 20 mho de-mineralized water, 2 units wire feed, tension of wire 4 units, servo voltage as 20 V, 15 Kg/cm² flushing pressure, 2100 unit servo feed and a peak voltage of 2 unit with 110 V DC were used during the experimental work. The prepared stir cum squeeze cast A413 with 12 wt% B_4C composites cylindrical specimen of 15 mm thickness was obtained from a rectangular piece, and it was used as a work specimen as shown in Fig. 4 for ease of machining. Analysis of variance was done to see which variable creates the most impact on the eventual result. As a consequence of this, the pulse on time, pulse off time, peak current variable process parameters and the rest are constant constraints through pilot experimental trails for the initial cut and different outputs were observed. Based on the observation, Table 3 shows the working ranges of the influential parameters and its levels being selected for experimental design methodology with response surface methodology. Figure 5 shows the prepared specimen for machining final experimental runs as per the design matrix.

Fig. 5 Prepared stir cum squeeze casted A413 with 12 wt% B_4C composites sample for WEDM process

Table 3 Machining parameter used in the experiments

Parameter	Symbol	Unit	Low level (− 1)	Middle level (0)	High level (+ 1)
Pulse on time	T_{on}	μs	109	115	121
Pulse off time	T_{off}	μs	47	53	59
Peak current	IP	Amps	160	180	200

2.5 Response surface methodology

The response surface methodology is a widely used technique in manufacturing applications to build up quantitative models. It is one of the most active and reliable statistical methods to create, analyse and manipulate the quadratic nature of the interdependency of the various variables under consideration. In the present study, RSM is used for modelling and analyzing the responses which are evaluated by performing experiment. Generally, the experimental data utmost fit into a quadratic model, and thus, Eq. (1) describes the second-order polynomial response.

$$Y = b_0 + b_2x_2 + b_1x_1 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \quad (1)$$

where the response is denoted by 'Y' and the quantitative variables are denoted by x_1 , x_2 , and x_3 . Likewise, the linear

CCRD technique, twenty different random experimental parametric combinations were taken.

2.6 Measuring of experimental responses

The MRR can be calculated by substituting the value of cutting speed, the kerf width and the kerf height in Eq. (2). The required cutting speed value is displayed on the computer display. At a distance of 4 mm from start, the removal of the cutting speed reading is noted to ensure the collection of stabilized values.

Mitutoyo's optical microscope is used to measure the

kerf width at 6 mm from the surface roughness cuttings. Three values of kerf width are obtained by measuring in different positions, and its mean was taken as kerf width to improve accuracy

$$\text{Material removal rate (MRR)} = \text{Cutting speed} * \text{Kerf width} * \text{Height (mm}^3/\text{min)} \quad (2)$$

effects are denoted by b_1 , b_2 and b_3 for x_1 , x_2 and x_3 ; correspondingly, b_{11} , b_{22} and b_{33} are used to denote the quadratic effects of $\times 1$, $\times 2$ and $\times 3$ correspondingly. The x_1 and x_2 , x_1 and x_3 , x_2 and x_3 interactions in linear-linear fashion are denoted by b_{12} , b_{13} and b_{23} , respectively. In the box and hunter technique in the centre, composite design was taken to access the coefficient of response. The response surface of the second order fits the model unerringly, and the replication was detached to find the error terms. The error of the mean square was determined by duplicating the points of the centre.

The design of 20 machining runs based on RSM is done in design expert software. A complete factorial CCRD was used to develop the design, and also, T_{on} , T_{off} and IP were the input parameters that were conglomerated for determining their response. In this central composite rotatable design, the three-factor, three-level design is taken to initialize the most favourable response on MRR and SR of stir cum squeeze cast A413 with 12 wt% B_4C composites processed by WEDM. The T_{on} , T_{off} and IP were the variable parameters, and they were coded -1 , 0 and $+1$. The output responses obtained are MRR and SR. The full factorial design technique of CCRD develops all the possible parametric possibilities of the various factors at two different levels (high $+1$ and low -1). The design is poised of the eight-star points, six central points (coded level 0) and six axial points ($+1.68179$, -1.68179). In accordance with

Every three times for a cutting distance of 4 mm, the SR values were measured in μm with the assistance of Mitutoyo's surface roughness testing device. The mean SR value is taken as the SR value for the analysis.

3 Results and discussion

3.1 WEDM process with their interaction

The various parametric levels of T_{on} , T_{off} and IP in accordance with the DOE were used to machine the squeeze cast components. The MRR and SR values obtained were $3.251\text{--}25.575 \text{ mm}^3/\text{min}$, $4.14\text{--}6.18 \mu\text{m}$, respectively, for a low-high range of aforesaid parameters. Electrode wire cut-off was eliminated during the machining of composites because the B_4C particulates were evenly distributed without any agglomeration and micro-porosity in the composites. As a result of being cast under optimal parametric conditions for the developed stir cum squeeze composites, the considerable amount of MRR and good SR were obtained because of pore-free high-strength A413 reinforced with 12 wt% of $44 \mu\text{m}$ size B_4C particles. Experimental design with its outputs as illustrated in Table 4 and Fig. 6 indicates the machined specimens of stir cum squeeze cast A413 with 12 wt% B_4C composites.

Table 4 Design of experiments with obtained responses

Std	Run	Block	A: T_{on} μs	B: T_{off} μs	C:lp Amp	Cutting velocity mm/min mm/min	Kerf width mm	R1:MRR mm ³ /min	R2:SR μm
20	1	Block 1	0.85	32.00	180.00	2.034	0.356	10.862	5.03
12	2	Block 1	0.85	52.00	180.00	1.404	0.359	7.561	4.72
10	3	Block 1	1.35	32.00	180.00	3.474	0.367	19.124	5.47
9	4	Block 1	0.35	32.00	180.00	0.63	0.344	3.251	4.4
15	5	Block 1	0.85	32.00	180.00	1.836	0.356	9.804	4.81
11	6	Block 1	0.85	12.00	180.00	3.996	0.352	21.099	5.18
17	7	Block 1	0.85	32.00	180.00	1.872	0.356	9.996	4.94
8	8	Block 1	1.15	44.00	200.00	2.538	0.369	14.048	5.11
16	9	Block 1	0.85	32.00	180.00	1.962	0.356	10.477	4.91
13	10	Block 1	0.85	32.00	150.00	1.01	0.323	4.935	4.14
3	11	Block 1	0.55	44.00	160.00	0.937	0.300	4.217	4.38
4	12	Block 1	1.15	44.00	160.00	1.26	0.354	6.691	4.59
7	13	Block 1	0.55	44.00	200.00	1.17	0.339	5.966	4.64
2	14	Block 1	1.15	20.00	160.00	2.862	0.337	14.467	5.04
1	15	Block 1	0.55	20.00	160.00	1.404	0.298	6.276	4.51
19	16	Block 1	0.85	32.00	180.00	1.926	0.356	10.285	4.87
5	17	Block 1	0.55	20.00	200.00	2.502	0.351	13.173	4.64
14	18	Block 1	0.85	32.00	210.00	3.432	0.384	19.769	5.12
6	19	Block 1	1.15	20.00	200.00	4.44	0.384	25.575	6.18
18	20	Block 1	0.85	32.00	180.00	1.728	0.356	9.228	4.98

Fig. 6 Machined specimen of stir cum squeeze casted A413 with 12 wt% B₄C composites

3.2 WEDM process parameters effects on responses

3.2.1 Material removal rate analysis on machining composites

Significant composites machining process parameters on WEDM such as maximum signal and minimal noise

ratio were derived from ANOVA technique. ANOVA report shows that the F -value is 50.6 for MRR model, and this considered model is significant. It is clear that there is a chance of 0.01% error for "model F -value" to occur owing to an error level. Model terms tended to be significant by viewing " $P > F$ " (lower than 0.05500) values. The terms A , B , C , AB , AC and BC were the terms which were to represent interactions of every input WEDM process parameters. Moreover, A , B and C were acknowledged as the most significant factors. The values of $P > 0.0500$ deliberate that these factors/terms of A^2 , B^2 and C^2 in the model were non-significant. The noise causes an accidental chance of 1.78% in "lack-of-fit F -value". There was a sensible agreement of 0.8510 for "predicted R-squared" with "adjusted R-squared" of 0.9592. The ratio between signal and noise was seen through "adequate precision." It is desirable to obtain a ratio of larger than 4; this ratio of 27.062 hints the adequate signal. The normal plots of residual are presented in Fig. 7. A normally distributed residuals were seen through these plots; hence, it showcases that the developed model honestly fits the observed experimental values. Figure 8 shows the relation between the residual and predicted fits. These plots show that the residuals were structure less. Thus, Eq. 3 shows the second-order equation obtained for MRR.

$$\begin{aligned}
 \text{MRR} = & 17.00812 - 12.87961 * T_{\text{on}} + 0.29219 * T_{\text{off}} \\
 & - 0.26883 * I_p - 0.34851 * T_{\text{on}} * T_{\text{off}} + 0.20456 * T_{\text{on}} * I_p \\
 & - 4.63490E - 003 * T_{\text{off}} * I_p + 0.78178 * T_{\text{on}}^2 \\
 & + 8.20418E - 003 * T_{\text{off}}^2 + 1.20518E - 003 * I_p^2
 \end{aligned} \quad (3)$$

In an analysis of variance, the input process parameters used for the experiment like T_{on} , T_{off} and I_p were initialized to be valid at 95% acceptance level. T_{on} was

the important factor that has the greatest impact on MRR with a contribution of 34.58%, followed by I_p and T_{off} which influences the output 28.01% and 27.24%, respectively, as shown in Table 5. It was noted from Fig. 9 that the increase in MRR has occurred when T_{on} and I_p

Fig. 7 Normal plot of residuals for MRR

Fig. 8 Residual versus predicted plot for MRR

Table 5 ANOVA for MRR

Source	Sum of squares	DF	Mean of square	F value	Contribution%	P value	Significant
Model	693.11	9	77.01	50.68	97.85	< 0.0001	*
A- T_{on}	245.00	1	245.00	161.23	34.58	< 0.0001	*
B- T_{off}	192.98	1	192.98	127.00	27.24	< 0.0001	*
C-IP	198.44	1	198.44	130.59	28.01	< 0.0001	*
AB	12.59	1	12.59	8.29	1.77	0.0164	
AC	12.05	1	12.05	7.93	1.70	0.0183	
BC	9.90	1	9.90	6.51	1.39	0.0287	
B^2	20.11	1	3.35	2.20	2.83	0.1685	
Residual	15.20	10	1.52		2.14		
Lack of fit	13.58	5	2.72	8.41	1.91	0.0178	
Pure error	1.62	5	0.32		0.22		
Total	708.31	19			100.00		

R-Squared: 0.9785, adj R-squared: 0.9592, pred R-squared: 0.8510, adeq precision: 27.062

*Significant

Design-Expert® Software

MRR
● MRRActual Factors
A: T_{on} = 0.85
B: T_{off} = 32.00
C: IP = 180.00 **Fig. 9** Perturbation plot for MRR

started to increase. However, with an increase in T_{off} , the MRR starts to decrease gradually. From Fig. 10, it was witnessed that the MRR has started to increase gradually with the rise in T_{on} and fall in T_{off} . Figure 11 shows that a gradual rise in T_{on} and IP surges MRR. Figure 12 reveals that as the T_{off} decreases and IP increases the MRR raises progressively.

It was experimentally observed that T_{on} and IP were noticeable influencing parameters over MRR while machining stir cum squeeze cast A413 with 12 wt% B_4C composite. With the increase in T_{on} , the sparking time increases which results in the transfer of high discharge

energy at the cutting zone, thus leading to an increase in the MRR, which can also be increased by increasing the IP like an increase in the intensity of the spark at the cutting zone. By means of this cumulative effect, the amount of energy discharged per spark is more while producing the machining surface. In response, a huge amount of metal was melted in the spark gap. Thus, the stronger energy discharge was generated because of the better T_{on} and IP value yields higher MRR. Though the MRR in WEDM operation was allied to the thermal diffusion of the material, it was calculated with means of thermal conductivity, bonding, reinforcement size, and density of the material. The

Design-Expert® Software

MRR

MRR = 9.804

Std # 19 Run # 16

X1 = A: Ton = 0.85

X2 = B: Toff = 32.00

Actual Factor

C: IP = 180.00

Fig. 10 Interaction plot (T_{on} vs. T_{off}) for MRR

Design-Expert® Software

MRR

X1 = A: Ton

X2 = C: IP

Actual Factor

B: Toff = 32.00

Fig. 11 Interaction plot (T_{on} vs. IP) for MRR

presence of reinforced particles has decreased the density but raises the melting point of the composite and consequently, leading to deterioration of MRR, when compared

to the conventionally stirred with gravity cast MMCs and stir cum squeeze casted high-strength aluminium alloy [13, 33, 34]. High discharge energy is required to melt the

Fig. 12 Interaction plot (T_{off} vs. IP) for MRR

A413 with 12 wt% B_4C composites as a result of strong bonding created by the applied pressure in the stir cum squeeze casting process. Also, it was observed that the shallow craters, recast layer, the absence of crack and particle pull out are considered as inaccuracy for machined samples in normal conventional stirred with gravity cast specimen. But, it was eliminated from the machined surfaces in the present work because of high-strength stir cum squeeze cast pore-free tightly bonded uniform distributed composites [35]. Therefore, to obtain effective machining with higher MRR without affecting the work material quality, there must be a proper balance between the IP and maximum T_{on} .

In WEDM process, T_{off} was a pause for the sparking to remove the debris accumulated during T_{on} (sparking). By increasing T_{off} value, the discharges occur in smaller numbers for a specified time period and it propagates to a lesser discharge of energy which causes sluggish and less amount of material removal. Decreasing the pulse off time lesser than the minimum level produces an insufficient removal of the debris. Therefore a minimum pulse off time must be maintained to obtain higher MRR [14, 35].

3.2.2 Surface roughness analysis on machining composites

The F -value (29.93) of the ANOVA model indicated that the predicted model is highly significant one. It was also

clear that only a possibility of 0.01% for "Model F -Value" to occur owing to noise. The other variables in the model were produced with values less than 0.0500 for " $P > F$ " which means these terms were highly important. In this experimental study A , B , C , AB , AC , C^2 were the noteworthy model items that are used to represent the input variables and their respective interactions. The parameters whose values are more than 0.0500 were denoted as non-significant terms. Thus A , B and C were the most significant factors, the non-significant terms were A^2 , BC , and B^2 . The lack of fit obtained was not due to the pure error when the "lack-of-fit F -value" is 3.30. The noise produces a "lack-of-fit F -value" with 10.78% accidental chance. The "predicted R -squared" of 0.7494 exhibits a sensible agreement with "adjusted R -squared" (0.9320). The ratio between signal and noise is shown in "adequate precision." For the better signal, the required ratio was greater than 4, now this value of 22.569 shows an adequate signal. The normal plots of residual were presented in Fig. 13. The errors were distributed normally as the residuals in the plot were placed along the linear straight line. Therefore, the model developed was in equal fit with the measured values. The residual vs. predicted fits were presented in Fig. 14 and these plots specified that the residuals were structure-less. Equation 4 shows the second-order equation developed for SR considering all the above-mentioned points is presented.

Fig. 13 Normal plot of residuals for SR

Fig. 14 Residual versus predicted plot for SR

$$\begin{aligned}
 SR = & -3.94433 - 2.39708 * T_{on} + 0.063005 * T_{off} \\
 & + 0.082475 * Ip - 0.048264 * T_{on} * T_{off} + 0.026458 * T_{on} * Ip \\
 & - 2.55208E - 004 * T_{off} * Ip + 0.17027 * T_{on}^2 + 1.43248E \\
 & - 004 * T_{off}^2 - 2.31273E - 004 * Ip^2
 \end{aligned} \quad (4)$$

By using ANOVA, all the input process parameters were considered and it was identified that the T_{on} was the important factor that has the highest impact in the

output SR with a contribution of 41.08%. Ip and T_{off} have the second and third impact with 27.02% and 11.62%, respectively, as shown in Table 6. From the collective

Table 6 ANOVA for SR

Source	Sum of squares	DF	Mean of square	F value	Contribution%	P value	Significant
Model	3.56	9	0.40	29.93	96.21	< 0.0001	*
A- T_{on}	1.52	1	1.52	114.55	41.08	< 0.0001	*
B- T_{off}	0.43	1	0.43	32.51	11.62	0.0002	
C-IP	1.00	1	1.00	75.69	27.02	< 0.0001	*
AB	0.24	1	0.24	18.25	6.48	0.0016	
AC	0.20	1	0.20	15.24	5.40	0.0029	
C ²	0.12	1	0.12	9.32	3.24	0.0122	
Residual	0.13	10	0.013		3.51		
Lack of fit	0.10	5	0.020	3.30	2.70	0.1078	
Pure error	0.031	5	6.147E-003		0.83		
Total	3.70	19					

R-squared: 0.9642, adj R-squared: 0.9320, pred R-squared: 0.7494, adeq precision: 22.569

*Significant

Design-Expert® Software

SR
• SRActual Factors
A: T_{on} = 0.85
B: T_{off} = 32.00
C: IP = 180.00 **Fig. 15** Perturbation plot for SR

perturbation response graph; Fig. 15, it was observed experimentally that when T_{on} and IP rises, an increase in SR is obtained whereas SR steps down as T_{off} improves. Figure 16 indicates that the improvement of SR with the rise in T_{on} and fall in T_{off} . Figure 17 hints that there was an abundant increase in SR when both T_{on} and IP increases. Figure 18 discloses that SR value is enhanced by disproving T_{off} value and improving the IP.

The longer spark duration produced due to a rise in T_{on} and IP results in high-intensity current transferred from wire to work piece resulted in a formation of shallow craters. The depth of the shallow craters during machining of composites and recast layer might not be

the major cause for increasing SR. The particle size and height of protruding B_4C particles in the matrix in the machined surface, corresponding shallow crater depth and recast layer show the overall roughness of the surface. However, the increase in T_{on} and IP for machining the sample leads to a higher range of SR. Also, it was observed that the absence of particle pullout from the machined surface because of stir cum squeeze cast leading to a pore-free tightly bonded uniform distributed composite with a nominal 12 wt% B_4C particles. As expected, the stir cum squeeze cast specimen showed lower SR value to the conventionally stirred with gravity casted MMCs work material [30, 33]. The electrode and

Design-Expert® Software

SR

X1 = A: Ton

X2 = B: Toff

Actual Factor

C: IP = 180.00

Fig. 16 Interaction plot (T_{on} vs. T_{off}) for SR

Design-Expert® Software

SR

X1 = A: Ton

X2 = C: IP

Actual Factor

B: Toff = 32.00

Fig. 17 Interaction plot (T_{on} vs. IP) for SR

material have generated bombarding forces in-between because of high discharge energy transferred by T_{on} and IP affects the surface properties of the machined components [36]. It was found that there was a decrease in SR with increase in T_{off} because of the smaller amount of

energy discharge striking the surface of composite for a specified time period which ensured in a few numbers of shallow craters and progressively removed tightly bonded B_4C particles without pull out from the matrix on the stir cum squeeze cast work piece surface. Thus,

Design-Expert® Software

SR
6.18
4.14

X1 = B: Toff
X2 = C: IP

Actual Factor
A: Ton = 0.85

Fig. 18 Interaction plot (T_{off} vs. IP) for SR

the uneven disparity in the surface roughness was minor due to high-strength stir cum squeeze cast specimen [36–38].

3.3 Additivity test for experimental versus predicted sets

The validation of the responses shown in Eqs. 3 and 4 is done by performing an additivity test for MRR and SR. Figures 19 and 20 show the graphical relationship and deviation between the RSM predictions and the end responses of the experimental data for SR and MRR of the composites. It can be noted from the graphs that there was no appreciable deviation and hence the overall error of the mathematical data to the real-time data was 6.47% and 1.52% for MRR and SR, respectively, which is low and hence the mathematical model is reliable. The conclusion from this test is that the developed RSM model would predict almost accurately the MRR and SR values and hence it can be used for the prediction of these values for different set-ups for monetary and temporal benefits.

3.4 Multi-objective optimization using desirability approach

The objective function, $D(X)$ was used in this technique, which is known as a desirability function. It portrays the enviable ranges for apiece response (di). Appropriate ranges were between zero (least desirable) and one

Fig. 19 Experiment sets versus RSM prediction for MRR

Fig. 20 Experiment sets versus RSM prediction for SR

(most desirable). The instantaneous response is given by the simultaneous objective function and is revealed by Eq. 5.

$$D = (d^1 \times d^2 \times \dots d^n)^{1/n} \quad (5)$$

In Eq. (5), ' n ' denotes the measured quantity of output values. Here the output obtained was 0 when if any one of the responses generated was beyond the desirable range. Each goal was allotted by a response with a high and low value for simultaneous optimization. On the worksheet, for "Goal" arena there should be one the five options for the responses: "none", "maximum", "minimum", "target", or "in range". The performance response would not be considered for optimization when the goal is none. For any number of responses, components and factors goals could be set but at a minimum one response must be involved in the target set. In the desirability objective function $D(X)$, an importance relative for the additional responses can be assigned for each solution. The importance of r_i varies from the minimum important (+) a value of 1, to the maximum important (++++) a value of 5. There was a decrease in simultaneous objective and settles to normal form for desirability when all the important values were the same.

In this experimentation, the desirability function method was taken for obtaining multi-response optimization of WEDM process parameters on stir cum squeeze cast A413 with 12 wt% B₄C composites machining. Various criteria, for instance, the weights and importance, were varied for three combinations of measuring trials. The higher MRR condition, importance value of 5(++++) are agreed for MRR and a lower importance value of 1(+) was agreed for SR. In the next condition the equal MRR and SR, an importance value of 3 (+++) was agreed equally for MRR and SR. In final the best

SR condition, importance value of 1(+) was agreed for MRR and the best importance value of 5 (++++) was agreed for SR. The ideal results are tabulated in Table 7.

3.5 Validation tests

The multi-response optimization through the processing of WEDM parameters for stir cum squeeze cast A413 with 12 wt% B₄C composites was verified using validation test runs for re-confirming. The percentage of error among optimal experimental trial values for the response is shown in Table 8.

The scientific community has investigated and reported WEDM process parameters for machining various commercially available materials. After a scientific study of this exclusive stir cum squeeze cast composite material, the factors that contribute to its properties have been mathematically studied and graphically exhibited and the WEDM process parameters for best possible results have been suggested.

3.6 Quality characteristics

The quality characteristics of composites machined surface would influence the amount of ceramic particles of 12 wt% B₄C having particle size of 44 μm . The effective bonding of the reinforced ceramic particles within the matrix, the grain structure of composites, and the equal distribution of reinforced ceramic particles in the matrix determines the quality of the machined surface. Figure 21a shows a machined higher MRR sample surface quality, it shows electrode wire impression due to higher T_{on} . In which T_{on} of 1.04 μs , T_{off} 21 μs , IP 200 Amp on around MRR 24.455 mm^3/min , SR 5.753 μm was obtained. Followed by

Table 7 Multi-response optimization of WEDM process parameter

Performance measures	Input factor			Output response		Desirability
	T_{on} (μs)	T_{off} (μs)	IP (Amp)	MRR (mm^3/min)	SR (μm)	
Higher MRR	1.04	21.00	200	24.455	5.753	0.738
Equal MRR & SR	0.65	20.00	200	16.103	4.926	0.595
Best RA	0.55	20.03	200	13.842	4.708	0.673

Table 8 Results of validation test

S. No	Input factor			Output response experimental		Output response predicted		% Error	
	T_{on} (μs)	T_{off} (μs)	IP (Amp)	MRR (mm^3/min)	SR (μm)	MRR (mm^3/min)	SR (μm)	MRR	SR
1	1.04	21.00	200	24.455	5.753	24.332	5.741	0.5	0.20
2	0.65	20.00	200	16.103	4.926	16.056	4.922	0.3	0.08
3	0.55	20.03	200	13.842	4.708	13.856	4.709	0.1	0.02

Fig. 21 **a** SEM image of machined higher MRR sample surface, **b** SEM image of machined equal MRR and SR sample surface, **c** SEM image of machined fine SR sample surface

Fig. 21b shows a machined equal MRR and SR surface quality with nominal effect of the machine sample. In which T_{on} of 0.65 μ s, T_{off} 20 μ s, IP 200 Amp on around MRR 16.103 mm³/mm, SR 4.926 μ s was obtained. Also Fig. 21c shows a machined fine SR surface quality with best effect of the machine sample. In which T_{on} of 0.55 μ s, T_{off} 20.03 μ s, IP 200 Amp on around MRR 13.842 mm³/mm, SR 13.842 μ s was obtained. The machined stir cum squeeze casted composites has no negative effect was being observed in the machined surface's, which shows great potential for improving machined surface quality. So it's evident that the quality and integrity of the machined surface improved because of good bonding with densification, fine structure, elimination of particle pullout/plucking and absence of surface micro-cracks due to stir cum squeezing casting processing route.

4 Conclusions

In the present investigation, the development of A413 with 12 wt% B₄C composites through stir cum squeeze casting technique is being performed and taken for WEDM process to study the response systematically. The key findings being drawn are as follows:

- The fabricated composites exhibited a higher hardness of 136 VHN, and 373 MPa ultimate tensile strength was obtained significantly with the addition of B₄C particles of harder and stiffer material in the soft A413 alloy. Also coupled with processing of stir cum squeeze casting technique confirmed through SEM observations, the sound quality pore-free uniform dispersion of the matrix and the reinforcements result in superior bonding.
- In short, B₄C particles resist plastic deformation and applied squeeze pressure increases the densification, thereby increasing grain boundary of particles within

the matrix resulting in strengthening of the composites.

- The major goal of this work is to facilitate effective parameter selection while machining of developed composites by WEDM process through systematic design approach by RSM technique. The influenced process parameters T_{on} , T_{off} , IP on MRR and SR are optimized.
- The statistical analysis based on ANOVA prediction is the most significant one for dominating control parameters like T_{on} and IP than least influenced parameter of T_{off} on more MRR and T_{off} significantly directs the better SR in WEDM process based on their contribution.
- The performance of the additivity test showed that the RSM results and experimental results were in pace with each other for average error percentage of around 6.47% and 1.52% for MRR and SR correspondingly.
- The desirability approach for using multi-objective optimization to seek the best parametric combinations of higher MRR, equal significance for both MRR and SR and the best SR was obtained with good concurrence through confirmation test in which the outcome of this research would offer a successful protocol of machined surface quality characteristics, and it was evident from SEM images which majorly contributes processing of composites through stir cum squeezing casting technique.

Data availability The experimental datasets obtained from this research work and then the analysed results during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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