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Effect of Chilling & B_4C Content on Machining Efficiency and Surface Quality in Wire-Cut Machining of Aluminum Matrix Chilled Composites

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ABSTRACT

Conventional machining techniques struggle to effectively process these materials. To overcome these challenges, advanced methods like wire electric discharge machining (EDM) are being explored for cutting electrically conductive composites. This study aims to investigate the impact of various chill materials (Mild Steel, Cast Iron, Stainless Steel, and Copper), cutting parameters (Pulse On, Pulse Off time, and Current), and the weight percentage of Boron Carbide on two crucial aspects: Metal Removal Rate (MRR) and Surface Roughness (SR) of Aluminum-Boron Carbide (Al-B_4C) chilled composites. By conducting ANOVA analysis, researchers seek to determine the individual and combined effects of these process variables on MRR and SR. Additionally, scanning electron microscopic analysis is employed to gain insights into the microstructure and quality of the machined surfaces. It's noteworthy that composites prepared using Cu-chill plates exhibit exceptional resistance to the machining process due to their superior mechanical properties, followed by SS-chill, CI-chill, and MS-chill. The thermal conductivity of the chill materials on solidified composites plays a pivotal role in influencing machinability and surface roughness. While the weight percentage of B_4C has a lesser impact on machinability studies, it significantly affects the surface finish of the machined surface.

1. Introduction

Metal Matrix Composites (MMCs) represent a novel category of engineered materials that exhibit superior physical and mechanical properties compared to non-reinforced metals, as documented in references [1-5]. Aluminum, which stands as the second most abundant metallic element globally, only recently emerged as a cost-effective option for engineering applications towards the end of the nineteenth century, as acknowledged by many authors [6-8]. Due to its intriguing mechanical attributes, structural characteristics, and unique microstructures, MMCs have garnered significant attention across a wide spectrum of industries. These particular qualities make them well-suited for applications within the automotive, aviation, aerospace, and electrical sectors. Aluminum is the most abundant metal and the third most common element on the globe, accounting for 8% of the earth's crust. Due to its versatility and low density, aluminum is the most widely used metal

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after steel. Such a light weight, as well as Aluminum alloys with better strength than structural steel can be used to design and construct strong, lightweight structures. They are particularly beneficial for moving items like spaceships and aircraft, as well as all types of land and water-based vehicles. A chill is a tool that aids in the solidification of a part of a metal casting mold. In many instances, the metal inside the mold cools at a specific rate relative to the thickness of the casting. When the mold design hinders the naturally directed solidification, the strategic insertion of a chill can assist in the cooling process. Wire electro-discharge machining (WEDM) is a technique for removing material from electrically conductive materials that uses a thermoelectric source of energy. It's one of the most advanced non-traditional machining techniques. Wire-cut EDM is commonly used to cut plates up to 300 mm thick and to create tools, punches, and dies out of strong metals that are difficult to manufacture using other methods. Material is removed by a series of repeating sparks between electrodes, such as the workpiece and the tool. WEDM has grown in popularity as a non-traditional machining method in the aerospace, nuclear, and automotive industries. Several researchers have looked at various areas of WEDM, but no comprehensive research work in the field of wire electrical discharge machining of this Al-6061 alloy utilizing molybdenum wire has yet to be published. As a result, an attempt was undertaken to investigate the effects of several process parameters. When compared to diamond-based cutting tools, WEDM is one of the most recent machining techniques for processing the Al 6061 aluminum alloy into any complex convoluted shapes with great accuracy and precision. S.S. Mahapatra et al. [5] used the Taguchi approach to optimize the WEDM parameters and discovered that the mix of significant elements for each performance metric varies, thus they constructed a mathematical model using the non-linear regression method. For each performance measure such as MRR, SF, and kerf, conformation experiments have shown less than a 5% prediction error [6]. R. Ramakrishnan et al. have modeled and optimized Inconel 718 on WEDM and established the effect of various machining parameters such as pulse on time, wire feed speed, delay time, and ignition current. Pulse on time, delay time, and ignition current were influenced more than wire feed on MRR. The optimal combination of pulse length, voltage, and dielectric pressure for modulating surface polish was discovered in a work carried out by J T Huang et al. [7]. K H Ho et al. [8] has found the ideal combination of pulse length, voltage, and dielectric pressure for controlling surface finish in their work. The WEDM method is commonly utilized in the aerospace, automobile, and tool and die sectors, where precision and surface polish are critical.

The present study is focused on knowing the influence of various parameters associated with the wire EDM machining process on MRR and the surface roughness of the composites. Also, an attempt is made to correlate the effect of chilling materials and the percentage of reinforcement on the MRR and surface roughness.

2. Experimental Setup

2.1. Molding and Casting

Autoclaved Aerated Concrete (AAC) blocks are used to prepare the mold because they provide exceptional thermal insulation and also features including thermal mass, thermal inertia, and low air infiltration. The Silica, in combination with the cement and lime mixture, combines with the aluminum to generate the millions of microscopic air cells that give AAC blocks their distinct features [10,21].

Table 1. Properties of mold materials

Mold Material / Chill materials	Thermal Conductivity (W/m° k)	Specific Heat (J/kg-k)
Mild Steel	50	510.789
Cast Iron	53.3	460.548
Stainless Steel-304	16.2	502.416
Copper	401	376.812
ACC- Brick	0.16	---

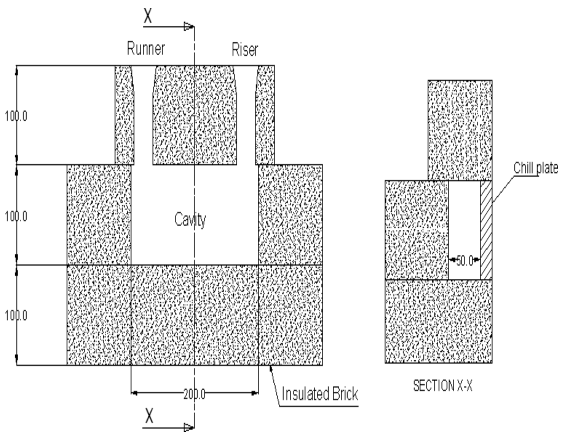


Fig. 1. Sectional front view and cross-sectional view of the mold [10].

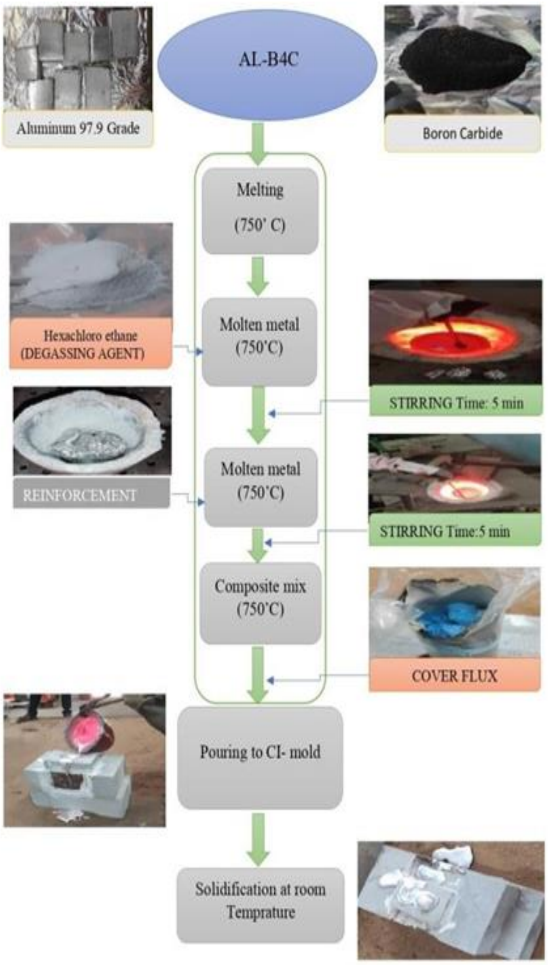


Fig. 2. Sequential procedure used in stir casting process

To maintain solidification under control, external chills are used. In order to control the solidification metal chills are used on one side of the mold, the complete arrangement and sectional view of the mold used are shown in Fig. 1 the thermal conductivity and specific heat of four metal chills used in the mold are shown in Table 1. The composite materials in this study were synthesized using the stir-casting method. Commercially available Al-6061 alloy was selected as a matrix material and boron carbide (B4C) of 105 microns in size was selected as reinforcement. The sequential procedure followed by the synthesis of composites using stir stir-casting process is shown in the block diagram indicated in Fig. 2.

3. Testing

The Solidified AL-B_4C composite casts are then machined using various conventional metal cutting techniques in order to get uniform geometry and dimensions. Specimens of dimensions 150 x 50 x 32 mm were extracted from all composite cast series as shown in Fig. 3 (a).

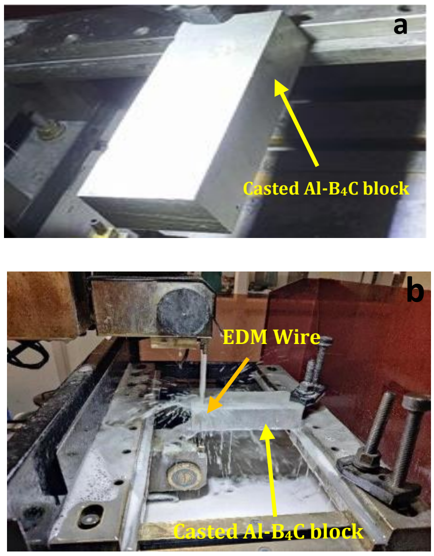


Fig. 3. (a) Machined sample of Al-B4C composite (b) W-EDM machine

To measure the metal removal rate (MRR) of the composites, the prepared specimens are then subjected to cutting operations using a CONCORD Wire-EDM machine with 0.18 mm molybdenum wire as shown in Fig. 3. Also, surface roughness (SR) of the cut surface was measured using Mitutoyo Surftest SJ-210 with a conical stylus with a 60° or 90° angle and a spherical tip with a 2μm radius is the ISO standard for measuring surface roughness to know the influence of various parameters.

To minimize the number of experiments, Taguchi, a statical approach is applied by considering the various parameters [9,11] and their levels as mentioned in Table 2. For all 16 sets of experiments, a straight-line cutting profile of 50 mm length as shown in Fig. 3(b) is used to know the influence of cutting parameters and material behavior, throughout the experiment. The set of L-16 orthogonal array of experiments is shown in Table 3 and specimens are shown in Fig. 4.

Table 2. Factors and levels considered for the experiments

Sl. No.	Factors	Levels			
		Level 1	Level 2	Level 3	Level 4
1	B_4C % age.	4	6	8	10
2	Chill materials	MS	CI	SS	CU
3	Pulse On (μs)	17.5	35	52.5	70
4	Pulse Off (μs)	2.5	5	7.5	10
5	Current (Amps)	1	2	3	4

Fig. 4. Cut specimens from the composite series

Table 3. L-16 Taguchi design matrix factors & levels considered for the experiments and responses

	Parameters					Responses	
Sl.No.	B4C % age	Chill Materials	Pulse On (μs)	Pulse Off (μs)	Current (Amps)	MRR (mm^3/ min)	SR(Ra)
1	4	MS	17.5	2.5	1	19.11	6.98
2	4	CI	35	5	2	19.85	7.79
3	4	SS	52.5	7.5	3	21.12	7.89
4	4	CU	70	10	4	16.85	9.02
5	6	MS	35	7.5	4	21.21	8.79
6	6	CI	17.5	10	3	17.82	6.56
7	6	SS	70	2.5	2	22.23	8.89
8	6	CU	52.5	5	1	11.92	6.78
9	8	MS	52.5	10	2	20.11	7.05
10	8	CI	70	7.5	1	20.12	7.77
11	8	SS	17.5	5	4	18.11	6.33
12	8	CU	35	2.5	3	12.15	7.56
13	10	MS	70	5	3	23.93	8.96
14	10	CI	52.5	2.5	4	21.19	8.35
15	10	SS	35	10	1	14.21	5.15
16	10	CU	17.5	7.5	2	9.23	4.3

Table 4. Analysis of variance

Source	DF	Adj SS	Adj MS	F- Value	P- Value
Regression	7	257.285	36.7550	88.10	0.000
%B4C	1	9.661	9.6605	23.16	0.001
Pulse on	1	50.403	50.4031	120.82	0.000
Pulse off	1	4.608	4.6080	11.05	0.010
Current	1	19.602	19.6020	46.99	0.000
Module	3	173.011	57.6704	138.24	0.000
Error	8	3.337	0.4172		
Total	15	260.622			

Model Summary

S	R-Sq	R-Sq (Adj)	R-Sq (Adj)
0.645893	98.72%	97.60%	94.66%

Table 5. Ranking Response Table

Level	%B4C	Module	Pulseon	Pulseoff	Current
1	19.23	21.09	16.07	18.67	16.34
2	18.30	19.75	16.86	18.45	17.86
3	17.62	18.92	18.59	17.92	18.75
4	17.14	12.54	20.78	17.25	19.34
Delta	2.09	8.55	4.71	1.42	3.00
Rank	4	1	2	5	3

4. Results and Discussions

Experiments are conducted in a controlled environment and all 16 trials are examined in a random fashion to avoid the influence of experimental errors. MRR was measured using the equation 1 [19].

$$MRR = F * DW * H \ldots \quad (1)$$

where F is the feed rate, DW is the diameter of the wire, and H is the Thickness of the workpiece.

When the weight percent of reinforcement is reduced, output performance improves. Because the distribution of reinforcement in AMMC is random all over the matrix, at higher wt. percent of reinforcement, the melting and evaporation of AMMC is less than that of the Al alloy as shown in Fig. 5. The inclusion of reinforcement reduces the conductivity of AMMC as the weight percent of reinforcement increases [12-15] thus, the efficiency of spark creation is poor and resulting in poor MRR.

Furthermore, the existence of a non-conductivity zone causes partial melting and evaporation of the material, resulting in layer recasting and delamination which can be seen in Fig. 7(a-b). Lower gap voltage (higher pulse on) results in higher MRR and surface quality. The peak current has a large impact on the responses which can be evident from Fig.s 5 and 6. Fig.s also shows that the chill materials have enough influence on MRR and SR during the cutting process. The MRR of the Cu-chilled cast is lower than compared to MS-chilled composites, this is because as the thermal conductivity of the chill materials increases the solidification rate will also increase resulting in smaller grains, stronger bonding of matrix and reinforcements, and better mechanical properties in the cast [16-18].

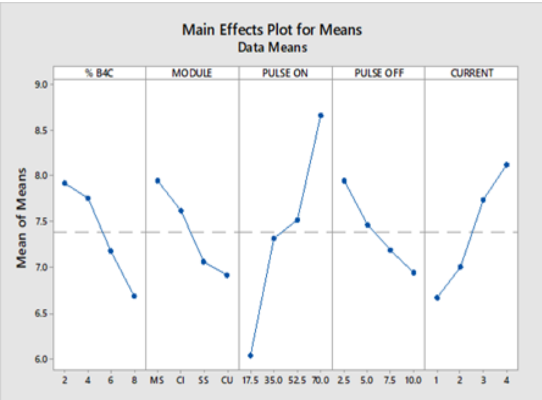


Fig. 5. Mean Effect plot for MRR

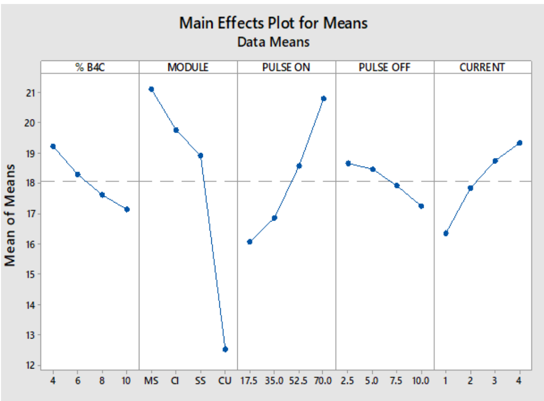


Fig. 6. Mean Effect plot for Surface roughness

During machining, the reinforcing particle in the Al matrix could be partially melted or entirely melted. The removal of totally melted material is aided by current, pulse on, and wire tension. Because current and voltage have such a large role in material melting and evaporation, wire tension is considered to be a minor impact. Figures 5 and 6 also show that the influences of chill materials and %age of B_4C are suppressed at higher current supply, this is because at larger amps of current the intensity of spark generation is more and enough to melt the hard phases of the composites the same as reported by many researchers [19-20].

A confirmation test was conducted to evaluate the design parameters influencing MRR and SR. The results of the conducted experiments were compared with the predicted value obtained from statistical analysis. The comparison showed that confirmation test results were very close to the predicted values and the maximum error percentage was within 10%. Table 6 shows the parameters used to predict the MRR and SR. Table 7 shows the Predicted and experimental values of the MRR and SR values. The error range from 2.8% to 9.4% in surface roughness is due to many reasons such as agglomeration of B_4C in that cutting section or less presence of B_4C in the cutting section, crater formation due to particle pullout during wire cut, and other environmental factors while cutting.

Table 6. Parameters considered for prediction of the MRR and SR

Chill	B_4C percentage	Pulseon	Pulseoff	Current
MS	4	15	2	0.5
CI	6	30	6	2.5
SS	8	75	11	5
CU	10	80	12	6

Table 7. Predicted and experimental value of the MRR and SR

Predicted SR value	Experimental SR results	Error in %	Predicted MRR value	Experimental MRR results	Error in %
6.8	6.2696	7.8	17.6	16.08816	8.59
7.23	6.82512	5.6	18.19	16.79847	7.65
8.93	8.09058	9.4	22.27	21.3213	4.26
8.97	8.71884	2.8	16.44	15.70349	4.48

5. Surface Topography

The machined surface has several micro ridges, microvoids, trans granular cuts, vacant pockets, ductile spikes, and brittle phases with different sizes and in various locations. Figure 7 (a-b) shows the trans granular cuts and formation of vacated pockets caused by the removal of hard B4C during machining. The microvoids are formed in a few regions due to the larger mold cavity filling with less escape space for hot air during the casting process which is shown in Fig. 7 (a-f). as the percentage of reinforcement increased in the matrix material the hardness of composites increases [22-24] as a result of solid solution strengthening, which offers more resistance to cut during the machining and causes micro ridges and crater wear with a dimension of 60 to 120 micrometers [26].

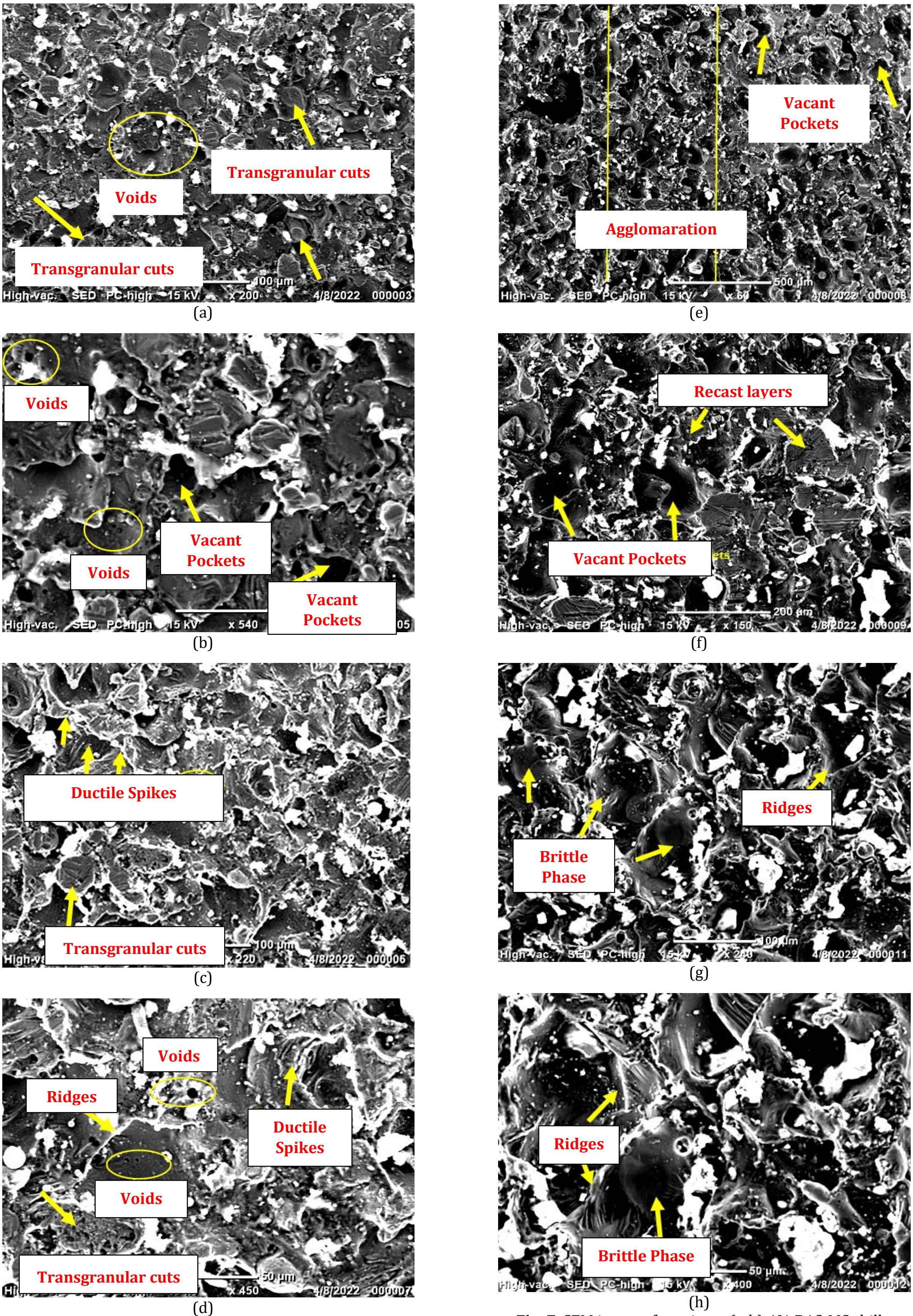
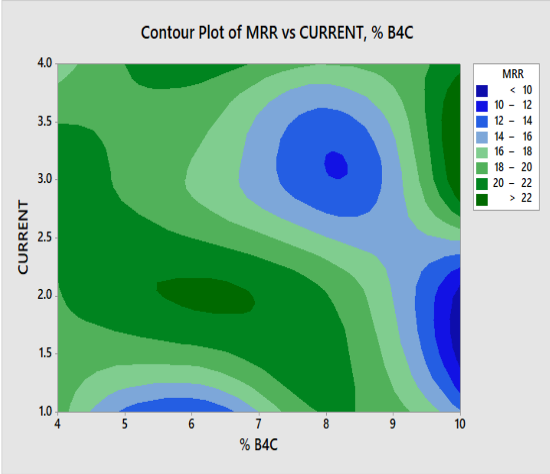


Fig. 7. SEM image of specimen (a-b) 4% B4C-MS chill (c-d) 6% B4C- CI chill (e-f) 8% B4C -SS chill (g-h)10% B4C - Cu chill

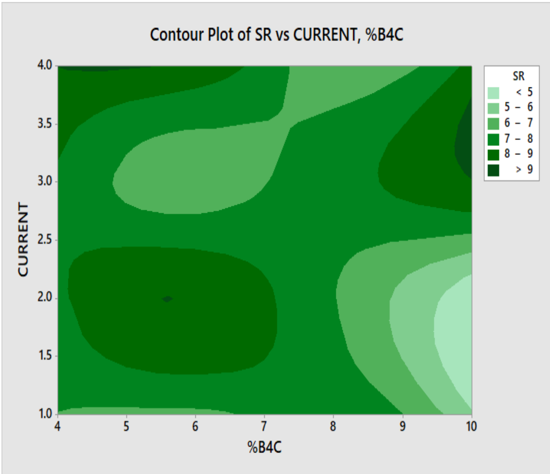
The existence of an intense population of B4C reinforcement can be seen in the middle region of the slot in 7(e) and 7(f). Furthermore, the agglomeration of reinforcement in the middle region is caused by the fact that the particles are forced to the central region of the specimen because of rapid solidification caused by the thermal conductivity of the Cu-chill plate, contributing to agglomeration and clustering of particles in some location. The deposition of partially molten metal on the machining zone that is not completely evaporated during sparking is known as recast layers. the presence of recast layers on the WEDM surface is most noticeable in Figs 7(g-h) Because the spark energy determines the creation of recast layers [25], correct management of electrical parameters reduces the recast layer in the WEDM process, higher current and pulse causes more recast layers were lower current and pluses leads to less MRR and higher surface roughness. As demonstrated in Fig 5.4, the vacant pockets are most noticeable in areas where reinforcement is most prevalent as the percentage of reinforcement is higher in this composite series.

6. Interactions

According to Fig. 8 (a), as seen in the contour plot, the current and MRR are strongly associated, therefore as the current increases, the MRR also increases. This is because when the current is higher, the practical melts more rapidly. There is no significance of B4C and the percentage of B4C on MRR during higher current rates. Fig. 8 (b) shows a high correlation between the current and SR, which is also evident in the main plot shown in Fig. 6, as the current increases, so does the SR. Because the carbide particles melt more quickly with greater currents and lead to the formation of recast layers on the cut surfaces. At a lower current and lower percentage of reinforcement, a good surface roughness can be obtained because of lower feeds associated with the lower current and fewer obstacles caused by the reinforcements. Thus, the elimination or less of micro ridges and recast layers were observed. Fig. 9 shows the 2D contour plots of pulse on and B4C v/s MRR and SR values, and Fig. 10 shows 2D contour plots of pulse off and B4C v/s MRR and SR values.

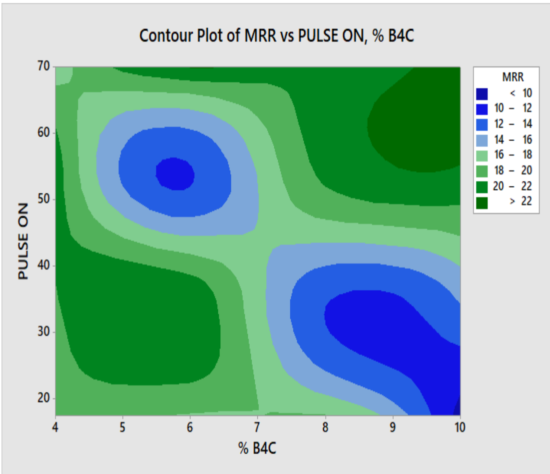


(a)

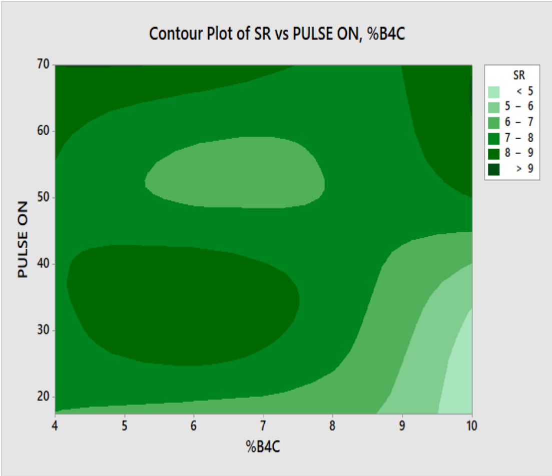


(b)

Fig. 8. 2D interaction plots of current and % age of B_4C v/s (a) Metal removal rate (b) surface roughness

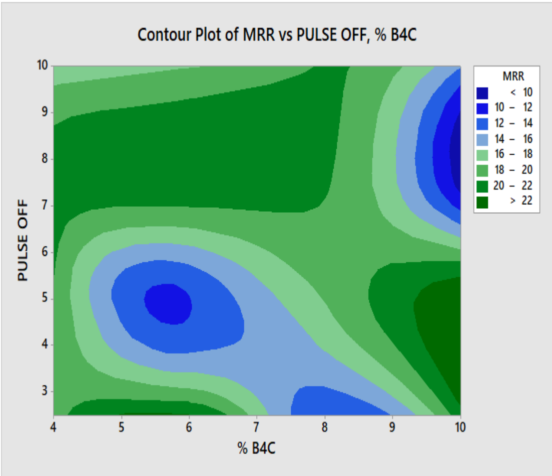


(a)

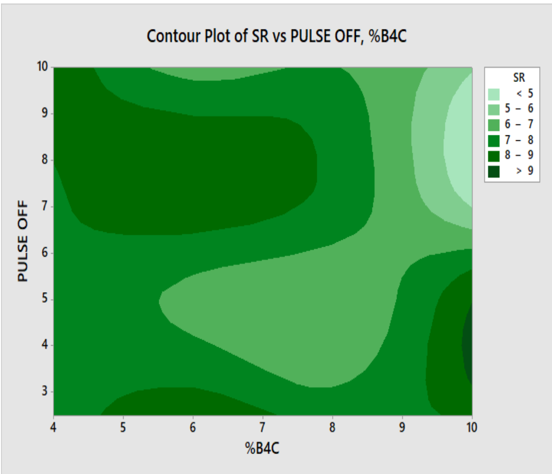


(b)

Fig. 9. 2D interaction plots of current and % age of B_4C v/s (a) Metal removal rate (b) surface roughness



(a)



(b)

Fig. 10. 2D interaction plots of current and % age of B_4C v/s (a) Metal removal rate (b) surface roughness

Since the pulse on and pulse off are inversely connected to the MRR, when the pulse interval increases the generation of high voltage sparks is more and enough to melt the MMC at a faster rate. But when the pulse-off rate increases the spark gaps are also increase which leads to lower melting of materials and causes less MRR the same has reported by many researchers in their findings. More sparks cause more recast layers on the cut surface leading to a lower surface finish. From Fig. 10 (b) a higher percentage of reinforcements and a higher value of pulse off leads to lower SR values this is because the spark gaps are not adequate to pass the wire through the hard particles embedded in the matrix alloy.

7. Conclusions

A stir casting process can be employed to synthesize the Al- B_4C composites with a fair uniform distribution of the particles in the matrix alloy. The thermal conductivity of the chill plates decides the strengths of the casted composites, composites cast using Cu-chill plates exhibit higher strength thus resulting in the lower MRR and surface finish. Molybdenum wire of Diameter 0.18mm can be employed to cut the Al-B_4C composites. The cutting parameters like current, pulse on and pulse off play a very predominant role in getting a good surface finish and MRR. Also, the composites prepared using Cu-chill plates show high resistance to the machining process because of their higher mechanical properties followed by SS-chill, Ci-Chill, and MS-chill. The thermal conductivity of the chill materials on solidified composites influences the machinability and surface roughness. The wt. percentage of B_4C has less significance in machinability studies but has more influence on the surface finish of the machined surface

Future scope

- Researchers can use non-metallic chills to know their influence on solidification and machinability characterization.
- It suggested that the addition of oxides can be done along with the B_4C particles to know its effects.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

References

[1] Harshavardhan, R., Anil, K.C., Sreenivas Rao, K.V., 2018. Evaluation of Fracture Toughness of Red Mud Reinforced Aluminum Matrix Composite. *Materials Today: Proceedings 5*, pp.24854–24861.

[2] Jayappa, K., Kumar, V. and Purushotham, G.G., 2021. Effect of reinforcements on mechanical properties of nickel alloy hybrid metal matrix composites processed by sand mold technique. *Applied Science and Engineering Progress, 14(1)*, pp.44-51.

[3] Khelge, S., Kumar, V. and Kumaraswamy, J., 2022. Optimization of wear properties on aluminum alloy (LM22) hybrid composite. *Materials Today: Proceedings, 52*, pp.565-570.

[4] Harish, R.S., Reddy, S. and Kumaraswamy, J., 2022. Wear characterization of Al 7075 alloy hybrid composites. *Metallurgical and Materials Engineering, 28(2)*, pp.291-303.

[5] Mahapatra, S.S. and Patnaik, A., 2007. Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method. *The International Journal of Advanced Manufacturing Technology, 34*, pp.911-925.

[6] Ramakrishnan, R. and Karunamoorthy, L., 2008. Modeling and multi-response optimization of Inconel 718 on machining of CNC WEDM process. *Journal of materials processing technology, 207(1-3)*, pp.343-349.

[7] Huang, J.T., Liao, Y.S. and Hsue, W.J., 1999. Determination of finish-cutting operation number and machining-parameters setting in wire electrical discharge machining. *Journal of Materials Processing Technology, 87(1-3)*, pp.69-81.

[8] Ho, K.H., Newman, S.T., Rahimifard, S. and Allen, R.D., 2004. State of the art in wire electrical discharge machining (WEDM). *International Journal of Machine Tools and Manufacture, 44(12-13)*, pp.1247-1259.

[9] Chalisgaonkar, R. and Kumar, J., 2013. Optimization of WEDM process of pure titanium with multiple performance characteristics using Taguchi's DOE approach and utility concept. *Frontiers of Mechanical Engineering, 8*, pp.201-214.

[10] Anil, K.C., Kumaraswamy, J. and Sanman, S., 2023. Experimental arrangement for estimation of metal-mold boundary heat flux during gravity chill casting. *Materials Today: Proceedings, 72*, pp.2013-2020.

[11] Kumar, S.S., Uthayakumar, M., Kumaran, S.T., Parameswaran, P., Mohandas, E., Kempulraj, G., Babu, B.R. and Natarajan, S.A., 2015. Parametric optimization of wire electrical discharge machining on aluminium based composites through grey relational analysis. *Journal of Manufacturing Processes, 20*, pp.33-39.

[12] Sharma, A., Garg, M.P. and Goyal, K.K., 2014. Prediction of optimal conditions for WEDM of Al 6063/ZrSiO4 (p) MMC. Procedia materials science, 6, pp.1024-1033.

[13] Singh, H. and Kumar, H., 2015. Review on wire electrical discharge machining (WEDM) of aluminum matrix composites. *International Journal of Mechanical and Production Engineering, 3(10)*, pp.1-5.

[14] Mythili, T. and Thanigaivelan, R., 2020. Optimization of wire EDM process parameters on Al6061/Al_2O_3 composite and its surface integrity studies. *Bulletin of The Polish Academy of Sciences Technical Sciences*, pp.1403-1412.

[15] Srivastava, A., Dixit, A.R. and Tiwari, S., 2014. Experimental investigation of wire EDM process parameteres on aluminum metal matrix composite Al2024/SiC. *International Journal of Advance Research and Innovation, 2(2)*, pp.511-515.

[16] Kandpal, B.C., Kumar, J. and Singh, H., 2015. Machining of Aluminium Metal Matrix Composites with Electrical Discharge Machining-A Review. *Materials Today: Proceedings, 2(4-5)*, pp.1665-1671.

[17] Sivaprakasam, P., Prakash, J.U., Hariharan, P. and Gowri, S., 2022. Micro-electric discharge machining (Micro-EDM) of aluminium alloy and aluminium matrix composites-a review. *Advances in Materials and Processing Technologies, 8(2),* pp.1-16.

[18] Srikanth, P. and Kumar, C.P., 2013. Electrical discharge machining characteristics of aluminium metal matrix composites-a review. *International Journal Of Science And Research*, 4, pp.1385-1394

[19] Kumba, A.B. and Venkata Ramaiah, P., 2019. Optimization in wire-cut edm of aluminium hybrid metal matrix composite using Taguchi coupled Deng's similarity based approach. *UPB Scientific Bulletin, Series D: Mechanical Engineering, 81(3)*, pp.169-186.

[20] Prasath, K., Prasanna, R. and Milon, D.S., 2018. Optimization of process parameters in wire cut EDM of mild steel and stainless steel using robust design. *International Journal for Chemical Technology Research CODEN (USA)*, 11(1), pp. 83-91.

[21] Sanman, S., Sreenivas Rao, K.V. and Anil, K.C., 2015. Effect of Mold Material on Boundary Heat Flux Transients during Gravity Die-Casting. *Applied Mechanics and Materials, 766*, pp. 405-409.

[22] Sanman, S., Prashanth, K.P., Anil K.C., Venkatesha, B.K., Gopal, Krishna, U. B. and Yuvaraj, L., 2021. Effect of percentage of reinforcement particulates on the corrosion behaviour of aluminium boron carbide composites. *Journal of Mines, Metals and Fuels*, 69(12), pp. 250-254.

[23] Sreenivasrao, K.V., Anil, K.C., Girish, K.G., and Akash, 2016. Mechanical characterization of red mud reinforced Al-8011 matrix composite. *ARPN Journal of Engineering and Applied Sciences, 11(1),* pp.229-234.

[24] Dhas, D.E.J., Velmurugan, C., Wins, K.L.D. and BoopathiRaja, K.P., 2019. Effect of tungsten carbide, silicon carbide and graphite particulates on the mechanical and microstructural characteristics of AA 5052 hybrid composites. *Ceramics International, 45(1)*, pp.614-621. https://doi.org/10.1016/j.ceramint.2018.09.216.

[25] Dhas, D.E.J., Velmurugan, C., and Wins, K.L.D. 2018. Investigations on the Effect of Tungsten Carbide and Graphite Reinforcements during Spark Erosion Machining of Aluminum Alloy (AA 5052) Hybrid Composite, *Silicon, 10*, pp.2769-2781. https://doi.org/10.1007/s12633-018-9817-0.

[26] Anil, K.C., Kumaraswamy, J., Reddy, M. and Mamatha, K.M., 2023. Air Jet Erosion studies on Aluminum-Red Mud Composites using Taguchi Design. *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 10*, Issue 01, pp.130-138.