EXPERIMENTAL INVESTIGATION AND OPTIMISATION IN ABRASIVE WATER JET MACHINING OF ALUMINIUM COMPOSITE

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ABSTRACT

The aim of the project is to investigate and optimise of aluminium composite in abrasive water jet machining(AWJM). Abrasive water jet machining is an emerging machining process in which the material removal takes place due to abrasion. A stream of abrasive particles mixed with filtered water is subjected to the work surface with high velocity. The present study is focused on the experimental research and evaluation of the abrasive water jet machining process in order to evaluate the technological factors affecting the machining quality of aluminium composite using response surface methodology. Different process parameters like Jet pressure, Traverse speed, and Standoff distance in three different levels are selected for optimization with three contravene responses. For Design of experiment L20 orthogonal array is prepared to set the input significant parameters for final product is calculated for better optimization purpose. From the study it is observed that the traverse speed have the most significant role, followed by Jet pressure and Stand off distance.

Keywords: *Aluminium composite, Optimise, surface methodology, AWJM*

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1. INTRODUCTION

Studies on aluminium composite reveal that it acts as a suitable inter-phase and reinforcement material [1].A water jet cutter is an industrial tool capable of cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance. The AWJM has no heat affected zone and the thermal free surface is exposed [2]. Experimental result of AWJM on the four different materials on surface finish reveals that smooth surface is acquired for the brittle materials and erosion on ductile materials [3]. The significant effect of JP is noticed while machining cast iron**,** where the least level of SOD and TS is preferred to get a smooth surface finish [4]. The effect of TS will be significantly higher in all of AWJM parameters on Ra because the increase in the thickness will have the larger depth of cut which may lead to having poor surface finish [5]. The influence of abrasive flow rate and the abrasive particle size on Ra is studied with varied input parameters on AWJM [6]. A drastic reduction of 78% on KA and 51% on Ra can be obtained with a decreased feed rate of AWJM [7]. The desired property of the cut material determines the kerf angle in AWJM [8].SOD signifies KA and MRR to a greater extent on brittle materials [9]. Wear behavior of the material depends on the material property and the property of the abrasive particle [10,11]. Studies on impingement effect of varied abrasives on eight different ceramic samples, the author's concluded that the hard abrasives can be used to machine high toughness materials [12].

Jet Pressure JP	Traverse speed TS
Stand off distance SOD	Abrasive flow rate Af
Material removal rate MRR	Abrasive water jet machine AWJM
Kerf angle KA	Central composite design CCD
Profile roughness Ra	Micron MM
Response surface methodolody RSM	Millimeter mm

AWJM studies on Si_3N_4 shows that the second-order polynomial equation of RSM fits the desire experimental values with less than 2% accuracy [13]. The relationship exhibits between the AWJM experimental observations and the predictive model (RSM) has found to have a significant fit [14]. Also, it is stated that RSM model with R^2 of 94.91% will yield a satisfactory measure on the output responses [15]. An improved quality characteristic was obtained by RSM on integrated Grey-RSM approach in plasma arc cutting [16].It is reported that a multi-objective optimistic condition using RSM was obtained in AWJM with 10% error [17]. In the present study, aluminium composite that was prepared through Aqueous Sol-Gel process is machined by AWJM. Through the literature survey, it is known that each parameter in AWJM will produce its effect based on the materials property and the working conditions. Lanthanum phosphate composite which is recently called as green composite has got no detail machining investigation records. Due to its low thermal conductivity and high brittle property, AWJM is found to be a suitable technique to understand the machinability of the aluminium Composite. JP, SOD, and TS are taken as the independent parameters whereas MRR, KA and Ra are taken as the output responses. The study on AWJM machining parameters and the influencing effects of each independent parameter is analyzed through CCD of RSM. To under-stand the surface morphology of the machined surface microscopy studies are performed and are discussed.

2. MATERIALS AND METHODS

2.1. Materials and methods

The machining property of aluminum composite prepared by the aqueous sol-gel process is evaluated using abrasive water jet machine. Jet pressure, Stand-off distance, and traverse speed are taken as the governing parameters on material removal rate, kerf angle and surface profile roughness. Garnet 80 mesh size is taken as abrasive. A linear cut is done on the composite of geometry for similar to the hardness test of 4 mm thickness for the L20 orthogonal array to study the process correlation that exhibits between the independent parameters. The equations are Predicted through response surface methodology are evaluated. From the observations, jet pressure has found to have a significant effect on material removal rate and kerf angle whereas, traverse speed significantly affects surface profile to the greater extent. The microscopic examination of the kerf surface reveals the plastic deformation surface, wear track and presence in the top kerf surface. The study on this new functional composite will improve the utilization of the composite and will be a database for the researchers, to improve and extends the usage of the composite for different applications.

2.2. Study methods

2.2.1. Abrasive water jet machining studies

AWJM of Model DIP 6D-2230 is used to cut the aluminium composite. The diameter of an orifice and tungsten carbide nozzle in AWJM is 0.25 mm and 0.67 mm, respectively. Garnet of 80 mesh size is used as abrasive particles. Fig. 1shows the experimental arrangements of AWJM. The surface roughness tester of model surfcom 1400G, that has a range of 350 mm with a probe speed of 0.25 mm/s over a span of 5 mm is used to measure the surface profile roughness on the kerf surface. The average of the three observations (top surface, intermit-tent surface, and rough surface) are made and tabulated as Ra. The high precision weighing the balance of Shimadzu made of model AUX 220 is used to weight the composite material before and after machining. The quantity of material removed per minute is calculated using the following equation (1).

$$MRR = \frac{(wt - wi)}{t} \tag{1}$$

where, W_i – Initial Weight of the workpiece in grams before cutting, W_f – Final Weight of the workpiece in grams after cutting, and t – Period of the trial (min).

2.2.2. Response surface design study

Design of Experiment is a systematic method to investigate the comprehensive assessment obtained through data collection and analysis. To shape the adequate mathematical design and to predict the accuracy of the experimental data, second order Central Composite Design is followed. Most of the work done in experimental optimization was related to second order CCD because of the limit in the number of variables [23]. The analysis of regression equation of RSM with CCD shows the higher degree of accuracy [24].The influences of each independent parameter over each dependent parameter are interrogated. The AWJM cutting is performed on the aluminium composite based on the CCD response surface methodology. The design comprises data from 20 experiments with 6 repetitive central experimental conditions that are used to construct a model equation for the AWJM and MRR, KA and Ra of the aluminium composites. Table 1presents the experimental values of the three factors of the independent variables under investigation, namely JP, SOD, and TS, at three levels. MRR, KA and Ra are taken as the dependent responses. The Design expet 6.0, a statistical software is used for the random generation of the order of the experiment.

Fig.1. AWJM Arrangement

Table :1 Selected Factor and Levels

S.No	Independent variables	Variation Levels		
		1	2	3
1	Jet Pressure	220	240	260
2	Stand-off-distance	1	2	3
3	Traverse Speed	20	30	40

2.2.3. Development of empirical model

The RSM approach is used to employ the three independent parameters with three levels each on the output responses of MRR, KA, and TS. The results are based on the experimental values of CCD method. Response Surface Regression is used to construct the empirical equation for the three output responses. Each of the output responses is subjected to the Analysis of Variance (ANOVA) with 95% confidential level. The general quadratic equation of RSM is shown in Eq. (2)

$$Y = b_0 + \sum_{i=1}^{\infty} b_i X_i + \sum_{i=1}^{\infty} b_{ii} X_i^2 + \sum_{i=1}^{\infty} \sum_{j>1}^{\infty} b_{ij} X_i X_j + \varepsilon \qquad (2)$$

where, Y = response factor (MRR, KA and Ra), b_0 = coefficient (Free Term), b_i = linear coefficient, b_{ii} = quadratic coefficient, b_{ij} = interaction coefficient and X_i, X_j = dimensionless coded independent variables

2.2.4. Surface roughness testing machine studies

The surface roughness tester of model surfcom 1400G, that has a range of 350 mm with a probe speed of 0.25 mm/s over a span of 5 mm is used to measure the surface profile roughness on the kerf surface. The average of the three observations (top surface, intermittent surface, and rough surface) are made and tabulated as Ra. The AWJM parameters have been found to influence the surface roughness measured in terms of Ra,Rp and Rz. Surface roughness is measured by using Profilometer (contact type).

Fig .2. Surface roughness testing machine

2.2.5. Kerf Angle studies

The most considerable parameter in AJW is the kerf angle. The kerf angle can be calculated by using the formula:

$$\tan\theta = \frac{T.K_f - B.K_f}{2t}$$

Where, t = thickness = 4mm (constant)

T. K_f = Top Kerf width (mm)

B. K_f = Bottom Kerf width (mm)

2.2.6. Experimetal design

KMT abrasive water jet machine will used in the experiments. The jet-line JL-50 ultra high pressure pump is used. Abrasive water jet machine possess the large number of process parameters, which all affect the quality of cutting. It is decided to select three machining parameters during cutting. Preliminary experiments are conducted to find out the working limit of the independent process parameter for aluminium composite material. The independent process parameters, which describes the three levels of selected parameters namely water pressure (P), Abrasive flow rate and standoff distance (D).

Table:2 Processing conditions for abrasive water jet machining process

Exp.no:	Jet pressure (bar)	Stand off distance (mm)	Traverse speed (mm/min)
1	260	1	40
2	240	2	30
3	220	1	40
4	240	2	30
5	260	2	30
6	240	3	30
7	260	3	40
8	220	2	30

9	240	2	40
10	220	3	20
11	240	1	30
12	240	2	20
13	260	3	20
14	220	3	40
15	260	2	20
16	240	3	20
17	220	1	20
18	240	3	40
19	260	3	30
20	220	1	20

2.2.7. Experimental procedure

To initiate investigation Full-factorial design of experiment is applied, where total 20 NOS of experiments are conducted. Throughout the experiments garnet particle used as abrasive material with mesh size of 80 and constant Abrasive flow rate 250 mm/min. All samples are machined from aluminium composite plate having dimensions of 600 x 600 x 4 mm are cut into equal piece of size 100 x 50 x 4 mm. Specimens after machining are Influence of machining parameters on Material removal rate (MRR), Surface roughness (Ra), and Kerf taper (KA).

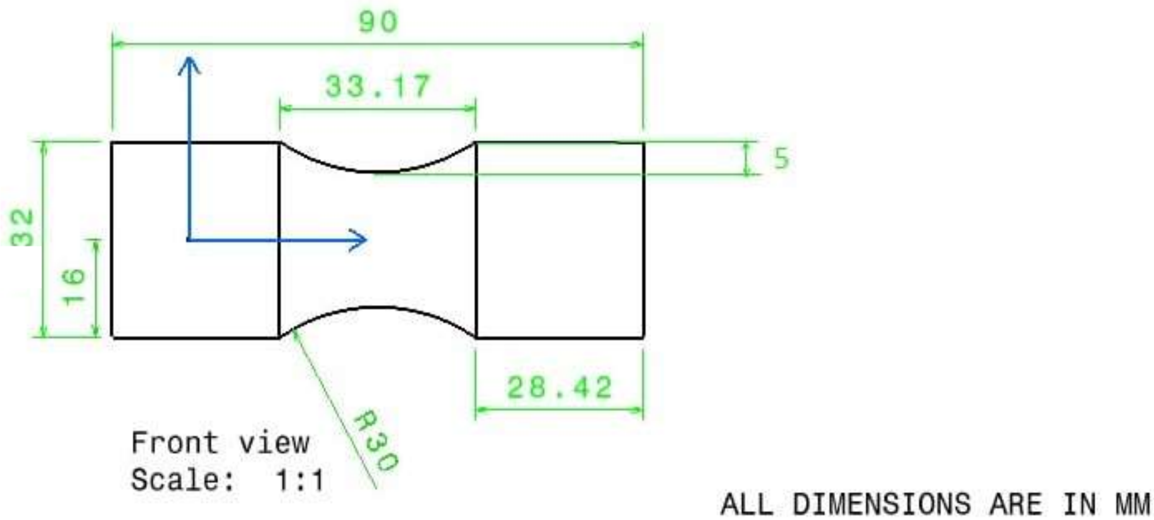
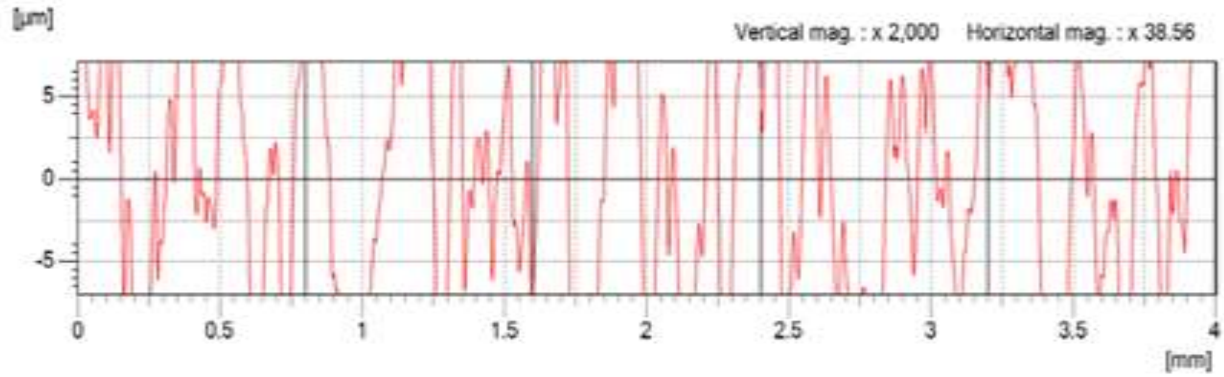
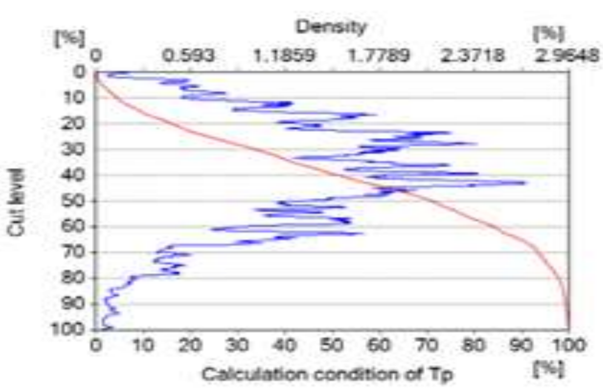


Fig .3. Profile to cut in aluminium composite

3. RESULTS AND DISCUSSION

3.1. Surface roughness graphs





Ra	1.6920
Ramax	3.2930
Ramin	0.1666
Rasd	4.7043
Ra+sd	2.7016
Ra-sd	0.6825
Ra(1)	1.9294
Ra(2)	1.3112
Ra(3)	3.2930
Ra(4)	0.1666
Rq	3.2782
Rz	32.7712

3.2. Empirical model and regression analysis on AWJM parameters of aluminium composites

Table 3 presents the experimental results of AWJM over the three independent parameters and dependent responses. Fig 4 (a–c) shows the residual plots of three dependent parameters. Linear distributions of experimental values are found to be bounded within the acceptable range. The above graph was stimulated using surface roughness testing machine. It shows Roughness curve by considering length of measurement Vs micron to find out surface waviness and also bearing curve by showing cumulative probability of profile amplitude distribution on aluminium composite material while machining under AWJM. It also show value for various roughness parameters while machining under aluminium composite on different control parameter.

Table:3 Empirical model and regression analysis on AWJM parameters of aluminium composites

Table:3 presents the experimental results of AWJM over the three independent parameters and dependent responses.

Exp.no:	Jet Pressure (bar)	Stand off Distance (mm)	Traverse speed (mm/min)	Material removal rate (g/s)	Kerf angle (deg)	Surface Roughness Ra, (µm)
1	260	1	40	0.04652	0.492	1.692
2	240	2	30	0.04291	0.355	1.529
3	220	1	40	0.02152	0.364	1.486
4	240	2	30	0.04291	0.349	1.531
5	260	2	30	0.02998	0.322	1.289
6	240	3	30	0.05014	0.468	1.656
7	260	3	40	0.06252	0.681	1.966

8	220	2	30	0.04311	0.37	1.526
9	240	2	40	0.04017	0.434	1.682
10	220	3	20	0.03471	0.298	1.344
11	240	1	30	0.04331	0.359	1.536
12	240	2	20	0.04526	0.293	1.331
13	260	3	20	0.06887	0.516	1.645
14	220	3	40	0.02895	0.342	1.675
15	260	2	20	0.05715	0.462	1.737
16	240	3	20	0.03412	0.364	1.494
17	220	1	20	0.03189	0.215	1.191
18	240	3	40	0.05715	0.462	1.737
19	260	3	30	0.03412	0.364	1.494
20	220	1	20	0.03189	0.215	1.191

3.3 Normal probability distribution on MRR, KA & Ra:

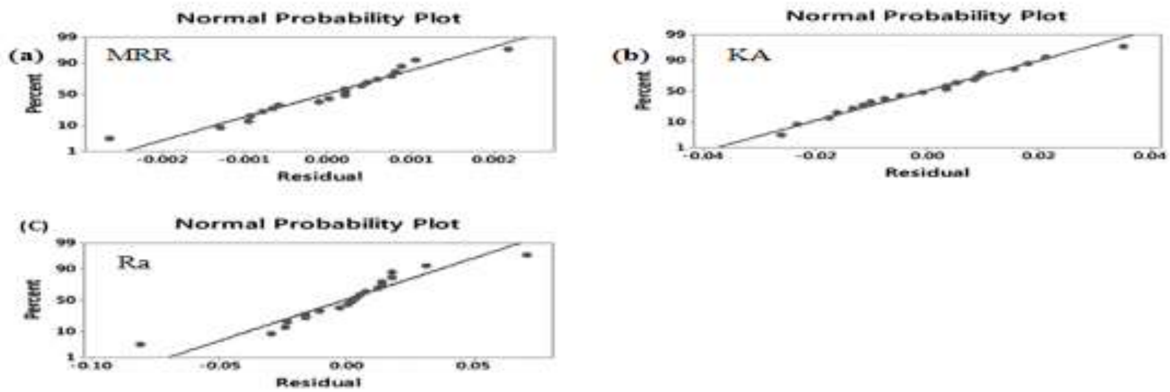


Fig. 4. Normal distribution data with the normal probability of (a) MRR, (b) KA, (c) Ra

Table:4 The estimated regression coefficient of MRR

Term	Coef	SE Coef	T-Value	P-Value
Constant	0.042695	0.000492	86.86	0.000
JP	0.014296	0.000452	31.62	0.000
SOD	0.005619	0.000452	12.43	0.000
TS	0.003600	0.000452	07.96	0.000
JP*JP	0.001092	0.000862	01.27	0.234
SOD*SOD	0.000343	0.000862	00.40	0.699
TS*TS	0.000242	0.000862	00.28	0.785
JP*SOD	0.002459	0.000506	04.86	0.001
JP*TS	0.000169	0.000506	00.33	0.745
SOD*TS	0.000836	0.000506	01.65	0.129

Table:5 The estimated regression coefficient of KA

Term	Coef	SE Coef	T-Value	P-Value
Constant	0.3666	0.00760	48.26	0.000
JP	0.0958	0.00699	13.71	0.000
SOD	0.0522	0.00699	07.47	0.000
TS	0.0643	0.00699	09.20	0.000

JP*JP	0.0158	0.01330	01.18	0.264
SOD*SOD	0.0398	0.01330	02.98	0.014
TS*TS	0.0127	0.01330	00.96	0.362
JP*SOD	0.0370	0.00781	04.74	0.001
JP*TS	0.0145	0.00781	01.86	0.093
SOD*TS	0.0105	0.00781	01.34	0.209

Table:6 The estimated regression coefficient of Ra

Term	Coef	SE Coef	T-Value	P-Value
Constant	1.5283	0.0140	109.15	0.000
JP	0.1478	0.0129	11.48	0.000
SOD	0.1000	0.0129	07.76	0.000
TS	0.1567	0.0129	12.17	0.000
JP*JP	0.0107	0.0246	00.44	0.672
SOD*SOD	0.0513	0.0246	02.09	0.063
TS*TS	0.0172	0.0246	00.70	0.499
JP*SOD	0.0193	0.0144	01.34	0.211
JP*TS	0.0045	0.0144	00.31	0.761
SOD*TS	0.0110	0.0144	00.76	0.463

3.4. Effect of control parameters on MRR

The three dimensional (3D) response surface plot of the control response (dependent parameter) for MRR is shown in Fig.5. It is noticed be seen from Fig.5.(a), that the highly significant influences of SOD on MRR compare to JP. Acceleration energy of Garnet increases with increase in JP. When this abrasive come out of the nozzle, the collision of these hard abrasives with itself will increase the width of the water beam. This influence the cutting surface and consequence to remove more material. Further increase in the width of the beam is noticed with a change in SOD. At low JP the rate of increase of MRR is low with respect to SOD ,TS and SOD surface Fig.5.(b), shows that MRR of aluminium reduced on increase in TS, where an increase in MRR is observed with increase in JP. High TS lowers the machining time and produces surface waviness and coarse surface in the rough cut region.

The rate of increase in MRR for the range 220 bar–240 bar is high compared to a range of 240 bar–260 bar. This is due to the hardness of the Garnet abrasive and the influence of the wider water beam. A similar trend is noticed in Fig.5.(c) for both the SOD and TS, which affect the MRR of the composite to a greater extent. Fig.5.(d) presents the distribution of the residual value over the mean value. To acquire a minimum of MRR, the predicted working condition of the independent variable are suggested to be a JP = 220 bar, SOD = 1 mm, and TS = 40 mm/min.

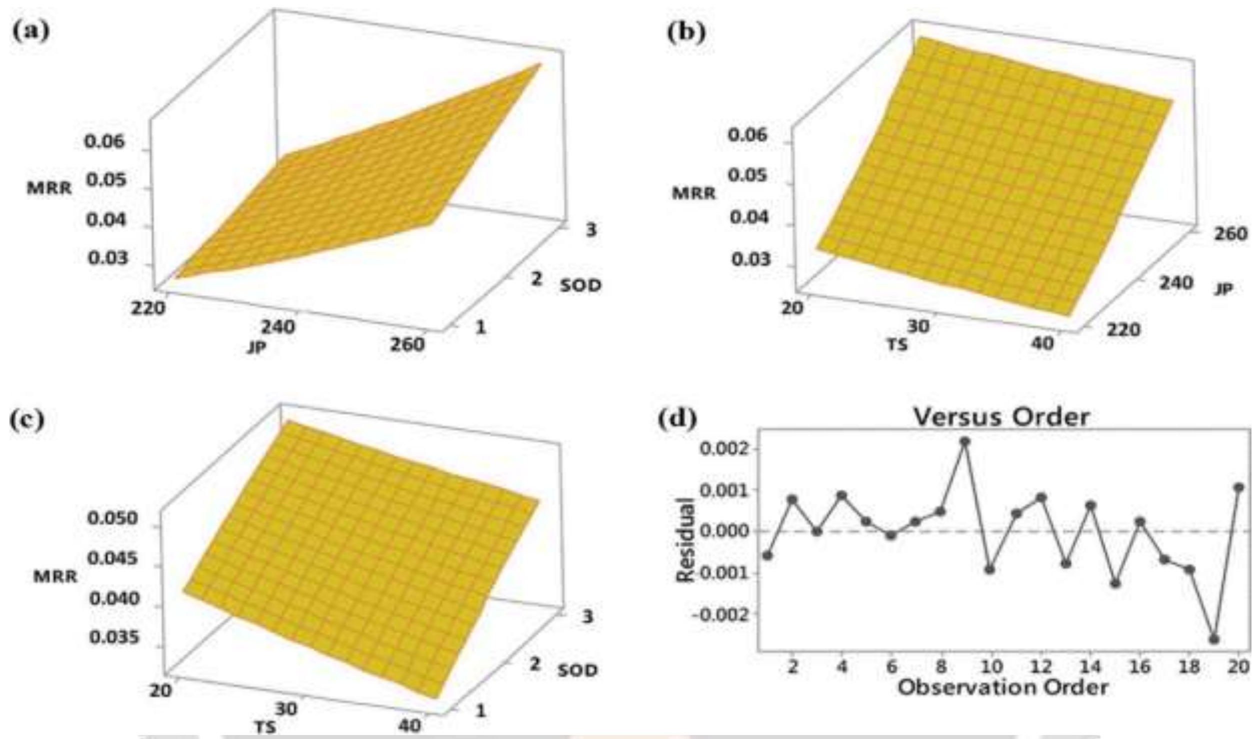


Fig.5. Surface plots of the combined effects of the independent parameters on MRR. (a) JP-SOD, (b) TS-JP, (c) TS-SOD, (d) MRR Residual Experimental order

3.5. EFFECT OF CONTROL PARAMETERS ON KA

The 3-D surface plot of the influencing independent parameters of KA is shown in Fig.6.where Fig.6.(a), a slight decrease with increase effect is observed for KA with the progressive increase in JP and SOD. Fig.6.(b) presents that there is a linear change in KA on increase in JP where an increase with decreasing effect is observed for TS. Fig.6.(c) shows a slight decrease and progressive rise in KA with a change in SOD, where a slight rise and fall on TS is recorded. Fig.6.(d) shows the distribution of the residuals from the mean and from the chart, it is interpreted that this model fits the experimental observations. From the result, it is observed that the influence of JP and TS are high irrespective of SOD. To perform a cutting operation in AWJM for this composite, a minimum level of JP and TS is recommended. An increase in TS irrespective of JP, the high accelerated hard abrasives fails to machine the bottom cut region because of the reduced machining time. This leads to having large KA value. In AWJM, with the JP of 240 bar and TS of 30 mm/min, a fine surface finish is ensued with a considerable increase in MRR. To reduce this effect, the developed model gives a new level for SOD. The hard Garnet, abrasives when it impinges the surface makes the deep cut and it wear the kerf surface with minimum distortion on aluminium composite. The optimum working condition to acquire minimum KA is predicted to be a JP = 220 bar, SOD = 1.6869 mm and TS = 20 mm/min.

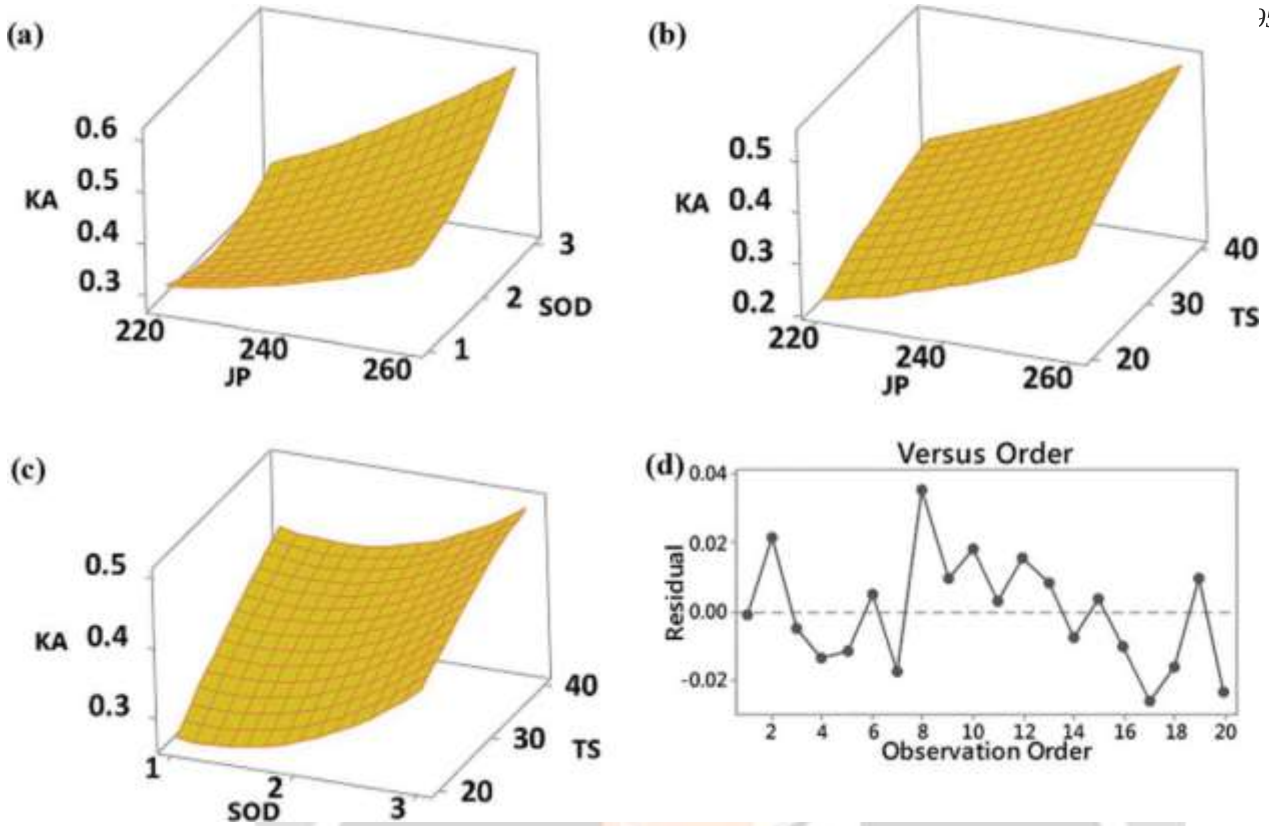


Fig.6. Surface plots of the combined effects of the independent parameters on KA. (a) JP-SOD, (b) JP-TS, (c) SOD-TS, (d) KA Residual Experimental order

3.6. EFFECT OF CONTROL PARAMETERS ON Ra

The 3-D response surface plot for Ra of the predicted model is shown in Fig.7. The combined effect of JP and SOD with Ra is shown in Fig.7. (a). The contribution of these two parameters on Ra is found to be equal to all considered levels. The combined regression surface plot of JP and TS on Ra is shown in Fig.7. (b). The significant effect of TS is high on the increase in JP. Fig.7. (c) shows the influencing effect of SOD and TS of Ra. The high significant level of TS on Ra is observed. Meanwhile, the Ra rate reduces with SOD to some extent that it increases with increase in TS. The Fig.7. (d) shows the distribution of the residuals plots from the mean. The values are distributed around the mean and the observed experimental values are in the acceptable level. From Fig.7.(a–c), it is seen that Ra effects for the three independent parameters have a significant effect on Ra. However the rate of change of the three influencing factors on Ra increase with the increase in levels. On sudden cooling, these surfaces impart micro cracks and flaws which could be visualized on SEM image when machined at high levels in AWJM. The minimum observation of Ra will be achieved when JP = 220 bar, SOD = 1.3232 mm and TS = 20 mm/min.

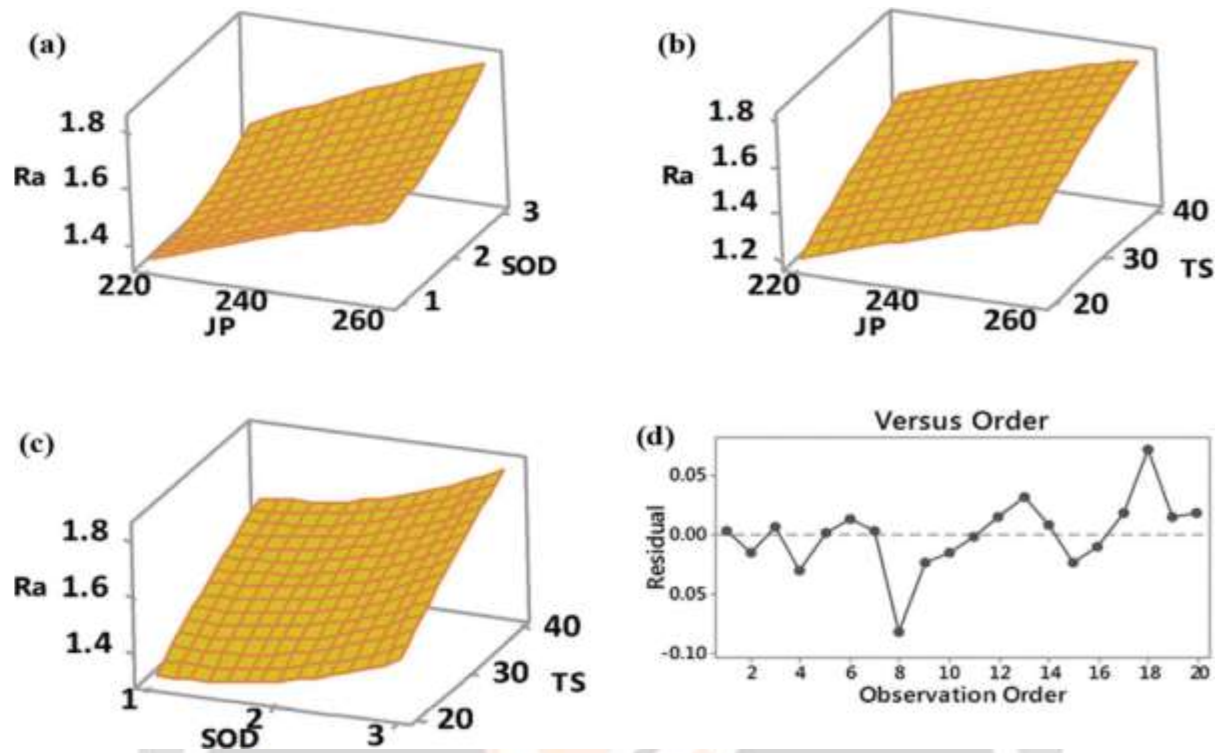


Fig.7. Surface plots of the combined effects of the independent parameters on Ra. (a) JP-SOD, (b) JP-TS, (c) SOD-TS, (d) Ra Residual- Experimental order

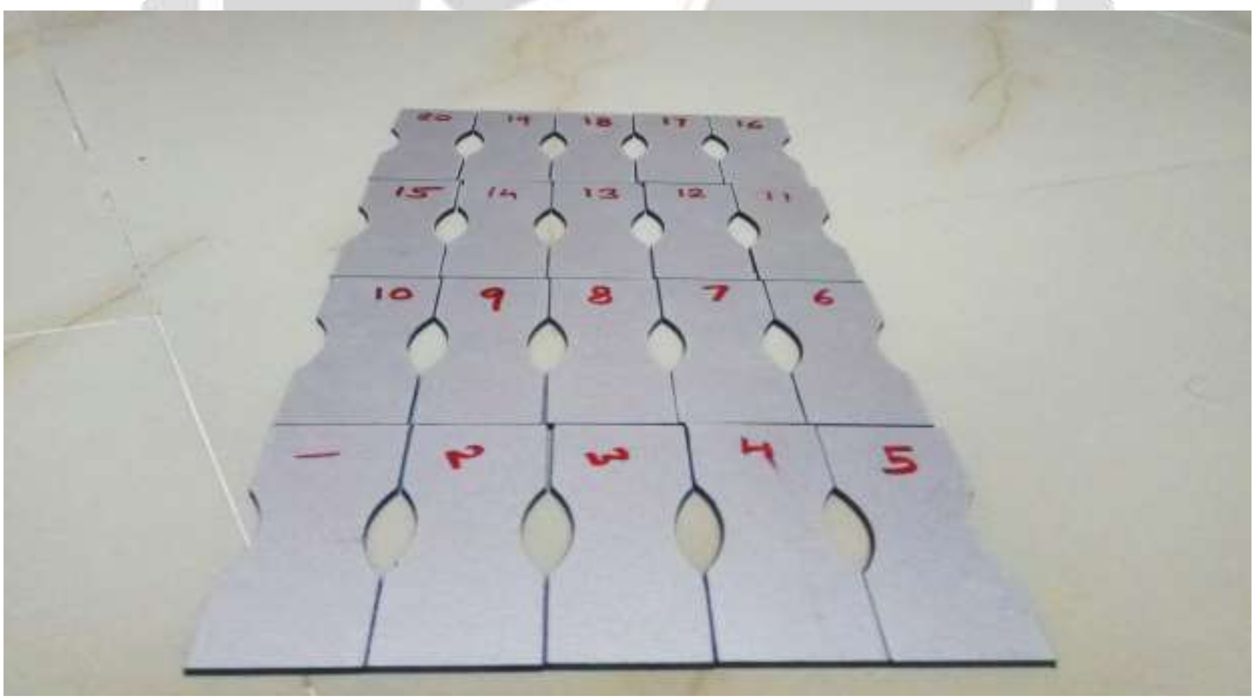


Fig.8. Aluminium composite material after machining

4.CONCLUSION

The AWJ machining of aluminium composite prepared by the aqueous sol-gel process is successfully performed to the L20 orthogonal array. The significant effect of each independent variable (JP, SOD, and TS) of

AWJM on the output responses (MRR, KA, and Ra) is examined through the central composite design of RSM and it is concluded as follows:

- From the observations, it can be stated that all the three considered independent parameters had played a significant role in the output responses. Generally, JP can be defined as a significant parameter in all observations and this is due to the hardness of the Garnet abrasive.
- From the ANOVA table of MRR, it is estimated that the three independent parameters affect the MRR in the following order; JP, SOD, and TS. A least significant effect is observed by Quadratic SOD and TS, respectively. To the interaction part, the least effect of JP and TS is recorded.
- By the ANOVA table of KA, the influencing factors are in the order as follows, JP, followed by TS and SOD. Among the other determinant factors, quadratic JP and TS, respectively and one interaction part of SOD and TS have a least significant effect.
- By ANOVA table of Ra, it is stated that TS have the most significant role, followed by JP and SOD. Least influencing parameters that affect the Ra is predicted to be the quadratic JP and TS, respectively and one interaction factor of JP and TS.
- The predicted optimization conditions for each output responses of the aluminium composite in AWJM are estimated to be; for MRR is JP = 220 bar, SOD = 1 mm, and TS = 40 mm/ min, for KA, is JP = 220 bar, SOD = 1.6869 mm, and TS = 20 mm/min and for Ra JP = 220 bar, SOD = 1.3232 mm and TS = 20 mm/min.

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