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Material Synthesis, Characterization and Machining Performance of Stir Cast Beryllium Copper Alloy Composites

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Abstract

Copper alloys play an important role in industrial fields due to their excellent properties. Beryllium Copper is one of the copper-based alloys which have the highest strength, excellent metal working and machining properties. Beryllium copper alloy composite is fabricated by Stir cast method. The characterization is studied through a Scanning Electron Microscope (SEM) and Energy Dispersive Analysis of X-rays (EDAX). The material properties of the stir cast Beryllium copper alloy composites are evaluated. Further, its hardness can be increased by the addition of Silicon Carbide particles. Abrasive water jet machining (AWJM) is one of the effective unconventional machining processes. In this process, high pressure water jet and abrasive particles are used to remove the material. The response parameters such as Material Removal Rate (MRR) and Circularity of the holes are considered. The comparison of machining with Electrical Discharge Machining (EDM) is also studied. The most influential factor which affects the responses is found out by Analysis of Variance (ANOVA). The optimization of machining parameters is performed through Taguchi method.

Keywords: Beryllium copper metal matrix, Abrasive water jet machining, SEM, Taguchi method, EDAX.

1. INTRODUCTION

Nowadays, a number of studies which focus on copper metal matrix have considerably increased due to exceptional properties, namely strength, ductility, malleability and corrosion resistance (Moshkovich.A.et al.2014). Beryllium exhibits excellent material properties when added as an alloying element into Copper. It is used in spring wires, load cells, precision measurement devices, bullets, and aerospace applications (Li.S.et al.2011).An experimental investigation was carried out in the hot rolling process of synthesized Cu-Al-Be-Mn alloy (Shivasidaramaiah A.G and Mallikarjun U.S. 2014). The high strength beryllium alloy was fabricated, and its properties were evaluated (Altenberger, I .et al.2015).The rapid solidification and grain sizes were studied for Cu-Al-Be alloy composites (Lara Rodriguez G.A.et al.2006).

Ceramics and aluminium materials were machined by abrasive water jet machining process and its predicted model was achieved (Wang.J. 2009). A surface roughness experimental investigation was carried out in abrasive water jet cutting of copper (Chithirai pon selvan M. 2012). Traverse speed was an influential parameter which has been found on abrasive water jet machining of the Ti-6Al-4V alloy (Hascalik et al. 2007). Unconventional machining processes, namely EDM and AWJM were used to machine the polymer matrix composites (Wang.J. 1999). High strength copper and brass alloys were machined by the EDM process (Amorim.F.L and Weingaertner W. L. 2004)(Marichamy.S.et al.2014).Abrasive water jet machining is the efficient material removal process that has more advantages such as high flexibility, lower cutting force and no thermal stresses are produced during machining process (Cojbasic et al.2016).The control parameters such as traverse speed, abrasive flow rate and abrasive size affected the machined surface (Lee K.C et al.2005).Taguchi design was used to reduce the number of experiments. (Sreenivasa Rao M.et al.2014)

The predicted model was used to measure the performance of material removal rate and surface roughness during machining of copper (Chithirai Pon Selvan and Mohanasundara Raju. 2012).The grain refinement and crack prevention were studied in order to study the phase behavior of Cu-Zn alloy (Peng.K et al.2007).In AWJM process, nozzle traverse speed and water pressure were the most influencing factors for MRR and SR (Nagdeve.L.et al.2012).The effects of machining parameters on the surface roughness were found in AWJM process. The grit size was the predominant factor which affected the surface roughness during the Taguchi method

(Ramulu and Arola 1994). In AWJM process, it is noticed that the machining accuracy was influenced by high cutting speed (Azmir M.A. and Ahsan A.K. 2008). Taguchi Method is one of the effective methods to find out the optimal combination of parameters (Lin C.L. 2004).

In this experimental investigation, the material is fabricated through stir cast technique, and its material properties and characterization are studied. The material is machined by AJWM process. The aim of the experimental investigation is to maximize the material removal rate and minimize the circularity of the holes. The optimal combination of machining parameters is found out by Taguchi method. Abrasive effects of material removal rate and circularity of the holes were studied. The Comparison of machining with EDM is also studied.

2 MATERIAL SYNTHESIS AND CHARACTERIZATION

2.1 Stir casting process

The Beryllium copper alloy composites are fabricated through Stir cast technique. The Copper and Beryllium are placed in a crucible furnace and heated up to 1050°C. Silicon carbide particles are added into the molten matrix. The stirring is done at 700RPM for achieving the uniform composition throughout the mixture. The molten metal is poured into the mold and the desired shape and size of 100x50x8mm were achieved. The density of the Beryllium copper metal matrix is 8.44 gm/cm³. The Beryllium copper alloy composites properties are evaluated and shown in the table.1.

2.2 Material characterization

The material characterization is studied through SEM and EDAX. The morphology of the material is studied through SEM image as shown in Figure.1 (a-c). The silicon carbide particles are properly mixed and uniformly dispersed in the material and coarse structure is also shown in Figure.1 (a). Figure.1 (b) shows porosity and greater quantity of silicon carbide particles (dark flecks). The placement of the SiC particles along with copper surface is enlarged in Figure.1 (c).

The continuous reinforcement is achieved by silicon carbide and the particles are entrenched into the matrix in a convinced direction. The composition is confirmed through

EDAX as shown in Figure.2. Hardness and strength is increased by the addition of silicon carbides particles.

3 MACHINING PERFORMANCE

3.1 Machining by AWJM

The stir cast beryllium copper alloy composites were machined by AWJM. The water pressure, abrasive flow rate and traverse speed were considered as the control parameters. MRR and circularity of the holes are considered as the control parameters. Holes 6mm in diameter are made on the surface of the alloy composites. The inner diameter of the nozzle is 0.30mm. The size of the abrasive is 150 μ m with 80 meshes. The high pressurized water jet is achieved through an intensifier pump. The video measuring system is used to measure the circularity of the holes. The parameter levels are shown in the table.2

The responses such as MRR and Circularity of the holes were evaluated by varying the control parameters. Nozzle should be extremely defiant to abrasion and it is made of synthetic sapphire. Material removal rate mainly depends on the nature of abrasive materials. In this experimental investigation, aluminum oxide and silicon carbides are used as abrasives. The abrasive particle grit size is 50 microns and 1.5mm standoff distance is maintained between the nozzle and the work piece. The velocity of the abrasive particle is 200m/s. The experimental results with abrasive as aluminum oxide only is tabulated and shown in table 3(a). The Material removal rate decreased, and the circularity of the holes increased when aluminum oxide was used as an abrasive. The experimental results with abrasive as aluminum oxide and silicon carbides are tabulated and shown in table 3(b). The Material Removal Rate increased and the circularity of the holes decreased when both aluminum oxide and silicon carbides were used as the abrasives.

3.2 Comparison of machining processes

The stir cast beryllium copper alloy composites are machined by Electrical Discharge Machining (EDM) process. Copper Tungsten is considered as an electrode material. Kerosene is considered as a dielectric fluid. Holes 6mm in diameter were made on the surface of the metal

matrix. During machining process peak current (9 -15 amp), voltage (40-50V) and pulse on time (80-120 μ s) were considered as the control parameters, whereas material removal rate and circularity of the holes were considered as the response parameters. The comparison of machining with EDM process experimental results are shown in the table 3(c).

The comparison of machining shows that the better the performances are observed from AWJM process. The comparison of machining processes shown in Figure.3

4 PARAMETRIC OPTIMIZATION

4.1 Taguchi parametric optimization

The orthogonal array is used to provide the enhanced features and reduce the number of experiments. This quality optimization technique is known as Taguchi method. The L_9 orthogonal array is considered for three control parameters (Patel K.M.et al.2009).The deviation between the performance characteristics and the desired target values are measured through Taguchi loss of function. The values of the loss Function are converted to Signal to Noise ratio.

4.1.1 S/N ratio analysis for MRR

Maximum material removal rate and minimum circularity of the holes are achieved by AWJM process. Hence the present investigations are discussed with AWJM process. The response characteristics are calculated by the S/N ratio whether it may be minimized or maximum criteria according to the given experiment (Ugrasen et al.2015)(Sreenivasa Rao M et al.2014).In this experiment, maximum MRR and minimum circularity of the holes are considered. Hence, larger the better criteria are considered for MRR and smaller the better criteria for circularity of the holes. Mean of S/N ratio for MRR is shown in table 4.

Figure.4 shows the compound linear graph of major effects and their distinction between levels of the parameters for MRR. To achieve maximum MRR, 'larger the better' criterion was selected. Hence the optimal level of parameter A3B1C2 is selected from the graph as shown in the Figure.3. The optimal values for MRR are water pressure of 4000 bar, Traverse speed of 30 mm/min and abrasive flow rate of 150 gm/mm.

ANOVA is extensively used arithmetical tool for calculating the outcomes of experimentation to find the percentage of involvement of each parameter. It is also used to authenticate the effect of all factors and their relations by finding out the variation between the mean square and investigational errors at definite confident levels (Bobbili.R et al.2015) (Balamurugan.M et al.2015). In the current study, ANOVA was used to find out the influence of input process parameters namely, traverse speed, mass flow rate and water pressure on the material removal rate and circularity of the holes during machining of Copper metal matrix which is fabricated through stir cast method. Table 5 shows the results of ANOVA for MRR. It is accomplished that, the water pressure is the foremost factor influencing all the responses. The same results are attained from the SN ratio analysis.

Figure. 5 shows the interaction of traverse speed, mass flow rate and water pressure for the response MRR. It is noticed that, among all the input factors the most dominant factor was water pressure. Water pressure was also the most dominant factor on MRR.

4.1.2 S/N ratio analysis for Circularity of the holes

Since minimum circularity of the holes are required, 'smaller the better' characteristic is selected according to the required output characteristics. 'Lower than better' criteria have been considered for calculating the Signal to Noise Ratio. The mean of SN ratios for all the responses are given in Table 6.

Based on the minimum circularity of the holes, the optimal level of parameter A1B2 C3 were selected from the graph as shown in Figure.6

The optimal values for circularity of the holes are water pressure of 3000 bar, traverse speed of 60 mm/min and abrasive flow rate of 225 gm/mm. Table 7 shows the results of ANOVA for circularity of the holes. It is observed that, Water pressure is the leading contributing factor influencing all the responses like MRR and the circularity of the holes. The same results are attained from the SN ratio analysis.

Figure.7shows the interaction of traverse speed, mass flow rate and water pressure. It is noticed that , the most dominant factor is water pressure among the input factors and water

pressure has more effect on the circularity of the holes. A Mathematical model has been developed for abrasive water jet machining of beryllium copper metal matrix and it is used to predict the responses such as material removal rate and circularity of the holes. Mathematical models are required to control and optimize the process (Wang 2007).

$$\text{MRR (g/min)} = 10.700 - 1.803 A - 0.250 A + 2.053 A + 0.567 - 1.057 B + 0.490 - 1.020 C + 0.640 C + 0.380 C$$

$$\text{Circularity of the holes (mm)} = 6.2078 - 0.0278 A + 0.0122 A + 0.0156 A - 0.0478 B + 0.0289 B + 0.0189 B + 0.0889 C - 0.0511 C - 0.0378 C$$

5 CONTOUR PLOT ANALYSES

5.1 Contour plots for MRR

Figure.8 shows the contour plots for MRR (a) water pressure versus traverse speed (b) water pressure versus abrasive flow rate (c) traverse speed versus abrasive flow rate. Figure.8(a) shows the higher MRR is achieved when the water pressure is 4000 bar and traverse speed is 90mm/min. Figure.8(b) shows the higher MRR is achieved when the water pressure is 4000 bar and abrasive flow rate is 140-200 gm/min. It is very clear that if the water pressure increased, the MRR also can be increased. The rate of metal cutting has been improved by high pressurized garnet abrasive particle (Pramanik.A.2014). No thermal distortion occurred during machining of materials in AWJM process. Rate of machining mainly depends on the type of abrasive mesh size and machining parameters. Figure.8(c) shows the higher MRR is achieved when the traverse speed is 90mm/min and abrasive flow rate is 140-160 gm/min.

5.2 Contour plots for circularity of the holes

Figure 9 shows the contour plots for circularity of the holes (a) water pressure versus abrasive flow rate (b) water pressure versus traverse speed (c) traverse speed versus abrasive flow rate. Figure 9(a) shows the circularity of the holes is increased at the higher level of water pressure. Figure 9(b) shows the circularity of the holes is decreased when the water pressure is 3200-3400 bar and traverse speed is 50-60mm/min. Figure 9(c) shows the higher circularity of

the holes can be achieved when the traverse speed is 90mm/min and abrasive flow rate is 170 gm/min.

6 CONCLUSIONS

- The Beryllium copper metal matrix is synthesized by Stir Cast method successfully.
- The morphology of the material is studied through a SEM and composition is confirmed through an EDAX.
- The Beryllium copper metal matrix properties are measured and possess better hardness (130BHN) and tensile strength (490 Mpa).
- The Stir cast beryllium copper metal matrix is successfully machined by AWJM process.
- The material removal rate increased and the circularity of the holes decreased, when both aluminum oxide and silicon carbides were used as the abrasives.
- The comparison of machining with EDM process is also discussed. The better performances are achieved by AWJM process.
- The optimal solutions are found out by Taguchi method and its listed below
 - For MRR : Water pressure is 4000bar, Traverse speed is 30 mm/min
Abrasive flow rate is 150 gm/min.
 - For Circularity: Water pressure is 3000bar, Traverse speed is 60 mm/min
Abrasive flow rate is 225 gm/min.
- From Analysis of Variance, the water pressure is the most dominant factor to affect the responses such as MRR and Circularity of the holes.
- From contour plot analysis, the interactions between control parameters and response parameters are studied.

REFERENCES

Altenberger, I., Kuhn, H. A., Müller, H. R., Mhaede, M., Kermanshahi, M. G., and Wagner, L. 2015. Material properties of high strength beryllium free copper alloys, *Int. J. Mater. Prod. Tec.* 50(2):124-146. <https://doi.org/10.1504/IJMPT.2015.067820>.

- Amorim.F.L and Weingaertner W. L. 2004. Die-Sinking Electrical Discharge Machining of a High-Strength Copper Based Alloy for Injection Molds, *J. of the Braz. Soc. of Mech. Sci. & Eng.* 26(2):137-144. <http://dx.doi.org/10.1590/S1678-58782004000200004>.
- Azmir M.A. and Ahsan A.K.2008. Investigation on glass/epoxy composite surfaces machined by abrasive water jet machining, *J.Mater.Proc. Technol.*198(1-3):122-128. <https://doi.org/10.1016/j.jmatprotec.2007.07.014>.
- Balamurugan.M, Biswanath.M and Sukamal.G.2009. Optimisation of machining parameters for hard machining: grey relational theory approach and ANOVA, *Int. J. Adv.Manuf. Technol.*45(11-12):1068–1086. 45.1068-1086. <https://doi:10.1007/s00170-009-2054-3>.
- Bobbili.R,Madhu.V and Gogia.2015.Multi response optimization of wire cut EDM process parameters of ballistic grade aluminium alloy, *Int.J.Eng.Sci.Techol.*18(4):720-736. <https://doi.org/10.1016/j.jestch.2015.05.004>
- Chithirai Pon Selvan and Mohanasundara Raju. 2012. Selection of process parameters in abrasive water jet cutting of copper, *Int. J. Adv.Eng. Sci. Technol.*7(2):254 – 257.
- Chithirai pon selvan M. 2012. Surface roughness in abrasive water jet cutting of copper – An experimental study, *Eng. Sci. Technol. Int. J.*2(3):372-376.
- Cojbasic, Petkovic ,Shamshirb, Tong,Sudheer, Jankovic and Ducic Baralic.2016.Surface roughness prediction by extreme learning machine constructed with abrasive water jet, *Precis. Eng.*43:86 –92.<https://doi.org/10.1016/j.precisioneng.2015.06.013>.
- Hascalik, Ahmet, Caydas.U and Gurun.H. 2007.Effect of traverse speed on abrasive water jet machining of Ti–6Al–4V alloy, *Mater. Des.*28(6):1953-1957.<https://doi.org/10.1016/j.matdes.2006.04.020>.
- Lara Rodriguez G.A., Gonalez G., Flores zuniga H., and Cortes perez J. 2006. The effect of rapid solidification and grain size on the transformation temperature of Cu-Al-Be alloys, *Mater. charact.* 57(3):154-159. <https://doi.org/10.1016/j.matchar.2005.12.017>.
- Lee K.C, Ho S.J and Ho S.Y.2005.Accurate estimation of surface roughness from texture features of the surface image using an adaptive neuro-fuzzy inference system, *Precis.Eng.* 29(1): 95-100. <https://doi.org/10.1016/j.precisioneng.2004.05.002>.
- Li.S, Imai.H,Atsumi.H and Kondoh.K. 2011. Contribution of Ti addition to characteristics of extruded Cu40Zn brass alloy prepared by powder metallurgy, *Mater. Des.* 32(1):192-197. <https://doi.org/10.1016/j.matdes.2010.06.008>.

- Lin C.L.2004. Use of the taguchi method and grey relational analysis to optimize turning operations with multiple performance characteristics, *Mater. Manuf. Proc.*19(4):209–220. <https://doi.org/10.1081/AMP-120029852>.
- Marichamy.S , Saravanan.M, Ravichandran.M and G. Veerappan. 2016. Parametric optimization of electrical discharge machining process on α - β brass using grey relational analysis, *J. Mater. Res.*31(16):2531-2537. <https://doi.org/10.1557/jmr.2016.213>.
- Moshkovich.A, Perfilyev.V, Lapsker.I and Rapoport.L. 2014. Friction, wear and plastic deformation of Cu and brass under lubrication conditions.*Wear.*320:34-40. <https://doi.org/10.1016/j.wear.2014.08.016>.
- Nagdeve.L,Chaturvedi.V and Vimal, J.2012.Implementation of Taguchi approach for optimization of abrasive water jet machining process parameters, *Int. J. Instr. Cont. Automation.* 1(3):9-13.
- Patel K.M,Pandeya P.M and Venkateswara Rao P.2009. Determination of an optimum parametric combination using a surface roughness prediction model for EDM of $\text{Al}_2\text{O}_3/\text{SiC}_w/\text{TiC}$ ceramic composite, *J.Mater.Manuf.Proc.*24(6):675-682.<https://doi.org/10.1080/10426910902769319>.
- Peng.K, Su. L,Shawb L.L and Qian K.W.2007. Grain refinement and crack prevention in constrained groove pressing of two-phase Cu–Zn alloys, *Sci. Mater.*56(11):987–990.<https://doi.org/10.1016/j.scriptamat.2007.01.043>
- Pramanik.A.2014. Developments in the non-traditional machining of particle reinforced metal matrix composites, *Int. J. Mach.Tool Manu.*86:44–61.<https://doi.org/10.1016/j.ijmachtools.2014.07.003>
- Ramulu and Arola.1994. The influence of abrasive water jet cutting conditions on the surface quality of graphite/epoxy laminates, *Int. J. Mach. Manuf.*34(3):295-313. [https://doi.org/10.1016/0890-6955\(94\)90001-9](https://doi.org/10.1016/0890-6955(94)90001-9).
- Shivasidaramaiah A.G and Mallikarjun U.S. 2014. Synthesis of Cu-Al-Be-Mn shape memory alloys, *Procedia Mater.Sci.*5:242 – 247. <https://doi.org/10.1016/j.mspro.2014.07.263>.
- Sreenivasa Rao M, Ravinder S and Seshu Kumar A. 2014. Parametric optimization of abrasive water jet machining for mild steel-Taguchi Approach,*Int.J. Curr. Eng. Technol.* 2:28-30

Ugrasen, Ravindra, Naveen Prakash and Theertha Prasad.2015.Optimization of process parameters in wire EDM of HCHCr material using taguchi's technique, Mater.Today:Proceed.2(4-5):2443-2452. <https://doi.org/10.1016/j.matpr.2015.07.185>.

Wang.2007. Predictive depth of jet penetration models for abrasive water jet cutting of alumina ceramics, Int. J. Mech.Sci. 49(3):306–316. <https://doi.org/10.1016/j.ijmecsci.2006.09.005>.

Wang.J. 1999. A machinability study of polymer matrix composites using abrasive waterjet cutting technology, J.Mater.Proc. Technol.94(1):30-35. [https://doi.org/10.1016/S0924-0136\(98\)00443-9](https://doi.org/10.1016/S0924-0136(98)00443-9).

Wang.J. 2009, A new model for the prediction of depth of cut in abrasive water jet contouring of alumina ceramics, J.Mater.Proc. Technol.209(5):2314-2320. <https://doi.org/10.1016/j.jmatprotec.2008.05.021>.

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Table 1 Material properties of the copper metal matrix

S. No.	Equipment used	Properties	No. of Samples	Values	Results	Std. Dev
1	Brinell hardness tester	Hardness	3	126,128,136	130BHN	5.29
2	Universal testing machine	Tensile strength	3	480,480,510	490 Mpa	17.32
3	Izod impact tester	Impact strength	3	11,10,15	12J	2.64
4	Universal testing machine	Percentage of elongation	3	12,14,13	13%	1.0

Table 2 Level of control parameters

Levels	Water Pressure (bar)	Traverse Speed (mm/min)	Abrasive Flow rate (gm/mm)
1	3000	30	75
2	3500	60	150
3	4000	90	225

Table 3 (a) Experimental results with abrasive as aluminum oxide

S. No.	A:Water Pressure (bar)	B:Traverse Speed (mm/min)	C:Abrasive Flow rate (gm /mm)	MRR (gm/min)	Circularity of the holes (mm)
1	3000	30	75	3.43	7.10
2	3000	60	150	5.32	7.08
3	3000	90	225	7.56	7.34
4	3500	30	150	9.45	7.21
5	3500	60	225	8.85	8.09

6	3500	90	75	4.87	8.02
7	4000	30	225	10.02	6.88
8	4000	60	75	6.77	6.56
9	4000	90	150	11.21	7.13

Table 3(b) Experimental results with abrasive as aluminum oxide and silicon carbides

S. No.	A:Water Pressure (bar)	B:Traverse Speed (mm/min)	C:Abrasive Flow rate (gm /mm)	MRR (gm/min)	Circularity of the holes (mm)
1	3000	30	75	9.12	6.08
2	3000	60	150	8.23	6.09
3	3000	90	225	9.34	6.11
4	3500	30	150	11.23	6.02
5	3500	60	225	10.45	6.04
6	3500	90	75	9.67	6.03
7	4000	30	225	13.45	5.98
8	4000	60	75	10.25	6.01
9	4000	90	150	14.56	5.99

Table 3(c) Comparison of machining with EDM experimental results

S. No.	AWJM		EDM	
	MRR (gm/min)	Circularity of the holes (mm)	MRR (gm/min)	Circularity of the holes (mm)
1	9.12	6.08	6.45	7.73

2	8.23	6.09	6.35	7.22
3	9.34	6.11	7.32	7.64
4	11.23	6.02	9.65	7.06
5	10.45	6.04	8.89	7.31
6	9.67	6.03	7.12	7.41
7	13.45	5.98	11.23	6.54
8	10.25	6.01	7.78	6.97
9	14.56	5.99	11.78	7.20

Table 4 Mean of S/N ratio for MRR

Level	Water pressure(bar)	Traverse speed(mm/min)	Abrasive flow rate(gm/mm)
1	8.897	11.267	9.680
2	10.450	9.643	11.340
3	12.753	11.190	11.080
Delta	3.857	1.623	1.660
Rank	1	3	2

Table 5 ANOVA table for the MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Water pressure	2	22.9	11.30	10.72	0.085
Traverse speed	2	5.03	2.51	2.39	0.30
Abrasive flow rate	2	4.78	2.39	2.27	0.31
Error	2	2.11	1.05		
Total	8	34.52			

S=1.0264; R-sq=93.89 % ; R-sq (adj)=86.67 %

Table 6 Mean of S/N ratio for Circularity of the holes

Level	Water pressure(bar)	Traverse speed(mm/min)	Abrasive flow rate(gm/mm)
1	6.093	6.027	6.040
2	6.030	6.047	6.033
3	5.993	6.043	6.043
Delta	0.100	0.020	0.010
Rank	1	2	3

Table 7 ANOVA table for circularity of the holes

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Water pressure	2	0.0153	0.0077	53.15	0.018
Traverse speed	2	0.0007	0.0003	2.38	0.30
Abrasive flow rate	2	0.0002	0.00008	0.54	0.65
Error	2	0.0003	0.0001		
Total	8	0.01648			

S=0.01201; R-sq=98.25 % ; R-sq (adj)=92.99 %

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Fig.7 Interaction curve for circularity of the holes

Fig. 8 Contour plots for MRR (a) water pressure versus traverse speed (b) water pressure versus abrasive flow rate (c) traverse speed versus abrasive flow rate

Fig.9 Contour plots for circularity of the holes (a) water pressure versus abrasive flow rate (b) water pressure versus traverse speed (c) traverse speed versus abrasive flow rate