iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 9 **Issue:** V **Month of publication:** May 2021

DOI: https://doi.org/10.22214/ijraset.2021.34356

An Investigation on Cut Quality and Geometrical Effect of Flyash and Hybrid AL7075 Metal Matrix Composites by Abrasive Waterjet Cutting

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Abstract: Metal matrix composites are difficult to machine in traditional machining methods. Abrasive water jet machining is a state-of-the art technology which enables machining of practically all engineering materials. Abrasive water jet machining is a very efficient machining process which overcomes tool wear issues and cutting temperature issues. This experimental investigates a particular study performed on hybrid metal matrix composites prepared by AL7075 and reinforced with 5% B_4C, 3% fly ash and 1% Mg in aluminum alloy and processed with abrasive water jets that are formed with garnet 80 mesh size. Particularly roughness average majorly influences with water jet traverse speed. Among interaction effects stand of distance and water jet traverse speed combination seen to contribute more on water pressure. Although developing the statistical models for predicting the depth of jet penetration achievable with Abrasive water jet produced by the variation of different process parameters. The study carried out in this work would help to choose the parameters carefully.
Keywords: Abrasive Water jet Cutting, Abrasives, Metal Matrix Composites, Sand Casting

I. INTRODUCTION

Abrasive water jet machining (AWJM) is a mechanical material removal process used to erode holes and cavities by the impact of abrasive particles of the slurry on hard and brittle materials. Since the process is non- thermal, non-chemical and non-electrical and it creates no change in the metallurgical and physical properties of the work piece.

II. BASIC PRINCIPLE

Abrasive Water Jet Machining is a non-traditional machining process, which makes use of the principles of Abrasive Jet Machining (AJM) and Water Jet Machining (WJM). The Abrasive Jet Machining process involves the application of a high-speed stream of abrasive particles assisted by the pressurized air on to the work surface through a nozzle of small diameter. Material removal takes place by abrading action of abrasive particles. Water jet machining is an erosion process technique in which water under high pressure and velocity precisely cuts through and grinds away minuscule amounts of material. The addition of an abrasive substance greatly increases the ability to cut through harder materials such as steel and titanium. Water jet Machining is a cold cutting process that involves the removal of material without heat. This revolutionary technology is an addition to non- traditional cutting processes like laser and plasma, and is able to cut through virtually any material. The water jet process is combined with CNC to precisely cut machine parts and etch designs. Since water jet machining is done with abrasives, it is often synonymous with abrasive jet cutting.
The combination of compressor, plumbing and cutting heads accomplishes the pressure and velocity to attain the cutting ability. High-pressure compressors create a jet of water under extreme pressure that exceeds the speed of sound. This slim jet of water produced from a small nozzle creates a clean cut. Before cutting, the materials are carefully laid on top of slates over or submerged in the catch tank.
Abrasive water jet uses the technology of high-pressure water typically between 2069 and 4137 bar, to create extremely concentrated force to cut stuff. A water cutter pressurizes a stream of pure water flow (without abrasive) to cut materials such as foam, rubber, plastic, cloth, carpet and wood. Abrasive jet cutters mix abrasive garnet to a pressurized water stream to cut harder materials. Examples are stainless steel, titanium, glass, ceramic tile, marble and granite. Water jet metal cutting machine yields very little heat and therefore there is no Heat Affected Zone (HAZ). Water jet machining is also considered as "cold cut" process and therefore is safe for cutting flammable materials such as plastic and polymers. With a reasonable cutting speed setting, the edges resulting are often satisfactory. Vin Abrasive Water Jet Machining, the abrasive particles are mixed with water and forced through the small nozzle at high pressure so that the abrasive slurry impinges on the work surface at high velocity.

Each of the two components of the jet, i.e., the water and the abrasive materials have both separate purpose and a supportive purpose. The primary purpose of the abrasive material in the jet stream is to provide the erosive forces. The water in the jet acts as the coolant and carries both the abrasive metric and eroded material to clear of the work. The schematic diagram of abrasive water jet machining process is shown in Figure 1

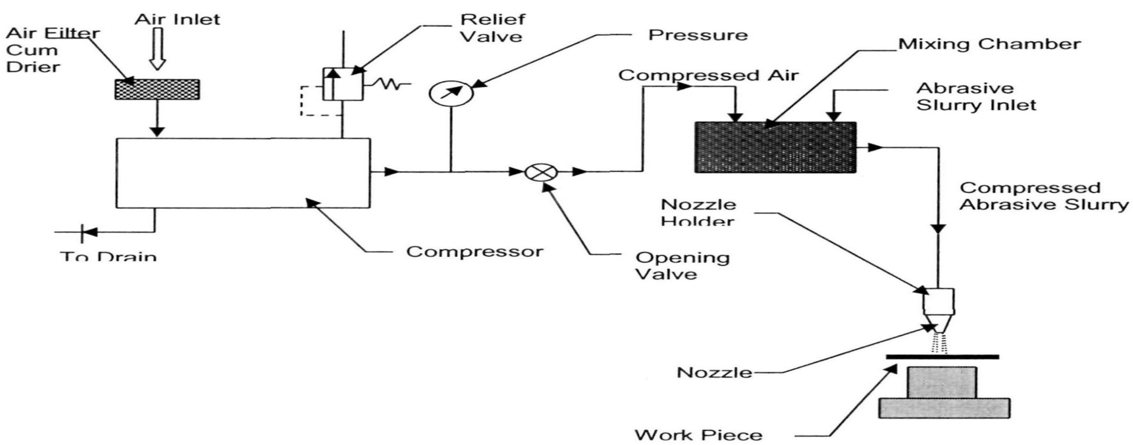

Figure 1. Abrasive water jet machining process

A. Abrasive Slurry

The slurry used in this process is a mixture of abrasive particles and a liquid component, mainly water. The ratio of abrasive to liquid can vary from 1: 6to 1: 14 (by volume). Slurry is to be fed through the nozzle, which directs the abrasive slurry centrally to the work piece. The slurry serves several purposes. It carries and distributes the abrasive grains on the work surface thus, removes the waste material and cools the work piece avoiding thermal stresses. The abrasives normally used in the process are boron carbide (cubic boron nitride), silicon carbide, aluminium oxide, garnet, tin oxide etc,.

B. Workpiece

The work piece material may be of any size and shape. It is held by means of a fixture. Many of the difficult to work materials may be machined by abrasive water jet machining. The abrasive water jet machining technique is especially suited for hard materials like tungsten carbide, titanium carbide and ceramics. Materials which exhibit high hardness and which have high impact brittleness can be successfully machined by this technique. Such materials are germanium, ferrites, glass and quartz. These materials often cannot withstand the forces needed for ordinary mechanical working.

C. Material Removal Mechanism

The main mechanisms responsible for the material removal in abrasive water jet machining are listed below.

1) Direct impact of the abrasive particles on the work piece.
2) Impact of the free moving abrasive particles on the work piece.
3) Erosion of the work surface due to cavitations effect of the abrasive slurry.
4) Chemical action associated with the fluid used.

D. Parameters

The different parameters, which influence the performance of abrasive water jet machining are:

1) *Machining Parameters:* The important machining parameters are type and size of the nozzle and Stand-off-distance which greatly influences the performance of abrasive water jet machining.
2) *Abrasive Slurry Characteristics:* The main characteristics of abrasive slurry is its type and size, its hardness and fracture tendency, the type of fluid used for forming the abrasive slurry and the concentration of the abrasive particles in the slurry. The above said characteristics influence the material removal rate along with the accuracy and surface finish.
3) *Work Piece Properties:* The properties such as Hardness, brittle and fracture characteristics, strength and fatigue properties of the work piece determine the machining rates. The other properties such as toughness, young's modulus also play some role in determining the rate of machining.

E. Applications

Abrasive water jet machining is used mostly to cut stronger materials such as steel, and even some tool steels can be cut. Though the applications are

Somewhat limited listed below are some of the applications.

1) *Machining Tool Steel:* Abrasive water jet cutting can be effectively used for cutting tool steels. Tool steel is generally very difficult to cut with conventional machining methods and may result in heat that could alter the metallurgical structure of the material. Abrasive water jet cutting, however, do not produce appreciable amount of heat and the metallurgical structure of the material is not altered thus the strength of the tool is retained.
2) *Manufacturing Industry:* The abrasive water jet machining is used to cut any profile required by Automobiles, Ships and Aircrafts. The glass industry calls for artistic work on different glass materials.
3) *Construction Industry:* To cut ceramic tile, mosaic and marble or granite for home/ commercial building or even pavement decoration the abrasive water jet cutting often referred as marble cutter or graphite cutting machine or granite cutter, can be effectively used.

III. LITERATURE SURVEY

The attempt is made to investigate the average surface roughness value of aluminium 6061 and its composites along the depth of penetration. The water jet pressure and traverse speed of the jet has a significant effect of average surface roughness of cut samples [1]. The experimental investigation are essentially meant to assess the penetration ability of abrasive water jets on different compositions of Al-SiCp MMCs produced by stir casting method. Abrasive water jet cutting experiments were conducted on trapezoidal shaped specimens of different composites as well on the constituent materials i.e., 100% aluminum alloy and 100% SiC specimens by varying water pressure, jet traverse speed and abrasive mass flow rate, each at three different levels[2]. It was presented a set of studies performed on turning of aluminum-silicon carbide metal matrix composite. The metal matrix composites are prepared by addition of 5, 10, 15% of SiC in aluminum alloy; the specimens are produced by stir casting method [3]. AA6061-B4C- CNT was machined using Abrasive Water jet Machining under different process parameters such as mesh size, abrasive flow rate, pressure and traverse speed. Boron carbide was used as reinforcement and Carbon Nanotube (CNT) was used as a solid lubricant. Two different composition of boron carbide (5, 15 vol %) and CNT (5, 15vol %) with residual volume percentage of aluminium as a core material were fabricated using stir casting method [4]. The analyzed details and results of an investigation into the machinability of SiC particle reinforced aluminium matrix composites using Abrasive Water Jet Machining (AWJM). Al-SiC MMC specimens, prepared with stir casting method [5]. The work carried an investigation of variation of depth of cut on Al7075-T6 and Fly ash metal matrix composites (AMMCs) in Abrasive water jet cutting (AWJC). The aluminum metal matrix was casted in stir casting process with variation of fly ash percentage (15%, 20% and 25%) [6]. Executed optimization and determination of significant process parameter for Abrasive Water Jet Machining of Al7075-TiB2metal matrix composite [7]. AWJT of low density polyethylene (LDPE) material were investigated in terms of average surface roughness (ASR) and material removal rate (MRR) values and process parameters were optimized by experimental design method [8]. Investigation on the cutting ability of abrasive water jet (AWJ) on Aluminium 6061 (Al6061). The effect dynamic input parameters such as abrasive mass flow rate, water jet pressure and traverse speed of jet on depth of cut of Al6061 is investigated [9]. Here the investigation on optimization of process parameters of abrasive water jet machining of hybrid aluminium 7075 metal matrix composites with 5%, 10% and 15% of TiC and B4C (equal amount of each) reinforcement [10].

IV. MATERIALS AND CASTING

A. Aluminum-7075

AL7075 has a good surface finish; high corrosion resistance is readily suited to welding and can be easily anodized. Most commonly available as T6 temper, in the T4 condition it has good formability.

Table 2. Al7075 mechanical properties

Density	2.7
Melting Point	660.2
Modulus of Elasticity	68.3gpa
Thermal conductivity	0.57cal/Cms°C
Crystal Structure	Fcc
Electrical resistivity	2.69

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
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Table 1. Typical chemical composition for aluminium alloy 7075

Element	% Present	
	min	Max
Si	-	0.40
Fe	-	0.50
Cu	1.2	2.0
Mn		0.30
Mg	2.1	2.9
Zn	5.1	6.1
Ti	-	0.20
Cr	-	0.28
Al	-	-

B. Boron Carbide

Boron Carbide is one of the hardest materials known, ranking third behind diamond and cubic boron nitride. It is the hardest material produced in tonnage quantities. It is originally discovered in mid-19th century as a by-product in the production of metal borides, boron carbide was only studied in detail since 1930.Boron carbide powder is mainly produced by reacting carbon with B2O3 in an electric arc furnace, through carbothermal reduction or by gas phase reactions. For commercial use B4C powders usually need to be milled and purified to remove metallic impurities.

Table 3. Typical properties of boron carbide.

Property	Value
Density (g.cm^{-3})	2.52
Melting Point (°C)	2445
Hardness (Knoop 100g) (kg.mm^{-2})	2900-3580
Fracture Toughness (MPa.m$^{-½}$)	2.9 - 3.7
Young's Modulus (GPa)	450 – 470
Electrical Conductivity (at 25°C) (S)	140
Thermal Conductivity (at 25°C) (W/m.K)	30 – 42
Thermal Expansion Co-eff. x10^{-6} (°C)	5
Thermal neutron capture cross section (barn)	600

C. Fly Ash

Fly ash, also known as flue-ash, is one of the residues generated in combustion, and comprises the fine particles that rise with the flue gases. Ash which does not rise is termed bottom ash. In an industrial context, fly ash usually refers to ash produced during combustion of coal.

Table 4. Typical properties of boron carbide

Density g/cm^3	1.93
Bulk Density g/cm^3	1.26
Moisture content %	2
Particle Shape	Spherical
Color	Grey

D. Magnesium

Magnesium is a chemical element with the symbol Mg and atomic number 12. Its common oxidation number is +2. Since magnesium is less dense than aluminum, these alloys are prized for their relative lightness and strength. In human biology, magnesium is the eleventh-most-abundant element by mass in the human body. Magnesium ions are sour to the taste, and in low concentrations they help to impart a natural tartness to fresh mineral waters. In this composite ratio magnesium were mixed 1% for all ratios.

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E. Casting

It is used sand mould casting for produce the requirement size. Sand casting, also known as sand moulded casting, is a metal casting process characterized by using sand as the mould material. It is relatively cheap and sufficiently refractory even for steel foundry use. A suitable bonding agent (usually clay) is mixed or occurs with the sand. The mixture is moistened with water to develop strength and plasticity of the clay and to make the aggregate suitable for moulding. In our project Aluminium metal matrix composite material melted coal fired crucible furnace. Mentioned Ratio was melted very successfully.

There are six steps in this process:

1) Place a pattern in sand to create a mould.
2) Incorporate the pattern and sand in a gating system.
3) Remove the pattern.
4) Fill the mould cavity with molten metal.
5) Allow the metal to cool.
6) Break away the sand mould and remove the casting.

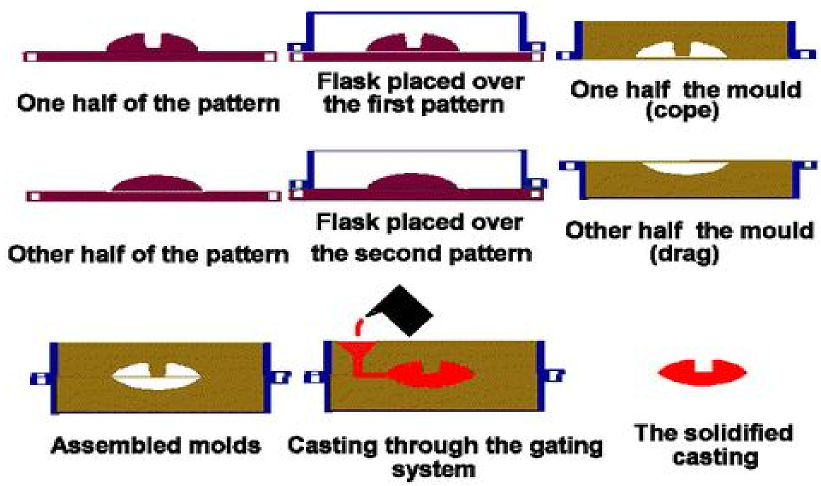

Figure 2. Casting Process

V. EXPERIMENTAL DESIGN

A large number of experiments have to be carried out when the number of the process parameters increases, to solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. The experimental results are then transformed into a signal – to – noise (S/N) ratio to measure the quality characteristics deviating from the desired values. Usually, there are three categories of quality characteristics in the analysis of the S/N ratio, i.e., the – lower – better, the – higher – better, and the – nominal – better. The S/N ratio for each level of process parameter is compared based on the S/N analysis. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics.

VI. DESIGN OF EXPERIMENT

Table 5. Process parameters and their levels

LEVELS		PROCESS PARAMETERS		
		LEVEL-1	LEVEL-2	LEVEL-3
1	WATER PRESSURE (Mpa)	100	150	200
2	CUTTING SPEED-mm/min	200	300	400
3	STAND OFF DISTANCE-mm	4	6	8

* Constant parameter: AMFR-250g/min & Grant Mesh size -80 (0.165mm)

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A. *MINITAB-17 Software*

By using Minitab-17 software have optimized the drilling parameters selected through DOE principle OF TAGUCHI sheet and Parameter selection shows on Figure 3

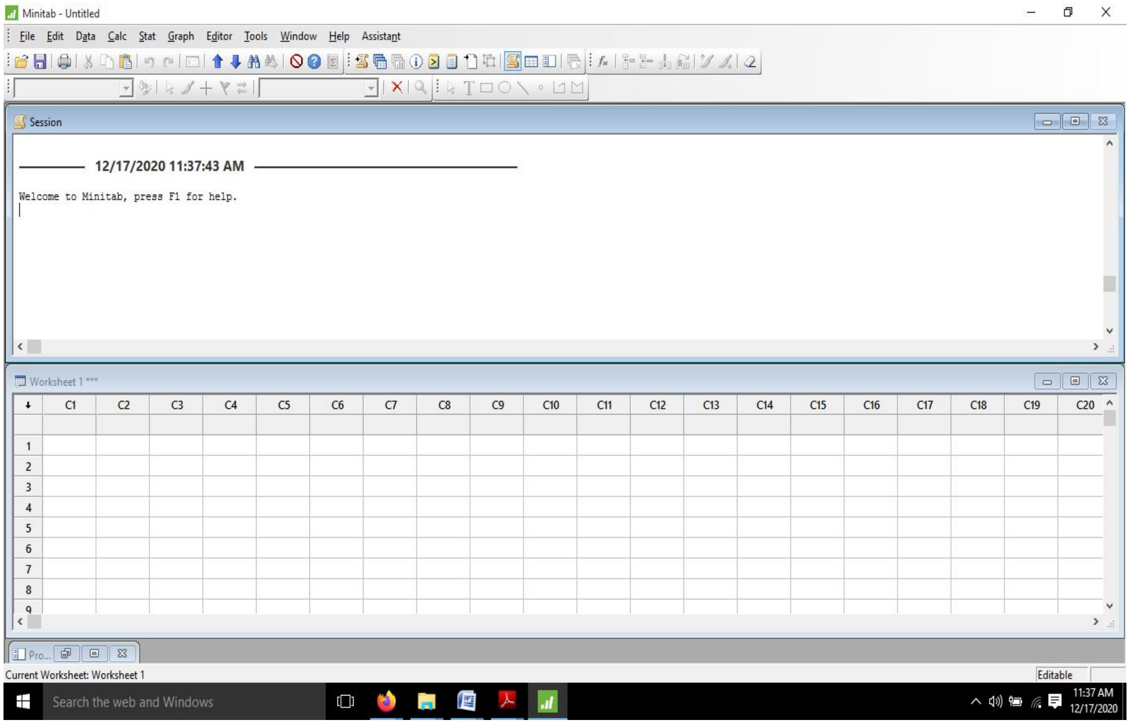

Figure 3. MINITAB 17 Work sheet

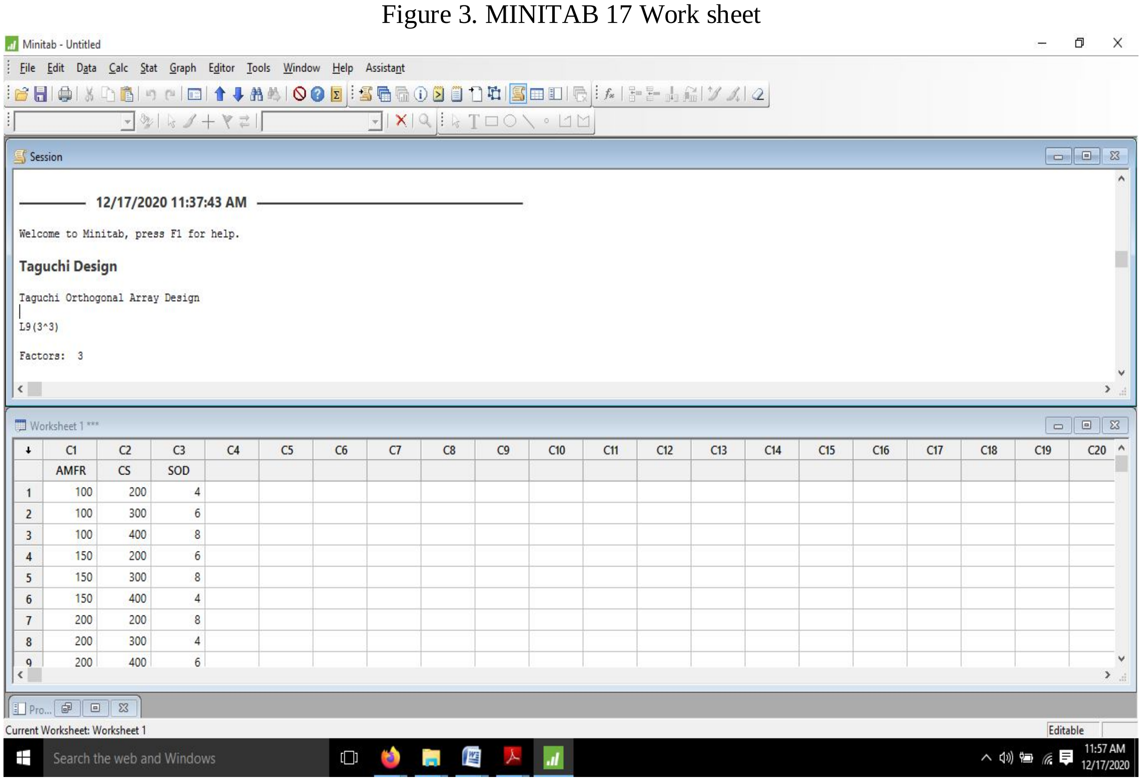

Figure 4. Process parameter image

B. *Work Piece Material*

Work material –AMMC, Work material size–260 x 150 x8mm

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
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C. AN Orthogonal Array L_9 Formation (Interaction)

Table 6. An orthogonal array L_9 formation (interaction) of AJM.

No	(A)WATER PR(MPa)	(B) TRAVERSE SPEED (mm/min)	SOD Mm
1	100	200	4
2	100	300	6
3	100	400	8
4	150	200	6
5	150	300	8
6	150	400	4
7	200	200	8
8	200	300	4
9	200	400	6

D. Experimental Data Analysis and Optimization

Table 7. Experimental data and output response analysis

IP/OP	WP	TS	SOD	RA	DIA-ERR	RE	CY
1	100	200	4	2.189	1.0525	0.1293	0.2797
2	100	300	6	2.128	1.2818	0.0340	0.1696
3	100	400	8	3.220	1.3079	0.0082	0.2141
4	150	200	6	2.890	1.0855	0.0419	0.1446
5	150	300	8	2.562	1.3205	0.0206	0.1672
6	150	400	4	2.128	1.2838	0.0573	0.2316
7	200	200	8	2.112	1.4930	0.0271	0.2768
8	200	300	4	2.922	1.3357	0.0215	0.1839
9	200	400	6	3.281	1.2715	0.0111	0.0757

E. RA (Analysis of Result)

Table 8. RA and S/N RATIO Values for the Experiments

IP/OP	WP	TS	SOD	RA	SN-RAIO
1	100	200	4	2.189	-6.8049
2	100	300	6	2.128	-6.5594
3	100	400	8	3.220	-10.1571
4	150	200	6	2.890	-9.2180
5	150	300	8	2.562	-8.1716
6	150	400	4	2.128	-6.5594
7	200	200	8	2.112	-6.4939
8	200	300	4	2.922	-9.3136
9	200	400	6	3.281	-10.3201

F. RA For Each Level of the Process Parameter

Table 9. Response Table for Signal to Noise RA-Smaller is better

LEVEL	WP	TS	SOD
1	-7.840	-7.506	-7.559
2	-7.983	-8.015	-8.699
3	-8.709	-9.012	-8.274
DELTA	0.869	1.507	1.140
RANK	3	1	2

Table 10. Means Table for RA

LEVEL	WP	TS	SOD
1	2.512	2.397	2.413
2	2.527	2.537	2.766
3	2.772	2.876	2.631
DELTA	0.259	0.479	0.353
RANK	3	1	2

Table 11. Factor Information

FACTOR	TYPE	LEVELS	VALUES
WP	FIXED	3	100,150,200
TS	FIXED	3	200,300,400
SOD	FIXED	3	4,6,8

Table 12. Analysis of Variance for RA

SOURCE	DF	SEQ SS	ADJ MS	F	P	% OF CONTRIBUTION
WP	2	0.1275	0.06374	0.11	0.904	7
TS	2	0.3644	0.18219	0.30	0.768	19
SOD	2	0.1907	0.09537	0.16	0.864	10
ERROR	2	1.2073	0.60366			64
TOTAL	8	1.8899				100

Regression Equation

RA = 2.604 - 0.091 WP_100 - 0.077 WP_150 + 0.168 WP_200 - 0.207 TS_200 - 0.066 TS_300
+ 0.273 TS_400 - 0.191 SOD_4 + 0.163 SOD_6 + 0.028 SOD_8

G. Diameter Error (Analysis Of Result)

Table. 13. Diameter (Analysis of Result)

IP/OP	WP	TS	SOD	DIA ERR	SNRA1
1	100	200	4	1.0525	-0.44444
2	100	300	6	1.2818	-2.15641
3	100	400	8	1.3079	-2.33149
4	150	200	6	1.0855	-0.71260
5	150	300	8	1.3205	-2.41477
6	150	400	4	1.2838	-2.16995
7	200	200	8	1.4930	-3.48120
8	200	300	4	1.3357	-2.51418
9	200	400	6	1.2715	-2.08633

H. *Diameter For Each Level Of The Process Parameter*

Table 14. Response Table for Signal to Noise Ratio-Circle Smaller Is Better

LEVEL	WP	TS	SOD
1	-1.644	-1.546	-1.710
2	-1.766	-2.362	-1.652
3	-2.694	-2.196	-2.742
DELTA	1.050	0.816	1.091
RANK	2	3	1

Table 15. Means Table for Signal to Noise Ratio- Circle

LEVEL	WP	TS	SOD
1	1.214	1.210	1.224
2	1.230	1.313	1.213
3	1.367	1.288	1.374
DELTA	0.153	0.102	0.161
RANK	2	3	1

Table 16. Factor Information

FACTOR	TYPE	LEVELS	VALUES
WP	FIXED	3	100,150,200
TS	FIXED	3	200,300,400
SOD	FIXED	3	4,6,8

Table 17. Analysis of Variance of Diameter Error

SOURCE	DF	SEQ SS	ADJ MS	F	P	% OF CONTRIBUTION
WP	2	0.04227	0.021137	1.32	0.430	30
TS	2	0.01708	0.008542	0.54	0.651	12
SOD	2	0.04844	0.024220	1.52	0.397	35
ERROR	2	0.03191	0.015956			23
TOTAL	8	0.13971				100

Regression Equation

DIAERR = 1.2702 - 0.0562 WP_100 - 0.0403 WP_200 + 0.0965 WP_300 - 0.0599 TS_200
+ 0.0424 TS_300 + 0.0175 TS_400 - 0.0462 SOD_4 - 0.0573 SOD_6 + 0.1036 SOD_8

I. *Roundness Error (Analysis of Result)*

Table 18. S/N RATIO Values for the ROUNDNESS 8.8.1

IP/OP	WP	TS	SOD	RE ERR	SNRA1
1	100	200	4	0.1293	17.7680
2	100	300	6	0.0340	29.3704
3	100	400	8	0.0082	41.7237
4	150	200	6	0.0419	27.5557
5	150	300	8	0.0206	33.7227
6	150	400	4	0.0573	24.8369
7	200	200	8	0.0271	31.3406
8	200	300	4	0.0215	33.3512
9	200	400	6	0.0111	39.0935

J. Roundness For Each Level Of The Process Parameter

Table 19. Response Table for Roundness -Smaller is better

LEVEL	WP	TS	SOD
1	29.62	25.55	25.32
2	28.71	32.15	32.01
3	34.60	35.22	35.60
DELTA	5.89	9.66	10.28
RANK	3	2	1

Table 20. Means Table for Roundness

LEVEL	WP	TS	SOD
1	0.05717	0.06610	0.06937
2	0.03993	0.02537	0.02900
3	0.01990	0.02553	0.01863
DELTA	0.03727	0.04073	0.05073
RANK	3	2	1

Table 21. Factor Information

FACTOR	TYPE	LEVELS	VALUES
WP	FIXED	3	100,150,200
TS	FIXED	3	200,300,400
SOD	FIXED	3	4,6,8

Table 22. Analysis of Variance-Roundness

SOURCE	DF	SEQ SS	ADJ MS	F	P	% OF CONTRIBUTION
WP	2	0.002087	0.001044	1.57	0.390	19
TS	2	0.003305	0.001652	2.48	0.287	30
SOD	2	0.004311	0.002155	3.23	0.236	39
ERROR	2	0.001333	0.000667			12
TOTAL	8	0.011036				100

Regression Equation

R0-ERR = 0.03900 + 0.0182 WP_100 + 0.0009 WP_200 - 0.0191 WP_300 + 0.0271 TS_200
- 0.0136 TS_300 - 0.0135 TS_400 + 0.0304 SOD_4 - 0.0100 SOD_6 - 0.0204 SOD_8

VII. RESULT AND CONCLUSION

The present study clearly indicates the suitability of sand-casting method for the production of larger-sized components. Contribution of waterjet pressure and traverse speed are more than the contribution of abrasive flow rate on the jet penetration depths. Particularly roughness average majorly influences with water jet traverse speed. Among interaction effects stand of distance is majorly influenced with geometrical properties except diameter error. Although developing the statistical models for predicting the machining characteristics and geometrical accuracy and the study carried out in this work would help to choose the parameters carefully. Hence, the result of the experiment was summarized and concluded as follows:

A. Optimal Control Factor

1) Surface roughness-A3 (WP -200 Mpa) B1 (TS -200 mm/min) C2 (SOD6 mm)
2) Circular Error-A2 (WP -150 Mpa) B3 (TS -400 mm/min) C1 (SOD4 mm)
3) Roundness Error- A3 (WP -200 Mpa) B2 (TS -300 mm/min) C1 (SOD4 mm)
4) Cylindricity Error- A3 (WP -200 Mpa) B2 (TS -300 mm/min) C1 (SOD 4 mm)

B. Percentage Contribution of Process Parameter

1) Surface roughness –Traverse Speed 19%
2) Circular Error – Water Pressure 30%
3) Roundness error – SOD 39%
4) Cylindricity Error - SOD 55%

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