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Experimental Control of Kerf Width Taper During Abrasive Water Jet Machining

Abrasive water jet machining (AWJM) is one of the effective non-conventional machining processes. AWJM has its effective influence on aeronautical and automobile engineering industries. This paper aims to study the outcome of AWJM process parameters on kerf width and kerf taperness of Inconel-825. Taguchi's DOE is designed for experimental approach. Orthogonal array L_{25} is selected for experimental work. The influence of various process factors such as Transverse speed, Abrasive flow rate and stand-off distance on the kerf width and kerf taperness was studied. The consequence of the machining parameters was analysed and the optimum process parameters were identified with the help of Grey's relational analysis. Confirmation test was carried out with the optimum values of machining parameters such as Transverse speed-60mm/min, Abrasive Flow Rate-200gm/min and Stand off Distance-4mm in order to illustrate the effectiveness of Grey's relational analysis. The Optical microscopy confirmation test is performed for characterization of morphology and identification of micro cracks.

Keywords: *Kerf Width, Kerf Taperness, Grey's relational analysis, Regression equation & Inconel-825.*

1. INTRODUCTION

Abrasive water jet machining (AWJM) process utilizes mechanical energy for machining of work pieces at economic machining speeds. AWJM can machine tough and hard materials like composites, super alloys and nimonics easily.The variety of industrial demands for manufacturing of different parts with a specific geometry has increased day by day with advanced technologies. AWJM machining process is environmentally safe as it provides an alternative approach for the improvement of the machining performance by enhancing the target material properties at low temperature in the machining processes. Material machining is done by erosion process.

Kumar Abhishek et. al, [1]. has found a novel application to manufacture high standard holes by utilizing micro-AWJM. Ruslan melentiev et. al, [2] suggested consequences of hydro mechanical abrasive machining parameters on abrasives kinetic energy and machined surface area in detail. J.Wang et. al, [3] have stated that AWJM machining can generate better kerf quality at higher production rates without any delamination if the cutting process is properly selected. M.A.Azmir et. al, [4] observed that kerf tameness ratio was shortened by developing the hydraulic pressure and reducing the SOD and transverse rate. V.V.Vanmore et.al, [5] stated that AWJM process minimizes damage during micro machining and negligible heat affected zone and lessens the processing time. For these reasons, it find its utilization in fabricating electronic devices and micro-fluidic channels.

K. Nagendra Prasad et. al, [6] explained through his experiments conducted on TI-6Al-4V by employing AWJM that, to achieve better quality of hole (kerf accuracy), the most influencing parameter is the SOD with 3mm respectively. Vishal gupta et. al, [7] in his investigation, proposed "θ" exhibits small for lower transverse speed but it will practically increase the production time. Mahabalesh et. al, [8] conducted various experiments in combination of AJM and chemicals to study the taperness of drilled holes, narrow beam of slurry jet machining on work surface leading to higher material removal eliminating the taper. Shu wang et. al, [9] through his experimental studies on kerf profile defect, which is not linear in most cases, eliminate taper error by tilting cutting nozzle a taper angle in the opposite direction. Xuecheng Zhang et. al, [10] explained through his experimentation regulated on abrasive particles the motion aspects of abrasive particles play crucial roles in quality and efficiency of AWJM closer to the jet axis, the impact velocity will be higher. Fuat kartal et al, [11] stated that AWJM becomes an outstanding process by eliminating the aspects of thermal effects during the process. It is mostly referred when heat affect zones have to be avoided. Libor M. Hlavac et. al, [12] has conducted experiment on the widths of rock materials on both top and bottom and the difference in the widths is evaluated. The taper changes with increasing transverse speeds.

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Previous investigations have made some efforts and have been picked up for improvement of MRR. In the present paper, the effect of transverse speed, abrasive flow rate and stand of distance on KW and θ are investigated using grey relational analysis and optical microscope test by applying grey Taguchi technique it can generates a good solution for sample size contained uncertainty limited information as compared to developed methods. For this purpose, five-level factors were considered for the analysis. Novel attempt has been made to produce holes with squareness by minimize KW and θ on inconel-825 super alloy by varying TS, SOD and AFR for in detail in this paper.

2. EXPERIMENTAL SETUP

In the present study, the material chosen is inconel-825, super alloy which is precipitation hardened material, with a high resistance to corrosion [13]. Inconel-825 is a nickel-iron-chromium alloy with additives of molybdenum, copper and titanium. It possess good yield strength and mechanical properties even at cryogenic temperatures to relatively high temperatures. It is resistant to highly corrosive acids like sulphuric acid and phosphoric acids.

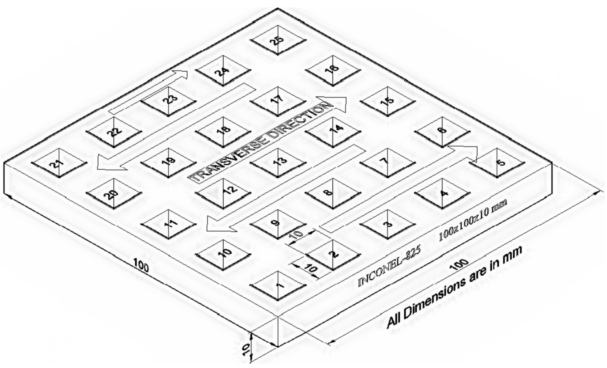

Figure 1. Inconel-825 Work piece Specimen

Table 1. Composition of Inconel-825

Element	Ni	Cr	Mo	Cu	Ti	Fe	C	Other
Weight %	42	21	3.0	2.25	0.9	22	0.05	1.73

Figure 2. Abrasive Water Jet Machining Setup

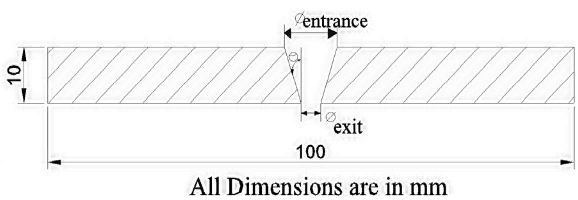

Figure 3. Kerf Taper geometry of an AWJM

Figure 2 represents the experimental setup of AWJM on which all experimental trails were carried out. An experiment was conducted on a CNC Abrasive excel WJM setup. To cut 10X10 mm^2 test specimens of 10 mm thickness, AWJM setup is equipped with Computer numerical machining control of high intensifier pump and a three axis robot positioning system. In AWJM, so many parameters like transverse speed, abrasive flow rate, standoff distance, abrasive grains, grit size, water pressure, work material, nozzle diameter and impact angle can effect the machining parameters of AWJM. In the present work, TS, AFR and SOD are varied; remaining input parameters are kept constant as listed in below Table 2. Table 3 represents variable process parameters and their levels.

Table 2. Experimental Parameter List

S.NO	Experimental Constant Parameters	Specifications
1.	Target material	Inconel-825
2.	Abrasive type	Garnet
3.	Abrasive mesh size	80
4.	Water: Abrasives	70:30
5.	Viscosity of water	1 mpa
6.	Water Pressure	$31X10^7 N/m^2$
7.	Orifice diameter	0.00035 m
8.	Nozzle diameter	0.0011m
9.	Water Pressure	$3.5x\ 10^8\ N/m^2$
10.	Water flow rate	0.04312 Kg/sec
11.	Controlling	CNC

2.1 Design of Experiments

The Taguchi design concept is utilised for getting the best combination of parameters affecting the machining performance. DOE states the number of observations it needs to take [14]. Taguchi method was used to identify robust conditions by offering simple and modeless approach for process optimization [15].In Taguchi method, Control factors indicate the input parameters for the process, and Response factors refers to corresponding output responses for the process.

DOF for a Control Factor =1+ No. of Parameters X(Number of stages – 1)

No. of Parameters =3, No. of Stages=5

DOF = 1+ 3(5-1) = 13

The nearest OA available for satisfying the condition of selecting OA is L25.The data intereption was performed from the experimental values obtained from the systematically derived standard L_{25} orthogonal array.

Table 3. Variable Process parameters and their levels

Parameter	Units	Levels				
		1	2	3	4	5
Transverse speed	mm/min	40	50	60	70	80
Abrasive Flow Rate	gm/min	50	100	150	200	250
Stand-off Distance	mm	1.0	2.0	3.0	4.0	5.0

3. RESULTS AND DISCUSSIONS

Kerf width and Kerf taperness are important criteria in assembling the automobile components. Kerf width is measured by using formula (1) and kerf taperness is inspected by formula(2). $\phi_{entrance}$ and ϕ_{exit} is shown in Figure 3. The effect of machining parameters were analyzed through Grey Relational Analysis.

$$\text{Kerf width}=\frac{S_1-S_2}{2} \tag{1}$$

$$\text{Kerf taper }(\theta)=\frac{\varphi_{entrance}-\varphi_{exit}}{2Xt} \tag{2}$$

where,

S_1 - Side of the machined specimen on the work piece
S_2 - Side of the cut piece from workpiece
t - Thickness of workpiece is 10 mm

Table 4. Process Parameters of Orthogonal Array L_{25}

Se. No	Transverse speed mm/min	Abrasive flow rate gm/min	Stand off Distance mm	S_1 m	S_2 m
1	40	50	1	0.0126	0.01026
2	40	100	2	0.01261	0.0102
3	40	150	3	0.01263	0.01016
4	40	200	4	0.01274	0.01014
5	40	250	5	0.01273	0.01017
6	50	50	2	0.01266	0.01036
7	50	100	3	0.01254	0.01032
8	50	150	4	0.01262	0.01033
9	50	200	5	0.01266	0.01025
10	50	250	1	0.01256	0.01033
11	60	50	3	0.01245	0.0105
12	60	100	4	0.01256	0.01042
13	60	150	5	0.01258	0.01031
14	60	200	1	0.01257	0.01036
15	60	250	2	0.01258	0.01033
16	70	50	4	0.01252	0.01032
17	70	100	5	0.01259	0.01034
18	70	150	1	0.01254	0.01041
19	70	200	2	0.01264	0.01029
20	70	250	3	0.01263	0.01028
21	80	50	5	0.01254	0.01042
22	80	100	1	0.0126	0.01026
23	80	150	2	0.01259	0.01036
24	80	200	3	0.01256	0.01029
25	80	250	4	0.01258	0.01026

Figure 4. Kerf width measurement by Vernier callipers

Side of machined specimen S_1 is measured by upper teeth of Vernier callipers and S_2 is side of cut piece from work piece is measured by lower jaws of Vernier callipers as shown in Figure 4. $\phi_{entrance}$ and ϕ_{exit} is measured by tool makers microscope as shown in Figure 5.

Table 5. Process Responses of Orthogonal Array L_{25}

S.No	$\phi_{entrance}$ radians	ϕ_{exit} radians	Kerf width m	Taperness radians	Grey Relational Coefficient	Grey Grade
1	12.60	10.26	0.00117	0.00125	0.45955	25
2	12.61	10.20	0.001205	0.005	0.52107	19
3	12.63	10.16	0.001235	0.00575	0.57265	14
4	12.74	10.14	0.0013	0.0005	0.49447	22
5	12.73	10.17	0.00128	0.0055	0.54827	15
6	12.66	10.36	0.00115	0.00275	0.45819	24
7	12.54	10.32	0.00111	0.00775	0.51711	19
8	12.62	10.33	0.001145	0.005	0.47226	23
9	12.66	10.25	0.001205	0.012075	0.49954	21
10	12.56	10.33	0.001115	0.006675	0.6743	4
11	12.45	10.50	0.000975	0.1375	0.58572	13
12	12.56	10.42	0.00107	0.001	0.52956	16
13	12.58	10.31	0.001135	0.0045	0.60322	10
14	12.57	10.36	0.001105	0.0005	0.61933	9
15	12.58	10.33	0.001125	0.0015	0.67617	3
16	12.52	10.32	0.0011	0.0015	0.65028	6
17	12.59	10.34	0.001125	0.0145	0.51694	20
18	12.54	10.41	0.001065	0.00875	0.63417	8
19	12.64	10.29	0.001175	0.00975	0.5212	18
20	12.63	10.28	0.001175	0.0155	0.64592	7
21	12.54	10.42	0.00106	0.0305	0.5986	11
22	12.60	10.26	0.00117	0.0235	0.59418	12
23	12.59	10.36	0.001115	0.007	0.73461	2
24	12.56	10.29	0.001135	0.00275	0.75525	1
25	12.58	10.26	0.00116	0.0015	0.65588	5

Figure 5. Kerf taper measurement by Tool Makers Microscope

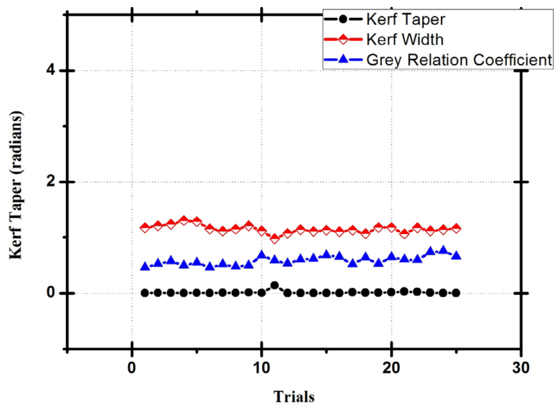

Figure 6. 1-D graph represents consequence of process parameters on Kerf width, kerf taper & Grey relational coefficient

The graph in Figure 6 represents the variation in kerfwidth and kerftaper for 25 trail runs, in order to investigate the effect of TS,AFR and SOD on KW and θ Grey relational analysis is performed.

3.1 Grey Relational Analysis

In order to investigate the significance of the process parameters on Kerf Width and taperness, Grey relational analysis or Grey-Taguchi analysis is performed. Grey-Taguchi analysis is a multi-parameter optimization technique. Using this technique, we can optimize process parameters [16] in relation to kerf width and taperness at a time. Steps to be followed to perform Grey-Taguchi technique are shown in the flowchart below in Figure 7.

3.2 Normalization of Experimental Results

The first step in Grey-Taguchi analysis is to normalize the experimental results of Kerf Width and kerf taperness. Each response value is normalized in the range of 0 to 1. For normalizing Kw and kerf taperness 'Lower-the-better' is to be selected as shown in formula (3).

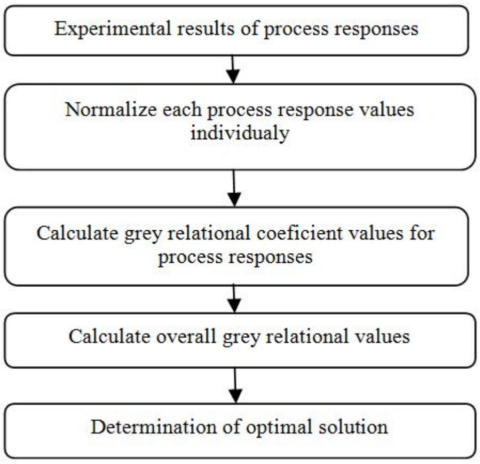

Figure 7. Grey-Taguchi technique flow chart

$$\mathbf{X_j}(\mathbf{v}) = \frac{\max y_j(v) - y_j(v)}{\max y_j(v) - \min y_j(v)} \tag{3}$$

where, X_j (v)= value after normalizing data/Grey relations generation value,
Min y_j (v) =smallest value of y_j (v),
Max y_j (v) =Largest value of y_j (v) for the v^{th} response.

3.3 Grey Relational Co-efficient

After normalizing the results of kerf width and kerf taperness, the next step is the calculation of grey relational coefficient values for kW and kerf taper. The grey relational coefficient ξ_j (v) can be calculated by using formula (4). Values of grey relational coefficient are represented in Table 5.

$$\xi_j(\mathrm{v}) = \frac{\Delta_{\min} + \varphi\Delta_{\max}}{\Delta_{oj}(v) + \varphi\Delta_{\max}} \tag{4}$$

where, ξ_j(v)=Grey relational coefficient, by averaging the grey relational coefficients, the grey relational grade can be given as

$$\gamma_j = \frac{1}{n}\sum_{v=1}^{n} \xi_j(k) \tag{5}$$

where, n = number of process responses,
Δ_{min}& Δ_{max} are the minimum and maximum values of smallest and
largest value of Δ_{oj} , respectively

By using this method, optimal combination of process parameters is achieved corresponding to the highest grey relational grade as represented in Table IV.

3.4 Prediction of values for optimum levels as per Grey-Taguchi technique

From the means of each level of process parameters, we will construct a response table for grey-relational grade. The response table for grey-relational grade is given in Table 6. S/N ratio is most significant factor to forecast the optimal outcome either it may be maximum or minimum as per their experimentation [17].

Table 6. Response Table for Grey relational grade

Level	Transverse Speed (A)	Abrasive Flow Rate (B)	Stand-off Distance (C)
1	0.7980	1.0425	0.9548
2	0.9135	1.0715	0.8350
3	0.7515*	0.8770	1.0160
4	1.0620	0.8458*	0.6720*
5	1.2025	0.8907	1.2497
Delta	0.4510	0.2257	0.5777
Rank	2	3	1

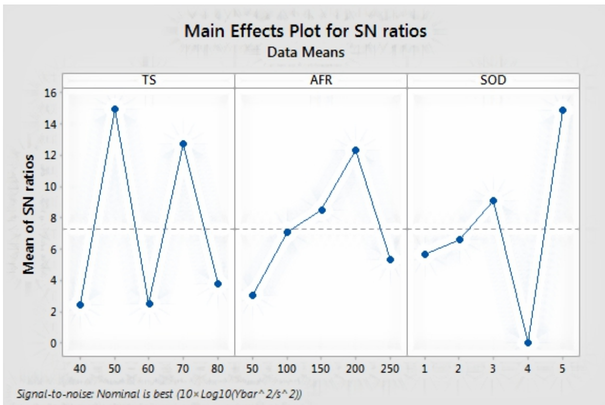

Figure 8. Main effect plot S/N Ratio for Over all Grey Relational grade.

From the above response table, the optimal condition for minimizing KW and kerf taperness simultaneously in Abrasive Water Jet Machining (AWJM) optimum process is found to be A3 B4 C4 i.e. Transverse speed is 60 mm/min, Abrasive Flow Rate is 200 gm/min and SOD is 4mm. For this optimal setting A3 B4 C4 experimentation is done for validating results. Grey- Taguchi analysis graph shows the influence of TS, AFR and SOD on KW and KT.

SOD should be maintained less than 5mm to obtain straight profile cuts. If it is beyond that, then there is a chance of kerf taperness. Hence if it is less than 1mm, then nozzle wear has to take place. Due to this, replacement of nozzle has to done.

If transverse speed is low, then machining will perform well. If it is increased, then undercuts are performed. Sometimes improper machining is performed. Due to this KW and kerf taperness will develop.

In AWJM, AFR is a combination of both water (70%) and abrasives (30%). Water will impart the required motion for abrasives thereby improving the AFR. Material removal rate also improves up to some limit. After a certain value of Abrasive flow velocity it decreases the MRR because of improvement in water percentage then abrasive percentage. Selection of abrasive size is important. If abrasives are of big size, then more amount of metal is removed by fracture during machining. Hence kerf width and kerf taperness is improved. By improving TS and AFR, Grey relational coefficient improved.

3.5 Regression Analysis

Regression analysis is based on curve fitting; it is used to find future behaviour of process responses based on process parameters. Regression equation was developed to predict kerf width and kerf taperness in terms of cutting parameters like TS, AFR and SOD. These predicted or optimal results are compared with experimental results. Regression equation develops a correlation between the process parameters with the quality characteristics of machined work piece.

By using regression model it is easy to predict mathematical model and also how the output responses change related to other influential factors. Small percentage factors interactions percentage is not taken in to consideration in regression model [18].

$$LN(KW) = 0.209 - 0.154LN(TS) + \\ +0.0502LN(AFR) + 0.0289LN(SOD) \quad (6)$$

$$KW = e\wedge(0.209) * TS\wedge(-0.154) * \\ *AFR\wedge(0.052) * SOD\wedge(0.0289) \quad (7)$$

$$LN(\theta) = -2.27 + 1.35LN(TS) - \\ -0.253LN(AFR) + 0.183LN(SOD) \quad (8)$$

$$\theta = e\wedge(-2.27) * TS\wedge(1.35) * \\ *AFR\wedge(-0.253) * SOD\wedge(1.083) \quad (9)$$

Formula(6),(8) represents Linear regression equation formula(7),(9) represents Nonlinear regression equation in actual practise the process response will vary independently based on process parameters.

If dependent variables (KW & θ) are more than one. Logistic regression technique is used for regression model. Its value is ranges from 0 to 1. The relation ship between dependent and independent variables(TS, AFR & SOD) doesn't require linear. Non linear relation ship of dependent and independent can also solved by applying non linear log tranformation. Standard deviation of model (error) is 0.033 (3.33%).

3.6 Confirmation Test

From the confirmation experiments, the error percentage of process responses from the predicted responses confidence level 95% and error less than 5% is acceptable.

Table 7. Verification and Optimum Parameter Control LEVEL

S.NO	Process response	Optimal Setting	Experimental Value	Optimal Value	Error %
1	Kerf width	$A_3B_4C_4$	0.935	0.8909	4.95
2	Taperness		0.05	0.0485	3.09

$$\text{Experimental error} = \frac{Optimal - Experimental}{Optimal} X100 \quad (10)$$

3.7 Confirmation Test

Investigation of the relationship between process parameters such as TS-60mm/min, AFR-200gm/min and SOD-4mm on the AWJM cut walls, proved that some micro parallel cracks are observed. Due to erosion of new abrasive particles, craters haven't appeared. The photograph, shown in figure 9, is 200 times the magnification.

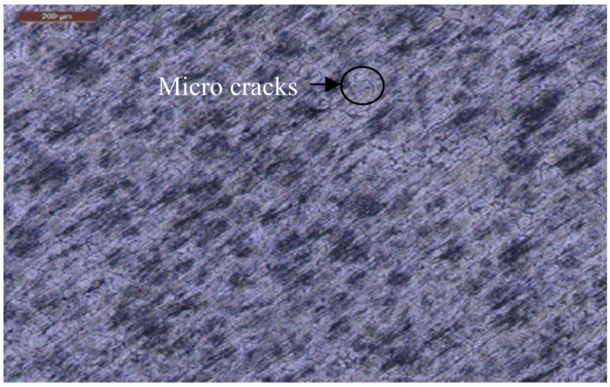

Figure 9. Optical microscope image of specimen machined with TS-40mm/min,AFR-100gm/min,SOD-4mm detail of micro cracks

4. CONCLUSION

In the present work based on experimental investigation for effective machining of INCONEL-825 by AWJM process, some important observations are drawn.

1. Traverse Speed (TS) is the most significant factor on Kerf width during AWJM. Meanwhile, Abrasive Flow Rate and Standoff distance are sub-significant in influencing.
2. In case of kerf taperness, Abrasive Flow Rate is the most significant control factor. If AFR improves then Material removal rate also improves up to some limit.
3. In case of kerf width, Kerf taperness transverse speed & abrasive flow rate are the most significant control factors. After a certain value of Abrasive flow velocity decreases to the extent that it results in reduction in MRR because of improvement in water percentage then abrasive percentage.
4. Kerf taperness is majorly influenced by standoff distance in AWJM up to 4mm. Standoff distance taperness is minimum and life time of nozzle is improved if SOD is beyond 4mm then kerf taperness will improve due to impingement of entrapped air.
5. In Optical Microscopy analysis some parallel micro cracks are observed and craters are not observed.

6. The optimal condition for optimum Kerf Width and kerf taperness simultaneously in Abrasive Water Jet Machining (AWJM) process, is found to be A3 B4 C4 i.e. Transverse speed is 60 mm/min, Abrasive Flow Rate is 200 gm/min and Stand Off Distance is 4 mm.

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NOMENCLATURE

AWJM	Abrasive Water Jet Machining
KW	Kerf Width
TS	Transverse Speed
AFR	Abrasive Flow Rate
SOD	Standoff distance
$\phi_{entrance}$	Entry diameter of hole in mm
ϕ_{exit}	Exit diameter of hole in mm
θ	Kerf taperness angle
T	Thickness of work piece
DOE	Design Of Experiments
GRA	Grey Relational Analysis
S_1	Side of the machined specimen on the work piece
S_2	Side of the cut specimen from the specimen

КОНУСНОСТ РЕЗА КОД ОБРАДЕ АБРАЗИВНИМ ВОДЕНИМ МЛАЗОМ – ЕКСПЕРИМЕНТАЛНО ИСТРАЖИВАЊЕ

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Обрада абразивним воденим млазом је једна од најефикаснијих неконвенционалних метода обраде. Од великог је значаја у авио и аутомобилској индустрији. У раду се истражује утицај параметара обраде абразивним воденим млазом на ширину реза и конусност реза код материјала inconel-825. Тагучијев метод планирања експеримента је примењен у експерименталном истраживању. Ортогонални низ L_{25} је одабран за експериментални рад. Испитан је утицај различитих фактора, брзине кретања, брзине тока абразивног воденог млаза и растојање млазнице од реза, на ширину реза и конусност реза. Анализиран је утицај параметара обраде и одређени су оптимални параметри обраде помоћу Грејове релационе анализе. Код конфирмационог испитивања коришћени су следећи параметри: брзина кретања – 60 мм/мин, брзина тока абразивног воденог млаза – 200гм/мин и растојање млазнице од реза – 4мм да би се доказала ефикасност Грејове релационе анализе. Конфирмационо испитивање оптичком микроскопијом је извршено у циљу карактеризације морфологије и идентификовања микропрслина.