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A Review on Optimization of Process Parameters in Abrasive Water Jet Machining/Cutting (AWJM) using various methods

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Abstract: - Machining is a vital part of producing required shapes and sizes for engineering materials. Material properties are modified and used according to its machinability properties. Among the various non-conventional methods for achieving effective machining or cutting of any material in the current scenario, the Abrasive Water Jet technique is most widely used due to its superior ability to machine a wide range of materials. For improved product consistency, increased profitability and increased economic performance, it is imperative to identify the most efficient abrasive water jet machining parameters in order to optimize the machining process. A good way to measure economic performance is to determine the productivity rate and compare them. During the machining process, input variable (pressure, abrasive flow rate, stand off distance, and transverse speed) is studied on the response variables (machining time, surface roughness, and MRR). Statistical analysis is performed using Taguchi Technique using Minitab 18 for the experimental work.In articles published between 2015 and 2022, the conclusions of a few scientific articles were revealed for a better understanding of the topic.

Keywords: Pressure, abrasive flow rate, stand off distance, transverse speed, machining time, surface roughness, MRR, Taguchi Technique, Minitab 18.

- **INTRODUCTION**

In engineering materials, alloys are competitive with steel, nickel alloys and composite materials. Among other unconventional machining processes, the water jet machine has shown to be one of the most promising methods to be used in manufacturing. In fact, the area affected by negligible heat has proved to be very suitable for machine materials that are not so easy to machine using conventional methods. Thermal properties of the material are not taken into account in this process[1-2]. Initially, flat-water jet technology made machining soft materials and cleaning and removing coatings easier and more efficient. Thereafter, the mixing of the abrasive with pressurized water resulted in a technique that is capable of cutting any type of material, starting from rubber to alloy by simply mixing abrasive with water under pressure. Nowadays, the usage of abrasive water jet machines for thorough cutting, outside home and office design is growing in popularity. With the advancement of computer technology, abrasive water jet machining is now capable of producing any form of profile. To raise the pressure to 400 MPa, water that is kept in a tank under the machine's table is pushed. When processing needs for it, the accumulator temporarily stores water under pressure and feeds it as needed without pressure fluctuations. The water is under pressure as it goes through small nozzles, where the pressure energy is changed into kinetic energy and a speed of about 1000 m/s is produced[3]. The abrasive enters the mixing chamber through high velocity water. To cut the sample being attacked by this jet, a mixed jet of water and abrasive particles is directed at it. Finally, the tank and hopper get water and abrasive from the collector. The most often used abrasive particles in the AWJM are garnet and aluminium oxide. Sand and glass globules are also employed as stripes outside of these materials. Due to its efficiency and performance, garnet is frequently chosen.

It is possible to conduct research and experiments on the AWJM using a variety of related parameters. Studying the impact of category-specific input factors on response parameters is possible. To understand the specific impact of each input variable on the response variables, a condensed report was presented.

The multiple optimization technique was developed over time to deal with rising industrial demand and constant pressure to make the best use of available machining facilities. Taguchi's method is widely used. It was regarded as a simple and direct technique with a dependable, systematic, and efficient tool for optimising various process parameters, including machining processes. The method entails submitting orthogonal network (OA) experiments with a compact difference for the experiment aimed at optimum settings. As a result, it aims to achieve the best optimal results possible through the design of experiments using the Taguchi method. The OA calculates the S/N ratio (SNR), which is a logarithmic function of the objective function's intended output. The Taguchi technique compares the objective function to SNR, which is the primary measure of the performance parameters of the experimentation work. ANOVA assesses the significance of experiments by analysing main factors such as degree of freedom (DOF) and sum of squares (SS), as well as variance and percentage contribution of specific input variables. SS accounts for the difference in experimental and mean value data. The Fisher's ratio (F value) and p values are calculated, which indicate the significant effect of a process parameter on the response's performance characteristics. According to the table, often these researchers examined the geometrical and surface features of the material, so a mixed combination taking quality and aspect into account was chosen for analysis.

The degree of freedom (DOF) and sum of squares (SS), as well as the variance and percent contributions of specific input variables are all included. The HS reports for the variation between the test data and the mean values. The Fisher rational (F value) and p values are used to determine whether a process parameter has a major effect on response performance characteristics. The work done on the material is summarized in table[4-6]s table is essential in completing the new experimental configuration and the research problem. The geometry and surface features of this alloy have been studied by the majority of researchers. As a result, an integration of quality and characteristic is chosen for the analytical work.

•ABRASIVE WATER JET MACHINING

Several non-traditional processes have been investigated to overcome the limitations of traditional machining methods. High energy beam technologies such as Laser Beam Machining (LBM), Electron Discharge Machining (EDM), and Abrasive Water Jet (AWJ) have made significant advances in recent years. AWJ is regarded as a versatile tool, particularly when cutting speed, environmental dust, thermal damage, and fatigue strength are of primary concern[1-16]. Because it has several distinct advantages over other non-conventional techniques, AWJ machining is widely used in industry. For example, it does not generate a heat-affected zone, and it provides high flexibility and accuracy, a faster cutting speed, and is environmentally friendly. Nonetheless, the use of AWJ causes erosion of the target material due to the application of a high velocity and pressure water jet mixed with abrasives. The development of kerf taper, delamination and surface roughness (SR), abrasive embedment, fibre pull-out, and other limitations associated with AWJ cutting reduce the quality of the manufactured parts[7-8]. This machining process can be optimised by appropriately adjusting the machining parameters and producing composite materials.

In summary, advanced nontraditional machining processes are divided into four categories[3]:

• Mechanical machining processes

• Thermal machining processes

• Electro-chemical and chemical machining processes

• Hybrid machining processes

The abrasive water jet-cutting process is filled with a variety of operational parameters that determine the total process's efficiency, economy, and quality. In particular, the parameters in AWJM can be classified into four types[3]:

1. Hydraulic parameters

– Water flow rate

– Water-orifice diameter

– Pressure pump

2. Mixing and acceleration parameters

– Focus diameter

– Focus length

3. Cutting parameters

– Impact angle

– Number of passes (np)

– Standoff distance (x)

– Traverse rate

4. Abrasive parameters

– Abrasive mass flow-rate

– Abrasive particle diameter

– Size distribution

– Shape

– Hardness

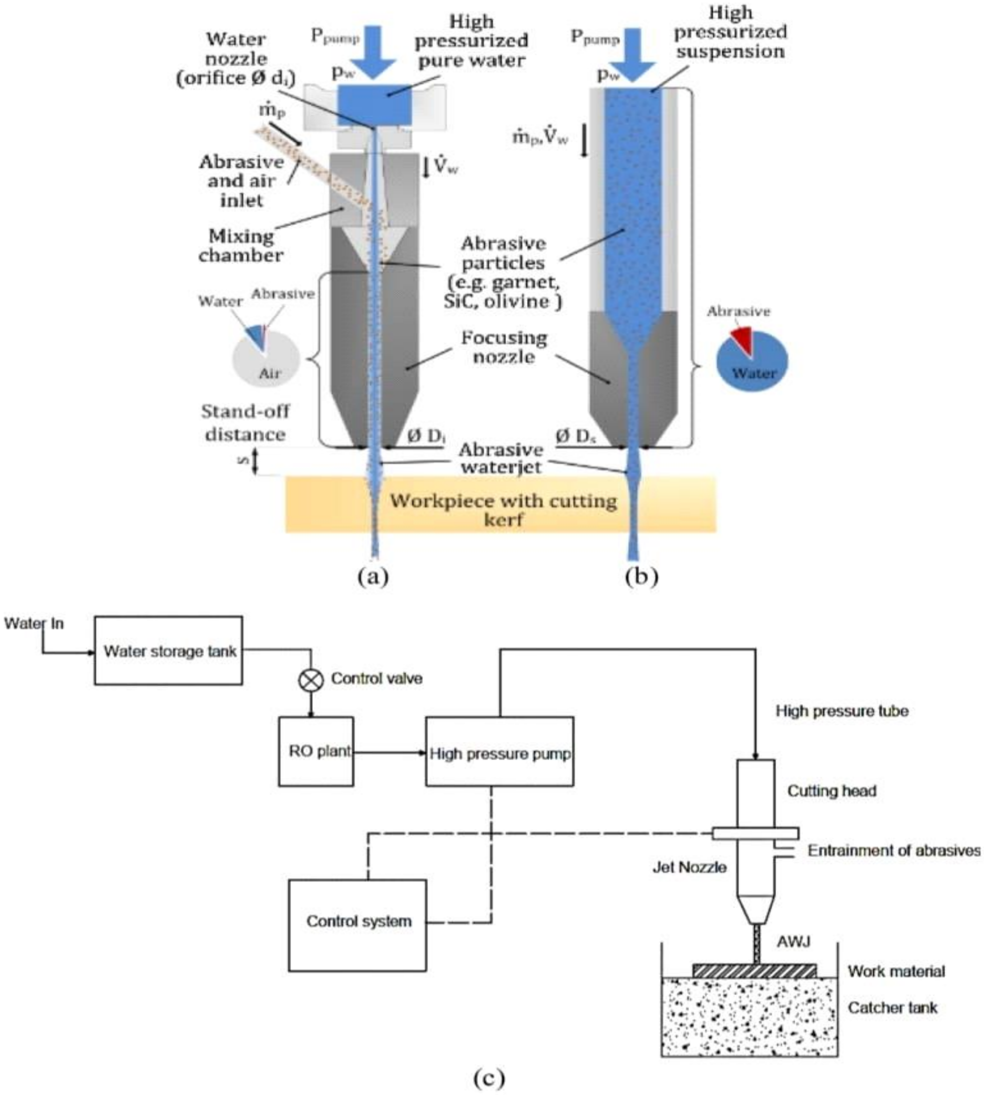

Fig1. a)Injection type [20], b)Suspension type[20] and c) layout of AWJM process[20]

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Due to inherently weak interfaces, machining of CFRP laminates resulted in severe damage, particularly near the exit side. When the jet entirely pierced or probably reached the smooth surface at the bottom of the CFRP laminate, the density of abrasive wear cracks increased. In comparison to Titanium, the energy distortion at the exit side had a significant influence on the penetration depth, resulting in a large depth variation at the bottom side. This can be attributed to CFRP's low machinability and increased sensitivity to damage and fatigue cracks[16].

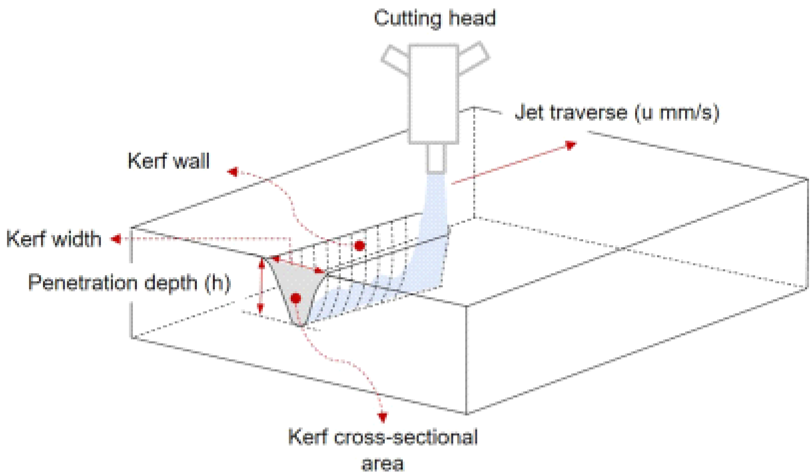

Fig2. Cutting geometry in partial depth AWJM

•DISCUSSION

To identify the machining set, the Taguchi orthogonal array is used. The surfaced roughness is analysed after machining. The ANOVA method is used to enhance the input parameters according to the surface roughness. This Taguchi method is used to determine the best process parameters for the AWJM process[33].

3.1.Taguchi technique

The Taguchi method is one of the best methods for optimisation process parameters for engineering analysis, particularly in material examination. The ANOVA analysis is used to determine the most influential independent process parameters for a specific profit maximization or reduction. The design of experiments (DOE) method is used to determine the number of trials with varying configurations of process parameters.

This technique has three signal-to-noise (S/N) ratios: "larger the better," "nominal the better," and "smaller the better."[33]

The formula for calculating the S/N ratio in order to minimise the kerf taper angle:

S/N ratio = $-10 \log [\Sigma (X^2/n)]$

Taguchi suggested a consistent method for implementing the approach to process optimization.

•Determine the control factors and their interactions.

•Determine the levels of each factor.

•Choose an appropriate orthogonal array .

•Assign the factors and interactions to the columns of the OA.

•Conduct the experiments.

•Analyze the experimental data.

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•Determine the optimal level of the factors.

•Conduct the confirmation experiment.

This initially proposed method is used to determine appropriate primacy by examining the individual and reliant process parameters. To obtain low surface roughness, the scientific process that nominal is better is chosen for enhancing both input and output process parameters (a = 0.05). It denotes that a confidence level of 95% is chosen to reduce surface roughness.

According to reference [33], the S/N ratio response and delta values demonstrate that the feed rate has a greater influence on surface roughness. The stand distance has a smaller effect on SR than the abrasive flow rate. The means response and delta values also show that the feed rate has a greater influence on surface roughness. The stand distance has a smaller effect on SR than the abrasive flow rate.

3.2.MINITAB

General statistics	**Design of experiments (DOE)**	**Quality and process improvement**	**Reliability and survival analysis**
Basic statistics	Factorial designs	Control charts	Test plans
Regression	Response surface designs	Measurement systems analysis	Distribution analysis
Analysis of variance (ANOVA)	Mixture designs	Process capability	Warranty analysis
Multivariate analysis	Taguchi designs	Quality planning tools	Repairable system analysis
Random data and probability	Optimal designs	Acceptance Sampling	Profit analysis

Table1. Methods provides by MINITAB[34]

3.3.Analysis of variance (ANOVA)

The ANOVA analysis takes into account input and output parameters, and Sum of Squares (SS), Square Means (MS), P-values, and F-values are displayed. P-value is utilized to analyze how various system characteristics affect output parameters. The particular parameter directly affects the output parameters if P is less than the "a" (0.05) value[33].

ANOVA for SR.

Source	DF	SS	MS	F	P
Feed rate	2	4.4435	2.2217	2.56	0.041
Stand of distance	2	0.9155	0.4577	2.32	0.05
Abrasive flow rate	2	1.9393	0.9696	2.43	0.048
Error	2	4.5384	2.2692		
Total	8	11.8366			

Table2. ANOVA Table[33]

The P-value for feed rate is 0.041; for SOD, it is 0.05; and for AFR, it is 0.048. Surface roughness has been influenced by all process variables.

3.4. Response Surface Methodology

According to K. Karthik, David Smith Sundarsingh, M. Harivignesh, R. Gopi Karthick, M. Praveen to obtain the process parameter's optimum value, one uses the response optimizer. The goal is to reduce the kerf top width and increase material removal rate. Maximum MRR is desired in the interest of reducing the process lead time, while minimum KTW is needed in order to reduce material waste. Based on the experiments, the restrictions on the replies are established[35].

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Figure 2 illustrates how the answers fluctuate as the input parameters change. In order to achieve both objectives for increasing water pressure, the software identifies a "sweet spot" that offers us a desirable value. For increasing values of water pressure, the MRR appears to increase and the KTW value follows a parabolic pattern. The maximum permitted feed rate is preferred since the MRR rises with higher feed rates while the KTW falls. It is noticeable that abrasive flow rate has little effect on MRR but has a significant impact on KTW; as a result, the software chooses a number where KTW is at its lowest._

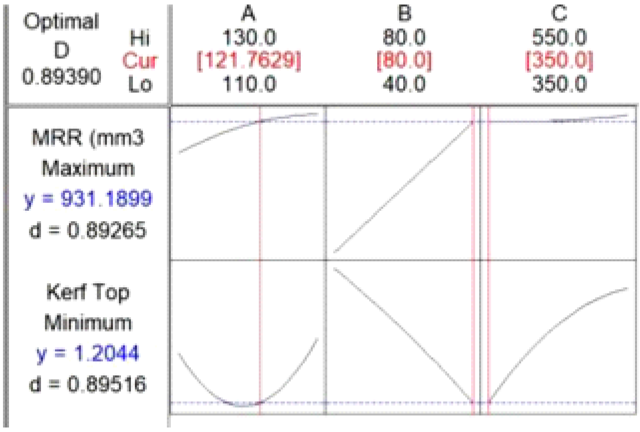

Fig3. Response Table

3.5.Grey relational analysis (GRA)

Ravi Kant, Sukhdeep S. Dhami applied GRA, which takes into account pressure, standoff distance, abrasive mass flow rate, and quality, allows for the optimization of machining time (t), surface roughness (Ra), and hardness (HRC).[36]

For Beneficial Attribute or Maximisation the Response,

$$x_i^* = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \qquad (1)$$

For Non-Beneficial Attribute or Minimisation of Response,

$$x_i^* = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \qquad (2)$$

Fig4. Equation of Response[36]

•RESULT AND DATA

This study was done by C. Joel,T. Jeyapoovan, Pinninti Praneeth Kumar to determine the optimal abrasive feed machining settings, standing distance, and nozzle speed for the AA6082 on abrasive water jet cutting to achieve the desired surface roughness, material removal rate, and hardness. In this investigation, the optimizations of AA6082 using the Response Surface Methodology were successful. For verification, a confirmatory experiment was performed with the use of a projected ideal parametric combination for AA6082 and revealed that the effect was 0.1548 g/sec of MRR, 4.90 Ra of SR and 92.86 BHN on the hardness that was considerably closer to optimal values[37].

K. Balaji, M. Siva Kumar, N. Yuvaraj analyzed on SS 304 was subjected to AWJ drilling operations using different abrasive mixes, stand-off distances, and feed rates. Using TGRA and KHA techniques, the main impact of the abrasive mixes on drilled hole characteristics was investigated in this innovative work. Additionally, a performance comparison between KHA and the GWO was done.Results of the KHA technique have demonstrated that it is more effective than TGRA in the AWJ drilling procedure. KHA's general performance index was determined to be 0.9992. Additionally, an abrasive blend of 60% garnet and 40% SiC, with SOD of

4.97 mm and FR of 128.70 mm/min, was anticipated to have the optimal parameter values. By predicting the setting of quality parameters, the suggested KHA approach has also demonstrated its effectiveness in improving the dimensional accuracy of the AWJ drilling properties. Because for all characteristics of the drilled hole, the error variation between anticipated and experimental results was determined to be less than 2%[28].

Ravi Kant, Sukhdeep S. Dhamiproposed the outcomes are far closer to the optimum value. The GRG has increased from the experimental data, which has a GRG of 0.7654, to the projected data, which has a GRG of 0.8145. Standoff Distance = 6 mm, and Quality = 1 are the multi objective optimum settings, and the response values are Machining Time = 36.5 sec, Surface Roughness = 1.61 mm, and Hardness = 28.6 HRC. The variables that have the greatest impact on the machining process are quality (traverse speed) and pressure[36].

David Smith Sundarsingh, M. Harivignesh, R. Gopi Karthick, and M. Praveen are among the participants. The current work is an experimental investigation into abrasive water jet machining of stainless steel 304. The effects of water pressure, feed rate, and abrasive flow rate on material removal rate and kerf top width have been studied. The experimental data and an empirical model developed using regression analysis for the prediction of material removal rate and kerf top width led to the following results. Water supply rate and pressure play a major role in material removal rate. Higher feed rates and lower abrasive flow rates result in minimum kerf top width.. The consistency and repeatability of this model were found to be in agreement with the results of the experimental validation[34].

Chandrakant Chaturvedi, P. Sudhakar Rao, Mohd. Yunus Khan experimented the results of the Ti-6Al-4V alloy's abrasive water jet machining are taken into account; conclusions may need to be retracted. The element that appeared to have the most influence on all three responses was pressure, which also contributed the most to the answer. For machining duration, the ideal setup is 310Mpa, 10 mm, 13 g/sec, and 250 mm/min. It is discovered that surface roughness is optimised at 275Mpa, 4 mm, 9 g/sec, and 70 m/min. The ideal HRC configuration is 170Mpa, 2 mm, 5 g/sec, and 250 m/min[38].

R.K. Thakur, K.K. Singh discovered that the weight % of multi-walled carbon nanotubes and the jet pressure had a disproportionately large impact on the overall effectiveness of the abrasive water jet machining. Standoff distance had very little impact on machining results. Under constant pressure, a field emission scanning electron microscopy image was created by increasing the weight fraction of multi-walled carbon nanotubes while lowering the traversal rate. Due to improved sticking ability, inter-laminar shear strength and flexural strength also increased as the multi-walled carbon nanotube content in the polymer matrix, and the bonding between fibres and the matrix got stronger. The traverse rate was reduced, which enhanced machining performance and increased the influence of abrasive particles in the cutting zone. With the right machining parameters, an Atomic force microscopy image has fewer peaks and troughs[24].

Balaji D.S. , Jeyapoovan T. analysed the results show that the genetic algorithm, which has a minimum variation of 0.82% and a maximum deviation of 4.48%, is one of the most useful tools for optimizing the parameters. By comparing the deviations, it can be seen that the experimental results, such as hardness and surface roughness, are in good agreement with the mathematical model. The optimized settings and the reactions they produce are in strong accord with one another. The Al 6063 alloy's hardness was reported to rise by up to 35.9% as a result of the peening operation. The abrasive deposition on the material, which is really used to speed up the material removal rate activity, is clearly visible in the microstructure. The main indicator of plastic deformation was the existence of border dislocation. During the surface finishing process on the material, the surface roughness of the peened sample increased by up to 26.6%. The smooth and dull surface is visible in the microstructure, which supports the increase in surface roughness[39].

Miroslav Radovanovic proposed the abrasive mass flow rate, traverse speed, standoff distance, three factors (perpendicular tolerance, surface roughness limit, and traverse speed for separation cut), three constraints (perpendicular tolerance, surface roughness limit, and traverse speed for separation cut), bounds, and three objectives comprise the optimization problem. It is challenging to solve multi-objective optimization problems where the objectives typically conflict. The multi-objective optimization issue was solved using the MATLAB multiobjective genetic algorithm solver. For cutting 6.5 mm thick carbon steel S235 using an abrasive water jet, the following factor levels were chosen: traverse rate vf=127 mm/min, abrasive flow rate ma=300 g/min, and standoff distance h=1 mm. To create a unit of cut surface at these factor values, the machining time is t=7.266 s/cm2 (productivity is Q=8.258 cm2/min), and the operating cost per metre of cut is C=2.048 EUR/m[40].

C. Joel ,T. Jeyapoovan has been decided to investigate the AWJ machining parameters for AA7075 using the new Grey-Taguchi approach. The GRA grade for the MRR, HD, and SR multi-response parameters has identified the ideal machining parameters. The best performance was determined after fifteen experiments were run. With 250 g/min abrasive feed rate, 3 mm stand-off distance, and 36 mm/min nozzle speed, the cutting parameter with the least amount of surface roughness and the most amount of MRR and hardness is obtained. The grey relational grade discovered in the experiment of confirmation is found to be 0.612, an improvement of 1.03% from its grade value.The characteristic that has the biggest impact on abrasive cutting operation is the one with an abrasive feed rate of 46.52%. The second-highest influencing factors are nozzle speed (36.76%) and stand-off distance (15.05%).It was discovered with a surface roughness minimising of 5.64 Ra and a material removal rate maximisation of 0.1216 g/sec and hardness 185.64 BHN[1].

M. Shunmugasundaram , A. Raji Reddy, Zareena Begum experimented on Hybrid metal matrix composites and are created using the stir casting technique, and the composites are machined using abrasive water jet machining. Surface roughness is a metric in this study that must be kept to a minimum. The S/N ratio response and means demonstrate that the feed rate is more affected than the other two process variables. The surface roughness is demonstrated by the ANOVA analysis to be influenced by all three process parameters. Aluminium, magnesium, and nickel are added as the matrix and silicon carbide and barium nitrate are added as reinforcement to create the hybrid metal matrix.The hybrid metal matrix composite is machined by abrasive metal matrix composites, and the L9 orthogonal array is used to discover the nine machining combinations of process parameters. The influence of independent process factors on surface roughness is confirmed using the contour plot. The results demonstrate that the ideal process parameters for achieving low surface roughness on produced composites are feed rate of 135 mm/min, distance stand of 0.5, and abrasive flow rate of 450 gm/min[41].

C. Joel, Linda Joel, S. Muthukumaran, P. Matilda Shanthini investigated abrasive water jet cutting of C360 brass was multi-objective optimised to balance the competing demands of decreasing surface roughness and maximising material removal rate and hardness. Multiobjective teaching and learning-based optimization was used to tackle the optimization of C360 brass. The experiment's optimised settings were then used to run it, and the cutting accuracy was assessed. The confirmatory experiment was conducted utilising the C360 Brass' best parametric combination, and the results revealed 0.1012 MRR, 5.61 Ra for SR, and 88.86 BHN in terms of hardness[26].

Vootkuri Naveen Reddy , Bellam Venkatesh focused on the surface roughness and delamination of AWJM-drilled holes. Abrasive water jet pressure and TR are two of the key variables that affect surface roughness (traverse rate). When the pressure of the abrasive water jet is increased, the surface roughness will be reduced. When the traverse rate is reduced, the surface roughness will also decrease. Delamination and fibre pull out happen at low abrasive water jet pressure. Delamination and fibre pull out will occur at a large standoff distance[42].

J. Jeykrishnana,B. Vijaya Ramnatha,S. SreeVignesha, P. Sridharana, B. Saravanana has been investigated how the process variables, such as water pressure, abrasive flow rate, and SOD, affect the kerf taper angle of AWJM in Inconel 625 alloy. Water pressure has the biggest impact on kerf taper angle, followed by variables like abrasive flow rate and SOD. The percentage contributions of the variables water pressure, abrasive flow rate, and SOD to kerf taper angle were determined to be 50.17%, 29.30%, and 16.5%, respectively. This indicates that water pressure has a greater impact on the response to the output. It has become clear that the ideal parameters for minimising the kerf taper angle must be the flow rate of the abrasives is 5 g/s, the water pressure is 300 MPa, and the distance between the nozzle and the work item, or SOD[43].

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BijayaBijeta Nayak, Kumar Abhishek, Siba Sankar Mahapatra, Diptikanta Das studied on numerous AJM performance characteristics are optimised to achieve the best possible parametric combination for increasing material removal rate while reducing workpiece surface roughness. The proposed multiple response optimization method, which combines Taguchi's robust design methodology with weighted principal component analysis, is quite capable of resolving correlation difficulties of responses. It has been shown that this method improves MRR and SR simultaneously, two performance traits of the AJM process[21].

Using abrasive water jet machining, N. M. Vaxevanidis, A. Markopoulo,G. Petropoulos tested micro-drilling on composite materials (AWJM). The two variables that have the most of an impact on how well micro holes are machined by AWJM are transverse feed rate (TFR) and stand-off distance (SOD). However, the variable that causes the most data dispersion is abrasive mass flow rate (AMFR). The zone impacted by erosion correlates with most of the region harmed at the material entrance. As a result, the cut's exit does not have this flaw. As TFR rises, the roundness of the hole at the cut's exit diminishes, which has an impact on the element's dimensional quality as it loses its round geometry because of jet lag. Reduced SOD and TFR yield the lowest kerf taper and delamination factor values[3].

•CONCLUSION

Conclusions based on Abrasive Water Jet can be withdrawn. The material is machined in accordance with the analytical action. Pressure appeared to be the most influential variable for all three responses, contributing the most to the outcome. Water pressure has the greatest influence on kerf taper angle, followed by abrasive flow rate and SOD. The percentage contribution of the variables water pressure, abrasive flow rate, and SOD relating to kerf taper angle was discovered, indicating that water pressure has the greatest effect on the output response. Finally, the experiment was carried out using optimized parameters, and the cutting accuracy was assessed.

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