To Investigate the Reduction in Kerf Taper Angle & Abrasive Waterjet lagging of Hard Ductile Inconel 625 with Abrasive Water Jet Machining with using Mathematical Model

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Abstract - Inconel 625 were studied to reduce in kerf taper angle by reducing water jet lagging with added polymer (PAM) to reduce the softening area when cutting the material on the abrasive waterjet cutting machine and to obtain a flat surface using the above listed materials. Used a combination of water pressure, abrasive particle size, nozzle size, polymer additive & Abrasives (Silica Sand) additive by percentage mass as process parameters & to check validation by mathematical model

Index Terms - Abrasive Particle Size , Mess Size Of Abrasive Particle , Taper Angle ,Inconel 625, , Abrasive Water Jet Cutting, Kerf ,Mathematical Model

Introduction

Abrasive water jet cutting, or AWJ, is a versatile and precise cutting method that utilizes an incredibly high-pressure stream of water mixed with abrasive particles. This powerful jet acts like a tiny, fast-moving saw, capable of cutting through a wide range of materials – from soft foams and rubber to tough metals, glass, and even ceramics. The process works by using a multi-stage pump to generate immense pressure for the water, which is then focused into a thin stream. Abrasive particles are then injected into the water just before it exits a narrow nozzle, creating the abrasive-laden jet that shaves away material with each precise hit. This method offers several advantages, including clean cuts since there's no heat involved, minimal environmental impact due to the lack of fumes or dust, and the ability to cut a vast array of materials with high accuracy.In the realm of industrial cutting, abrasive water jet cutting, or AWJ, stands out as a technological marvel. Imagine a tool that utilizes an incredibly high-pressure stream of water, infused with gritty particles, to act like a microscopic, high-speed saw. This is the essence of AWJ – its ability to precisely cut through a mind-boggling array of materials. From the soft and yielding nature of rubber and foam to the unyielding strength of metals, glass, and even delicate ceramics, AWJ tackles them all with remarkable versatility.The magic behind AWJ lies in its multi-stage pump, which generates a pressure so immense it transforms water into a powerful cutting force. This pressurized water is then focused through a narrow orifice, creating a thin, high-velocity jet. To add an extra layer of cutting power, a precise injection system introduces abrasive particles like garnet or aluminum oxide into the water stream just before it exits the nozzle. This abrasive-laden jet then becomes the workhorse, meticulously shaving away tiny particles of the target material with each precise hit.[1]
The cutting head as per Figure 1 is used to pass and control the water jet. Its diameter is usually materials, Diamond perforated plates generally have an operating life of main

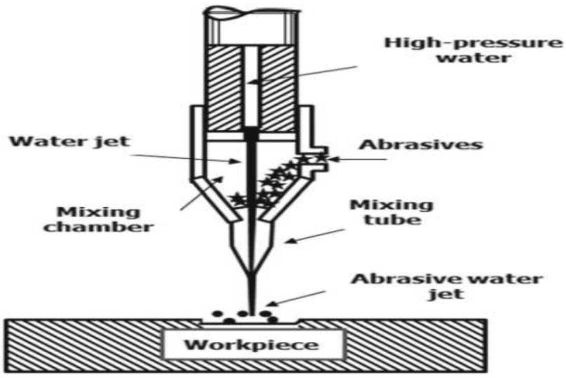

Figure 1 principle of the AWJM

One way to achieve optimal performance is to require constant changes in, this means, as the nozzle length being shorter than required will prevent the need to accelerate the abrasive material, when the nozzle length is longer it will cause excessive wear. cost to Strength loss also occurs due water jet cutting. The law of mechanical erosion is the process used to remove or cut material from the workpiece in above machining. The principle is depend on the combination of the abrasive type material with the highest water jet to focus on the given structure [2]

Littarature Review

Rana, M., & Akhai, S. et al. discussed in this article how the Taguchi grey relational analysis (TGRA) was used on Inconel-625, a high-performance engineering material with a broad variety of industrial applications, by machining it through abrasive water jet machining. Abrasive water jet machining (AWJM) has been shown to be capable of imitating the machining capabilities of Inconel 625, as shown in this study by the use of the TGRA approach for multi objective optimization of its machining parameters. Taguchi method is used to model the influence of three input parameters, namely Standoff distance (SOD), Abrasive mass flow rate (AMF), and Transverse Speed (TS), on three selected responses - material removal rate (MRR) and surface roughness (SR). The regression equations, mathematical models[3]

Rajesh, M., Vijayakumar, R., Rajkumar, K., & Ramraji, K. et al. Abrasive waterjet (AWJ) technology is a viable production method for machining metal matrices with its own set of benefits. AWJD is a fantastic option for Despite its higher cost, the metal matrix is increasingly being used in many applications such as space, aviation, marine, architecture, and automobiles because of its superior physical and mechanical characteristics AWJ drilling of Inconel 718, on the other hand, has several drawbacks. The striation angle quality and surface morphology/integrity were investigated in this study [4]

Ceritbinmez, F., Günen, A., Gürol, U., & Çam, G. et al.In recent years, the cost-effective wire arc additive manufacturing (WAAM) method is increasingly replacing traditional production methods for Ni-based superalloys. However, the effect of high heat input and elemental segregation in the WAAM method on machinability has not yet been adequately investigated. For this purpose, drilling of wrought and WAAM Inconel 625 samples with thermal (i.e., die-sinking micro-EDM and micro-EDM) and mechanical drilling techniques (i.e., orbital and conventional drilling) was investigated in this study. It was observed that thermal drilling methods formed a white layer with a thickness of 20-25 μm and 35-50 μm in the cross-section of wrought and WAAM specimens, respectively, while no white layer was formed in the mechanical methods.[5]

Kumar, P. A., Vivek, J., Senniangiri, N., Nagarajan, S., & Chandrasekaran, K. et al.Carbon Fiber Reinforced Polymers (CFRPs) have been applied potentially for various application components owing to their lightweight and better mechanical properties. However, the machining of CFRP has been observed to be poor machinability due to the properties of the CFRP composites. Micro-feature fabricating on CFRP macro-component is a challenging task due to the selection of inadequate process parameters and machines. However, micron-level blind square holes are required in CFRPs for proposing the applications of micro-robotics, micro-vibration measurements, and micro-detection of cracking. These square holes produced on CFRP have the difficult task of being machined using the Electrical Discharge Machining (EDM) process[6]

Huang, S., Fu, Z., Liu, C., & Li, J. et al. Laser cutting can achieve ultra-precision cutting of materials by using appropriate parameters. In order to optimize processing parameters and obtain better processing quality, conducted experimental research on laser cutting of Glass fiber reinforced plastic (GFRP). In this study, the impact of four process parameters (laser power, cutting speed, assistant gas pressure and focus position) on quality characteristics (kerf width, kerf taper and kerf section roughness) was evaluated through analysis of variance (ANOVA), the regression relationship between laser processing parameters and quality characteristics was analyzed [7]

Jeykrishnan, J., Ramnath, B. V., Vignesh, S. S., Sridharan, P., & Saravanan, B et al. Abrasive water jet machining is one of the primarily utilized non-traditional machining processes as it tends to cut highly hard and brittle materials and it is a best alternative for the traditional machining processes. The main intent of this paper is to optimize the process parameters such as the pressure of water, flow rate of the abrasives used and the stand-off distance in inconel 625 alloys in order to obtain the minimized kerf taper angle. The experimental trials have been done and the parameters of abrasive water jet machining were optimized by employing Taguchi's technique.[8]

Srirangarajalu, N., Vijayakumar, R., & Rajesh, M. et al. Inconel-625 is a tough-to-cutting material used in ultra-supercritical power plants for flanges, offshore oil sectors, and turbine blades, among other high-temperature components. The objective of this article is to determine the link between four key process independent variables: traverse speed (T_{SP}), abrasive mass flow rate (AM_{FR}), abrasive aqua jet pressure (AA_{JP}), and gap distance (G_d) to the surface roughness (SR_a), kerf angle (KE_A), and erosion rate (M_{RR}). The response surface methodology-Central composite design (RSM-CCD) was used to perform the experimental interpretations. The influence of individual abrasive aqua jet cutting (AAJC) factors was determined using analysis of variance technique (ANOVA). [9]

Salinas, L. C., Moussaoui, K., Hejjaji, A., Salem, M., Hor, A., & Zitoune, R et al.Inconel 718 (IN718) is a precipitation hardened nickel-base super-alloy exhibiting high strength and good corrosion resistance at elevated temperatures and on the downside; it is characterized by poor machinability. Abrasive water jet (AWJ) process offers a potential method to machining difficult-to-cut materials such as IN718. The present work investigates the influence of AWJ parameters on surface roughness, topography, depth of cut, and residual stress when milling IN718. Surface characterization was conducted through 3D optical microscopy and SEM techniques.[10]

Arun, A., Rajkumar, K., Sasidharan, S., & Balasubramaniyan, C et al.This research examines the optimum machining features for abrasive water jet cutting of Monel 400 alloy. This alloy system faces significant

challenges in conventional machining and can be surpassed by using the coolest machining technology, such as AWJM. In this experimental investigation, the water beam jet pressure (A_P), the nozzle jet traverse speed (N_S), and the abrasive flow rate (A_{MF}) were used to explore the kerf taper angle (K_{ta}) and surface roughness (R_a) response variables. The experimental L-9 layout (Taguchi's/L^{-9}(−|-) standard orthogonal array) was used to run the experiment. The S/N ratios for each experimental run were determined using a mono-output response optimization technique[11]
Singh, M. K., Trehan, R., & Gupta, A. et al. Present work attempts to optimise the significant process parameters to enhance the surface properties and productivity during machining of marine grade Inconel. Taguchi-based Grey analysis was applied to optimise the parameters of abrasive water jet machining (AWJM) for minimum surface roughness and higher material removal rate (MRR). Three most influential input parameters were taken, i.e. standoff distance (SOD), abrasive flow rate (AFR) and jet traverse speed (JTS). The three levels of input parameters of SOD, AFR and JTS were 1, 2, 3 mm, 300, 350, 400 g/min and 20, 28, 36 mm/min, respectively. MRR was maximum in case of machining performed at SOD of 3 mm, AFR of 350 g/min and JTS of 36 mm/min..[12]

Materials and Methods

AWJ machining technology has been increasingly used since it has various distinguished advantages over other cutting processes. No thermal damage or distortioncarried out to AWJM. The heat generated is instantaneously carried away by the water. As a result, no temperature rise occurs in the work piece. It can cut material like pre- hardened steels, titanium alloys, copper, brass, nickel alloy and aluminum, brittle materials like glasses,ceramics and quartz.[6] The common Silica Sand is in red color, which can be classified into six kinds by its chemical composition[7] The pump is the heart of the waterjetsystem. The pump pressurizes the water and delivers it continuously so that a cutting headcan then turn that pressurized water into a supersonic waterjet stream. The intensifier is a reciprocating pump, in that the biscuit/plunger assembly reciprocates back and forth, delivering high-pressure water out one side of the intensifier while low-pressure water fillsthe other side. [9] They are using Auto abrasive delivery system. It has the capability of storing abrasive and deliver the abrasive to the hopper automatically. The design shows our continuous effort to improve efficiency and reduce labor requirements High sensitive sensor gives indication to operator when the hopper is empty. System can supply abrasive for continuous operation of 500 to 800 minutes[13], Inconel 625 alloy under a wide range of temperatures and pressures is a primary reason for its wide acceptance in the chemical processing field. Because of its ease of fabrication, it is made into a variety of components forplant equipment. Alloy 625 is a nickel-chromium-molybdenum alloy possessing excellent resistance to oxidation and corrosion over a broad range of corrosive conditions, including aerospace and chemical process applications. The alloy has outstanding strength and toughness at temperatures ranging from cryogenic to elevated temperatures in the range of - 423°F to 1300°F (-252.77 °C to 704.44 °C).[12]
With using L27 orthogonal array as per Table 1 with above mentioned parameters like nozzle diameter, pressure, Polymer additive, Abrasive Particle, Particle mess size number,for final output for reducing kerf angle with using different polymeric additives in different proportion,it can be researched with using polymeric additive kerf angle can be reduce significantly by experiment

Table 1 Process Parameter Table

Factors	Level 1	Level 2	Level 3
Nozzle diameter (mm)	0.20	0.50	0.92
Pressure (MPa)	450	550	650
Polymer additive(%mass)	0	0.25	0.50
Abrasive particle(%mass)	5	15	25
Abrasive Particle mesh number	80	100	120

The response parameters consist of parameters related to the target of the machining. parameters are the kerf taper angle , The width of the cut depends mainly on the diameter of the syringe but is also affected by the duration of exposure of the product to the syringe.[18-19] The center of the cut will be affected by more objects than those near the cut. This will ensure faster removal of data in the middle and less material removed from the side.The kerf taper angle is the angle of the kerf side compared to the perpendicular edge. In cases where the width of the upper slit differs from the width of the lower slit, the angle is defined as half the angle of the two sides. By tilting the waterline at an angle equal to the cutting angle, the part achieves a vertical line.[23-25]

Result and discussion

Based on Taguchi analysis of the experiment of Inconel 625 here as seen in above Table 2 Polymer additives appear to be the most effective parameter with a rank of 1. While exhibits the highest delta value (0.08731).

Table 2 Response Table for Means of Inconel 625 material

Level	Nozzle Diameter (mm)	Water Pressure (Mpa)	Polymer additives % bymass	Silica Sand Particle% by mass	Silica Sand size (mess)
1	0.11123	0.12458	0.16462	0.08001	0.11092
2	0.09144	0.13081	0.07731	0.14459	0.11366
3	0.15277	0.10006	0.11351	0.13084	0.13087
Delta	0.06132	0.03076	0.08731	0.06458	0.01994
Rank	3	4	1	2	5

This suggests that while a higher delta will be very very significant parameters for kerf taper angle, polymer additives seem to consistently contribute to better results across different parameter combinations. Taguchi analysis, named after its developer Genichi Taguchi, is a powerful statistical method used to improve the quality and robustness of products and processes. It focuses on minimizing variability and optimizing performance by identifying influential factors and their ideal settings

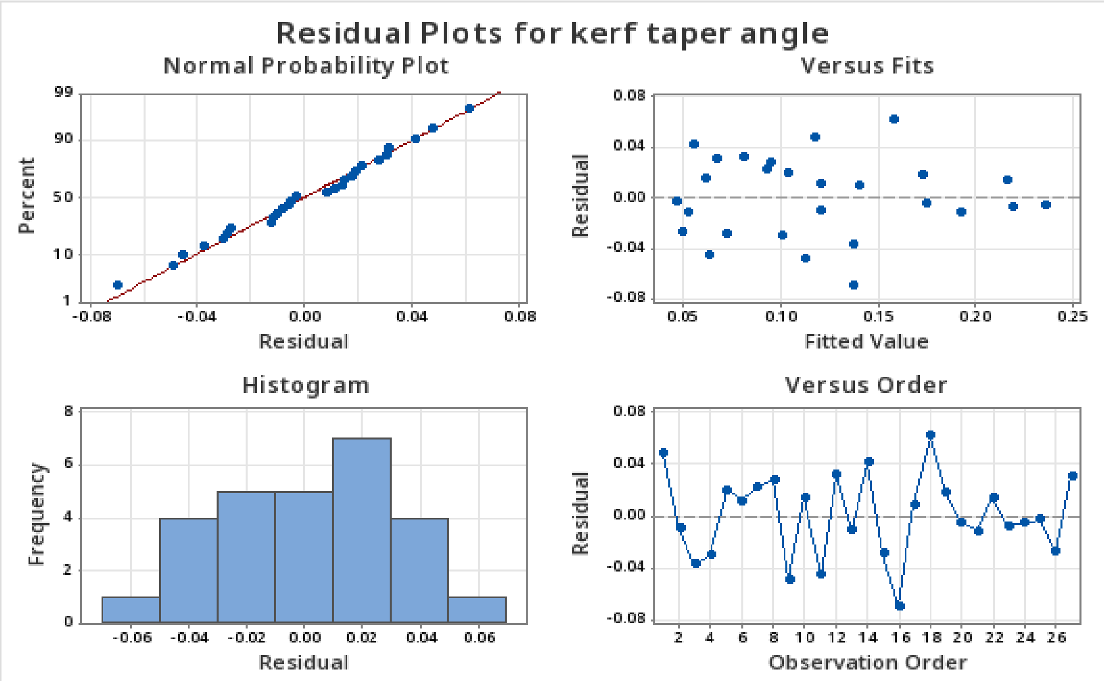

Figure 2 – Residual Plots for Kerf taper angle of Inconel 625

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
0.0403285	75.45%	60.10%	80.08%

- Focus on Polymer Additives: The significant impact of polymer additives suggests that careful adjustment of their concentration can substantially influence kerf taper angle, offering a promising avenue for optimization.
- Consider Nozzle Diameter and Abrasive Particles: Optimization of nozzle diameter and alumina particle percentage can also contribute to controlling kerf taper, but their effects might be less pronounced than those of polymer additives.
- As shown in Figure 2 the top left plot is a normal probability plot, which shows the distribution of the residuals plotted against the expected normal distribution. In this case, the data points roughly follow the straight line, suggesting that the residuals are normally distributed. This is a good assumption for linear regression analysis.
- The top right plot is a fitted value plot, which shows the residuals plotted against the fitted values. Ideally, the residuals should be randomly scattered around zero, with no pattern or trend. In this case, there does not appear to be any obvious trend in the residuals, which is another good sign for the model.
- The bottom left plot is a histogram, which shows the distribution of the residuals. Ideally, the histogram should be roughly symmetrical and bell-shaped, with most of the residuals near zero. In this case, the histogram is also roughly symmetrical, which is another good indication that the model is doing a good job of fitting the data.
- The bottom right plot is an observation order plot, which shows the residuals plotted against the order in

which the data were collected. Ideally, the residuals should be randomly scattered around zero, with no trend or pattern. In this case, there does not appear to be any obvious trend in the residuals, which is a good sign that there are no temporal effects in the data.

- Overall, these residual plots suggest that the model is doing a good job of fitting the kerf taper angle data.

Mathematical Model

From the experimental study, it is evident that the kerf taper is something that can be reduced by using a controlled combination of performance parameters. In doing so, a basic understanding of kerf taper formation begins with the characteristics of the jet. The radial velocity distribution of the jet is believed to be a key factor in calculating the kerf in order to change the jet speed it must overcome the breaking force required to destroy the property. In the abrasive injection system the material is considered to be removed only by the changing force of the particles and therefore the flow rate of water is not calculated in the model. The shortest distance between the orifice and the cover exit particle speed, V1, and waterjet speed at the outlet of the pipe, V, can betreated alternately. Using the Bernoulli equation for unbalanced flow V through orifice provides when P is waterpressure and w water density [25].Dimensional analysis has proven to be successful and effective in generating analytical formulae for complex systems involving a large number of variables , Mathematically a non-dimensional quantity is proportional to the product of other dimensionless groups raised to a rational power Because of the simplicity and wide use of this power-law formulation, it is used in this study, so that the complete dimensional equation is given by

$$\theta = f\left(\frac{p}{\delta_w}, \frac{d_j}{t}, d_p, m_a, m, H, E\right) \quad (1)$$

and Group will be formed by Buckingham pie theorem

$$f(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5) = 0 \quad (2)$$

π1,π2,π3,π4,π5, Respectively Represent Kerf taper angle,Represent effect of Jet diameter,Represents the effectof exposure time,Represent Abrasive Mass Effect,Represent effect of Young Modulus

$$\theta = \left(\frac{p.Mp}{\delta_w\,(dp)^3\,H}\right)^a \left(\frac{dj}{v}\sqrt{\frac{dp.H}{mp}}\right)^b \left(\frac{ma}{mp}\right)^c \left(\frac{E}{H}\right)^d \quad (3)$$

where a, b, c and d are the exponents, k1, is the correction factor[15] Regression analysis used to find unknown exponent to complete Mathematical model equation so Here, K is curve fitting constant and a to d be indices which needs to be calculated by multi variable regression analysis at95 percent confidence interval by uisng Matlab, As per multi variable regression analysis at 95 percent confidence interval using data obtained in experimentalpart of this investigation ,Validating an abrasive water jet (AWJ) system involves a series of tests to ensure it meets specific cutting requirements. The goal is to assess factors like accuracy, material compatibility, cut quality, and speed. Imagine a test where the AWJ tackles a chosen material with precise parameters – like water pressure and abrasive selection. After the cut is made, meticulous measurements with calipers or a CMM (coordinate measuring machine) verify dimensional accuracy. Inspectors scrutinize the cut surface for defects, while the cutting speed is recorded and compared to expectations

Conclusion

This study identifies a specific combination of parameters to effectively achieve a flat cutting surface with minimal kerf angle in Inconel 625 using water jet technology. The validated mathematical model proves valuable for predicting and optimizing cutting parameters for different materials and desired results. In addition, the identified importance of the polymer additive for high-strength materials provides valuable insights for further research and development of waterjet cutting technologies. Inconel 625 grooves to the sweet spot of 0.25% polymer combined with 5% 80-mesh silica sand, fueled by the highest 650 MPa pressure and a mid-sized 0.5 mm nozzle. This symphony minimizes water jet lagging and delivers the flattest cuts.

References

1. Mostafa Mohamed “Waterjet Cutting up to 900 MPa” Hannover, in July 2004 .
2. Divyansh Patel, Puneet Tandon “Experimental investigations of thermally enhanced abrasive water jet machining of hard-to-machine metals” CIRP Journal of Manufacturing Science and Technology (2015) .
3. Rana, M., & Akhai, S. (2022). Multi-objective optimization of Abrasive water jet Machining parameters for Inconel 625 alloy using TGRA. Materials Today: Proceedings, 65, 3205-3210.
4. Rajesh, M., Vijayakumar, R., Rajkumar, K., & Ramraji, K. (2022). Experimental investigation and striation

study of Inconel 718 by using abrasive water jet drilling. Materials Today: Proceedings, 62, 1277-1281.

5. Ceritbinmez, F., Günen, A., Gürol, U., & Çam, G. (2023). A comparative study on drillability of Inconel 625 alloy fabricated by wire arc additive manufacturing. Journal of Manufacturing Processes, 89, 150-169.
6. Kumar, P. A., Vivek, J., Senniangiri, N., Nagarajan, S., & Chandrasekaran, K. (2022). A study of added SiC powder in kerosene for the blind square hole machining of CFRP using electrical discharge machining. Silicon, 14(4), 1831-1849.
7. Huang, S., Fu, Z., Liu, C., & Li, J. (2023). Multi-objective optimization of fiber laser cutting quality characteristics of glass fiber reinforced plastic (GFRP) materials. Optics & Laser Technology, 167, 109720.
8. Jeykrishnan, J., Ramnath, B. V., Vignesh, S. S., Sridharan, P., & Saravanan, B. (2019). Optimization of process parameters in abrasive water jet machining/cutting (AWJM) of nickel alloy using traditional analysis to minimize kerf taper angle. Materials Today: Proceedings, 16, 392-397.
9. Srirangarajalu, N., Vijayakumar, R., & Rajesh, M. (2022). Multi performance investigation of Inconel-625 by abrasive aqua jet cutting. Materials and Manufacturing Processes, 37(12), 1393-1404.
10. Salinas, L. C., Moussaoui, K., Hejjaji, A., Salem, M., Hor, A., & Zitoune, R. (2021). Influence of abrasive water jet parameters on the surface integrity of Inconel 718. The International Journal of Advanced Manufacturing Technology, 114, 997-1009.
11. Arun, A., Rajkumar, K., Sasidharan, S., & Balasubramaniyan, C. (2024). Process parameters optimization in machining of monel 400 alloy using abrasive water jet machining. Materials Today: Proceedings, 98, 28-32.
12. Singh, M. K., Trehan, R., & Gupta, A. (2021). Application of Grey approach to enhance the surface properties during AWJ machining of marine grade Inconel. Advances in Materials and Processing Technologies, 7(3), 429-445
13. Chidambaram Narayanan, Reto Balz, Daniel A.Weiss, Kurt C. Heiniger(2013) “Modelling of abrasive particle energy in water jet machining ” ,Journal of Materials Processing Technology 213 2201– 2210
14. Mustafa Kemal Kulekci(2002) “Processes and apparatus developments in vindustrial water jet applications International”, Journal of Machine Tools & Manufacture 42 ,1297– 1306.
15. Keyur Kumar J. Patel (2004) “Quantitative evaluation of abrasive contamination in ductile material during abrasive water jet machining and minimizing with a nozzle head oscillation technique International” Journal of Machine Tools & Manufacture 44 ,1125–1132.
16. Deaconescu tudor and deaconescu andrea 2013 “optimization of abrasive jet cutting by means of taguchi methods” Nonconventional Technologies Review Romania, December, Gujarat Technological University, Ahmedabad Page 91
17. M.Chithirai Pon Selvan, Dr. N. Mohana Sundara Raju(2011) “Assessment of Process Parameters in Abrasive Waterjet Cutting of Granite” International Conference on Trends in Mechanical and Industrial Engineering (ICTMIE'2011) Bangkok Dec.,.
18. Farhad Kolahan, A. Hamid Khajavi (2009) “Modeling and Optimization of Abrasive Waterjet Parameters using Regression Analysis” World Academy of Science, Engineering and Technology 35.
19. Azlan Mohd Zaina, Safian Sharifc (2011) “Optimization of process parameters in the abrasive waterjet machining using integrated SA–GA” Applied Soft Computing 11 ,5350– 5359 .
20. D.K. Shanmugam, F.L. Chen, E. Siores, M. Brandt (2002) “Comparative study of jetting machining technologies over laser machining technology for cutting composite materials”, Composite Structures 57 289–296 .
21. H. Y. Zhenga, Z. Z. Han’, Z. D. Chen, W. L. Chena, S. Yeo (1996) “Quality and Cost Comparisons between Laser and Waterjet Cutting”, Journal of Materials Processing Technology 62 294-298 .
22. Jagadish, & Gupta, K. (2020). Abrasive water jet machining of engineering materials. Springer.
23. Ceritbinmez, F., & Günen, A. (2024). Comparison of drilling of Inconel 625 by AWJM and WEDM. Aircraft Engineering and Aerospace Technology.
24. Mahesh, K., Philip, J. T., Joshi, S. N., & Kuriachen, B. (2021). Machinability of Inconel 718: A critical review on the impact of cutting temperatures. Materials and Manufacturing Processes, 36(7), 753-791.
25. Magri, A., Diniz, A. E., & Suyama, D. I. (2018). Evaluating the use of high-pressure coolant in turning process of Inconel 625 nickel-based alloy. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 232(7), 1182-1192.

DOI: https://doi.org/10.15379/ijmst.v9i2.3676