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Multi-Criteria Decision Making of Abrasive Water Jet Machining Process for 2024-T3 Alloy Using Hybrid Approach

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ABSTRACT

Abrasive water jet machining (AWJM) is one of the most environmentally friendly non-conventional machining processes, which can be employed to cut hard and thin materials without any thermal effects. In this study, the technique for order of preference by similarity to ideal solution (TOPSIS) has been combined with the Entropy method and employed to find out the multi-criteria decision-making of process parameters. Experimental investigations have been conducted to evaluate the performance of the AWJM process in terms of surface roughness (Ra) and kerf angle (Ka). The selected process parameters are a stand-off distance (SOD), traverse speed (TS), and abrasive flow rate (AFL), whereas the AL-alloy 2024-T3 was selected as the workpiece material. The image process technique has been utilized to measure the values of the Ka. The results demonstrate that the optimal solutions of the AWJM process, which give the smallest value of Ra and minimizes Ka, are 2 mm, 20 mm/min, and 100 g/min, for SOD, TS, and AFL respectively.

Keywords: Abrasive water jet machining, TOPSIS, entropy, image processing.

INTRODUCTION

One of the main challenges in the manufacturing field is reducing production costs without impacting product quality [1]. This challenge arises during the manufacturing of a hard-to-machine material or complex geometry. Therefore the utilization of optimization approaches in the manufacturing process leads to more control of the process parameters [2]. One of the recent non-traditional machining methods is the abrasive water jet machining. This approach has the benefits of no thermal alteration, multifunctional machining process, high adaptability, relatively low cutting force, cost-effectiveness, and environmentally friendly [3]. The quality of machined parts can be efficiently improved based on the level of process variables through the adoption of an optimization approach [4].

Gaikwad et al. [5] imposed the impact of the abrasive water jet machining (AWJM) process parameters such as pressure, abrasive flow rate (AFL), abrasive size, traverse speed (TS), and stand-off distance (SOD) on the Ra and metal removal rate of Inconel – 188. The Taguchi method is used to reduce the number of experiments. In addition, Satyanarayana and Srikar [6] presented the effect of pressure, AFL, and SOD on the kerf width and material removing rate in abrasive water jet machining of Inconel-718. Taguchi (GRA) is adopted to find out the optimum multi-response of the outputs. The results indicated that the jet pressure parameter has more effect on the material removal rate and kerf width compared to the SOD and AFL. In another study, Kumar et al. [7] have proposed the use of fuzzy logic with grey relational analysis to obtain the best values of the process responses (Ka, kerf width, Ra, and MRR) in machining glass fiber-reinforced polymer composites. In that work, the input parameters of the abrasive water jet machining process were AFL, jet pressure, TS, and SOD. The results demonstrated that the TS is more effective on the outputs rather than other parameters used in the work.

Furthermore, Bethapudi [8] has proposed the use of the Taguchi method to design experiments of the abrasive water jet machining process. The parameters selected are material thickness, pressure, SOD, AFL, and nozzle diameter. The conclusion of the work is that this process cannot be used to cut metals of high thicknesses and hardness. Additionally, Singh and Shukla [9] presented the use of the response surface methodology (RSM) to obtain the machinability of Inconel-600. The RSM has been used to evaluate the effect of the abrasive water jet machining process parameters on the taper angle and kerf top width. The best results obtained are a taper angle of 0.583 and a kerf top width of 27.461 mm. Besides, Elattar et al. [10] investigated the utilization of the abrasive water jet process to cut the Armox shieling steel plate with a thickness of 7.6 mm. The effects of pressure, AFL, SOD, TS on MRR, and Ra have been investigated. The results demonstrate no effects of the jet pressure on the MRR and Ra. However, the TS has a stronger effect on Ra. Also, increasing AFL led to more material removal and decreased Ra.

Kumar et al. [11] proposed a Taguchi orthogonal array (L9) to determine the effects of the abrasive water jet machining process parameters such as pressure and SOD on the Ka, MRR, and surface finish. The achieved results indicated that the Ra is influenced by AFL while the MRR is influenced by SOD. llanto et al. [12] investigated the influence of material thickness and TS to achieve high MRR and lower kerf taper angle using an abrasive water jet machining process. Austenitic stainless steel 304L has been cut with different contour profiles. From ANOVA indicated that the material thickness has contributed within 62–69% on MRR and 69–91% on the kerf taper angle while the effect of TS is less within 27–36% for MRR and 5–18% for kerf taper angle. Additionally, Yadav and Singh [13] proposed using the response surface methodology (Box-Behnken) to achieve good surface quality in the abrasive water jet machining process. Aluminum material has been cut, and the effect of some parameters of the AWJM process such as TS, SOD, and pressure have been investigated. In the results reported, the SOD has less effect on the Ra compared to that of pressure and TS.

Deaconescu and Deaconescu [14] investigated the influence of the AWJM process such as pressure, SOD, TS, and grit size on the Ra of the stainless steel (X2 CrNiMo 17-12-2). The response surface methodology is used to reduce the time of the experimental work and is used to obtain the optimum parameters to achieve the minimum Ra. In addition, Llanto et al. [15] studied the effects of the AWJM process parameters (material thickness, TS, AFL, and pressure) on the MRR and Ra of the stainless steel (304L). The Taguchi method was used to design of experiments and determine the influence of AFL, pressure, material thickness, and TS on the Ra and MRR. The results indicated that the best Ra and high MRR have been achieved when increasing the abrasive AFL and the pressure of the water jet.

Duspara et al. [16] verified whether the use of AWJ cutting technology instead of conventional machining processes is possible while maintaining the quality of the machined surface and productivity. The steel, AISI 316L has been cut at a depth of 25 mm and the effects of the cutting parameters were investigated in this process. The results suggested to using the abrasive water jet cutting instead of the conventional machining processes to satisfy the required values of the machined surface.

The main aim of this work is to determine the optimal conditions which give the smoother surface and lower Ka by imposing the Multi-Criteria Decision Making by TOPSIS approach combined with the entropy method.

EXPERIMENTAL IMPLEMENTATION

Machine

A series of practical experiments have been performed on the CNC Teen king (TK-TRUMP50-G3020) abrasive water jet machine which is presented in Figure.1. In addition, the MAX general specifications of this machine are highlighted in Table 1.

Workpiece material

Al alloy with grade 2024-T3 has been utilized as a workpiece material with dimensions of 120×55×6.5 mm. This workpiece is machined by the AWJM process as a square shape with dimensions of 10×10 mm as illustrated in Figure 2. In general, the 2024-T3 alloy has high strength, good workability, and poor corrosion resistance. Therefore this alloy has been employed in the aerospace industry and other industrial applications, which require a high strength-to-weight

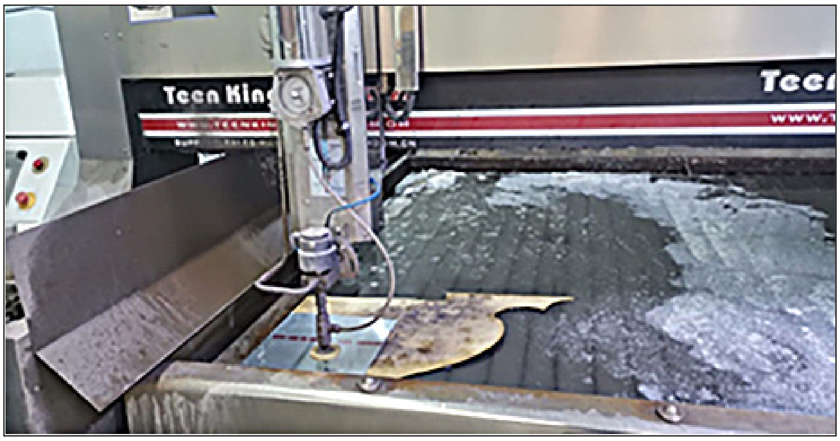

Figure 1. Abrasive water jet machine

ratio. The chemical composition of the workpiece material is highlighted in Table 2.

Controllable parameters and their levels

The input controllable parameters are the variables that influence Ra and Ka (θ) of the machined surface by AWJM. The parameters that have been considered in this work are SOD, TS, and concentration percentage of red granite abrasive with different levels as illustrated in Table 3. Design of experiments (DOE) has been utilized in this work to reduce the series of practical experiments, thereby minimizing the total cost of the machining process. Taguchi method is an efficient, systematic, and simple method to design the controllable AWJM process Orthogonal array L9 has been imposed to carry out the nine experiments as illustrated in Table 4.

Image processing technique

In this work, image processing is used to measure the kerf width of the specimen which is cut using the AWJM process as illustrated in Figure 3. Image processing has been applied using the MATLAB program where the specimen image is captured and converted to a grayscale image, which is then converted to a binary image from which the object's boundary can be detected. A canny edge detection algorithm has been utilized to detect the boundaries of the objects. After the edge detection, the top and bottom kerf widths have been measured and the Ka has been determined using equation 1 as shown in Figure 4.

$$\tan\theta = \frac{\mathrm{T}_{kw} - \mathrm{B}_{kw}}{2T} \quad (1)$$

RESULTS

Analysis of surface roughness and kerf angle

Experimental investigations were carried out on the abrasive water jet machine to investigate the impact of the process parameters on the quality of the machined surface in terms of Ra and Ka.

From Figure 5 can be noticed that the increases in the values of SOD results in increases in the roughness of the machined surface, this is due to the fact at a larger SOD the diameter of the water jet is expanded, therefore reduces the kinetic energy of abrasive jet at impingement. Also, the increases in the TS results in increases in the Ra, which can be explained by decreased the number of the impinging particles with a given target area at higher TS. Whereas the Ra is inversely proportional to the AFL. This is due to the fact that increasing the probability of particle collision with a higher number of abrasive included in mixing which results in reducing the average diameter of the impinging particles.

Table 1. Machine specification

Max flowrate	3.7 L/M
Waterjet pump power	500HP/37KW
Waterjet table size	3000×2000 mm
Max pressure	420 Mpa
Specification	ISO9001,CE

Figure 2. Machined workpiece by AWJM

Table 2. Chemical composition of 2024-T3 alloy

Element	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	AL
%	0.095	4.2	0.35	1.4	0.65	0.38	0.12	0.19	Bal.

Table 3. Controllable Parameters and their levels

Parameter	Level 1	Level 2	Level 3
Stand-off distance (mm)	2	2.5	3
Traverse speed (mm/min)	20	30	40
Abrasive flow rate (g/min)	100	150	200

Table 4. Design matrix of process parameters

No. of experiments	SOD (mm)	TS (mm/min)	AFL (g/min)
1	2.0	20	100
2	2.0	30	150
3	2.0	40	200
4	2.5	20	150
5	2.5	30	200
6	2.5	40	100
7	3.0	20	200
8	3.0	30	100
9	3.0	40	150

From Figure 6 can be concluded the Ka is directly proportional to SOD, TS, and AFL. The link between Ra and SOD can be explained as minimizing the effective machining zone which directly influences the Ka obtained with the larger value of the SOD due to diverging off the jet thereby losing its coherence. In addition, higher TS decreases in the overlapping of the jet on the machining zone due to the decrease in the available time for machining. The increase in AFL results in an increased Ka, which can be explained by increasing the collision of particles among themselves thereby minimizing the energy required to fracture the material. The experimental results of Ra and Ka are highlighted in Table 5.

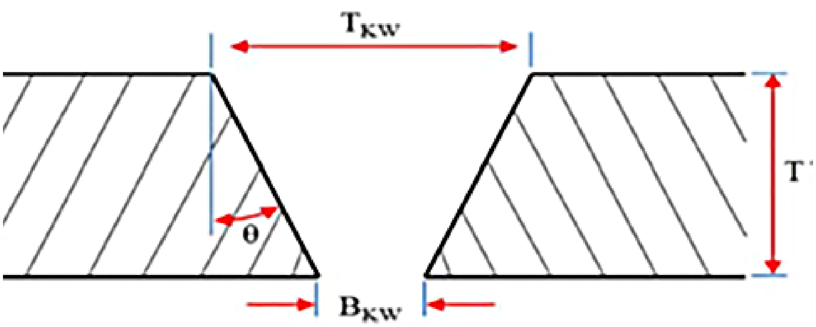

Figure 3. Kerf angle [7]

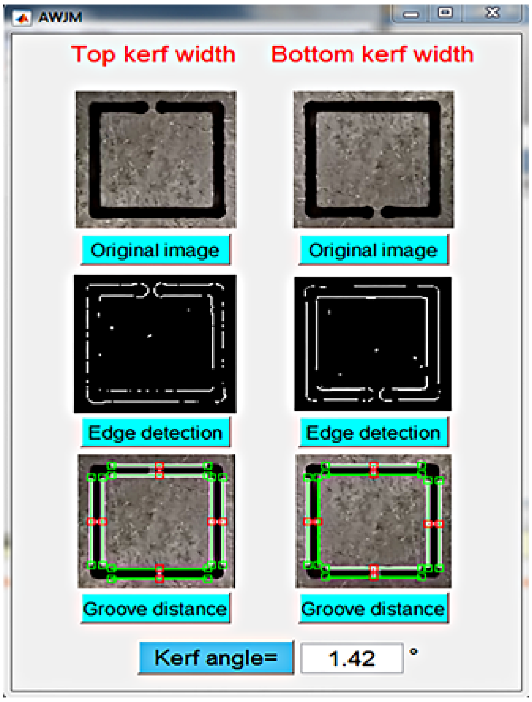

Figure 4. Measured value of kerf angle using image processing

Multi-criteria decision making for the process response

Entropy method to determine the importance of weight [17]

Generally, multi-criteria decision making (MCDM) can be utilized to find out the optimal solutions of machining parameters for all responses of the AWJM process. The first step of the solution should be to determine the importance weights of each criterion. The importance OF weight has been studied based on the Entropy Method as explained in the following steps.

Step 1 – normalization of the decision matrix (performance indices) to calculate the project outcomes P_{ij} as demonstrated in equation 2. It should be noted that all values of this equation are highlighted in Table 6 and the decision matrix is equal to $A = X_{ij_{m*n}}$

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}}, m = 9 \quad (2)$$

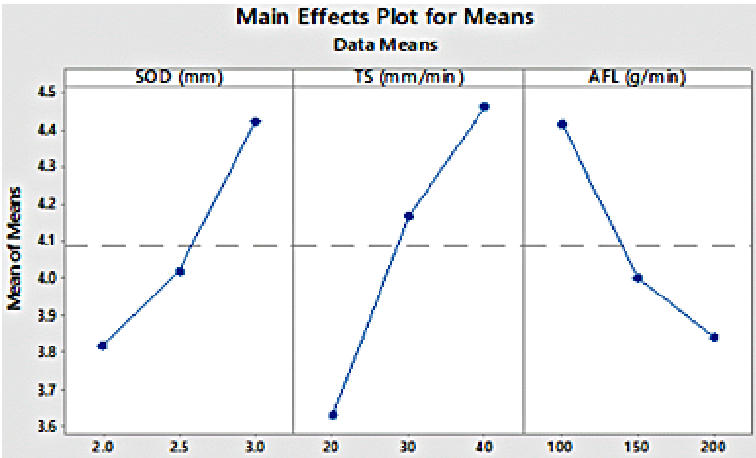

Figure 5. Main effects plot for ra

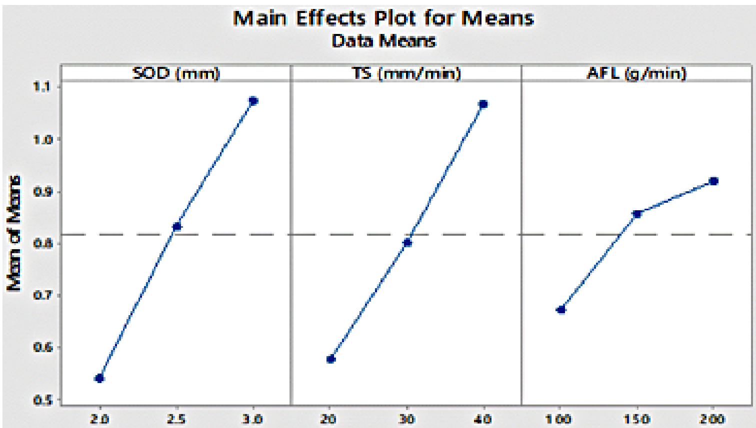

Figure 6. Main effects plot for kerf angle

Table 5. Experimental results of surface roughness and kerf angle

No. of experiments	SOD (mm)	TS (mm/min)	AFL (g/min)	Ra (μm)	θ degree
1	2.0	20	100	3.56	0.22
2	2.0	30	150	3.87	0.56
3	2.0	40	200	4.03	0.85
4	2.5	20	150	3.56	0.59
5	2.5	30	200	3.72	0.98
6	2.5	40	100	4.78	0.93
7	3.0	20	200	3.78	0.93
8	3.0	30	100	4.91	0.87
9	3.0	40	150	4.58	1.42

Step 2 – the computation of entropy for each index as illustrated in equation 3, Table 7 represented the values of this step.

$$E_j = -k \sum_{i=1}^{m} \mathrm{P}_{ij} \ln \mathrm{P}_{ij} \tag{3}$$

$$K = \frac{1}{\ln m} \tag{4}$$

Step 3 – determine the deviation degree of essential data for individual criteria, as illustrated in equation 5 and Table 7.

$$\mathrm{D}_j = 1 - \mathrm{E}_j,\ j = 1,\ldots,n \tag{5}$$

Step 4 – the entropy weight criteria determination can be determined by equation 6. The results of this step are highlighted in Table 7.

$$\mathrm{W}_j = \frac{\mathrm{D}_j}{\sum_{j=1}^{n} \mathrm{D}_j} \tag{6}$$

where: W_j represents the importance weight of the jth criteria.

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS was developed by Yoon and Hwang based on the theory that the preferred parameter should have the longest distance from the worst solution and the shortest distance from the best solution [18]. TOPSIS approach has been utilized to find out the multi-criteria decision making based on the importance weight determined by the Entropy method. This approach can be performed according to the following steps:

Step 1 – calculate the normalized matrix using equation 7, using the parameters given in Table 8.

$$\overline{\mathrm{X}}_{ij} = \frac{\mathrm{X}_{ij}}{\sqrt{\sum_{j=1}^{n} \mathrm{X}_{ij}^2}} \tag{7}$$

Step 2 – calculate the weighted normalized matrix by multiplying the normalized value by the related weight calculated by the entropy method, as illustrated in equation 8, The values of this step are highlighted in Table 8.

The weight values have been determined based on the entropy method for Ra is 0.5043,

Table 6. Normalized values of machining characteristics

No. of experiments	SOD (mm)	S (mm/min)	M (g/min)	Experimental values		Normalized values (P_{ij})	
				Ra	θ	Ra	θ
1	2.0	20	100	3.56	0.22	0.0968	0.0299
2	2.0	30	150	3.87	0.56	0.1052	0.0762
3	2.0	40	200	4.03	0.85	0.1095	0.1156
4	2.5	20	150	3.56	0.59	0.0968	0.0803
5	2.5	30	200	3.72	0.98	0.1011	0.1333
6	2.5	40	100	4.78	0.93	0.1299	0.1265
7	3.0	20	200	3.78	0.93	0.1027	0.1265
8	3.0	30	100	4.91	0.87	0.1335	0.1184
9	3.0	40	150	4.58	1.42	0.1245	0.1932

Table 7. Weight Importance Calculation.

No. of experiments	Ra (P_{ij}·lnP_{ij})	θ (P_{ij}·lnP_{ij})
1	-0.2260	-0.1050
2	-0.2369	-0.1962
3	-0.2422	-0.2495
4	-0.2260	-0.2025
5	-0.2317	-0.2687
6	-0.2652	-0.2616
7	-0.2338	-0.2616
8	-0.2688	-0.2526
9	-0.2594	-0.3176
Sum	-2.1899	-2.1151
E_j	-0.9967	-0.9626
D_j	1.9967	1.9626
Sum D_j	3.9593	
W_j	0.5043	0.4957

whereas the weight of Ka is 0.4957 as highlighted in Table 7.

$$\mathrm{V}_{ij} = \overline{\mathrm{X}}_{ij} \times \mathrm{W}_j \quad (8)$$

Step 3 – calculate the ideal best (V^+) and worst (V^-) values. In this work, the ideal best for Ra and Ka is minimum, whereas the ideal worst is maximum for Ra and kerf width as illustrated in Table 9.

Step 4 – calculate euclidean from the ideal best and ideal worst as shown in equations 9 and 10 respectively. The values of these equations are highlighted in Table 10.

$$\mathrm{S}_i^+ = \left[\sum_{j=1}^{m}(\mathrm{V}_{ij} - \mathrm{V}_j^+)^2\right]^{0.5} \quad (9)$$

$$\mathrm{S}_i^- = \left[\sum_{j=1}^{m}(\mathrm{V}_{ij} - \mathrm{V}_j^-)^2\right]^{0.5} \quad (10)$$

Step 5 – calculate the closeness coefficient factor (C_i) based on equation 11, as illustrated in Table 10.

$$C_i = \frac{\mathrm{S}_i^-}{S_i^+ + S_i^-} \quad (11)$$

Step 6 – rank the value of the closeness factor, the larger value of C_i is the better performance for each alternative, as illustrated in Table 10.

The highest value of the closeness coefficient refers to the best performance experiment based on the objective of the process responses, thereby experiment no. 1 represents the optimal condition which gives the smoothness surface and smallest value of the Ka.

CONCLUSIONS

A hybrid approach of TOPSIS and entropy method has been employed in this study to find out the multi-objective optimization of machining parameters of the AWJM process namely SOD, TS, and AFL to minimize of Ra and Ka during the machining of a 2024-T3 AL-alloy. Therefore the following conclusions can be drawn. Entropy method is successfully adopted to determine the individual weight of the AWJM process responses. The hybrid approach of the TOPSIS and Entropy method has been utilized to choose the best interaction of the AWJM process. Based on the relative closeness, the experiments are sorted in ranking as 1, 2, 4, 3, 7, 8, 6, 5, and 9. The optimal

Table 8. TOPSIS Normalized and weighted values

No. of experiments	Normalized values		Weighted normalized values	
	Ra	θ	Ra·0.5043	θ·0.4957
1	0.2882	0.0838	0.1453	0.0415
2	0.3133	0.2132	0.1580	0.1057
3	0.3262	0.3237	0.1645	0.1604
4	0.2882	0.2247	0.1453	0.1114
5	0.3011	0.3732	0.1519	0.1850
6	0.3869	0.3541	0.1951	0.1755
7	0.3060	0.3541	0.1543	0.1755
8	0.3974	0.3313	0.2004	0.1642
9	0.3707	0.5407	0.1870	0.2680

Table 9. The ideal best and worst values

Parameter	Ra	θ
Ideal best (V^+)	0.1453	0.0415
Ideal worst (V^-)	0.2004	0.2680

Table 10. Separation measures, closeness coefficient, and rank for each experiment

No.	S_i^+	S_i^-	C_i	Rank
1	0.0000	0.2331	1.0000	1
2	0.0654	0.1678	0.7195	2
3	0.1205	0.1134	0.4850	4
4	0.0698	0.1661	0.7040	3
5	0.1436	0.0962	0.4012	7
6	0.1430	0.0926	0.3932	8
7	0.1343	0.1034	0.4349	6
8	0.1345	0.1038	0.4356	5
9	0.2303	0.0135	0.0553	9

conditions of AWJM process parameters that provide the smoothness surface and minimize Ka are 2 mm, 20 mm/min, and 100 g/min for SOD, TS, and AFL respectively. The experimental results demonstrated that the Ra is directly proportional to SOD and TS, whereas the AFL is inversely proportional to Ra. In addition, Ka is directly proportional to all parameters of the machining process.

REFERENCES

1. Varun R., Nanjundeswaraswamy T. A Literature Review on Parameters Influencing Abrasive Jet Machining and Abrasive Water Jet machining. Journal of Engineering Research and Application. 2019; 9, 1: 24–29.
2. Bhavin P., Ripalkumar P. Post Graduate Student. A Review on Effect of Process Parameters on Abrasive Water Jet Machining. International Journal of Creative Research Thoughts. 2018; 6(2): 1059–1064.
3. Gaikwad T., Salunke N., Raut G., Chandgude A., Student B. A Review on Effect & Optimization of Abrasive Water Jet Machining Process Parameters. In IJSRD-International Journal for Scientific Research & Development. 2019; 6: 569–572.
4. Jankovic P., Igic T., Nikodijevic D. Process parameters effect on material removal mechanism and cut quality of abrasive water jet machining. Theoretical and Applied Mechanics. 2013: 40(2): 277–291.
5. Gaikwad T., Salunke S., Raut G., Chandgude A. A Review on Effect & Optimization of Abrasive Water Jet Machining Process Parameters. International Journal for Scientific Research & Development. 2019; 6(11): 569–572.
6. Satyanarayana B., Srikar G. Optimization of Abrasive Water Jet Machining Process Parameters Using Taguchi Grey Relational Analysis (TGRA). International Journal of Mechanical and Production Engineering. 2014; 2(9): 82–87.
7. Vidyapati K., Partha P., Shankar C. Grey-fuzzy method-based parametric analysis of abrasive water jet machining on GFRP composites. Indian Academy of science Sadhana. 2020; 45: 1–18.
8. Jayasree B., Sagar M., Dixith R., Sruthi A. Experimental Investigation and Optimisation of Process Parameters in Abrasive Water Jet Machine. Compliance Engineering Journal. 2022; 13(1): 132–136.
9. Dinesh S., Rajkamal S. Investigation of kerf Characteristics in Abrasive Water Jet Machining of Inconel 600 using Response Surface Methodology. Defense Science Journal. 2020; 70(3): 313–322.
10. Elattar Y., Sonbol H., Mahdy M. Evaluation of Abrasive Water Jet Machining Process Parameters on Cutting High Strength Hard Material (Armox). Proceedings of the 18th Int. AMME Conference. 2018; 223–234.
11. Senthil R., Gajendran S., Lingaraj L., Kesavan R. Optimization of Process Parameters for Machining Marble using Abrasive Water Jet Machining through Multi Response Techniques. Indian Journal of Science and Technology. 2016; 9: 1–6.
12. Jennifer L., Majid T., Ana V., Muhammad A. Impacts of traverse speed and material thickness in abrasive water jet contour cutting of Austenitic stainless steel AISI 304L. Applied Sciences. 2021; 11(11): 1–16.
13. Ganesh S., Brijesh K. Effect of Process Parameter in Abrasive Water Jet Cutting Using Response Surface Method. International Research Journal of Engineering and Technology. 2016; 3(6): 981–985.
14. Andrea D., Tudor D. Response Surface Methods Used for Optimization of Abrasive Waterjet Machining of the Stainless Steel X2 CrNiMo 17-12-2. Materials. 2021; 14: 1–16.
15. Jennifer M., Ana V., Muhammad A., Majid T. Analysis and Optimization of Process Parameters in Abrasive Waterjet Contour Cutting of AISI 304L. Metals. 2021; 11: 1–25.
16. Miroslav D., Valnea S., Ivan S., Marko H. Optimization of Abrasive Waterjet Machining Process Parameters. 2017; 11(4): 143–149.
17. Gholamreza D., Salim F., Rosli M., Nazirah Z. A hybrid approach using entropy and TOPSIS to select key drivers for a successful and sustainable lean construction implementation. B Institute for Advanced Sustainability Studies. 2020.
18. Ponugot I., Ranga, Koka N., Ravi S. Optimizing cutting parameters in hard turning of AISI 52100 steel using TOPSIS approach. Journal of Mechanical and Energy Engineering. 2019; 43(3): 227–232.