IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.311 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 13, Issue 11, November 2026

DOI: 10.17148/IARJSET.2026.131148

Multi-Response Optimization of Abrasive Water Jet Machining of Low-Carbon Steel Using Grey Relational Analysis

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Abstract: This study investigates the multi-response optimization of abrasive water jet machining (AWJM) of low-carbon steel using grey relational analysis (GRA). A two-level full factorial design supplemented with three centre-point runs was employed, comprising eleven experiments. Water pressure, traverse speed, and stand-off distance were investigated within ranges of 270–310 MPa, 400–600 mm/min, and 3–5 mm, respectively. Material removal rate (MRR) and surface roughness (SR) were selected as performance responses, aiming to maximize MRR and minimize SR. The responses were normalized, and grey relational grades were calculated using equal response weights and a distinguishing coefficient of 0.5. Experiment 4 achieved the highest grey relational grade of 1.000 at 310 MPa, 600 mm/min, and 3 mm, producing the highest observed MRR of 25.57 and the lowest observed SR of 0.72 µm. Analysis of the mean grey relational grades identified A3B1C1, corresponding to 310 MPa, 400 mm/min, and 3 mm, as the preferred combination based on factor-level averages. Thus, A3B1C1 represents the combination selected from marginal means, while Experiment 4 remains the best observed experimental run.

Keywords: Abrasive water jet machining; low-carbon steel; grey relational analysis; multi-response optimization; material removal rate; surface roughness.

I. INTRODUCTION

Abrasive water jet machining (AWJM) is an advanced non-traditional machining process that offers an alternative to conventional cutting techniques. It employs a high-velocity stream of pressurized water mixed with abrasive particles, typically garnet, to remove material through erosion. Material removal occurs as the abrasive particles transfer kinetic energy to the workpiece, progressively removing material along the cutting path. Computer numerical control facilitates precise control of jet movement, enabling the production of complex geometries in a wide range of materials, including metals, glass, polymers, and composites. The process also limits thermal effects during cutting, making it suitable for applications in which heat-induced changes are undesirable. From an environmental perspective, AWJM generally eliminates the need for conventional cutting oils, potentially reducing lubricant-related contamination and facilitating the recovery of suitable scrap materials. However, its overall environmental performance depends on water and energy consumption, abrasive usage, and the appropriate management of the resulting waste. Previous studies have investigated material characterization, machining performance, and multi-response optimization using several analytical approaches. Ravikant and Dhami [1] verified the chemical composition of EN31 steel through spectroscopic analysis. Taguchi-based methods combined with grey relational analysis (GRA) have also been employed to optimize abrasive water jet machining parameters while considering multiple performance characteristics [2]. Kumar et al. [4] reported improvements in material removal rate and surface roughness, supported by confirmation experiments. In a related investigation of material properties, Sudhakar et al. [5] reported enhanced strength and hardness in the forged steels examined. Multi-criteria optimization methods, including GRA and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), have been used to identify favourable process settings [6]. Armagan et al. [7] identified traverse speed as an influential factor affecting surface roughness, whereas Kumar et al. [8] determined operating conditions that provided favourable surface finish and a high deposition rate. Natrajan and Murugasen [9] examined deformation during the initial stage of cutting. Babu and Muthukrishnan [10] validated their selected parameter combination through confirmation experiments, reporting an improvement in the grey relational grade. Other investigations have highlighted the influence of individual machining parameters on surface quality and cutting geometry. Abhang et al. [11] observed that surface roughness increased with feed rate but decreased as cutting speed and tool nose radius increased. John et al. [12] identified nozzle diameter as an important factor governing mean kerf width and surface roughness. Singh et al. [13] combined multiple response characteristics into a single grey relational grade to facilitate parameter optimization.

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II. EXPERIMENTAL CONDITIONS AND PROCEDURES

The experimental investigation was conducted on low-carbon steel using abrasive water jet machining (AWJM). Water pressure, traverse speed, and stand-off distance were selected as the input process parameters, with their working ranges and levels established based on previous studies and preliminary tests, as presented in Table 1. A three-factor, two-level full factorial design (2^3), supplemented with three centre-point runs, was employed, resulting in eleven experimental runs. Material removal rate (MRR) and surface roughness (SR) were selected as the response variables to evaluate machining productivity and surface quality, respectively. The optimization objectives were to maximize MRR and minimize SR using grey relational analysis (GRA).

Table 1: Machining parameters and their levels

Std	WP	TS	SOD	MRR	SR
1	270	400	3	10.31	0.76
2	310	400	3	22.18	0.78
3	270	600	3	1.14	0.72
4	310	600	3	25.57	0.72
5	270	400	5	14.97	1.63
6	310	400	5	12.5	1.07
7	270	600	5	8.17	1.67
8	310	600	5	9.94	1.37
9	290	500	4	11.41	1.26
10	290	500	4	13.08	1.38
11	290	500	4	11.39	1.24

Factor	Input process parameters	Notation	Unit		Level	
				-1	0	+1
1	Water Pressure	WP	MPa	270	290	310
2	Traverse Speed	TS	mm/min	400	500	600
3	Stand of Distance	SOD	mm	3	4	5

Table 2: Experimental plan and results



Fig. 1 Machine Model RC3020 WJM

III. ANALYSIS METHOD

Since the objective of this study was to maximize Material Removal Rate while minimizing Surface Roughness, different normalization criteria were applied to the two responses before performing Grey Relational Analysis. The larger-the-better normalization criterion was applied to Material Removal Rate because higher MRR values indicate improved

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machining productivity. Conversely, the smaller-the-better normalization criterion was applied to Surface Roughness, since lower SR values correspond to better surface quality. After normalization, all response values were transformed into dimensionless values ranging from 0 to 1. This transformation removes the influence of different measurement units and allows direct comparison between the two machining responses during the optimization process. The "higher is the better" concept is used for normalizing the MRR. However, the lower is the better concept is used for normalizing the variable SR .

For the smaller-the-better characteristic (surface roughness),

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$$

For the larger-the-better characteristic (material removal rate),

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}$$

The terms xi (k) is the ith series in the original value of k; order xi*(k) is the ith series and k order after normalization, min xi(k)is the minimum value in the ith series, max xi(k) is the maximum value in the ith series. Table 3 shows the normalized results of experimental results obtained for performances.

Table 3 Normalization (data pre-processing) of the experimental results

NO	MRR	SR
1	0.37535817	0.957894737
2	0.86123619	0.936842105
3	0	1
4	1	1
5	0.56610725	0.042105263
6	0.46500205	0.631578947
7	0.28776095	0
8	0.36021285	0.315789474
9	0.42038477	0.431578947
10	0.48874335	0.305263158
11	0.41956611	0.452631579

Table 4 Deviation sequence values for MRR and SR

NO	MRR	SR
1	0.624642	0.042105263
2	0.138764	0.063157895
3	1	0
4	0	0
5	0.433893	0.957894737
6	0.534998	0.368421053
7	0.712239	1
8	0.639787	0.684210526
9	0.579615	0.568421053
10	0.511257	0.694736842
11	0.580434	0.547368421

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Table 5 Grey Relational Coefficients for MRR and SR

NO	θMRR	θSR
1	0.444586	0.9223301
2	0.782762	0.8878505
3	0.333333	1
4	1	1
5	0.535393	0.3429603
6	0.483093	0.5757576
7	0.41246	0.3333333
8	0.438678	0.4222222
9	0.463128	0.4679803
10	0.494434	0.4185022
11	0.462777	0.4773869

Table 6 Grey relational coefficients, grades and rank

NO	Grey Relational Coefficient		Grey relational grade (γ)	Rank
	ΘMRR	ΘSR		
1	0.444586	0.9223301	0.68345804	3
2	0.782762	0.8878505	0.8353062	2
3	0.333333	1	0.66666667	4
4	1	1	1	1
5	0.535393	0.3429603	0.43917684	9
6	0.483093	0.5757576	0.52942516	5
7	0.41246	0.3333333	0.37289662	11
8	0.438678	0.4222222	0.43045031	10
9	0.463128	0.4679803	0.46555413	7
10	0.494434	0.4185022	0.45646826	8
11	0.462777	0.4773869	0.47008199	6

Since the experimental design is based on 2-Level Factorial Design, the performance different levels can be predicted from the effects of the main factor. For example, factor A (water pressure) has three levels, 270, 290, and 310, where the main effect (GRG) for factor A at level 3 (310) is equal to the average from GRG values at the1.5A level, which also applies to other levels. Therefore, the optimal levels for factor A will be highest effect among the levels. Table 7 presents the mean GRG values for each level of the process.

Table 7 Average GRG of each level of process parameters (γ)

Machining parameters	Grey Relational Grade			Main Effect	Rank
	Level 1	Leve l2	Level 3		
Water Pressure (WP)	0.5405495	0.4640348	0.6988	0.238452	2
Traverse Speed (TS)	0.6218416	0.4640348	0.6175	0.1578068	3
Stand-off distance (SOD)	0.7963577	0.4640348	0.4429872	0.3533705	1
Total mean value of the Grey relational grade (γ) = 0.577226 * Levels for optimum GRG					

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Basically, the larger the GRG, the closer it is to the ideal value. Therefore, the optimal parameters setting for high MRR or less SR as (A3B1C1) are shown in Table 7.

IV. CONCLUSION

The highest mean grey relational grades were obtained at the third level of water pressure and the first levels of traverse speed and stand-off distance, corresponding to 310 MPa, 400 mm/min, and 3 mm, respectively (A3B1C1).

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