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Research Article

Fuzzy logic-based optimization of AWJM for core mat and cfrp: A grey relational approach

Dipak S. PATIL[1,*], M. M. BHOOMKAR[1]

[1]Department of Mechanical Engineering, PVG's College of Engg & Tech., Pune, Maharashtra, India

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ABSTRACT

The current research focuses on experimentally assessing the influence of process parameters in Abrasive Water Jet Machining (AWJM) on Core MAT and Carbon Fiber Reinforced Polymer (CFRP) materials. The objective of this study is to enhance our comprehension of how various process variables, including water pressure, abrasive flow rate, standoff distance, and traverse speed, impact the cutting effectiveness and quality of Core Mat and CFRP. To evaluate the machining parameters for abrasive water jet (AWJ) machining, It was decided to adopt the well-established Taguchi approach and utilized the L9 orthogonal array configuration. AWJ machining employs high-velocity water with abrasive particles to cut a range of materials, encompassing soft, hard, ductile, and brittle materials. Through the planning of control parameters such as feed rate, pressure, standoff distance, and abrasive flow, it was successfully achieved the proposed way of an increase in material removal rate (MRR) while simultaneously reducing surface roughness (Ra). To identify the key factors independently influencing the process, the widely recognized S/N ratio analysis was adopted. Subsequently, grey relational analysis was chosen to optimize multiple performance aspects by rating distinct level combinations of the variables according to their grey relational grade. Finally, these results were verified by using Grey fuzzy relations. The data demonstrates significant improvements in the machining process.

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INTRODUCTION

Abrasive water jet machining (AWJM) is a well-known unconventional method that may be employed in a wide range of industrial processes and applications [1, p. 18], [2]. Pure water jet machining is mostly used to cut materials including paper, wood, fabric, and plastic [3]. Due to its benefits, such as high strength, light weight, heat resistance, and hardness, composite materials were developed in the late 1970s [4-7]. However, the absence of appropriate procedures to efficiently produce such materials has limited their usage and applications. The absence For instance, the industry began developing abrasive waterjet machines in the 1980s, and by the end of 1983, they were widely accessible for purchase [8]. Garnet, silicon carbide, aluminium oxide, and glass chips are a few examples of abrasives [9-12]. The

*Corresponding author.
*E-mail address: dsp_mech@pvgcoet.ac.in

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range of grades that can be cut with a waterjet substantially expands when abrasives are introduced. In this method of cutting, a narrow, high-speed water jet accelerates abrasive particles before directing them into the material to be cut by an abrasive water jet nozzle [13, 14]. All sorts of materials may be cut using abrasive waterjet cutting systems, which also have the benefits of no thermal distortion, low cutting forces, great flexibility, and environmental friendliness. Due to these advantages, this cutting technique is less expensive than traditional techniques [15-17]. The cutting geometry is determined by the grit shape and cutting parameters of the particular non-traditional machining process [18]. Olivine, aluminum oxide (Al2O3), quartz sand, glass beads, silicon carbide (SiC), garnet and zirconium are among the various abrasives employed in AWJM (Abrasive Water Jet Machining) [12, 19]. However, a survey found that garnet is used as an abrasive by 90% of AWJM. The hardness of the abrasive particles is a crucial property that greatly impacts the cutting geometry. Moreover, the penetration depth of the jet is predominantly affected by the ratio of the target material's hardness to that of the abrasive particles [20, 21].

Improved fuel efficiency, lower pollutants, and an increase in the aircraft's load bearing capacity are all benefits of using carbon fibres, which are frequently used to lighten the weight of structural components on aeroplanes. Additionally, CFRP was used in vehicle components such as the chassis, propeller shaft, compressed natural gas tank, bonnet, roof, and body panels for buses. n sports equipment such as skis, bicycles, fishing rods, hockey sticks, badminton rackets, and golf shafts, AWJM operations are also utilized, as illustrated in Figure 1. Some researchers underscore the necessity for additional investigation and research in the domain of enhancing the tribological performance of interacting surfaces. The research focuses on assessing how process parameters in Abrasive Water Jet Machining (AWJM) affect Core MAT and Carbon Fiber Reinforced Polymer (CFRP) materials. It aims to understand the impact of variables like water pressure, abrasive flow rate, standoff distance, and traverse speed on cutting effectiveness and quality. The Taguchi approach and L9 orthogonal array are used to evaluate machining parameters. Control parameters such as feed rate, pressure, standoff distance, and abrasive flow are planned to increase material removal rate (MRR) and reduce surface roughness (Ra). Key factors influencing the process are identified using S/N ratio analysis. Grey relational analysis is used to optimize performance aspects by rating variable combinations. Results are verified using Grey fuzzy relations, showing significant improvements in the AWJM process [22,23].

CFRP Composite: (Carbon and Coremat)

Multiple levels of 200 gsm carbon fibre fabric are utilised to create the CFRP sheets, while Coremat is employed as the core material (3mm). Sandwich laminate is a sort of prepared laminate. The Sandwich is made up of Coremat, Two layers of carbon fabric, 4 layers of carbon fabric, as well as 4 layers of Coremat. The CFRP Sheets are created that used a compression moulding press. The chosen sheet has a 15 mm thickness [24,25] as shown in Figure 2.

0.025 mm repeatability precision was achieved using a three-axis CNC AWJ machine 23) (provided by OMAX Water Cutter Co. Ltd., make: OMAX2626- Jet machining centre, Highest Speed: 4572 mm/min, Highest Operating Pressure: 500 MPa). The investigation was carried out after Coremat-based CFRP was being machined as shown in Figure 1. A Taguchi L16 orthogonal array has been employed in the trial [26-28]. The research looked at how pressures of waterjet, abrasive flow rate, stand-off distance, traverse speed as well as feed rate are affect the responses. In order to simplify experimentation, three distinct levels of each variable are explored. To anticipate the importance of the selected characteristics, the Signal to Noise (S/N) ratio is used in conjunction with Analysis of Variance (ANOVA) [29]. Because both objectives are inherently competing, achieving both concurrently with a single set of process variables is extremely challenging. The Grey Relational Analysis (GRA) approach is used in this study to construct a set of process variables that gives a high MRR while keeping the KERF and surface roughness suitably low [30].

Coremat is a core material commonly employed in the production of composite materials, particularly Carbon Fiber Reinforced Polymer (CFRP) sheets. CFRP sheets are

Figure 1. Setup for AWJM operations.

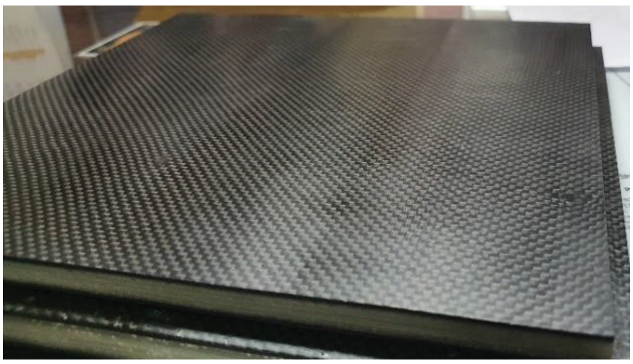

Figure 2. Coremat based CFRP sheet.

composite structures comprised of carbon fibers embedded in a polymer matrix. In this capacity, Coremat functions as a core or filler substance within the CFRP sheet, offering numerous advantages with regard to structural robustness and overall performance.

MATERIALS AND METHODS

Grey Relational Analysis (GRA) is a mathematical and statistical tool for making multi-criteria decisions and analyzing data. This method can be used to examine the relationships between several causes and an outcome, which is especially useful in circumstances with uncertain or inaccurate data. Its utility covers multiple domains, playing a critical role in decision-making and optimization processes. The Grey Relational Analysis is a viable approach whereby every sequence must meet comparability constraints such as non-dimension, scaling, and polarisation qualities before being analysed among sequence groups. It may also be used to solve complex interrelationships among several replies. This approach is utilised in experimental investigations to examine multi-performances and has certain benefits over statistical methods. When such experimental technique cannot be followed perfectly, grey relational analysis may be utilized to correct for the flaw in statistical regression. Grey relation analysis is an excellent approach for studying the connection between sequences with minimum data and can examine many parameters, overcoming the limitations of statistical methods. Grey analysis does not seek the optimum answer, but rather strategies for selecting a good solution, one that is suited for a real-world situation [30,31]. When the sequence's span is too vast or the standard value is too large, the effect of some components is ignored. Furthermore, if the elements' aims and orientations alter with in order, the relational analysis may provide inaccurate conclusions. As a result, pre-processing among all data is required

S/N Ratio

The Taguchi method finds the optimal combination of parameters with the least degree of performance variation. The signal-to-noise ratio (S/N ratio, η) is a useful method for determining meaningful parameters by analysing minimal variance. Experiments are conducted using an experimental setup to fine-tune the parameters with the goal of achieving an optimal minimum KERF value and maximum MRR. The S/N ratios for each KERF value are calculated using the "lower is better" equations, however the MRR S/N ratios are calculated using the "higher-is-better" methods, since the MRR has to be the highest.

Grey Relational Generation with Calculation of Grade

In order to calculate normalising data of higher quality,

$$xh * i\,h(\mathbf{m}) = \frac{(x0ih\,(\mathbf{m})\ -\ \min x0ih\,(\mathbf{m}))}{(\ \max x0ih\,(\mathbf{m})\ -\ \min x0i\,h(\mathbf{m})\ )} \quad (1)$$

In order to compute normalising data of lower quality,

$$xl * i\,h(\mathbf{m}) = \frac{(\max x0il\,(\mathbf{m})\ -\ x0il\,(\mathbf{m}))}{(\ \max x0il\,(\mathbf{m})\ -\ \min x0i\,l(\mathbf{m})\ )} \quad (2)$$

The correlation between the theoretical concept and the experimental trial is denoted by the grey relational coefficient. This coefficient is calculated using the normalized experimental data.

I(k) for the K^{th} Performance characteristics in i^{th} experiment is

$$I(K) = (\Delta\min + \Psi\Delta\mathbf{max})/(\Delta oi + \Psi\Delta\mathbf{max})$$

The grey relation coefficients associated with each process response are averaged to determine the grey relation grade. The grey relational grade serves as the foundation for the overall assessment of the numerous process answers. The best answers are provided by high grey relational grades.

Obtaining the grey relationship grade entails:

The grey relational grade

$$yi = \frac{1}{n}\sum \in i(k) \quad (3)$$

To assess the values of the grey relation, various formulae are employed. These formulae help compare the experimental and anticipated values to validate the findings. Additionally, Matlab is used to implement an additional grey fuzzy relation, and the results obtained from the Grey Relation Grade (GRG) and Grey Fuzzy Relation Grade (GFRG) are compared. The equation utilized to verify the results in GRG and GFRG is as follows

$$GRG = GRG\ mean + \sum_{i=1}^{n}(GRGi - GRGmean) \quad (4)$$

Fuzzy Logic

The integration of fuzzy reasoning into the optimization process within this study aims to enhance comprehension of the interactions between various AWJM parameters and core materials and CFRP composites. These parameters encompass factors such as jet pressure, abrasive flow rate, standoff distance, and traverse speed.

Develop an extensive fuzzy rule base [2] that comprehensively captures the intricate relationships among these parameters and their impact on cutting performance [2,32]. This includes considerations related to material removal rates, surface finish, and delamination.

- Validate the effectiveness of the fuzzy reasoning-based approach through experimental assessments conducted using real-world samples of core materials and CFRP.
- Provide insights into the potential for substantial savings in time and resources when compared to traditional

trial-and-error methods. Additionally, this approach aims to enhance the overall quality of the machining process.

- This research endeavors to advance the field of AWJM by harnessing the capabilities of fuzzy reasoning for optimizing process parameters when working with core materials and CFRP composites. The anticipated outcomes not only promise to improve machining efficiency but also hold the potential to reduce material wastage and enhance the quality of components produced in aerospace and automotive applications.

RESULTS AND DISCUSSION

The L16 orthogonal design matrix is a type of design matrix commonly used in experimental design. It is created based on the L16 orthogonal array, which consists of 16 rows and a predetermined number of columns representing the input parameters as shown in Table 1. In the L16 orthogonal design matrix, each column corresponds to an input parameter, while each row represents a unique combination of parameter values. The matrix is carefully designed so that every possible combination of parameter values occurs exactly once, and each parameter occurs an equal number of times within each column [33,34].

The experiments were carried out using an L16 orthogonal array as shown in Table 2. AWJM setup was used to conduct the test with Silicon carbide (SiC 60 micron) as a specimen and Al2O3 (60 micron) is mixed with water and directed towards the work surface. The nozzle jet was constructed of sapphire material for excellent resistance. In accordance with the Taguchi Design of Experiments L16 orthogonal array, Coremat based CFRP is the platform of choice for the tests. Abrasive flow rate, water pressure, stand of distance along with Traverse Speed are considered as variable whereas shape of abrasive, grit size of abrasive and diameter of nozle are kept constant28). The output was measured in the terms of KERF, MRR and Ra as given in Table 3. Additionally, grey relation evaluation was employed to identify the best parameters.

Table 1. The values assigned to the input parameters

S. N.	Water pressure (MPa)	Traverse speed (mm/min)	Abrasive flow rate (g/min)	Stand-off distance (mm)
1	120	80	260	2.0
2	160	100	300	2.5
3	200	120	340	3.0
4	240	140	380	3.5

Table 2. Input parameter design matrix

Trial No.	Water pressure (MPa)	Traverse speed (mm/min)	Abrasive flow rate (g/min)	Stand-off distance (mm)
1	120	80	260	2.0
2	120	100	300	2.5
3	120	120	340	3.0
4	120	140	380	3.5
5	160	80	300	3.0
6	160	100	260	3.5
7	160	120	380	2.0
8	160	140	340	2.5
9	200	80	340	3.5
10	200	100	380	3.0
11	200	120	260	2.5
12	200	140	300	2.0
13	240	80	380	2.5
14	240	100	340	2.0
15	240	120	300	3.5
16	240	140	260	3.0

Table 3. Result table for MMR, KERF, Ra

Trial no.	Water pressure (MPa)	Traverse speed (mm/min)	Abrasive flow rate (g/min)	Stand-off distance (mm)	MMR (g/min)	KERF	Ra (µm)
1	120	80	260	2.0	9.824	2.39	5.1
2	120	100	300	2.5	9.153	2.50	4.8
3	120	120	340	3.0	8.320	2.53	4.6
4	120	140	380	3.5	9.74.	2.77	3.9
5	160	80	300	3.0	8.932	2.61	4.1
6	160	100	260	3.5	8.155	2.48	4.4
7	160	120	380	2.0	9.840	2.77	4.8
8	160	140	340	2.5	8.202	2.69	5.0
9	200	80	340	3.5	7.315	2.65	5.3
10	200	100	380	3.0	9.605	2.80	3.7
11	200	120	260	2.5	8.479	2.51	4.0
12	200	140	300	2.0	8.930	2.66	3.7
13	240	80	380	2.5	9.813	2.63	3.8
14	240	100	340	2.0	9.913	2.59	3.5
15	240	120	300	3.5	9.235	2.41	4.6
16	240	140	260	3.0	9.122	2.13	4.6

Material Removal Rate

As the rise in traverse velocity, there is a corresponding decline in the material removal rate (MRR). The MRR attains its highest point at a minimum speed of 80 mm/min. Conversely, slower speeds enable the abrasives to remove more material. The least SOD value led to the attainment of the highest MRR. To achieve the optimal MRR, an AFR of 2 kg/min and an SOD of 1.5 mm are recommended. Increasing the AFR results in a higher MRR. At an SOD of 1.5 mm, the desired MRR is attained. The size of the abrasive particles significantly affects the MRR in AWJM. Larger abrasive particles lead to a greater increase in MRR. When different SODs are used, the abrasive particles gain more energy, resulting in deeper craters due to the high AFR.

The material removal rate (MRR) rises with increasing water pressure. The MRR reaches its maximum at a water pressure of 300 MPa and an SOD of 1 mm. The high kinetic energy of the particles has a significant impact on the material surface, resulting in increased material erosion. The significant difference in MRR can be attributed to the abrasion process or corrosion that occurs during machining at high jet pressures. The minimum MRR was observed for high SOD values compared to low SOD values.

Kerf

As the Abrasive Flow Rate (AFR) rises, so does the Kinetic Energy of Abrasives (KA). Additionally, it has been observed that an increase in Traverse Speed (Ts) results in a higher Kerf Angle (KERF). The formation of tapers in the base material, caused by the high-speed abrasives, becomes evident. When the water pressure is elevated from 150 to 250 MPa, a slight increment in KA is observed. It is noteworthy that for an AFR not exceeding 2.5 kg/min and a Standoff Distance (STD) of 2 mm, the KERF taper remains limited. Conversely, a higher AFR combined with an STD of 1 mm results in reduced taper formation.

Surface Roughness (Ra)

As the Abrasive Flow Rate (AFR) is raised, the Surface Roughness (SR) also increases, assuming that the Standoff Distance (SOD) remains constant at 1 mm. This increase in SR is attributed to the high kinetic energy of the jet, which impacts the abrasive particles and leads to the primary removal of the base material in the form of large ploughed chips. Consequently, this contributes to a rough surface as discussed in reference 28). Notably, the SR reaches its peak under conditions of high water pressure and a high AFR. It is observable that a significant rise in SR occurs within the range of 1.5 to 2 kg/min AFR. Specifically, when the water pressure is set at 250 MPa with a SOD of 1 mm, the SR exhibits notably elevated values.

ANOVA

ANOVA study was carried out to investigate the effect of various process parameters as shown in Table 4, Table 5 and Table 6.

Regression Equation

ANOVA study was carried out to investigate the effect of various process parameters as shown in Table 4, Table 5and Table 6.

$$Ra = 5.95 - 0.00456\,A - 0.00212\,B - 0.00281\,C + 0.135\,D$$

Table 4. ANOVA results for Ra

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	1.04650	0.26162	0.78	0.561
A	1	0.66613	0.66613	1.99	0.186
B	1	0.03612	0.03612	0.11	0.749
C	1	0.25312	0.25312	0.76	0.403
D	1	0.09112	0.09112	0.27	0.612
Error	11	3.68787	0.33526		
Total	15	4.73437			

Regression Equation

MMR = -27936 - 51.1 A + 102.2 B + 51.1 C + 4089 D

Regression Equation

KERF = 1.885 - 0.000763 A - 0.00030 B + 0.002912 C - 0.0280 D

Implementation of Fuzzy Logic

In a Fuzzy Logic system, the process of fuzzification involves the application of membership functions to transform the Grey Relational Coefficient (GRC) into linguistic variables for each performance characteristic. The chosen input parameters encompass Water Pressure, Ts, AFR, and SOD, while the output is categorized into one of five fuzzy sets: 'very low,' 'low,' 'medium,' 'high,' or 'very high,' represented by membership functions denoted as μY. Fuzzy rules are formulated based on the principle that higher values correspond to superior performance characteristics 29). The input-output relationships for the Fuzzy Inference System are illustrated in the accompanying figure 3. The rule editing and grade achievement within Fuzzy logic are illustrated in the accompanying figure 4.

The utilization of Fuzzy Logic in combination with Fuzzy Reasoning Grade for Core Mat in Abrasive Water Jet Machining (AWJM) and CFRP (Carbon Fiber Reinforced Polymer) machining introduces an innovative strategy aimed at enhancing the precision and efficiency of these cutting procedures. This section will explore the primary findings and implications of this study, emphasizing the importance of incorporating fuzzy logic and fuzzy reasoning grade into AWJM for Core Mat and CFRP materials.

Table 5. ANOVA results for MMR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	334463972	83615993	2.54	0.100
A	1	83614821	83614821	2.54	0.139
B	1	83618330	83618330	2.54	0.139
C	1	83635457	83635457	2.54	0.139
D	1	83595365	83595365	2.54	0.139
Error	11	362404428	32945857		
Total	15	696868400			

Table 6. ANOVA results for KERF

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.294690	0.073672	5.69	0.010
A	1	0.018605	0.018605	1.44	0.256
B	1	0.000720	0.000720	0.06	0.818
C	1	0.271445	0.271445	20.95	0.001
D	1	0.003920	0.003920	0.30	0.593
Error	11	0.142510	0.012955		
Total	15	0.437200			

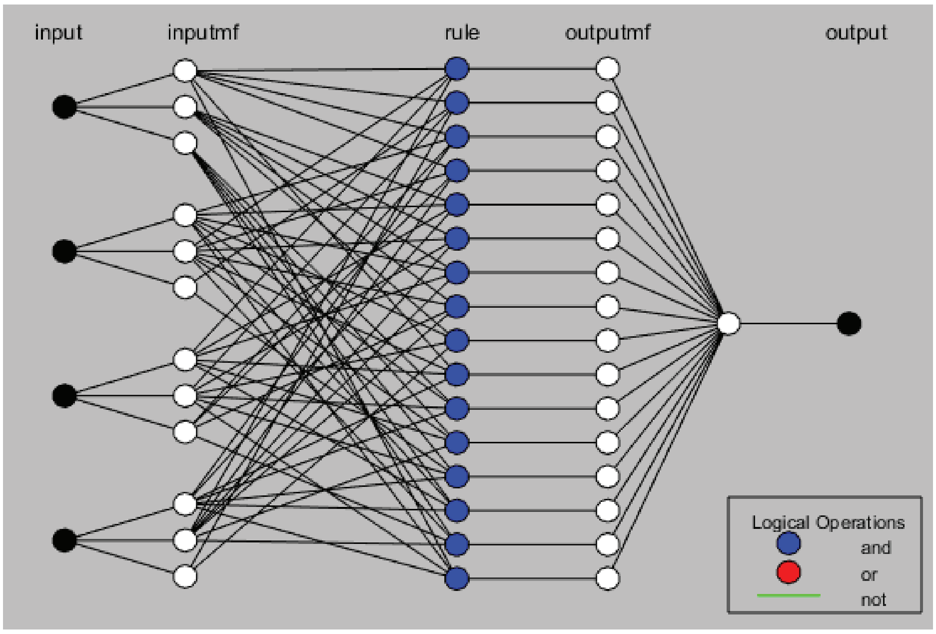

Figure 3. ANN model for training the dataset.

The outcomes derived from the experiments clearly illustrate that the integration of fuzzy logic and fuzzy reasoning grade exerts a substantial influence on the precision of machining in Core Mat and CFRP materials. Fuzzy logic serves as a valuable tool for modeling imprecise or uncertain information, particularly pertinent in AWJM, where variables such as material hardness and surface irregularities can introduce variability. By employing fuzzy reasoning grade to evaluate and regulate cutting parameters, this study successfully attained heightened precision in material removal and surface finishing.

Confirmation Test

To evaluate the quality characteristics of ceramics in AJM (Abrasive Jet Machining), a confirmation test were conducted using optimal parameters and their levels as shown in Table 7. Grey relational analysis was employed to

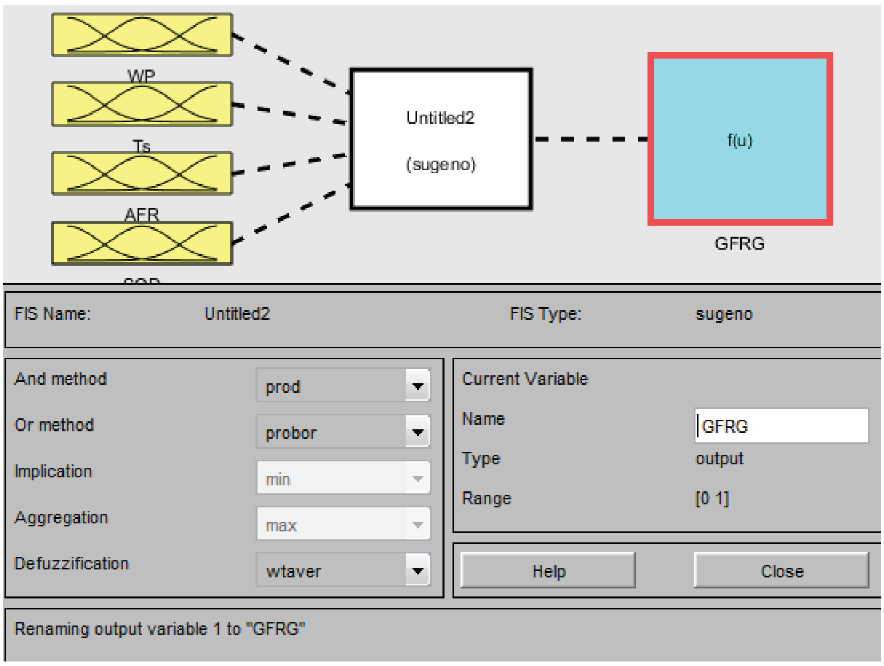

Figure 4. Fuzzy module for GFRG.

Table 7. Comparative results for GTA and FLA

Techniques used	Selected experiment	MRR	KERF	Ra
Grey taguchi approach	14	9.899	2.56	3.49
Fuzzy logic approach	14	9.904	2.57	3.5
Change in percentage	0	0	0	0

identify the maximum Grey Relation Grade (GRG) from the nine conducted experiments. It highlights the initial process parameter combination as (A2 B2 C2 D1) to achieve superior performance across multiple characteristics. The equation discussed earlier forecasts the optimal Grey Relation Grade (GRGopt), and the table presents both the experimental and projected GRG values. The projected value for the optimal grey relation grade is derived by assuming n = 4, taking into account the influence of four significant parameters.

CONCLUSION

The research of AWJM process parameters utilizing Fuzzy Reasoning Grade for Core Mat with AWJM and CFRP yielded the following findings. Based on the Grey Relation Grade (GRG) analysis, it is determined that experiment number 14 in the L16 orthogonal array yields the highest grey relational grade. This particular experiment involves water pressure set at 250 MPa, TS (Tool Speed) at 100 mm/min, AFR (Abrasive Flow Rate) at 350 gm/min, and SOD (Standoff Distance) at 2 mm. The corresponding levels of machining characteristics in this experiment are given as Metal Removal Rate (MRR) at 9.914 g/min, Kerf Width (KERF) at 2.5870 and Surface Roughness (Ra) at 3.5 microns.

In conclusion, the introduction of Fuzzy Logic alongside Fuzzy Reasoning Grade for Core Mat in AWJM and CFRP machining signifies a promising progression in the realm of manufacturing and materials processing. This research not only contributes to our understanding of the applicability of fuzzy logic but also underscores its potential to revolutionize machining procedures across a wide spectrum of materials and applications. As industries increasingly demand precision, adaptability, and efficiency, fuzzy logic-based approaches hold the promise of becoming a fundamental technology in contemporary manufacturing.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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