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Fuzzy Logic Technique and Response Surface Methodology to Predict the Material removal rate of Abrasive Water Jet Process (AWJM) Parameters on Inconel – 188

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تقنية المنطق الغامض ومنهجية سطح الاستجابة للتنبؤ بمعدل إزالة المواد لمعلمات عملية نفث الماء الكاشطة (AWJM) على إنكونيل – 188

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Abstract:
Abrasive waterjet machining (AWJM) is a non-traditional machining process that uses a high-pressure jet of water and abrasive particles to remove material from a workpiece. The AWJM process is complex and highly dynamic, making it difficult to predict and control the machining parameters. In this paper two models have been developed using Fuzzy Logic Technique (FL) and Response Surface Methodology (RSM) in order to predict material removal rate (MRR). The Mean absolute percentage error (MAPE) statistical criteria were 2.8% and 2.40% for the FL and RSM, respectively. As a result, using fuzzy logic to anticipate the MRR of the AWJM process is recommended.

Keywords: Fuzzy Logic, RSM, AWJM, and MRR.

الملخص
المعالجة بنفث الماء الكاشطة (AWJM) هي عملية تصنيع غير تقليدية تستخدم نفاثًا عالي الضغط من الماء والجزيئات الكاشطة لإزالة المواد من قطعة العمل. تعتبر عملية AWJM معقدة وديناميكية للغاية، مما يجعل من الصعب التنبؤ بمعلمات المعالجة والتحكم فيها. في هذا البحث تم تطوير نموذجين باستخدام تقنية المنطق المضبب (FL) ومنهجية سطح الاستجابة (RSM) من أجل التنبؤ بمعدل إزالة المواد (MRR). وكانت المعايير الإحصائية لمتوسط النسبة المئوية للخطأ المطلق (MAPE) هي 2.8% و2.40% لـ FL وRSM، على التوالي. ونتيجة لذلك، يوصى باستخدام المنطق الغامض لتوقع MRR لعملية AWJM.

الكلمات المفتاحية: المنطق الضبابي، RSM، AWJM، MRR.

1. Introduction:

The nontraditional processes have been developed since World War II largely in response to new and unusual machining requirements that could not be satisfied by conventional methods. The term nontraditional machining refers to this group that removes excess material by various techniques involving mechanical, thermal, electrical, or chemical energy (or combinations of these energies). They do not use a sharp cutting tool in the conventional sense [1]. Abrasive Waterjet Machining (AWJM) is a versatile and effective non-traditional machining process that has gained popularity in various industries due to its ability to cut a wide range of materials with high precision and minimal heat-affected zones. However, the AWJM process is complex and highly dynamic, making it difficult to predict and control the machining parameters. Therefore, modeling and prediction techniques are essential for optimizing the AWJM process and improving its efficiency and accuracy [1]. Abrasive Water Jet Machining

(AWJM) is non- traditional machining process. This belongs to mechanical group of nontraditional processes. In these processes AWJM the mechanical energy of water and abrasive phases are used to achieve material removal or machining. In these processes AWJM the mechanical energy of water and abrasive phases are used to achieve material removal or machining. AWJM is the technology of using high velocity coherent stream of water and abrasives to cut almost all materials uses high pressure (140 to 420 MPa), to accelerate large volume of water 70% and abrasives 30% mixture up to velocity of 2.5 times the speed of sound. High velocity water jet is directed at a target in such a way that the velocity is reduced to zero on striking the workpiece [2, 3]. In this paper two models have been developed using fuzzy logic technique (FL) and response surface methodology (RSM) in order to predict material removal rate (MRR).

2. Literature Review

Various modeling and prediction techniques have been developed for AWJM, including analytical, numerical, and empirical models. Analytical models are based on mathematical equations that describe the physical principles of the AWJM process, such as the momentum and energy equations. Analytical models are useful for understanding the fundamental mechanisms of the AWJM process, but they are limited by their assumptions and simplifications [4]. Numerical models are based on computational fluid dynamics (CFD) simulations that use finite element or finite difference methods to solve the equations governing the AWJM process. Numerical models can be used to predict the flow behavior of the abrasive waterjet, the erosion pattern on the workpiece, and the machining parameters such as the cutting speed and surface roughness. However, numerical models require significant computational resources and are limited by the accuracy of the input parameters and boundary conditions [5]. Empirical models are based on experimental data collected from actual AWJM processes. Empirical models use statistical analysis techniques to identify the relationships between the machining parameters and the output variables such as the cutting rate and surface finish. Empirical models are simple and easy to use, but they are limited by their dependence on the specific experimental conditions and may not be applicable to different AWJM setups [6]. Fuzzy logic-based modeling and prediction techniques for AWJM have been developed in recent years, including the design of fuzzy logic controllers, fuzzy rule-based systems, and fuzzy inference systems. Fuzzy logic controllers are used to control the AWJM process by adjusting the machining parameters such as the cutting speed and abrasive flow rate based on the input variables such as the workpiece material and thickness. Fuzzy rule-based systems are used to predict the output variables such as the cutting rate and surface finish based on the input variables such as the abrasive particle size and standoff distance. Fuzzy inference systems are used to combine the input and output variables to generate a comprehensive model of the AWJM process. The advantages of fuzzy logic-based modeling and prediction techniques for AWJM include their ability to handle uncertainty and incomplete information, their flexibility in incorporating expert knowledge, and their ability to adapt to changing conditions. However, the limitations of fuzzy logic-based approaches include the need for expert knowledge to design the fuzzy rules and membership functions, the sensitivity of the results to the choice of parameters, and the difficulty in validating the models [7]. This studied have extensively investigated the utilization of Rolled Homogeneous Armor steel (RHA) in military combat vehicles due to its exceptional properties, including high tensile strength, toughness, and hardness. RHA, being a high-strength low alloy steel, is widely suitable for various military applications on the battlefield. This study aims to analyze the prognostic outputs, such as material removal rate (MRR), surface roughness (Ra), and kerf angle (Ka), in armour steel machined by Abrasive Water Jet Machining (AWJM), employing regression and semi-empirical models. The AWJM experiments were conducted using an L27 factorial design, where the process variables, namely standoff distance (SOD), jet traversing speed (JT), and jet water pressure (P), were each set at three levels. A regression model was developed using the response surface method (RSM) and data acquired from the experimental trials. Furthermore, a semi-empirical model was formulated using both experimental data and material property data, employing dimensional analysis and Buckingham's π-theorem. The predictions generated by these models exhibited a strong correlation with the experimental results obtained under identical conditions. Additionally, microscopic investigations utilizing a scanning electron microscope (SEM) were performed to examine the MRR and Ra. The optimal values for the output responses of the machined armor steel plate were determined, resulting in a higher MRR of 298.92 mm3/min, a lower Ka of 0.651°, and a lower Ra of 2.23 µm. This study conclusively demonstrates that semi-empirical models can accurately forecast the output responses in AWJM of armor steel [8].

3. Methodology

At Ram Engineers, vatva GIDC, Ahmedabad, the SL-V50 AWJM 3-axis machine with CNC programming has been used for the abrasive water jet machining. The Water Jet Model: DWJ1525-FA, which has an SL-V50 pressure pump with a specified pressure of 290MP, was the machine utilized to prepare the samples (see Fig. 1). Additionally, the machine has an abrasive feeder system, a pneumatically controlled valve, an abrasive hopper that is fed by gravity, and a work piece table that measures 3000 mm by 3000 mm. The high-pressure water was changed into a collimated jet using a sapphire aperture, and an abrasive water jet was created using a carbide nozzle. Abrasive water jet cutting procedure setup [9]. There are two main methods, namely fuzzy logic technique and Response Surface Methodology, to be utilized in this study.

Figure 1: DWJ1525-FA AWJM [9]

3.1 Response Surface Methodology (RSM)

The design of experiment (DOE) method is a statistical method for studying a process with a limited number of tests. Response surface methodology (RSM) is a common and powerful regression-based modeling approach that uses a mathematical model to determine the relationship between multiple complicated factors and process responses It also has significant uses in the development, formulation, and design of new items as well as in the improvement of designs for already-existing ones. The manufacturing industry is where RSM is most commonly utilized, especially when multiple input factors have the ability to affect measurements of performance or process or characteristics of a product. The response refers to these characteristics of quality or performance indicators. While sensory reactions, ranks, and attribute responses are not uncommon, they are usually measured on a continuous scale. The majority of RSM practical uses will require multiple responses. When used in a test or experiment, the input variables—also referred to as independent variables—are within the engineer's or scientist's control [10].

3.2 Fuzzy Logic (FL)

In classical set theory, an element's membership is typically explained by one of two distinct, opposing states: either the element is a member of the set (membership degree = 1.0), or it is not (membership degree = 0.0). Later, in fuzzy set theory, membership degrees with values between 0.0 and 1.0 are used to explain how an element fits into a given set . This provides an opportunity in modelling the uncertain expressions of real-life mathematically and performs fuzzy set operations between these uncertainties and finally reaching fuzzy results that cannot be achieved analytically [11]. The three input variables specified in Table 1 with their upper (+1) and lower (-1) levels as well as an appropriate design matrix had all been investigated [9]. The output variable is specified in Table 2.

Table 1: Input factors and their levels [9]

No. S.	Factors	Notation	Unit	Level		
				-1	**0**	**+1**
1	Stand of distance	SOD	mm	2	3	4
2	Traverse speed	TS	mm/min	80	90	100
3	Abrasive flow rate	AFR	g/min	200	250	300

Table 2: The response selected for these experiments [9]

No. S.	Response	Notation	Unit
1	Metal removal rate	MRR	g/sec

4. Results and Discussion

4.1 Discussion based on RSM

The effects of the three input process parameters, abrasive flow rate, input 1 (SOD (mm)), input 2 (TS (mm/min), and input 3 (AFR (g/min)) and their effects on the response material removal rate MRR (g/sec) is analyzed and studied using the experimental values. An experiment is a sequence of tests, referred to as runs, in which modifications are made to the input process parameters in order to determine the causes of variations in the output response. The experimental results are given in Table 3.

Table 3: Experimental result using RSM [9]

Run	SOD (mm)	TS (mm/min)	AFR (g/min)	MRR (g/sec)
1	3	90	250	1.566667
2	3	90	250	1.666667
3	4	100	200	1.5222
4	4	80	300	1.682352
5	3	90	250	1.566667
6	2	100	200	1.440741
7	2	100	300	1.7102
8	3	90	250	1.566667
9	3	80	250	1.382352
10	4	90	250	1.6333
11	4	80	200	1.382352
12	3	90	250	1.566667
13	3	100	250	1.740741

14	2	90	250	1.566667
15	3	90	300	1.566667
16	2	80	300	1.5676
17	3	90	200	1.466667
18	2	80	200	1.382352
19	3	90	250	1.55
20	4	100	300	1.7222

The goal is to predict a response (output variable) that is impacted by a number of independent variables (input process parameters) through accurate experiment design in Table 4.

Table 4: Actual and predicted RSM output for MRR

Run	SOD (mm)	TS (mm/min)	AFR (g/min)	Actual MRR (g/sec)	Predicted MRR (g/sec)
1	3	90	250	1.566667	1.575586
2	3	90	250	1.666667	1.575586
3	4	100	200	1.5222	1.538958
4	4	80	300	1.682352	1.618731
5	3	90	250	1.566667	1.575586
6	2	100	200	1.440741	1.500635
7	2	100	300	1.7102	1.696306
8	3	90	250	1.566667	1.575586
9	3	80	250	1.382352	1.495093
10	4	90	250	1.6333	1.634922
11	4	80	200	1.382352	1.392519
12	3	90	250	1.566667	1.575586
13	3	100	250	1.740741	1.642908
14	2	90	250	1.566667	1.579953
15	3	90	300	1.566667	1.629592
16	2	80	300	1.5676	1.547115
17	3	90	200	1.466667	1.41865
18	2	80	200	1.382352	1.34355
19	3	90	250	1.55	1.575586
20	4	100	300	1.7222	1.757275

4.2 Discussion based on FL

The FL model developed in the present study is built using MATLAB R2013a GUI. For predicting the material removal rate of AWJM process by FL, the model is established using twenty datasets. In the present study one response/output (MRR) is considered. In FL modeling, the number of membership functions (MFs) and type of fuzzy rules, are considered to be the important factors to develop the accurate model. In the present study Mamdani type fuzzy-based rule has been used for the development of predictive models .

In the present study the number and type of MFs for input 1 (SOD (mm)), input 2 (TS (mm/min), and input 3 (AFR (g/min)), as well as for the output (MRR (g/sec)) are selected as shown in Fig. 2 to Fig. 5. The model is developed using three triangular MFs (Trimf) for the inputs and three trapezoid MFs (Trampmf) for the output.

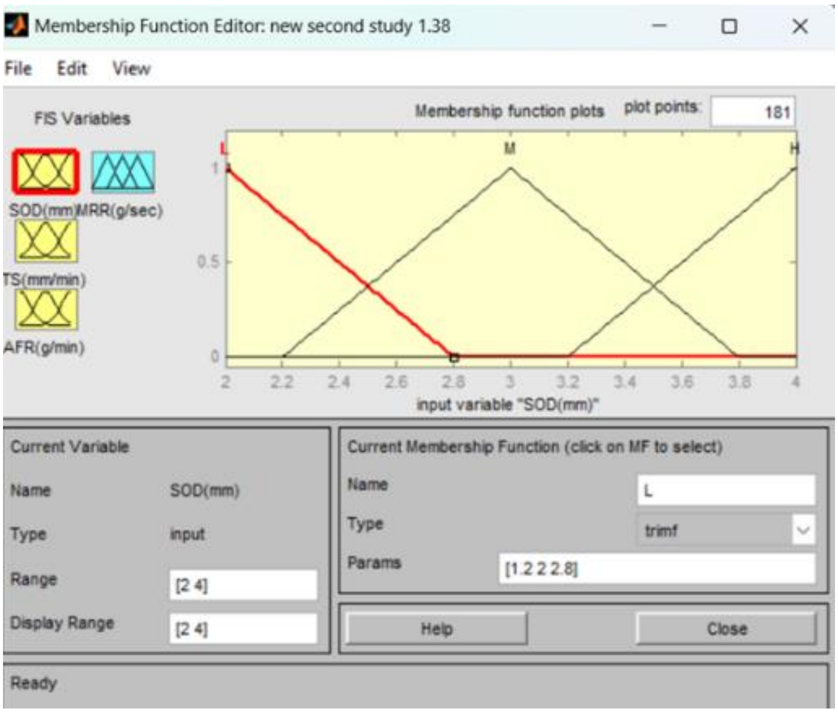


Figure 2 . Membership function for input 1 process parameter SOD (mm)

Figure 3: Membership function for input 2 process parameter TS (mm/min)

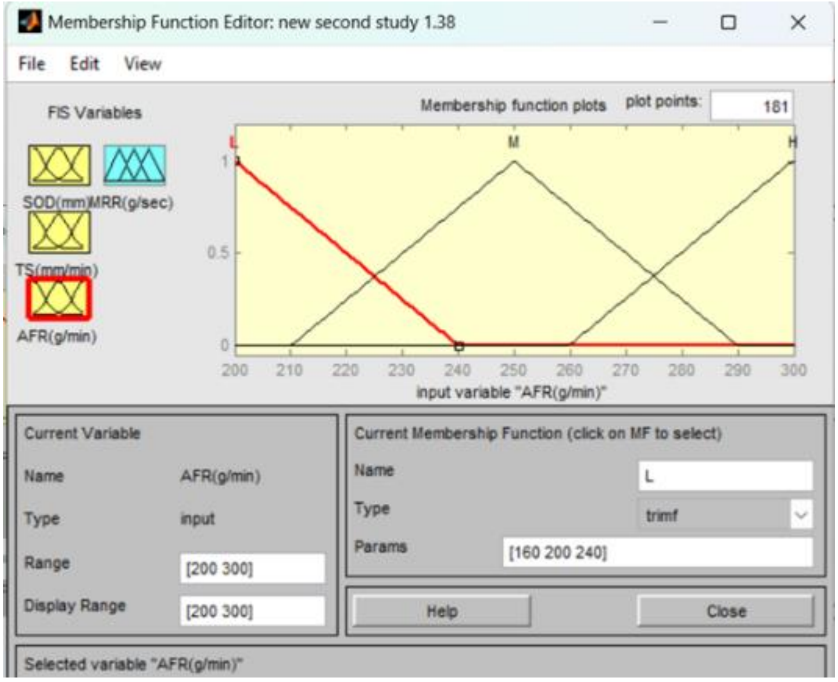


Figure 4: Membership function for input process parameter AFR (g/min)

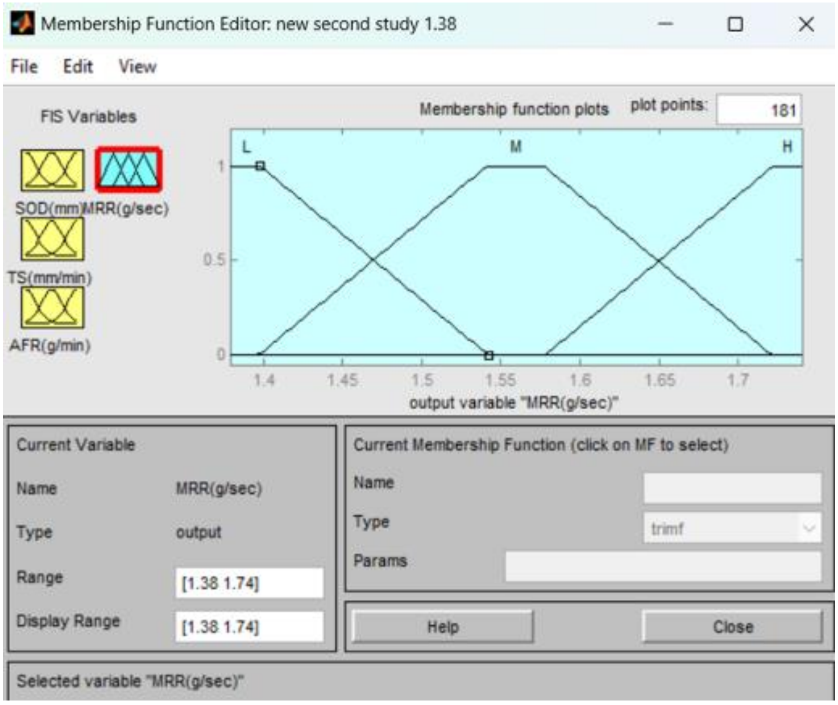
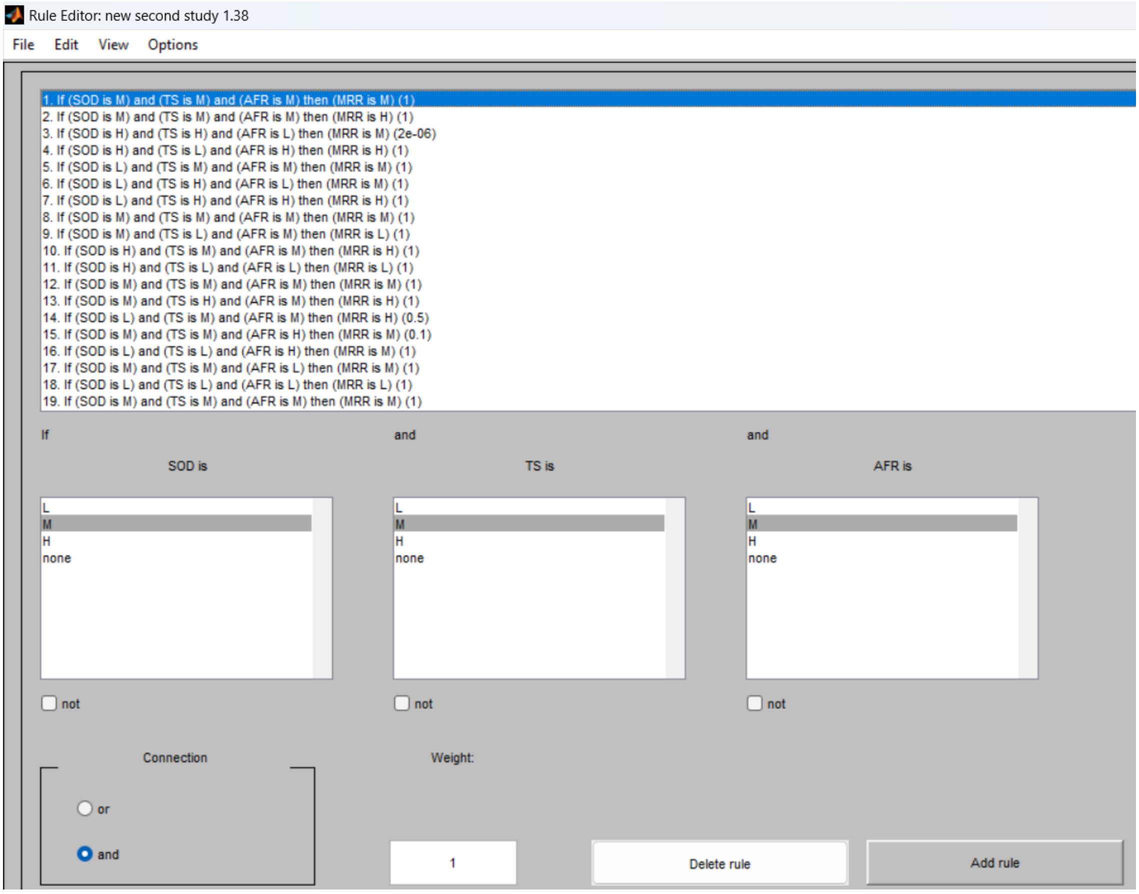


Figure 5: Membership function for output MRR (g/sec)

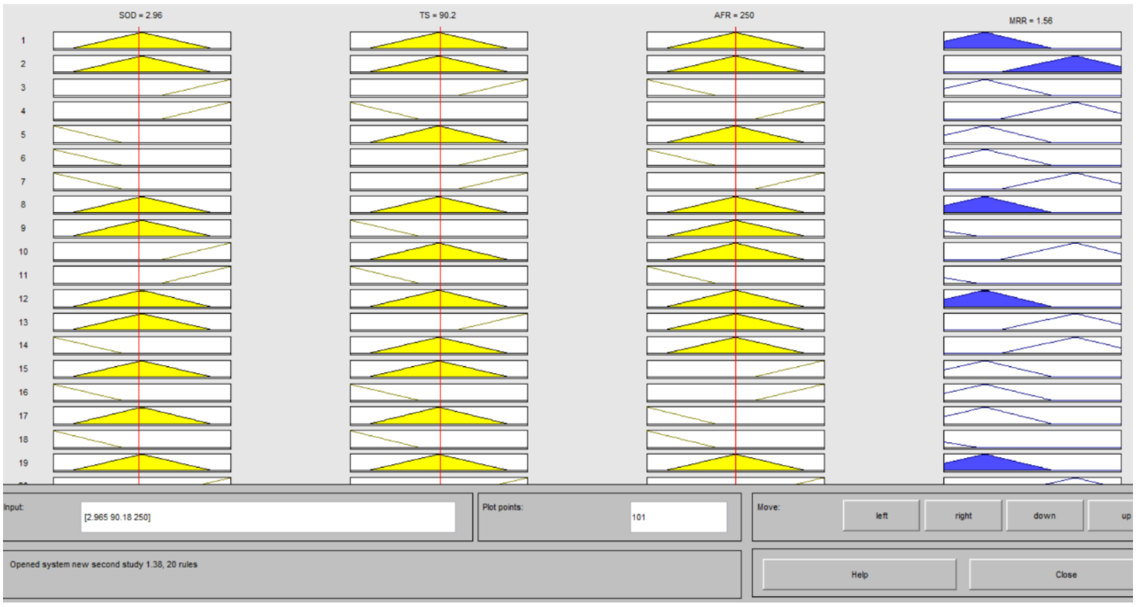
Twenty rules are used in the present study. The fuzzy IF-THEN rules is of the form:

1. If (SOD (mm) is M) and (TS (mm/min) is M) and (AFR(g/min) is M) then (MRR(g/sec) is M (1)

The rules and rule viewer for the developed FL model of MRR using trapmf is shown in Fig. 6 (a)–(b), respectively.



(a)



(b)

Figure 6: a) Rules and b) Rule viewer for the developed FL model of MRR using trapmf

Experiment design matrix with their actual and predicted FL output using trapmf, for MRR are depicted in Table 5.

Table 5. Experimental, predicted FL output using trapmf for MRR

Run	SOD (mm)	TS (mm/min)	AFR (g/min)	Actual MRR (g/sec)	Predicted MRR (g/sec)
1	3	90	250	1.566667	1.575586
2	3	90	250	1.666667	1.5647
3	4	100	200	1.5222	1.49
4	4	80	300	1.682352	1.6608
5	3	90	250	1.566667	1.5647
6	2	100	200	1.440741	1.474
7	2	100	300	1.7102	1.6608
8	3	90	250	1.566667	1.5647
9	3	80	250	1.382352	1.4061
10	4	90	250	1.6333	1.6608
11	4	80	200	1.382352	1.4061
12	3	90	250	1.566667	1.5647
13	3	100	250	1.740741	1.6608
14	2	90	250	1.566667	1.54
15	3	90	300	1.566667	1.49
16	2	80	300	1.5676	1.474
17	3	90	200	1.466667	1.474
18	2	80	200	1.382352	1.4061
19	3	90	250	1.55	1.5647
20	4	100	300	1.7222	1.6608

Based on the value of the mean absolute percentage error (MAPE) as given by eqn -1, a comparison between the actual values and the anticipated values of MRR is used to validate the fuzzy logic model and RSM model, respectively. It was determined what (MAPE) was worth 2.28% and 2.40%, respectively. Additionally, Fig. 7 and Fig. 8 compare the MRR predicted values to their actual values in the fuzzy logic model and RSM model, respectively. Indicates how fuzzy logic models can more accurately represent actual MRR values than the RSM model.

$$\text{MAPE}=\frac{1}{n}\sum_{i=1}^{n}\left|\frac{A-P}{A}\right| ☒ 100\% \quad (1)$$

where:

A: The actual value for MRR

P: The predicted value for MRR

n: Number of Experiments

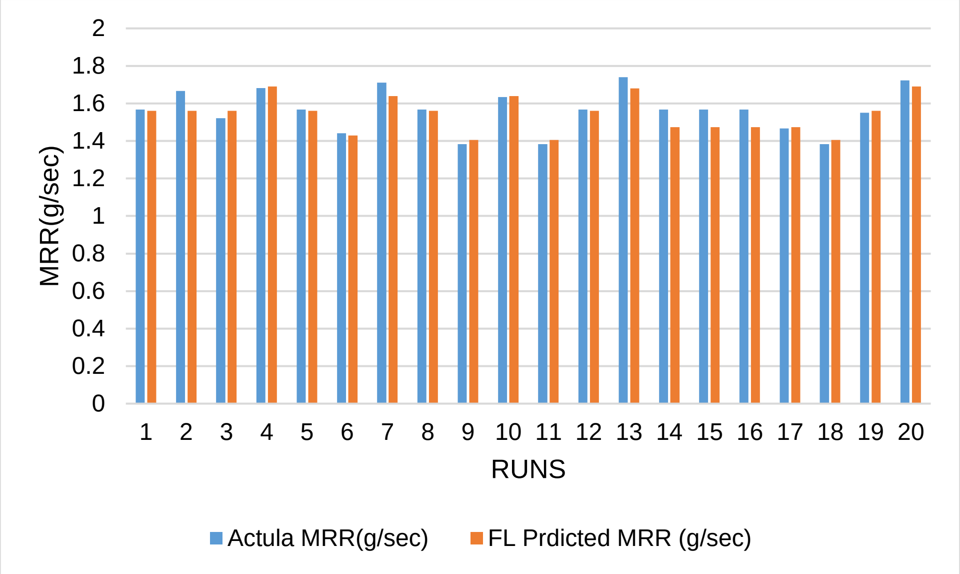


Figure 7: Comparison between actual and predicted of MRR by FL

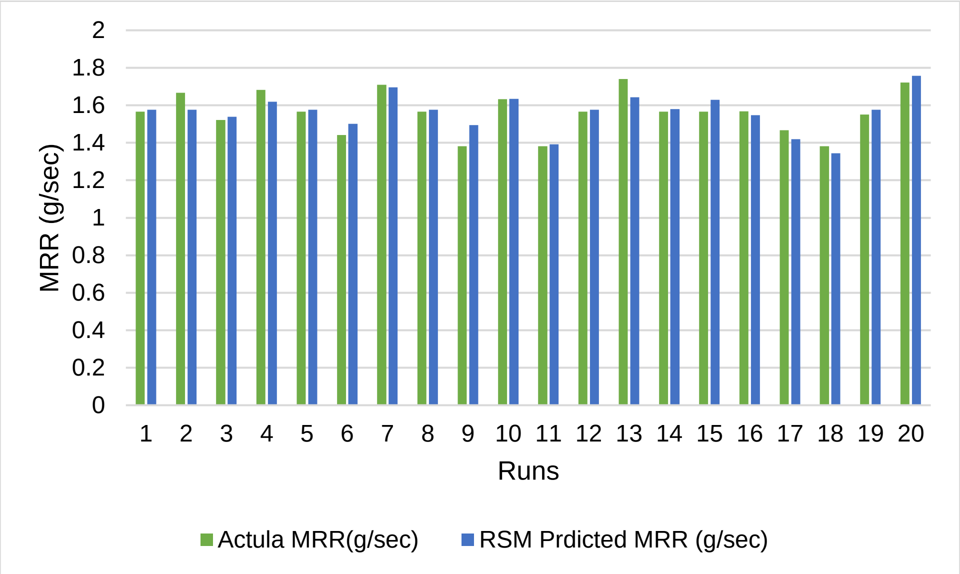


Figure 8: Comparison between actual and predicted of MRR by RSM

5. Conclusion

In this study, three input process parameters, namely: (SOD (mm)), (TS (mm/min), and (AFR (g/min), respectively. Were utilized in order to predict the MRR using RSM and FL, respectively. It was observed that the fuzzy logic model gave an MAPE of 2.28%. On the other hand, the RSM prediction model gave an MAPE 2.40% which indicate that FL model is more accurate than RSM prediction model. Therefore, the fuzzy logic technique is recommended for prediction of the MRR of AWJM process.

Recommendations and Future Scope

The overall presentation of the study is a relatively short and simple in order to help to understand the flow of the study. The model is not developed using other MFs. Further study can be carried out to improve the current results using different prediction tools such as ANN. The study can be also extended to the optimization of process parameters using the developed ANFIS model.

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