Performance Estimation of an Abrasive Water Jet Cutting Process Using Fuzzy Reasoning

Asif Iqbal, Juliana Zaini, Malik M. Nauman

Abstract—**Abrasive water jet cutting (AWJC) is an erosion-based material removal mechanism that can cut thick stocks of any material. The quality of the cut surface is an important performance indicator, which is quantified in terms of arithmetic average surface roughness, kerf width, and proportion of striations free zone. Jet pressure, abrasive flow rate, jet's traverse speed, and stock thickness are the important control parameters which affect the three performance measures. The work presents development of a fuzzy reasoning system from the AWJC experimental data to accurately estimate the performance measures. Triangular fuzzy sets are developed in respect of all the parameters involved. The exhaustive combination of the fuzzy members of the control parameters is linked with the most appropriate members of the performance measures' fuzzy sets, in form of IF-THEN rules, based on the results of the experimental data. The resulting fuzzy rule-base is applied to estimate the performance measures of another set of experimental data. The surface roughness, kerf width, and proportion of striations free zone are estimated with the percentage errors of about 5 %, 7 %, and 12 %, respectively.**

Index Terms—**Rule-based system, fuzzy sets, abrasive cutting, surface quality, kerf.**

I. INTRODUCTION

ABRASIVE water jet cutting (AWJC) is an efficient way of cutting thick stocks of almost all kinds of solid materials into any two dimensional profile. It uses a high-pressure water jet to accelerate the particles of an abrasive material to high cutting speeds. These particles, possessing high levels of kinetic energy, then create a cut in the work surface through erosion [1]. The CNC control moves the nozzle precisely in the desired path to cut the stock in the required shape.

The process's performance is assessed in terms of the cut surface quality metrics, such as percentage of the depth of cut surface free of striations, average arithmetic roughness of the striations free surface, and maximum kerf width [2]. A high value of the first measure, whereas low values of the other two are desired. The process control parameters which are known to have significant effects on the aforementioned performance measures include jet pressure, abrasive flow rate, nozzle's traverse speed, and stock thickness. As AWJC is a complex mechanical process, there is hardly a reliable analytical model available that could accurately predict the performance measures against the various settings of the control parameters. Such a situation calls for application of heuristics and artificial intelligence tools. Fuzzy reasoning, worked out from experimental data, is one of them.

Chakravarthy et al have applied a genetic algorithm–fuzzy logic hybrid approach for optimizing the parameters of AWJC [3]. The authors have claimed superiority of the method in optimizing the process through an experimental case study. A fuzzy logic based expert system is used to predict the depth of cut [4]. It is claimed that an automatic development of the expert system yields better estimation than a manually developed knowledge based. Likewise, another study has reported a hybrid application of empirical models and fuzzy logic in optimizing the cutting process [5]. Application of artificial neural networks has been reported in estimation of surface roughness in water jet cutting of an aluminum alloy [6]. Another study has detailed the application of two modes of neural networks: radial basis function networks and backpropagation, in estimation of the selected responses of the AWJC process [7]. Zain et al have applied genetic algorithm as well as simulated annealing algorithm to optimize the AWJC process and to estimate the performance measures against the optimized settings of the control parameters [8]. Sharma et al have put forward a Taguchi-Fuzzy model to enhance productivity of the water jet cutting process [9]. Fuzzy reasoning was used to cover the uncertainty involved in the less-than-normal number of experimental runs suggested by the Taguchi design of experiments. Likewise, fuzzy TOPSIS was used in conjunction with Taguchi full factorial design of experiments for the identification of influential AWJC process parameters [10].

The presented work utilizes the data generated from a series of AWJC experiments to develop a set of fuzzy IF-THEN rules, which connect the control parameters and the performance measures with a blend of heuristic and factual knowledge. The fuzzy rule-base is then utilized to estimate the performance measures with respect to another set of AWJC experimental data.

II. EXPERIMENTAL WORK

A. Predictors, Responses, and Design of Experiments

The following predictors (control parameters) are controlled in the experiments:

1. Jet Pressure, P (bars). The three levels tested are 2,500, 3,000, and 3,500 bars.

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2. Jet's traverse speed, *v* (mm/min). The three levels used in the experiments are 20, 30, and 40 mm/min.
3. Abrasive flow rate, *AFR* (g/min). This predictor is controlled with two levels, 110 and 220 g/min.
4. Stock thickness, *t* (mm). The two levels tested are 25 and 40 mm.

The above listed predictors and their tested levels resulted in 36 (= 3×3×2×2) experimental runs following a full-factorial design of experiments. The following three responses (performance measures) are measured in each experimental run:

1. Average arithmetic roughness of the striation free zone of the cut surface, R_a, measured in µm.
2. Maximum kerf width, *KW*, measured in mm.
3. Proportion of the area on the cut surface without striations, P_{SF}, measured in %.

B. Work Material and Fixed Parameters

The work material used in the experiments is a high strength low alloy steel, AISI 4340. Two plate thicknesses, 25 mm and 40 mm are used. The work material's heat treatment is so controlled to achieve work surface hardness of 48 HRc. All the experimental runs are performed on a CNC water jet cutting machine having a maximum water intensifier pressure of 4,000 bars. All the test specimens are cut into 65 mm × 55 mm rectangular pieces, yielding a total length of cut of 240 mm for each run. 80-mesh garnet is used as the abrasive, which is sucked into the water jet prior to impact the work surface at the controlled mass flow rates. Nozzle diameter and standoff distance are fixed to 1 mm each. Mahr Perthometer M1 and a standard vernier caliper are used to measure the surface roughness and the other two responses, respectively.

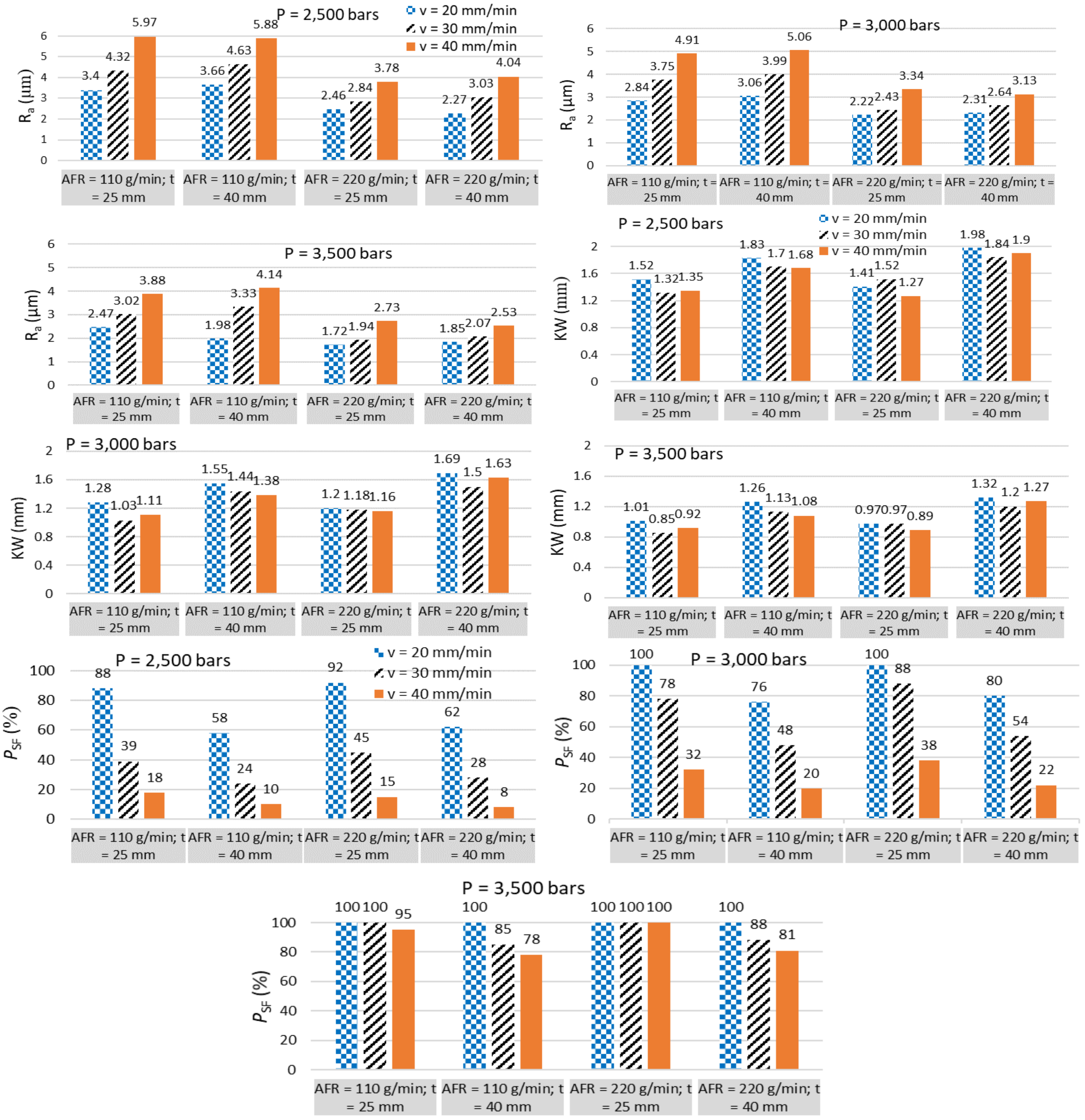
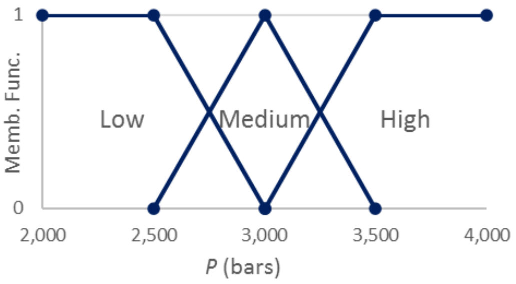


Fig. 1. Experimental results regarding R_a, *KW*, and P_{SF}, categorized by jet pressure.

C. Experimental Results

The three rows of Fig. 1 show the experimental results in respect of the three responses: R_a, KW, and P_{SF}. A few inferences can be drawn from the plots. (1) High traverse speed yields high surface roughness. It also performs poorly in respect of proportion of striations free zone, especially at the low and medium levels of jet pressure. Regarding kerf width, the medium level of traverse speed is found to yield the minimum values. (2) The high level of abrasive flow rate yields significantly better surface finish, but it is also found to increase the kerf width. It causes marginal improvements in P_{SF} as well. (3) The high level of jet pressure has a favorable but marginal effect on cut surface roughness. It also causes significant reductions in kerf width of the cut but its effect in increasing proportion of striations free zone is very strong. (4) Stock thickness possesses no significant effect on surface roughness. On the other hand, its high value yields unfavorable on the other two responses, leading to significant increases in kerf width and reductions in P_{SF}.



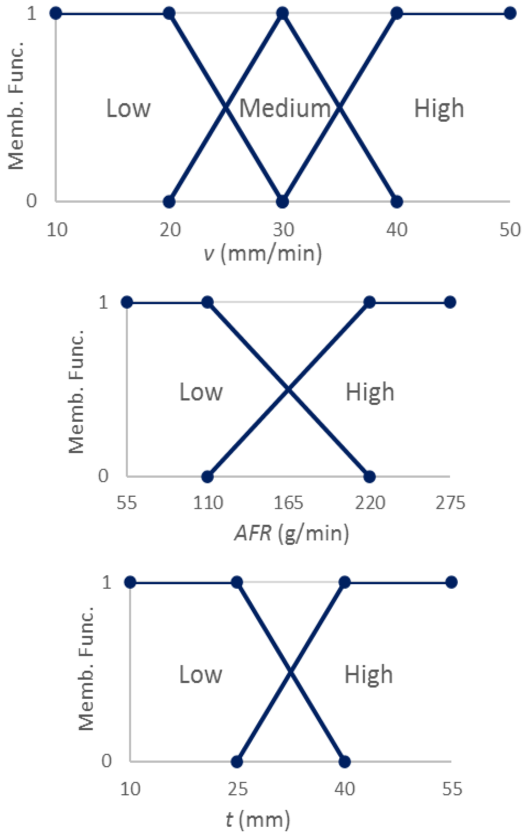


Fig. 2. Triangular fuzzy sets for jet pressure, traverse speed, abrasive flow rate, and stock thickness.

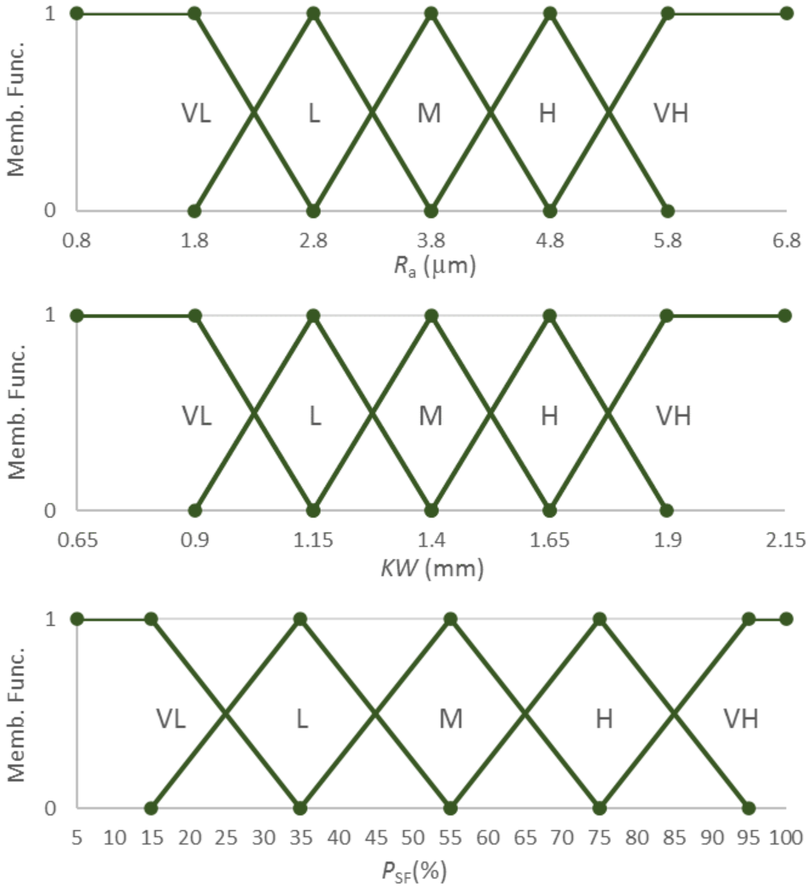


Fig. 3. Triangular fuzzy sets for surface roughness, kerf width, and proportion of striations free zone.

TABLE I
THE FUZZY RULE-BASE

Rule number	Antecedents				Consequents		
	P	v	AFR	t	R_a	KW	P_{SF}
1	Low	Low	Low	Low	L & M	M & H	H &VH
2	Low	Low	Low	High	M	H & VH	M
3	Low	Low	High	Low	VL & L	M	VH
4	Low	Low	High	High	VL & L	VH	M & H
5	Low	Medium	Low	Low	M & H	M	L
6	Low	Medium	Low	High	H	H	VL & L
7	Low	Medium	High	Low	L	M & H	L & M
8	Low	Medium	High	High	L	H & VH	VL & L
9	Low	High	Low	Low	VH	M	VL
10	Low	High	Low	High	VH	H	VL
11	Low	High	High	Low	M	L & M	VL
12	Low	High	High	High	M	VH	VL
13	Medium	Low	Low	Low	L	L & M	VH
14	Medium	Low	Low	High	L	M & H	H
15	Medium	Low	High	Low	VL & L	L	VH
16	Medium	Low	High	High	VL & L	H	H
17	Medium	Medium	Low	Low	M	VL & L	H
18	Medium	Medium	Low	High	M	M	L & M
19	Medium	Medium	High	Low	VL & L	L	H & VH
20	Medium	Medium	High	High	L	M & H	M
21	Medium	High	Low	Low	H	L	L
22	Medium	High	Low	High	H	M	VL
23	Medium	High	High	Low	L & M	L	L
24	Medium	High	High	High	L & M	H	VL & L
25	High	Low	Low	Low	L	VL & L	VH
26	High	Low	Low	High	VL	L & M	VH
27	High	Low	High	Low	VL	VL	VH
28	High	Low	High	High	VL	L & M	VH
29	High	Medium	Low	Low	L	VL	VH
30	High	Medium	Low	High	L & M	L	H & VH
31	High	Medium	High	Low	VL	VL	VH
32	High	Medium	High	High	VL	L & M	H & VH
33	High	High	Low	Low	M	VL	VH
34	High	High	Low	High	M & H	L	H
35	High	High	High	Low	L	VL	VH
36	High	High	High	High	L	L & M	H & VH

Although, the high level of traverse speed does not yield favorable results in respect of the performance measures quantified in this work, it does contribute favorably toward another important performance metric, the productivity. Regarding AWJC process, the product of traverse speed and stock thickness ($v \times t$) is a very important productivity measure. It represents the work area cut per unit time. The six v-t combinations: 20-25, 20-40, 30-25, 30-40, 40-25, and 40 mm/min-40 mm, respectively, yield the following values of the productivity metric: 500, 800, 750, 1,200, 1,000, and 1,600 mm^2/min.

III. THE FUZZY RULE-BASE

The section covers development of fuzzy sets for the parameters (control and measured), formation of the rule-base, and its working for parameter estimation.

A. Fuzzy Sets

Triangular fuzzy sets are developed for all the parameters. Three uniformly distributed members of the fuzzy sets for each of jet pressure and traverse speed and two for each of abrasive flow rate and stock thickness are worked out. Fig. 2 presents the fuzzy sets for the four control parameters used in the experiments. The uniformity of the members' distribution in the sets of jet pressure and traverse speed reflects on the equal differences between the low and the medium levels and the medium and the high levels of the respective parameters controlled in the experiments. Fig. 3 presents the triangular fuzzy sets of the three responses: R_a, KW, and P_{SF}. Five members for each fuzzy set of a response are used to cover the range of measurements obtained in the experimental work. VL, L, M, H, and VH stand for very low, low, medium, high, and very high, respectively.

B. Development of the Fuzzy Rule-Base

Table I presents the fuzzy rule-base that connects the most appropriate members of the responses' fuzzy sets with the exhaustive combination of the members of the predictors' fuzzy sets. Each row of the table forms a separate IF-THEN rule. For instance, Rule number 21 can be stated as follows:

IF jet pressure is Medium *And* traverse speed is High *And* abrasive flow rate is Low *And* stock thickness is Low THEN surface roughness is H (high) *And* kerf width is L (low) *And* proportion of striations free zone is L (low).

The parts of the rule before and after THEN are called as antecedent and consequent, respectively. The consequent part of each rule is worked out by carefully matching the response's experimental value with the most appropriate member of the relevant fuzzy set. Some of the entries in the consequent part of Table I include a symbol "&". It represents the intersection operator that returns the intersection of the two neighboring members of the fuzzy set. For instance, the entry L & M in the table's first row means intersection of the members L (low) and M (medium) of the fuzzy set related to surface roughness (R_a). The intersection operator is used when the data point of a response falls somewhere close to the intersection point of the two neighboring members of the set. In such a case, the shared portion of the two members is returned.

C. Working of the Fuzzy Rule-Base

The working of the fuzzy rule-base starts with fuzzification of the numeric data related to the four control parameters in accordance with the relevant fuzzy sets. Based on the members of the fuzzy sets utilized during the fuzzification process, all the rules of the rule-base involving those members are fired with varying degrees of impact. All the fired rules are amalgamated and the fuzzified values of the responses are obtained through the max-min composition approach of fuzzy rules. The details of the approach can be read from the article [11]. The returned fuzzy values of the responses are defuzzified using the CoG (center of gravity) method. The method yields smoothly varying output of responses for gradual variations in control parameters. More details of the method can be read from the article [12]. The defuzzification process converts a fuzzy output of the rule-based system into a crisp value, which is most central to the output's distribution. Fuzzy CLIPS (C Language Integrated Production Systems) is used to develop and run the fuzzy rule-based system.

IV. CONFIRMATORY EXPERIMENTS AND VALIDATION OF THE RULE-BASE

A total of ten confirmatory AWJC experiments are performed at different settings of the control parameters to generate additional data for quantifying estimation accuracy of the fuzzy rule-base. The rule-base is run against each of the ten combinations of the confirmatory experiments and the estimated values of the three responses are noted. Table II presents the new levels of the control parameters, the measured values of the responses, the estimated values of the responses worked out by the rule-based system, and percentage differences between the two.

The last row of the table shows the average values of the percentage difference. Clearly, the estimation error in respect of average arithmetic surface roughness (5.11 %) is the best, followed by kerf width (7.12 %). The accuracy regarding proportion of striations free zone is comparatively much worse than the other two responses, which can be attributed to vagueness in its quantification and associated difficulty in measurement. Nevertheless, the estimation errors within the range 5 – 10 % are highly acceptable considering the complex mechanics of the abrasive water jet cutting process.

Looking deeply into the data presented in Fig. 1 and Table II, it can be inferred that to collectively optimize the AWJC process in respect of the three performance measures considered, the process should be operated at the high levels of jet pressure (3,500 bars) and abrasive flow rate (220 g/min). Additionally, the stock of 25 mm thickness should be cut at the high level of traverse speed (40 mm/min) whereas, the one with 40 mm thickness should be cut at the medium level of traverse speed (30 mm/min). Should the suggested setting for $t = 40$ mm result in striations on the cut surface, the traverse speed could further be reduced. Considering the highly significant effect of traverse speed on proportion of striations free zone, its optimal value would depend on the productivity-striations trade-off. Furthermore, the recommendations regarding the increases in jet pressure and abrasive flow rate would have caps depending on the operational costs, machine capacity, and environmental impacts they might cause.

The presented work is expected to have industrial applicability with a wide impact. As AWJC is excessively used in industry for profile cutting of thick stocks, any improvement in cut quality, operational cost, productivity, or environmental impact would cause an enhancement in manufacturing sustainability at a global scale.

TABLE II
DATA GENERATED BY THE CONFIRMATORY EXPERIMENTS AND COMPARISON WITH THE RESULTS GENERTED BY THE FUZZY RUL-BASE

S / No.	P (bars)	v (mm/min)	AFR (g/min)	t (mm)	Experimental measurements			Estimated values generated by the fuzzy rule-base			Percentage difference (%)		
					R_a (µm)	KF (mm)	P_{SF} (%)	R_a	KF	P_{SF}	R_a	KF	P_{SF}
1	2750	25	165	25	2.97	1.35	85	3.16	1.31	77	6.40	2.96	9.41
2	2750	25	165	40	3.31	1.57	70	3.16	1.72	60	4.53	9.55	14.29
3	2750	35	165	25	3.94	1.18	62	4.04	1.25	52	2.54	5.93	16.13
4	2750	35	165	40	3.78	1.63	39	4.04	1.66	36	6.88	1.84	7.69
5	3000	20	138	25	2.53	1.33	100	2.68	1.25	97	5.93	6.02	3.00
6	3000	40	192	40	3.61	1.48	18	3.46	1.52	22	4.16	2.70	22.22
7	3250	25	165	25	2.43	1.22	100	2.6	1.08	94	7.00	11.48	6.00
8	3250	25	165	40	2.85	1.52	70	2.6	1.42	82	8.77	6.58	17.14
9	3250	35	165	25	3.39	1.24	75	3.36	1.03	82	0.88	16.94	9.33
10	3250	35	165	40	3.23	1.27	52	3.36	1.36	60	4.02	7.09	15.38
										Average	**5.11**	**7.12**	**12.06**

V. CONCLUSION

The study presents development and application of a fuzzy reasoning mechanism for estimation of performance measures of an abrasive water jet cutting process. The knowledge contained in the fuzzy rule-based comes from a series of experiments performed in cutting of a steel-based stock. The prediction results show that the metrics of surface roughness and kerf width are estimated with high levels of accuracy whereas the third metric, proportion of striations free zone, is also estimated with an acceptable level of accuracy. It can, thus, be concluded that a fuzzy rule-base system can be used to accurately estimate the performance measures of an abrasive water jet cutting process.

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