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EXPERIMENTAL AND NUMERICAL COMPUTATION OF DELAMINATION FACTOR OF HYBRID COMPOSITE LAMINATES USING SOFT COMPUTING TECHNIQUE

Due to their enhanced qualities, such as high rigidity and high strength, fibre reinforced polymers are widely employed in the automotive and aviation industries. To reduce the weight of aviation components, hybrid laminates containing fibre and aluminium layers, such as ARALL (Aramid Aluminium Laminate) and GLARE (Glass Laminates Aluminum Reinforced Epoxy), have recently been developed. Due to the delamination surrounding the holes in GLARE composites, which is the main cause of their low quality, drilling operations are difficult. In this study, a statistical model for delamination during drilling is created using the Response Surface Methodology (RSM), with a core composite design which has two elements and three layers and it is also examined how the input parameters (spindle speed and feed rate) affect the output response (delamination) when working with fiber-metal laminates. The fuzzy logic technique is employed to predict the delamination factor as a function of diverse combination of the input process parameters.

Keywords: FML; ARALL; GLARE; Drilling; RSM; Delamination factor; Fuzzy logic; Solid carbide tool

1. Introduction

Fiber-metal laminates (FMLs), which are created by joining a metal – typically an aluminium alloy – and a fiber-reinforced composite, like a glass-fiber-reinforced epoxy, are regarded as a promising type of hybrid material. Many aerospace manufacturers now opt to instal GLARE for main aircraft components. Due to its intriguing properties, including low density, high static strength, improved Fatigue and Damage Tolerance (F&DT), high impact resistance, and flame resistance, this new material has been used to construct the front and rear fuselage of the Airbus A380 [15]. Additionally, they have been employed as lightweight materials to increase efficiency. The family of fibre metal laminates includes hybrid materials, which are a combination of aluminium sheets and fibres. Composite materials can be machined using conventional techniques including drilling, turning, sawing, routing, and grinding [7]. Drilling is a component of more than 40% of the machining process in the aircraft industry. It's a difficult undertaking to conduct this drilling operation in GLARE composites. Delamination around the perforations is the key factor contributing to their poor quality.

The drilling process encounters a number of issues with regard to the ideal operating conditions and even the right tool selection because of the various mechanical properties of the GLARE elements. In some instances, improperly managed drilling operations can result in a variety of damages that can shorten the lifespan of a bolted or riveted system. Less research has been done on GLARE machinability data in the literature. However, some researchers have conducted intriguing studies into the damage that this hybrid composite material sustains during drilling [4]. Currently, numerous techniques are used to evaluate the delamination in FML following drilling. Significant damage to the work item and quick tool wear are also possible. While optical microscopy was being utilised to check the hole quality and tool condition, the drilling parameters were being investigated to ascertain their effects on the thrust force, torque, and surface roughness. The results demonstrated that cutting forces were unaffected by ply orientation and that surface roughness for grade 3 was greater than for grade 2B for similar cutting conditions. Through the analysis of twist drilling operations, [5] provided research to improve understanding of the machining of fibre metal laminates. Spindle impacts on drilling parameters were investigated. The delamination in drilling has been connected to the thrust force employed to exit the drill [7]. Numerous researchers' investigations show that there is a critical thrust force below which no damage occurs. [7] Advocated saw

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drill and candle stick drill over ordinary twist drill for reducing delamination at the drill's exit side.

Using multiple regression analysis, [22] demonstrated a correlation between spindle speed, feed rate, and drill diameter to cause delamination in a CFRP laminate. The effects of speed and feed rate on thrust force, torque, and delamination in drilling of chopped composites with various fibre volume fractions were examined experimentally by [13]. Based on the findings of the experiments, empirical models to determine the drilling conditions were constructed. ANOVA is used to study the process variables that significantly affect the performance attributes. ANOVA yields the most important process parameter [3]. A model has been created for accurately forecasting the delamination in drilling GFRP composites. A twist drill was used to conduct the studies.

For GFRP composite materials, feed rate is the cutting parameter that has the greatest impact on surface roughness (33.43%) and delamination (35.49%). [16] inferred that surface roughness and delamination increase with both feed rate and angle of fibre orientation, so the composite damage is greater for higher feed rate and higher fibre orientation [12]. It has been noted that whereas drills with 104° and 118° point angles produce poor outcomes, drills with 90° point angles produce good results. Thrust force is dependent on the drill point angle and the feed rate, and it rises as the point angle and feed rate are increased [20]. RSM [11] makes it simple to forecast how many influential combinations of machining factors would interact and have an impact. When compared to tools made of cemented carbide, tools coated with PCD behave better in terms of surface roughness and cutting pressure [17]. Many soft computing and artificial intelligence techniques have been deployed for prediction and optimization of machine process parameters ((Khazi et al.) [1]. The process parameters influencing the response variable (delamination factor) are spindle speed and feed rate. Based on the effects of these machine parameters, the delamination factor is analysed and the prediction is established through the application of fuzzy logic [2]. Therefore, the main objective of this study is to compute the influence of different input parameters such as spindle speed and feed rate on GLARE composites to evaluate delamination.

2. Experimental setup and delamination measurement

8 plies of glass fibre and 2 plies of aluminium mesh make up the work material, which is reinforced by epoxy resin. The GLARE is produced by hand layup. The thickness of the plate is 6 mm. Aluminium mesh is 0.7 mm thick, but glass fibre is just 0.3 mm thick. The size of the plate is 300 × 300 × 5 mm.

An CNC machine is used to conduct the experiment. It can deliver spindle speeds of up to 10,000 rpm [10]. To achieve the least amount of delamination, holes in the GLARE were drilled using solid carbide coated with TiAlN, as shown in Fig. 1.

The experimental set up is shown in Fig. 2.

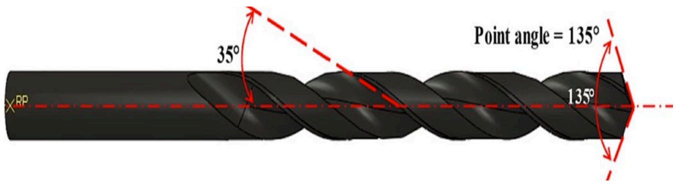

Fig. 1. Soild carbide tool coated with TiALN

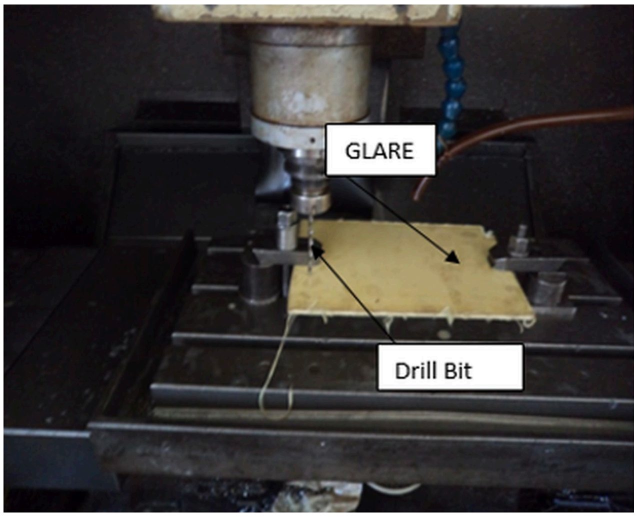

Fig. 2. Machining setup

In order to forecast the impact of each input element on the response, experiments for each set of parameters are designed using mixed orthogonal array with 20 runs [10]. The lowest and maximum bounds of the factors have been chosen after a thorough analysis. The factors' upper and lower limits are determined by the analysis and are listed below. Previous research suggested that as feed rate increases, the delamination factor rises [12]. As a result, the feed rate was set between 0.04 to 0.12 mm/rev. In comparison to feed rate, spindle speed is less important in the machining of composites. The spindle speed in the current investigation is set between 1000 and 2000 rpm.

The Video Measuring System (VMS) depicted in Fig. 3 was used to analyse how much the drilled holes were delaminating.

Fig. 3. Video Measuring System

The work material is set up on the VMS's XY stage. The damage around the holes was then quantified as Dmax when a light source from the Z axis was set to fall on the work material. The machine has a measurement range of up to 150 × 150 mm [10].

Eq. (1) provides the delamination evaluation formula:

$$D_{max}/D = F_d \quad (1)$$

Where F_d is the delamination factor, D_{max} is the maximum diameter and D is the hole diameter [10].

3. Experimental design

The objective is to investigate the connection between the input elements and the response received. The response surface can be written as $y = f(x_1, x_2,..., x_k)$ if it is assumed that all variables are quantifiable [10]. The aim of this research is to optimize the response variable 'y' (Delamination factor). Predicting a relationship between the response attained and the independent input factors is necessary (speed and feed rate). TABLE 1 displays the convenience translation of input parameters into coded variables with 20 runs in accordance with the RSM.

TABLE 1

Experimental design with delamination factor values

Run	Variables		Delamination Factor
	Feed rate F (mm/min)	Cutting Speed V (m/min)	F_d
1	0.08	1500	1.389
2	0.12	1000	1.479
3	0.08	1500	1.423
4	0.12	2000	1.644
5	0.08	2000	1.444
6	0.08	1500	1.441
7	0.08	1000	1.367
8	0.08	1500	1.388
9	0.12	1000	1.471
10	0.04	1000	1.051
11	0.04	1000	1.081
12	0.12	2000	1.692
13	0.04	1500	1.212
14	0.04	2000	1.351
15	0.08	1500	1.380
16	0.08	1500	1.432
17	0.08	1500	1.412
18	0.08	1500	1.441
19	0.12	1500	1.572
20	0.04	2000	1.370

4. Results and discussion

One of the most important considerations when choosing the ideal cutting settings is delamination. It is influenced by a number of input factors, including spindle speed and feed rate. Quadratic model is statistically significant for delamination analysis [10]. TABLE 2 provides the ANOVA result of the quadratic model for delamination.

For delamination, the R^2 value and corrected R^2 value are 93.91 and 88.21%, respectively. As a result, the study of the regression model offers a clearer understanding of how the input parameters relate to the output response. The P-value for this model is less than 0.05 The effects of factors A, B, and AB on delamination are substantial. The remaining model terms are all inconsequential.The findings indicate that feed rate, along with cutting speed, is the most important component for delamination [10]. The following relation has been created for GLARE composite delamination after the experimental values were analysed using response surface analysis.

Final calculation using coded factors:

$$\text{Delamination } (F_d) = 1.299 + 0.069 \times A + 0.019 \times B + 0.019 \times A \times B - 6.969 \times 10^{-3} \times A \times B - 0.098 \times A^2 - 5.101 \times 10^{-3} \times B^2 \quad (2)$$

Final calculation using actual factors:

$$\text{Delamination } (F_d) = 1.093 + 1.5998 \times \text{feed rate} + 3.098 \times 10^{-5} \times \text{spindle speed} + 1.0957 \times 10^{-3} \times \text{feed rate} \times \text{spindle speed} - 1.399 \times 10^{-6} - 6.0143 \times \text{feed rate}^2 - 2.009 \times 10^{-8} \times \text{spindle speed}^2 \quad (3)$$

TABLE 2

ANOVA Table for the delamination factor

	Sum of squares	Df	Mean square	F value	P value (prob>F)	Effect	Percentage contribution
Model	0.061	5	0.677×10^{-3}	17.99	<0.0001	significant	93.91
A	0.0570	1	0.057	134.89	<0.0001	significant	77.19
B	0.4568×10^{-4}	1	0.4568×10^{-4}	10.91	0.0069	significant	6.29
AB	0.3773×10^{-4}	1	0.3773×10^{-4}	9.99	0.0121	significant	5.49
A^2	0.2735×10^{-5}	1	0.2735×10^{-5}	0.69	0.3997	Insignificant	0.38
B^2	0.7423×10^{-6}	1	0.7423×10^{-6}	0.20	0.6901	Insignificant	0.09
Error	0.368×10^{-5}	6	0.368×10^{-5}				5.61
Total	0.069				16		
R^2 = 93.91%, adjusted R^2 = 88.21%							

The correlation between the expected and actual levels of delamination during machining of the GLARE composite is shown in Fig. 4.

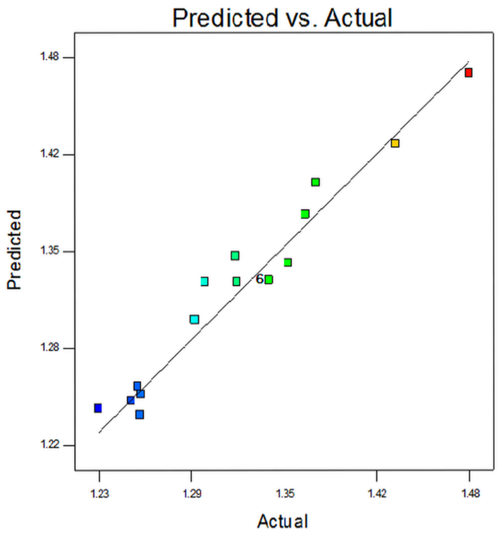

Fig. 4. Correlation between Predicted Vs Actual delamination factor

TABLE 3

Response to delamination

Level	Feed rate (f) mm/rev	Spindle speed (V) m/min
–1	1.2494	1.3048
0	1.3293	1.3282
1	1.4007	1.3474
Delta	0.1513	0.0426
Rank	1	2

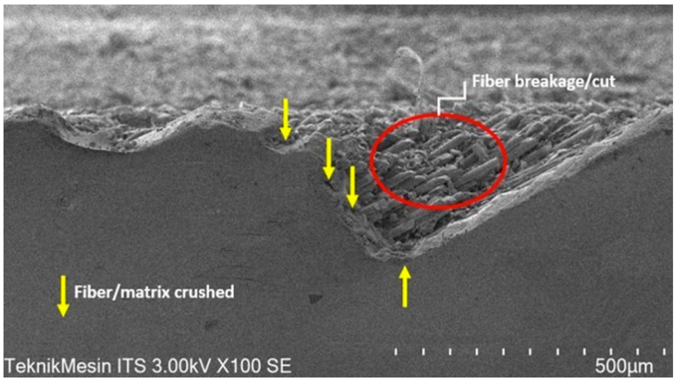

Fig. 5. SEM image of damaged GLARE Composite

GLARE composites are machined, and the effects of various cutting settings are investigated using a response model graph and response table. TABLE 3 illustrates how drilling factors affect delamination, and Fig. 5 illustrates their primary consequences.

According to the response TABLE 3, spindle speed is second in importance to feed rate [11]. when it comes to influencing the delamination factor, hence higher feed rates result in greater composite damage as shown in Fig. 5.

Fig. 5 illustrates the delamination on one side of the cut slot, when the cut width is greater than the slot width (equal to the end-milling diameter). It is shown that the fiber has been cut and the matrix/resin part has been peeled off or crushed.

The contour graph in Fig. 6 shows that delamination increases as feed rate and spindle speed are increased. This is caused by the work piece's thrust force, which provides the energy needed for incremental delamination during drilling, and the body's increased strain energy as a result of the crack propagation [4].

Additionally, it is clear from the investigation that thrust force and delamination have a favourable association. One of the primary strategies for reducing the damage caused by drilling-related delamination may be to decrease thrust force.

Optimization using Fuzzy logic

In the present study, an effort has been taken to identify the near optimal values of process parameters during drilling operation. To decide the optimal values of input process parameters, the prediction model is established using MATLAB fuzzy logic toolbox software. A simple Mamdani based fuzzy logic technique has been applied to accomplish the objective. Here spindle speed and feed rates have been considered as inputs and the delamination factor as the response varaiable as shown in Fig. 7.

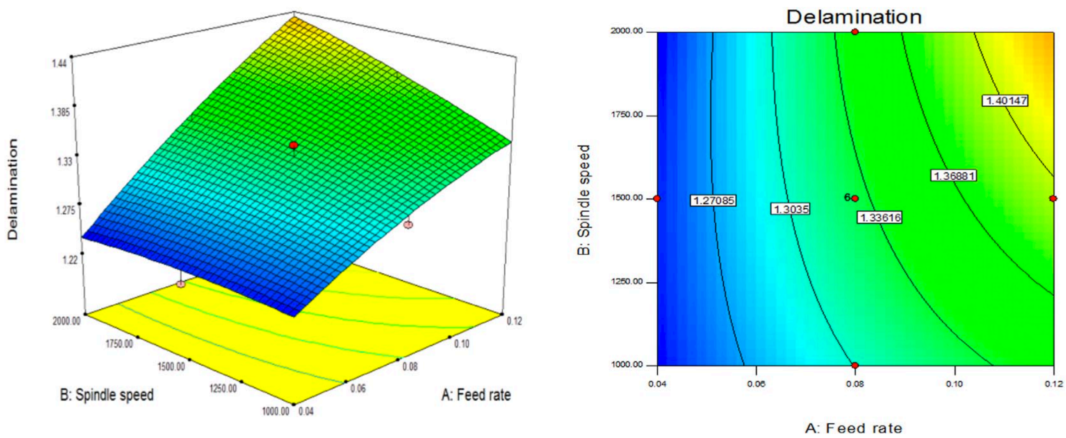

Fig. 6. 3D surface and contour plots for delamination

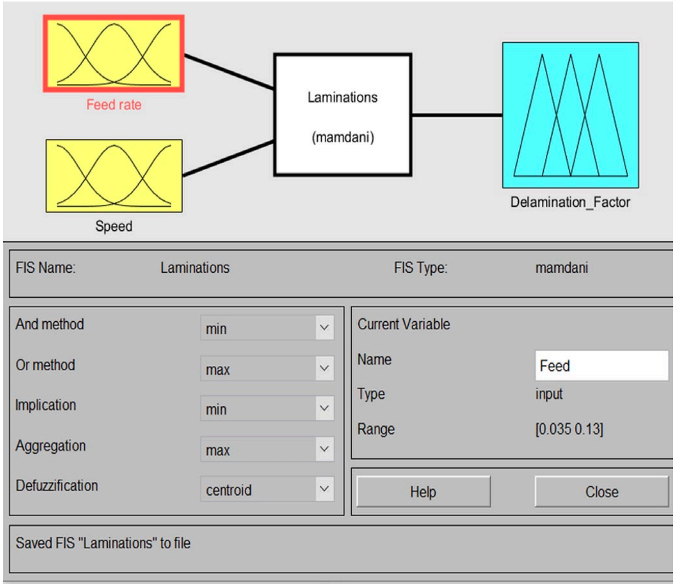

Fig. 7. Fuzzy Logic structure

The linguistic values for all the parameters are divided in five categories. The inputs are fuzzified using triangular membership functions namely, Very Low (VL), Low (L), Moderate (M), High (H) and Very High (VH) and the same hold for the response variable too. The membership functions for the inputs and outputs are depicted in Figs. 8-10.

The inference engine is designed by if-then rules that explicates the relationship between the input parameters and the response variable through linguistic quantifying terms. The rules framed and the triangular membership functions fuzz ify the crisp inputs to fuzzy sets. The 3D surface plot of the logic system suggested can be visualized from Fig. 11.

Fuzzy modelling is executed using fuzzy inference engine and 25 rules have been framed as like:

- 1. If (Feed_rate is VL) and (Speed is VL) then (D_Factor is VL)
- 2. If (Feed_rate is VL) and (Speed is L) then (D_Factor is VL)
- 3. If (Feed_rate is VL) and (Speed is M) then (D_Factor is L)
- ……
- …….
- 25. If (Feed_rate is VH) and (Speed is VH) then (D_Factor is VH)

Fig. 12 depicts the rule structure of the whole set of rules framed for the suggested system.

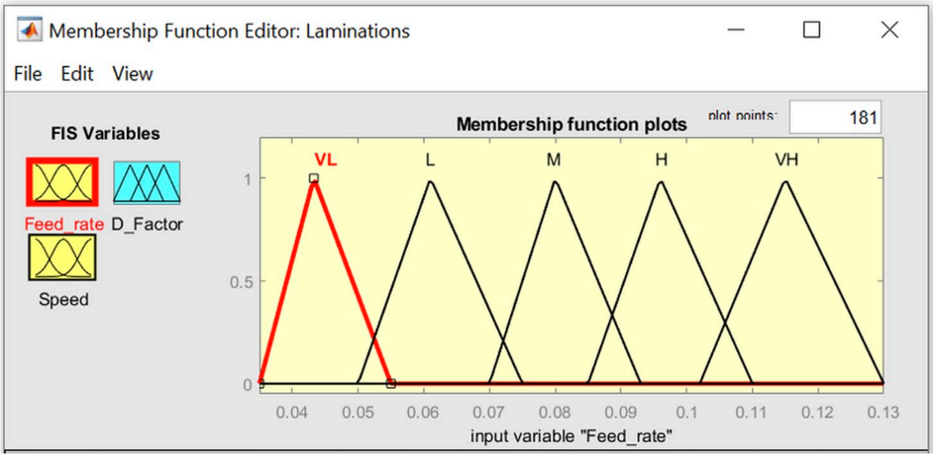

Fig. 8. Membership function for the input variable feed rate

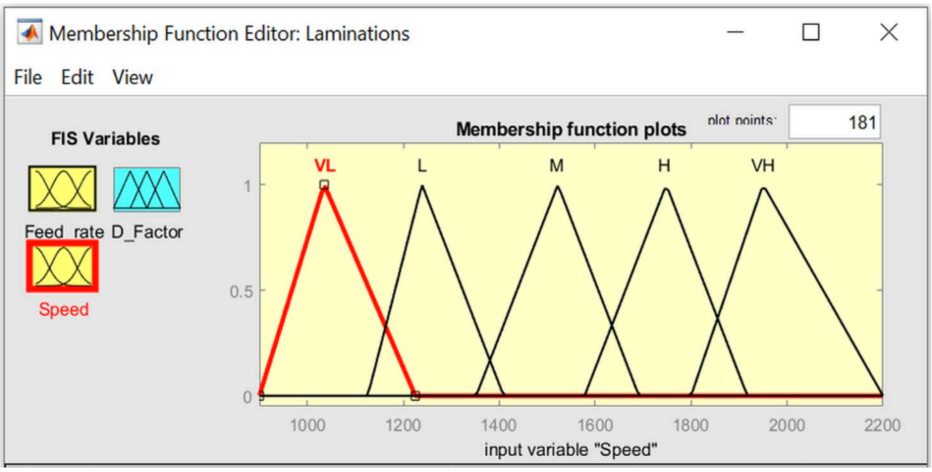

Fig. 9. Membership function for the input variable speed

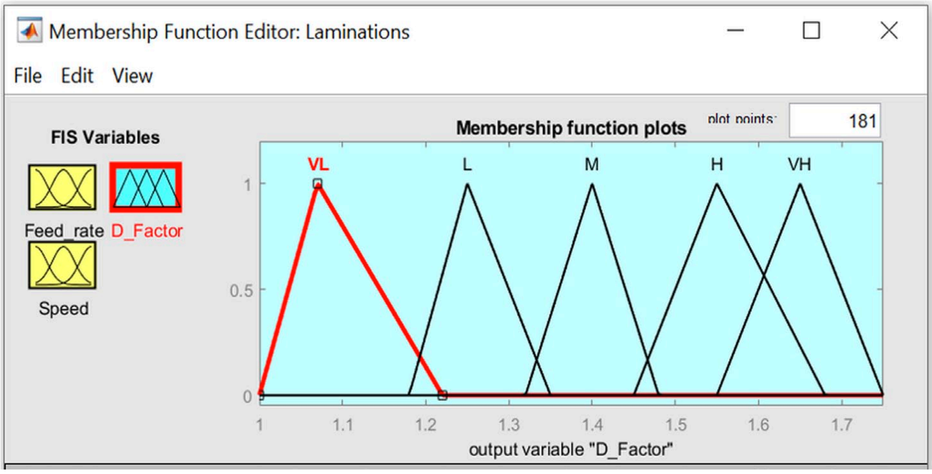

Fig. 10. Membership function for the output variable delamination factor

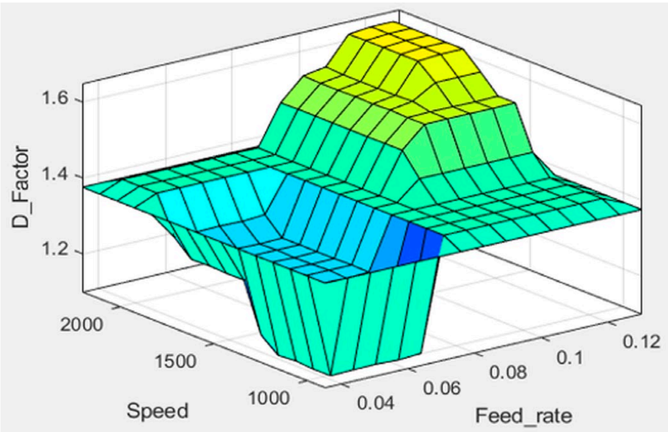

Fig. 11. Surface plot of Fuzzy logic system

Then, the data is defuzzified using centroid method and the delamination factor is determined. The lower the value of delamination factor, the lower is the damage that happens only with optimal feed rate and speed. Fig. 13 displays for an optimal feed rate of 0.04 mm/rev and speed of 1050 rpm, the delamination factor is 1.099 which is very low surrounding the holes in GLARE composite sand is recommended as there is no damage during drilling operation.

Confirmation test

TABLE 4 calculates and displays the delamination error. A confirmation test was used to validate the aforementioned

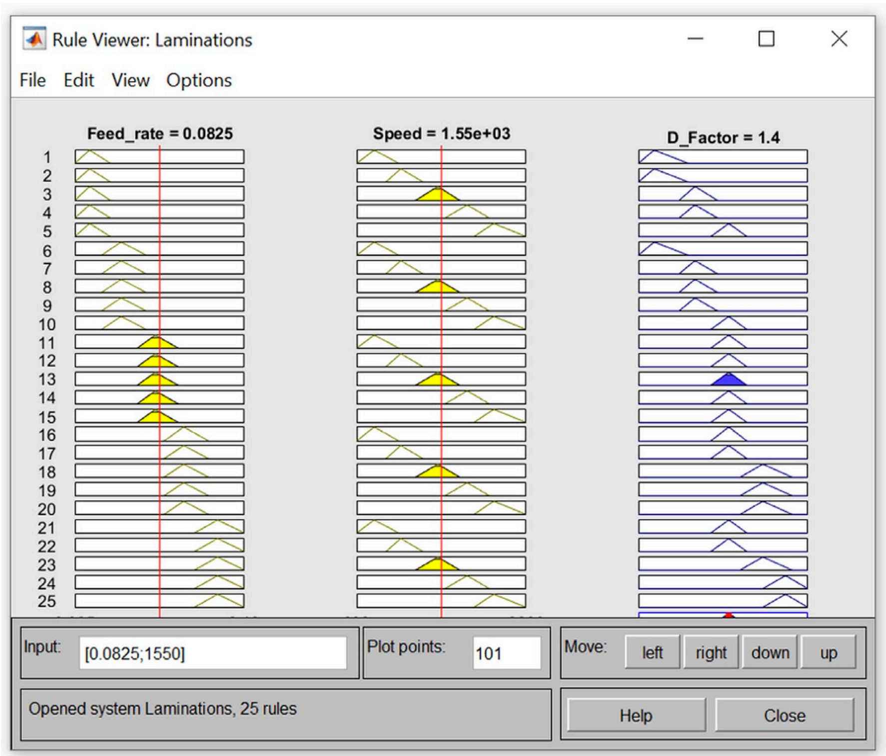

Fig. 12. Fuzzy rules for delamination factor determination

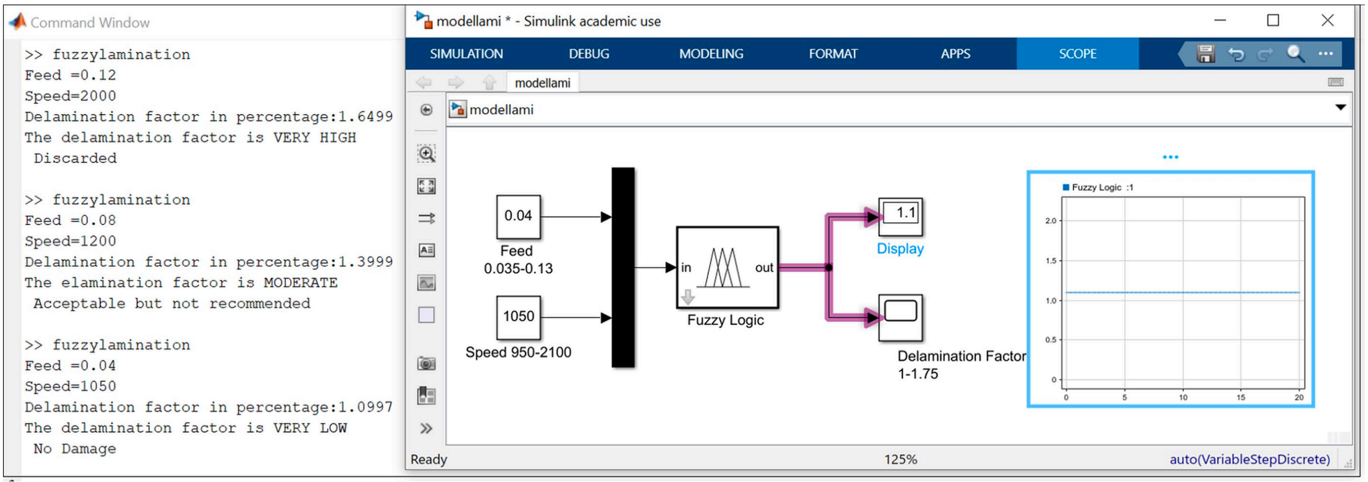

Fig. 13. Simulation results for delamination factor determination

TABLE 4

Experimental and projected delamination factor error comparison

Run	Experimental F_d value	Calculated F_d value	Error (%)
1	1.389	1.3349	0.0541
2	1.479	1.4661	0.0129
3	1.423	1.369	0.0540
4	1.644	1.5849	0.0591
5	1.444	1.4736	–0.0296
6	1.441	1.3911	0.0499
7	1.367	1.3775	–0.0105
8	1.388	1.3181	0.0699
9	1.471	1.4768	–0.0058
10	1.051	1.0471	0.0040
11	1.081	1.0766	0.0055
12	1.692	1.6851	0.0071
13	1.212	1.2321	–0.0199
14	1.351	1.3541	–0.0029
15	1.380	1.3991	–0.0199
16	1.432	1.4593	–0.0277
17	1.412	1.3631	0.0499
18	1.441	1.3891	0.0519
19	1.572	1.4978	0.0742
20	1.370	1.3182	0.0518

delamination model, and the error was discovered to be within 0.35%.

The model is shown to be a practical and efficient method for assessing delamination drilling of GLARE composites.

5. Conclusions

Delamination has been examined as an important factor during drilling operation. The following conclusions were reached during the drilling of GLARE composites based on the aforementioned findings. The impact of FML delamination can fluctuate depending on how the input parameters are changed. With an increase in feed rate and a modest rise in spindle speed, the delamination increases gradually. Therefore, using a low feed rate and a medium spindle speed will result in the least amount of delamination and were considered as the optimal parameters predicted and verified using the fuzzy logic soft computing technique. For GLARE composite materials, feed rate has a significant impact on delamination (79.17%). Additionally, the established mathematical model is used to accurately forecast the delamination of GLARE composites during drilling. The confirmation test was used to check the created second-order response surface model, and the error percentage was found to be within 0.35%.

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