MATERIALE PLASTICE
https://revmaterialeplastice.ro
https://doi.org/10.37358/Mat.Plast.1964

Modeling and Analysis of Surface Roughness Parameters in Drilling of Silk-glass/epoxy Composite

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Abstract: *In the recent past, the demand for multifunctional and lightweight materials have increased steadily creating an increase in demand for Hybrid polymer matrix composite which consists multiple fibers in conventional resins. In this study, a hybrid composite comprising of two reinforcements - natural silk fiber and E-Glass fiber - in an Epoxy resin matrix which is a partially eco-friendly composite has been fabricated and the effect of drilling, by using an 8 facet solid carbide drill, on the surface roughness has been studied. Taguchi's L27 Orthogonal array was used for experimentation by modifying three parameters - feed rate, spindle speed and drill diameter - on three levels (low, medium and high) and thereby studying the effects. From the results of experimentation it has been observed that increase in spindle speed and drill diameter reduces surface roughness however it increases with increase in feed rate. Further, regression analysis and Fuzzy modeling are used in order to determine optimum parameter values to get the desired surface finish. Good agreement between the experimental, regression and fuzzy model is observed with the correlation coefficient of 0.9814 and 0.9677 respectively.*

Keywords*: drilling, fuzzy modeling, hybrid polymer composite, regression modeling, surface roughness*

1. Introduction

As technology is constantly advancing, improved multifunctional and lightweight materials are being increasingly demanded by the widening fields of industry [1] These materials are sought because of the special property they possess such as high stiffness, corrosion resistance, low thermal expansion light weight etc., composite materials are in high demand, mainly in the fields of science and engineering [2]. Composite materials are considered as alternate materials over conventional materials because of the special characteristics such as high strength, high stiffness, good dimensional stability, higher fracture toughness. It is due to these factors the use of composites has increased tremendously in aerospace and automobile sector. They are also sought in Marine, Power plant and Transportation sector with demand increasing in industries producing Sporting goods as well. We can witness a constant increase in their global demand year after year [3]. Hybrid composite materials developed by combining different fibers using resin had drawn the interest of the Global community resulting in surge in their demand. Hybrid composites consist of more than one type of reinforcement fiber. The characteristics of the hybrid composites and thereby their performance can be altered through various fabrication factors, such as the nature and volume fraction of fiber, fiber orientation, stacking pattern, lamination form and fabrication methods [1]. Studies regarding hybrid composites have shown that hybrid composites (with two types of fiber) have a higher wear resistance than that of single fiber reinforced composites [4].

The advantages associated with natural fiber-reinforced composites over conventional synthetic composites are plenty. The primary advantages include the fibers low density, low cost, high specific properties with lightweight and reuse options. Composites with natural fibers have low mechanical strength and are hydrophobic nature. Their mechanical strength is much lower than composites made of synthetic fibers such as nylon, aramid, glass, rayon and carbon. These composites exhibit high moisture resistance and good mechanical performance as well. Synthetic fibers are however costlier and is made of fibers from non- renewable sources. It is therefore believed that composites developed by a mixture

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of both natural and synthetic fibers in the same matrix could create a balance between the advantages and disadvantages of the two types of reinforcement material. Inclusion of more than one fiber type into a single matrix composite has led to the development of hybrid composites. Studies reveal that hybrid composites comprising both natural and manmade fibers have resulted in composites with superior performance compared to conventional composites [5].

The surface finish is a significant parameter in the process of machining, and it has been the focus area for many years due to its effect on properties like wear resistance and fatigue strength [6]. Surface finish has become a crucial design feature in various applications involving parts subject to fatigue loads, fastener holes, exact fits, and visually appealing requirements. Along with tolerances, surface roughness is an important and critical constraint for selection of cutting parameters and selection of machinery in process planning. Surface topography and roughness characterization is crucial for areas involving friction, wear, and lubrication. Friction in common is used to increase with increase in average surface roughness. It is therefore clear that surface roughness parameters play an important role in products such as brake linings, tires, and floor surfaces. The surface generated by machining determines the material capability to withstand conditions of stress, corrosion, and temperature, which thereby determines durability and reliability of products made of the composite [7].

Composites, although fabricated to near net shapes by processes like autoclave molding, compression molding or filament winding, post fabrication machining operation, like drilling, milling, boring, or turning is often necessary to ensure the required composite shape. It is however known that machining of composites is very difficult compared to machining of traditional metals or alloys owing to varying material properties across a composite.

The drilling of composites using twist drills is one of the most frequently employed machining operation for generating required shapes in structural assemblies for purposes such as riveting and fastening assemblies in aerospace and automobile industries. The delamination induced due to drilling is known to be one of the major defects occurring in composites. The delamination severely deteriorates the surface finish and fatigue properties, thereby reducing the life of the composite. Studies have therefore been conducted to minimize the cutting forces generated during drilling with the objective of reducing the delamination and surface roughness for better quality of the drilled hole [8, 9].

B.V. Kavad et al. [10] have reviewed the effects of drilling in GFRP (Glass Fiber Reinforced Plastic) composites and have showed how alterations in parameters have an effect on delamination and other damage factors. They concluded that tool material and cutting speed have the biggest influence on delamination and that low feed rate gives rise to less delamination. K Palanikumar et al. [11,12] explored the process of drilling of GFRP composites by studying the parametric influence such as Fiber orientation, depth of cut, feed rate and drill diameter on Surface roughness. From the study they concluded that there is a decrease in surface roughness with respect to the increase in cutting speed and depth of cut however with increase in cutting speed and depth of cut, surface roughness increases.

Palanikumar et al. [13] also studied the parametric influence on thrust force during drilling of Glass/ Polypropylene thermoplastic composite. Arun Kumar Parida et al. [14] have optimized the process parameters with improved results in surface roughness in machining of GFRP composites. They concluded that feed rate and depth of cut are the most significant parameter which might affect surface roughness. Sener Karabulut et al. [15] studied the parametric influence of milling parameters on surface roughness and cutting force in metal matrix composites using Taguchi's method and tried to optimize them. T. Rajmohan et al. [16] modeled and analyzed the drilling of hybrid metal matrix composites using response surface analysis. Their experiments concluded that the feed rate has a significant impact on surface roughness, thrust force, tool wear and burr height. A K Parida et al. [17] modeled surface roughness in drilling of GFRP by considering three individual parameter and interaction effects of these parameters. The parameters such as spindle speed, feed rate and drill diameter are considered, and they concluded that with increase in spindle speed surface roughness decreases and is the most critical parameter of all.

K Palanikumar et al. [18] studied the effect of drilling by a poly-crystalline diamond tool on Glass Fiber Reinforced Plastic composites with respect to surface roughness and developed a mathematical model using fuzzy logic. They designed the experiment using Taguchi L27 orthogonal array by varying 3 parameters - spindle speed, feed rate, depth of cut in 3 levels - low, medium, high. Their experiment proved that increase in cutting speed resulted in decrease of surface roughness whereas increase in feed rate increase surface roughness. Feed rate is the most significant parameter whereas depth of cut is the least influential one. B Latha et al. [19] have inspected the effect of 3 parameters - spindle speed, feed rate, drill diameter in drilling of GFRP composites using fuzzy logic and deduced that delamination factor increases with feed rate and drill diameter whereas decreases with spindle speed. Erol Kilickap et al. [20] explored the effect of parameters like cutting speed, feed rate and point angle in GFRP composite drilling to study its influence on delamination and surface roughness. It has been observed that delamination factor increased when there is a cutting speed and feed rate and was concluded that delamination is maximum at the exit. B Latha et al. [21] studied the geometric influence on drill tool in drilling GFRP composites and concluded that brad and spur drills exhibit more thrust force whereas it was the least for step drills. K Palanikumar et al. [22] also conducted parametric influence study in drilling of GFRP composite using Regression analysis. They concluded that the feed rate followed by the spindle speed are the most significant factors in the study of GFRP composite drilling. B Latha [23] also evaluated the application of fuzzy logic in drilling and analysis of surface roughness parameters in drilling of GFRP Composites.

It is seen that sufficient research has not gone into the study of surface roughness due to drilling in hybrid polymer matrix composites. More specifically, surface roughness studies have focused more on GFRP composites and not on newer materials like hybrid composites. The aim of this paper is to thereby bridge this gap which exists and focus more study on surface roughness in hybrid composites owing to their vast potential application in the future.

In this work, a hybrid composite comprising of Natural silk fiber and E-Glass fiber reinforced in Epoxy resin matrix, which is partially eco-friendly has been fabricated and the consequence of drilling on the surface roughness has been studied. The drilling is performed as per Taguchi's L27 Orthogonal array by changing parameters like feed rate, spindle speed and drill diameter at three different levels. The surface roughness for each hole is then measured and analyzed. Further, the surface roughness has been modeled using both Regression Analysis and Fuzzy Modeling in order to determine optimum parameter values for a particular desired surface roughness and correlate the parameters causing them.

Table 1. Properties of fiber

Properties	Fiber	
	E-Glass	**Silk**
Density g/cm^3	2.55	1.3
Tensile strength (MPa)	2400	1300-2000
Young's modulus E (GPa)	73	30
Specific modulus (E/density)	29	23.07
Elongation at failure (%)	3	28-30
Moisture absorption (%)	-	11

2. Materials and methods

2.1. Composite fabrication

Raw resources required to fabricate the hybrid composite are Silk Fiber, E-Glass Fiber, Epoxy Resin and Hardener. Silk Fibers have unique property like resistance to failure during compression and is inert to temperature change because of the servicing coating. Silks also have an unique property of being insoluble in solvents like water, acid and alkali. The largeness of the internal and external surfaces is positively correlated to the silk fibers reactivity with chemical agents. In general, Elastic modulus and tensile strength of composites made of silk fibers are high.

E-Glass, Alumina-calcium-borosilicate glasses with maximum alkali content of weight 2% are used in specific areas which require composites with high electrical resistivity and strength. Epoxy resin (Araldite LY 556) is usually referred asBisphenol-a-diglycidyl-ether. For fabrication of composite Hardener (araldite) HY951 is used. Its IUPAC name is NNO-bis (2- Aminoethyl Ethane-1,2diamin) this has a viscosity of 10-20 poise at 25ºC. By using hand layup process composite were fabricated. It involves applying the elements successively onto a mould surface.

E-Glass, Alumina-calcium-borosilicate glasses with maximum alkali content of weight 2% used as general-purpose fibers where strength and high electrical resistivity are required. Epoxy resin (Araldite LY 556) its common name is Bisphenol-a-diglycidyl-ether. In the present work, Hardener (araldite) HY951 is used. Its IUPAC name is NNO-bis (2- Aminoethyl Ethane-1,2diamin) this has a viscosity of 10-20 poiseat 25ºC.Thecomposite was fabricated by means of the Hand Lay-up process. It involves applying the elements successively onto a mould surface.

2.2. Experimentation

The experimental plan is as per Taguchi's L27 orthogonal array. The three parameters - drill diameter, spindle speed, and feed rate - are considered at three levels (low, medium and high) and the experiment is designed carefully so that no effect of any of the input parameters is missed out. The experiment is conducted on the Hybrid Polymer Composite Matrix after drilling out 27 holes - 9 holes of with 4 mm drill bit, 9 holes of with 6mm drill bit, and 9 holes with 8mm drill bit. The drill bits used are shown in Figure 1. The drilling is done on a radial drilling machine with variable feed drive using the solid carbide drill bits, shown in Figure 2.

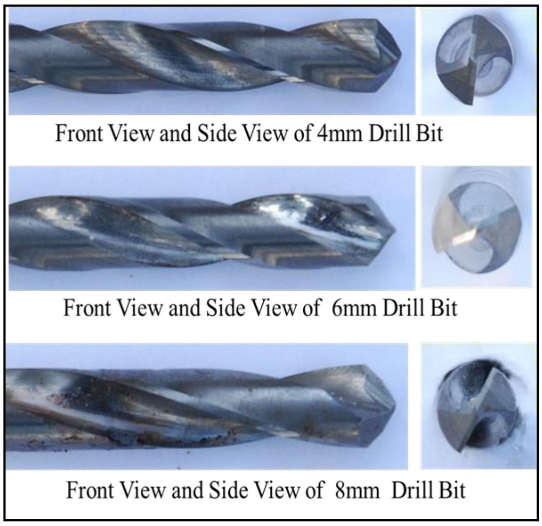


Figure 1. Solid carbide drill bits

The 9 holes of each drill bit size vary in 3 spindle speed and 3 Feed Rate combinations. The 3 Spindle Speeds chosen are: 500 (low), 1000 (medium), and 1500 (high) rpm. The 3 Feed Rates chosen are: 100 (low), 300 (medium), and 500 (high) mm/min. The holes drilled are then checked for surface roughness using the Surface Roughness Tester machine, shown in Figure 3, and the results were tabulated. The roughness tester gives the value of average surface roughness (Ra) in micrometers.

Figure 2. Experimental setup

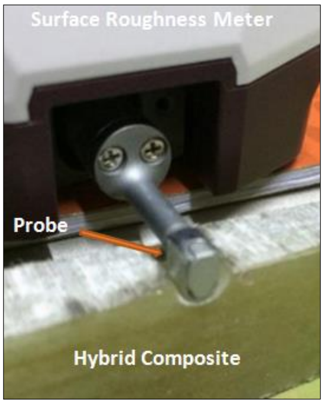


Figure 3. Measurement of surface roughness

3. Results and discussions

3.1. Trend analysis

The effect of drilling parameters on surface roughness is presented in Figures 4, 5 and 6. The trend graphs are obtained using Minitab 16. Figure 4 shows the relationship between drill diameter and surface roughness. It is seen that surface roughness decreases with increase in drill diameter. Figure 5 shows the variation of Surface roughness with Spindle speed. It can be deduced that with increasing spindle speed, Surface roughness decreases. From Figure 6, it can be concluded that with increasing feed rate, surface roughness increases too.

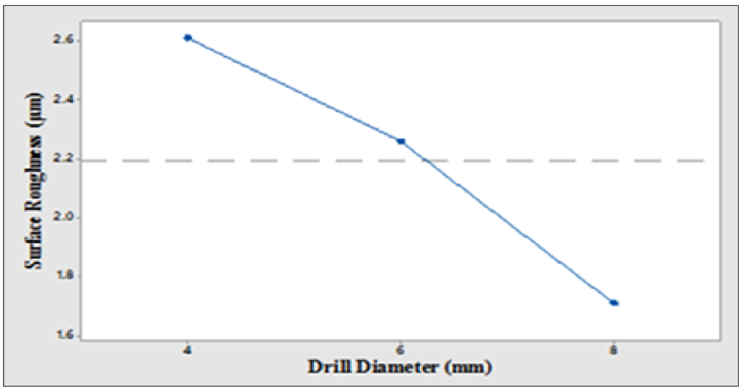


Figure 4. Main effects plot of surface roughness vs. drill diameter

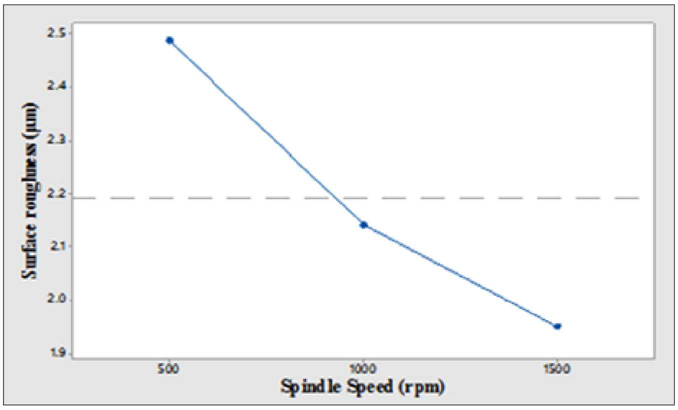


Figure 5. Main effects plot of surface roughness vs. spindle speed

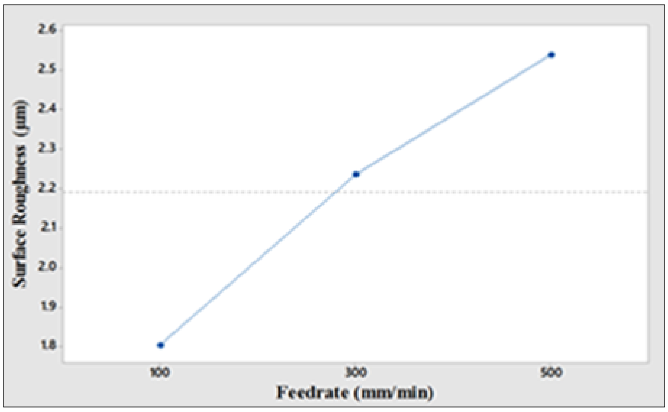


Figure 6. Main effects plot of surface roughness vs. feed rate

3.2. ANOVA analysis of surface roughness

Table 2. ANOVA table

Source	Degrees of Freedom	Adj. SS	Adj. MS	F-Value	P-Value	Percentage Contribution
Drill Diameter (mm)	2	3.681	1.85051	194.8	0	46.8023
Spindle speed (rpm)	2	1.3299	0.66495	70.38	0	16.9089
Feed Rate (mm/min)	2	2.4525	1.22662	129.8	0	31.1817
Drill Diameter (mm) x Spindle speed (rpm)	4	0.1359	0.03398	3.6	0.058	1.7280
Drill Diameter (mm) x Feed rate (mm/min)	4	0.1572	0.0393	4.16	0.041	1.9987
Spindle speed (rpm) x Feed rate (mm/min)	4	0.033	0.00824	0.87	0.521	0.4191
Error	8	0.0756	0.00945			
Total	26	7.865				

ANOVA (Table 2) has been chosen in this research work as the probability of error is small. It helps in identifying whether the factors considered impact the surface roughness. It also makes the interaction study easier. The results have been analysed with a 95% confidence interval.

From the F values of Table 2, we infer that the null hypothesis is rejected for drill diameter, spindle speed and feed rate. Similarly, the effects of drill diameter and spindle speed acting simultaneously and that of drill diameter and feed rate cannot be overlooked. Hence, they become significant factors that would affect the surface roughness. However, the effects of simultaneous action of spindle speed and feed rate on the surface roughness is negligible and can therefore be neglected.

3.3. Regression modeling

To predict the surface roughness under any uncertainty, regression theory is used. The equation for surface roughness (Ra) is developed:

$$Ra\ (\mu m) = 3.225 - 0.1555\alpha - 0.000516\beta + 0.002391\gamma - 0.000022\alpha\beta - 0.000155\alpha\gamma + 0.000000\beta\gamma \quad (1)$$

where:

α denotes the drill diameter (mm), β denotes the spindle speed (rotations per min),
γ denotes the feed rate (mm/min).
As 'βγ' term does not affect the surface roughness the equation (1) is further simplified as follows:

$$Ra\ (\mu m) = 3.225 - 0.1555\ \alpha - 0.000516\ \beta + 0.002391\ \gamma - 0.000022\ \alpha\beta - 0.000155\ \alpha\gamma \quad (2)$$

Using the regression model equation for surface roughness, the values for surface roughness are calculated and these are then compared with the values obtained from experiments. Figure 7 shows the comparison of the experimental values and the model values for eachofthe16 experiments. Graph of surface roughness (model values) versus surface roughness (experimental values) is shown in Figure 8. A trend line is fitted on the data set, and it gives a co-efficient of determination value, R^2 of 0.9814. The R^2 value shows that the data points are closely related to the trend line.

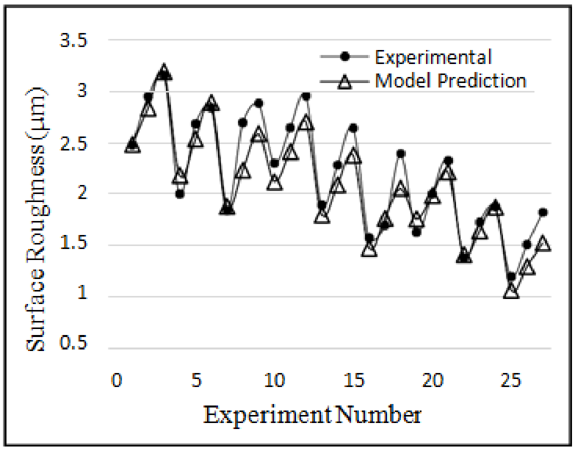


Figure 7. Comparison of experimental and regression model values

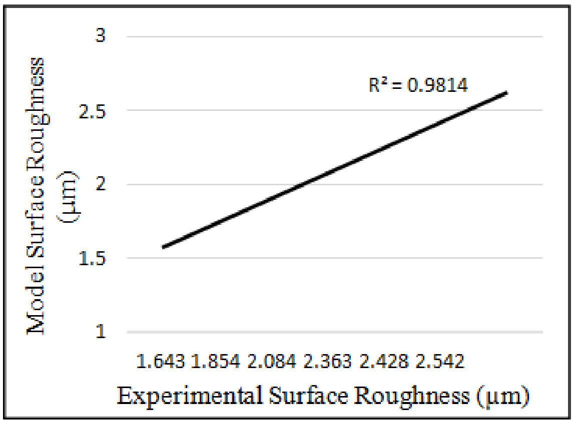


Figure 8. Plot of model vs. measured experimental surface Roughness with regression line

3.4. Fuzzy modeling

Fuzzy Logic Modeling is a useful prediction methodology which combines the concepts of probability theory, multi-valued logic and artificial intelligence methods for solving complex problems. The main steps involved in Fuzzy logic are shown in Figure 9 graphically.

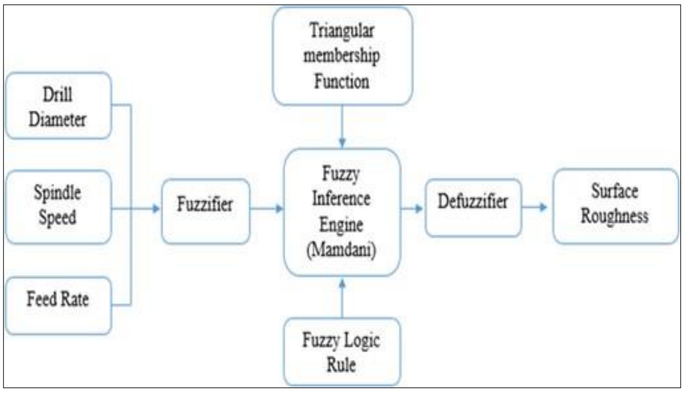


Figure 9. Outline of basic Fuzzy Logic System Process [24]

The First step is the conversion of Numerical crisp values of the input parameters into Linguistic terms (For example: Low, Normal and high), this process is known as Fuzzification. Then for each of the input and output parameters membership functions are allocated. Membership functions of a parameter maps the parameter to the real interval [0,1].

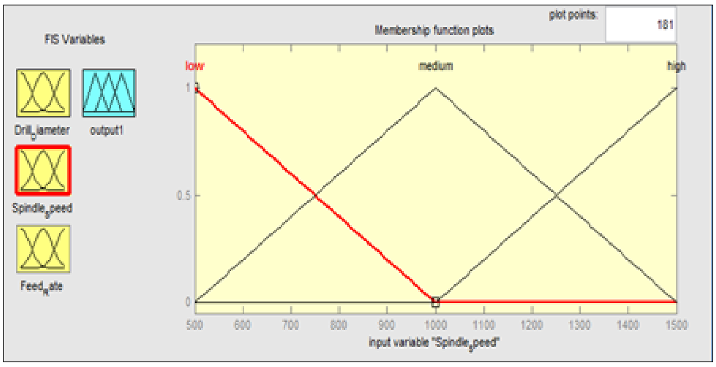
Triangular membership function is employed for all the input and output parameters and is given by the equation:

$$f(y: p, q, r) = \left\{ \left(\begin{matrix} 0 & y \leq p \\ \frac{y-p}{q-p} & p \leq y \leq q \\ \frac{r-y}{r-q} & q \leq y \leq r \\ 0 & r \leq y \end{matrix} \right) \right\}$$

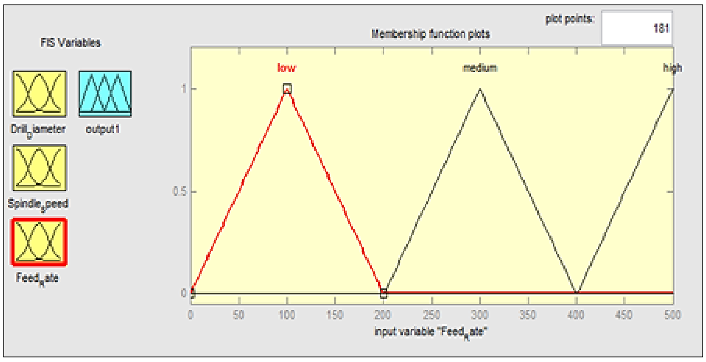
Fuzzy Logic rules in the form of IF-THEN rules are specified with three inputs p1, p2, p3 and one output q.

If p1 = A1 and p2 = B1 and p3 = C1 then q = D1elseif p1 = A2 and p2 = B2 and p3 = C2 then q = D2. Similarly, if p1 =An and p2 =Bn and p3 =Cn then q1 = Dn. Where An, Bn, Cn and Dn are the subsets defined by the corresponding membership functions. The Final step is where the linguistic results, generated after the application of fuzzy rules is converted back into numerical values by Centroid method.

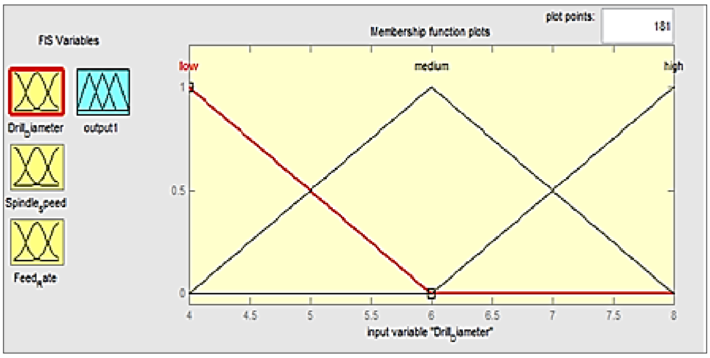
In our case, the Fuzzy Logic modeling is done using MATLAB software. The graphs of the membership functions for the input parameters versus output parameters are shown in Figure 10.



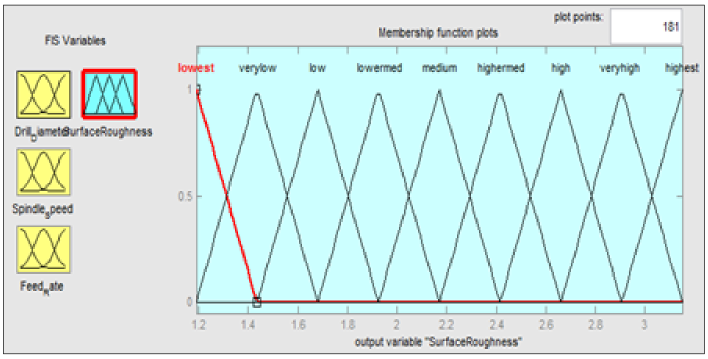
(i)



(ii)



(iii)



(iv)

Figure 10. Membership functions for (i) spindle speed, (ii) feed rate, (iii) drill diameter and (iv) surface Roughness

Figure 11 shows the closeness of the Experimental and Fuzzy modeled values. To further find the effectiveness of the model, R-squared test was done, and its value was found to be 96.6%. Figure 12 is the Rule viewer of our Fuzzy model. By changing the values of the input parameters, we will get the Fuzzy modeled output value of Surface Roughness from the rule viewer itself. Figure 13 is a plot of Fuzzy modeled values V/s Experimental Values.

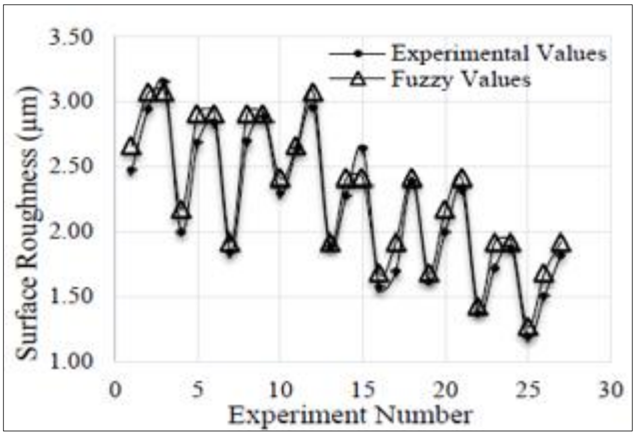


Figure 11. Fuzzy vs. experimental values of surface Roughness for each experiment

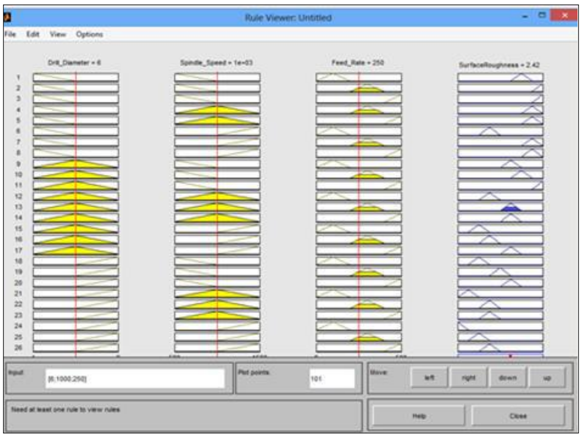


Figure 12. Rule viewer of the Fuzzy model

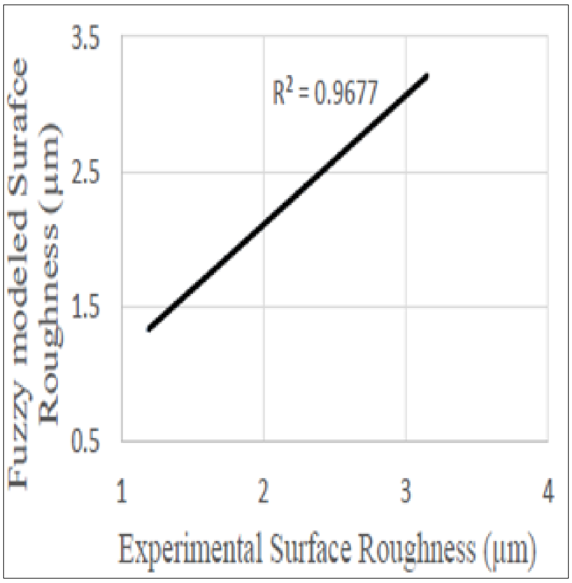


Figure 13. R^2graph for surface Roughness

3.5. Validation

To validate the regression model equation and the Fuzzy model, the surface roughness is calculated for specific values of drill diameter, spindle speed and feed rate. The calculated values are then compared with the measured values, which are obtained by measuring the surface roughness in newly drilled holes. Figure 14 shows the variation between the Regression modeled, Fuzzy modeled and Experimental values.

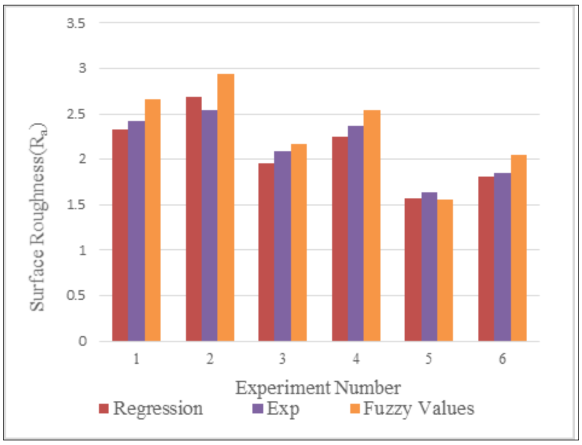


Figure 14. Comparison Chart between the Measured and Modeled Values

4. Conclusions

A hybrid polymer matrix composite has been fabricated by using natural silk and E-glass fiber reinforcements in an epoxy resin matrix. Taguchi's orthogonal array techniques was used to perform investigations on the surface roughness of the designed silk reinforced hybrid polymer composite matrix under the effects of varying spindle speed, feed rate and drill diameter at low, medium and high levels each.

1) To find the effect of the process parameters on the surface roughness, Minitab was used. The results of the effects of the drilling parameters are as follows:

• Decrease in surface roughness was observed with increase in drill diameter.
• Decrease in surface roughness was observed with increase in spindle speed.
• Increase in surface roughness was observed with increase in feed rate.

2) In regard to the effect of interaction of the parameters, it was found, according to the ANOVA analysis that

•Diameter of the drill and Spindle Speed
•Diameter of the drill and Feed Rate

had a significant impact on the surface roughness. However, the effect of interaction of spindle speed and feed rate was found to have a negligible effect on the surface roughness and should therefore be neglected.

2) To develop an empirical relation between the surface roughness and the process parameters regression modeling was done. The equation for average surface roughness (Ra) is:

$$Ra\ (\mu m) = 3.225 - 0.1555\ \alpha - 0.000516\ \beta + 0.002391\ \gamma - 0.000022\ \alpha\beta - 0.000155\ \alpha\gamma$$

where:

α denotes the drill diameter in mm, β denotes the spindle speed in rotations per min and γ denotes the feed rate in mm/min.

It was found that values of surface roughness generated by using the regression modeled equation was almost equal with the values obtained from the experiment. In order to quantify the effect of drilling parameters on surface roughness in a silk reinforced hybrid polymer composite matrix, this developed regression model can be used.

4) Fuzzy Modeling was done for the following case and the values obtained from the experiments were found to be extremely nearer to the values obtained from Fuzzy model. Further, an R-squared value of 96.6% was got for the experiment from which it was inferred that the Fuzzy prediction model can be used in the determination of Surface Roughness while drilling of Silk and E-Glass fiber Hybrid polymer composite.

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Manuscript received: 15.09.2020