

# Controlling Process Factors to Optimize Surface Quality in Drilling of GFRP Composites by Integrating DoE, ANOVA and RSM Techniques

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## Abstract

Polymer Matrix Composites are the preferred materials now a days and are used in all the fields of engineering because of its encouraging properties over traditional materials. Glass Fiber Reinforced Polymers (GFRP) is the materials that are used in the manufacturing of household appliances up to aircraft and automobile components. Drilling operation is the common machining operation used to make holes for the fasteners in the mechanical part assembly operations. The surface quality of the hole depends upon the drill machining conditions. The drill hole quality gets degraded because of inefficiency or wear of the drill tools to make holes that are dimensionally accurate and are reliable. The tool wear takes place due to improper machining conditions and wrong working procedures. The tool wear disturbs the structural stability of the composite laminates and virtually, the quality of drilled holes. The poor quality of drilled holes affects the proper assembling of the parts and the operational performance of the final product. The objective of this research work is to control the drill process factors through a systematic approach and to analyze their significance on the quality of machined surface while drilling GFRP composite laminates using High Speed Steel (HSS) twist drills. Optimized numbers of experiments were planned and executed using Design of Experiments (DoE). Full Factorial Design (FFD) of experiments was carried out to collect surface roughness data. A statistical model was established by applying Response Surface Methodology (RSM) technique, to calculate the impact of process parameters on the hole surface quality. The capability of the model is checked using Analysis Of Variance (ANOVA). The outcomes of ANOVA indicated that the most significant factor which influences the surface quality is the drill diameter followed by drill feed rate and drill spindle speed.

**Keywords:** ANOVA, DoE, Drilling, GFRP, RSM, Surface Quality

## 1. Introduction

### 1.1 Composite Materials

Composite material generally holds the combination of two or more physically distinct and mechanically separable materials. The behavior of the composite as a whole is higher and possibly exclusive in some specific reference to the properties of separable components. In

general, a composite material is composed of at least two components of which one is a bulk material called the matrix, and the other one is reinforcement material, which is usually referred as fiber material.

The main classification of composites is based on the type of matrix i.e., Polymer Matrix Composites (PMC), which use a polymer material as the matrix, and a range of fibers such as glass, carbon and aramid

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as the reinforcement or strengthening material. With the support of fiber material like silicon carbide, Metal Matrix Composites (MMC) use aluminium as the resin or matrix material. Ceramic Matrix Composites (CMC) uses the ceramic material as the matrix and generally reinforces it with either silicon carbide or boron nitride. The composites possess light weight, high strength to weight ratio, high tensile and flexural strength, good compression and impact strength, hold excellent rigidity and dimensional stability. Because of these advantages composites replace the conventional metals in aerospace, automobile, chemical, marine and electrical industrial applications.

## 1.2 Glass Fiber-Reinforced Polymer (GFRP) Composites

Fiber reinforced polymer composites are the generally used composite materials in aquatic and marine applications. The composite laminates include Fiber Reinforced Polymer Laminates (FRPL) and Fiber Metal Composite Laminates (FMCLs). Of these, with increased demand, Glass Fiber-Reinforced Polymer (GFRP) composites are being used in many industrial applications which include major industrial sectors, such as in automobile, aircraft, spacecraft and sporting goods. The GFRP composites gained popularity because of their light weight, high specific strength, high elastic modulus, high strength-to-weight and stiffness-to-weight ratios and excellent corrosion resistance, etc. Glass Fiber-Reinforced Polymer (GFRP) are used in fairings, passenger compartments, room doors and windows, bath room and wash room appliances due to their better mechanical properties.

## 1.3 Machining of Composites

The machining of composites is difficult and the mechanism involved in machining of composites is different from that of metals. Machining composite material is a tedious task owing to its anisotropy and heterogeneity nature, thermal sensitiveness and more importantly due to the abrasiveness of the fiber materials like carbon, glass etc<sup>1</sup>. Because of these, significant damage to the work piece occurs. This leads to the marginal wear rate of the cutting tools and ends up with the deterioration of the machined surface quality<sup>2</sup>. However, conventional machining operations like drilling, turning, milling and grinding can be carried out on composite materials through innovative tool design and operating conditions but, the machining cost

may shoot up. So, conventional machining techniques of composite machining still use HSS tools since they are economical and results in efficient machining<sup>1</sup>.

Among many kinds of machining approaches, drilling is considered as the complex machining operation since it involves the simultaneous rotational motion and reciprocating motion of the drill bit. Drilled holes are mainly used while assembling the different parts of mechanical component using fasteners. Sometimes improper fit or the slackness of the different parts may lead to failure of the assembly. The slackness or the loose fit of the parts may be due to the dimensional inaccuracy of the drilled holes. The dimensional inaccuracy is because of the selection of wrong machining procedures and wrong selection of cutting parameter values. The incorrect usage of machining parameters will lead to the tool wear and damage of the machined surface. So, controlling the machining parameters in order to improve the surface quality of drilled holes has traditionally received considerable research attention.

Apart from these, other problems such as, thermal softening of the tool as well as the work material, tool wear, tool damage etc., are the additional difficulties in drilling of composite materials. This could be owing to the heterogeneity and anisotropy of the material since the composite materials contain matrix and fibers which are normally soft and hard by nature respectively. Therefore the machining of such sophisticated composite materials needs a sound knowledge of metal cutting processes in order to achieve and retain the required dimensional accuracy and machining efficiency<sup>2</sup>. Rapid tool wear, poor surface finish on final components and the crack generation on the surface layer are some of the problems met during the composite machining<sup>3</sup>.

With regard to this the subsequent research works were carried out. Some of them are: Ogawa et al.<sup>4</sup> studied and tried to relate the surface roughness and the cutting force in drilling of small-diameter holes on GFRP. The researchers invented that the drill tool cutting edge has significant influence on the surface quality than the chisel edge of the drill. Surface finish or surface quality of the drilled holes play an important role in many product design circumstances such as parts that are subjected to fastener holes, fatigue loads, precision fits and assembly requirements. Therefore characterization of the surface quality signifies one of the most important features in manufacturing process. Tsao and Hocheng<sup>5</sup> have gauged the surface roughness in drilling of composite materials. The outcome of the research indicated that the feed rate

and spindle speed have more degree of significance and contribute most to the surface roughness.

In composite materials, a number of machining parameters affect the drilling machinability. The important machining parameters which affect the tool wear and surface roughness are: drill spindle speed, drill feed rate, drill diameter, chisel angle etc. Different researchers have studied the difficulties and the damages that occurred in drilling of GFRP and other composites. The investigators have mentioned and discussed about the difficulties that are encountered in the machining composite materials, through conventional machining techniques<sup>6-10</sup>. The research groups have also carried out damage analysis of the drilled hole surface and the tool surface and came to a conclusion that the drill feed rate, drill spindle speed, drill diameter and lip angle are the prominent machining parameters that affect the composite machinability. The fiber parameters like the fiber geometry, fiber angle, and thickness of the laminate are the parameters related to the material, which significantly influence the cutting tool damage, tool war and delamination in drilling of GFRP composites<sup>11-13</sup>.

So, from the above studies it is evident that to have an efficient assembly fit of mechanical component, the hole should be drilled precisely and should have to have a very good surface quality in order to have a strong mechanical assembly. Therefore this research work focuses on minimizing the roughness of drilled hole surface or improving the surface quality of the drilled holes by controlling the process parameters while machining GFRP composite laminates using uncoated HSS drills.

## 2. Experimentation Facts

### 2.1 GFRP Composite Fabrication

The composite material laminate used for the

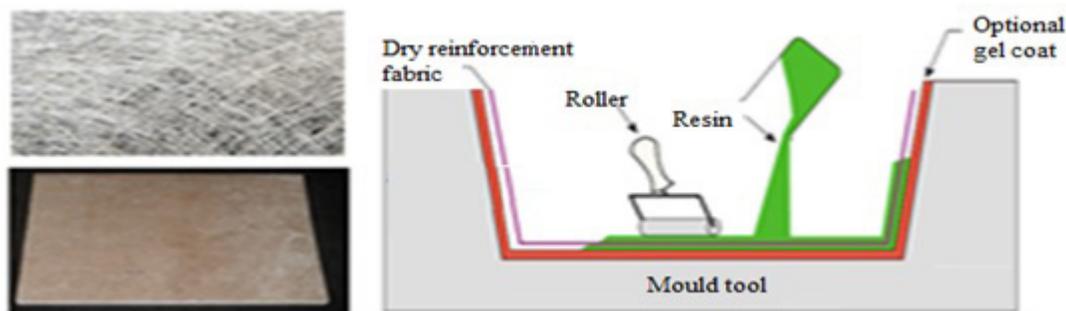


Figure 1. Fabrication of GFRP using hand layup.

experimental work was manufactured by means of hand-layup procedure. The S-glass fiber (15 microns diameter) mat with random fiber orientation was used as the reinforcement. The resin material was Isophthalic polyester resin and Poly Ether Ether Ketone (PEEK) was used as binder and hardener material. Hand lay-up technique was used for the GFRP laminate fabrication, followed by atmospheric curing. The thickness of the GFRP laminate was set to 10 mm and the fibre-weight fraction was set as 0.33 (Figure 1).

### 2.2 Experimental Setup

The holes were drilled on the GFRP composite laminates, by operating 3 - Axis Computerised Numerically Controlled Vertical Machining Centre (CNCVMC), shown in Figure 2. The locations of the holes are decided as per the design specifications of drill holes for fasteners<sup>7</sup>. 80 holes were drilled on each sample and the experiments were carried out for 2 replicates.

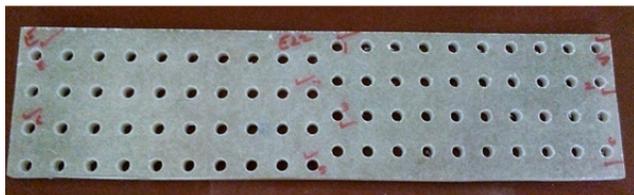


Figure 2. Vertical machining centre.

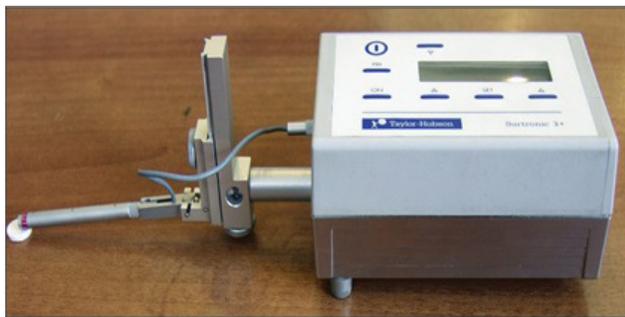
### 2.3 Experimental Procedure

Full Factorial Design of Experiments (DoE) was designed and the number of experimental run were found by

taking 3 factors and 3 levels (Table 1) i.e.,  $3^3 = 27$ . Each experimental run was replicated two times. 80 holes were drilled on each laminate (Figure 3). The center distance between the holes was calculated as per design specifications for fastening joints. The drilled surfaces were measured for the surface roughness using Taylor Hobson Surtronic 3+ surface roughness tester (Figure 4 and 5). For each experimental run, the average surface roughness of the 1<sup>st</sup>, 40<sup>th</sup> and 80<sup>th</sup> hole was measured. Each experimental run was replicated twice and the average surface roughness was calculated for reliability and accuracy of data (Table 2).



**Figure 3.** GFRP laminate with 80 holes drilled.



**Figure 4.** Taylor hobson surtronic surface roughness tester.



**Figure 5.** Taylor hobson surtronic surface roughness tester measuring the surface quality of the drilled hole of GFRP composites.

**Table 1.** Process factors and levels

| Symbols | Factors             | No. of Levels |         |         |
|---------|---------------------|---------------|---------|---------|
|         |                     | Level 1       | Level 2 | Level 3 |
| A       | Spindle speed (rpm) | 1200          | 1500    | 1800    |
| B       | Feed (mm/rev)       | 0.1           | 0.2     | 0.3     |
| C       | Drill diameter (mm) | 6             | 8       | 10      |

## 2.4 Response Surface Regression: Surface Roughness vs. Spindle Speed, Feed Rate and Drill Diameter

### 2.4.1 Analysis of Variance

#### Model Summary

| S        | R-sq   | R-sq(adj) | PRESS   | R-sq(pred) |
|----------|--------|-----------|---------|------------|
| 0.287835 | 95.47% | 91.54%    | 3.61829 | 85.78%     |

#### Regression Equation for surface roughness

$$\begin{aligned} \text{Surface roughness} = & - 4.59 + 0.00806 \text{ Spindle speed} \\ & - 10.43 \text{ Feed rate} + 0.780 \text{ Drill diameter} \\ & - 0.000003 \text{ Spindle speed} \\ & * \text{ Spindle speed} + 10.0 \text{ Feed rate} * \\ & \text{Feed rate} - 0.0229 \text{ Drill diameter} * \\ & \text{Drill diameter} + 0.00344 \text{ Spindle speed} \\ & * \text{Feed rate} + 0.000106 \text{ Spindle speed} \\ & * \text{Drill diameter} - 0.271 \text{ Feed rate} * \text{Drill diameter}. \end{aligned}$$

## 3. Results and Discussions

### 3.1 Analysis of Variance (ANOVA)

The surface roughness analysis was carried out on MiniTab software. The Analysis of Variance (ANOVA) table was generated after analyzing the surface roughness data (Table 3) using Response Surface Methodology. The data from the ANOVA table infers that the process factors i.e., Spindle speed, Feed and Drill diameter have significant influence on the response (surface roughness) since the P-value corresponding to each of these factor is  $< 0.05$  (corresponding to 95% confidence level). Also, there is no significant influence of interaction effect of the two process factors on the response since all the corresponding P-values are  $> 0.05$ . From the table it is clear that the drill diameter has more significant influence (75.76 %) on the response (surface roughness) followed by feed rate (8.34%) and spindle speed (7.57%). High  $R^2$  value (95.47%) confirms the reliability and accuracy of data collected.

### 3.2 Residual Plots

It can be seen from the Figure 6 that all the surface roughness data points lie close to the best fit line (mean line) on the normal plot. This denotes that the data are reliable and normal and a small deviance from the normality can be neglected. It is noticed that the residuals

**Table 2.** Experimental data for full factorial DoE

| Spindle speed (rpm) | Feed rate (mm/rev) | Drill diameter (mm) | Average Surface roughness |
|---------------------|--------------------|---------------------|---------------------------|
| 1800                | 0.1                | 6                   | 5.28                      |
| 1800                | 0.1                | 8                   | 6.79                      |
| 1500                | 0.2                | 10                  | 6.93                      |
| 1200                | 0.2                | 8                   | 5.12                      |
| 1200                | 0.1                | 8                   | 6.1                       |
| 1500                | 0.3                | 6                   | 4.7                       |
| 1500                | 0.3                | 10                  | 6.73                      |
| 1800                | 0.2                | 8                   | 6.39                      |
| 1200                | 0.2                | 10                  | 6.7                       |
| 1200                | 0.2                | 6                   | 4.57                      |
| 1500                | 0.1                | 8                   | 6.29                      |
| 1800                | 0.1                | 10                  | 7.18                      |
| 1500                | 0.2                | 8                   | 6.2                       |
| 1500                | 0.1                | 10                  | 7.93                      |
| 1200                | 0.3                | 6                   | 4.46                      |
| 1800                | 0.2                | 10                  | 7.01                      |
| 1200                | 0.1                | 10                  | 6.78                      |
| 1200                | 0.1                | 6                   | 5.04                      |
| 1500                | 0.1                | 6                   | 5.15                      |
| 1800                | 0.3                | 8                   | 6.02                      |
| 1500                | 0.2                | 6                   | 4.65                      |
| 1200                | 0.3                | 8                   | 4.69                      |
| 1200                | 0.3                | 10                  | 5.98                      |
| 1800                | 0.3                | 6                   | 4.73                      |
| 1800                | 0.2                | 6                   | 4.98                      |
| 1500                | 0.3                | 8                   | 6.1                       |
| 1800                | 0.3                | 10                  | 6.95                      |

**Table 3.** ANOVA table for surface roughness

| Source              | DoF       | Seq SS         | Contribution   | Adj SS  | Adj MS  | F-Value | P-Value |
|---------------------|-----------|----------------|----------------|---------|---------|---------|---------|
| Spindle speed       | 2         | 1.9273         | 7.57           | 1.9273  | 1.9273  | 23.26   | 0.0000  |
| Feed                | 2         | 2.1218         | 8.34           | 2.1218  | 2.1218  | 25.61   | 0.0000  |
| Drill diameter      | 2         | 19.2820        | 75.76          | 19.2820 | 19.2820 | 232.74  | 0.0000  |
| Spindle speed *     |           |                |                |         |         |         |         |
| Spindle speed       | 3         | 0.3902         | 1.53           | 0.3902  | 0.3902  | 4.71    | 0.401   |
| Feed * Feed         | 3         | 0.0600         | 0.24           | 0.0600  | 0.0600  | 0.407   | 0.407   |
| Drill diameter *    |           |                |                |         |         |         |         |
| Drill diameter      | 3         | 0.0504         | 0.2            | 0.0504  | 0.0504  | 0.72    | 0.446   |
| Spindle speed *     | 3         |                |                |         |         |         |         |
| feed                |           | 0.1281         | 0.5            | 0.1281  | 0.1281  | 0.61    | 0.231   |
| Spindle speed *     |           |                |                |         |         |         |         |
| Drill diameter      | 3         | 0.0481         | 0.19           | 0.0481  | 0.0481  | 1.55    | 0.58    |
| Feed*Drill diameter | 3         | 0.0352         | 0.14           | 0.0352  | 0.0352  | 0.58    | 0.523   |
| Error               | 17        | 1.4084         | 5.53           | 1.4084  | 1.4084  | 0.42    |         |
| <b>Total</b>        | <b>41</b> | <b>25.4517</b> | <b>100.00%</b> |         |         |         |         |

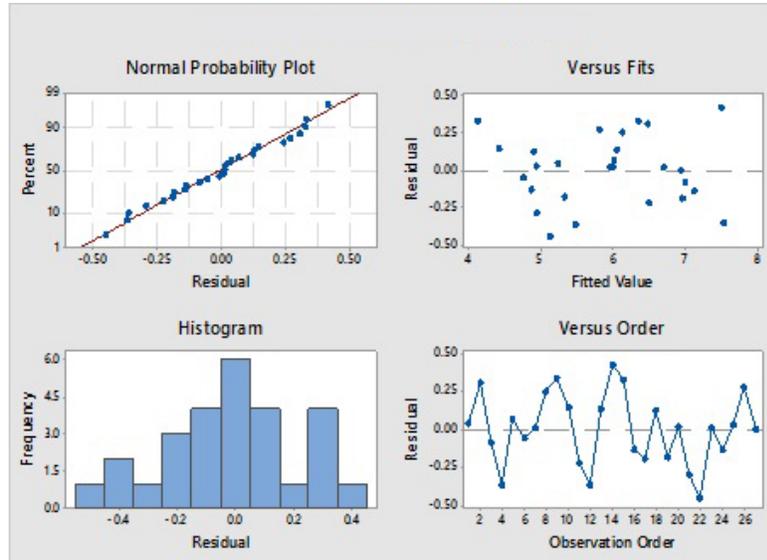


Figure 6. Residual plot from machining parameters.

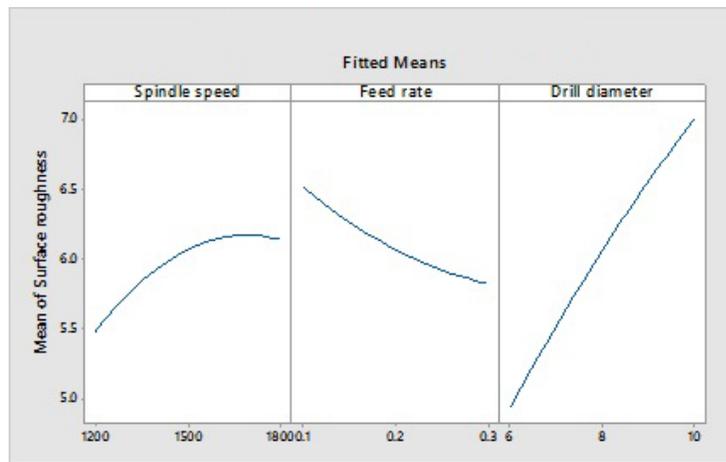


Figure 7. Main effect plot for surface roughness.

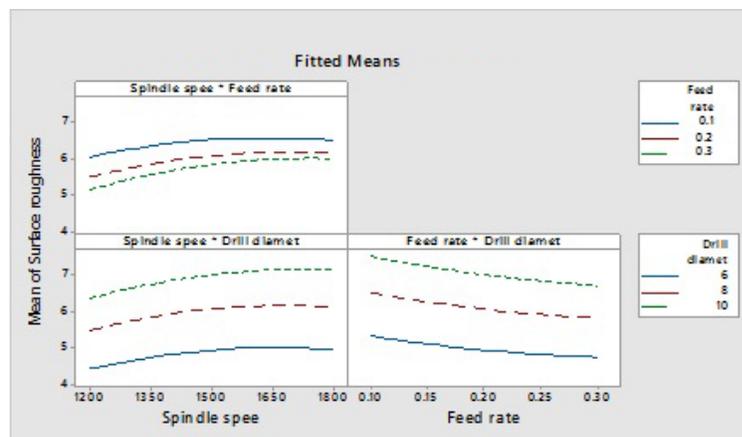


Figure 8. Interaction plot for surface roughness.

fall in a straight line, which implies that the errors are normally distributed. In addition, Fits and Order plots revealed that there is no evident of any pattern or unusual structure present in the data. These linearity, normality and residuality indicate that the data considered for the regression analysis are reliable and thus the regression model thus generated is validated.

The main effect plot (Figure 7) shows that the slope of the drill diameter is much more than that of feed rate and spindle speed which implies that the surface roughness varies significantly due to a small change in the drill diameter. This is also supported by the more percentage contribution of the drill diameter on the response (75.76%) compared to that of the percentage contribution of the feed rate (8.34%) and spindle speed (7.57%) respectively.

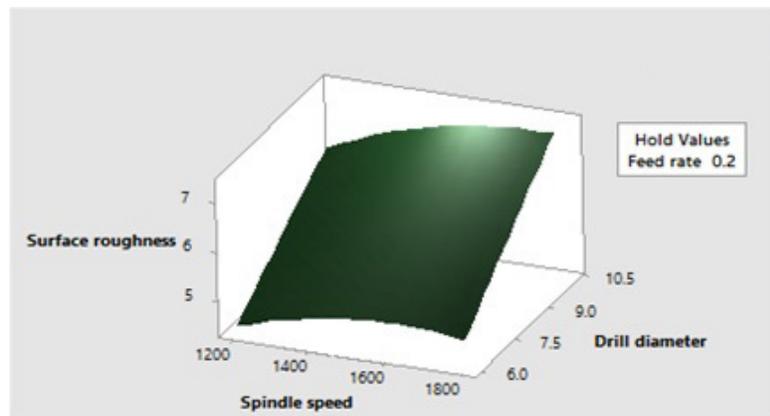
From the interaction plot (Figure 8), it is seen that the graphs corresponding to all the interactions parallel to each other which in other words infers that there is

no significant influence of interaction of the machining parameters on the surface roughness in drilling GFRP laminates using uncoated HSS drills.

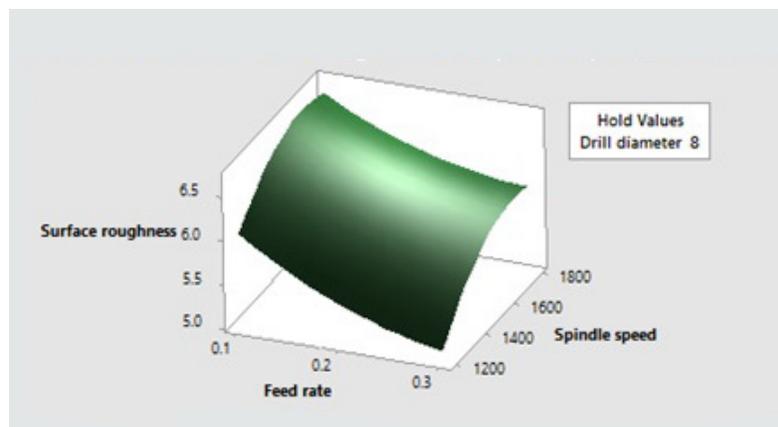
### 3.3 Surface Plots

Increase in spindle speed results in increased frictional force between tool and work piece, which will have a direct impact on the increase in surface roughness (Figure 9). Increase in temperature at the tool work piece/ tool chip interface zone with the increase in the spindle speed will initiate different modes of tool wear which also contributes to the increased surface roughness, as the drilling progresses<sup>12</sup>. The heat generated at the cutting region will also contribute to the increase in the tool wear as well as increased surface roughness (Abrasion and Adhesive wear).

Increase in drill tool feed reduces the surface roughness (Figure 10). The reason could be increase in feed results



**Figure 9.** Surface plot of surface roughness vs spindle speed and drill diameter.



**Figure 10.** Surface plot of surface roughness vs spindle speed and feed rate.

in reduced cutting time, which in turn reduces the tool wear and reduces the surface roughness of the drilled hole. The increase in temperature at the contact zone due to increased feed rate may lead to thermal softening of the cutting edge of the drill as well, and as a result, reduces the fiber damage<sup>14</sup>, which might have reduced the surface roughness. Apart from all these, there is a probability that the drills might have come across less dense fiber structure and also the fibers which are oriented in the direction of cutting, which might have reduced the surface roughness of drilled holes.

From the graph (Figure 11), it is seen that the surface roughness of the drilled hole increases with increase in the diameter. The reason could be as the cutting velocity is directly proportional to diameter and as the diameter increases, cutting speed increases and increase in the cutting speed, increases the cutting force, which leads to increased friction between tool and work piece<sup>12</sup>. The increased frictional force will lead to increased surface roughness. When the drill diameter increases the surface

contact between the tool and the drill increases, this leads to increase the frictional coefficient and hence increase in the surface roughness.

### 3.4 Process Factor Optimization

Figure 12 shows that the optimum machining conditions to get minimum surface roughness of the drilled holes on the above said GFRP composite laminate. Under the specified machining conditions, for a laminate thickness of 10 mm, Spindle speed = 1200 rpm; drill feed = 0.28 mm/rev and drill diameter = 6 mm, are considered as the optimum drill process parameters which give a minimum surface roughness value of 4.13 which support the previous discussions.

## 4. Conclusion

- Main effect plot graph informs that there is influence of main factors (Cutting Speed, feed and drill diam-

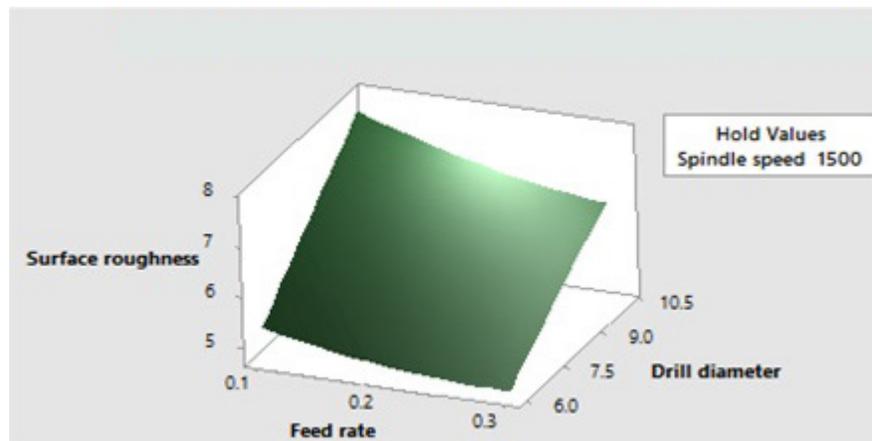


Figure 11. Surface plot of surface roughness vs feed rate and drill diameter.

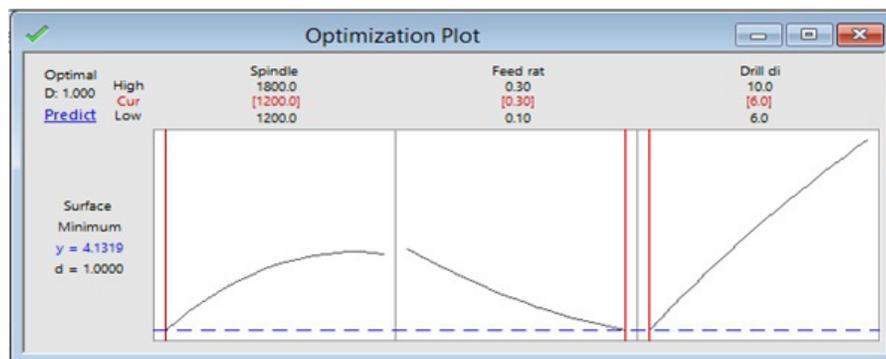


Figure 12. Optimisation plot of surface roughness.

- eter) on the surface roughness of GFRP composite while drilling with HSS tool at 95% confidence level.
- There is no impact of the interaction effect of the process factors on the surface roughness.
  - The  $R^2$  value of flank wear is above 95% (i.e., 95.47%) which says that the regression model provides excellent relationship between the independent variables (factors) and the response (surface roughness).
  - Residual plots show the good linearity, normality and residuality for the response, which indicate that the data considered for the regression analysis are reliable and the regression model thus generated is validated.
  - ANOVA results indicate that the surface roughness is influenced by drill diameter (75.76%), drill spindle speed (8.34%) and drill feed (7.57%) respectively.
  - Surface graph indicates that the surface roughness of the drilled holes increase with increase in the spindle speed and increase in drill diameter but decrease with increase in feed rate.
  - Optimization plot says, for getting minimum surface roughness (i.e., 4.13), the optimum machining parameters are drill diameter = 6 mm, drill feed = 0.3 mm/rev and cutting speed = 1200 rpm (i.e., cutting speed = 22 m/min).

## 5. References

1. Tsao CC. Experimental study of drilling composite materials with step-core drill. *International Journal of Materials and Design*. 2008; 29:1740–4.
2. Lubin G. *Hand Book of Composites*, Van Nostrand Reinhold. 1982.
3. An S-O, Lee E-S, Noh S-L. A study on the cutting characteristics of glass fiber reinforced plastics with respect to tool materials and geometries. *J Mater Process Tech*. 1997; 68:60–7.
4. Ogawa K, Aoyama E, Inoue H, Hirogaki T, Nobe H, Kitahara Y, Katayama T, Gunjima M. Investigation on cutting mechanism in small diameter drilling for GFRP (thrust force and surface roughness at drilled hole wall. *Compos Struct*. 1997; 38:343–50.
5. Tsao CC, Hocheng H. Evaluation of thrust force and surface roughness in drilling composite material using Taguchi analysis and neural network. *J Mater Process Tech*. 2008; 203:342–8.
6. Hocheng H, Tsao CC. Comprehensive analysis of delamination in drilling of composite materials with various drill bits. *J Mater Process Tech*. 2003; 140:335–9.
7. Davim JP, Reis P, Conceicao AC. Drilling Fiber Reinforced Plastics (FRPs) manufactured by hand lay-up: Influence of matrix (Viapal VUP 9731 and ATLAC 382–05). *J Mater Process Tech*. 2004; 155–156:1828–33.
8. Davim JP, Reis P, Conceicao AC. Experimental study of drilling Glass Fiber Reinforced Plastics (GFRP) manufactured by hand lay-up. *Composites Science and Technology*. 2004; 64:289–97.
9. Khashaba UA. Delamination in drilling GFR-thermoset composites. *Compos Struct*. 2004; 63:313–27.
10. Mohan NS, Kulkarni SM, Ramachandra A. Delamination analysis in drilling process of Glass Fiber Reinforced Plastic (GFRP) composite materials. *J Mater Process Tech*. 2007; 186:265–71.
11. Sedlacek J, Slany M. Analysis of delamination in drilling of composite materials. *M M Science Journal*.
12. Sathish Rao U, Rodrigues LLR. Minimising tool wear in drilling of polymer composites using statistical techniques. *Elixir International Journal of Mechanical Engineering*. 2015; 79:30253–9.
13. El-Sonbaty I, Khashaba UA, Machaly T. Factors affecting the machinability of GFR/epoxy composites. *Compos Struct*. 2004; 63:329–38.
14. Palanikumar K. Experimental investigation and optimization in drilling of GFRP composites. *Measurement*. 2011; 44:2138–48.