Available online at www.elixirpublishers.com (Elixir International Journal)

Mechanical Engineering

Elixir Mech. Engg. 79 (2015) 30253-30259

ISSN: 2229-712X

Minimising flank tool wear in drilling of polymer composites using statistical techniques

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ARTICLE INFO

Article history:

Received: 10 December 2014;

Received in revised form:

20 January 2015;

Accepted: 5 February 2015;

Keywords

Fiber Reinforced Composites,

Response Surface Methodology,

Machining parameters,

HSS drill, Flank wear,

Glass fibers, Tool wear.

ABSTRACT

In recent days, the Fiber Reinforced Composites have replaced many of the engineering components and the composite material manufacturing area is experiencing substantial growth. FRC's also have replaced materials used in the civil construction area, sporting goods, automobile and aircraft parts, and boat and ship hulls. The composites in general, offer many advantages over homogenous materials like high strength to weight ratio, less weight, structural and dimensional stability, corrosion and wear resistance. Because of the anisotropy in nature, machining composite materials with drilling and milling is a complex process. Especially for composites, these operations were found to be costly affair as the cutting tool wears out quickly as it comes in contact with the hard resin and abrasive reinforcement material during machining. Thus the quality of the drilled hole in composites depends on the performance of the drill tool. The performance of the drill depends on the magnitude of respective process parameters. Hence the present investigation focusses on the study of effect of the machining parameters such as spindle speed (1200, 1500 and 1800 rpm), feed rate (0.1, 0.2 and 0.3 mm/rev), drill diameter (6, 8 and 10mm) on HSS drill tool flank wear in the drilling of Glass Fiber Reinforced Polyester (GFRP) composites. The present work also aims to optimize the machining parameters in drilling minimize the flank tool wear. The experiment is designed using full factorial design of experiments. Measure of land width was used to assess the Flank wear of HSS drill. To optimize the drill flank wear, the process parameters are optimized applying Response Surface Methodology (RSM). Mathematical model was generated by through regression analysis by developing a Regression equation for flank wear of HSS drill.

Introduction

Composite Materials are extensively used in various fields of engineering applications because of their superior mechanical and tribological properties. Though composites are manufactured in single mould, secondary operations such as drilling, turning, sawing, routing and grinding, etc are required in order to give dimensional accuracy and surface finish during assembly. Drilling is one of the most important metal-cutting operations performed on the composite. It constitutes nearly 33% of all machining operations [3]. Generally in aerospace, aircraft, and automobile industries for drilling operation on composite materials, HSS twist drills are used. It is observed that poor quality of the hole on products leads to rejections of components estimated to about 60% which proved costly [4].

Tool wear depends on the thrust force and torque developed during drilling which depends on drill size, feed rate and spindle speed. Literatures shows that tool breakage, tool wear are strongly dependent on cutting force. The change in drill tool geometry results in lesser material removal rate and generates poor machined surface [5]. Tool wear leads to lowering strength of the cutting edge, increase of tool forces as well as power consumption, increase in cutting temperatures, reduction in surface finish, loss of dimensional accuracy and productivity [6]. It has been estimated that a good cutting tool can increase cutting speeds from 10-50% and reduces machine down time by10-40% [14].

Drill tool wear is a progressive and a slow phenomenon when compared with the failure of the cutting tool and cutting edge damage and breakage, which is catastrophic. The drill tool wear starts as soon as it begins its operation, and increases its rate rapidly once it becomes blunt or dull. In common, the temperature and heat distribution during machining operation, pressure difference, friction, and the stress distribution at the tool–work interface zone influence the wear patterns [7].

A number of research works reveal that the outer corner wear as the major type of wear in drilling. But practically, the significant type of wear in drilling are flank and crater wear [8]. Many investigations say that the tool wear in drilling occurs due to abrasion of tool material at lower cutting speeds and due to the atomic diffusion mechanism for cutting tools operating at higher cutting speeds. The atomic diffusion carries the tool material along with the chip material at the tool work interface. This will also lead to significant reduction in tool life [15].

In general, the composite materials are difficult to machine Because of inhomogeneity and anisotropy nature, and because of the abrasive nature of reinforcements. So, damage to the work piece is significant and tool will high wear at higher rate [9]. The alloyed tool steel material can withstand hardness at higher temperatures and are found to be better than high carbon and low alloy steels. Due to this observation, the research is focused on HSS drilling on composite materials.

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Response Surface Methodology:

Response Surface Methodology, RSM, was developed by Box and Wilson in the 1950's. It uses experimental designs and statistical techniques for construction of models and optimisation. This methodology has been applied to a wide range of fields, including those of agriculture, manufacturing and scientific research.

RSM usually involves three stages: (1) design of experiments; (2) response surface modelling through regression, and (3) optimisation. This latter stage is an example of an area where genetic algorithms are beginning to provide an alternative to traditional methods. Genetic algorithms are search algorithms for optimisation based on natural selection and genetics. This approach to optimisation in RSM has been used more and more in recent years.

RSM is a combination of experimental designs and statistical techniques for empirical model building and optimisation. RSM was originally developed for the model-fitting of physical experiments by Box and Draper [1, 2] and later extended to other fields. RSM is very useful for modelling and analysis where a response of interest is influenced by several variables and the objective is to optimise this response. By conducting experiments and the posterior application of regression analysis a model of the response variable of interest is obtained. The real relationship between the response and the independent variables is unknown. For that reason, the first step in RSM is to find an approximation of the true functional relationship between the response and the independent variables. The observedresponse , can be written as a function of the independent variables , y= $x_1,x_2,x_3,……..x_k$ as follows:

, y= f($x_1,x_2,x_3,……..x_{k)}$ +ε where ε is a random error.

Plotting the expected response, a surface known as the response surface is obtained. As remarked previously, the form of *f* is unknown and can be complicated. This is why an approximation is needed. Frequently, a low-order polynomial function is employed in some region. If the response is well-modelled with a linear function, the approximation function is a first-order model. If the system has curvature, a higher-order polynomial model must be used, such as a quadratic model.

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}\sum \beta_{ij} x_i x_j + \varepsilon$$

Almost all RSM problems use one of these models. However, it is unlikely that a polynomial model will be a good approximation of a true functional relationship over the entire space of the independent variables; but for small regions polynomial models work reasonably well.

When RSM is used, the objective is not only to investigate the response over the space, but also to locate the region where the response reaches its optimum or near-optimum value. By studying the response surface model, the combination of factors (*i.e.,* values of the independent variables) which gives the optimal response can be obtained [4].

GFRP composite fabrication:

The composite material specimens used for experimental work were manufactured using hand-layup procedure. The S-glass fiber mat with random fabric was used for the reinforcement. The glass fiber mats were cut according to the mould size. Isophthalic polyester resin is used as the matrix and Araldite was used as binder and hardener material. Hand lay-up technique was used as the fabricating method followed by curing under normal atmospheric conditions. The laminate thickness was set to 10mm and the fiber- volume fraction of the specimen was set at 0.33 (Figure 1).

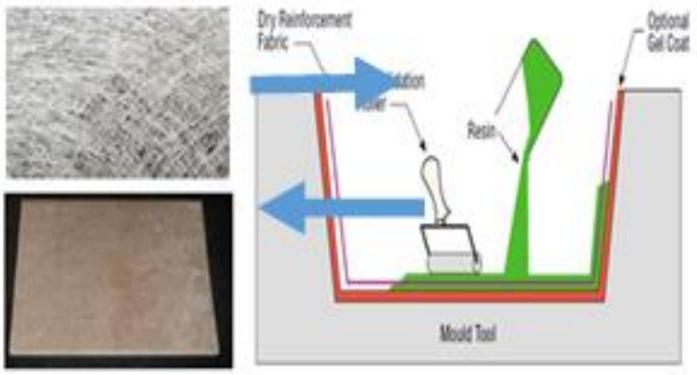


Figure 1. Fabrication of GFRP using hand layup

Material Specifications :

- Matrix : Isophthalic Polyester resin
- Fiber : S - Glass fiber
- Fiber diameter : 15 microns
- Fabric type : Laminated
- Fiber Orientation : Random
- Density : 1.6 g/mm^3
- Fiber weight Fraction : 33%
- Laminate thickness : 10mm
- Laminate Manufacturing Technique : Hand Lay up with atmospheric curing.

Experimental details

The holes were drilled on the GFRP laminates accordingly. The machining operations were carried out on 3 - Axis CNC Vertical Machining Center (VMC), AMS Spark machine, shown in Figure 3. The location of the holes (shown in Figure 3) are decided based on the design specifications of drill holes for fasteners [7]. 80 holes were drilled on each sample and the experiments were carried out for 3 replicates.

Figure 2. Laminated GFRP sample

Experimental Procedure:

The experiments were designed using Full Factorial design of experiments. The total number of experiments to be carried out were found by considering 3 drill process factors and their 3 levels as shown in Table2. The total number of experiments were 33 = 27 and each experimental run was replicated three times to ensure reliability and accuracy of data (flank wear measurement) collection. The drill bits are cleaned using acetone before and after the drilling operation in order to remove the atmospheric contaminations and impurities accumulated during the machining operation. The flank wear was measured by considering the difference in the land width of the drill before and after the machining. Tool maker's microscope was used for the measurement purpose and the average flank wear of the three replicates was considered for the data analysis.

Table 1. Drill tool specifications

Drill No.	1	2	3
Tool diameter	6 mm	8 mm	10mm
No. of Flutes	2	2	2
Point angle	118º	118º	118º
Helix angle	30º	30º	30º
Flute length	67 mm	77 mm	87 mm
Shank type	Cylindrical	Cylindrical	Cylindrical

Figure 3. HSS drills (6,8and 10mm)

Table 2. Factors and their levels

Symbols	Factors	No. of Levels		
		Level 1	Level2	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

Figure 4. GFRP composite drilling operation on VMC

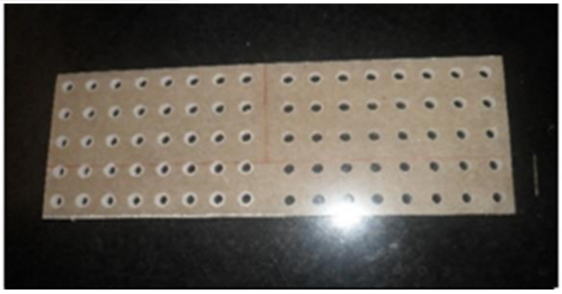


Figure 5. Composite laminate with 80 holes drilled

Table 3. Experimental design values

Spindle speed (rpm)	Cutting speed (m/min)	Drill feed (mm/rev)	Drill diameter (mm)	Average Flank wear (mm)
1800	34	0.1	6	0.320
1800	45	0.1	8	0.316
1500	47	0.2	10	0.291
1200	30	0.2	8	0.249
1200	30	0.1	8	0.257
1500	28	0.3	6	0.221
1500	47	0.3	10	0.284
1800	45	0.2	8	0.313
1200	37	0.2	10	0.278
1200	22	0.2	6	0.235
1500	37	0.1	8	0.297
1800	56	0.1	10	0.347
1500	37	0.2	8	0.271
1500	47	0.1	10	0.301
1200	22	0.3	6	0.216
1800	56	0.2	10	0.331
1200	37	0.1	10	0.268
1200	22	0.1	6	0.301
1500	28	0.1	6	0.291
1800	45	0.3	8	0.285
1500	28	0.2	6	0.254
1200	30	0.3	8	0.218
1200	37	0.3	10	0.256
1800	34	0.3	6	0.232
1800	34	0.2	6	0.291
1500	37	0.3	8	0.253
1800	56	0.3	10	0.315

Results and Discussion

Response Surface Regression: Analysis of variance for Flank wear

Table 4. ANOVA table for flank wear measurement

Source	DoF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Spindle speed	1	0.011300	35.25%	0.011300	0.011300	156.55	0.000
Feed	1	0.010225	31.90%	0.010225	0.010225	141.65	0.000
Drill diameter	1	0.005000	15.60%	0.005000	0.005000	69.27	0.000
Spindle speed * Spindle speed	1	0.000280	0.87%	0.000280	0.000280	3.88	0.065
Feed * Feed	1	0.000060	0.19%	0.000060	0.000060	0.83	0.374
Drill diameter * Drill diameter	1	0.000193	0.60%	0.000193	0.000193	2.67	0.121
Spindle speed * feed	1	0.000001	0.00%	0.000001	0.000001	0.02	0.893
Spindle speed * Drill diameter	1	0.001008	3.15%	0.001008	0.001008	13.97	0.002
Feed*Drill diameter	1	0.002760	8.61%	0.002760	0.002760	38.24	0.000
Error	17	0.001227	3.83%	0.001227	0.000072		
Total	26	0.032055	100.00%				

Model Summary	S	R-sq	R-sq (adj)	PRESS	R-sq (pred)
	0.0084961	96.17%	94.15%	0.0034919	89.11%

Table 5. Coded coefficients for flank wear measurement

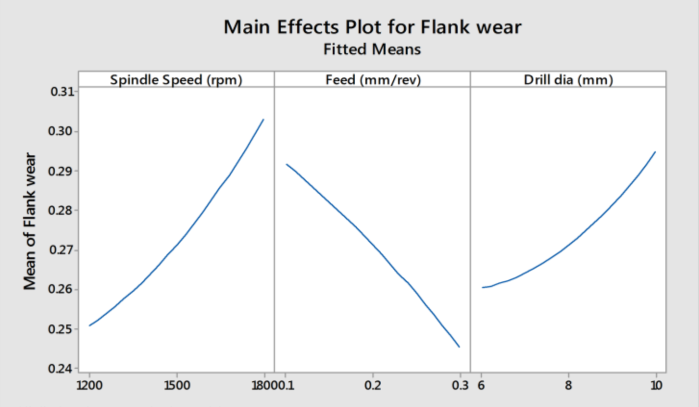
Term	Coef	SE Coef	T-Value	P-Value
Spindle speed	0.02506	0.00200	12.51	0.000
Feed	-0.02383	0.00200	-11.90	0.000
Drill diameter	0.01667	0.00200	8.32	0.000
Spindle speed * Spindle speed	0.00683	0.00347	1.97	0.065
Feed * Feed	-0.00317	0.00347	-0.91	0.374
Drill diameter * Drill diameter	0.00567	0.00347	1.63	0.121
Spindle speed * Feed	-0.00033	0.00245	-0.14	0.893
Spindle speed * Drill diameter	0.00917	0.00245	3.74	0.002
Feed * Drill diameter	0.01517	0.00245	6.18	0.000

Table 6. Regression coefficients for flank wear

Term	Coefficients
Constant	0.678
Spindle speed (m/min)	0.000264
Feed rate (mm/rev)	-0.702
Drill dia (mm)	-0.0524
Spindle speed* Spindle speed	0.000000071
Feed *Feed	-0.317
Drill dia * Drill dia	0.001417
Spindle speed * Feed	-0.000011
Spindle speed * Drill dia	0.000015
Feed * Drill dia	0.0758

Regression (mathematical) Equation for flank wear measurement

Flank wear (Fw) = 0.678-(0.000264*spindle speed)-(0.702*feed)-(0.0524*drill diameter)+(7.1e-8*spindle speed*spindle speed)- (0.317*feed*feed) +(0.001417*drill diameter*drill diameter)-(0.000011*spindle speed *feed)+(0.000015*spindle speed*drill diameter)+(0.0758*feed*drill diameter)



All displayed terms are in the model.

Figure 6. Main effect plot for flank wear

From the ANOVA table it is clear that the flank tool wear is influenced by drill Spindle speed (35.25%), followed by drill diameter (31.90%) and drill feed (15.60%).

Surface Plots:

From the surface graph, the following observations are done.

1. Increase in spindle speed results in increased frictional force between tool and work piece, which will increase the temperature at the tool work piece / tool chip interface zone. These will have a direct effect on the flank wear which gradually increases with the increase in the spindle speed (Figure 8). Since HSS tool is used which does not absorb heat will also contribute to the increase in the tool wear at higher cutting speed (Abrasion and Adhesive wear).

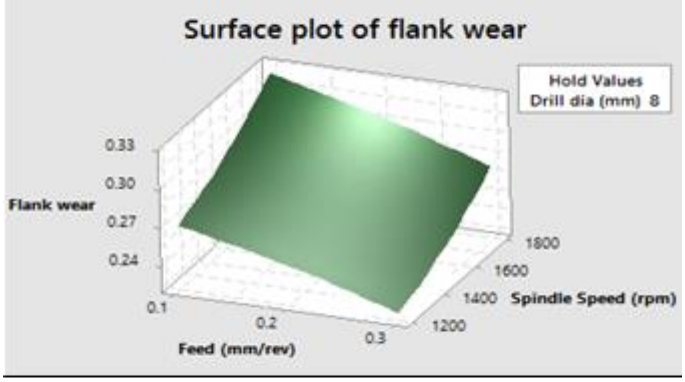


Figure 8. Surface plot of Flank wear vs Feed rate, Spindle speed

2. Increase in tool feed results in reduced cutting time, which in turn reduces the propagation of flank wear. In addition to this, due to low coefficient of thermal expansion of FRP, the wear rate decreases in the initial stage. The tool wear reduces with increase in the feed rate (Figure 9). Since the composite is a heterogonous material, when the feed rate is given, due to the impact of the drill on the work piece, the fibers that come across the twist drill are pulled out in the tool traverse direction, which will reduce the inter laminar strength. This reduction in inter laminar strength will lead to irregular, abrupt material removal from the surface of the drilling hole. This will make the surface of the tool not to come in contact with the actual (theoretical) contact area of the work material which will reduce the tool wear. One more reason could be the formation of cracks in the composite due to the entry of the drill into the work piece. These cracks will entrap air within them during machining which will reduce the temperature at the tool chip interface zone. This reduced temperature could be one of the reasons for reduction in tool wear.

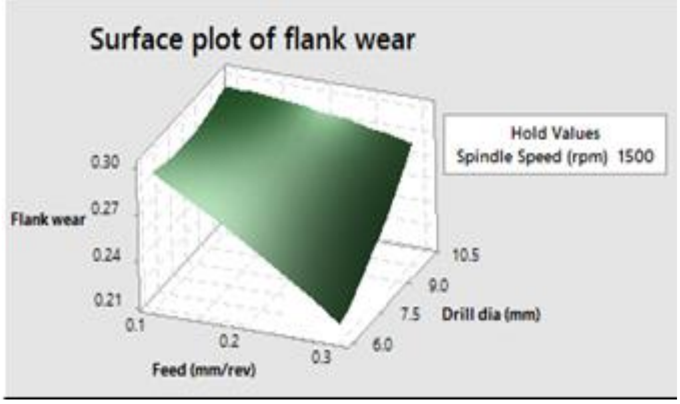


Figure 9. Surface plot of Flank wear vs Feed rate, Drill diameter

3. From the graph (Figure 10), it is seen that the flank tool wear of the drill bit increases with increase in the diameter. The reason could be as the cutting velocity is directly proportional to diameter and as the velocity increases, the cutting force increases and it lead to increased friction between tool and work piece. The increased frictional force will lead to increased flank wear. When the drill diameter increases, the surface contact between the tool and the drill increases, which will increase the frictional coefficient and hence increase in the tool wear. The wear mechanism associated with this is adhesion. The temperature generated during drilling might make the debris to stick on to the wear land in the form of built up edges which could be one of the reasons for increase in tool wear at higher cutting speed. From the graph the rate at which the wear rate increases with respect to the change in diameter.

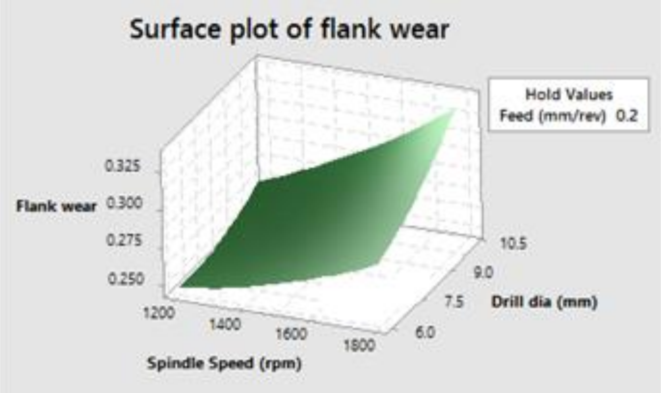


Figure 10. Surface plot of Flank wear vs Spindle speed, Drill diameter

Contour plots:

1. A contour based interaction analysis between the drill diameter and drill feed is shown in Figure 11. The drill diameter for this analysis was set at 8mm. From this plot, it is observed that the minimum flank wear can be obtained at low feed rates and lower diameter values. From the contour plot it is seen that the minimum flank wear (<0.25mm) can be obtained at a feed rate ranging from 0.22 - 0.30 mm/rev and at a drill diameter ranging from 6 - 8.25mm.

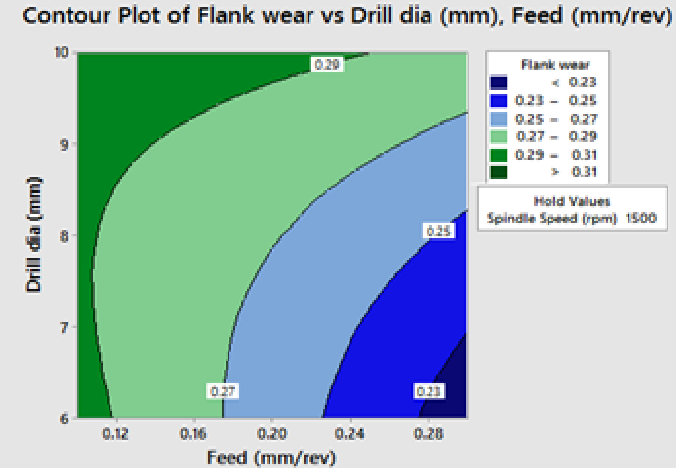


Figure 11. Contour plot for flank wear vs drill diameter and feed rate

2. The interaction analysis between the drill diameter and cutting speed can be seen with the help of a contour plot as shown in Figure 12. The feed rate for this analysis was set at a 0.2mm/rev. From the contour plot it is observed that the flank wear can be minimized at higher spindle speed and lower diameter values. From this plot, it is clear that the minimum value for the flank wear (<0.25mm) is seen at a drill diameter

ranging from 6 – 7.8 mm and at spindle speed ranging from 1200-1270 rpm.

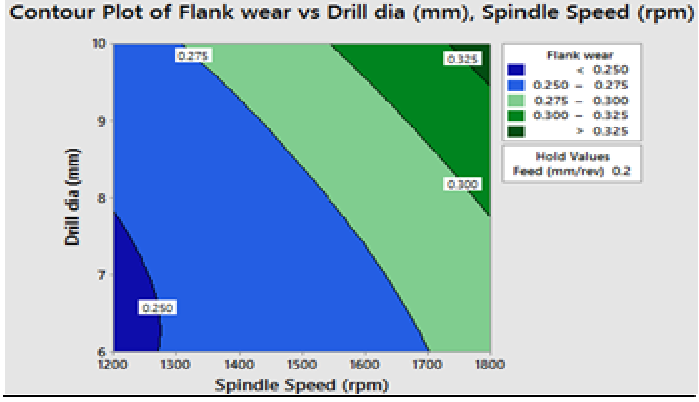


Figure 12. Contour plot for flank wear vs drill diameter and spindle speed

A contour based interaction analysis between the drill speed and drill feed can be seen in Figure 13. The spindle speed for this analysis was set at a 1500 rpm. From this plot, it is observed that the lowest flank wear can be obtained at low feed value and high spindle speed value. It is seen that the lowest flank wear (<0.25mm) can be obtained at a feed rate ranging from 0.20 – 0.30 mm/rev and at spindle speed ranging from 1200 -1550 rpm.

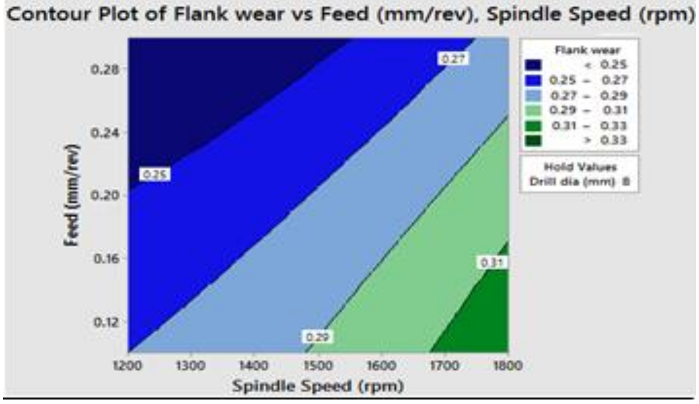


Figure 13. Contour plot for flank wear vs spindle speed and drill feed

Process Factor Optimisation:

Figure 14 shows that the optimum machining conditions to get minimum flank wear on the above said PMC material. Under the specified machining conditions, for a laminate thickness of 10mm, Spindle speed =1200 rpm; drill feed = 0.3mm/rev and drill diameter =6mm, gives the optimum flank wear which support the previous discussions.

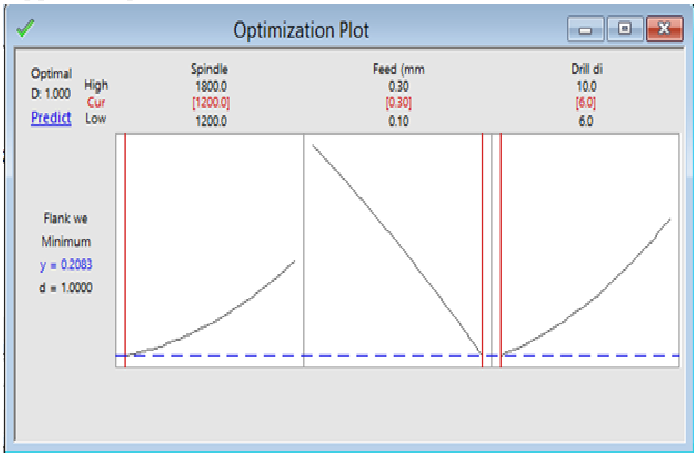


Figure 14. Factor optimization plot for minimum Flank tool wear

Conclusions:

1. RSM result informs that there is influence of main factors (Cutting Speed, Feed and Drill diameter) on the drill flank wear during the drilling of GFRP composite with HSS tool at 95% confidence level.
2. Main effect plot trend and ANOVA results indicate that the flank wear is influenced by drill feed (35.25%), drill spindle speed (31.90%) and drill diameter (15.60%)
3. The R^2 value of flank wear is 96.17% which means that the regression model provides excellent relationship between the independent variables (factors) and the response (Flank wear).
4. The interaction plot concludes that there is not much effect of the interaction effect of process factors on drill flank wear
5. Surface graph of flank wear clearly indicates that the flank wear of drill increases with increase in the spindle speed and the drill diameter but reduces with increase in feed rate.
6. From the interaction plot it is seen that, for a given speed, minimum flank wear can be seen by increasing the drill feed rate and the drill diameter.
7. It is also observed for the interaction plot that, for a given diameter of the drill bit, the flank wear can be minimized by increasing the drill feed rate and by reducing the spindle speed.
8. From the interaction plot it is found that for a given drill feed rate, the flank wear can be reduced for the lower range of spindle speed and diameter.
9. The approximate range of process factors which can be set to improve the performance of the drill during machining of above configured GFRP composite can be Spindle speed : 1200-1300rpm; Drill feed : 0.2 – 0.3 mm/rev; Drill diameter: 6-8 mm.
10. Optimization plot says, for getting minimum tool wear, the optimum machining parameters are drill diameter=6mm, drill feed=0.3mm/rev and spindle speed= 1200rpm.

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