

Hole quality assessment in drilling process of basalt/epoxy composite laminate subjected to the magnetic field

Farhad Najarian¹, Roozbeh Alipour², Abbas Razavykia³, and Ali Farokhi Nejad^{3,*}

¹ Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor 81310, Malaysia

² Department of Mechanical Engineering, Mahshahr Branch, Islamic Azad University, Mahshahr, Iran

³ Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Turin, Italy

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Abstract. Drilling is one of the most important machining processes which are currently carried out on fiber-reinforced composites. These composites possess a layered structure and different properties through their thickness. When drilling such structures, internal defects like delamination occur, caused by the drilling forces and their uneven distribution among the plies. The current study investigates the effect of magnetic field on drilling process of basalt/epoxy composite laminate in order to reduce delamination and the thrust force and improve some hole quality parameters i.e. roughness and cylindricity. A comparison is made between the responses for both normal drilling and drilling with applying a magnetic field. For this purpose, after finding the best combinations of normal drilling parameters, magnetic field is applied to the different configurations of solenoids on the setup of the drilling process. The results highlighted that using different magnet solenoids on the top and the bottom of drilling zone reduces the delamination and can obtain better roughness and cylindricity with lower damage.

Keywords: Drilling process / magnetic field / basalt/epoxy composite / thrust force / surface roughness

1 Introduction

Due to owning lightweight and flexibility characteristics, the use of fiber-reinforced composites is widely extending in aerospace fields and driven by the developments in manufacturing technologies, which have made the production process more cost effective. This extensive application rises from the excellent customizable mechanical properties while being much more lightweight than metallic alloys [1–3]. For instance, some reports show that composite materials are used extensively on new generation aircraft, even as important structural components e.g. horizontal stabilizer, vertical fin, fuselage floor beams, fuselage, Wings, the central wing, fuel tank and other primary load-bearing structures [4]. Since components made from the fiber-reinforced composites are generally integrated into a mechanical assembly, drilling is the most frequently encountered machining process in the production plan to provide fixing features like holes [5].

Delamination, debonding and fiber pull-out are the critical aspect of the drilling process of fiber reinforced, since it can cause failure in use and components with such

defects are generally cast off. In addition, these defects, which generally occur at the onset and the end of drilling process [6], are not routinely detectable visually and hence, some expensive NDT inspections e.g. ultrasonic and acoustic emission is indispensable [7–10]. On the other hand, joining fiber-reinforced composite laminates to other components of structures is not avoidable [11], and bolt joining efficiency and quality depend critically on the quality of drilled holes [5]. Several drilling operations are widely employed to create riveted and bolted joints during assembly process of laminates with other parts. For rivets and bolted joints, precise holes need to be drilled in the parts to guarantee enough joint strength and precision. Nonetheless, some particular characteristics of laminates like non-homogeneous, anisotropic, high abrasive and hard reinforced fibers, result in them difficult to drill [12,13]. Also, it is reported that the most effective parameter during drilling induced the abovementioned defects is thrust force which depends on material properties, feed rate, and cutting speed [14,15]. As well, some researches focused on the effect of backup force to reduce the delamination defect e.g. using a backup plate support [16–19]. However, it provides a constant force and adjusting the force around defected zone needs a complex design.

* e-mail: ali.farokhi@polito.it

Basalt fiber-reinforced polymer composites BFRPs are natural based materials that are more environment-friendly than glass and carbon-based composite. BFRPs have higher strength in comparison with E-glass material; however, they have similar cost [20–23]. The promising potential for chemical stability, thermal and electrical resistance makes BFRPs as a superseded option for face sheet laminate composites [24]. However, the presence of imperfections, or non-homogeneous nature in the hybrid laminate composites, makes the delamination and debonding as one of the most common possible defects during drilling of BFRPs.

There are several studies that have contributed to improving the quality of drilling results. For instance, Naohiko Sugita et al. proposed a design of a drill tool with a shape that suppresses burrs and delamination during the drilling of composite materials. Different tool shapes, such as tip, groove, land, were determined, and a nick shape that cuts off chips and reduces heat generation is adopted. Results showed that by using these type of tools, the delamination reduces remarkably [25]. The general review of drilling-induced delamination for composite laminates can be observed in [26]. Browsing this recent reference, it can be realized that most of researches focused on analyzing only the total thrust and torque generated during drilling or separately the forces caused by the chisel edge and cutting lips by drilling with or without pilot hole [27–31]. However, a part of studies suggested that it is possible to explore the effect of magnetic field on drilling operation to obtain a better set of hole quality characteristics. For instance, the results of drilling gray cast iron and malleable cast iron in dry machining condition with HSS drills during the drilling under the magnetic field revealed that presence of the magnetic field significantly reduced the wear rate and intensity of magnetization [32]. Similarly, a relationship between the magnetic field and accuracy of the drill hole under the strength of magnetic field and polarity has been reported [33]. The magnetic field applies a damping force to the drill bit, which decreases the tool vibration and hence, improves tolerance [34]. Therefore, if the vibrated or misalignment tool crosses the magnetic field solenoid, the phenomenon of magnetic force starts to stabilize the tool in center of solenoid [35]. As the matter of fact, magnetic field is utilized as an active backup force leading to reduction in the delamination effect. However, to optimize usage of magnetic field the configuration of solenoids and number of them need to be investigated [6,14,36].

The present study investigates the effect of magnetic field on drilling process of basalt/epoxy composite laminate in order to reduce delamination and the thrust force and improve some hole quality parameters i.e. roughness and cylindricity. To aim this goal, after finding the best combinations of normal drilling parameters, magnetic field is applied to the different configurations of solenoids on the setup of drilling process. Thus, the position of applied magnetic field for more reliable drilling condition for drilling of the basalt composite plate is reported.

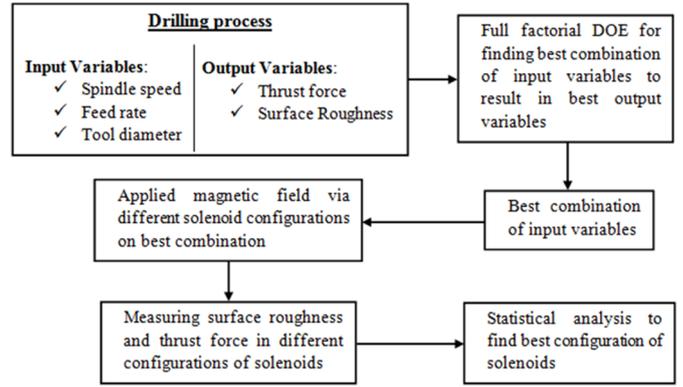


Fig. 1. Research methodology overview.

2 Methods and procedures

The research procedure of this study is divided into two parts: (1) finding the best combination of input variables of composite drilling under normal condition (without magnetic field) and (2) realizing best configuration of solenoids during applying magnetic field on composite drilling process to reach best possible hole quality. Figure 1 summarizes the overview of research methodology used in this study. Detail explanations of different steps are described in the following sections.

2.1 Theoretical estimation of thrust force

By changing the electric current orientation the magnetic field direction can also be changed. This is an advantage to apply non-contact distribution load on the top and down composite layers in order to avoid delamination and debonding. Moreover, the drill bit will be maintained in center of rotational axis and will bring better roundness and cylindricity. Figure 2 illustrates the schematic view of applied magnetic field on a composite laminate subjected to drilling process.

During a drilling process, a critical thrust force exists in which delamination and/or unfavorable hole quality characteristics may occur. Figure 3 shows a physical model of delamination which is based on the mode I [37] in fracture mechanics. As it is shown, the drill bit applies a force on the last laminate layer so that it bends downward.

In this case, equation (1) expresses the theoretical thrust force in the absence of magnetic field or any backup force [38,39].

$$F^* = \pi \left[\frac{8G_{IC}Eh^3}{3(1-\nu^2)} \right]^{1/2}, \quad (1)$$

where G_{IC} , E , ν and h are the critical crack propagation energy, module of elasticity, Poisson's ratio and the remained layers thickness, respectively. However, the thrust force in presence of magnetic field can be calculated

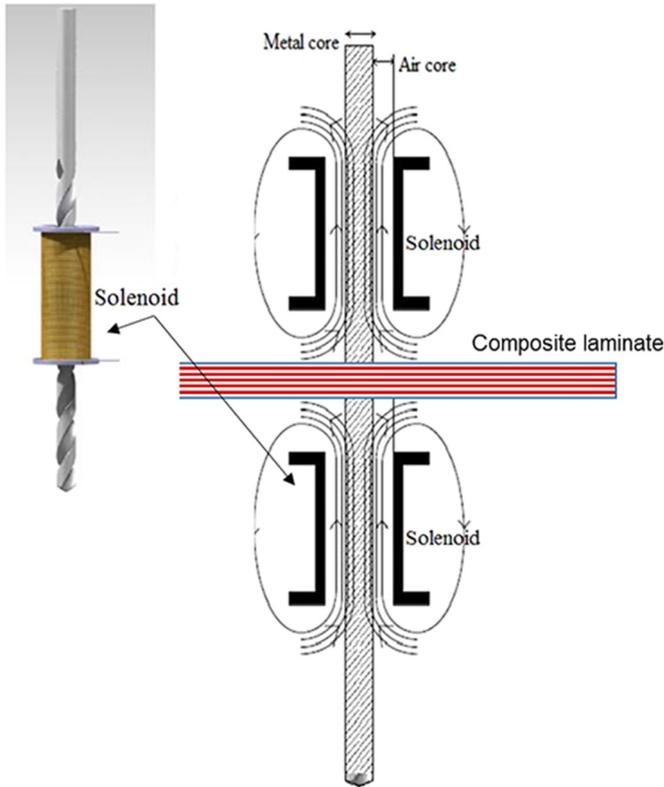


Fig. 2. Schematic view of magnetic field on drilling process.

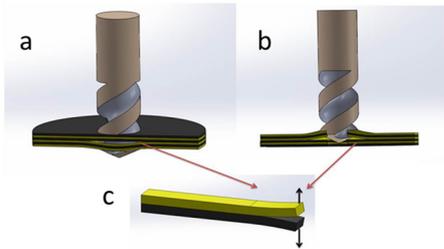


Fig. 3. Schematic representation of delamination (a), peel up delamination (b), push out delamination (c) equivalent mode I fracture due to delamination.

through equation (2) [14].

$$F_B^* = F^* \cdot \sqrt{\frac{1}{(1 - \gamma^2) - 2\gamma^2(1 + \xi)^2} S^2 - \gamma^2(1 + \xi)^4 S^4}, \quad (2)$$

where $\xi = F_B/R$, $\gamma = (b-c)/c$, $S = c/a$ are the delamination-projected distances from center of drill tool. Figure 4 indicates the mentioned parameters during drilling process.

2.2 Experiments without magnetic field

The composite laminate was fabricated from woven prepreg basalt with 60% fiber volume fraction. The

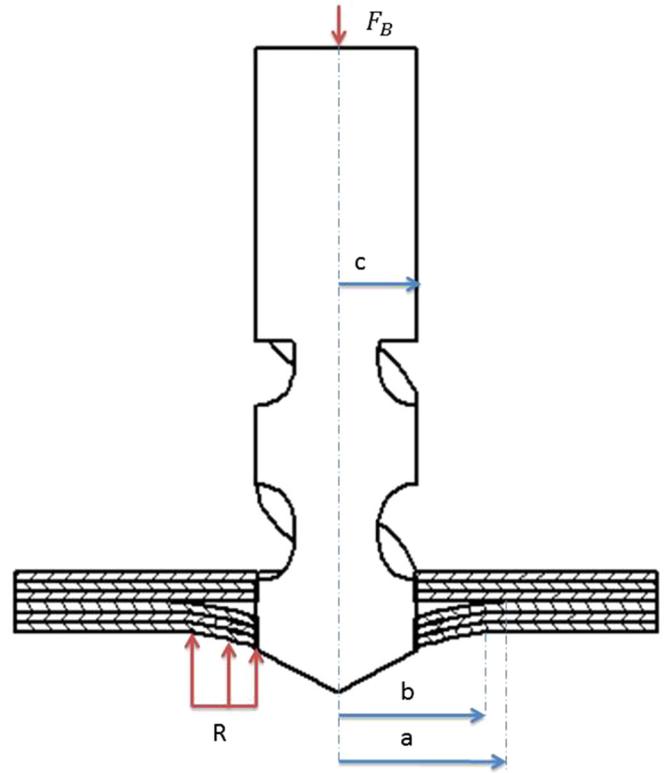


Fig. 4. Effective parameters in presence of back up force based on circular plate model.

Table 1. Mechanical properties of 24 plies $[0/90]_{12s}$ basalt/epoxy.

Property	Symbol	Value
Young's modulus	E_{bending} (GPa)	4.4
Bending stress	σ_{bending} (MPa)	129
Fracture energy	G_{IC} (kJ/m ²)	8.5
Density	ρ (kg/m ³)	1700
Poisson's ratio	ν_{12}	0.29

laminate thickness was 8 mm including 24 plies $[0/90]_{12s}$. The samples were cut into 80×80 mm with a diamond saw. After sample preparation based on ASTM D3171-99-G, the resin of three samples was burned off and the volume fractions of the fabricated samples with $\pm 2\%$ were controlled. Table 1 shows the material properties of basalt/epoxy material used in this study [40].

In the first step, the samples were drilled without magnet in order to identify the best machining condition. Spindle speed, feed rate and drill bit size were chosen as the drilling process factors. Three different spindle speeds, 1000, 1500 and 2000 RPM were set on 3-axis CNC machine and three different feed rates, 50, 100, and 150 mm/min were examined. To measure the drilling force, the machine was equipped with a Kistler 9441B piezoelectric dynamometer. Two different twist drill bit sizes; 4 and 5 mm

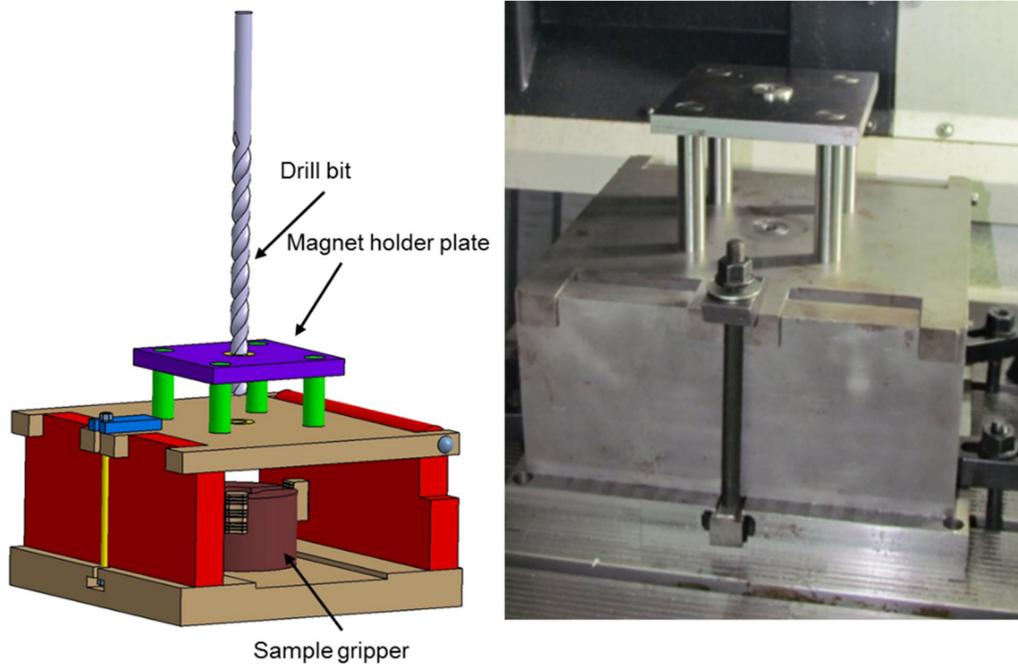


Fig. 5. Setup of experiment in the absence of magnet.

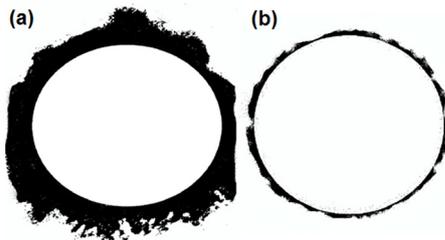


Fig. 6. Result of ultrasonic C-scan for different samples with spindle speed 1200 rpm and feed rate 100 mm/min (a) without magnet (b) with magnet solenoid.

diameter were used. To characterize the best combination of drilling factors in the absence of magnetic field, 18 experiments were conducted. After investigation of best combination, it was repeated for verification. This verification test was implemented for both drill bit sizes and the best condition was selected to investigate the magnetic backup force effect. A schematic of the experimental setup in the absence of magnet is shown in Figure 5.

After finishing the drilling process, the delamination area was measured with C-scan machine with 0.25 mm resolution scanning bridge. In this study, the images with 100×100 pixels were obtained in the scanning process. Figure 6 compares two scanned images between (a) with and (b) without magnet samples. In order to measure the surface roughness of each sample a Zeiss surface profile meter machine was used. The mean surface roughness value for all test was $0.72 \mu\text{m}$ with 0.015 standard deviation. In order to measure the cylindricity of drilled holes a stationary roundness meter was utilized.

Table 2. Magnet solenoids specifications.

Solenoid No	Number of turning	Magnet length (mm)	Wire diameter (mm)	Maximum Tesla capability
Solenoid 1	2500	90	0.55	1
Solenoid 2	2000	55	0.55	1

2.3 Experimental setup equipped by magnetic field

To investigate the effect of magnetic field, a couple of magnet solenoids with a different number of turning wire were fabricated. Table 2 shows the magnet solenoids specifications. The magnet solenoids were fixed to the top and bottom of a drilling fixture and the sample was clamped inside of the fixture. The magnetic field activated during the drilling process, and it turned off after finishing the process immediately. The values for ξ were 0.1, 0.15, and 0.2 which can be reached by changing the magnet spool diameter. Moreover, the γ was depending on the magnetic force and the number of applied magnetic fields. A power supply with 24 V voltage and maximum 5 A current were used to provide the magnetic field. Figure 7 illustrates the setup of experiment for drilling composite plate with magnetic field. For roughness measurement, the Zeiss surface meter was used.

2.4 Design of experiments in the absence of magnetic field

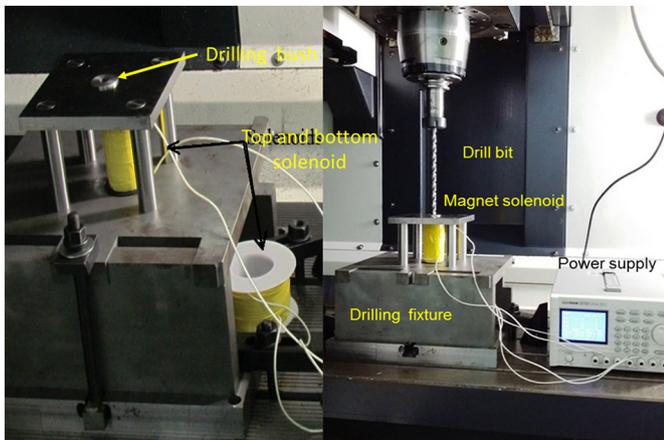
Regarding the guidelines introduced by Montgomery, the influential parameters can be distinguished as controllable

Table 3. Design summary.

Factor	Name	Unit	Type	No. of levels	Low	Mean	High
A	Spindle speed	RPM	Numeric	3	1000	1500	2000
B	Feed rate	mm/min	Numeric	3	50	100	150
C	Tool diameter	mm	Categorical	2	4		5

Table 4. Analysis of variance table for surface roughness.

Source	Sum of squares	DoF	Mean square	<i>F</i> -value	<i>p</i> -value	
Model	1.93	6	0.32	4.70	0.0131	Sign.
A	0.65	1	0.65	9.56	0.0102	Sign.
B	0.52	1	0.52	7.62	0.0185	Sign.
C	0.72	1	0.72	10.54	0.0078	Sign.
AB	0.020	1	0.020	0.29	0.5993	
AC	0.013	1	0.013	0.20	0.6672	
BC	8.33e-04	1	8.33e-04	0.012	0.9141	
Residual	0.75	11	0.068			
Cor Total	2.68	17				
Std. Dev.	0.26		R-squared		0.7195	
Mean	5.87		Adj. R-squared		0.5665	
CV %	4.46		Pred. R-squared		0.3302	
			Adeq. precision		7.872	

**Fig. 7.** Setup of experiment to apply the magnet force during the drilling process.

and uncontrollable (Noise) factors [33,41]. Based on conducted investigations, the most important parameters that affect the drilling process of basalt/epoxy composite laminate in order to reduce delamination and the thrust force are spindle speed (RPM), feed rate (mm/min) and tool diameter (mm). The factors and their level are tabulated in Table 3.

Thrust force and surface roughness were measured as responses and empirical models were subsequently presented to predict the response factors. Based on the

multilevel full factorial design, the design comprised two factors at three levels and one categorical factor at two level resulting eighteen experiment trials.

3 Results and discussion

3.1 Statistical analysis of factors affecting surface roughness

Based on ANOVA table (Tab. 4), spindle speed (factor A) and feed rate (factor B) and tool diameter (factor C) are found to be significant as *p*-value is less than 0.05 at 95% confidence. R-squared (R^2) shows how accurate the model predicts the response values or measures the amount of variation around the mean, lower deviation from 1 is more desirable which in this case a value of 0.7195 is fairly acceptable. The predicted R^2 of 0.3302 is in reasonable agreement with the adjusted R^2 of 0.5665 as the difference between them is less than 0.2 [42]. Signal to noise ratio is presented by adequate precision, which compares the range of the predicted value at the design points to the average prediction error, and the desirable ratio is greater than 4 that in this analysis is 7.872.

Figure 8 shows single-variable effect on surface roughness drilled hole. Lines with negative slopes indicate that increasing that factor would reduce the surface roughness; the opposite is true as well. The value of the slope is a measure of how significant the factor is.

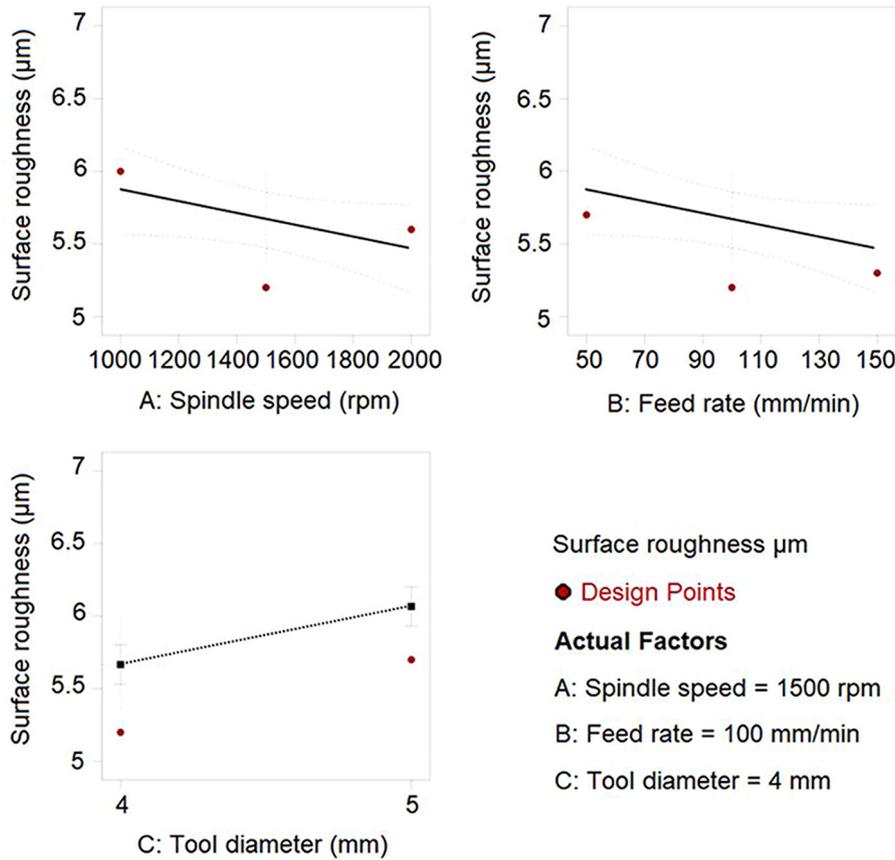


Fig. 8. Effect of each single variable.

Therefore, the higher spindle speed the better surface finish and higher feed rate results in lower surface roughness.

Empirical models are presented in two different forms using coded or actual terms. The equation based on coded terms assigns +1/−1 levels to each independent process variable and encourages the prediction of responses for given levels of each parameter [43]. The following equations were driven as final empirical models; coded terms (Eq. (3)).

$$\begin{aligned} \text{Roughness} = & 5.87 - 0.23 \times A - 0.21 \times B \\ & - 0.20 \times C + 0.05 \times AB - 0.03 \times AC \\ & - 8.33e - 03 \times BC. \end{aligned} \quad (3)$$

3.2 Statistical analysis of factors affecting thrust force

The significant drilling process that affect the thrust force are spindle speed (factor A), feed rate (factor B) and tool diameter (factor C) as well as interaction of spindle speed and tool diameter (AC) regarding to ANOVA Table 5. R-squared is equal to 0.9741 which deviates from one by 0.0259; which fairly measures the amount of the variation around the mean estimated by the model. The predicted R-squared by the value of 0.9196 and adjusted R-squared of 0.96 are in reliable conformance to each other as the difference of them is less than 0.2. Adequate precision larger than 4 is desirable as is 27.574 in this analysis.

Figure 9 illustrates the effect of single-variables on thrust force. All single variables have positive effect of thrust force as they increase, thrust force increase. Final empirical models were driven to estimate thrust force in coded terms (Eq. (4))

$$\begin{aligned} \text{Thrust force} = & 92.17 + 4 \times A + 2.42 \times B + 4.83 \times C \\ & + 1.50 \times A \times C + 0.083 \times B \times C. \end{aligned} \quad (4)$$

3.3 Effect of feed rate

Figure 10a shows the variation of thrust force with respect to different feed rate while there was no magnetic force. Moreover, Fig. 10b illustrates the magnitude of roughness for different feed rates. Comparison between different feed rates and spindle speeds show that the best machining condition for 4 mm drilling tool was 1500-rpm spindle speed and 100 mm/min.

3.4 Effect of critical thrust force

Figure 11 illustrates the critical thrust force with magnetic field by changing the different levels of ξ and γ . It can be seen that increasing the magnet force will increase the thrust force. In other word, when the magnet force reaches

Table 5. Analysis of variance table for thrust force.

Source	Sum of squares	DoF	Mean square	F-value	p-value	
Model	709.67	6	118.28	69.08	<0.0001	Sign.
A-Spindle speed	192.00	1	192.00	112.14	<0.0001	Sign.
B-Feed rate	70.08	1	70.08	40.93	<0.0001	Sign.
C-Tool diameter	420.50	1	420.50	245.60	<0.0001	Sign.
AB	0.000	1	0.000	0.000	1.0000	
AC	27.00	1	27.00	15.77	0.0022	Sign.
BC	0.083	1	0.083	0.049	0.8294	
Residual	18.83	11	1.71			
Cor Total	728.50	17				

Std. Dev.	1.31	R-squared	0.9741
Mean	92.17	Adj. R-squared	0.9600
CV %	1.42	Pred. R-squared	0.9196
		Adeq. precision	27.574

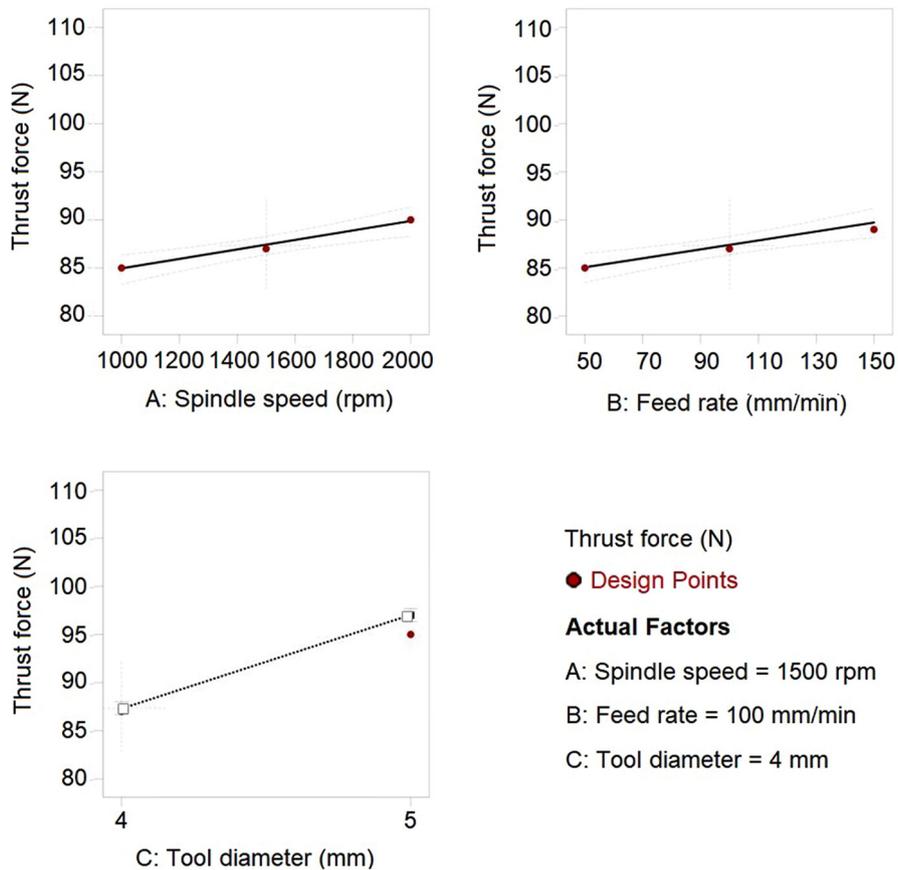


Fig. 9. Effect of each single variables.

drilling force the critical thrust force can be increased more than two times rather than without magnet force condition. The higher thrust force rate will control the delamination area in a small region but the feasible condition for the backup force should be considered.

However, the magnet backup increases the machining process regarding minimum delamination area. In addition, changing the magnet spool diameter will provide different magnitude of ξ but this number was less effective rather than γ values.

3.5 Effect of magnet position

The magnet position is the other effective parameter in the composite drilling process. Figure 12 shows the variation of delamination area at different magnetic force levels those applied with different magnet solenoid position. In this study, delamination area was measured from top and bottom side of each sample and the maximum number was considered. Moreover, when two magnet solenoids were used 70% of force applied from bottom solenoid and 30% was from the top one. Figure 13 compares the delamination

area for different cases with magnetic backup and without back up force. Using magnetic field reduced the delamination area 28–36% in different cases. It can be seen that implementing the lower magnet solenoid is the best option to reduce the delamination area.

Figure 14a and b shows the roughness and cylindricity for different cases, respectively. The results show that the cylindricity and roughness for the cases equipped with magnetic backup increased more than 46% and 20%, respectively. It can be seen that the cylindricity highly depends on top magnet. Moreover, the top magnet solenoid helps to lowest run-out error for deeper holes. In addition, the roughness can be improved by using dual magnet solenoid. In the other word, it can be expected that dual magnetic field provides the lowest delamination area regarding the best roughness and minimum cylindricity.

Table 6 displays the results of drilling composite laminates with and without magnetic field in terms of drilling properties. Comparing the results, it is realized that the worst case is occurred when 5 mm drill bit is used without magnetic field. It can be said that when there is no magnetic field the surface roughness can be reached to 5.7 μm whereas when the magnetic field is applied on both side of laminate, it can be reduced to 4.3 μm . By changing the size of drill bit the value of surface roughness can be varied. The other drilling properties such as cylindricity, delamination and thrust force are also worst while there is no magnetic field applied on 5 mm drill bit. This results show that, the effect of magnetic field on the center axis of rotation may effect the cylindricity of the hole by reducing the vibration of drill bit and maintaining the drill tool along the rotational axis. Controlling the vibration of drill tool also will have an effect on the surface roughness improvement. Also, reduction of thrust force by applying magnetic field on the top and lower layer relieves the stress in each layer and will control the crack propagation through the layers. These advantages reduce the delamination area significantly. The non-contact distributed load

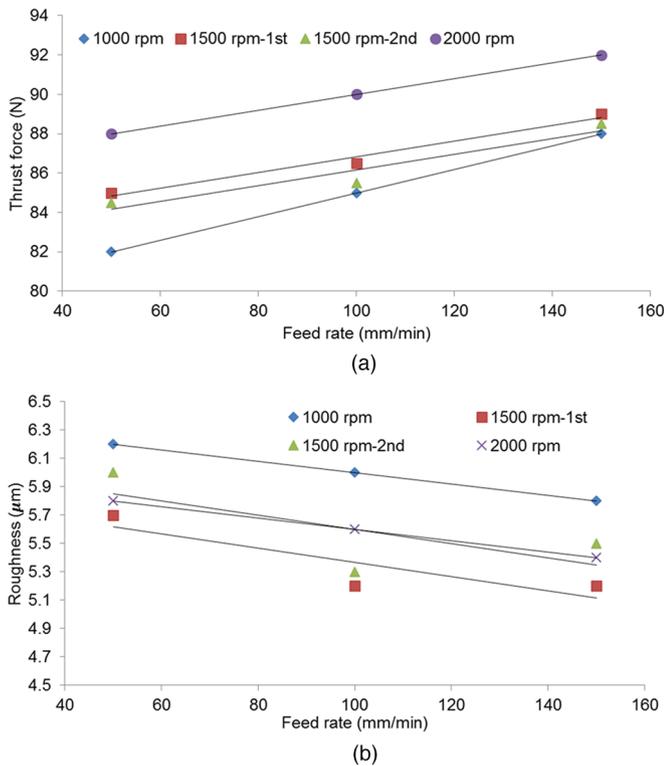


Fig. 10. Variation of (a) thrust force (b) roughness with respect to feed rate in different spindle speed.

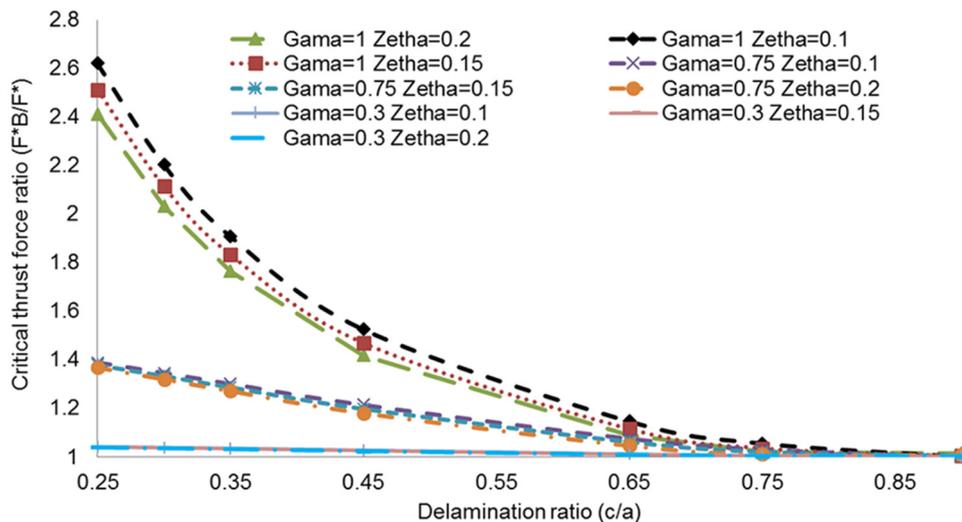


Fig. 11. Critical thrust force variation in different values of ξ and γ .

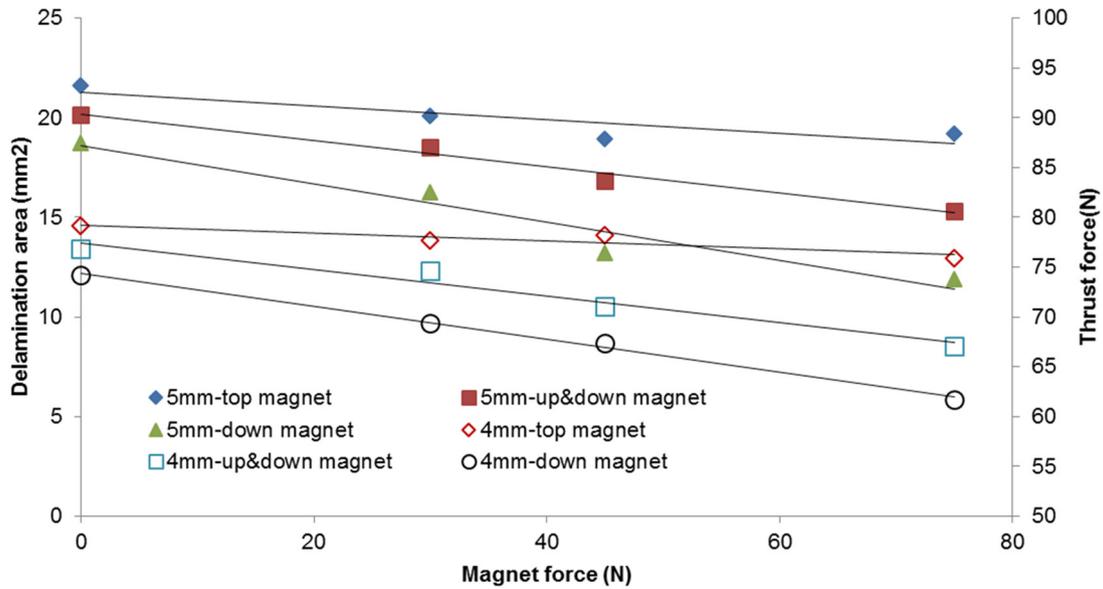


Fig. 12. Effect of magnet force to reduce the delamination area and thrust force in different diameters of drill bit.

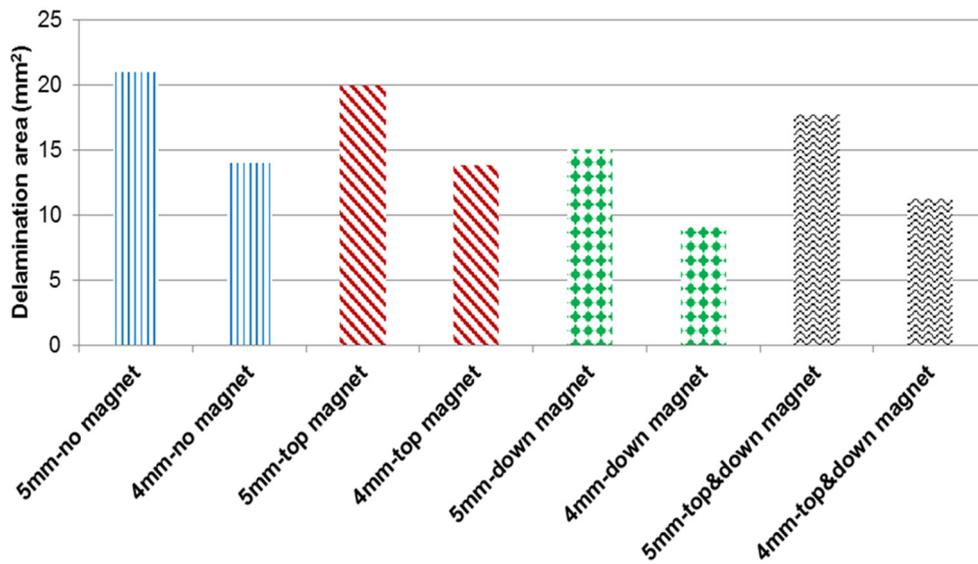


Fig. 13. Comparison of different drilling conditions regarding delamination area.

Table 6. Summary of experimental results.

	Tool diameter (mm)	Magnet position	Surface roughness (μm)	Cylindricity (mm)	Delamination (mm^2)	Thrust force _{max} (N)
Without magnet	5	–	5.7	0.15	21	92
	4	–	5.2	0.12	14	84
With magnet	5	Top	5.4	0.1	19.98	90.5
		Down	4.8	0.07	15.01	86
	4	Top & down	4.3	0.06	13.86	78
		Top	5	0.08	17.68	72
	4	Down	4.6	0.065	11.21	67
		Top & down	4.05	0.05	9.08	65

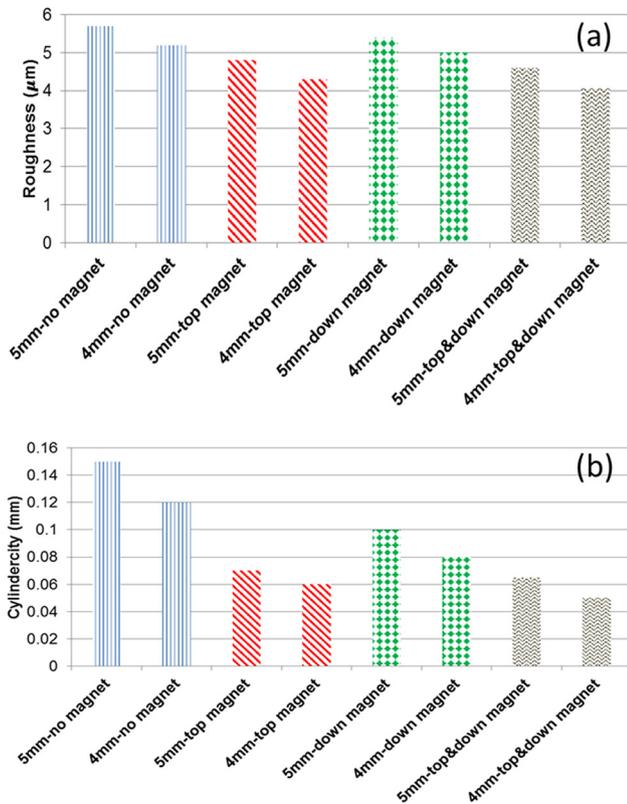


Fig. 14. Comparison between different drilling conditions regarding (a) roughness (b) cylindricity.

on both side of drilled area can be a good solution to improve hole quality of sandwich plates subjected to drilling process.

4 Conclusion

In this paper, the effect of magnetic field on drilling process of basalt/epoxy composite laminate in order to reduce delamination and the thrust force and improve some hole quality parameters i.e. roughness and cylindricity was investigated. Based on DOE approach and full factorial design, a series of experiments were conducted in the absence of magnetic field. Three different levels of spindle speeds and feed rates were involved in the study. ANOVA has been conducted on the responses and the best combination of machining parameters was considered as the guideline for further experiments. Then, the effect of magnetic field backup for the BFRP composite laminate subjected to twist drilling was investigated. The results showed that not only the magnetic backup decreases the delamination area but also the other quality factors such as roughness and cylindricity can be improved significantly. Using different magnet solenoids on the top and the bottom of drilling zone reduces the delamination propagating up to 30%. Moreover, the roughness and cylindricity as the quality factors highly depend on the magnet solenoid

position. In the practical point of view, using different magnetic fields provide higher machining spindle speed and feed rate regarding higher quality and lower damage.

Nomenclature

a	The extent delamination radius
b	Radius of suppressing load
c	Drilling tool radius
DoF	Degree of freedom
F^*	The critical thrust force without backup force
F_B^*	The critical thrust force with magnetic force
E	Elastic modulus
G_{IC}	Critical fracture energy
ν	Poisson's ratio
h	Remained layer thickness
ξ	Force ratio
γ	Drilling shape factor
R	Reaction force
S	Critical drilling shape factor

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