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Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments

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Abstract

In this paper is presented a new comprehensive approach to select cutting parameters for damage-free drilling in carbon fiber reinforced epoxy composite material. The approach is based on a combination of Taguchi's techniques and on the analysis of variance (ANOVA). A plan of experiments, based on the techniques of Taguchi, was performed drilling with cutting parameters prefixed in an autoclave carbon fiber reinforced plastic (CFRP) laminate. The ANOVA is employed to investigate the cutting characteristics of CFRP's using high speed steel (HSS) and Cemented Carbide (K10) drills. The objective was to establish a correlation between cutting velocity and feed rate with the delamination in a CFRP laminate. The correlation was obtained by multiple linear regression. Finally, confirmation tests were performed to make a comparison between the results foreseen from the mentioned correlation.

Keywords: Drilling; Carbon fiber reinforced plastics; Delamination factor; Taguchi's techniques; Analysis of variance

1. Introduction

Owing to the growing use of composite materials, specifically the fiber reinforced plastics (FRP) outside the defence industry and the aerospace industry, the *unit cost* replaces the *performance at any cost* as the main concern for production. So, the production technologies, especially the machining of composites, are assuming a more and more significant role as they condition the economic viability of the product.

Machining composite materials is a rather complex task owing to its heterogeneity, heat sensitivity, and to the fact that reinforcements are extremely abrasive. Conventional machining methods should be adapted in such a way that they diminish thermal and mechanical damage.

Drilling is a frequently practiced machining process in industry owing to the need for component assembly in mechanical pieces and structures.

The drilling of laminate composite materials is significantly affected by the tendency of these materials to delaminate and the fibers to bond from the matrix under the action of machining forces (thrust force and torque).

Many authors [1–3], when reporting about the drilling of laminated composite materials by conventional tools, have shown that the quality of the cut surfaces is strongly dependent on the drilling parameters, tool geometry and tool material. An inappropriate choice of these parameters can lead to unacceptable material degradation, such as fiber pull-out, matrix cratering, thermal damage and delamination. Among the defects caused by drilling, delamination appears to be the most critical.

Laminated fiber reinforced ply's under machining forces are subject to the risk of interlaminar crack propagation, called delamination.

Koenig et al., studied in 1985 the machining of fiber reinforced plastics and concluded that a high feed rate of drilling will cause a crack around the exit edge of the hole [4].

Miller presented in 1987 a database on optimum cutting parameters for drilling holes with minimum local machining damage [5].

Hocheng and Puw [1], in 1992 presented a study of the chip formation and assesses the machinability of two composite materials (Thermoset-based and Thermoplastics-based) and concluded that from cutting chips the former presents a large amount of deformation in chip formation, while the latter tends to fracture. He

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also noticed that carbon/ABS is superior to carbon/epoxy for surface quality and both hole edges.

Chambers and Bishop [6] in 1995 investigated the effect of the cutting parameters on drilling carbon/epoxy and carbon/peek and concluded that the drilling of carbon composites is dependent upon the characteristics of the matrix and the helical PCD drill geometry gave the best overall performance.

In addition to the problems of tool wear, it is very difficult to achieve the quality of surface needed for the accurate assembly of components in mechanical structures.

Lin et al. [7] in 1996, carried out a study on drilling of carbon fiber reinforced composite at high speed and concluded that an increase of the cutting velocity leads a increasing of the drill wear. In this way the fact of increasing the wear of drill causes a rising of thrust force.

Wen-Chou Chen [3] in 1997 studied the variations of cutting forces with or without onset delamination during the drilling operations and concluded that the delamination-free drilling processes may be obtained by the proper selections of tool geometry and drilling parameters.

Piquet et al. [8] in 2000 carried out a study of drilling thin carbon/epoxy laminates with two types of drills, a helical drill and a drill of special geometry, and concluded that both drills leads a damage at the entrance in the wall and the exit of the hole, with the exception of special geometry drill which is possible a significant reduction in the final damage.

Enemuoh et al. [9] in 2001, realize that with the application of the technique of Taguchi and other methods, were possible to achieve the cutting parameters that allowed the absence of damage in the drilling of fiber reinforced plastics.

All the above works contributes to the practice of cutting composite materials, but they do not show the basic mechanisms of cut and the characterization of the machinability.

2. Experimental procedure

2.1. Means and materials

In order to achieve the objective of this experimental work, mainly the establishing of correlations between the cutting conditions with the delamination, machining issues were effectuated with different cutting conditions, and were used carbon fiber reinforced plastics (CFRP's) (Epoxy matrix reinforced with 55% of carbon fiber) for tests.

This composite material was produced by autoclave with a fiber orientation of 0/90 degrees, as we can observe on Fig. 1.

The experiments had been carried out in an autoclave laminate made up of 16 layers of fibers with 4 mm of thickness, using three different types of 5 mm diameter drills presented in the Fig. 2. A helical flute high speed

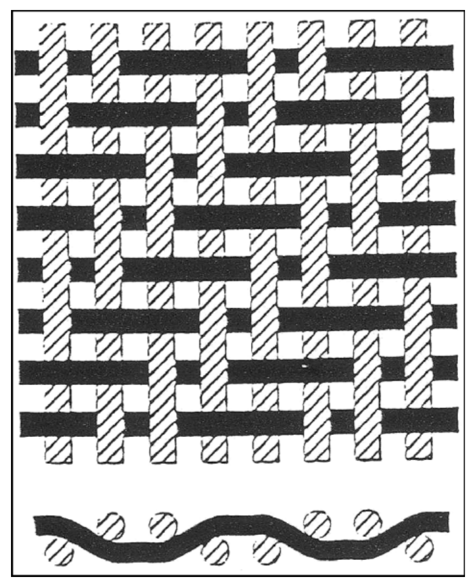


Fig. 1. Plate produced by autoclave with a fiber orientation of 0/90 degrees.

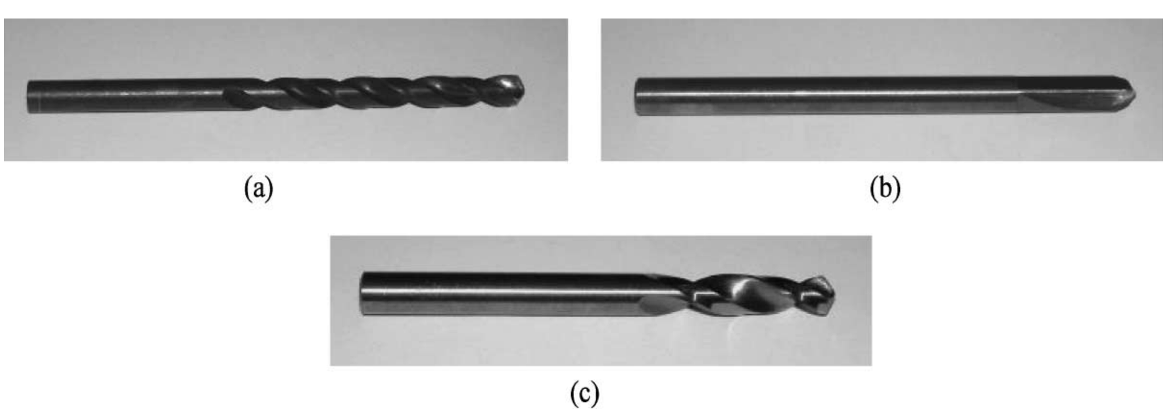


Fig. 2. (a) Helical flute HSS drill; (b) four-flute K10 drill; (c) helical flute K10 drill.

steel (HSS) drill (R415.5-0500-50-8C0), a four-flute cemented carbide (K10) drill (R950.01 H10F) and finally a helical flute K10 carbide drill (R415.5-0500-30-AC0), according to ISO 1832.

A drilling machine with 2,2 kW spindle power and a maximum spindle speed of 2500 rpm was used to perform the experiments.

The used drills have an 118° point angle.

The squeeze of the laminate, in the press of jaw of the drilling machine was made by a system of clamps, to make sure that vibrations and displacement does not exist, as we can observe in Fig. 3.

The damage around the holes was measured with a shop microscope, Mitutoyo TM 500, with 30× magnification and 1 μm resolution.

2.2. Plan of experiments (Taguchi's techniques)

Taguchi's techniques have been used widely in engineering analysis. These techniques consist of a plan of experiments with the objective of acquiring data in a controlled way, executing these experiments, in order to obtain information about the behavior of a given process.

The treatment of the experimental results is based on the analysis average and the analysis of variance (ANOVA) [10–13].

For the elaboration of experiments plan we used the method of Taguchi for two factors at three levels. By levels we mean the values taken by the factors. Table 1 indicates the factors to be studied and the assignment of the corresponding levels.

The array chosen was the L_9 (2^4), which has nine rows corresponding to the number of tests (eight degrees of freedom) with two columns at three levels, as shown in Table 2. The factors and the interactions are assigned to the columns.

The plan of experiments is made of nine tests (array rows) in which the first column was assigned to the cutting velocity (V) and the second column to the feed rate (f) and the remaining were assigned to the interactions. The response to be studied is the delamination factor (F_d) in CFRP laminate.

Table 1
Assignment of the levels to the factors

Level	Revolution n (rpm)	Feed rate f (mm/rev)	Cutting velocity V (m/min)
1	1000	0.04	16
2	1500	0.08	24
3	2000	0.15	32

Table 2
Orthogonal array L_9 (2^4) of Taguchi [10]

L_9 (2^4) Test	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Linear graph L_9 (2^4) [10].

3. Results and discussion

3.1. Influence of the cutting parameters in the delamination factor

The damage around the holes was measured using a shop microscope Mitutoyo TM-500, following the schema presented in the Fig. 4.

After measuring the maximum diameter (D_{max}) in the damage zone, i.e. around each hole, we carried out to determined the value of the delamination factor (F_d). This factor is determined by the ratio the maximum diameter (D_{max}) of the damage zone to the hole diameter (D).

Fig. 3. Squeeze of the plate in the press of jaw of the drilling machine.

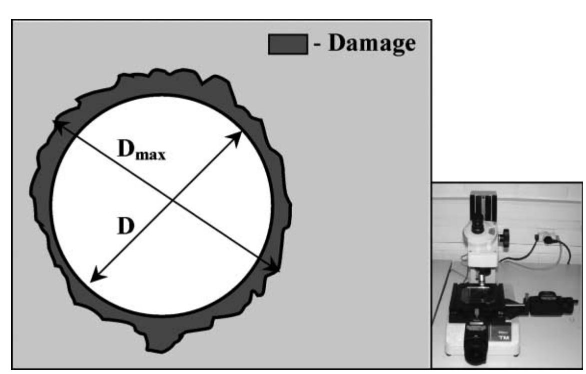


Fig. 4. Schema of the measurement of the maximum diameter (D_{max}) with a shop microscope *Mitutoyo TM 500*.

The value of delamination factor (F_d) can be obtained by the following equation:

$$F_d = \frac{D_{max}}{D} \tag{1}$$

being, D_{max} the maximum diameter of the damage hole in μm and D the diameter of the hole in μm.

Table 3 shows the results of the delamination factor (F_d), for the three sets of drilling tests, obtained by the Eq. (1) in function of the cutting parameters.

In the Figs. 5 and 6 we can observe the evolution of the delamination factor (F_d) with the feed for the different cutting speed values.

In Fig. 5 we can evidence that the F_d increases with the feed rate, and with the cutting speed. According to the graph, we can observe that the carbide drill presents a better performance than the HSS drill, i.e. under the same cutting conditions (cutting speed and feed rate), the HSS drill causes always a bigger delamination factor, witch means higher damage in the composite laminate.

We also can observe that in Fig. 6, the F_d increases with the feed rate, and with the cutting speed.

Table 3
Values of delamination factor (F_d) in function of the cutting parameters

Test	V (m/min)	f (mm/rev)	Delamination factor (F_d)		
			Helical flute HSS drill	Four-flute K10 drill	Helical flute K10 drill
1	16	0.04	1.044	1.064	1.042
2		0.08	1.052	1.066	1.045
3		0.15	1.051	1.066	1.047
4	24	0.04	1.061	1.069	1.057
5		0.08	1.070	1.071	1.054
6		0.15	1.079	1.078	1.064
7	32	0.04	1.063	1.073	1.052
8		0.08	1.069	1.075	1.062
9		0.15	1.078	1.080	1.069

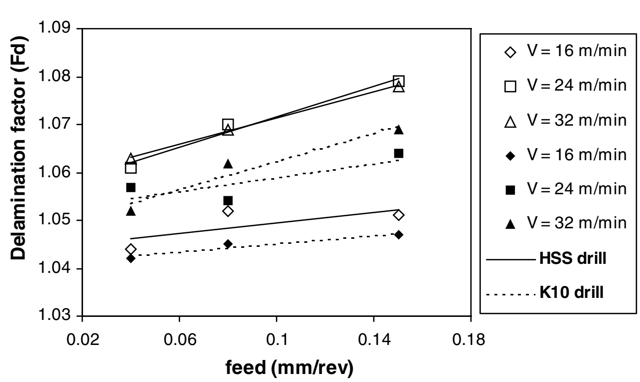


Fig. 5. Delamination factor (F_d) in function of the cutting parameters to drills, for two tool materials, which have the same geometry.

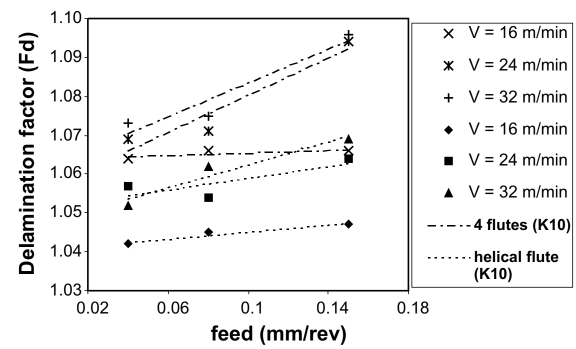


Fig. 6. Delamination factor (F_d) in function of the cutting parameters to drills, for two tool materials, which are manufactured with the same material.

We can evidence that the helical flute (K10) drill presents a better performance than the four-flute (K10) drill, i.e. under the same cutting conditions (cutting speed and feed rate). The four-flute drill causes always a bigger delamination factor, except in the test which have the higher feed rate and the lower cutting velocity.

Geometrical differences between the two types of drill may be the reason for this fact.

With an optical microscope (OM) was possible to observe the damage around the holes, and notice the influence of the cutting velocity (V) have on the delamination factor (F_d), as we can see on Fig. 7.

In Fig. 7, we can evidence that, for a constant a feed rate, an increase of the cutting velocity increases the delamination factor (F_d) as well.

An analysis of variance of the data with the delamination factor (F_d) in CFRP laminate, with the objective of analyzing the influence of the cutting velocity (V), of feed rate (f) on the total variance of the results.

The statistical treatment of the data was made in two phases. The first phase was concerned with the analysis of variance and the effect of the factors and of the interactions. The second phase allowed us to obtain the correlation between the parameters (V and f).

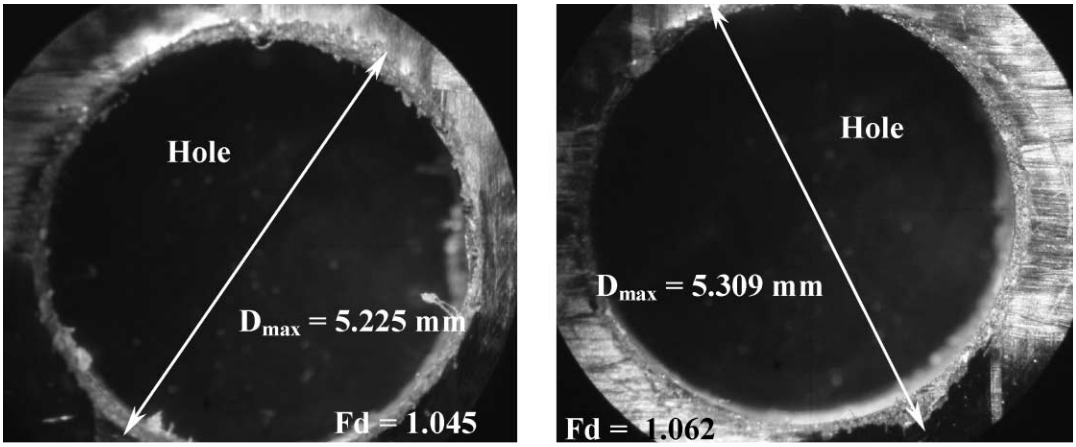
Tables 4–6 show the results of the analysis of variance with the delamination factor (F_d) in CFRP laminate.

From the analysis of Table 4, we can observe that the cutting velocity ($P = 72.5\%$) and the feed rate factor ($P = 20.5\%$), have statistical and physical significance on the delamination factor (F_d) obtained, especially the cutting velocity factor.

The factors (V and f) present a statistical significance test $F > F\alpha = 5\%$. Notice that the error associated to the table ANOVA for the F_d was approximately 7%.

From the analysis of Table 5, we can observe that the cutting velocity factor ($P = 65.9\%$), have statistical and physical significance on the F_d obtained.

The factor feed rate ($P = 19.3\%$) does not present percentage of statistical significance of contribution on the F_d.



V = 16 m/min V = 32 m/min

Fig. 7. Delamination factor (F_d) in function of the cutting speed, MO: amplification of 30×.

Table 4
ANOVA for the delamination factor (F_d) to the helical flute HSS drill

Source of variance	SDQ	gl	Variance	Test F	$F\alpha = 5\%$	P
V (m/min)	8.7E−4	2	4.3E−4	42.26	6.94	72.5
f (mm/rev)	2.6E−4	2	1.3E−4	12.69	6.94	20.5
Error	4E−5	4	1E−5	/	/	7.0
Total	1.17E−3	8	/	/	/	100.0

SDQ—sum of squares, gl—degrees of freedom, P—percentage of contribution.

Table 5
ANOVA for the delamination factor (F_d) to the four-flute K10 drill

Source of variance	SDQ	gl	Variance	Test F	$F\alpha = 5\%$	P
V (m/min)	1.7E−4	2	9E−5	18.81	6.94	65.9
f (mm/rev)	6E−5	2	3E−5	6.20	6.94	19.3
Error	2E−5	4	5E−6	/	/	14.8
Total	2.5E−4	8	/	/	/	100.0

SDQ—sum of squares, gl—degrees of freedom, P—percentage of contribution.

Table 6
ANOVA for the delamination factor (F_d) to the helical flute K10 drill

Source of variance	SDQ	gl	Variance	Test F	$F\alpha = 5\%$	P
V (m/min)	4.6E−4	2	2.3E−4	14.11	6.94	63.5
f (mm/rev)	1.5E−4	2	7E−5	4.54	6.94	17.1
Error	1E−4	4	2E−5	/	/	19.4
Total	6.7E−4	8	/	/	/	100.0

SDQ—sum of squares, gl—degrees of freedom, P—percentage of contribution.

The factor cutting velocity present a statistical significance test $F > F\alpha = 5\%$, witch does not happens to the factor feed rate because the test $F < F\alpha = 5\%$.

Notice that the error associated to the table ANOVA for the F_d was approximately 14.8%.

From the analysis of Table 6, we can observe that the cutting velocity factor ($P = 63.5\%$), have statistical and physical significance on the F_d obtained.

The factor feed rate ($P = 17.1\%$) does not present percentage of physical significance of contribution on the F_d, because P (percentage of contribution) < Error associated.

From the reasons above presented, the factor cutting velocity present a statistical significance and the factor feed rate does not.

Notice that the error associated to the table ANOVA for the F_d was approximately 19.4%.

3.2. Correlation (delamination factor/cutting parameters)

The correlations between the factors (cutting velocity, feed rate) and the delamination factor (F_d) in CFRP laminate were obtained by multiple linear regression.

The equations obtained were as follow:

Helical flute HSS drill –

$$F_d = 1.021 + 1.31 \times 10^{-3}\ \mathrm{V} + 0.117f \quad R = 0.76 \tag{2}$$

Four-flute K10 drill –

$$F_d = 1.037 + 1.0 \times 10^{-3}\ \mathrm{V} + 0.158f \quad R = 0.74 \tag{3}$$

Helical flute K10 drill –

$$F_d = 1.010 - 1.16 \times 10^{-4}\ \mathrm{V} + 0.097f \quad R = 0.86 \tag{4}$$

being, V the cutting of velocity in m/min, and f the feed rate in mm/rev.

3.3. Confirmation tests

Table 7 shows the cutting conditions used on the confirmation tests.

The results obtained by a comparison between the foreseen values by the by the models developed in the present work (Eqs. (2)–(4)) and the experimentally obtained results by delamination factor (F_d), are shown in Table 8. From the analysis of the refereed table, we can observe that the gained through the actual model show a maximum error of about 2%. We also can consider that Eqs. (2)–(4), correlates the evolution of the delamination factor (F_d) in the laminate with the cutting conditions (cutting velocity and feed) with a good degree of approximation.

Table 7
Cutting conditions used in drilling confirmation tests

Type of drill	Test	Revolution n (rpm)	V (m/min)	f (mm/rev)
Helical flute HSS	1c	1250	20	0.08
	2c	1750	27	0.08
Four-flute K10	3c	1250	20	0.08
	4c	1750	27	0.08
Helical flute K10	5c	1250	20	0.08
	6c	1750	27	0.08

Table 8
Experimental plan confirmation drilling tests and their comparison with the results

Test	Delamination factor (F_d)		
	Experimental values	Model Eqs. (2)–(4)	Error (%)
1	1.047	1.056	0.87
2	1.071	1.066	0.40
3	1.084	1.069	1.32
4	1.092	1.077	1.36
5	1.023	1.010	1.31
6	1.041	1.033	0.73

4. Conclusions

From this study on delamination when, drilling of CFRPs, the following conclusions can be drawn:

- The helical flute K10 drill promotes less damage on the composite laminate than the four-flute carbide (K10) drill, i.e., the delamination factor (F_d) is smaller.
- The helical flute K10 drill, presents a better performance, than helical flute HSS drill, i.e., the carbide drill is the better choice for drilling CFRP.
- The delamination factor increases with both cutting parameters, which means that the composite damage is bigger for higher cutting speed and for higher feed.
- The cutting velocity is the cutting parameter that has the highest physical as well statistical influence the delamination factor in CFRP laminate (63.91% and 65.9%), for the three drills.
- Both carbide drills shows an almost null wear land in the flank surface, while the HSS drill presents a wear value of 0.012 mm, measured at 1/4 the drill radius, apart from the corner.
- The confirmation tests showed that the error associated to the delamination factor (F_d) (maximum value 2% and minimum 0.4%) is excellent.

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