ISSN 1330-3651
UDC/UDK 620.172.2:678

# INFLUENCE OF CUTTING PARAMETERS ON THRUST FORCE, DRILLING TORQUE AND DELAMINATION DURING DRILLING OF CARBON FIBRE REINFORCED COMPOSITES

*Nikša Koboević, Mate Jurjević, Žarko Koboević*

Preliminary notes

Composite materials have become valuable construction materials in aerospace, defense and in recent years in automotive industry. The advantage of composite materials over conventional materials stems largely from their higher specific strength, stiffness and fatigue characteristics. Composite components are joined by mechanical fasteners, accurate, precise high quality holes need to be drilled to ensure proper and durable assemblies. Drilling of composite materials causes several damages, such us: delamination, fibre-pull out, edge chipping, uncut fibers and others. Delamination is a major problem associated with drilling fiber reinforced composite materials. It causes poor assembly tolerance, reduces structural integrity of material and the potential for long term performance deterioration. The thrust force has been cited as main cause of delamination. In this paper the objective was to establish correlation between cutting parameters and thrust force, drilling torque and delamination. Drilling tests were carried out on carbon epoxy composite material using three different drills, HSS-Co twist drill, Multi Constructional twist drill and "Brad & Spur" drill. The data have been processed by the "DesignExpert" software package which generated the mathematical models.

***Keywords***: *carbon fibre reinforced composite material, delamination, drilling, hole quality*

## Utjecaj parametara rezanja na aksijalnu silu, moment bušenja i delaminaciju pri bušenju ugljičnim vlaknima ojačanog kompozitnog materijala

Prethodno priopćenje

Kompozitni materijali su postali značajni konstrukcijski materijali u zrakoplovnoj, vojnoj, a u posljednje vrijeme i u automobilskoj industriji. Prednost kompozitnih materijala nad konvencionalnim proizlazi najviše iz njihove visoke specifične čvrstoće, žilavosti i radnih osobina. Dijelovi od kompozitnog materijala spajaju se pomoću elemenata za spajanje, što iziskuje bušenje otvora visoke kvalitete kako bi se osigurao ispravan i trajan spoj. Pri bušenju kompozitnog materijala dolazi do pojave oštećenja kao što su: delaminacija, izvlačenje vlakana, krzanje rubova, neodrezana vlakna i druga. Delaminacija je najveći problem pri bušenju vlaknima ojačanog kompozitnog materijala. Ona je uzrok loše kvalitete spoja, smanjenja strukturalnog integriteta materijala i slabljenja osobina tijekom vremena. Kao glavni uzrok delaminacije navedena je aksijalna sila. Cilj ovog članka je uspostaviti vezu između parametara rezanja, aksijalne sile, momenta bušenja i delaminacije. Bušenje je izvedeno na ugljičnim vlaknima ojačanom kompozitnom materijalu uz pomoć tri različite vrste svrdla, HSS-Co svrdla, višenamjenskog i "Brad & Spur" svrdla. Uz pomoć programskog paketa "DesignExpert" dobiveni su matematički modeli.

***Ključne riječi***: *bušenje, delaminacija, kvaliteta provrta (rupa), ugljčnim vlaknima ojačani kompozitni materijal*

## 1 Introduction

Composite materials are increasingly used in demanding constructions, due to their hardness to weight and stiffness to weight ratios. They are often applied in aerospace, defence and in recent years in automotive industries. Parts made out of composite materials are joined and connected by joining elements into complex construction sections and subsections. Therefore machining process such as drilling are often required to assemble and join different components. Due to the inhomogeneous and anisotropic nature of composite materials, their machining behaviour differs in many respects from metal machining.

When drilling fibre reinforced composites, typical problem such as delamination, rapid tool wear and fibre pull out can be encountered. The occurrence of damage reduces the fatigue strength, causing poor assembly tolerance and affecting the composite structure integrity. Delamination is a major problem associated with drilling fibre reinforced composite materials and, in addition to reducing the structural integrity of the material, it also leads to poor assembly tolerances and has the potential for long-term performance deterioration. Delamination can occur both on the entrance and exit side of the workpiece. The delamination on the exit surface, generally referred to as push-down delamination, is as a rule more extensive, and is consequently considered the most dangerous.

The mechanics of drilling composite materials has been studied along with quality of the hole and effects of tool geometry and tool material [1]. Chen [2] proposed a delamination factor to characterize delamination in drilling carbon fibre reinforced plastic. Lin and Chen [3] studied the effects of increasing cutting speed on drilling of CFRP. They concluded that an increase of cutting speed leads to an increasing drill wear and increasing the thrust force. Koenig at al. [4, 5] investigated the effect of cutting parameters on drilling damage. Dharan and Won [6] developed an intelligent machining system to determine the key process parameters for various cutting conditions. Enemuoh et al. [7] realised that with application of the technique of Taguchi and multi-objective optimisation criterion, it is possible to achieve cutting parameters that allow the absence of damage in drilling of fiber reinforced plastics.

According to Hocheng and Dharan [8] two modes of delamination failure were that identified, push-out during drill exit and peel-up during drill entry. During push-out delamination, the uncut-thickness decreases as drill is fed through the material and at a critical point the drilling thrust force exceeds the interlaminar bond strength resulting in delamination. Peel-up delamination occurs in the same mechanism, the cutting introducing a peeling force upwards forcing the layers to delaminate.

## 2 Experimental part

The objective of this experimental work was to establish a correlation between cutting velocity and feed rate with thrust force, drilling torque and delamination in carbon fibre reinforced composite materials. Correlation was obtained by "DesignExpert" software package.

## 2.1 Means and materials

Composite materials for drilling were fabricated from woven fabric carbon fibre/epoxy matrix, Fig. 1. The stacking sequence of the laminates was 0°/90° and had a 55 % cured fibre volume fraction. The specimens were approximately 3,175 mm (1/8") thick and size 76,2 mm × 152,4 mm (3" × 6").

**Figure 1** Test specimen

The experiments have been carried out using three different types of 6 mm diameter drills presented in Fig. 2.

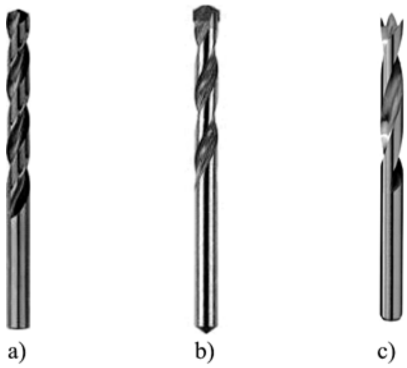


**Figure 2** Three different type drills: a) HSS-Co twist drill; b) Multi Constructional twist drill; c) "Brad & Spur" drill

HSS-Co twist drill bit made of alloyed high speed steel according to DIN 338, cobalt content 5 %, drill bit tip 135°, split point manufactured to DIN 1412 by BOSH company.

Multi Constructional twist drill, special multi-purpose diamond ground tungsten carbide cutters, 118° drill bit tip, manufactured by BOSH company and

"Brad & Spur" K10 drill, were manufactured according to DIN 6539 by M. A. Ford company.

A Vertical Machining Centre "SPINNER VC560" with 13 kW spindle power and maximum spindle speed of 12.000 rpm was used to perform the experiments, Fig. 3.

A Kistler® piezoelectric dynamometer 9271A with load amplifier was used to acquire the thrust force and drilling torque. The dynamometer signals were then processed to make them suitable for computer. This was achieved via charge amplifiers and an analog to digital (A/D) converter and then to PC.

The damage around the holes and uncut fibres was measured with a microscope OLYMPUS S7X9, with 30× magnification and 1 μm resolution. With digital camera were made photos of entrance and exit side of each hole were made. Delamination area was measured with software OLYMPUS DP Soft C3030Z. Screen and ways of measure are shown in Fig. 4.


**Figure 3** Vertical Machining Centre

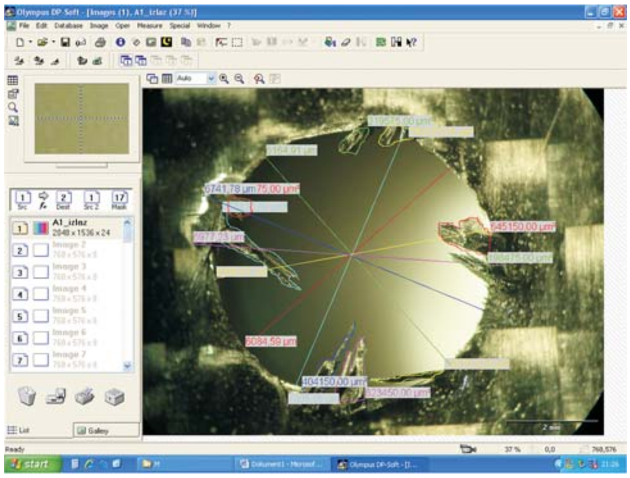

**Figure 4** Screen of software used for measuring delamination

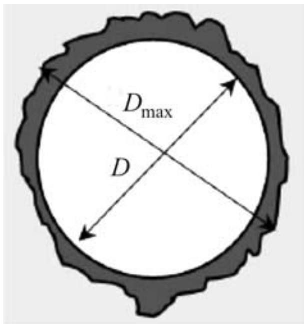


**Figure 5** Scheme of delamination factor

The delamination factor is determined by the ratio of the maximum diameter ($D_{max}$) of the delamination zone to the hole diameter ($D$). The scheme is shown in Fig. 5. The value of delamination factor ($K_d$) can be expressed as follows:

$$K_{\mathrm{d}} = \frac{D_{\max}}{D}. \tag{1}$$

## 2.2 Experimental results

Design of experiment is a powerful analysis tool for modelling and analysing the influence of process variables over some specific variable, which is an unknown function of these process variables. For elaboration of the plan of experiments method of three-level factorial design was used. Tabs. 1÷3. show the input cutting parameters and values of the measured output parameters for three different drills [9].

**Table 1** Values of thrust force, drilling torque and delamination factor as a function of cutting parameters for HSS-Co twist drill

| Standard order | Run order | Cutting speed, $v$ /mm/min | Feed rate, $f$ /mm/rev | Thrust force, $F_0$ /N | Drilling torque, $M$ /N·m | Delamination factor, $K_d$ |
|---|---|---|---|---|---|---|
| 1 | 13 | 10 | 0,02 | 232,704 | 0,990 | 1,191 |
| 2 | 7 | 14 | 0,02 | 227,243 | 0,774 | 1,279 |
| 3 | 12 | 18 | 0,02 | 227,214 | 0,794 | 1,314 |
| 4 | 1 | 10 | 0,05 | 292,213 | 0,839 | 1,194 |
| 5 | 4 | 14 | 0,05 | 261,027 | 0,872 | 1,289 |
| 6 | 8 | 18 | 0,05 | 278,898 | 0,969 | 1,240 |
| 7 | 11 | 10 | 0,08 | 336,949 | 0,782 | 1,342 |
| 8 | 10 | 14 | 0,08 | 348,232 | 0,880 | 1,371 |
| 9 | 5 | 18 | 0,08 | 324,496 | 1,069 | 1,275 |
| 10 | 3 | 14 | 0,05 | 270,241 | 0,875 | 1,303 |
| 11 | 2 | 14 | 0,05 | 265,670 | 0,872 | 1,247 |
| 12 | 9 | 14 | 0,05 | 264,987 | 0,874 | 1,268 |
| 13 | 6 | 14 | 0,05 | 262,883 | 0,873 | 1,284 |

**Table 2** Values of thrust force, drilling torque and delamination factor as a function of cutting parameters for Multi Constructional twist drill

| Standard order | Run order | Cutting speed, $v$ /mm/min | Feed rate, $f$ /mm/rev | Thrust force, $F_0$ /N | Drilling torque, $M$ /N·m | Delamination factor, $K_d$ |
|---|---|---|---|---|---|---|
| 1 | 13 | 10 | 0,02 | 145,730 | 0,392 | 1,176 |
| 2 | 7 | 14 | 0,02 | 131,427 | 0,473 | 1,161 |
| 3 | 12 | 18 | 0,02 | 137,544 | 0,461 | 1,149 |
| 4 | 1 | 10 | 0,05 | 185,728 | 0,489 | 1,193 |
| 5 | 4 | 14 | 0,05 | 186,755 | 0,492 | 1,158 |
| 6 | 8 | 18 | 0,05 | 184,701 | 0,552 | 1,152 |
| 7 | 11 | 10 | 0,08 | 235,885 | 0,544 | 1,198 |
| 8 | 10 | 14 | 0,08 | 239,743 | 0,572 | 1,171 |
| 9 | 5 | 18 | 0,08 | 225,651 | 0,612 | 1,173 |
| 10 | 3 | 14 | 0,05 | 188,799 | 0,492 | 1,181 |
| 11 | 2 | 14 | 0,05 | 188,799 | 0,492 | 1,183 |
| 12 | 9 | 14 | 0,05 | 189,827 | 0,512 | 1,168 |
| 13 | 6 | 14 | 0,05 | 192,898 | 0,533 | 1,184 |

**Table 3** Values of thrust force, drilling torque and delamination factor as a function of cutting parameters for "Brad & Spur" drill

| Standard order | Run order | Cutting speed, $v$ /mm/min | Feed rate, $f$ /mm/rev | Thrust force, $F_0$, /N | Drilling torque, $M$ /N·m | Delamination factor, $K_d$ |
|---|---|---|---|---|---|---|
| 1 | 13 | 10 | 0,02 | 134,013 | 0,269 | 1,057 |
| 2 | 7 | 14 | 0,02 | 125,820 | 0,249 | 1,094 |
| 3 | 12 | 18 | 0,02 | 118,833 | 0,273 | 1,174 |
| 4 | 1 | 10 | 0,05 | 149,740 | 0,354 | 1,078 |
| 5 | 4 | 14 | 0,05 | 164,438 | 0,426 | 1,102 |
| 6 | 8 | 18 | 0,05 | 159,922 | 0,378 | 1,183 |
| 7 | 11 | 10 | 0,08 | 172,440 | 0,374 | 1,186 |
| 8 | 10 | 14 | 0,08 | 191,016 | 0,456 | 1,181 |
| 9 | 5 | 18 | 0,08 | 189,103 | 0,436 | 1,214 |
| 10 | 3 | 14 | 0,05 | 163,045 | 0,415 | 1,098 |
| 11 | 2 | 14 | 0,05 | 163,469 | 0,419 | 1,086 |
| 12 | 9 | 14 | 0,05 | 163,865 | 0,411 | 1,112 |
| 13 | 6 | 14 | 0,05 | 168,011 | 0,420 | 1,108 |

### 2.2.1 Influence of cutting parameters on the thrust force

The value of thrust force $F_0$ was measured using Kistler® piezoelectric dynamometer. Tabs. 1-3 show the results of the thrust force for drilling with three different drills, as a function of the cutting parameters. The data have been processed by the Design Expert software – ANOVA (variance analysis) module, which is presented in Tab. 4.

**HSS-Co twist drill**

The Model $F$-value of 65,10 implies the model is significant. There is only a 0,01 % chance that a "Model $F$-Value" this large could occur due to noise. Values of "Prob > $F$" less than 0,0500 indicate model terms are significant. In this case B are significant model terms. Feed rate has statistical and physical significance on thrust force. Cutting speed $A$ does not present a statistical significance. The

**Table 4** Analysis of variance – thrust force for HSS-Co twist drill

| Source | Sum of squares | Degrees of freedom | Mean square | *F* value | *P* value Prob > *F* |
|---|---|---|---|---|---|
| **Model** | 17498,94 | 2 | 8749,47 | 65,10 | < 0,0001 |
| *A* – Cutting speed | 162,84 | 1 | 162,84 | 1,21 | 0,2968 |
| *B* – Feed rate | 17336,10 | 1 | 17336,10 | 128,99 | < 0,0001 |
| **Residual** | 1343,95 | 10 | 134,40 | | |
| Lack of fit | 1295,78 | 6 | 215,96 | 17,93 | 0,0073 |
| Pure error | 48,18 | 4 | 12,04 | | |
| **Cor total** | 18842,89 | 12 | | | |

**Table 5** Summary statistics for the model

| | |
|---|---|
| Standard Deviation | 11,59 |
| Mean | 276,37 |
| R-Squared | 0,9287 |
| Adjusted R-Squared | 0,9144 |
| Predicted R-Squared | 0,8893 |

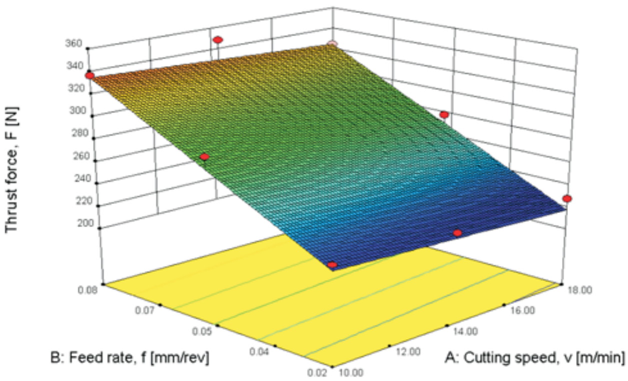


**Figure 6** The dependence of thrust force on cutting parameters for HSS-Co twist drill

overview of statistical data about the model is presented in Tab. 5.

Fig. 6 shows the dependence of thrust force on cutting parameters.

**Table 6** Coded and actual values of the parameters

| Parameter | Coded value | Actual value |
|---|---|---|
| Cutting speed | *A* | *v* |
| Feed rate | *B* | *f* |

Model for thrust force can be described by equation in terms of coded factors:

$$F_0 = +\,276{,}37 - 5{,}21 \cdot A + 53{,}75 \cdot B. \quad (2)$$

Final Equation in Terms of Actual Factors:

$$F_0 = +\,205{,}01198 - 1{,}30242 \cdot v + 1791{,}75776 \cdot f. \quad (3)$$

**Multi Constructional twist drill**

The Model F-value of 330,84 implies the model is significant. In this case B are significant model terms. The overview of statistical data about the model is presented in Tab. 8.

Fig. 7 shows the dependence of thrust force on cutting parameters.

**Table 7** Analysis of variance – thrust force for Multi Constructional twist drill

| Source | Sum of squares | Degrees of freedom | Mean square | *F* Value | *P* value Prob > *F* |
|---|---|---|---|---|---|
| **Model** | 13750,86 | 2 | 6875,43 | 330,84 | < 0,0001 |
| *A* – Cutting speed | 63,03 | 1 | 63,03 | 3,03 | 0,1122 |
| *B* – Feed rate | 13687,83 | 1 | 13687,83 | 658,65 | < 0,0001 |
| **Residual** | 207,82 | 10 | 20,78 | | |
| Lack of fit | 187,68 | 6 | 31,28 | 6,21 | 0,0493 |
| Pure error | 20,14 | 4 | 5,03 | | |
| **Cor total** | 13958,67 | 12 | | | |

**Table 8** Summary statistics for the model

| | |
|---|---|
| Standard Deviation | 4,56 |
| Mean | 187,19 |
| R-Squared | 0,9851 |
| Adjusted R-Squared | 0,9821 |
| Predicted R-Squared | 0,89715 |

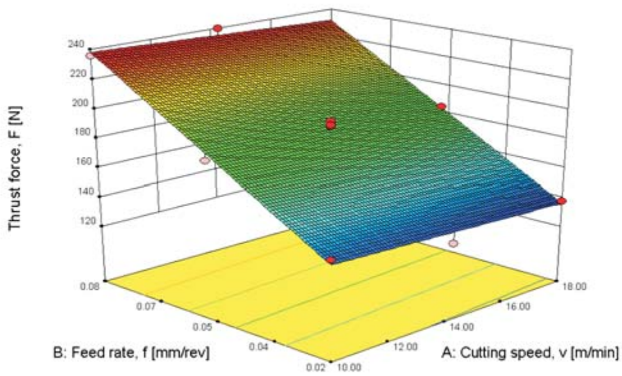


**Figure 7** The dependence of thrust force on cutting parameters for Multi Constructional twist drill

Model for thrust force can be described by equation in terms of coded factors:

$$F_0 = +\,187{,}19 - 3{,}24 \cdot A + 47{,}76 \cdot B. \quad (4)$$

And final equation in terms of actual factors:

$$F_0 = +\,118{,}93039 - 0{,}81029 \cdot v + 1592{,}10000 \cdot f. \quad (5)$$

**"Brad & Spur" drill**

**Table 9** Analysis of variance – thrust force for "Brad & Spur" drill

| Source | Sum of squares | Degrees of freedom | Mean Square | *F* value | *P* value Prob > *F* |
|---|---|---|---|---|---|
| **Model** | 5605,56 | 5 | 1121,11 | 77,34 | < 0,0001 |
| *A* – Cutting speed | 22,68 | 1 | 22,68 | 1,56 | 0,2512 |
| *B* – Feed rate | 5039,80 | 1 | 5039,80 | 347,66 | < 0,0001 |
| *AB* | 253,49 | 1 | 253,49 | 17,49 | 0,0041 |
| $A^2$ | 149,71 | 1 | 149,71 | 10,33 | 0,0148 |
| $B^2$ | 39,37 | 1 | 39,37 | 2,72 | 0,1434 |
| **Residual** | 101,48 | 7 | 14,50 | | |
| Lack of fit | 85,58 | 3 | 28,53 | 7,18 | 0,0435 |
| Pure error | 15,89 | 4 | 3,97 | | |
| **Cor total** | 5707,04 | 12 | | | |

The Model $F$-value of 77,34 implies the model is significant. In this case $B$, $AB$, $A^2$ are significant model terms. The overview of statistical data about the model is presented in Tab. 10.

Fig. 8 shows the dependence of thrust force on cutting parameters.

**Table 10** Summary statistics for the model

| | |
|---|---|
| Standard Deviation | 3,81 |
| Mean | 158,75 |
| R-Squared | 0,9822 |
| Adjusted R-Squared | 0,9695 |
| Predicted R-Squared | 0,8531 |

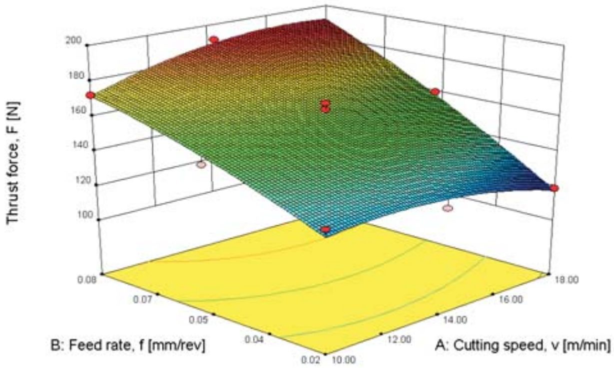


**Figure 8** The dependence of thrust force on cutting parameters for "Brad & Spur" drill

Model for thrust force can be described by equation in terms of coded factors:

$$F_0 = +163 + 1{,}94 \cdot A + 28{,}98 \cdot B + 7{,}96 \cdot A \cdot B - \\ - 7{,}36 \cdot A^2 - 3{,}78 \cdot B^2. \tag{6}$$

And final equation in terms of actual factors:

$$F_0 = +54{,}54077 + 10{,}05326 \cdot v + 456{,}880656 \cdot f + \\ + 66{,}33958 \cdot v \cdot f - 0{,}46015 \cdot v^2 - 4194{,}88506 \cdot f^2. \tag{7}$$

### 2.2.2 Influence of cutting parameters on drilling torque

#### HSS-Co twist drill

**Table 11** Analysis of variance – drilling torque for HSS-Co twist drill

| Source | Sum of squares | Degrees of freedom | Mean square | $F$ value | $P$ value Prob > $F$ |
|---|---|---|---|---|---|
| **Model** | 0,080 | 5 | 0,016 | 18,77 | 0,0006 |
| $A$ – Cutting speed | 8,410E-003 | 1 | 8,410E-003 | 9,61 | 0,0173 |
| $B$ – Feed rate | 4,988E-003 | 1 | 4,988E-003 | 5,89 | 0,0456 |
| $AB$ | 0,058 | 1 | 0,058 | 68,85 | < 0,0001 |
| $A^2$ | 8,476E-003 | 1 | 8,476E-003 | 10,01 | 0,0159 |
| $B^2$ | 1,289E-003 | 1 | 1,289E-003 | 1,52 | 0,2572 |
| **Residual** | 5,929E-003 | 7 | 8,470E-004 | | |
| Lack of fit | 5,922E-003 | 3 | 1,974E-003 | 1161,26 | < 0,0001 |
| Pure error | 6,800E-006 | 4 | 1,700E-006 | | |
| **Cor total** | 0,086 | 12 | | | |

The Model $F$-value of 18,87 implies the model is significant. In this case $A$, $B$, $AB$, $A^2$ are significant model terms. The overview of statistical data about the model is presented in Tab. 12.

Fig. 9 shows the dependence of drilling torque on cutting parameters.

**Table 12** Summary statistics for the model

| | |
|---|---|
| Standard Deviation | 0,029 |
| Mean | 0,88 |
| R-Squared | 0,9309 |
| Adjusted R-Squared | 0,8816 |
| Predicted R-Squared | 0,3677 |

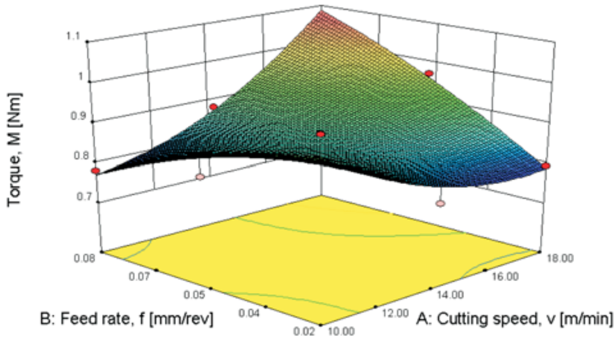


**Figure 9** The dependence of drilling torque on cutting parameters for HSS-Co twist drill

Model for drilling torque can be described by equation in terms of coded factors:

$$M = +0{,}87 + 0{,}037 \cdot A + 0{,}029 \cdot B + 0{,}12 \cdot A \cdot B + \\ + 0{,}055 \cdot A^2 - 0{,}022 \cdot B^2. \tag{8}$$

And final equation in terms of actual factors:

$$M = +2{,}01217 - 0{,}13805 \cdot v - 10{,}72601 \cdot f + \\ + 1{,}00625 \cdot v \cdot f + 0{,}00346 \cdot v^2 - 24{,}00383 \cdot f^2. \tag{9}$$

#### Multi Constructional twist drill

**Table 13** Analysis of variance – drilling torque for Multi Constructional twist drill

| Source | Sum of squares | Degrees of freedom | Mean square | $F$ value | P value Prob > $F$ |
|---|---|---|---|---|---|
| **Model** | 0,034 | 2 | 0,017 | 52,63 | < 0,0001 |
| A – Cutting speed | 6,667E-003 | 1 | 6,667E-003 | 20,88 | 0,0010 |
| B – Feed rate | 0,027 | 1 | 0,027 | 84,37 | < 0,0001 |
| **Residual** | 3,192E-003 | 10 | 3,192E-004 | | |
| Lack of fit | 1,855E-003 | 6 | 3,092E-004 | 0,93 | 0,5569 |
| Pure error | 1,337E-003 | 4 | 3,342E-004 | | |
| **Cor total** | 0,037 | 12 | | | |

The Model $F$-value of 52,63 implies the model is significant. In this case $A$, $B$ are significant model terms. The overview of statistical data about the model is presented in Tab. 14.

Fig. 10 shows the dependence of drilling torque on cutting parameters.

**Table 14** Summary statistics for the model

| | |
|---|---|
| Standard Deviation | 0,018 |
| Mean | 0,51 |
| R-Squared | 0,9132 |
| Adjusted R-Squared | 0,8959 |
| Predicted R-Squared | 0,8560 |

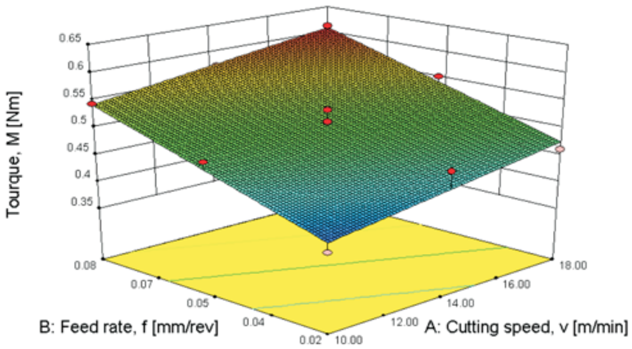


**Figure 10** The dependence of drilling torque on cutting parameters for Multi Constructional twist drill

Model for drilling torque can be described by equation in terms of coded factors:

$$M = +0,51 + 0,033 \cdot A + 0,067 \cdot B. \tag{10}$$

And final equation in terms of actual factors:

$$M = +0,28059 + 0,00833 \cdot v + 2,23333 \cdot f. \tag{11}$$

### "Brad & Spur" drill

**Table 15** Analysis of variance – drilling torque for "Brad & Spur" drill

| Source | Sum of squares | Degrees of freedom | Mean square | *F* value | *P* value Prob > *F* |
|---|---|---|---|---|---|
| **Model** | 3,36 | 5 | 0,67 | 711,52 | < 0,0001 |
| *A* – Cutting speed | 0,063 | 1 | 0,063 | 66,47 | < 0,0001 |
| *B* – Feed rate | 2,19 | 1 | 2,19 | 2311,90 | < 0,0001 |
| *AB* | 0,027 | 1 | 0,027 | 28,06 | 0,0011 |
| $A^2$ | 0,28 | 1 | 0,28 | 294,73 | < 0,0001 |
| $B^2$ | 0,40 | 1 | 0,40 | 421,00 | < 0,0001 |
| **Residual** | 6,618E-003 | 7 | 9,445E-004 | | |
| Lack of fit | 2,481E-003 | 3 | 8,272E-004 | 0,80 | 0,5552 |
| Pure error | 4,137E-003 | 4 | 1,034E-003 | | |
| **Cor total** | 3,37 | 12 | | | |

The Model F-value of 711,52 implies the model is significant. In this case *A*, *B*, *AB*, $A^2$, $B^2$ are significant model terms. The overview of statistical data about the model is presented in Tab. 16.

Fig. 11 shows the dependence of drilling torque on cutting parameters.

**Table 16** Summary statistics for the model

| | |
|---|---|
| Standard Deviation | 0,031 |
| Mean | 2,72 |
| R-Squared | 0,9980 |
| Adjusted R-Squared | 0,9966 |
| Predicted R-Squared | 0,9927 |

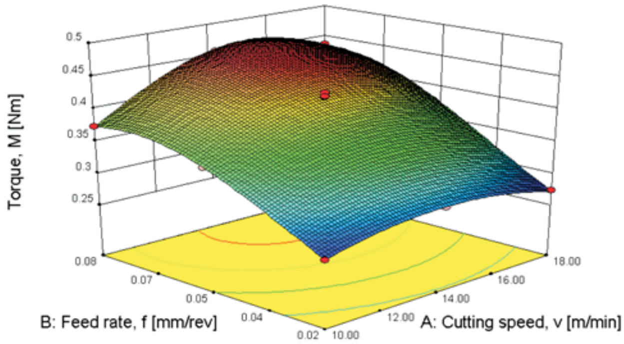


**Figure 11** The dependence of drilling torque on cutting parameters for "Brad & Spur" drill

Model for drilling torque can be described by equation in terms of coded factors:

$$M^{-1} = +2,40 - 0,10 \cdot A - 0,60 \cdot B - 0,081 \cdot A \cdot B + \\ +0,32 \cdot A^2 + 0,38 \cdot B^2. \tag{12}$$

And final equation in terms of actual factors:

$$M^{-1} = +8,23371 - 0,54752 \cdot v - 52,79957 \cdot f - \\ -0,67865 \cdot v \cdot f + 0,019853 \cdot v^2 + 421,8129 \cdot f^2. \tag{12}$$

## 2.2.3 Influence of cutting parameters on delamination

### HSS-Co twist drill

**Table 17** Analysis of variance – delamination factor for HSS-Co twist drill

| Source | Sum of squares | Degrees of freedom | Mean square | *F* value | *P* value Prob > *F* |
|---|---|---|---|---|---|
| **Model** | 0,029 | 5 | 5,873E-003 | 15,96 | 0,0010 |
| *A* – Cutting speed | 1,734E-003 | 1 | 1,734E-003 | 4,71 | 0,0665 |
| *B* – Feed rate | 6,936E-003 | 1 | 6,936E-003 | 18,85 | 0,0034 |
| *AB* | 9,025E-003 | 1 | 9,025E-003 | 24,53 | 0,0017 |
| $A^2$ | 7,799E-003 | 1 | 7,799E-003 | 21,20 | 0,0025 |
| $B^2$ | 8,313E-003 | 1 | 8,313E-003 | 22,60 | 0,0021 |
| **Residual** | 2,575E-003 | 7 | 3,679E-004 | | |
| Lack of fit | 7,323E-004 | 3 | 2,441E-004 | 0,53 | 0,6855 |
| Pure error | 1,843E-003 | 4 | 4,607E-004 | | |
| **Cor total** | 0,032 | 12 | | | |

The Model *F*-value of 15,96 implies the model is significant. In this case B, AB, $A^2$, $B^2$ are significant model terms. The overview of statistical data about the model is presented in Tab. 18.

Fig. 12 shows the dependence of delamination factor on cutting parameters.

**Table 18** Summary statistics for the model

| | |
|---|---|
| Standard Deviation | 0,019 |
| Mean | 1,28 |
| R-Squared | 0,9194 |
| Adjusted R-Squared | 0,8618 |
| Predicted R-Squared | 0,7026 |

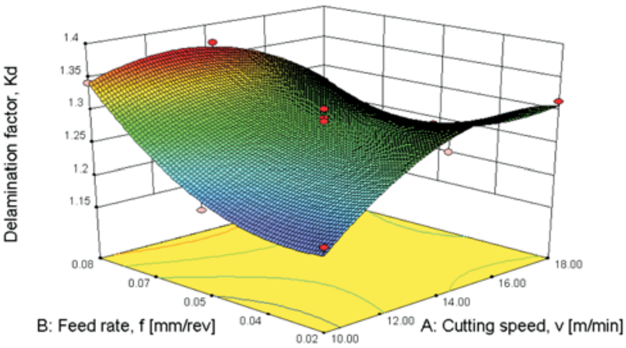


**Figure 12** The dependence of delamination factor on cutting parameters for HSS-Co twist drill

Model for delamination factor can be described by equation in terms of coded factors:

$$K_{\mathrm{d}} =+1{,}28+0{,}017 \cdot A+0{,}034 \cdot B-0{,}048 \cdot A \cdot B- -0{,}053 \cdot A^2+0{,}055 \cdot B^2. \quad (14)$$

And final equation in terms of actual factors:

$$K_{\mathrm{d}} =+0{,}38410+0{,}11703 \cdot v+0{,}57921 \cdot f- -0{,}39583 \cdot v \cdot f-0{,}00332 \cdot v^2+60{,}95785 \cdot f^2. \quad (15)$$

### Multi Constructional twist drill

**Table 19** Analysis of variance – delamination factor for Multi Constructional twist drill

| Source | Sum of squares | Degrees of freedom | Mean square | $F$ value | $P$ value Prob > $F$ |
|---|---|---|---|---|---|
| **Model** | 1,964E-003 | 2 | 9,821E-004 | 12,76 | 0,0018 |
| $A$ – Cutting speed | 1,441E-003 | 1 | 1,441E-003 | 18,73 | 0,0015 |
| $B$ – Feed rate | 5,227E-004 | 1 | 5,227E-004 | 6,79 | 0,0262 |
| **Residual** | 7,695E-004 | 10 | 7,695E-005 | | |
| Lack of fit | 2,507E-004 | 6 | 4,179E-005 | 0,32 | 0,8955 |
| Pure error | 5,188 E-003 | 4 | 1,297E-004 | | |
| **Cor total** | 2,734E-003 | 12 | | | |

The Model $F$-value of 12,76 implies the model is significant. In this case $A$, $B$ are significant model terms. The overview of statistical data about the model is presented in Tab. 20.

Fig. 13 shows the dependence of delamination factor on cutting parameters.

**Table 20** Summary statistics for the model

| | |
|---|---|
| Standard Deviation | 0,0087 |
| Mean | 1,17 |
| R-Squared | 0,7185 |
| Adjusted R-Squared | 0,6622 |
| Predicted R-Squared | 0,6003 |

Model for delamination factor can be described by equation in terms of coded factors:

$$K_{\mathrm{d}} =+1{,}17-0{,}015 \cdot A+0{,}0093 \cdot B. \quad (16)$$

And final equation in terms of actual factors:

$$K_{\mathrm{d}} =+1{,}21154-0{,}00387 \cdot v+0{,}31111 \cdot f. \quad (17)$$

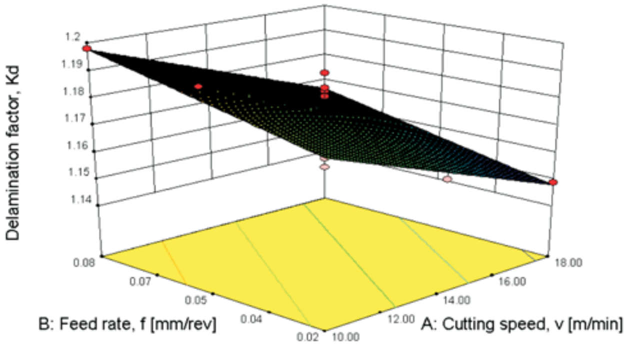


**Figure 13** The dependence of delamination factor on cutting parameters for MultiConstructional twist drill

### "Brad & Spur" drill

**Table 21** Analysis of variance – delamination factor for "Brad & Spur" drill

| Source | Sum of squares | Degrees of freedom | Mean square | $F$ value | $P$ value Prob > $F$ |
|---|---|---|---|---|---|
| **Model** | 0,031 | 5 | 6,116 E-003 | 52,50 | < 0,0001 |
| $A$ – Cutting speed | 0,010 | 1 | 0,010 | 89,42 | < 0,0001 |
| $B$ – Feed rate | 0,011 | 1 | 0,011 | 93,76 | < 0,0001 |
| $AB$ | 1,980 E-003 | 1 | 1,980 E-003 | 17,00 | 0,0044 |
| $A^2$ | 1,717 E-003 | 1 | 1,717 E-003 | 14,74 | 0,0064 |
| $B^2$ | 2,816E-003 | 1 | 2,816E-003 | 24,17 | 0,0017 |
| **Residual** | 8,155E-004 | 7 | 1,165 E-004 | | |
| Lack of fit | 4,107E-004 | 3 | 1,369E-004 | 1,35 | 0,3765 |
| Pure error | 4,048E-004 | 4 | 1,012E-004 | | |
| **Cor total** | 0,032 | 12 | | | |

The Model $F$-value of 52,50 implies the model is significant. In this case $A$, $B$, $AB$, $A^2$, $B^2$ are significant model terms. The overview of statistical data about the model is presented in Tab. 22.

Fig. 14 shows the dependence of delamination factor on cutting parameters.

**Table 22** Summary statistics for the model

| | |
|---|---|
| Standard Deviation | 0,011 |
| Mean | 1,13 |
| R-Squared | 0,9740 |
| Adjusted R-Squared | 0,95550 |
| Predicted R-Squared | 0,8541 |

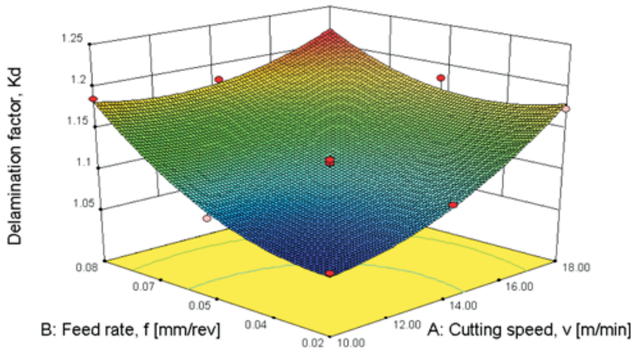


**Figure 14** The dependence of delamination factor on cutting parameters for "Brad & Spur" drill

Model for delamination factor can be described by equation in terms of coded factors:

$$K_{\mathrm{d}} = +1{,}10 + 0{,}042 \cdot A + 0{,}043 \cdot B - 0{,}022 \cdot A \cdot B + + 0{,}025 \cdot A^2 + 0{,}032 \cdot B^2. \quad (18)$$

And final equation in terms of actual factors:

$$K_{\mathrm{d}} = +1{,}14981 - 0{,}023942 \cdot v + 0{,}47016 \cdot f - - 0{,}18542 \cdot v \cdot f + 0{,}00155 \cdot v^2 + 35{,}47893 \cdot f^2. \quad (19)$$

## 3 Conclusion

Based on the experimental results presented, the following conclusions can be drawn.

In the experimental part of the work thrust force, drilling torque and delamination factor when drilling carbon fibre reinforced carbon composite materials were measured.

The obtained results were processed by means of the "DesignExpert" software package which generated the models which show the influence of the cutting paremeters.

Experimental results show that the feed rate and cutting speed are the main parameters that influence the thrust force and delamination.

Delamination increases with both cutting parameters, which means that the damage is bigger for higher cutting speed and for higher feed rate.

The "Brad & Spur" drill produces less damage than the HSS-Co twist drill and Multi Construction twist drill, the delamination factor is smaller.

The "Brad & Spur" drill presents less thrust force, drilling torque than the HSS-Co and Multi Construction drill.

Thrust force and delamination depend on the cutting speed, feed rate and tool geometry.

The HSS-Co twist drill always causes a bigger delamination factor, which means higher damage in composite laminate.

According to the graph, we can observe that the "Brad & Spur" drill presents better performance than the HSS-Co twist drill and Multi Constructional twist drill, under the same cutting conditions (cutting speed and feed rate).

## 4 References

[1] Hocheng, H.; Puw, H. On drilling characteristics of fiber-reinforced thermoset and thermoplastics. // International Journal of Machine Tools and Manufacture, 32, 4(1992), pp. 583-592.

[2] Chen, W. C. Some experimental investigation in drilling of carbon fiber-reinforced plastic (CFRP) composite laminates. // International Journal of Machine Tools and Manufacture, 37, 8(1997), pp. 1097-1108.

[3] Lin, S. C.; Chen, I. K. Drilling carbon fiber-reinforced composite material at high speed. // Wear, 194, (1996), pp. 156-162.

[4] Koenig, W.; Grass, P.; Heintze, A.; Okcu, F.; Schmitz-Justin, C. Developments in drilling contouring composites containing Kevlar. // Production Engineer, 63, 8(1984), pp. 56-61.

[5] Koenig, W.; Wulf, C.; Grass, P.; Willerscheid, H. Machining of fibber reinforced plastic. // Annals of the CIRP, 34, 2(1985), pp. 538-548.

[6] Dharan, C. K. H.; Won, M. S. Machining parameters for intelligent machining system for composite laminates. // International Journal of Machine Tools and Manufacture, 40, 3(2000), pp. 415-426.

[7] Enemouh, U. E.; El-Gizawy, S. A.; Chukwujekwu, O. A. An approach for development of damage-free drilling of carbon fiber reinforced thermosets. // International Journal of Machine Tools and Manufacture, 41, 12(2001), pp. 1795-1814.

[8] Hocheng, H.; Dharan, C. K. H. Delamination during drilling in composite laminates. // Journal of Engineering Industry, 112, (1990), pp. 236-239.

[9] Koboević, N. Optimizacija procesa izrade otvora bušenjem u kompozitnim materijalima, Doktorska disertacija, Sveučilište u Mostaru, Fakultet strojarstva i računarstva, Mostar, 2010.

**Authors' addresses**

***Nikša Koboević, Ph.D.***
University of Dubrovnik
Ćira Carića 4
20000 Dubrovnik, Croatia
e-mail: niksa@unidu.hr

***Docent Mate Jurjević, Ph.D.***
University of Dubrovnik
Ćira Carića 4
20000 Dubrovnik, Croatia
e-mail: mjurjevic@unidu.hr

***Žarko Koboević, Mech. Eng.***
University of Dubrovnik,
Ćira Carića 4
20000 Dubrovnik, Croatia
e-mail: zarko.koboevic@unidu.hr