A Study on the Derivation of Parametric Cutting Force Equations in Drilling of GFRP Composites

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The aim of the present work is to derive machine force equations in the drilling of [0°/+45°/90°/–45°] oriented glass fiber reinforced polymeric matrix composites (GFRP). The novelty is in the use of the Shaw and Oxford model, which was initially developed for metals, for GFRP composites. The machining was performed on the GFRP samples using 118° point angle drills under dry conditions. During machining, drill torques and thrust force fluctuations were recorded using a dynamometer–amplifier–computer combination with different feed rates and drill diameters. The collected data were then analysed using mathematical models to investigate the empirical relationships between the essential parameters. The cutting forces in the drilling of GFRP materials were calculated using empirical equations and the results were compared with the measured data to verify the accuracy of the derived equations for the drilling of glass fiber reinforced polymer matrix materials. Moreover, the whole surface morphology of the drilled GFRP samples was examined by optical microscope and scanning electron microscope (SEM).
Keywords: glass fiber reinforced polymer (GFRP), machinability, surface morphology, thrust force, drill torque, empirical equation

1 INTRODUCTION

Glass fiber reinforced polymer matrix (GFRP) composite materials offer superior properties such as high specific strength, high specific modulus of elasticity, high damping capacity, good corrosion resistance, good tailoring ability, excellent fatigue resistance, good dimensional stability and a low coefficient of thermal expansion [1] to [8]. Hence, they are used in many fields, such as the automotive, aerospace, sporting goods, marine, chemical industry, electrical industry, etc. [5], [6], [8] and [9]. In these fields, the drilling of GRFP composite materials is generally needed for the joining of composite structures. However, drilling of GFRP implies coping with problems that are not encountered when machining other conventional materials. The drilling of GFRP composite materials may lead to widespread damage and may cause many problems, such as fiber delamination, fiber breakage, fiber pull out, stress concentration, thermal damage, microcracking, etc. due to the inhomogeneity and anisotropic nature of GFRP composite materials [4], [5] and [10]. These problems cause aesthetic problems, but may also compromise the mechanical properties of the finished part [4]. For this reason, numerous researchers have investigated the GFRP drilling process and reported the factors that affect the quality of the finished part. Hence, many researchers have investigated the influence of these factors in the drilling of GFRP composites [5] to [7] and [9] to [12]. Moreover, many researchers have investigated the effects of various parameters (cutting speed, feed rate, point angle, thrust force, cutting tool geometry, etc.) particularly on the delamination behavior of GFRP composites [13] to [17]. In addition to these studies, some researchers

have investigated the modelling of the drilling of materials. Unfortunately, most of the models developed for metals have proved to be unsuitable for composites, as the cutting mechanism is different [17] to [20]. In the literature survey on machining it was observed that only the action of the cutting lips and the chisel edge are generally considered in modelling, however in the machining stage several types of damages observed in composite drilling are directly related to cutting force and torque. In particular, the structural damages mentioned above can be related to the thrust force during drilling. The presence and extension of the different kinds of damage depend on the composite material characteristics, tool geometry and material, and the process parameters [21] to [25]. The damage is particularly detrimental to the residual mechanical properties and significantly reduces the composite performance in use. Consequently, special care should be given to avoid the generation of defects during drilling. Therefore, it is particularly important when modelling the cutting action to derive analytical equations that predict the machining forces as a function of process parameters.

In the present work, the aim is to derive machine force equations for the drilling of GFRP composites. Thus, GFRP composite material was drilled in a specially designed drilling system and drill torques and thrust force fluctuations were recorded using a dynamometer–amplifier–computer combination with different feed rates and drill diameters. The appropriate model for drilling GFRP was chosen and its performance tested on GFRP. The experimental data were examined using mathematical models to investigate the empirical relationships between essential parameters. The cutting forces in the drilling of GFRP materials were calculated using empirical

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equations and the results were compared with the measured data to verify the accuracy of the derived equations for the drilling of glass fiber reinforced polymer matrix materials. Moreover, following investigation of the test data for the derivation of empirical equations, hole surface morphology of GFRP samples were investigated using an optical microscope and scanning electron microscope (SEM).

2 EXPERIMENTAL PROCEDURES

2.1 Specimen Preparation and Mechanical Properties

In this study, [0°/+45°/90°/–45°] oriented glass fiber reinforced polymer matrix composite samples were used. Samples were cut to 200×37×10 mm rectangles from 200×200×10 mm plates. Properties of the laminate are presented in Table 1. The polymeric matrix material is an orthophtalic polyester and composite laminates were produced using the vacuum assisted resin transfer molding technique.

Table 1. *Properties of composite samples*

Fiber type	Density [g/m³]	Number of laminates	Hardness of Brinell
Glass	940	14	43.1 HB

2.2 Equipments and Machine Tools Used in the Test Set-up

In the experiment, an Arsenal PK–40 drilling machine was used. Properties of the drill machine are shown in Table 2.

Table 2. *Feed rates and angular speed of main shaft of drilling machine*

Trade name of drilling machine	Arsenal PK–40
Main drill shaft speed-range	5 to 1500 rev/min
Automatic feed rate of drill shaft	0.1 to 0.40 mm/rev
Main drive power	2.2 kW

Other equipment used in addition to the drilling machine are four axes piezoelectric type Kistler drill dynamometers and their auxiliary devices for measuring machining forces. Thus, the measurement set up combination consists of a Kistler–9272 drill dynamometer, Kistler–5070A amplifier and computer. When machining, the signal produced by the dynamometer related to the thrust force and torque is transferred by RS–232 connection to the computer. The data acquisition process is performed using a program called as DynoWare written by Kistler Co. In the drilling of GFRP samples, DIN 338 HSS drills with a right hand helical form and 118° point angle with four different diameters were used.

2.3 Drilling Process of GFRP Samples

Tests were performed without using any coolant in the drilling operation. The revolution of the drill machine spindle was set at a constant speed of 265 rpm. Machining of the GFRP samples was performed with different diameters of drills and different feed rates. The drilling force measurement plan for GFRP material is shown in Table 3. To minimize vibration during machining, ythe drill dynamometer was fixed to the table of the machine table rigidly without distorting the sensitive parts of the device. Then, all connections between the stations for measuring and data acquisition were made. Drill studies were performed by using the drill force measurement plan. Each drill was worked with samples at four different feed rates.

Table 3. *Drill force measurement plan*

Spindle rpm [rev/min]	Drill diameter [mm]	Feed Rate [mm/rev]			
265	4	0.10	0.16	0.25	0.40
265	6	0.10	0.16	0.25	0.40
265	8	0.10	0.16	0.25	0.40
265	10	0.10	0.16	0.25	0.40

These combinations were repeated five times on the GFRP samples. The collected results were then analyzed using the DynoWare–Kistler data acquisition program. Mean values of the fluctuation curve due to thrust force and torque were determined and the tabulated data were used to investigate the empirical equations.

3 RESULTS AND DISCUSSIONS

3.1 Derivation of Drill Torque Equation on GFRP

A cutting model for drilling was chosen to study the empirical equations related to the forces in a drilling process performed on GFRP. We chose to use Shaw and Oxford's drill model. Since this model was originally used on metal cutting parameters, it was not clear from the outset whether the model would be suitable for detection of the cutting forces on GFRP. Thus, the study also tests the validity of the proposed model. Using Eq. (1) and the collected test data, the empirical torque equation with respect to drill diameter and drill feed rate was determined [26] and [27]. In Eq. (1), *a* is evaluated by the relationship

between the specific cutting energy, *u* and *f·d* [26]. For a given GFRP material, *s* is considered a constant in order to simplify the complex calculations.
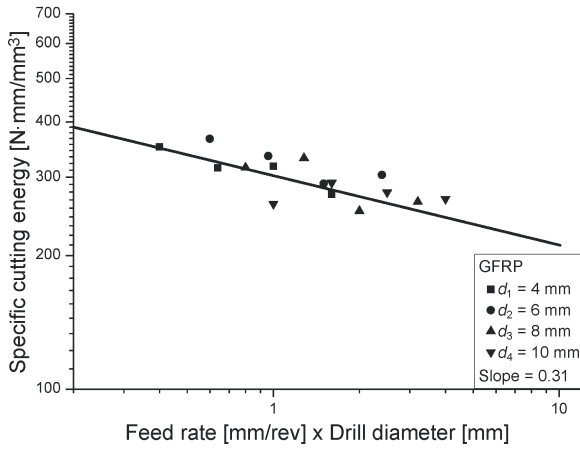

Fig. 1. *Specific energy u versus f·d in drilling*

The test data is checked using Eq. (1) to see whether there is a correlation between the measured and calculated values using the [26] to [30].

$$\frac{M_d}{d^3 H_B} = K_6 \frac{s^{2a} f^{1-a}}{d^{1+a}} \left[\frac{f^{0.8}}{d^{1.2}} \frac{1-(\frac{c}{d})^2}{1+(\frac{c}{d})^a} + K_7 (\frac{c}{d})^{2-a} \right], \quad (1)$$

where M_d is drill torque, [N·cm], H_B Brinell hardness of GFRP samples, [kg/mm²], f feed rate, [mm/rev], d drill diameter, [mm], S the average distance between imperfections in the material, [mm] and a, K_6, K_7 constants.

Specific cutting energy is defined as given in Eq. (2) [24] to [25]:

$$U = \frac{8 M_d}{f d^2}. \quad (2)$$

Fig. 1 shows the use of the test results on the evaluation of specific cutting energy versus (*f·d*) drawn in logarithmic scale. From the slope of the regression curve, the *a* value was determined to be *a* = 0.31.

After determination of drill torque data, "feed rate versus drill torque" and "drill diameter versus drill torque" graphics were drawn on a logarithmic scale to find out the relationship between of them. The graphics are shown in Figs. 2 and 3, respectively.
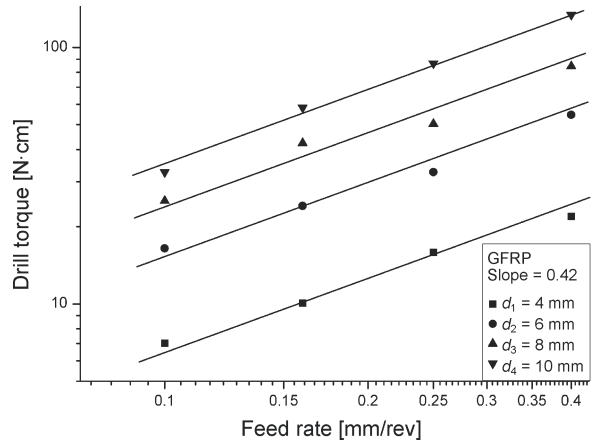

Fig. 2. *Drill torque versus to drill feed rate on GFRP*

The slope of the curves in Figs. 4 and 5 are as 0.42 and 0.51, respectively. The ratio [*c/d*], which is the ratio of length of the chisel edge to drill diameter, taken as a constant (0.213) for the drills used in the experiments [26].
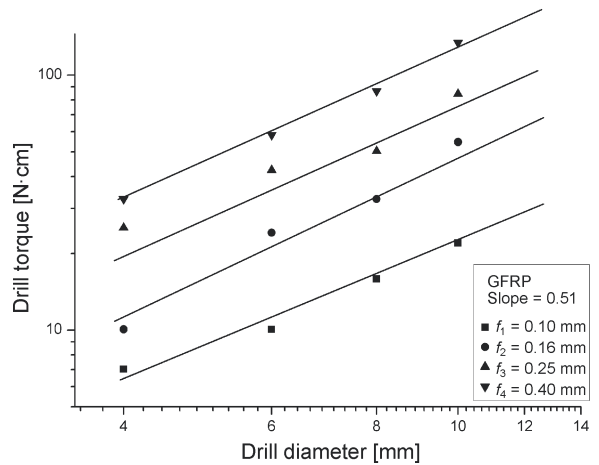

Fig. 3. *Drill torque versus to drill diameter on GFRP*

Consequently Eq. (1) can be transformed into a simplified form as given in Eq. (3) by substituting these numerical values.

$$M_d = K_8 f^{0.42} d^{0.51}, \quad (3)$$

or

$$M_d = K_9 H_B f^{0.42} d^{0.51}. \quad (4)$$

In Fig. 1, the value of the specific energy on the vertical line cut by the regression curve shown to be around 390 N/mm². Using this value, Eqs. (5) to (7) can be derived for the drill torque in GFRP.

$$U = \frac{8 M_d}{f d^2} = \frac{390}{(f d)^{0.31}}, \quad (5)$$

$$M_d = \frac{390\,f\,d^2}{8(f\,d)^{0.31}} = 48.75\,f^{0.69}d^{1.69}, \qquad (6)$$

$$M_d = K_8\,f^{0.42}d^{0.51} = 48.75\,f^{0.69}d^{1.69}. \qquad (7)$$

By inserting material hardness into Eqs. (7) and (8), the final Eq. (9) can be determined.

$$K_8 = 48.75\,f^{0.27}\,d^{1.18} = K_9\,H_B, \qquad (8)$$

$$K_9 = 1.131\,f^{0.27}\,d^{1.18}. \qquad (9)$$

Eq. (9) is then inserted in Eq. (4). Thus, the required drilling torque on glass fiber reinforced polyester composite material can be derived as given in Eq. (10).

$$M_d = 0.131\,H_B\,f^{0.69}\,d^{1.69}. \qquad (10)$$

3.2. Derivation of the Drill Thrust Force Equation on GFRP

With the help of dimensional analysis, Shaw and Oxford's parametric relation for drill thrust force is presented in Eq. (11) [26].

$$\frac{T_v}{d^2 H_B} = K_{13}S^{2a}\frac{f^{1-a}}{d^{1+a}}\left[\frac{1-\frac{c}{d}}{(1+\frac{c}{d})^a}+K_{14}(\frac{c}{d})^{1-a}\right]+$$

$$+K_{12}(\frac{c}{d})^2, \qquad (11)$$

where T_v is axial force [daN], K_{12}, K_{13}, K_{14} are constants and $a = 0.31$.

In the Eq. (11), the value of a has been calculated to be $a = 0.3$. Moreover s, which is the distance between imperfections in the material, is taken to be a constant value ($s = 1$) for simplification. The thrust force equation can then be defined by Eq. (12).

$$\frac{T_v}{d^2 H_B} = K_{15}\frac{f^{0.69}}{d^{1.31}}\left[\frac{1-\frac{c}{d}}{(1+\frac{c}{d})^{0.31}}+K_{14}(\frac{c}{d})^{0.69}\right]+$$

$$+K_{12}(\frac{c}{d})^2. \qquad (12)$$

After performing machining, the collected data related to thrust force are plotted in logarithmic scale and the corresponding graphs are drawn with combinations of "Thrust force versus to feed rate" and "Thrust force versus to drill diameter" in Figs. 4 and 5, respectively.
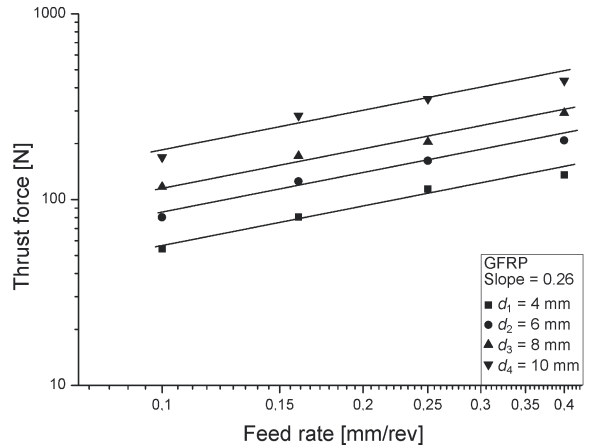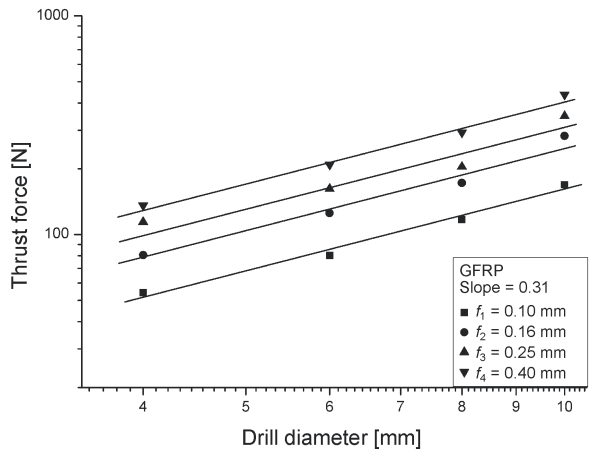

Fig. 4. *Thrust force versus feed rate*
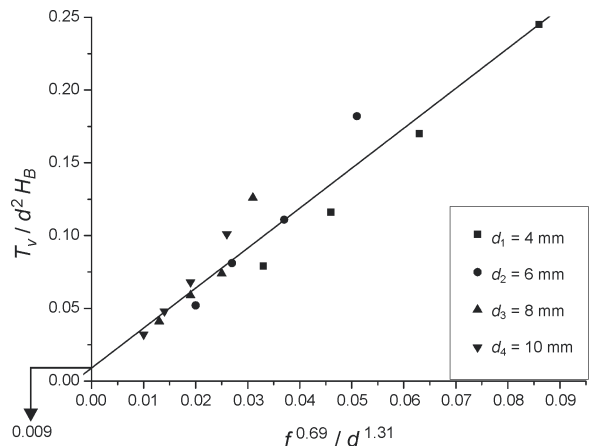

Fig. 5. *Thrust force versus drill diameter*

Fig. 6. *Graphic representation of the relationship between*

$$\{\frac{T_v}{d^2 H_B}\}\ vs\ \{\frac{f^{0.69}}{d^{1.31}}\}.$$

The measured data are input into the thrust force Eq. (12). Then the relationship between the

parameters $\{\frac{T_v}{d^2 H_B}\}$ vs $\{\frac{f^{0.69}}{d^{1.31}}\}$ can be determined as shown in Fig. 6. The equation of the line in Fig. 6 has been derived as given in Eq. (13). The equation for this line defines teh "thrust force" in drilling of GFRP samples.

$$T_v = 2.7576\, H_B\, f^{0.69}\, d^{0.69} + 0.009\, H_B\, d^2\, [\text{N}]. \quad (13)$$

3.3 Comparison of the Theoretical Results and Experimental Results

In this section, the theoretical results of the drill torque and thrust values were calculated by using derived empirical equations as a function of feed rate and drill diameter. The results were then compared with the experimental records. In Figs. 7 and 8 comparisons of the theoretical and empirical data on drill torques and thrust force are given as a function of feed rate and drill diameter.
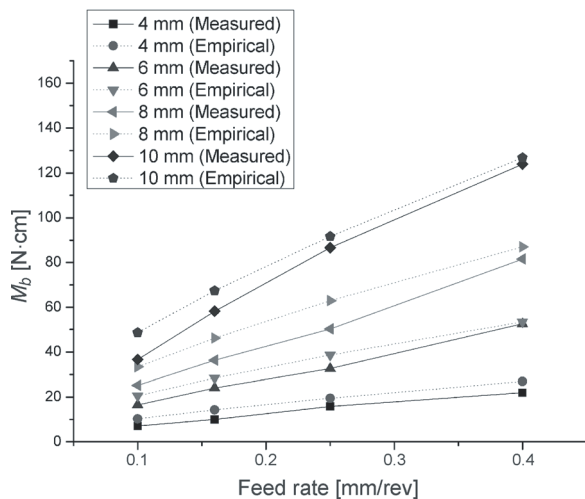

Fig. 7. *Comparison of experimental and theoretical drill torque values as a function of feed rate and drill diameter*

Machining of composite materials differs significantly in many respects from machining of conventional metals and their alloys. In the machining of composites, the material behavior is not only non-homogeneous and anisotropic, but it also depends on diverse reinforcement and matrix properties, as well as on the volume fraction of matrix and reinforcement. The tool encounters, alternatively, matrix and reinforcement materials, whose response to machining can be entirely different. Graphics shows good correlations between the measured and calculated values. Nominal fluctuation of the

measured and theoretical values is around 5% and this is an acceptable level for this kind of handmade artificial materials. In Fig. 8, the variation between the experimental and theoretical drill trust values of the samples drilled with 10 mm drills seems greater compared to the samples drilled with 4mm, 6mm, and 8mm drills. The reason for this result can be explained by the higher probability of encountering imperfections, due to the inhomogeneous nature of the GFRP composites, with the increase in the tool diameter.
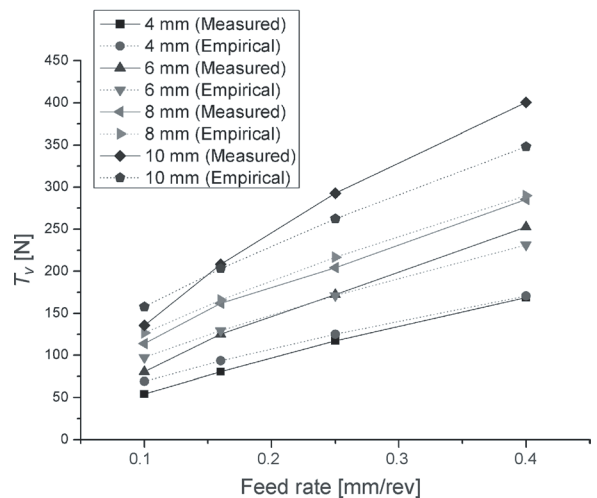

Fig. 8. *Comparison of experimental (a) and theoretical (b) drill thrust values as a function of feed rate and drill diameter*

3.4 Investigation of Hole Surface Morphology of Drilled GFRP Samples

The important topic in the machining of a composite material is to detect real hole entry defects, the circular defect and damage from a heat source in the wall of the hole, the lamination at the exit hole. Therefore, following analysis of test data for the derivation of empirical equations, hole surface morphology of GFRP samples was investigated by using an optical microscope and scanning electron microscope (SEM). From the various machining operations, a brief summary of drilling performance and defects has been presented below, with views of the samples. As expected, all forms of defects occurred as shown in Figs. 9 and 10. In Fig. 9, the exit side of the tools from the samples with delaminated fibers are shown. As seen in Figs. 9a, b, c and d, limited delaminations were observed on the drilling surfaces. Such limited delaminations may not cause remarkable defects in GFRP composites. However, for further understanding of delaminations and cutting effects in GFRP holes,
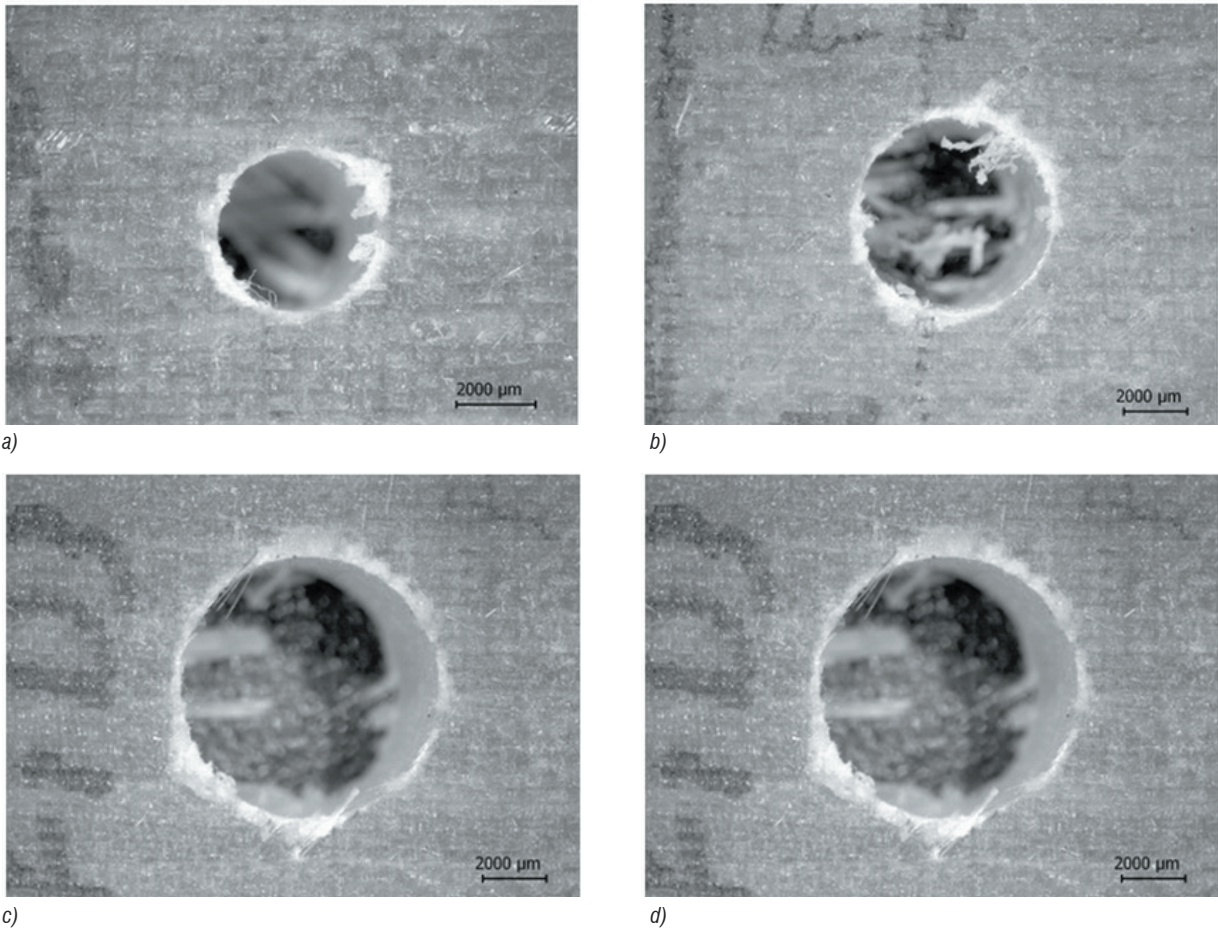
a)

b)

c)

d)

Fig. 9. *View of exit side of the drilled GFRP samples machined by: (a) 4 mm drill, (b) 6 mm drill, (c) 8 mm drill and (d) 10 mm drill*

samples were cut from the axis of the tool, and then the surfaces cut by the lips of the drills are shown in Fig. 10 with the help of a SEM. The polyester matrix and glass fibers can be seen clearly in Figs. 10a and b. Good adhesion between the matrix and fibers is observed in these figures. In Fig. 12c and d, fiber tips broken during the drilling process are shown. As seen in Figs. 10c and d, fibers were broken in a brittle manner during the drilling process. However, they remained embedded in the polyester matrix and limited delaminations were observed. From Figs. 9 and 10, we can conclude that glass fibers have a strong adhesion to the polyester matrix. Thus, it has been determined that surface quality and dimensional ovality are at an acceptable level for mechanical connecting using bolts.

4 CONCLUSIONS

From the above study on the derivation of empirical equations related to GFRP using a conventional drill, the following results can be summarized.

1) It was determined that when the drill diameter and feed rate are increased while machining GFRP, the thrust force and drill torque increase. This result also verifies that if the drill diameter is increased then the un–deformed chip material volume increases. This means that for processing of continuous chip formation at high feed rates, a higher power requirement is demanded by the tool to get rid of cutting, friction and extrusion forces. This creates high torque and thrust forces in the machining operations.

2) In this study, the model we used, which was developed for metals by Shaw and Oxford, showed very good accordance with the derivation of the empirical relationship for the drilling of
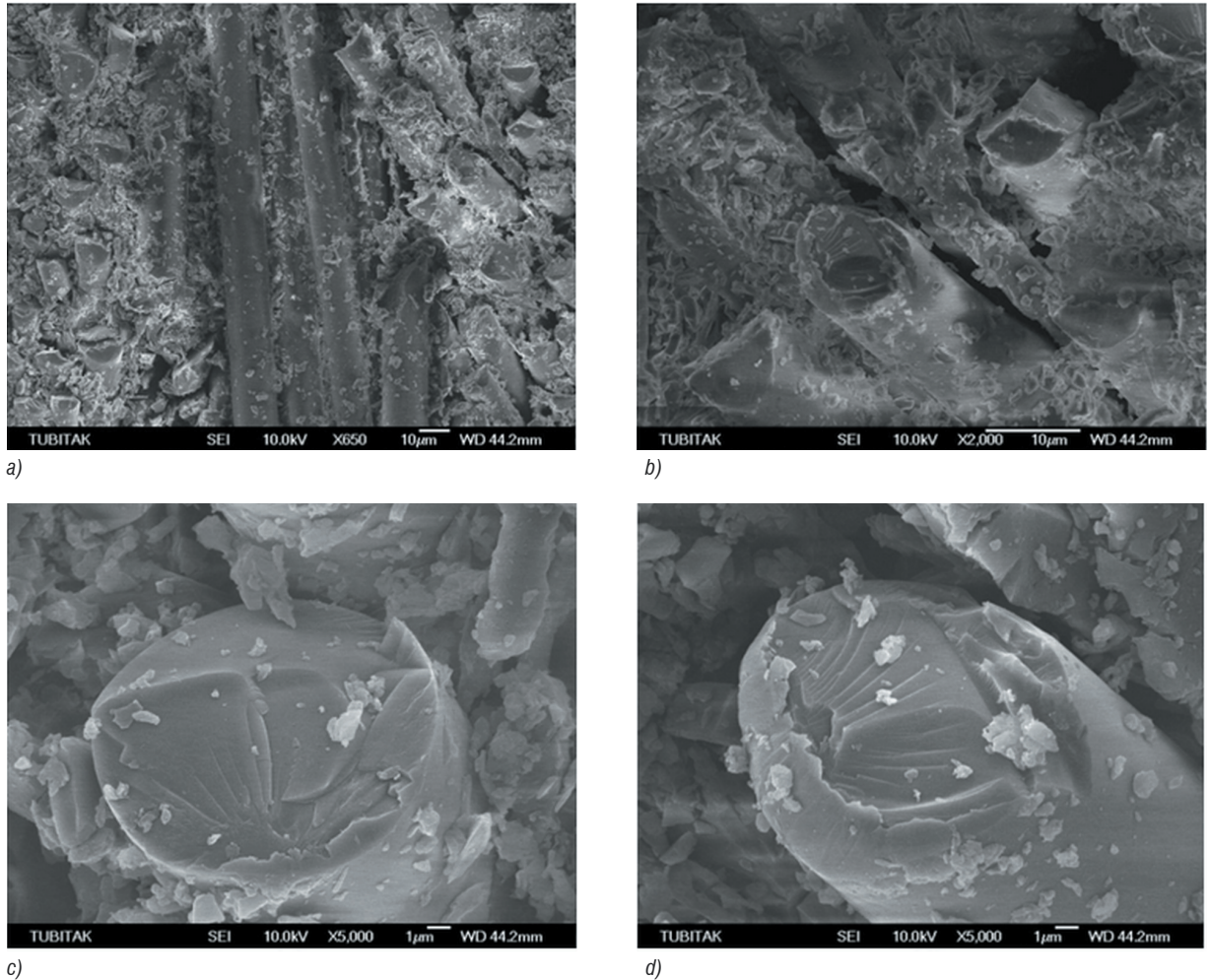
a)

b)

c)

d)

Fig. 10. *SEM photos of; (a) vertical cut of the drill holes and (c) view surfaces of drilled GFRP samples under different magnifications*

glass fiber reinforced oriented "0°/+45°/90°/-45°" in the polymer matrix composite. As a conclusion, the equations presented below can be used to estimate the machining forces on drilling operations for the defined composites. The empirical equations for torque and thrust forces are given below;

Torque equation:

$$M_d = 0.131 H_B f^{0.69} d^{1.69} \, [\text{N cm}],$$

Thrust force equation:

$$T_v = 2.7576 H_B f^{0.69} d^{0.69} + 0.009 H_B d^2 \, [\text{N}].$$

3) Comparing the measured and empirical results for drilling forces, some differences have been determined. These differences are unavoidable due to the microstructure of the GFRP. Not surprisingly, the machining characteristics of the composite materials with a non-isotropic nature

results in fluctuations compared to homogenous and isotropic or quasi- isotropic materials. Therefore, cutting force fluctuation should be expected from the machining of these kinds of materials. However, these differences are not that important for estimating the level of machining forces by empirical equations as empirical equations give approximate values to engineers not exact ones. Finally by tolerating some of the deviations, the derived empirical relations for similar types materials can be used effectively to give some design and constructive ideas.

4) In this study, the main aim was to determine the relationship between cutting forces and the essential parameters of the machining tool. Additionally, machined hole quality and damage development due to drill feeding of the material were also very important. Delamination of the

fibers occurred at the exit side of the holes, although it was determined that surface quality and dimensional ovality are at an accepted level for mechanical connecting with bolts. Surface quality and roughness of the machined holes are due to structural discontinuities in the GFRP. Discontinuities of the artificial materials were also determined to be essential reasons for the force fluctuations.

5) Chisel edge length relative to drill diameter is indicative of delamination of GFRP due to increasing thrust force [31]. This effect also can be seen somewhat in the Fig. 8 by increases in the mesured thrust force rather than by the calculated data for the same cutting parameters.

6) Structural parts made of composite frequently have to be drilled in the structural, aircraft and automobile industries. However, little is known about the conditions between the drilling tool and material. This study aimed to show whether the model verified for ferro-alloys can be used for pre-estimation of drilling forces in the machining of GFRP composites. It has been proven that drilling forces applied to construction parts designed for the structural and machine industry can be easily determined. This will help to prevent excessive force application during these processes in order to prevent damage to composite structures.

5 REFERENCES

[1] Abrao, A.M., Faria, P.E., Rubio, J.C., Reis, P., Davim, J.P. (2007). Drilling of fiber reinforced plastics: A Review. *Journal of Material Processing Technology*, vol. 186, no. 1-3, p. 1-7, DOI:10.1016/j.jmatprotec.2006.11.146.

[2] Tsao, C.C., Hocheng, H. (2007). Effect of tool wear on delamination in drilling composite materials. *International Journal of Mechanical Sciences*, vol. 49, no. 8, p. 983-988, DOI:10.1016/j.ijmecsci.2007.01.001.

[3] Arul, S., Vijayaraghavan, L., Malhotra, S.K., Krishnamurthy, R. (2006). The effect of vibratory drilling on hole quality in polymeric composites. *International Journal of Machine Tools and Manufacture*, vol. 46, no. 3-4, p. 252-259, DOI:10.1016/j.ijmachtools.2005.05.023.

[4] Davim, J.P., Rubio, J.C., Abrao, A.M. (2007). A novel approach based on digital image analysis to evaluate the delamination factor after drilling composite laminates. *Composite Science and Technology*, vol. 67, no. 9, p. 1939-1945, DOI:10.1016/j.compscitech.2006.10.009.

[5] Palanikumar, K. (2010). Modeling and analysis of delamination factor and surface roughness in drilling GFRP composites. *Materials and Manufacturing Processes*, vol. 25, no. 10, p. 1059-1067, DOI:10.1080/10426910903575830.

[6] Arul, S., Samuel, R., Vijayaraghavan, L., Malhotra, S.K., Krishnamurthy, R. (2006). Modeling and Optimization of Process Parameters for Defect Toleranced Drilling of GFRP Composites. *Materials and Manufacturing Processes*, vol. 21, no. 4, p. 357-365, DOI:10.1080/10426910500411587.

[7] Latha, B., Senthilkumar, V.S. (2009). Analysis of thrust force in drilling glass fiber-reinforced plastic composites using fuzzy logic. *Materials and Manufacturing Processes*, vol. 24, no. 4, p. 509-516, DOI:10.1080/10426910802714688.

[8] Ramkumar, J., Malhotra, S.K., Krishnamurthy, R. (2002). Studies on drilling of glass/epoxy laminates using coated high-speed steel drills. *Materials and Manufacturing Processes*, vol. 17, no. 2, p. 213-222, DOI:10.1081/AMP-120003531.

[9] Palanikumar, K., Prakash, S., Shanmugam, K. (2008). Evaluation of delamination in GFRP composites. *Materials and Manufacturing Processes*, vol. 23, no. 8, p. 858-864, DOI:10.1080/10426910802385026.

[10] Faraz, A., Heymann, T., Biermann, D. (2011). Experimental investigations on drilling GFRP epoxy composite laminates using specialized and conventional uncoated cemented carbide drills. *Materials and Manufacturing Processes*, vol. 26, no. 4, p. 609-617, DOI:10.1080/10426911003636969.

[11] Zhang, J.Z., Chen, J.C. (2009). Surface roughness optimization in a drilling operation using the taguchi design method. *Materials and Manufacturing Processes*, vol. 24, no. 4, p. 459-467, DOI:10.1080/10426910802714399.

[12] Bhatnagar, N., Singh, I., Nayak, I. (2004), Damage investigation in drilling of glass fiber reinforced plastic composite laminates. *Materials and Manufacturing Processes*, vol. 19, no. 6, p. 995-1007, DOI:10.1081/AMP-200034486.

[13] Gaitonde, V.N, Karnik, S.R., Rubio, J.C., Correia, A.E., Abrao, A.M., Davim, J.P. (2008). Anaylsis of parametric influence on delamination in high-speed drilling of carbon fiber reinforced plastic composites. *Journal of Materials Processing Technology*, vol. 203, no. 1-3, p. 431-438, DOI:10.1016/j.jmatprotec.2007.10.050.

[14] Rubio, J.C., Abrao, A.M., Faria, P.E., Correia, A.E., Davim, J.P. (2008). Effects of high speed in the drilling of glass reinforced plastics: Evaluation of the delamination factor. *International Journal of Machine Tools & Manufacture*, vol. 48, no. 6, p. 715-720, DOI:10.1016/j.ijmachtools.2007.10.015.

[15] Abrao, A.M., Rubio, J.C., Faria, P.E., Davim, J.P. (2008). The effects of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite. *Materials and Design*, vol. 29, no. 2, p. 508-513, DOI:10.1016/j.matdes.2007.01.016.

[16] Davim, J.P., Reis, P., Antonio, C.C. (2004). Drilling fiber reinforced plastics (FRPs) manufactured

by hand lay-up: influence of matrix (Viapal VUP 9731 and ATLAC 382-05). *Journal of Material Processing Technology*, vol. 155-156, p. 1828-1833, DOI:10.1016/j.jmatprotec.2004.04.173.

[17] Mauch, C.A., Lauderbaugh, L.K. (1990). Modeling the drilling processs – An analytica model to predict thrust force and torque, computer modeling and simulation of manufacturing processes. *ASME Production Engineering Division*, vol. 48, p. 59-65.

[18] Armarego, E.J.A., Wright, J.D. (1984). Predictive models for drilling thrust and torque—a comparison of three flank configurations. Ann CIRP, vol. 33, no. 1, p. 5-10, DOI:10.1016/S0007-8506(07)61368-7.

[19] Ehmann, K.F., Kapoor, S.G., DeVor, R.E., Lazoglu, I. (1997). Machining process modeling: A review. *Journal of Manufacturing Science and Engineering*, vol. 119, no. 4B, p. 655-659, DOI:10.1115/1.2836805.

[20] Chandrasekharan, V., Kapoor, S.G., DeVor, R.E. (1995). A mechanistic approach to predicting the cutting forces in drilling: with application to fiber-reinforced composite materials. *ASME Journal of Engineering for Industry*, vol. 117, no. 4, p. 559-570, DOI:10.1115/1.2803534.

[21] El-Sonbaty, I., Khashaba, U.A., Machaly, T. (2004). Factors affecting the machinability of GFR/epoxy composites. Composite Structures, vol. 63, no. 3-4, p. 329-338, DOI:10.1016/S0263-8223(03)00181-8.

[22] Tagliaferri, V., Caprino, G., Diterlizzi, A. (1990). Effect of drilling parameters on the finish and mechanical properties of GFRP composites. *International Journal of Machine Tools and Manufacture*, vol. 30, no. 1, p. 77-84, DOI:10.1016/0890-6955(90)90043-I.

[23] Caprino, G., Tagliaferri, V. (1995). Damage development in drilling glass fibre reinforced plastics. *International Journal of Machine Tools and Manufacture*, vol. 35, no. 6, p. 817-829, DOI:10.1016/0890-6955(94)00055-O.

[24] Di Ilio, A., Tagliaferri, V., Veniali, F. (1991). Cutting mechanisms in drilling of aramid composites. *International Journal of Machine Tools and Manufacture*, vol. 31, no. 2, p. 155-165, DOI:10.1016/0890-6955(91)90001-J.

[25] Veniali, F., Di Ilio, A., Tagliaferri, V. (1995). An experimental study of the drilling of aramid composites. *ASME Journal of Energy Resources Technology*, vol. 117, no. 4, p. 271-278, DOI:10.1115/1.2835423.

[26] Shaw, M.C., Oxford, C.J. (1957). On the drillings of metals: II. The torque and thrust in drilling. *Transaction of. ASME*, vol. 79, p. 139-148.

[27] Karabay, S. (1986). *Design and Construction of a Strain-Gage Type Drill Press Dynamometer and Investigation of Drilling Characteristics of MKEK Ç-1020-Steel*. MSc. Thesis, Middle East Technical University, Ankara.

[28] Langella, A., Nele, L., Maio, A. (2005). A torque and thrust prediction model for drilling composite materials. *Composite Part A*, vol. 36, no. 1, p. 83-93.

[29] Fernandes, M., Cook, C. (2009). Drilling of carbon composites using a one shot drill bit. Part II:Empirical modelling of maximum thrust force. *International Journal of Machine Tools & Manufacture*, vol. 46, no. 1, p. 76-79. DOI:10.1016/j.ijmachtools.2005.03.016.

[30] Fernandes, M., Cook, C. (2006). Drilling of carbon composites using a one shot drill bit. Part II: Empirical modelling of maximum thrust force. *International Journal of Machine Tools & Manufacture*, vol. 46, no. 1, p. 70-75, DOI:10.1016/j.ijmachtools.2005.03.015.

[31] Tsao, C.C., Hocheng, H. (2003). The effect of chisel length and associated pilot hole on delamination when drilling composite material. *International Journal of Machine Tools & Manufacture*, vol. 43, no. 11, p. 1087-1092, DOI:10.1016/S0890-6955(03)00127-5.