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RESEARCH ARTICLE

Measurement and analysis of thrust force and torque in drilling of sisal fiber polymer composites filled with coconut shell powder

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Abstract During the last few years, natural fiber (Sisal) have received much more attention than ever before from the research community. They have an outstanding potential as reinforcement in thermosets, the reinforcing materials are strong with low densities while the matrix is usually a ductile, or tough, material. The natural fiber Reinforced polymer composite materials used in general engineering applications, utilize the advantages offered by renewable resources for the development of polymer composite materials based on polymers, natural fibers and natural shell particles has been made through fabrication of Natural fiber and particulates reinforced polymer (NFPRP) composite material by using vinyl ester resin. Drilling of holes is an important machining operation to determine the assembly operations in complicated composite parts used in engineering applications. The present work focuses on optimization of the operating variable, tool geometry and the prediction of thrust force and torque of the NFPRP composite materials, and the values, compared with the Regression model and the Scheme of Delamination factor using machine vision system.

Keywords CSP · NFPRP · Thrust force · Torque · Regression model · SPSS

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Introduction

Composites are combinations of two materials in which one of the materials, called the reinforcing phase, are in the form of fibers, sheets, or particles, and are embedded in the other materials called the matrix phase. The reinforcing material and the matrix material can be metal, ceramic, or polymer. Typically, reinforcing materials are strong with low densities while the matrix is usually a ductile, or tough, material. If the composite is designed and fabricated correctly, it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material.

Vinylester resins are one of the most important classes of thermosetting polymers which are widely used as matrices for fiber reinforced composite materials and as structural adhesives [1, 2]. They are amorphous, highly cross-linked polymers and this structure results in these materials possessing various desirable properties such as high tensile strength and modulus, uncomplicated processing, good thermal and chemical resistance, and dimensional stability [1]. However, it also leads to low toughness and poor crack resistance, which should be upgraded before they can be considered for many applications [1, 2].

FRP composite use polymers either thermoplastics or thermosets, as matrix and fibers of various types as reinforcement. The fibers of FRP composites give them their mechanical characteristics. The purpose of the matrix material is to bind the fibers together. Since the 1990s, natural fiber composite are rising as realistic alternatives to replacement the glass fiber reinforced composite in many applications. Natural fiber composites material used in automotive application because of lower cost and lower density. Natural fiber composites are also claimed to offer environmental advantages such as reduced dependence on non-renewable energy/material sources, lower pollutant emissions, lower greenhouse gas emission, and enhanced energy recovery and of life biodegradability of components [3]. Natural fibers such as banana, cotton, coir, sisal and jute have attracted the attention of scientists and technologists for application in consumer goods, low cost housing and other civil structures. It has been found that these natural fiber composites possess better electrical resistance, good thermal and acoustic insulating properties and higher resistance to fracture. Natural fibers have many advantages compared to synthetic fibers, for example low weight, low density; low cost, acceptable specific properties and they are recyclable and biodegradable. They are also renewable and have relatively high strength and stiffness and cause no skin irritations. On the other hand, there are also some disadvantages, for example moisture uptake, quality variations and low thermal stability. Many investigations have been made on the potential of the natural fibers as reinforcements for composites and in several cases the result have shown that the natural fiber composites own good stiffness, but the composites do not reach the same level of strength as the glass fiber composite. Sisal fiber has been used as reinforcement in low-density polyethylene. The effect of natural waxy surface layer of the fiber on fiber/matrix interfacial bonding and composite properties has been studied by single fiber pullout test and evaluating the tensile properties of oriented discontinuous fiber composites [4].

Growing attention is nowadays being paid to natural fiber. The incorporation of filler such as coconut shell powder (*CocosNucifera)* into thermosetting materials is used to reduce the production costs of the molded products [5]. Coconut shell powder (*CocosNucifera*) is widely available at very low cost, so it is an ideal filler material in this regard. Coconut shell powder is made from the most versatile part of the coconut which is from the shell where this shell is organic in nature. High filler content, however many adversely affect the processability, ductility and strength of the composites [6].

Investigate the effects of the cutting variables, speed and feed, on the thrust force, torque, and delamination in drilling chopped composites with different fiber volume fractions. Based on the results from this investigation, empirical formulas are developed. Although it is known that the thrust force and torque increases with the increase of the feed, this work provides quantitative measurements of such relationships for the composite materials. On the other hand, increasing the cutting speed reduces the thrust force and the torque. Empirical formulas that determine the cutting forces based on fiber volume fractions, feeds, and speeds are obtained using multivariable linear regression analysis [6].

The evaluation of thrust force and surface roughness produced by candlestick drill using regression analysis of experiments and RBFN. The authors found the feed rate and the drill diameter are recognized the most significant factors affecting the thrust force, while the feed rate and spindle speed are seen to make the largest contribution to the surface roughness. In the confirmation tests, RBFN is demonstrated more effective than multi-variable regression analysis for the evaluation of drilling-induced thrust force and surface roughness in drilling of composite material [7].

A series of experiments were conducted to study the effects of cutting speed as wel1 as other cutting parameters on drilling characteristics, including cutting forces and tool wear when drilling carbon fiber-reinforced composite materials at high speed. Based on the experimental results, the authors concluded that the average thrust force increases as cutting speed increases for both multifaceted drill and twist drill. Tool wear is one of the major reasons for these changes in force. Tool wear is mainly affected by cutting speed and drilled length within the range examined. Tool wear increases significantly as cutting speed increases. Therefore, more suitable tool materials should be adopted for cutting carbon fiber-reinforced composite materials at such high speeds [8].

The effect of the cutting speed on the cutting forces is insignificant for the same drill material. The cutting forces on the other hand were found to be lower at lower feed rates. It was further concluded that in order to improve the hole quality at exit, the feed rate at exit needs to be decreased during the drilling process [9].

The common objective of the efforts worldwide has been to formulate the drilling operation in context of the FRP composite materials to minimize the drilling induced damage. The present research initiative is an attempt to investigate the relative significance of the drilling parameters, speed and feed rate and the point angle on the thrust force and torque.

Materials and methods

The experiment started with the Procurement of the natural fiber (Sisal), coconut shell powder (CSP), Vinylester, Accelerator (Methyl Ethyl Ketone), Catalyst (Cobalt) and mold (35 mm diameter).

The Material was procured from a local supplier in Madurai, Tamilnadu. The resin is vinylester resin with the density of 1.80 g/cm.

Preparation of the composites

The fabrication of the various composite materials is carried out through the Hand lay-up technique. The filler contents were set at 20 % weight of the matrix. Three different types of Polymer composites were fabricated with three different filler loadings vinylester resin. The designations of these composites are as following:

$$\text{Vinylester }(80\,\text{wt\%}) + \text{Coconut shell filler }(20\,\text{wt\%})$$

$$\text{Vinylester }(80\,\text{wt\%}) + \text{Sisal fiber }(10\,\text{mm length})\,(20\,\text{wt\%})$$

$$\text{Vinylester }(80\,\text{wt\%}) + \text{Sisal fiber }(10\,\text{wt\%})\text{ and coconut shell filler }(10\,\text{wt\%}).$$

Filler Composite Samples Molds used in this study were made from GI materials. They were open molds. Each mold has a cavity to accommodate the composite samples. The dimensions and shapes of cavities used in this study is a cylindrical rod of 65 × 35 mm made of natural fiber (sisal) and coconut shell particles reinforced composite material.

Vinylester and hardener were mixed with sisal and CSP in a container and stirred well for 5–7 min. Before the mixture was placed inside the mould, the mold has initially been polished with a release agent to prevent the composites from sticking onto the mold upon removal. Finally, the mixture was poured into the mold and left at room temperature for 24 h until the mixture was hardened and curing.

Experimental setup

High speed steel (HSS) 6 mm Twist drilling tool used in the project work and its Indian standard (IS drilling tool—6.00-IS:5101HS-H-118 (ADDISION Tool Traders, Chennai), IEIOS-Model: 651 drilling tool dynamometer with the Range of thrust force 0-5000N, Torque 0-500N.cm were used.

Design of experiments

The cutting speed and the feed rate are the two most important parameters that characterize the drilling operation and have been selected for investigation. It has been established that cutting forces and the resulting damage are dependent on the various drill point geometry parameters. Chen Stated a smaller point angle is a good choice for drilling in composite materials because thrust force is decrease while drilling the carbon fiber reinforced plastic composite laminates. Therefore, drill point geometries with smaller point angles have been chosen to study the influence of smaller point angle on drilling induced damage. The drill point angle, the feed rate and the speed are the three parameters under investigation in the present study. A 3^3 full factorial experimental design with a total of 27 experimental runs was carried out. The factors and their respective levels are shown in Table 1. The thrust force and torque were the response variables recorded for each run.

The significant factors were then used to develop predictive equation for the thrust force and the torque using the regression analysis.

Tables show the comparisons between the experimental and the predicted values from the thrust and torque models. It is clear that the thrust and torque models fit the experimental data reasonably well and can be used to predict the drilling force while drilling NFPRP composite materials. It has proven statistically that it is the feed rate and the point angle that significantly affect the drilling forces while drilling the NFPRP composite materials.

The development of model to predict the thrust force and torque of drilling tool requires some experimental data within the range specified. Both the input and output parameters were required to retain database. The database refers to the internal architecture of the modeling techniques(regression model) based on the experimental values of input and output parameters, the training of database could be established and the errors could be minimized, if there were more number of experimental values, after training the database, a model will be created using RM. To check the performance of the developed model, validation test was conducted. The validation comprises the experiments of different cutting condition, apart from the training values within the range of cutting parameters, were conducted.

The models were created by RM were utilized to predict the output parameter for the experiments in the validation test and the results of RM and measured were compared.

Prediction techniques

Regression model

The statistical tool, regression analysis helps to estimate the value of one variable from the given value of another. In regression analysis, there are two types of variables. The variable whose value is influenced or is to be predicted is called dependent variable and the variable, which influences the values or used for prediction is called independent variables. The tool, regression can be extended to three or more variables. If two variables are taken into account, then it is called

Table 1 Assignment of the level to the factors

Trail no.	Speed (rpm)	Feed (mm/rev)	Point angle (°)
1	500	0.1	90
2	1000	0.2	104
3	1500	0.3	118

simple regression. The tool of regression when extended to three or more variables is called multiple regressions.

SPSS

SPSS (originally, Statistical Package for the Social Sciences) was released in its first version in 1968. SPSS is among the most widely used programs for statistical analysis in social science. It is used by market researchers, health researchers, survey companies, government, education researchers, marketing organizations and others. In addition to statistical analysis, data management (case selection, file reshaping, creating derived data) and data documentation (a metadata dictionary is stored with the data) are features of the base software. Statistics included in the base software:

- Descriptive statistics: Cross tabulation, Frequencies, Descriptives, Explore.
- Descriptive Ratio Statistics.
- Bivariate statistics: Means, *t* test, ANOVA, Correlation (bivariate, partial, distances), nonparametric tests.
- Prediction for numerical outcomes: Linear regression.
- Prediction for identifying groups: Factor analysis, cluster analysis (two-step, K means, hierarchical), Discriminant.

Statistical output is to a proprietary file format (*.spo file, supporting pivot tables) for which, in addition to the in-package viewer, a stand-alone reader is provided. The proprietary output can be exported to text or Microsoft Word. Alternatively, output can be captured as data (using the OMS command), as text, tab-delimited text, HTML, XML, SPSS dataset or a variety of graphic image formats (JPEG, PNG, BMP and EMF).

A 3^2 factorial was selected, since there were 3 inputs, to design the different combinations of the inputs variables. In this way nine experiments were carried out with different combinations of the levels of the input parameters. In this project work, the power type Regression model has been implemented. To develop a regression model, a software known as SPSS, was used and the model will be in the form of

Non-linear regression equation

$$F = K\, a^x f^y$$

$$T = K\, a^x f^y$$

The figure shows the values for the constants of regression model which used to predict the thrust force and torque by utilizing the values for the constants in the equation from the output of SPSS software, the regression model was developed as

Output for thrust force

$$F = 2.449700428\ f^{0.566408733} a^{0.745757628}$$

$$R\ \text{squared} = 1 - \ \text{Residual SS}/\text{Corrected SS} = 0.94585$$

Output for torque

$$T = 301.99122608\ f^{0.720345849} a^{-0.735283000}$$

$$R\ \text{squared} = 1 - \ \text{Residual SS}/\text{Corrected SS} = 0.91434$$

In the above equation, where F—Thrust force (N), T—Torque (N-cm), a—Point angle (°), f—feed rate (mm/rev), k, x, y—constants (Tables 2, 3, 4, 5, 6, and 7).

Nonlinear Regression Summary Statistics   Dependent Variable F

Source	DF	Sum of Squares	Mean Square
Regression	3	8470.40972	2823.46991
Residual	6	41.59028	6.93171
Uncorrected Total	9	8512.00000	
(Corrected Total)	8	768.00000	

R squared = 1 - Residual SS / Corrected SS = .94585

Parameter	Estimate	Asymptotic Std. Error	Asymptotic 95 % Confidence Interval Lower	Upper
K	2.449700428	3.009383344	-4.913995342	9.813396197
X	.566408733	.064674452	.408156050	.724661416
Y	.745757628	.262904493	.102453508	1.389061749

Asymptotic Correlation Matrix of the Parameter Estimates

	K	X	Y
K	1.0000	.0799	-.9965
X	.0799	1.0000	.0000
Y	-.9965	.0000	1.0000

Nonlinear Regression Summary Statistics   Dependent Variable T

Source	DF	Sum of Squares	Mean Square
Regression	3	87.82817	29.27606
Residual	6	1.12183	.18697
Uncorrected Total	9	88.95000	
(Corrected Total)	8	12.09556	

R squared = 1 - Residual SS / Corrected SS = .90725

Parameter	Estimate	Asymptotic Std. Error	Asymptotic 95 % Confidence Interval Lower	Upper
K	301.99122608	586.00610653	-1131.914061	1735.8965130
X	.720345849	.115708372	.437217662	1.003474036
Y	-.735283000	.418297509	-1.758820132	.288254132

Asymptotic Correlation Matrix of the Parameter Estimates

	K	X	Y
K	1.0000	.0872	-.9959
X	.0872	1.0000	.0000
Y	-.9959	.0000	1.0000

Table 2 Comparison results of sisal fiber thrust force and torque

Trail no.	Speed (rpm)	Feed (mm/rev)	Point angle (°)	Thrust force (N)	Torque (N-m)	(RM) Thrust force (N)	(RM) torque (N-m)
1	500	0.1	90	16	2.4	16.19	1.71
2	1000	0.1	90	15	2.6	15.45	2.6321
3	1500	0.1	90	17	1.9	17.23	1.9453
4	500	0.1	104	17	1.8	17.65	1.8334
5	1000	0.1	104	16	2.3	16.34	2.3343
6	1500	0.1	104	19	1.7	18.04	1.5467
7	500	0.1	118	22	1.8	22.23	1.8566
8	1000	0.1	118	23	1.3	23.67	1.3453
9	1500	0.1	118	21	1.2	19.82	1.4023
10	500	0.2	90	23	3.7	23.87	3.7345
11	1000	0.2	90	27	2.4	27.45	2.4654
12	1500	0.2	90	28	2.9	27.25	3.3122
13	500	0.2	104	24	3.2	23.74	3.2675
14	1000	0.2	104	26	2	25.89	2.3452
15	1500	0.2	104	27	2.7	30.35	2.9835
16	500	0.2	118	43	3.9	44.45	3.9567
17	1000	0.2	118	51	3.2	53.45	3.2656
18	1500	0.2	118	31	3.2	33.35	2.7134
19	500	0.3	90	47	4.6	48.34	4.6457
20	1000	0.3	90	34	4.5	34.45	4.5234
21	1500	0.3	90	37	4.7	35.51	4.6477
22	500	0.3	104	47	4.4	46.21	4.4123
23	1000	0.3	104	33	4.2	31.98	4.2457
24	1500	0.3	104	37	4.7	39.55	4.1712
25	500	0.3	118	57	3.0	59.23	3.0452
26	1000	0.3	118	44	3.2	46.23	3.2134
27	1500	0.3	118	47	3.3	43.36	3.8023

Measurement of delamination factor

Drilling was done in the CNC MAXMILL for three different drill bit angle 90, 104, 118 respectively. To determine the differing extent of intrinsic hole machining defects (delamination) caused by drilling, both the upper (Peel up delamination) and lower (Push down delamination) surfaces of each specimens (Fig. 1) were examined using the MACHINE VISION (Fig. 4) system to capture the digital image of the hole drilled. The value of delamination factor (F_d) can be obtained by the following equation:

- A circle was drawn using the draw tool available in the AUTO CAD software for both maximum diameter and nominal diameter.

Table 3 Comparison results of coconut shell powder thrust force and torque

Trail no.	Speed (rpm)	Feed (mm/rev)	Point angle (°)	Thrust force (N)	Torque (N-m)	(RM) thrust force (N)	(RM) torque (N-m)
1	500	0.1	90	13	2.0	13.15	2.1123
2	1000	0.1	90	12	2.1	14.25	2.3351
3	1500	0.1	90	14	1.7	16.33	1.7452
4	500	0.1	104	15	1.6	16.35	1.6331
5	1000	0.1	104	14	2.1	15.14	2.3344
6	1500	0.1	104	17	1.6	17.24	1.5463
7	500	0.1	118	17	1.7	17.23	1.7564
8	1000	0.1	118	18	1.2	18.37	1.3452
9	1500	0.1	118	22	1.2	22.82	1.2026
10	500	0.2	90	21	3.0	21.87	3.1347
11	1000	0.2	90	22	2.0	22.35	2.1654
12	1500	0.2	90	23	2.2	23.25	2.3127
13	500	0.2	104	21	2.9	21.74	3.0676
14	1000	0.2	104	24	1.9	24.39	2.0453
15	1500	0.2	104	25	2.0	25.35	2.1836
16	500	0.2	118	42	3.1	42.45	3.1566
17	1000	0.2	118	50	2.9	50.45	2.8657
18	1500	0.2	118	55	2.6	55.35	2.6134
19	500	0.3	90	45	3.9	45.34	4.0457
20	1000	0.3	90	32	4.1	32.35	4.0235
21	1500	0.3	90	34	4.0	34.51	4.1474
22	500	0.3	104	45	4.0	46.11	4.1127
23	1000	0.3	104	32	3.8	31.98	4.2458
24	1500	0.3	104	35	4.5	35.55	4.6716
25	500	0.3	118	54	3.0	55.23	3.0454
26	1000	0.3	118	42	2.9	42.23	3.0136
27	1500	0.3	118	45	3.1	45.36	3.1025

- From the values of Dmax and Dnom, delamination factor was calculated using the following formula:

(F_d) = Dmax/Dnom, D_{max}—maximum diameter corresponding to the delamination zone, D_{nom}—nominal diameter (Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13).

Conclusion

The following conclusions can be extracted from the experimental results obtained:

Effect of Thrust Force In general, the thrust and torque parameters will mainly depend on the manufacturing conditions employed, such as feed, cutting speed, tool geometry, machine tool, and cutting tool rigidity. A larger thrust force occurs for

Table 4 Comparison results of sisal fiber and CSP thrust force and torque

Trail no.	Speed (rpm)	Feed (mm/rev)	Point angle (°)	Thrust force (N)	Torque (N-m)	(RM) thrust force (N)	(RM) torque (N-m)
1	500	0.1	90	19	3.1	19.21	3.1456
2	1000	0.1	90	18	2.9	18.34	2.9235
3	1500	0.1	90	18	2.2	18.54	2.2352
4	500	0.1	104	17	2.2	17.66	2.2634
5	1000	0.1	104	17	2.3	17.78	2.3878
6	1500	0.1	104	21	2.1	21.98	2.1567
7	500	0.1	118	24	2.3	24.44	2.3545
8	1000	0.1	118	26	1.9	26.67	1.9754
9	1500	0.1	118	26	1.8	26.34	1.8745
10	500	0.2	90	25	4.3	25.67	4.3574
11	1000	0.2	90	29	3.1	29.45	3.1745
12	1500	0.2	90	29	3.9	29.67	3.9457
13	500	0.2	104	26	3.9	26.55	3.9545
14	1000	0.2	104	29	2.5	29.77	2.5345
15	1500	0.2	104	31	3.2	31.45	3.2464
16	500	0.2	118	46	4.5	46.65	4.5346
17	1000	0.2	118	55	4.7	55.54	4.7346
18	1500	0.2	118	37	3.9	37.74	3.9345
19	500	0.3	90	49	4.9	49.34	4.9567
20	1000	0.3	90	38	5.3	38.34	5.3467
21	1500	0.3	90	41	5.6	41.66	5.6685
22	500	0.3	104	51	5.8	51.75	5.8457
23	1000	0.3	104	38	5.9	38.34	5.9235
24	1500	0.3	104	41	5.8	41.67	5.8634
25	500	0.3	118	62	4.2	62.34	4.2634
26	1000	0.3	118	51	4.5	51.64	4.5537
27	1500	0.3	118	53	4.6	53.64	4.6634

wider point angle and higher feed rates. In other words, feed rate and point angles are recognized as the most significant factors affecting the thrust force. Although tools are worn out quickly and the thrust force increases drastically as cutting speed increases, an acceptable hole entry and exit is maintained. We found that the thrust force is drastically reduced when the hole is predrilled to 0.4 mm or above. The thrust force increases with the increase in fiber volume fraction. Although it is known that the thrust force increases with the increase in the feed, this study provided quantitative measurements of such relationships for the present composite materials. In general, increasing the cutting speed will decrease the thrust force. This work has shown that the cutting speed has an insignificant effect on the thrust

Table 5 Delamination factor (sisal)

S. no.	Feed	Speed	Delamination (F_d)		
			Point angle = 90°	Point angle = 104°	Point angle = 118°
1	0.1	500	1.3349	1.3481	1.3613
2	0.1	1000	1.3282	1.3413	1.3545
3	0.1	1500	1.3137	1.3267	1.3397
4	0.2	500	1.2726	1.2852	1.2978
5	0.2	1000	1.2625	1.2750	1.2875
6	0.2	1500	1.2490	1.2614	1.2738
7	0.3	500	1.1413	1.1526	1.1639
8	0.3	1000	1.1329	1.1441	1.1553
9	0.3	1500	1.1194	1.1305	1.1416

Table 6 Delamination factor (CSP)

S. no.	Feed	Speed	Delamination (F_d)		
			Point angle = 90°	Point angle = 104°	Point angle = 118°
1	0.1	500	1.3230	1.3243	1.3256
2	0.1	1000	1.3163	1.3176	1.3189
3	0.1	1500	1.3020	1.3033	1.3046
4	0.2	500	1.2613	1.2625	1.2638
5	0.2	1000	1.2513	1.2525	1.2538
6	0.2	1500	1.2379	1.2391	1.2404
7	0.3	500	1.1311	1.1323	1.1334
8	0.3	1000	1.1228	1.1239	1.1250
9	0.3	1500	1.1094	1.1105	1.1117

Table 7 Delamination factor (sisal and CSP)

S. no.	Feed	Speed	Delamination (F_d)		
			Point angle = 90°	Point angle = 104°	Point angle = 118°
1	0.1	500	1.3745	1.3878	1.4010
2	0.1	1000	1.3676	1.3808	1.3939
3	0.1	1500	1.3527	1.3657	1.3787
4	0.2	500	1.3104	1.3230	1.3356
5	0.2	1000	1.3000	1.3125	1.3250
6	0.2	1500	1.2861	1.2985	1.3109
7	0.3	500	1.1752	1.1865	1.1978
8	0.3	1000	1.1665	1.1778	1.1890
9	0.3	1500	1.1527	1.1637	1.1748

Fig. 1 Sisal-vinylester composite specimen

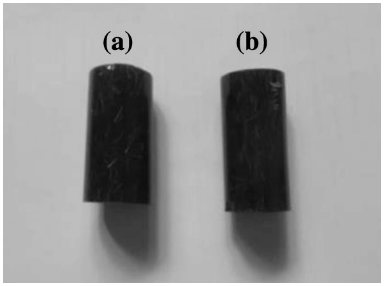

Fig. 2 Sisal-vinylester with CSP composite specimen

Fig. 3 Drilled specimen

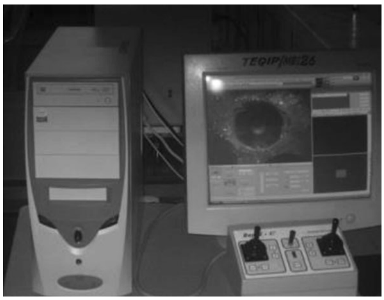

Fig. 4 Machine vision system

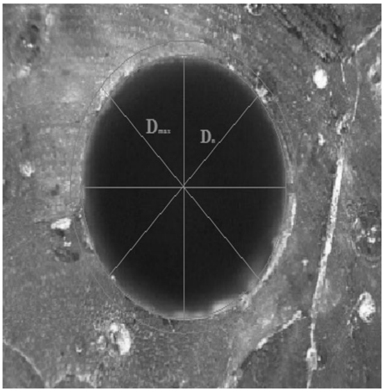

Fig. 5 Delamination zone (for sisal/vinylester 90°)

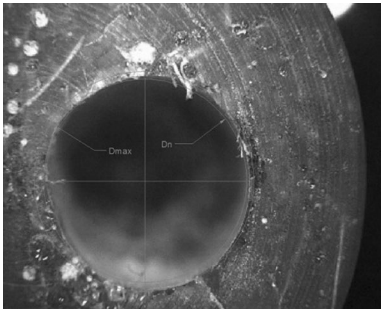

Fig. 6 Delamination zone (for sisal/vinylester 104°)

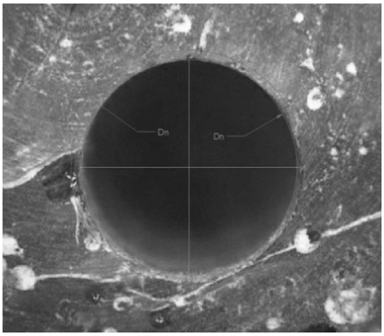

Fig. 7 Delamination zone (for sisal/vinylester 118°)

force when drilling at low feed values. At high feed values, the thrust force decreases with an increased cutting speed.

It can be observed that thrust force and torque increase with the drill tool point angle and feed rate. By examining these results, it can be concluded that the torque slightly increases as the cutting speed increases. However, we found that the increase in torque was much smaller than that in thrust force, with the increasing

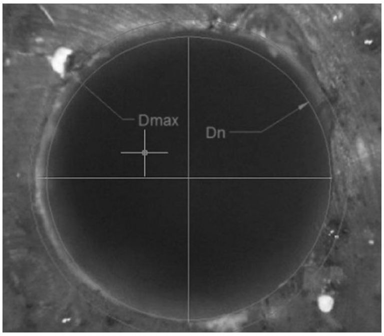

Fig. 8 Delamination zone (for CSP/vinylester 90°)

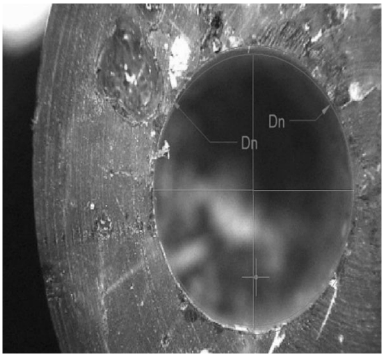

Fig. 9 Delamination zone (for CSP/vinylester 104°)

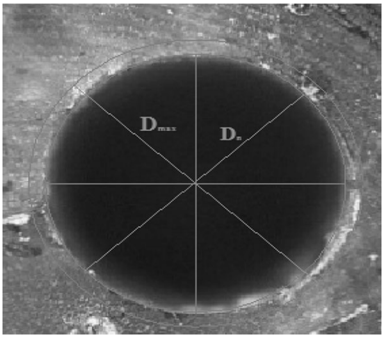

Fig. 10 Delamination zone (for CSP/vinylester 118°)

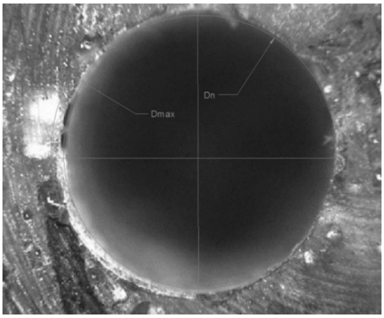

Fig. 11 Delamination zone (for CSP and sisal/vinylester 90°)

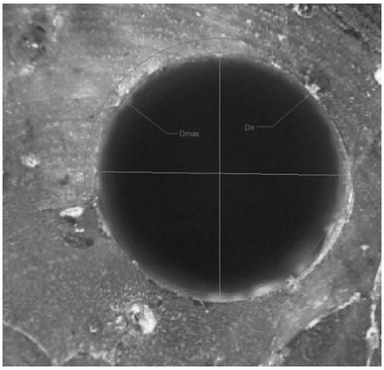

Fig. 12 Delamination zone (for CSP and sisal/vinylester 104°)

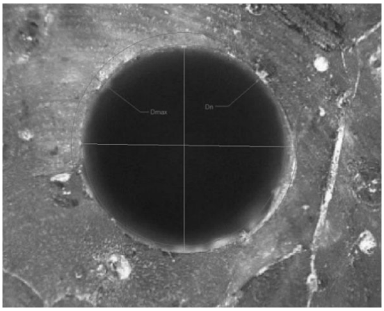

Fig. 13 Delamination zone (for CSP and sisal/vinylester 118°)

cutting speed. The results indicate that the torque increases as the feed increases. This increase is owing to the increasing cross-sectional area of the undeformed chip. The result also indicates that the torque decreases when increasing the cutting speed.

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