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Halaman Lampiran

Designation: D 5766/D 5766M – 02

Standard Test Method for
Open Hole Tensile Strength of Polymer Matrix Composite Laminates[1]

This standard is issued under the fixed designation D 5766/D 5766M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method determines the open hole tensile strength of multidirectional polymer matrix composite laminates reinforced by high-modulus fibers. The composite material forms are limited to continuous-fiber or discontinuous-fiber (tape or fabric, or both) reinforced composites in which the laminate is balanced and symmetric with respect to the test direction. The range of acceptable test laminates and thicknesses are described in 8.2.1.

1.2 The values stated in either SI units or inch-pound units are to be regarded separately as standard. Within the text the inch-pound units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in nonconformance with the standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 792 Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement[2]
D 883 Terminology Relating to Plastics[2]
D 2584 Test Method for Ignition Loss of Cured Reinforced Resins[3]
D 2734 Test Methods for Void Content of Reinforced Plastics[3]
D 3039/D 3039M Test Method for Tensile Properties of Polymer Matrix Composite Materials[4]
D 3171 Test Methods for Constituent Content of Composite Materials[4]
D 3878 Terminology for Composite Materials[4]
E 6 Terminology Relating to Methods of Mechanical Testing[5]
E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[6]
E 456 Terminology Relating to Quality and Statistics[6]
E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[6]
E 1309 Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases[4]
E 1434 Guide for Recording Mechanical Test Data of Fiber-Reinforced Composite Materials in Databases[4]
E 1471 Guide for Identification of Fibers, Fillers and Core Materials in Computerized Material Property Databases[4]

3. Terminology

3.1 *Definitions*—Terminology D 3878 defines terms relating to high-modulus fibers and their composites. Terminology D 883 defines terms relating to plastics. Terminology E 6 defines terms relating to mechanical testing. Terminology E 456 and Practice E 177 define terms relating to statistics. In the event of a conflict between terms, Terminology D 3878 shall have precedence over the other standards.

3.2 *Definitions of Terms Specific to This Standard:*:

NOTE 1—If the term represents a physical quantity, its analytical dimensions are stated immediately following the term (or letter symbol) in fundamental dimension form, using the following ASTM standard symbology for fundamental dimensions, shown within square brackets: [*M*] for mass, [*L*] for length, [*T*] for time, [θ] for thermodynamic temperature, and [*nd*] for non-dimensional quantities. Use of these symbols is restricted to analytical dimensions when used with square brackets, as the symbols may have other definitions when used without the brackets.

3.2.1 *nominal value, n*—a value, existing in name only, assigned to a measurable property for the purpose of convenient designation. Tolerances may be applied to a nominal value to define an acceptable range for the property.

3.2.2 *principal material coordinate system, n*—a coordinate system with axes that are normal to the planes of symmetry inherent to a material.

3.2.2.1 *Discussion*—Common usage, at least for Cartesian axes (123, *xyz*, and so forth), generally assigns the coordinate

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[1] This test method is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.05 on Structural Test Methods.

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[2] A l 08.01.

[3] A l 08.02.

[4] A l 15.03.

[5] *Annual Book of ASTM Standards*, Vol 03.01.

[6] *Annual Book of ASTM Standards*, Vol 14.02.

system axes to the normal directions of planes of symmetry in order that the highest property value in a normal direction (for elastic properties, the axis of greatest stiffness) would be 1 or *x*, and the lowest (if applicable) would be 3 or *z*. Anisotropic materials do not have a principal material coordinate system due to the total lack of symmetry, while, for isotropic materials, any coordinate system is a principal material coordinate system. In laminated composites the principal material coordinate system has meaning only with respect to an individual orthotropic lamina. The related term for laminated composites is "reference coordinate system."

3.2.3 *reference coordinate system, n*—a coordinate system for laminated composites used to define ply orientations. One of the reference coordinate system axes (normally the Cartesian *x*-axis) is designated the reference axis, assigned a position, and the ply principal axis of each ply in the laminate is referenced relative to the reference axis to define the ply orientation for that ply.

3.2.4 *specially orthotropic, adj*—a description of an orthotropic material as viewed in its principal material coordinate system. In laminated composites, a specially orthotropic laminate is a balanced and symmetric laminate of the $[0_i/90_j]_{ns}$ family as viewed from the reference coordinate system, such that the membrane-bending coupling terms of the laminate constitutive relation are zero.

3.3 *Symbols:*

3.3.1 *A*—cross-sectional area of a specimen.

3.3.2 *CV*—coefficient of variation statistic of a sample population for a given property (in percent).

3.3.3 *D*—hole diameter.

3.3.4 *h*—specimen thickness.

3.3.5 *n*—number of specimens per sample population.

3.3.6 *N*—number of plies in laminate under test.

3.3.7 F_x^{OHTu}—ultimate open hole (notched) tensile strength in the test direction.

3.3.8 P^{max}—maximum load carried by test specimen prior to failure.

3.3.9 s_{n-1}—standard deviation statistic of a sample population for a given property.

3.3.10 *w*—specimen width.

3.3.11 x_i—test result for an individual specimen from the sample population for a given property.

3.3.12 $\bar{x}$—mean or average (estimate of mean) of a sample population for a given property.

3.3.13 σ—normal stress.

4. Summary of Test Method

4.1 A uniaxial tension test of a balanced, symmetric laminate is performed in accordance with Test Method D 3039/D 3039M, although with a centrally located hole. Edge-mounted extensometer displacement transducers are optional. Ultimate strength is calculated based on the gross cross-sectional area, disregarding the presence of the hole. While the
hole c and reduced net section, it is
comm velop notched design allow-
able s ection stress to account for
variou ener holes, free edges, flaws,
damag icitly modeled in the stress
analys

4.2 The only acceptable failure mode for ultimate open-hole tensile strength is one which passes through the hole in the test specimen.

5. Significance and Use

5.1 This test method is designed to produce notched tensile strength data for structural design allowables, material specifications, research and development, and quality assurance. Factors that influence the notched tensile strength and should therefore be reported include the following: material, methods of material fabrication, accuracy of lay-up, laminate stacking sequence and overall thickness, specimen geometry, specimen preparation (especially of the hole), specimen conditioning, environment of testing, specimen alignment and gripping, speed of testing, void content, and volume percent reinforcement. Properties that may be derived from this test method include the following:

5.1.1 Open hole (notched) tensile strength (OHT).

6. Interferences

6.1 *Hole Preparation*—Due to the dominating presence of the notch, and the lack of need to measure the material response, results from this test method are relatively insensitive to parameters that would be of concern in an unnotched tensile property test. However, since the notch dominates the strength, consistent preparation of the hole, without damage to the laminate, is important to meaningful results. Damage caused by hole preparation will affect strength results. Some types of damage, such as delaminations, can blunt the stress concentration because of the hole, increasing the load-carrying capacity of the specimen and the calculated strength.

6.2 *Geometry*—Results are affected by the ratio of specimen width to hole diameter; this ratio should be maintained at 6, unless the experiment is investigating the influence of this ratio. Results may also be affected by the ratio of hole diameter to thickness; the preferred ratio is the range from 1.5 to 3.0 unless the experiment is investigating the influence of this ratio.

6.3 *Material Orthotropy*—The degree of laminate orthotropy strongly affects the failure mode and measured OHT strength. Valid OHT strength results should only be reported when appropriate failure modes are observed, in accordance with 11.4.

6.4 *Thickness Scaling*—Thick composite structures do not necessarily fail at the same strengths as thin structures with the same laminate orientation (that is, strength does not always scale linearly with thickness). Thus, data gathered using this test method may not translate directly into equivalent thick-structure properties.

6.5 *Other*—Additional sources of potential data scatter in testing of composite materials are described in Test Method D 3039/D 3039M.

7. Apparatus

7.1 Apparatus shall be in accordance with Test Method D 3039/D 3039M. Additionally, a micrometer or gage capable of determining the hole diameter to ±0.025 mm [±0.001 in.] is required.

8. Sampling and Test Specimens

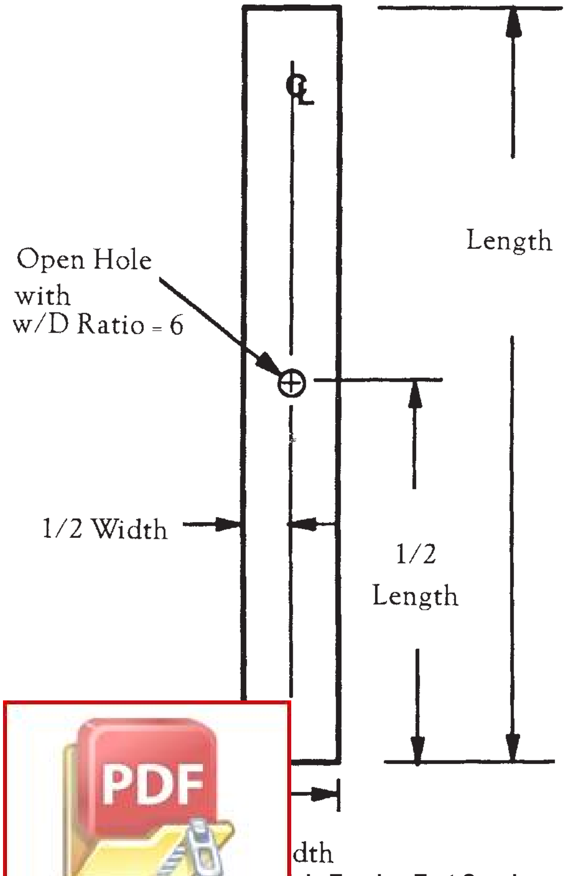
8.1 *Sampling*—Sampling shall be in accordance with Test Method D 3039/D 3039M.

8.2 *Geometry*—The specimen geometry shall be in accordance with Test Method D 3039/D 3039M, as modified by the following, and illustrated by the schematic of Fig. 1. Any variation of the stacking sequence, specimen width or length, or hole diameter from that specified shall be clearly noted in the report.

8.2.1 *Stacking Sequence*—The standard tape and fabric laminates shall have multidirectional fiber orientations (fibers shall be oriented in a minimum of two directions), and balanced and symmetric stacking sequences. Nominal thickness shall be 2.5 mm [0.10 in.], with a permissible range of 2 to 4 mm [0.080 to 0.160 in.], inclusive. Fabric laminates containing satin-type weaves shall have symmetric warp surfaces, unless otherwise noted in the report.

NOTE 2—Typically a $[45_i/-45_i/0_j/90_k]_{ms}$ tape or $[45_i/0_j]_{ms}$ fabric laminate should be selected such that a minimum of 5 % of the fibers lay in each of the four principal orientations. This laminate design has been found to yield the highest likelihood of acceptable failure modes.

8.2.2 *Dimensions*—The width of the specimen is 36 ± 1 mm [1.50 ± 0.05 in.] and the length range is 200 to 300 mm [8.0 to 12.0 in.]. The notch consists of a centrally located hole, 6 ± 0.06 mm [0.250 ± 0.003 in.] in diameter, centered by length to within 0.12 mm [0.005 in.] and by width to within 0.05 mm [0.002 in.]. While tabs may be used, they are not required and generally not needed, since the open hole acts as sufficient stress riser to force failure in the notched region.



ole Tension Test Specimen

8.3 *Specimen Preparation*—Special care shall be taken to ensure that creation of the specimen hole does not delaminate or otherwise damage the material surrounding the hole. Holes should be drilled undersized and reamed to final dimensions. Record and report the specimen hole preparation methods. Other specimen preparation techniques and requirements are noted in Test Method D 3039/D 3039M.

9. Calibration

9.1 Calibration shall be in accordance with Test Method D 3039/D 3039M.

10. Conditioning

10.1 Conditioning shall be in accordance with Test Method D 3039/D 3039M.

11. Procedure

11.1 *Parameters To Be Specified Prior to Test*:

11.1.1 The tension specimen sampling method, specimen type and geometry, and conditioning travelers (if required).

11.1.2 The tensile properties and data reporting format desired.

NOTE 3—Determine specific material property, accuracy, and data reporting requirements prior to test for proper selection of instrumentation and data recording equipment. Estimate the specimen strength to aid in transducer selection, calibration of equipment, and determination of equipment settings.

11.1.3 The environmental conditioning test parameters.

11.1.4 If performed, extensometry requirements and related calculations.

11.1.5 If performed, the sampling method, specimen geometry, and test parameters used to determine density and reinforcement volume.

11.2 *General Instructions*:

11.2.1 Report any deviations from this test method, whether intentional or inadvertent.

11.2.2 If specific gravity, density, reinforcement volume or void volume are to be reported then obtain these samples from the same panels being tension tested. Specific gravity and density may be evaluated by means of Test Methods D 792. Volume percent of the constituents may be evaluated by one of the matrix digestion procedures of Test Method D 3171, or, for certain reinforcement materials such as glass and ceramics, by the matrix burn-off technique of Test Method D 2584. The void content equations of Test Methods D 2734 are applicable to both Test Method D 2584 and the matrix digestion procedures.

11.2.3 Condition the specimens as required. Store the specimens in the conditioned environment until test time, if the test environment is different than the conditioning environment.

11.2.4 Following any conditioning, but before the tensile testing, measure and report the specimen hole diameter to the nearest 0.025 mm [0.001 in.]. Inspect the hole and areas adjacent to the hole for delaminations. Report the location and size of any delaminations found. Perform other measurements in accordance with Test Method D 3039/D 3039M.

11.3 *Tensile Testing*—Perform other measurements, and the tension test of the laminate specimen, in accordance with the

Procedure section of Test Method D 3039/D 3039M. If strain response local to the hole is to be determined, attach either one or two extensometers to the specimen edge(s) ensuring the hole is located within the extensometer gage section.

11.4 *Failure Modes*—Failures that do not occur at the hole are not acceptable failure modes and the data shall be noted as invalid. The failure is often heavily influenced by delamination and the failure mode may exhibit much delamination. Three-place failure mode descriptors for these modes, following those given in Test Method D 3039/D 3039M and summarized in Table 1, shall be used. This notation uses the first place to describe failure type, the second to describe failure area, and the last to describe failure location. Failure mode codes for valid tests for this test method are limited to *GM, where the second and third place holders are limited to “Gage Middle.” The first place holder would normally be either L for Lateral, A for Angled, or M for Multi-mode. Fig. 2 illustrates these three acceptable failure modes. The mode of failure may be found to vary on different sides of the hole.

12. Validation

12.1 Values for ultimate properties shall not be calculated for any specimen that breaks at some obvious flaw, unless such flaw constitutes a variable being studied. Retests shall be performed for any specimen on which values are not calculated.

12.2 A significant fraction of failures in a sample population occurring away from the center hole shall be cause to reexamine the means of load introduction into the material. Factors considered should include the grip pressure, grip alignment, and specimen thickness taper.

13. Calculation

13.1 *Ultimate Strength*—Calculate the ultimate open hole tensile strength using Eq 1 and report the results to three significant figures.

$$F_x^{OHTu} = P^{max}/A \tag{1}$$

where:

F_x^{OHTu} = ultimate open hole tensile strength, MPa [psi],
P^{max} = maximum load prior to failure, N [lbf], and
A = gross cross-sectional area (disregarding hole) from Test Method D 3039/D 3039M, mm^2 [in.^{2}].

NOTE 4—The hole diameter is ignored in the strength calculation; the gross cross-sectional area is used.

TABLE 1 Three-Place Failure Mode Codes

First Character		Second Character		Third Character	
Failure Type	Code	Failure Area	Code	Failure Location	Code
Angled	[illegible]	[illegible]ab	I	Bottom	B
edge D[illegible]	[illegible]	[illegible]	A	Top	T
Grip/tab[illegible]	[illegible]	[illegible]rip/tab	W	Left	L
Lateral	[illegible]	[illegible]	G	Right	R
Multi-m[illegible]	[illegible]	[illegible]as	M	Middle	M
long. Sp[illegible]	[illegible]	[illegible]	V	Various	V
eXplosi[illegible]	[illegible]	[illegible]	U	Unknown	U
Other	[illegible]				

13.2 *Width to Diameter Ratio*—Calculate the actual width to diameter ratio, as shown in Eq 2. Report both the nominal ratio calculated using nominal values and the actual ratio calculated with measured dimensions.

$$w/D \text{ ratio} = \frac{w}{D} \tag{2}$$

where:

w = width of specimen across hole, mm [in.], and
D = diameter of hole, mm [in.].

13.3 *Diameter to Thickness Ratio*—Calculate the actual diameter to thickness ratio, as shown in Eq 3. Report both the nominal ratio calculated using nominal values and the actual ratio calculated with measured dimensions.

$$D/h \text{ ratio} = \frac{D}{h} \tag{3}$$

where:

D = diameter of hole, mm [in.], and
h = specimen thickness near hole, mm [in.].

13.4 *Percent Bending*—If two edge-mounted extensometers are used, edgewise percent bending may be calculated in accordance with Test Method D 3039/D 3039M.

13.5 *Statistics*—For each series of tests calculate the average value, standard deviation, and coefficient of variation (in percent) for each property determined:

$$\bar{x} = (\sum_{i=1}^{n} x_i)/n \tag{4}$$

$$s_{n-1} = \sqrt{(\sum_{i=1}^{n} x_i^2 - n\bar{x}^2)/(n-1)} \tag{5}$$

$$CV = 100 \times s_{n-1}/\bar{x} \tag{6}$$

where:

$\bar{x}$ = sample mean (average),
s_n-1 = sample standard deviation,
CV = sample coefficient of variation, in percent,
n = number of specimens, and
x_i = measured or derived property.

14. Report

14.1 The report shall include all appropriate parameters in accordance with Test Method D 3039/D 3039M, making use of Guides E 1309, E 1471, and E 1434.

14.2 In addition, the report shall include the following information, or references pointing to other documentation containing this information, to the maximum extent applicable (reporting of items beyond the control of a given testing laboratory, such as might occur with material details or panel fabrication parameters, shall be the responsibility of the requestor):

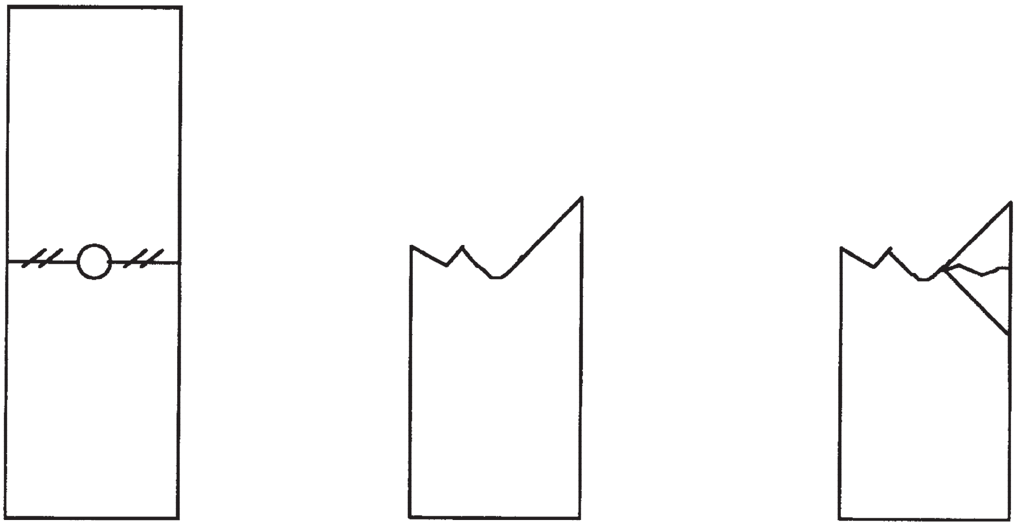
14.2.1 The revision level or date of issue of this test method.

14.2.2 Any variations to this test method, anomalies noticed during testing, or equipment problems occurring during testing.

14.2.3 Nominal width to diameter ratio, and actual width to diameter ratio for each specimen.

14.2.4 Nominal diameter to thickness ratio and actual diameter to thickness ratio for each specimen.

14.2.5 Individual ultimate open hole tensile strengths and average value, standard deviation, and coefficient of variation



LGM

Laminate tensile failure laterally across the center of the hole. Splits and delaminations may be present.

AGM

Laminate generally fails in tension at the hole, but remnants of angle plies cross the hole lateral centerline. Splits and delaminations may be present.

MGM

Laminate fails in tension at the hole and exhibits multiple modes of failure in various sublaminates. Extensive splitting and delamination present.

FIG. 2 Acceptable Open Hole Tensile Failure Modes

(in percent) for the population.

14.2.6 Extensometer type, stress-strain curves, tabulated stress versus strain data, or percent bending versus load or head displacement, or combination thereof, for each specimen so evaluated.

14.2.7 Failure mode and location of failure for each specimen.

15. Precision and Bias

15.1 *Round-Robin Results*—A round robin for precision data was conducted on this test method in 1989. Nine laboratories participated in the evaluation of three material systems from three different material suppliers, using quasi-isotropic laminates. Each laboratory tested at ambient laboratory conditions a randomly distributed sample of 5 specimens of each material type, prepared by the material supplier, using a loading rate of 0.05 in./min. All specimens were untabbed, and gripping methods among the laboratories varied. The conduct of the round-robin deviated from this test method in two respects: thickness was measured via a double-ball micrometer, and material moisture content was not controlled. The average results for each laboratory are listed in Table 2.

TABLE 2 1989 Round-Robin Data

Lab	F_x^{OHTu}, MPa [ksi]					
	Material A[A]		Material B[B]		Material C[C]	
	Average	CV	Average	CV	Average	CV
1	279 [40.5]	2.72	422 [61.2]	1.12	477 [69.2]	1.31
2	283 [41.1]	7.98	400 [58.0]	2.60	475 [68.9]	1.90
3	276 [40.0]	6.98	412 [59.8]	1.92	465 [67.5]	1.07
4	272 [39.4]	4.47	422 [61.2]	1.72	472 [68.4]	3.00
5	283 [41.0]	5.51	414 [60.0]	1.52	473 [68.6]	3.41
6	283 [41.0]	3.15	419 [60.8]	2.12	485 [70.4]	3.61
7	280 [40.6]	5.64	416 [60.4]	4.30	470 [68.1]	5.39
8	273 [39.6]	7.04	414 [60.0]	3.55	482 [69.9]	2.22
9	265 [38.5]	2.75	419 [60.7]	3.31	480 [69.6]	6.70
Avera			[60.2]	2.46	476 [69.0]	3.18
CV			86		3.53	

[A] C −45/90]*s* using 34 Msi modulus carbon fiber.

[B] C 45/0/−45/90]2*s* using 42 Msi modulus carbo

[C] C -45/90]2*s* using 42 Msi modulus carbon fiber.

TABLE 3 1989 Round-Robin Statistics

Material System	Between Observation 95 % Confidence Interval	
	Within Laboratory Repeatability[A] $2.8 \times S_r$	Between Laboratories Reproducibility[A] $2.8 \times S_R$
A	15.1	15.1
B	7.44	8.09
C	10.2	10.2

[A] Normalized to mean, in percent.

15.2 *Precision*:

15.2.1 The precision is defined as a 95 % confidence interval, which can be expressed two ways. Practice E 691 suggests that for this degree of confidence the maximum difference between an individual observation and the average should be within 2.0 standard deviations, while the maximum difference between any two observations should be within 2.8 standard deviations. For brevity, only the magnitude of the latter is reported; the former can be derived from the latter. Two types of precision can also be defined: within-laboratory (the repeatability) or between-laboratory (the reproducibility); both of which are reported.

15.2.2 The within-laboratory conditions were essentially single-operator, one-day, same-apparatus conditions, during

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which time neither the apparatus nor environment was likely to change appreciably.

15.2.3 The results, summarized in Table 3 indicate that this test method is relatively insensitive to minor variations in testing practices, but is sensitive to material type.

15.3 *Bias*—Bias cannot be determined for this test method as no acceptable reference standard exists.

16. Keywords

16.1 composite materials; open hole tensile strength; tension testing

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Taguchi Design

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Taguchi Orthogonal Array Design

L9(3^2)

Factors:  2
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Columns of L9(3^4) Array

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Taguchi Analysis: Fd entry versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                    Spindle
Level  Feed rate      speed
1         -1.677     -1.466
2         -1.554     -1.700
3         -1.525     -1.590
Delta      0.152      0.234
Rank           2          1


Response Table for Means

                    Spindle
Level  Feed rate      speed
1          1.213      1.184
2          1.196      1.216
3          1.192      1.201
Delta      0.021      0.032
Rank           2          1
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                    Spindle
Level  Feed rate      speed
1         -2.372     -1.921
2         -2.084     -2.429
3         -2.530     -2.636
Delta      0.446      0.715
Rank           2          1


             e for Means

                    Spindle
             ate      speed
             314      1.250
             275      1.324
             339      1.355
```

```
Delta      0.064    0.105
Rank           2        1
```

Main Effects Plot for SN ratios

Surface Plot of Fd entry vs Feed rate; Spindle speed

Surface Plot of Fd exit vs Feed rate; Spindle speed

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One-way ANOVA: Fd entry versus Feed rate

```
Method

Null hypothesis         All means are equal
Alternative hypothesis  At least one mean is different
Significance level      α = 0.05

Equal variances were assumed for the analysis.


Factor Information

Factor     Levels  Values
Feed rate       3  0.10; 0.18; 0.24


Analysis of Variance

Source     DF    Adj SS    Adj MS  F-Value  P-Value
Feed rate   2  0.000759  0.000380     0.87    0.465
Error       6  0.002608  0.000435
Total       8  0.003367


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0208473  22.55%      0.00%       0.00%


Means

Feed
rate  N    Mean   StDev       95% CI
0.10  3  1.2132  0.0250  (1.1837; 1.2426)
0.18  3  1.1960  0.0190  (1.1665; 1.2254)
0.24  3  1.1920  0.0179  (1.1626; 1.2215)

             = 0.0208473
```

of Fd entry vs Feed rate

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General Linear Model: Fd entry versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF    Adj SS    Adj MS  F-Value  P-Value
  Feed rate       2  0.000759  0.000380     1.46    0.334
  Spindle speed   2  0.001568  0.000784     3.02    0.159
Error             4  0.001039  0.000260
Total             8  0.003367


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0161185  69.14%     38.27%       0.00%


Coefficients

Term                Coef  SE Coef  T-Value  P-Value   VIF
Constant         1.20040  0.00537   223.42    0.000
Feed rate
  0.10           0.01279  0.00760     1.68    0.168  1.33
  0.18          -0.00441  0.00760    -0.58    0.593  1.33
Spindle speed
  93            -0.01653  0.00760    -2.18    0.095  1.33
  443            0.01578  0.00760     2.08    0.106  1.33


Regression Equation

Fd entry = 1.20040 + 0.01279 Feed rate_0.10 - 0.00441 Feed rate_0.18 - 0.0083
8 Feed rate_0.24
           - 0.01653 Spindle speed_93 + 0.01578 Spindle speed_443
           + 0.00076 Spindle speed_1420
```

Normplot of Residuals for Fd entry

General Linear Model: Fd exit versus Feed rate; Spindle speed

```
Method

              g  (-1; 0; +1)


              ation

               Type   Levels  Values
               Fixed       3  0.10; 0.18; 0.24
```

```
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source          DF    Adj SS    Adj MS  F-Value  P-Value
  Feed rate      2  0.006327  0.003163     0.68    0.558
  Spindle speed  2  0.017540  0.008770     1.88    0.266
Error            4  0.018659  0.004665
Total            8  0.042526


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0682997  56.12%     12.25%       0.00%


Coefficients

Term              Coef  SE Coef  T-Value  P-Value   VIF
Constant        1.3094   0.0228    57.51    0.000
Feed rate
  0.10          0.0050   0.0322     0.15    0.885  1.33
  0.18         -0.0347   0.0322    -1.08    0.342  1.33
Spindle speed
  93           -0.0598   0.0322    -1.86    0.137  1.33
  443           0.0144   0.0322     0.45    0.678  1.33


Regression Equation

Fd exit = 1.3094 + 0.0050 Feed rate_0.10 - 0.0347 Feed rate_0.18 + 0.0297 Fee
d rate_0.24
          - 0.0598 Spindle speed_93 + 0.0144 Spindle speed_443 + 0.0454 Spind
le speed_1420
```

Normplot of Residuals for Fd exit

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General Linear Model: SNRA1 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


               ariance

                DF   Adj SS   Adj MS  F-Value  P-Value
                 2  0.03927  0.01963     1.44    0.338
              eed  2  0.08217  0.04108     3.01    0.159
                 4  0.05457  0.01364
                 8  0.17600
```

```
Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.116796  69.00%     37.99%       0.00%


Coefficients

Term              Coef  SE Coef  T-Value  P-Value   VIF
Constant       -1.5854   0.0389   -40.72    0.000
Feed rate
  0.10         -0.0919   0.0551    -1.67    0.170  1.33
  0.18          0.0316   0.0551     0.57    0.597  1.33
Spindle speed
  93            0.1195   0.0551     2.17    0.096  1.33
  443          -0.1144   0.0551    -2.08    0.106  1.33


Regression Equation

SNRA1 = -1.5854 - 0.0919 Feed rate_0.10 + 0.0316 Feed rate_0.18 + 0.0604 Feed
 rate_0.24
       + 0.1195 Spindle speed_93 - 0.1144 Spindle speed_443 - 0.0050 Spindle
 speed_1420
```

Normplot of Residuals for SNRA1

General Linear Model: SNRA2 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source            DF  Adj SS  Adj MS  F-Value  P-Value
  Feed rate        2  0.3071  0.1536     0.71    0.543
  Spindle speed    2  0.8122  0.4061     1.89    0.265
Error              4  0.8601  0.2150
Total              8  1.9795


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.463715  56.55%     13.10%       0.00%


Coefficients

Term             Coef  SE Coef  T-Value  P-Value   VIF
               -2.329    0.155   -15.07    0.000

               -0.043    0.219    -0.20    0.854  1.33
                0.245    0.219     1.12    0.326  1.33

                0.408    0.219     1.86    0.136  1.33
               -0.100    0.219    -0.46    0.672  1.33
```

```
Regression Equation

SNRA2 = -2.329 - 0.043 Feed rate_0.10 + 0.245 Feed rate_0.18 - 0.202 Feed rat
e_0.24
        + 0.408 Spindle speed_93 - 0.100 Spindle speed_443 - 0.308 Spindle sp
eed_1420
```

Normplot of Residuals for SNRA2

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Taguchi Design

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Taguchi Orthogonal Array Design

L9(3^2)

Factors:  2
Runs:     9


Columns of L9(3^4) Array

1 2
```

Taguchi Analysis: Fd entry versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                   Spindle
Level  Feed rate     speed
1        -0.9644   -1.0086
2        -1.1004   -1.1285
3        -1.2650   -1.1927
Delta     0.3006    0.1841
Rank           1         2


Response Table for Means

                   Spindle
Level  Feed rate     speed
1          1.117     1.123
2          1.135     1.139
3          1.157     1.147
Delta      0.039     0.024
Rank           1         2
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                   Spindle
Level  Feed rate     speed
1         -1.556    -1.726
2         -1.779    -1.789
3         -1.928    -1.748
Delta      0.372     0.063
Rank           1         2


             e for Means

                   Spindle
             ate     speed
             197     1.221
             227     1.229
             249     1.223
```

```
Delta      0.052    0.008
Rank           1        2
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                   Spindle
Level  Feed rate     speed
1         -1.556    -1.726
2         -1.779    -1.789
3         -1.928    -1.748
Delta      0.372     0.063
Rank           1         2


Response Table for Means

                   Spindle
Level  Feed rate     speed
1          1.197     1.221
2          1.227     1.229
3          1.249     1.223
Delta      0.052     0.008
Rank           1         2
```

Main Effects Plot for SN ratios

Surface Plot of Fd entry vs Feed rate; Spindle speed

Surface Plot of Fd exit vs Feed rate; Spindle speed

11/04/2019 17:12:15

```
Welcome to Minitab, press F1 for help.
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REFF\PENDUKUNG\dia 06.MPJ’
```

Main Effects Plot for Fd entry

One-way ANOVA: Fd entry versus Feed rate

```
Method

Null hypothesis         All means are equal
Alternative hypothesis  At least one mean is different
              level     α = 0.05

               ces were assumed for the analysis.


               ation

               evels  Values
                   3  0.10; 0.18; 0.24
```

```
Analysis of Variance

Source     DF    Adj SS    Adj MS  F-Value  P-Value
Feed rate   2  0.002343  0.001172     6.21    0.035
Error       6  0.001132  0.000189
Total       8  0.003475


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0137350  67.43%     56.57%      26.71%


Means

Feed
rate  N     Mean    StDev         95% CI
0.10  3  1.11743  0.00463  (1.09803; 1.13683)
0.18  3  1.13511  0.01314  (1.11571; 1.15451)
0.24  3   1.1569   0.0193  ( 1.1375;  1.1763)

Pooled StDev = 0.0137350
```

Interval Plot of Fd entry vs Feed rate

Residual Histogram for Fd entry

15/04/2019 13:55:19

```
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REFF\PENDUKUNG\dia 06.MPJ’
```

General Linear Model: Fd entry versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF    Adj SS    Adj MS  F-Value  P-Value
  Feed rate       2  0.002343  0.001172    20.68    0.008
  Spindle speed   2  0.000905  0.000453     7.99    0.040
Error             4  0.000227  0.000057
                  8  0.003475



             R-sq  R-sq(adj)  R-sq(pred)
             .48%     86.96%      66.99%
```

```
Coefficients

Term               Coef  SE Coef  T-Value  P-Value   VIF
Constant        1.13647  0.00251   452.99    0.000
Feed rate
  0.10         -0.01904  0.00355    -5.37    0.006  1.33
  0.18         -0.00136  0.00355    -0.38    0.720  1.33
Spindle speed
  93           -0.01331  0.00355    -3.75    0.020  1.33
  443           0.00241  0.00355     0.68    0.534  1.33


Regression Equation

Fd entry = 1.13647 - 0.01904 Feed rate_0.10 - 0.00136 Feed rate_0.18 + 0.0204
1 Feed rate_0.24
           - 0.01331 Spindle speed_93 + 0.00241 Spindle speed_443
           + 0.01090 Spindle speed_1420
```

Normplot of Residuals for Fd entry

———— 17/04/2019 6:41:58 ————————————

—

```
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REFF\PENDUKUNG\dia 06.MPJ’
```

General Linear Model: SNRA1 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source          DF   Adj SS    Adj MS  F-Value  P-Value
  Feed rate      2  0.13596  0.067981    21.46    0.007
  Spindle speed  2  0.05240  0.026201     8.27    0.038
Error            4  0.01267  0.003168
Total            8  0.20104


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0562810  93.70%     87.40%      68.09%


Coefficients

                  Coef  SE Coef  T-Value  P-Value   VIF
               -1.1099   0.0188   -59.16    0.000

                0.1455   0.0265     5.49    0.005  1.33
                0.0095   0.0265     0.36    0.737  1.33
            d
                0.1013   0.0265     3.82    0.019  1.33
```

```
  443          -0.0186   0.0265    -0.70    0.523  1.33


Regression Equation

SNRA1 = -1.1099 + 0.1455 Feed rate_0.10 + 0.0095 Feed rate_0.18 - 0.1551 Feed
 rate_0.24
        + 0.1013 Spindle speed_93 - 0.0186 Spindle speed_443 - 0.0828 Spindle
 speed_1420
```

Normplot of Residuals for SNRA1

General Linear Model: SNRA2 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF    Adj SS    Adj MS  F-Value  P-Value
  Feed rate       2  0.210388  0.105194     1.23    0.382
  Spindle speed   2  0.006202  0.003101     0.04    0.965
Error             4  0.340949  0.085237
Total             8  0.557539


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.291954  38.85%      0.00%       0.00%


Coefficients

Term              Coef  SE Coef  T-Value  P-Value   VIF
Constant       -1.7541   0.0973   -18.02    0.000
Feed rate
  0.10           0.198    0.138     1.44    0.223  1.33
  0.18          -0.025    0.138    -0.18    0.867  1.33
Spindle speed
  93             0.029    0.138     0.21    0.846  1.33
  443           -0.035    0.138    -0.25    0.813  1.33


Regression Equation

SNRA2 = -1.7541 + 0.198 Feed rate_0.10 - 0.025 Feed rate_0.18 - 0.174 Feed ra
te_0.24
        + 0.029 Spindle speed_93 - 0.035 Spindle speed_443 + 0.006 Spindle sp
eed_1420
```

f Residuals for SNRA2

17/04/2019 7:39:54 ————————————————————————

```
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REFF\PENDUKUNG\dia 06.MPJ’
```

11/05/2019 14:31:10

```
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REFF\PENDUKUNG\dia 06.MPJ’
```

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                   Spindle
Level  Feed rate     speed
1         -1.556    -1.726
2         -1.779    -1.789
3         -1.928    -1.748
Delta      0.372     0.063
Rank           1         2


Response Table for Means

                   Spindle
Level  Feed rate     speed
1          1.197     1.221
2          1.227     1.229
3          1.249     1.223
Delta      0.052     0.008
Rank           1         2
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                   Spindle
Level  Feed rate     speed
1         -1.556    -1.726
2         -1.779    -1.789
3         -1.928    -1.748
Delta      0.372     0.063
Rank           1         2


Response Table for Means

                   Spindle
Level  Feed rate     speed
1          1.197     1.221
2          1.227     1.229
3          1.249     1.223
Delta      0.052     0.008
               1         2
```

Plot for SN ratios

lysis: Fd Exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                   Spindle
Level  Feed rate     speed
1         -1.455    -1.726
2         -1.880    -1.789
3         -1.928    -1.748
Delta      0.473     0.063
Rank           1         2


Response Table for Means

                   Spindle
Level  Feed rate     speed
1          1.183     1.221
2          1.242     1.229
3          1.249     1.223
Delta      0.066     0.008
Rank           1         2
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd entry versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                   Spindle
Level  Feed rate     speed
1         -1.014    -1.009
2         -1.051    -1.128
3         -1.265    -1.193
Delta      0.251     0.184
Rank           1         2


Response Table for Means

                   Spindle
Level  Feed rate     speed
1          1.124     1.123
2          1.129     1.139
3          1.157     1.147
Delta      0.033     0.024
Rank           1         2
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd Exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                   Spindle
Level  Feed rate     speed
             455    -1.726
             880    -1.789
             928    -1.748
             473     0.063
               1         2


              e for Means
```

```
                    Spindle
Level  Feed rate    speed
1          1.183    1.221
2          1.242    1.229
3          1.249    1.223
Delta      0.066    0.008
Rank           1        2
```

Main Effects Plot for SN ratios

Surface Plot of Fd entry vs Feed rate; Spindle speed

Surface Plot of Fd Exit vs Feed rate; Spindle speed

General Linear Model: SNRA7 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF   Adj SS    Adj MS  F-Value  P-Value
  Feed rate       2  0.11020  0.055098     5.73    0.067
  Spindle speed   2  0.05240  0.026201     2.73    0.179
Error             4  0.03844  0.009609
Total             8  0.20104


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0980272  80.88%     61.76%       3.21%


Coefficients

Term              Coef  SE Coef  T-Value  P-Value   VIF
Constant       -1.1099   0.0327   -33.97    0.000
Feed rate
  0.10          0.0957   0.0462     2.07    0.107  1.33
  0.18          0.0594   0.0462     1.28    0.268  1.33
Spindle speed
  93            0.1013   0.0462     2.19    0.093  1.33
  443          -0.0186   0.0462    -0.40    0.708  1.33


Regression Equation

                  99 + 0.0957 Feed rate_0.10 + 0.0594 Feed rate_0.18 - 0.1551 Feed

                  013 Spindle speed_93 - 0.0186 Spindle speed_443 - 0.0828 Spindle
```

f Residuals for SNRA7

General Linear Model: SNRA8 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF    Adj SS    Adj MS  F-Value  P-Value
  Feed rate       2  0.406708  0.203354     5.62    0.069
  Spindle speed   2  0.006202  0.003101     0.09    0.919
Error             4  0.144629  0.036157
Total             8  0.557539


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.190151  74.06%     48.12%       0.00%


Coefficients

Term              Coef  SE Coef  T-Value  P-Value   VIF
Constant       -1.7541   0.0634   -27.68    0.000
Feed rate
  0.10          0.2993   0.0896     3.34    0.029  1.33
  0.18         -0.1256   0.0896    -1.40    0.234  1.33
Spindle speed
  93            0.0286   0.0896     0.32    0.766  1.33
  443          -0.0348   0.0896    -0.39    0.718  1.33


Regression Equation

SNRA8 = -1.7541 + 0.198 Feed rate_0.10 - 0.1256 Feed rate_0.18 - 0.1738 Feed
rate_0.24
        + 0.0286 Spindle speed_93 - 0.0348 Spindle speed_443 + 0.0062 Spindle
 speed_1420
```

Normplot of Residuals for SNRA8

9/1/2020 10:07:16 PM

```
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REFF\PENDUKUNG\dia 06.MPJ'
```

09/04/2019 18:46:33

```
Welcome to Minitab, press F1 for help.
```

Taguchi Design

```
Taguchi Orthogonal Array Design

L9(3^2)

Factors:  2
Runs:     9


Columns of L9(3^4) Array

1 2
```

Taguchi Analysis: Fd entry; Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                    Spindle
Level  Feed rate      speed
1         -1.073     -1.183
2         -1.217     -1.240
3         -1.425     -1.292
Delta      0.351      0.110
Rank           1          2


Response Table for Means

                    Spindle
Level  Feed rate      speed
1          1.132      1.146
2          1.150      1.154
3          1.178      1.160
Delta      0.046      0.014
Rank           1          2


Response Table for Standard Deviations

                    Spindle
Level  Feed rate      speed
1        0.01426    0.02744
2        0.02544    0.01808
3        0.02837    0.02255
Delta    0.01411    0.00935
Rank           1          2
```

Main Effects Plot for Means

Main Effects Plot for SN ratios

of Fd entry vs Feed rate; Spindle speed

of Fd exit vs Feed rate; Spindle speed

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Dynamic Response

       Feed  Spindle
Level  rate    speed
1         *        *
2         *        *
3         *        *
Delta     *        *
Rank    1.5      1.5


Response Table for Slopes

                  Spindle
Level  Feed rate    speed
1          1.018    1.034
2          1.032    1.022
3          1.035    1.028
Delta      0.017    0.012
Rank           1        2
```

Main Effects Plot for Slopes

```
* ERROR * No graphs will be plotted for SN ratios. All values are missing.
```

Taguchi Analysis: Fd entry versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                  Spindle
Level  Feed rate    speed
1        -0.9955  -1.0343
2        -1.0796  -1.1429
3        -1.2734  -1.1712
Delta     0.2779   0.1369
Rank           1        2


Response Table for Means

                  Spindle
Level  Feed rate    speed
1          1.121    1.127
2          1.132    1.141
3          1.158    1.144
Delta      0.036    0.018
Rank           1        2
```

Main Effects Plot for Means

Main Effects Plot for SN ratios

lysis: Fd exit versus Feed rate; Spindle speed

```
e for Signal to Noise Ratios
tter

          Spindle
ate         speed
149        -1.324
```

```
2         -1.351   -1.335
3         -1.570   -1.410
Delta      0.420    0.086
Rank           1        2


Response Table for Means

                   Spindle
Level  Feed rate     speed
1          1.142     1.165
2          1.168     1.166
3          1.198     1.176
Delta      0.056     0.011
Rank           1         2
```

Main Effects Plot for Means

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

Predicted values

```
* NOTE * The response labeled “Ln(StDev)” contains all missing values. No pre
dictions will be
         computed or stored for this response.
* NOTE * The response labeled “StDev” contains all missing values. No predict
ions will be
         computed or stored for this response.


S/N Ratio     Mean
 -1.11645  1.13764


Factor levels for predictions

Feed  Spindle
rate    speed
 0.1       93
```

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
* NOTE * Unable to perform linear model analysis.


Response Table for Signal to Noise Ratios
Smaller is better

                   Spindle
Level  Feed rate     speed
1         -1.149   -1.324
2         -1.351   -1.335
3         -1.570   -1.410
Delta      0.420    0.086
Rank           1        2


             e for Means

                   Spindle
             ate     speed
             142     1.165
             168     1.166
```

```
3          1.198    1.176
Delta      0.056    0.011
Rank           1        2


Response Table for Standard Deviations

       Feed  Spindle
Level  rate    speed
1         *        *
2         *        *
3         *        *
Delta     *        *
Rank    1.5      1.5
```

Main Effects Plot for Means

Main Effects Plot for SN ratios

Taguchi Analysis: Fd entry versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                  Spindle
Level  Feed rate    speed
1        -0.9955  -1.0343
2        -1.0796  -1.1429
3        -1.2734  -1.1712
Delta     0.2779   0.1369
Rank           1        2


Response Table for Means

                  Spindle
Level  Feed rate    speed
1          1.121    1.127
2          1.132    1.141
3          1.158    1.144
Delta      0.036    0.018
Rank           1        2


Response Table for Standard Deviations

       Feed  Spindle
Level  rate    speed
1         *        *
2         *        *
3         *        *
Delta     *        *
Rank    1.5      1.5
```

Main Effects Plot for SN ratios

lysis: Fd exit versus Feed rate; Spindle speed

```
le to perform linear model analysis.


e for Signal to Noise Ratios
tter
```

```
                  Spindle
Level  Feed rate    speed
1         -1.149   -1.324
2         -1.351   -1.335
3         -1.570   -1.410
Delta      0.420    0.086
Rank           1        2


Response Table for Means

                  Spindle
Level  Feed rate    speed
1          1.142    1.165
2          1.168    1.166
3          1.198    1.176
Delta      0.056    0.011
Rank           1        2


Response Table for Standard Deviations

       Feed  Spindle
Level  rate    speed
1         *        *
2         *        *
3         *        *
Delta     *        *
Rank    1.5      1.5
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

Predicted values

```
* NOTE * The response labeled “Ln(StDev)” contains all missing values. No pre
dictions will be
         computed or stored for this response.
* NOTE * The response labeled “StDev” contains all missing values. No predict
ions will be
         computed or stored for this response.


S/N Ratio     Mean
 -1.11645  1.13764


Factor levels for predictions

Feed  Spindle
rate    speed
 0.1       93
```

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

Predicted values

```
             response labeled “Ln(StDev)” contains all missing values. No pre
              be
            uted or stored for this response.
             response labeled “StDev” contains all missing values. No predict

            uted or stored for this response.
```

```
S/N Ratio     Mean
 -1.12811  1.13863


Factor levels for predictions

Feed  Spindle
rate    speed
 0.1      443
```

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
* NOTE * Unable to perform linear model analysis.


Response Table for Signal to Noise Ratios
Smaller is better

                  Spindle
Level  Feed rate    speed
1         -1.149   -1.324
2         -1.351   -1.335
3         -1.570   -1.410
Delta      0.420    0.086
Rank           1        2


Response Table for Means

                  Spindle
Level  Feed rate    speed
1          1.142    1.165
2          1.168    1.166
3          1.198    1.176
Delta      0.056    0.011
Rank           1        2


Response Table for Standard Deviations

       Feed  Spindle
Level  rate    speed
1         *        *
2         *        *
3         *        *
Delta     *        *
Rank    1.5      1.5
```

Main Effects Plot for SN ratios

10/04/2019 12:27:45

```
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```

Surface Plot of Fd entry vs Feed rate; Spindle speed

of Fd exit vs Feed rate; Spindle speed

11/04/2019 17:02:57

```
Welcome to Minitab, press F1 for help.
Retrieving project from file: ‘E:\BATTY\000000DISSERTATION
REFF\PENDUKUNG\dia 08.MPJ’
```

Taguchi Analysis: Fd entry versus Feed rate; Spindle speed

```
* NOTE * Unable to perform linear model analysis.


Response Table for Signal to Noise Ratios
Smaller is better

                  Spindle
Level  Feed rate    speed
1        -0.9955  -1.0343
2        -1.0796  -1.1429
3        -1.2734  -1.1712
Delta     0.2779   0.1369
Rank           1        2


Response Table for Means

                  Spindle
Level  Feed rate    speed
1          1.121    1.127
2          1.132    1.141
3          1.158    1.144
Delta      0.036    0.018
Rank           1        2


Response Table for Standard Deviations

       Feed  Spindle
Level  rate    speed
1         *        *
2         *        *
3         *        *
Delta     *        *
Rank    1.5      1.5
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
* NOTE * Unable to perform linear model analysis.


Response Table for Signal to Noise Ratios
Smaller is better

                  Spindle
Level  Feed rate    speed
1         -1.149   -1.324
2         -1.351   -1.335
3         -1.570   -1.410
             420    0.086
               1        2


             e for Means

                  Spindle
             ate    speed
```

```
1          1.142    1.165
2          1.168    1.166
3          1.198    1.176
Delta      0.056    0.011
Rank           1        2


Response Table for Standard Deviations

       Feed  Spindle
Level  rate    speed
1         *        *
2         *        *
3         *        *
Delta     *        *
Rank    1.5      1.5
```

Main Effects Plot for SN ratios

15/04/2019 12:45:17

```
Welcome to Minitab, press F1 for help.
Retrieving project from file: ‘E:\BATTY\000000DISSERTATION
REFF\PENDUKUNG\dia 08.MPJ’
```

General Linear Model: Fd entry versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF    Adj SS    Adj MS  F-Value  P-Value
  Feed rate       2  0.002105  0.001053    22.37    0.007
  Spindle speed   2  0.000537  0.000269     5.71    0.067
Error             4  0.000188  0.000047
Total             8  0.002831


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0068599  93.35%     86.70%      66.34%


Coefficients

Term                Coef  SE Coef  T-Value  P-Value   VIF
Constant        1.13726  0.00229   497.35    0.000

               -0.01579  0.00323    -4.88    0.008  1.33
               -0.00491  0.00323    -1.52    0.203  1.33
            d
               -0.01072  0.00323    -3.31    0.030  1.33
                0.00350  0.00323     1.08    0.340  1.33
```

```
Regression Equation

Fd entry = 1.13726 - 0.01579 Feed rate_0.10 - 0.00491 Feed rate_0.18 + 0.0207
0 Feed rate_0.24
           - 0.01072 Spindle speed_93 + 0.00350 Spindle speed_443
           + 0.00721 Spindle speed_1420
```

Normplot of Residuals for Fd entry

General Linear Model: Fd exit versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF    Adj SS    Adj MS  F-Value  P-Value
  Feed rate       2  0.004783  0.002391     5.28    0.075
  Spindle speed   2  0.000223  0.000112     0.25    0.793
Error             4  0.001811  0.000453
Total             8  0.006816


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0212751  73.44%     46.88%       0.00%


Coefficients

Term              Coef  SE Coef  T-Value  P-Value   VIF
Constant       1.16935  0.00709   164.89    0.000
Feed rate
  0.10         -0.0277   0.0100    -2.76    0.051  1.33
  0.18         -0.0010   0.0100    -0.10    0.923  1.33
Spindle speed
  93           -0.0040   0.0100    -0.40    0.710  1.33
  443          -0.0030   0.0100    -0.30    0.779  1.33


Regression Equation

Fd exit = 1.16935 - 0.0277 Feed rate_0.10 - 0.0010 Feed rate_0.18 + 0.0287 Fe
ed rate_0.24
          - 0.0040 Spindle speed_93 - 0.0030 Spindle speed_443 + 0.0070 Spind
le speed_1420
```

Normplot of Residuals for Fd exit

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```

General Linear Model: SNRA1 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF   Adj SS    Adj MS  F-Value  P-Value
  Feed rate       2  0.12189  0.060947    22.49    0.007
  Spindle speed   2  0.03134  0.015670     5.78    0.066
Error             4  0.01084  0.002710
Total             8  0.16408


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0520621  93.39%     86.78%      66.55%


Coefficients

Term              Coef  SE Coef  T-Value  P-Value   VIF
Constant       -1.1161   0.0174   -64.32    0.000
Feed rate
  0.10          0.1207   0.0245     4.92    0.008  1.33
  0.18          0.0366   0.0245     1.49    0.210  1.33
Spindle speed
  93            0.0818   0.0245     3.33    0.029  1.33
  443          -0.0268   0.0245    -1.09    0.337  1.33


Regression Equation

SNRA1 = -1.1161 + 0.1207 Feed rate_0.10 + 0.0366 Feed rate_0.18 - 0.1573 Feed
 rate_0.24
        + 0.0818 Spindle speed_93 - 0.0268 Spindle speed_443 - 0.0551 Spindle
 speed_1420
```

Normplot of Residuals for SNRA1

General Linear Model: SNRA2 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

               Type   Levels  Values
               Fixed       3  0.10; 0.18; 0.24
             d Fixed       3  93; 443; 1420


            ariance

                 DF   Adj SS    Adj MS  F-Value  P-Value
```

```
  Feed rate        2  0.26526  0.132632     5.13    0.079
  Spindle speed    2  0.01316  0.006581     0.25    0.787
Error              4  0.10337  0.025843
Total              8  0.38180


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.160757  72.93%     45.85%       0.00%


Coefficients

Term               Coef  SE Coef  T-Value  P-Value   VIF
Constant        -1.3564   0.0536   -25.31    0.000
Feed rate
  0.10           0.2073   0.0758     2.74    0.052  1.33
  0.18           0.0057   0.0758     0.08    0.943  1.33
Spindle speed
  93             0.0327   0.0758     0.43    0.689  1.33
  443            0.0210   0.0758     0.28    0.795  1.33


Regression Equation

SNRA2 = -1.3564 + 0.2073 Feed rate_0.10 + 0.0057 Feed rate_0.18 - 0.2131 Feed
 rate_0.24
        + 0.0327 Spindle speed_93 + 0.0210 Spindle speed_443 - 0.0537 Spindle
 speed_1420
```

Normplot of Residuals for SNRA2

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Taguchi Design

```
Taguchi Orthogonal Array Design

L9(3^2)

Factors:  2
Runs:     9


Columns of L9(3^4) Array

1 2
```

Taguchi Analysis: Fd Entry versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                  Spindle
Level  Feed rate    speed
1        -0.8700  -0.8906
2        -0.9594  -1.0539
3        -1.0945  -0.9794
Delta     0.2245   0.1633
Rank           1        2


Response Table for Means

                  Spindle
Level  Feed rate    speed
1          1.105    1.108
2          1.117    1.129
3          1.134    1.119
Delta      0.029    0.021
Rank           1        2
```

Main Effects Plot for Means

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                  Spindle
Level  Feed rate    speed
1         -1.236   -1.393
2         -1.344   -1.471
             561   -1.277
             325    0.194
               1        2


           e for Means

                  Spindle
             ate    speed
```

```
1          1.153    1.175
2          1.167    1.185
3          1.197    1.158
Delta      0.044    0.026
Rank           1        2
```

Main Effects Plot for SN ratios

Surface Plot of Fd Entry vs Feed rate; Spindle speed

Surface Plot of Fd exit vs Feed rate; Spindle speed

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General Linear Model: Fd Entry versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source            DF    Adj SS    Adj MS  F-Value  P-Value
  Feed rate        2  0.001268  0.000634    10.32    0.026
  Spindle speed    2  0.000659  0.000329     5.36    0.074
Error              4  0.000246  0.000061
Total              8  0.002172


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0078367  88.69%     77.38%      42.75%


Coefficients

Term               Coef  SE Coef  T-Value  P-Value   VIF
Constant        1.11886  0.00261   428.31    0.000
Feed rate
  0.10         -0.01339  0.00369    -3.62    0.022  1.33
  0.18         -0.00207  0.00369    -0.56    0.605  1.33
            d
               -0.01074  0.00369    -2.91    0.044  1.33
                0.01019  0.00369     2.76    0.051  1.33


            uation

             11886 - 0.01339 Feed rate_0.10 - 0.00207 Feed rate_0.18 + 0.0154
             .24
```

```
            - 0.01074 Spindle speed_93 + 0.01019 Spindle speed_443
            + 0.00055 Spindle speed_1420
```

Normplot of Residuals for Fd Entry

General Linear Model: Fd exit versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF    Adj SS    Adj MS  F-Value  P-Value
  Feed rate       2  0.003009  0.001504     1.40    0.347
  Spindle speed   2  0.001051  0.000525     0.49    0.646
Error             4  0.004307  0.001077
Total             8  0.008367


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0328155  48.52%      0.00%       0.00%


Coefficients

Term              Coef  SE Coef  T-Value  P-Value   VIF
Constant        1.1726   0.0109   107.20    0.000
Feed rate
  0.10         -0.0193   0.0155    -1.25    0.280  1.33
  0.18         -0.0053   0.0155    -0.34    0.751  1.33
Spindle speed
  93            0.0023   0.0155     0.15    0.890  1.33
  443           0.0119   0.0155     0.77    0.483  1.33


Regression Equation

Fd exit = 1.1726 - 0.0193 Feed rate_0.10 - 0.0053 Feed rate_0.18 + 0.0246 Fee
d rate_0.24
          + 0.0023 Spindle speed_93 + 0.0119 Spindle speed_443 - 0.0142 Spind
le speed_1420
```

Normplot of Residuals for Fd exit

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ar Model: SNRA1 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF    Adj SS    Adj MS  F-Value  P-Value
  Feed rate       2  0.07666  0.038330     9.95    0.028
  Spindle speed   2  0.04012  0.020060     5.21    0.077
Error             4  0.01542  0.003854
Total             8  0.13220


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0620791  88.34%     76.68%      40.97%


Coefficients

Term               Coef  SE Coef  T-Value  P-Value   VIF
Constant        -0.9746   0.0207   -47.10    0.000
Feed rate
  0.10           0.1046   0.0293     3.57    0.023  1.33
  0.18           0.0153   0.0293     0.52    0.629  1.33
Spindle speed
  93             0.0840   0.0293     2.87    0.045  1.33
  443           -0.0793   0.0293    -2.71    0.054  1.33


Regression Equation

SNRA1 = -0.9746 + 0.1046 Feed rate_0.10 + 0.0153 Feed rate_0.18 - 0.1199 Feed
 rate_0.24
        + 0.0840 Spindle speed_93 - 0.0793 Spindle speed_443 - 0.0047 Spindle
 speed_1420
```

Normplot of Residuals for SNRA1

General Linear Model: SNRA2 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


             ariance

                 DF    Adj SS   Adj MS  F-Value  P-Value
                  2  0.16482  0.08241     1.40    0.345
             eed  2  0.05729  0.02865     0.49    0.646
                  4  0.23480  0.05870
                  8  0.45691
```

```
Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.242282  48.61%      0.00%       0.00%


Coefficients

Term               Coef  SE Coef  T-Value  P-Value   VIF
Constant        -1.3803   0.0808   -17.09    0.000
Feed rate
  0.10            0.145    0.114     1.27    0.274  1.33
  0.18            0.036    0.114     0.32    0.767  1.33
Spindle speed
  93             -0.013    0.114    -0.11    0.915  1.33
  443            -0.091    0.114    -0.79    0.472  1.33


Regression Equation

SNRA2 = -1.3803 + 0.145 Feed rate_0.10 + 0.036 Feed rate_0.18 - 0.181 Feed ra
te_0.24
        - 0.013 Spindle speed_93 - 0.091 Spindle speed_443 + 0.104 Spindle sp
eed_1420
```

Normplot of Residuals for SNRA2

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Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                     Spindle
Level  Feed rate       speed
1         -1.236      -1.393
2         -1.344      -1.471
3         -1.561      -1.277
Delta      0.325       0.194
Rank           1           2


Response Table for Means

                     Spindle
Level  Feed rate       speed
1          1.153       1.175
2          1.167       1.185
3          1.197       1.158
Delta      0.044       0.026
Rank           1           2
```

s Plot for SN ratios

lysis: Fd Entry versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                    Spindle
Level  Feed rate      speed
1        -0.8622    -0.8906
2        -0.9672    -1.0539
3        -1.0945    -0.9794
Delta     0.2323     0.1633
Rank           1          2


Response Table for Means

                    Spindle
Level  Feed rate      speed
1          1.104      1.108
2          1.118      1.129
3          1.134      1.119
Delta      0.030      0.021
Rank           1          2
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                    Spindle
Level  Feed rate      speed
1         -1.236     -1.393
2         -1.344     -1.471
3         -1.561     -1.277
Delta      0.325      0.194
Rank           1          2


Response Table for Means

                    Spindle
Level  Feed rate      speed
1          1.153      1.175
2          1.167      1.185
3          1.197      1.158
Delta      0.044      0.026
Rank           1          2
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                    Spindle
Level  Feed rate      speed
1         -1.236     -1.393
             344     -1.471
             561     -1.277
             325      0.194
               1          2


          e for Means
```

```
                  Spindle
Level  Feed rate    speed
1          1.153    1.175
2          1.167    1.185
3          1.197    1.158
Delta      0.044    0.026
Rank           1        2
```

Main Effects Plot for SN ratios

Taguchi Analysis: Fd exit versus Feed rate; Spindle speed

```
Response Table for Signal to Noise Ratios
Smaller is better

                  Spindle
Level  Feed rate    speed
1         -1.175   -1.393
2         -1.406   -1.472
3         -1.561   -1.277
Delta      0.387    0.195
Rank           1        2


Response Table for Means

                  Spindle
Level  Feed rate    speed
1          1.145    1.175
2          1.176    1.185
3          1.197    1.158
Delta      0.052    0.026
Rank           1        2
```

Main Effects Plot for SN ratios

Surface Plot of Fd exit vs Feed rate; Spindle speed

Surface Plot of Fd Entry vs Feed rate; Spindle speed

General Linear Model: SNRA1 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


              ariance

                 DF   Adj SS    Adj MS  F-Value  P-Value
                  2  0.08121  0.040603    14.94    0.014
             eed  2  0.04012  0.020060     7.38    0.045
                  4  0.01087  0.002717
                  8  0.13220
```

```
Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0521291  91.78%     83.55%      58.37%


Coefficients

Term              Coef  SE Coef  T-Value  P-Value   VIF
Constant       -0.9746   0.0174   -56.09    0.000
Feed rate
  0.10          0.1124   0.0246     4.57    0.010  1.33
  0.18          0.0075   0.0246     0.30    0.776  1.33
Spindle speed
  93            0.0840   0.0246     3.42    0.027  1.33
  443          -0.0793   0.0246    -3.23    0.032  1.33


Regression Equation

SNRA1 = -0.9746 + 0.1124 Feed rate_0.10 + 0.0075 Feed rate_0.18 - 0.1199 Feed
 rate_0.24
        + 0.0840 Spindle speed_93 - 0.0793 Spindle speed_443 - 0.0047 Spindle
 speed_1420
```

Normplot of Residuals for SNRA1

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General Linear Model: SNRA2 versus Feed rate; Spindle speed

```
Method

Factor coding  (-1; 0; +1)


Factor Information

Factor         Type   Levels  Values
Feed rate      Fixed       3  0.10; 0.18; 0.24
Spindle speed  Fixed       3  93; 443; 1420


Analysis of Variance

Source           DF   Adj SS   Adj MS  F-Value  P-Value
  Feed rate       2  0.22706  0.11353     2.64    0.186
  Spindle speed   2  0.05789  0.02895     0.67    0.560
Error             4  0.17200  0.04300
Total             8  0.45696


Model Summary

                  -sq  R-sq(adj)  R-sq(pred)
                  36%     24.72%       0.00%



                  Coef  SE Coef  T-Value  P-Value   VIF
               -1.3807   0.0691   -19.97    0.000
```

```
Feed rate
  0.10          0.2061   0.0978     2.11    0.103  1.33
  0.18         -0.0256   0.0978    -0.26    0.807  1.33
Spindle speed
  93           -0.0126   0.0978    -0.13    0.904  1.33
  443          -0.0913   0.0978    -0.93    0.403  1.33
```

```
Regression Equation

SNRA2 = -1.3807 + 0.2061 Feed rate_0.10 - 0.0256 Feed rate_0.18 - 0.1805 Feed
 rate_0.24
        - 0.0126 Spindle speed_93 - 0.0913 Spindle speed_443 + 0.1039 Spindle
 speed_1420
```

Normplot of Residuals for SNRA2

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Journal of Physics: Conference Series

An optimization of the machining parameters on delamination in drilling ramie woven reinforced composites using Taguchi method

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An optimization of the machining parameters on delamination in drilling ramie woven reinforced composites using Taguchi method

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Abstract. In this study, the drilling parameters will be evaluated to obtain optimal parameters in minimizing the impact of drilling damage on composite materials reinforced by ramie woven. The impact of damage observed in the study is delamination that occurs in the drill hole, where the smaller value is desired. The drilling parameters are optimized using the Taguchi method with two control factors, namely the feed rate and spindle speed, each parameter is designed in three levels. This experiment then carried out on four different diameter drill bits, i.e., 4, 6, 8 and 10 mm. While experimental planning uses L_9 orthogonal arrays and the "smaller is better" approach is given as a standard analysis. By performing an analysis of variance (ANOVA) statistics can be determined for the significance of each drilling parameter. A series of experiments were carried out to get the appropriate optimization. It was found that the critical factor causing delamination in drilling is the feed rate followed by spindle speed, where this phenomenon occurs in each diameter of the drill bit.

Keywords: delamination, ramie woven, Taguchi method and ANOVA.

1. Introduction

The growing demand for composite materials and in 2017 is expected to reach $ 29.9B with a 7% annual growth projection [1]. The primary industries of composite users are in the fields of aerospace, construction, transportation, and wind energy. To obtain the final geometry of a composite product, manufacturing and machining processes will be needed, such as edge cutting machines and drill machines. However, it is challenging to obtained maximize finishing compared to the machining process in metals. The leading cause is the homogeneity of the material, anisotropic properties and complex damage phenomena that occur during the cutting process. This results in a poor surface finish, dimensional inaccuracy, and component rejection, [2].

According to Bosco et al. [3], during the machining process of the composite, various problems as damage to reinforcing fibers, cracks in the matrix, detachment of bonds between iber pull-out, fuzzing, thermal degradation, spalling and delamination. Delamination he entry and exit side of the composite is significant and must reduce because it can strength and material stability. Damage and delamination due to processing processes

---

generally occur due to the thrust force of the cutting tool against the composite material. Delamination on the drilling process can be analyzed by looking directly at the delamination factor or by searching for thrust force or torque in drilling composite materials. Delamination is an occurrence of damage, which comes up because of the anisotropy and the brittleness of composite materials. In practice, it is needed to determine optimal machining parameters to reduce defects in the machining process to produce high-quality products.

Several approaches have been made before to get the machining process parameters to optimize production results, including using the Taguchi and ANOVA method applications. With this approach, researchers have been able to maximize the parameters used in machining on composite materials. Pang et al. [4], reported that the application of the Taguchi method in hybrid composites with epoxy matrix reinforced by halloysite nanotubes and aluminum was able to determine the best combination of machining parameters that provided an optimal response with lower surface roughness and cutting forces. Mohan et al. [5] used the Taguchi method to analyze delamination damage and use multiple factors in the process of GFRP composite material and suggested optimization of machining parameters. With the same method Sunny et al. [6], concluded that using ANOVA was able to reveal that the feed rate as the primary parameter in machining had much influence on the high delamination factor. Likewise in a study conducted by Tsao [7] using the Response Surface Methodology based on Taguchi method in evaluating the effect of drilling parameters on delamination damage found that there are several factors that are crucial factors in influencing damage factors, i.e.; cutting velocity ratio, feed rate, inner drill type and inner drill diameter. Balaji et al. [8], have applied Taguchi and ANOVA methods to observe the effect of machining parameters on drill bit vibrations and surface roughness. Delamination factors on the entry and exit side of the drilling process have also been analyzed using ANOVA by comparing between experimental results and ANFIS predictions, and it was found that on average the delamination damage at the entry side was smaller than on the exit side, [9]. With the same method Gashemi et al. [10], show that delamination factors increase from low and high parameter values in the experimental range of predetermined settings. Ultimately, delamination factors can be minimized by optimizing machining parameters. Hamdan et al. [11] claim that the Taguchi optimization method is the most effective method for optimizing machining parameters, where response variables can be identified. The optimal combination of drilling parameters is obtained using the signal-to-noise ratio (S/N) analysis, concluded that the feed rate and cutting speed are the most influential factors on delamination. Meanwhile, the best delamination results are obtained at lower cutting speeds and feed rates, [12].

The primary goal of this paper is to optimization and analyze the effect of machining parameters, such as feed rate, spindle speed by different diameter drill bit on delamination damage produced by drilling polymer composites reinforced by ramie's woven (NFRP) using the Taguchi and ANOVA method designs.

2. Material and Experimental Set-up

2.1. Workpiece Material

The workpiece used in the experiment was made using the hand lay-up technique. Ramie's woven from ramie yarn type S12/3 (Fig. 1) is used as a polyesters YUKALAC @ 157 BQTN-EX reinforcement. The workpiece material is made in the form of plat measuring 200 × 200 × 5 ± 0.2 mm.

The drilling process uses a Pillar drill type TCA-35 ERLO (Fig.2.a). The drill bits used are type brad & drill bits spurs with diameters of 4, 6, 8 and 10 mm respectively (Fig.2.b). The drilling process is carried out without using coolant. The machining parameters used are feed rates 0.1, 0.18 and 0.24 mm/rev, while the spindle speed is 93, 443 and 1420 rpm. Delamination damage around the drill hole
SON L220 scanner with 2400 DPI resolution, and delamination was measured using
us 4.5 software application.

Fig. 1. Ramie woven with S12/3 type yarn

a) b)

Fig. 2. a) Pillar drill TCA-35 ERLO; b) “Brad & spur” drill’s bit

2.2. *Delamination Factor (F_d)*

Most studies on the damage caused by drilling on composite materials say that the most common cause is delamination observed appearing on the entry and exit side of the hole. Delamination factor is using to illustrate the level of delamination damage. The delamination factor can be solved using the following equation:

$$F_d = \frac{D_{max}}{D} \quad (1)$$

Where, D_{max} is the maximum diameter created due to delamination around the hole and D is the hole or drill diameter.

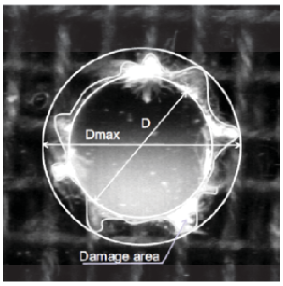


Fig.3. Illustrating the definition of delamination size

2.3. Taguchi method, analysis of variance (ANOVA) and experimental set-up

The Taguchi method was first coined by Dr. Genichi Taguchi in 1949, this method was developed to improve the quality of products and processes and to be able to reduce costs and resources to a minimum. The Taguchi method is off-line quality control which means preventive quality control. Off-line quality control is carried out at the beginning of the life cycle product, namely repairs at the beginning to produce the product (to get right first time). Taguchi's contribution to quality is loss function, orthogonal array, and robustness. In the Taguchi method, there are three stages to optimize product design or production processes, namely system design, parameter design, and tolerance design [13]. Orthogonal arrays are used to determine the number of minimal experiments that can provide as much information as possible of all the factors that affect the parameters. The most critical part of orthogonal arrays lies in selecting the combination of levels from the input variables for each experiment. The experimental results are then converted into a signal-to-noise (S/N) ratio to measure quality characteristics that deviate from the desired value [5]. Furthermore, Mohan et al. [5] stated that in practice, there were three categories of quality characteristics in the S/N ratio analysis. The three categories and equations are as follows:

Nominal is the best characteristic:

$$\frac{S}{N} = 10\ log\frac{\bar{y}^2}{S_{\bar{y}}^2} \tag{2}$$

Smaller the better characteristic:

$$\frac{S}{N} = -10\ log\frac{1}{n}\left(\sum y^2\right) \tag{3}$$

And larger the better characteristic:

$$\frac{S}{N} = -log\frac{1}{n}\left(\sum \frac{1}{y^2}\right) \tag{4}$$

Where, $\bar{y}$ is the average of observed data, s^2 the variation of y, n the number of observations, and y is the observed data.

In this study, the feed rate and spindle speed are two machining parameters that are used as control factors and each parameter is designed in three levels. This analysis is done at four different tool diameters and does not compare each other. Drilling parameters and levels used in this experiment are as shown in table 1. For the delamination factor, S/N ratio was calculated using *smaller is the best* characteristic.

Table 1. Parameters and level experiment set-up

Drilling parameter	**Level 1 (Low)**	**Level 2 (Medium)**	**Level 3 (High)**
Feed rate, *f* (mm/rev)	0.1	0.18	0.24
Spindle speed, *N* (rpm)	93	443	1420

Three control factors were accommodated into experimental studies using orthogonal arrays based on the Taguchi method L_9 as shown in Table 2. Taguchi method analysis in this study was done using
ftware. Contributions of factors, interactions and the effect of each process on
were investigated using analysis of variance (ANOVA). ANOVA is a statistical
rmine the degree of difference or similarity between two or more groups of data [14].

The desired level of significance in this analysis is α = 0.05, to identify drilling parameters that affect delamination damage.

Table 2. Orthogonal array based on Taguchi method L_9

Experiments	**Feed rate**	**Spindle speed**
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

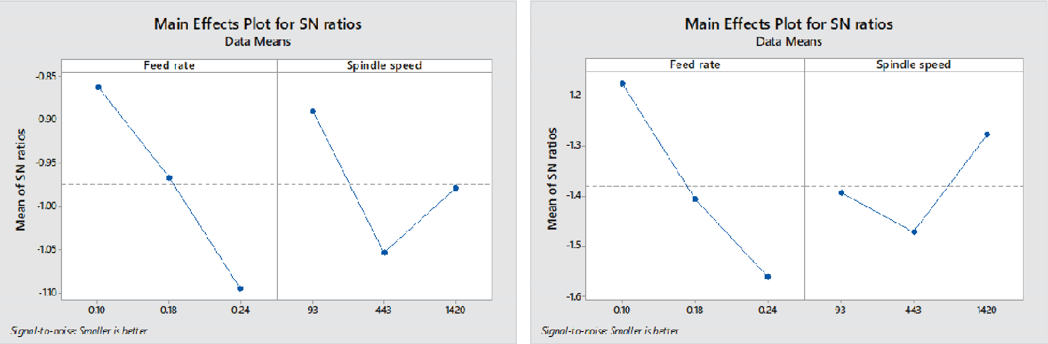
3. Result and Discussion

3.1. Diameter 10 mm

Table 3. S/N response table for delamination factor on diameter drill bits 10 mm.

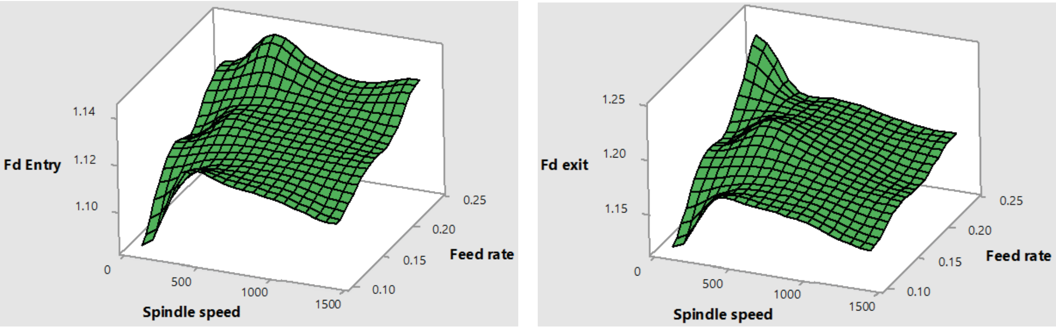
Exp. No.	Design of Experiment		Delamination Factor		S/N ratio	
	Feed rate	Spindle speed	Entry side	Exit side	Entry side	Exit side
1	0.10	93	1.085	1.119	-0.712	-0.976
2	0.10	443	1.121	1.172	-0.990	-1.379
3	0.10	1420	1.107	1.144	-0.884	-1.169
4	0.18	93	1.111	1.172	-0.918	-1.380
5	0.18	443	1.124	1.197	-1.014	-1.562
6	0.18	1420	1.118	1.158	-0.970	-1.277
7	0.24	93	1.128	1.234	-1.042	-1.823
8	0.24	443	1.143	1.185	-1.158	-1.476
9	0.24	1420	1.133	1.173	-1.084	-1.384

Tables 3, 5, 7 and 9 are experimental results which are transformed into the signal to noise (S/N) ratio, each table is made in different diameters of drill bits. Fig.4 shows the effect of parameters on delamination damage on the entry side and exit side of the borehole. On the input side the optimal parameters are obtained at the feed rate of 0.1 mm/rev and the spindle speed of 93 rpm, likewise on the output side of the optimum occurs at the feed rate 0.1 mm/rev but differs from the spindle speed, the optimal parameters are obtained at the spindle speed of 1420 rpm. From the two parameters, it can be seen that the addition of the feed rate significantly causes the increase in delamination damage, whereas the increase in the spindle speed does not affect to the delamination damage substantially. These results are in line with several previous studies e.g., Gashemi et al. [10], Sunny et al. [6] and Kilickap [12]. This phenomenon occurs because according to Gashemi, the increase in delamination due to the rise in the feed rate is caused by heat generation that occurs when the contact between the drill tool and the workpiece. Fig.5 is a 3D surface plot that shows the interaction between the feed rate and spindle speed to the delamination factor on the entry side and exit side. The graph shows that the nation factor occurs at a feed rate of 0.1 mm/rev and a spindle speed of 93 rpm.



a) entry side b) exit side

Fig. 4 Main effect plot for S/N ratio on delamination damage in diameter drill bits 10 mm



a) entry side b) exit side

Fig.5 3D interaction (f × N) plot on the diameter drill bit 10 mm

The results of the analysis of variance (ANOVA) in delamination damage due to drilling on the 10 mm drill bit are shown in table 4. From both sides of the drill hole, only the factor on the entry side has a P-value <0.05, which means that the data is significant. Whereas in other factors the P-value >0.05 shows that statistically, the information is not substantial to the growth of delamination damage. When viewed from a percentage of contribution both factors have a statistically and physically significant contribution to delamination damage both in the entry side and exit side, it can be seen that the participation of the feed rate factor is higher than the spindle speed of 61.4% on the entry side and 50.0% on the exit side. But if we review the percentage of errors on the exit side by 37.5% higher than the acceptable level (15%). According to Kahwash et al. [2], this occurs because the emergence of interactions is unconsidered among several control factors.

Table 4. Analysis of variance for means on diameter drill bits 10 mm

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	% contribution
Entry side						
Feed rate	0.08121	2	0.040603	14.94136	0.01394	61.4%
Spindle speed	0.04012	2	0.020059	7.381850	0.045444	30.3%
Error	0.01087	4	0.002717			8.2%
Total	0.132195	8				
	0.22706	2	0.11353	2.666301	0.183702	50.0%
	0.05789	2	0.02895	0.668985	0.561523	12.5%

Error	0.17200	4	0.04300		37.5%
Total	0.45696	8			

Fig.6 illustrates the correlation between the control factor (feed rate and spindle speed) and the delamination factor on the entry side and exit side in the form of a multiple linear regression graph. The following equation obtains the chart:

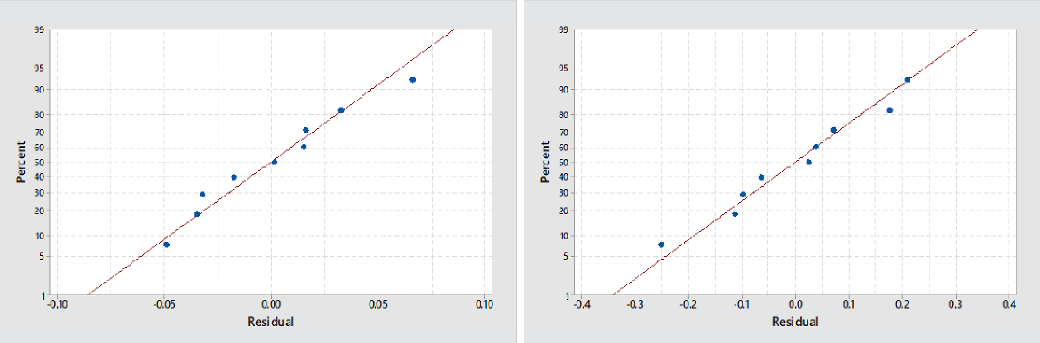
$$F_d \text{ entry} = -0.9746 + 0.1124 \cdot f_{0.10} + 0.0075 \cdot f_{0.18} - 0.1199 \cdot f_{0.24} + 0.0840 \cdot N_{93} - 0.0793 \cdot N_{443} - 0.0047 \cdot N_{1420} \qquad (5)$$

$$R^2 = 0.9178$$

$$F_d \text{ exit} = -1.3807 + 0.2061 \cdot f_{0.10} + 0.256 \cdot f_{0.18} - 0.1805 \cdot f_{0.24} - 0.0126 \cdot N_{93} - 0.0913 \cdot N_{443} + 0.1039 \cdot N_{1420} \qquad (6)$$

$$R^2 = 0.6236$$

Where F_d is a delamination factor that occurs in the entry side or exit side, *f* is the feed rate in mm/rev and *N* is the spindle speed in rpm.



a) entry side b) exit side

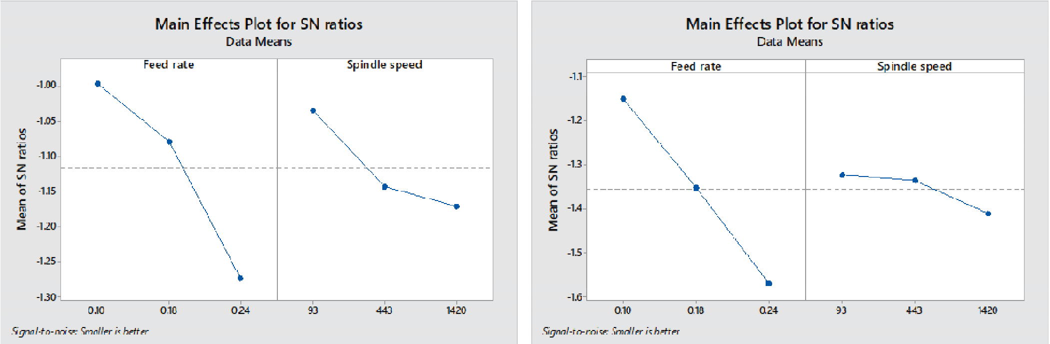
Fig.6 Normal probability plot (response is delamination factor)

3.2. *Diameter 8 mm*

Table 5. S/N response table for delamination factor on diameter drill bits 8 mm

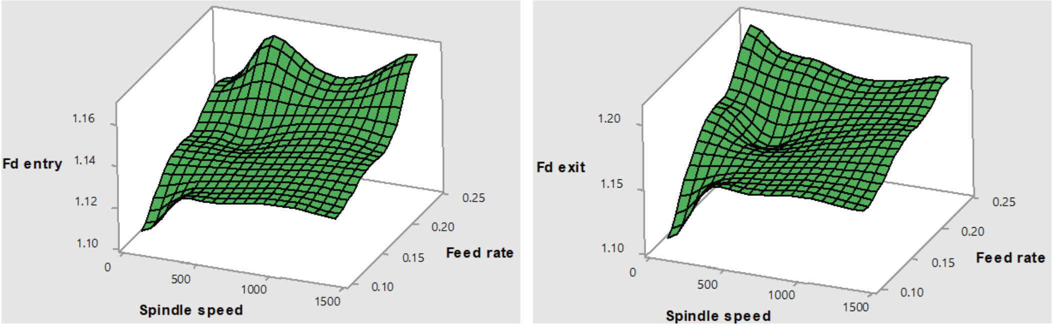
Exp. No.	Design of Experiment		Delamination Factor		S/N ratio	
	Feed rate	Spindle speed	Entry side	Exit side	Entry side	Exit side
1	0.10	93	1.108	1.112	-0.892	-0.920
2	0.10	443	1.127	1.157	-1.041	-1.267
3	0.10	1420	1.129	1.156	-1.054	-1.260
4	0.18	93	1.130	1.175	-1.064	-1.398
5	0.18	443	1.130	1.150	-1.059	-1.217
6	0.18	1420	1.137	1.180	-1.116	-1.437
7	0.24	93	1.141	1.210	-1.147	-1.653
8	0.24	443	1.165	1.191	-1.329	-1.522
9	0.24	1420	1.167	1.193	-1.344	-1.534

Fig.7 show the effect of the parameter process on delamination factors that have been he S/N ratio. At the 8 mm drill bit diameter, it can be seen that the optimal parameters are obtained in the feed rate and spindle speed which are smaller at 0.1 mm/rev and 93 rpm. The same thing is earned both on the entry side and exit side. In general, the influence of the feed rate on delamination factors looks very significant compared to the effect of spindle speed. Likewise, from the interaction between the feed rate and spindle speed to the delamination factor, that to obtain smaller delamination damage is collected on the feed rate parameter 0.1 mm/rev and the 93 rpm spindle speed as shown in Fig. 8.



a) entry side b) exit side

Fig. 7 Main effect plot for S/N ratio on delamination damage in diameter drill bits 8 mm



a) entry side b) exit side

Fig.8 3D interaction (f × N) plot on the diameter drill bit 8 mm.

As in table 6, the results of an analysis of variance (ANOVA) delamination factor on the 8 mm drill diameter indicates that the feed rate has the most significant contribution as the cause of delamination damage in the drill holes of 74.3% (entry side) and 69.5% (exit side). Conversely, the spindle speed parameter does not show a significant contribution to drilling this diameter, i.e., 19.1% (entry side) and 3.4% (exit side). This result is in line with the results of previous researcher Tsao et al. [15] and Palanikumar et al. [16], which revealed that the feed rate contributed significantly to delamination compared to spindle speed.

Table 6. Analysis of variance for means on diameter drill bits 8 mm

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	% contribution
Entry side						
Feed rate	0.121895	2	0.060947408	22.48598	0.006672	74.3%
	0.03134	2	0.015669894	5.781262	0.066063	19.1%
	0.010842	4	0.002710463			6.6%
	0.164076	8				

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Exit side						
Feed rate	0.265264	2	0.1326321	5.132236	0.078634	69.5%
Spindle speed	0.013163	2	0.006581372	0.254668	0.786855	3.4%
Error	0.103372	4	0.025842945			27.1%
Total	0.381799	8				

The correlation between control factors and delamination factors on both sides of the drill hole is depicted in the multiple linear regression graph as in Fig. 9, with the regression equation as follows:

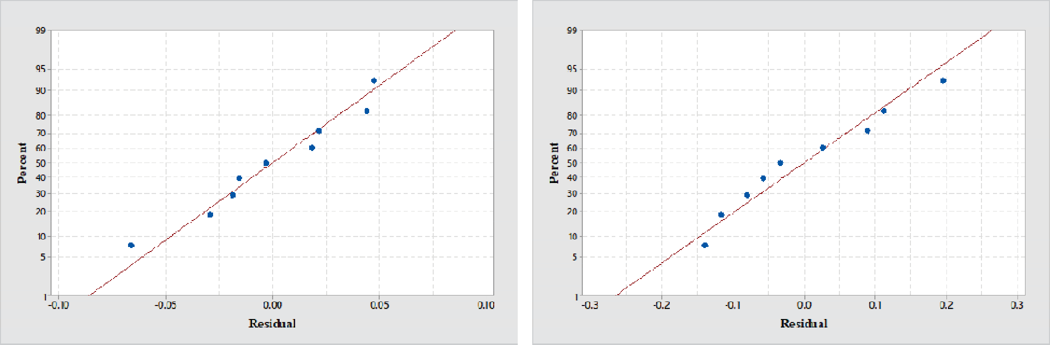
$$F_d \text{ entry} = -1.1161 + 0.1207 \cdot f_{0.10} + 0.0366 \cdot f_{0.18} - 0.1573 \cdot f_{0.24} + 0.0818 \cdot N_{93} - 0.0268 \cdot N_{443} - 0.055 \cdot N_{1420} \quad (7)$$

$$R^2 = 0.9339$$

$$F_d \text{ exit} = -1.3564 + 0.2073 \cdot f_{0.10} + 0.0057 \cdot f_{0.18} - 0.2131 \cdot f_{0.24} + 0.0327 \cdot N_{93} + 0.0210 \cdot N_{443} - 0.0537 \cdot N_{1420} \quad (8)$$

$$R^2 = 0.7293$$

Where F_d is a delamination factor that occurs in the entry side or exit side, *f* is the feed rate in mm/rev and *N* is the spindle speed in rpm.



a) entry side b) exit side

Fig.9 Normal probability plot (response is delamination factor).

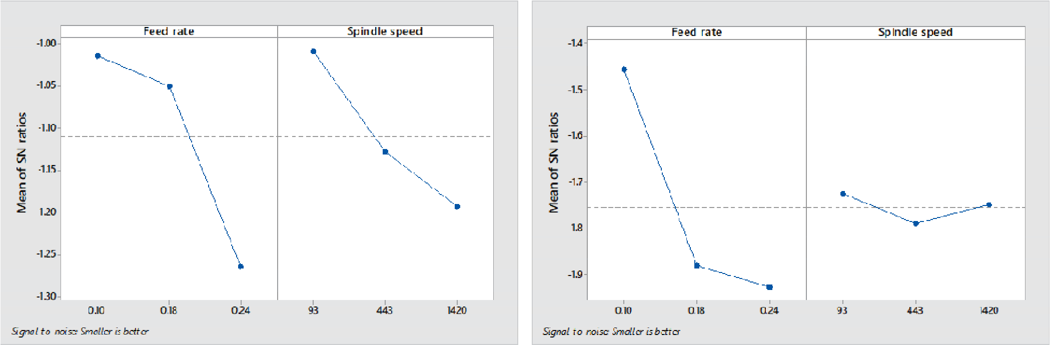
3.3. *Diameter 6 mm*

The phenomenon that occurs in drilling results with 6 mm drill bit diameter has the same inclination as drilling 8 mm drill bit diameter. Optimal parameters are obtained at the feed rate of 0.10 mm/rev and the 93 rpm spindle speed. The effect of the significance of the machining settings on delamination is due more to the feed rate than to the spindle speed, and this applies equally to the entry side and exit side (see table 7 and Fig. 10).

Table 7. S/N response table for delamination factor on diameter tools 6 mm

Exp. No.	Design of Experiment		Delamination Factor		S/N ratio	
	Feed rate	Spindle speed	Entry side	Exit side	Entry side	Exit side
	0	93	1.113	1.150	-0.929	-1.214
	0	443	1.117	1.247	-1.113	-1.617
	0	1420	1.122	1.193	-1.001	-1.534

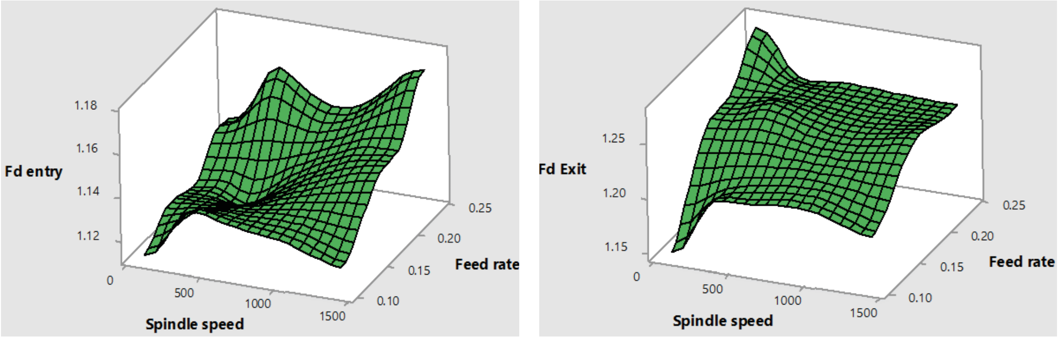
4	0.18	93	1.121	1.236	-0.994	-1.840
5	0.18	443	1.137	1.205	-0.963	-1.920
6	0.18	1420	1.147	1.242	-1.194	-1.880
7	0.24	93	1.135	1.277	-1.103	-2.123
8	0.24	443	1.163	1.235	-1.309	-1.830
9	0.24	1420	1.173	1.235	-1.383	-1.830



a) entry side b) exit side

Fig. 10 Main effect plot for S/N ratio on delamination damage in diameter drill bits 6 mm

Interaction between feed rate and spindle speed on delamination factors as described in Fig.11 shows that the smallest delamination factor is obtained from machining parameters, of each feed rate 0.1 mm/rev and spindle speed 93 rpm, both on the exit side and entry side.



a) entry side b) exit side

Fig.11 3D interaction (f × N) plot on the diameter drill bit 6 mm.

From the results of the analysis of variance (ANOVA) on drilling drill diameter of 6 mm (table 8), it is explained that the significance of the influence of drilling parameters (feed rate and spindle speed) on delamination damage is not visible on both sides of the borehole. This can be seen in the P-value both the feed rate and the spindle speed above the significance level specified (P-value >0.05). In contrast, when viewed from the contribution of drilling parameters to the delamination damage, the feed rate has the highest participation of 54.8% followed by the spindle speed of 26.1%. On the exit side, in terms of contribution to damage only the feed rate contributes to delamination which is 72.9%.

From the above results, it can be said that it is essential to use a minimum feed rate to reduce mage to drilling as mentioned by Gaitonde et al. [17], that a low feed rate will reduce fect and produce less heat, which will reduce the defects that occur in the drilling

Table 8. Analysis of variance for means on diameter 6 mm

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	% contribution
Entry side						
Feed rate	0.11020	2	0.0550976	5.7338	0.0669	54.8%
Spindle speed	0.05240	2	0.0262013	2.7266	0.1790	26.1%
Error	0.03844	4	0.0096093			19.1%
Total	0.20104	8				
Exit side						
Feed rate	0.40671	2	0.203354	5.6242	0.0688	72.9%
Spindle speed	0.00620	2	0.003101	0.0858	0.9195	1.1%
Error	0.14463	4	0.036157			25.9%
Total	0.55754	8				

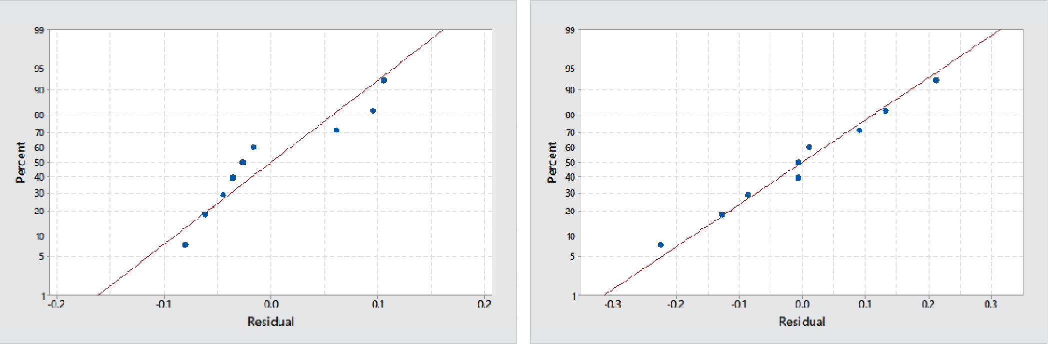
The graph of the correlation between control factors and delamination factor (Fig. 12) is described in the form of multiple linear regression, with the following equation:

$$F_d \text{ entry} = -1.1099 + 0.0957 \cdot f_{0.10} + 0.0594 \cdot f_{0.18} - 0.1551 \cdot f_{0.24} + 0.1013 \cdot N_{93} - 0.0186 \cdot N_{443} - 0.0828 \cdot N_{1420} \quad (9)$$

$$R^2 = 0.8088$$

$$F_d \text{ exit} = -1.7541 + 0.198 \cdot f_{0.10} - 0.126 \cdot f_{0.18} - 0.174 \cdot f_{0.24} + 0.029 \cdot N_{93} - 0.035 \cdot N_{443} + 0.006 \cdot N_{1420} \quad (10)$$

$$R^2 = 0.7406$$



a) entry side b) exit side

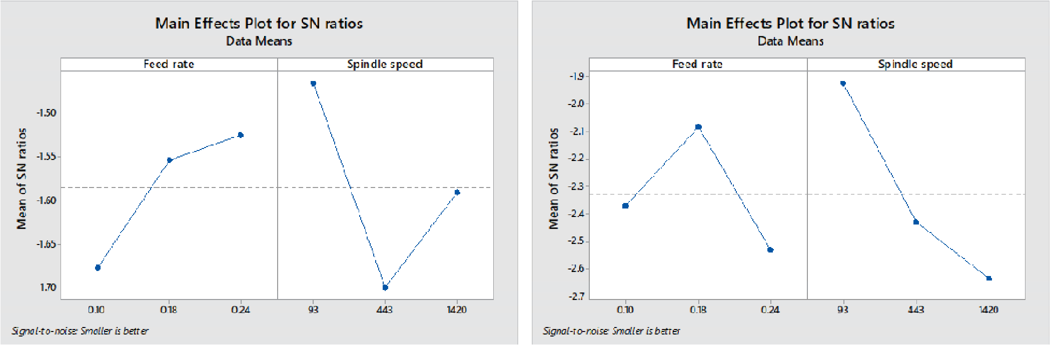
Fig.12 Normal probability plot (response is delamination factor)

3.4. *Diameter 4 mm*

In drilling a drill diameter of 4 mm, the results are in contrast to drilling on drill diameters 10, 8 and 6 mm. At this drill diameter, the optimal parameters occur at the feed rate 0.24 mm/rev and the 93 rpm spindle speed for the entry side boreholes. While for optimal exit side parameters occur at the feed rate 0.18 mm/rev and the spindle speed of 1420 rpm (see table 9 and Fig. 13). Likewise, the interaction of two variables (feed rate and spindle speed) on delamination induced by drilling described in response [illegible] (Fig. 14) does not show the significance of delamination damage changes due to [illegible] parameters.

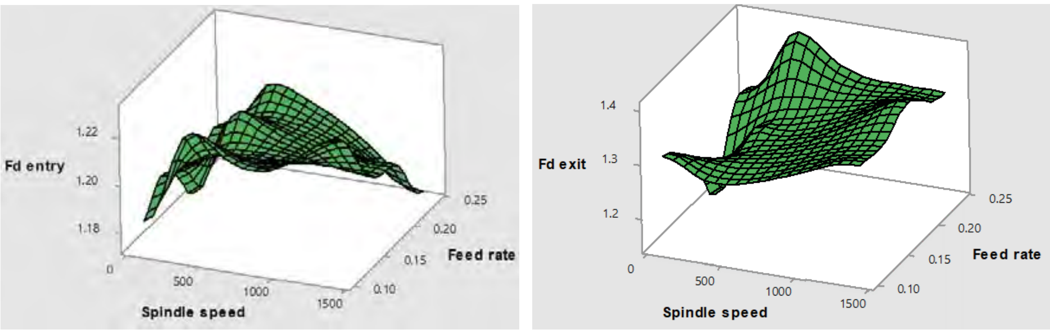
Table 9. S/N response table for delamination factor on diameter tools 4 mm

Exp. No.	Design of Experiment		Delamination Factor		S/N ratio	
	Feed rate	Spindle speed	Entry side	Exit side	Entry side	Exit side
1	0.10	93	1.185	1.312	-1.471	-2.360
2	0.10	443	1.225	1.278	-1.760	-2.131
3	0.10	1420	1.230	1.353	-1.801	-2.624
4	0.18	93	1.176	1.152	-1.408	-1.230
5	0.18	443	1.214	1.292	-1.682	-2.223
6	0.18	1420	1.198	1.380	-1.572	-2.799
7	0.24	93	1.191	1.284	-1.519	-2.174
8	0.24	443	1.210	1.401	-1.658	-2.932
9	0.24	1420	1.175	1.331	-1.398	-2.486



a) entry side b) exit side

Fig. 13 Main effect plot for S/N ratio on delamination damage in diameter drill bits 4 mm



a) entry side b) exit side

Fig.14 3D interaction (f × N) plot on the diameter drill bit 4 mm

From the observation of the results of the analysis of variance (ANOVA) the significance of changes in setting parameters for delamination due to drilling as a controlling factor was not seen in the 4 mm drill diameter (P-value> 0.05). However, these parameters have a high contribution to the occurrence of delamination damage, this can be seen from the percentage of contributions from each ding 15%, namely at the entry side feed rate of 22.3%, 46.7% spindle speed and on eed rate is 15.5% and spindle speed 41.0%.

Table 10. Analysis of variance for means on diameter 4 mm

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	% contribution
Entry side						
Feed rate	0.039265	2	0.019632728	1.439209	0.338176	22.3%
Spindle speed	0.082168	2	0.041084139	3.011739	0.159251	46.7%
Error	0.054565	4	0.013641334			31.0%
Total	0.175999	8				
Exit side						
Feed rate	0.307132	2	0.153566056	0.714155	0.542989	15.5%
Spindle speed	0.81225	2	0.40612477	1.888672	0.264519	41.0%
Error	0.860128	4	0.215031889			43.5%
Total	1.979509	8	1.979509207			

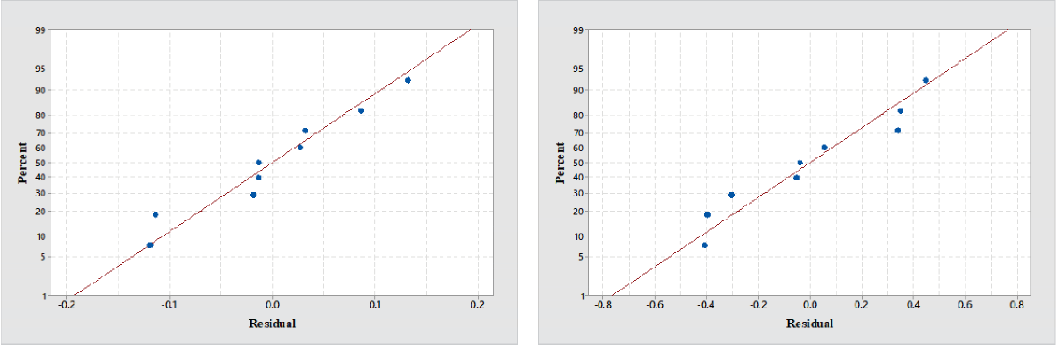
In mathematical modeling, the output performance characteristics are illustrated by the control factor correlation graph with delamination factor (Fig. 15), and are described in the regression equation as follows:

F_d entry = $-1.5854 - 0.0919 \cdot f_{0.10} + 0.0316 \cdot f_{0.18} + 0.0604 \cdot f_{0.24} + 0.1195 \cdot N_{93} - 0.1144 \cdot N_{443} - 0.0050 \cdot N_{1420}$ (11)

R^2 = 0.6900

F_d exit = $-2.329 - 0.043 \cdot f_{0.10} + 0\ .245 \cdot f_{0.18} - 0.202 \cdot f_{0.24} + 0.408 \cdot N_{93} - 0.100 \cdot N_{443} - 0.308 \cdot N_{1420}$ R2 (12)

R^2 = 0.5655



a) entry side b) exit side

Fig.15 Normal probability plot (response is delamination factor)

4. Conclusions

This paper presents an experimental study of optimizing machining parameters in composite drilling reinforced by ramie woven. The significance of machining parameters was analyzed and identified using the Taguchi and ANOVA methods. Experimental planning uses L_9 orthogonal arrays with a "smaller is better" approach, where the process parameters (feed rate and spindle speed) as a r. From the results of the analysis the conclusions are as follows:

he feed rate is the machining parameter which is the main factor causing delamination e drilling hole.

- The significance of the feed rate for delamination damage is more influential than the spindle speed parameter. Spindle speed even though it contributes sufficiently to delamination, but does not have a substantial effect.
- Taguchi and ANOVA designs can suggest the best combination of machining parameters to obtain drilling results with minimal delamination damage.

Acknowledgment

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ORIGINAL ARTICLE

Experimental Study and Investigation of Thrust Force and Delamination Damage of Drilled Ramie Woven Reinforced Composites

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ABSTRACT – One of the machining failures in composite materials is delamination damage. In this paper, machining parameters and delamination damage caused by the drilling process on ramie woven reinforced composite material with an unsaturated polyester matrix were investigated. The ramie woven used is ramie yarn type 12S/3. The machining process used 1.5 kW pillar drills, with variations in the diameter of the brad and spur drill of 4 mm, 6 mm, 8 mm and 10 mm. This work focused on the influence of machining parameters like feeds rate and spindle speed. Holes quality was analysed in terms of thrust force and delamination failure. From the results of this study, the thrust force value obtained at the time of drilling is very closely related to the delamination damage that happens. Delamination damage occurs on both sides of the holes drill.

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Delamination;
Thrust force;
Ramie woven

INTRODUCTION

Machining of laminated composite materials is still a complicated process for various reasons, such as high specific stiffness, fragility, anisotropic, non-homogeneous, and low thermal conductivity. This condition have an impact on the quality of machining, which gains on tears, defects, low surface quality, and high wear of the chiseled surface. To acquire excellent quality machining, need accurate and precise predictions to determining parameters such as cutting force, cutting speed, and feed rate. Incorrect in determining parameters, tool geometry, and the material increases the rejection rate. The rejection rate for machining laminated composites, especially in the drilling process, reaches up to 60%. Most of the damage is in form of delamination, concentration of stresses, and poor quality of the borehole affects the increase in production costs, [1].

Many previous studies have been conducted to analyse and study the effect of machining on composite materials. According to Quadros et al. [2], statistical analysis shows that the feed rate gives a significant influence on the thrust force and torque behaviour than cutting speed. The widest delamination occurs at a higher feed rate due to the increased thrust force [3]. In research on drilling of thermoplastic composite materials, Srinivasan et al. [4] indicate increased feed rate and drill bits diameter increased thrust force while spindle speed gradually reduced the thrust force. Kavad et al. [5], have concluded that in conventional machining, delamination damage is greatly influenced by feed rate, material tools, and cutting speed. In investigations on CFRP drilling, the change in diameter does not contribute significantly to the increase in thrust force when compared to the feed rate and spindle speed, [6]. In a study of investigating tools geometry, Feito et al. [7] reported that between the stepped drill and twist drill indicated fewer thrust force values and delamination factor, especially at low feed rates. Abrao et al. [8] have previously examined the effect of drill bit geometry on thrust force and holes damage. Abrao et al. recommends "brad & spur" drill bits because it produces the lowest thrust force, although in the study it was said that thrust force and delamination were not directly proportional.

Melentiev et al. [9] has investigated the effect of machining parameters and concluded that increasing both feed rate and cutting speed has consequences in improved thrust force and delamination failure. The feed rate was mentioned to have the most substantial impact on delamination. Therefore it is recommended to use machining parameters with lower values. Velaga and Cadambi [10] studied experimentally and simulated variations of machining parameters such as spindle speed and feed rate to obtain optimal process parameters. The results show that both the experiment and the simulation correspond to each other. In another study, Eneyew and Ramulu [11] examined the effect of machining parameters on the drilled hole surface quality in a composite laminate. The result obtained that the thrust force is more influenced by the feed rate than the cutting speed. Bonnet et al. [12] reported, the correlation between fiber orientation and holes quality in the inner wall of the hole cannot be denied.

g behaviour in composite materials is more emphasised in composites reinforced by synthetic
s (GFRP). Meanwhile, research on machining behaviour in natural fiber reinforced polymer
ely studied. On the other hand, the development of the use of this material is increasing. Goda
at glass fiber reinforced plastic materials have advantages in thermal and mechanical properties,
the disposal and decomposition processes. This problem is becoming serious with world
ted to the recycling process. There are several reasons why people turn to natural fibers, among
tages of a lightweight, durable, biodegradable, renewable, and abundant presence. In the last

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few decades, the use of natural fibers like ramie [14], hemp [15], jute [16], sisal [17], kenaf [18], banana [19], gnetum [20], coir [21] fibers and others has been developed as a composite reinforcement in lieu of synthetic fibers.

The use of natural fibers as a material of automotive interior panels has been developed since the 1940s until now, [20]. Chandrabakty et al. [20] have carried out research using composite materials reinforced with gnetum bast fibers as vehicle door panel materials. These fibers have a continuous fiber structure and strength natural woven and can reduce weight from 10% to 30% (which is the main thing in automotive design). Bakri et al. [21], reported that coir reinforced polymer composites are potential using as an alternative material for making windmill blades. Natural fibers have different properties and characteristics from synthetic fibers, thus requiring different machining parameters. Therefore this study aims to investigate the machining behaviour on ramie woven reinforced composites to obtain optimal process parameters.

MATERIALS AND METHOD

Materials

Ramie woven reinforced unsaturated polyester laminates were used as workpiece materials. Hand lay-up technique is carried out to produce laminates with a volume fraction of 19%, were to produce a thickness of laminates 5.0 ± 0.2 mm, we apply six alternating layers. Ramie woven (density 1.52 gr/cm^3) is formed by ramie yarn type 12S/3 which is spinning by a loom machine (Figure 1), and the unsaturated polyester resin is YUKALAC @157 BQTN-EX (density 1.215 gr/cm^3) product of PT. Justus Kimiaraya.

Figure 1. Ramie plain weave fabric model with 12S/3 yarn type.

Drilling Operation

Drilling process executes by pillar drill TCA-35 ERLO on a 1,5 kW power and maximum 1420 rotational speed machine center. Brad and spur drill is the tools materials and geometries chosen in this experimental work with varied diameter of 4 mm, 6 mm, 8 mm, and 10 mm, as shown in Figure 2. This tool drill type widely used in drilling wood material. The advantage of this tool is that they have a brad point end that functions to match the drilling position and "spurs" that function to produce the surface of a clean and smooth hole, as shown in Figure 3(a). The parameters and their ranges used for the experimentation are given in Table 1.

The thrust force that occurs due to the drilling process is measured using a dynamometer sensor equipped with a 20 kg maximum pressure load cell and placed under the specimen that connected to acquisition data, after which to the computer. Then the MakerPlot software was engaged in reading the thrust force data, the experimental set-up, as shown in Figure 4. To analyse delamination failure around the inlet and exit sides of the borehole, firstly, the hole recorded take by the scanner with resolution 2400 DPI, then evaluated using Image-pro plus v4.5 application.

Figure 2. “Brad & spur” drill diameter 4, 6, 8 and 10 mm.

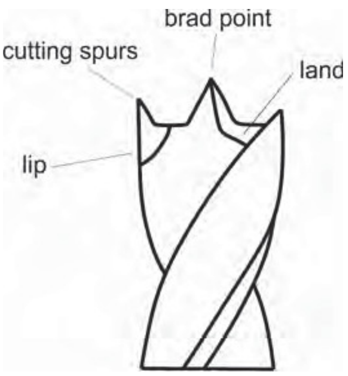


Figure 3. Brad and spur drill's detail.

Table 1. Design of experiments.

Parameter	Range			
Tools diameter (mm)	4	6	8	10
Feed rate (mm/rev)	0.1	0.18	0.24	
Spindle speed (rpm)	93	443	1420	

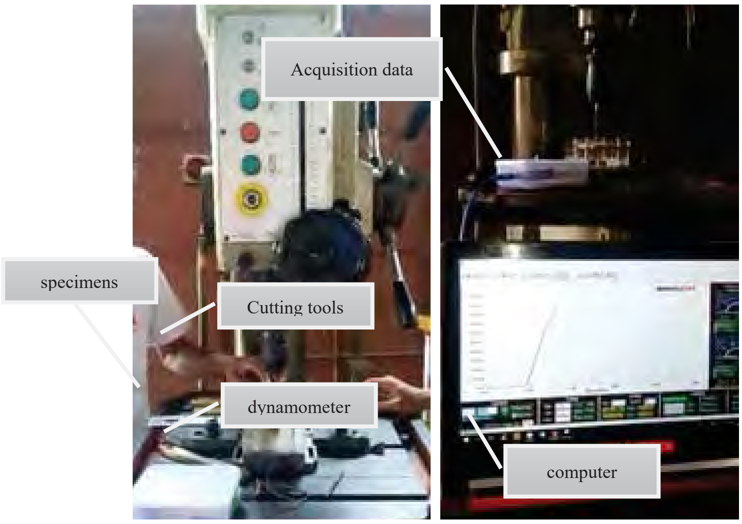


Figure 4. Experimental set-up.

Delamination Factor (F_d)

Delamination around the drilling hole impacts reduced the strength of the structure, poor assembly quality, and reducing the life span of the laminated composite. Delamination due to the drilling process occurs on both sides of the drill hole [22]. The rate of delamination can be determined using an index or a factor namely the delamination factor (F_d). The delamination factor (F_d) can be solved using the following equation, [23] :

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

where D_{max} is the maximum diameter formed by delamination around the hole, while D is the diameter of the borehole. The definition of delamination measurement is illustrated in Figure 5. Delamination damage appears on both sides of the borehole, i.e., the inlets and exits. As was mentioned by Khasabah et al. [24] that the occurrence of delamination is caused by a peel-up mechanism on the entry side and a push-out on the exit side of the drill tool.

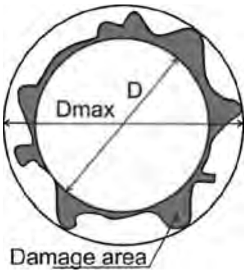
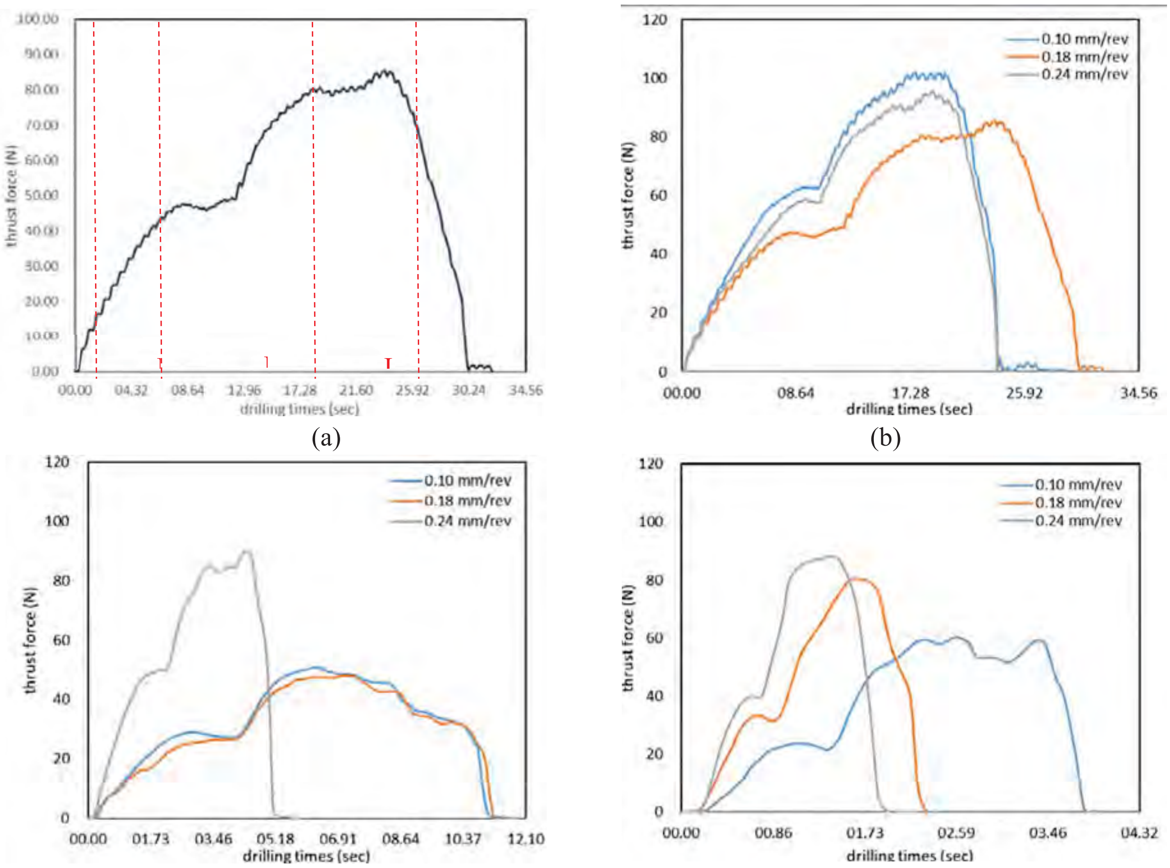


Figure 5. Delamination measurement method [25].

RESULT AND DISCUSSION

Thrust force

Figure 6 to Figure 9 show the complete drilling cycle on composite material reinforced by ramie woven with variations in tool diameter 4, 6, 8, and 10 mm. The drilling process consists of four stages, as illustrated in Figure 6(a). Phase I begins when the drill tip has been touched the surface of the workpiece until the "spur" cutting edges penetrate the top layer of the specimen. Phase II is the process when the drill bit penetrates the matrices until it touches the ramie's woven plies. At this stage, the thrust force tends to be flat. Phase III is when the brad-point tip pierces the ramie woven layer, and at the same time, the spur cutting edges cut the ramie woven layer to ensure the desired holes diameter. The thrust force moves to its peak at this stage. Phase IV occurs when the drill bit has penetrated the last layer of the workpiece until the reaming process it happens, the thrust force will decrease drastically to zero. In some operations, small peaks appear caused by thrust force when the "spurs" edges were cutting and penetrate the last matrices ply to ensure holes drilling.

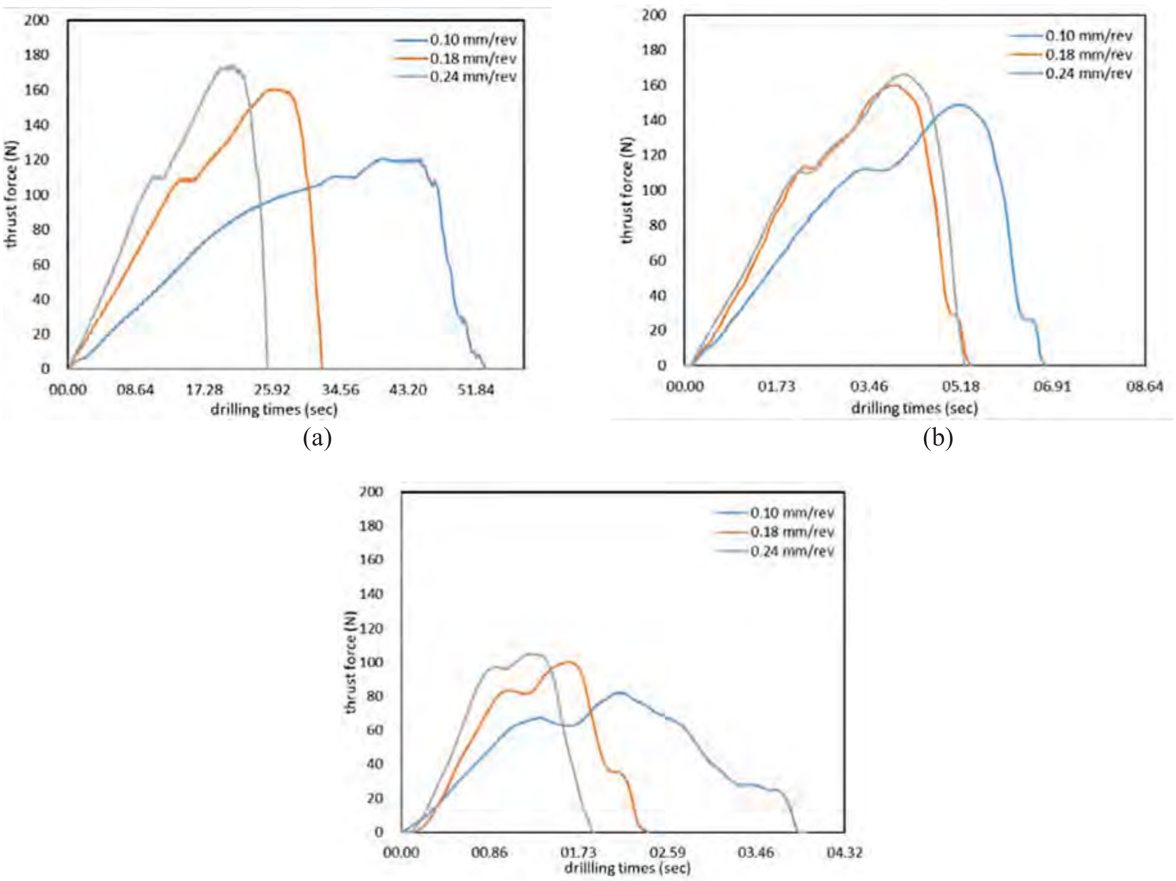


(a) (b)

(c) (d)

ver drilling cycle of tools diameter 4 mm for (a) a single drilling operation, at spindle speed of (b) 93 rpm, (c) 443 rpm and (d) 1420 rpm.

is significantly related to the length of the drilling time. Where the feed rate and spindle speed me. The more feed rate and spindle speed increases, the faster the drilling time is used, while eter does not have much effect on the time of drilling. The longer the drilling time is used, the is phenomenon occurs because there is a "time" for the spurs to cut the fibers in each ply. It is sure, which can increase the load and cutting force.

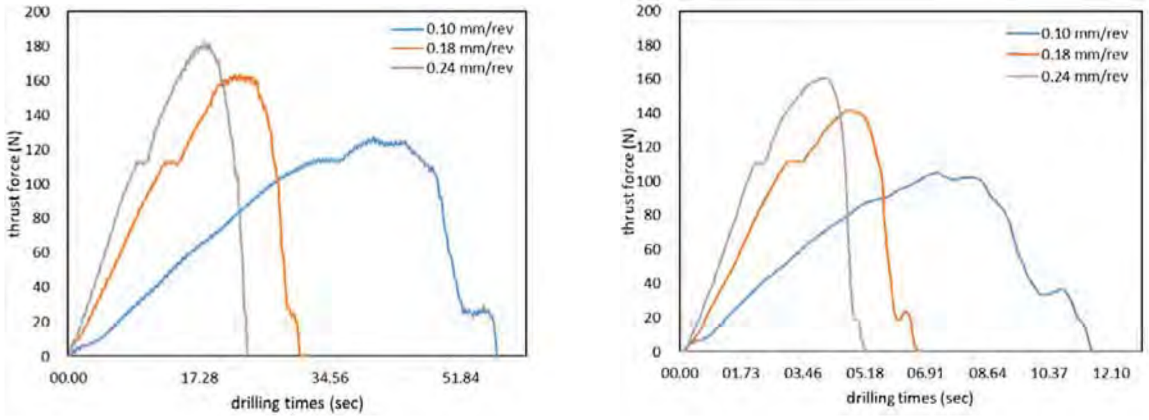


(a) (b)

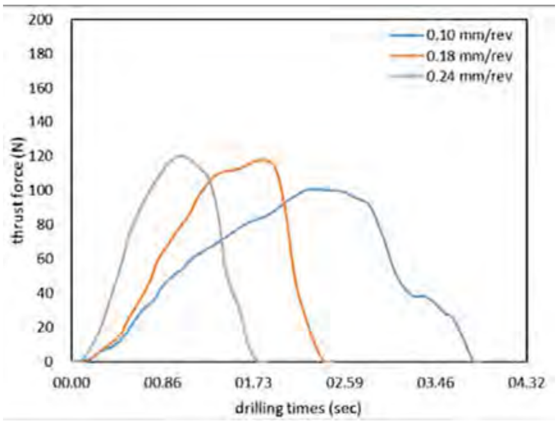
(c)

Figure 7. Thrust force over drilling cycle of tools diameter 6 mm at spindle speed of (a) 93 rpm, (b) 443 rpm and (c) 1420 rpm.

Figure 10 shows the relationship between the thrust force and feed rate, where the increasing thrust force is obtained as the feed rate increases. This tendency is appearing in all variations in tool diameter used. However, with the different results when viewed from the effect of spindle speed, there is a decrease in thrust force during the increase in spindle speed. The impact of high spindle speed plays a role in facilitating the drill bit to cut the matrices and the layer of ramie's woven perfectly. High spindle speed makes cutting force lower by reducing the occurrence of splintering, and the cutting process becomes smooth.

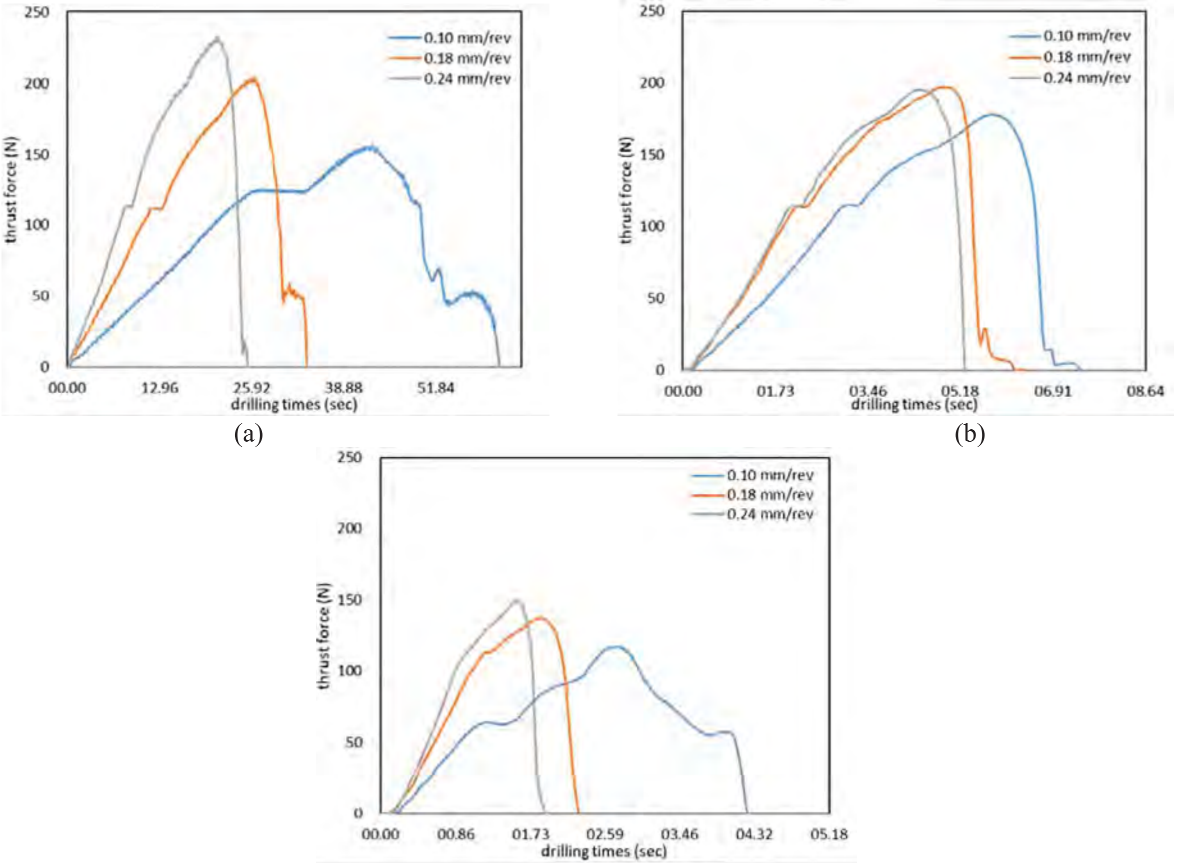


(a) (b)



(c)

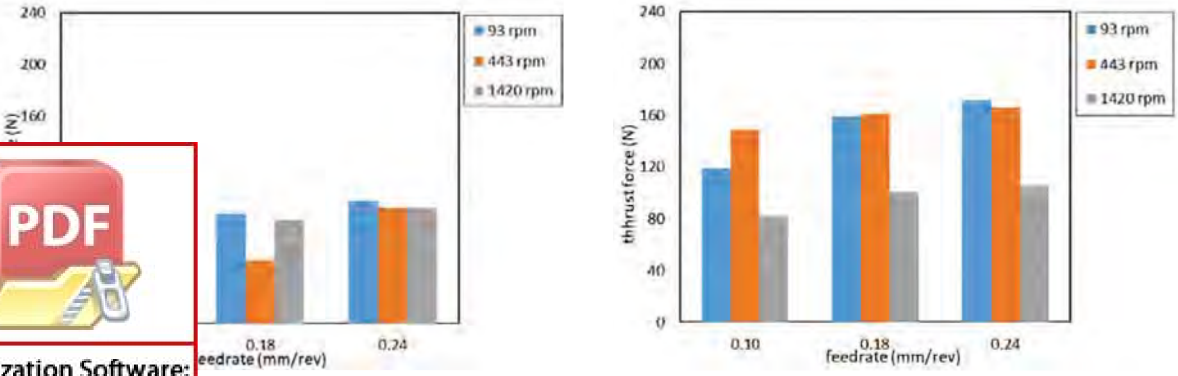
Figure 8. Thrust force over drilling cycle of tools diameter 8 mm at spindle speed of (a) 93 rpm, (b) 443 rpm and (c) 1420 rpm.



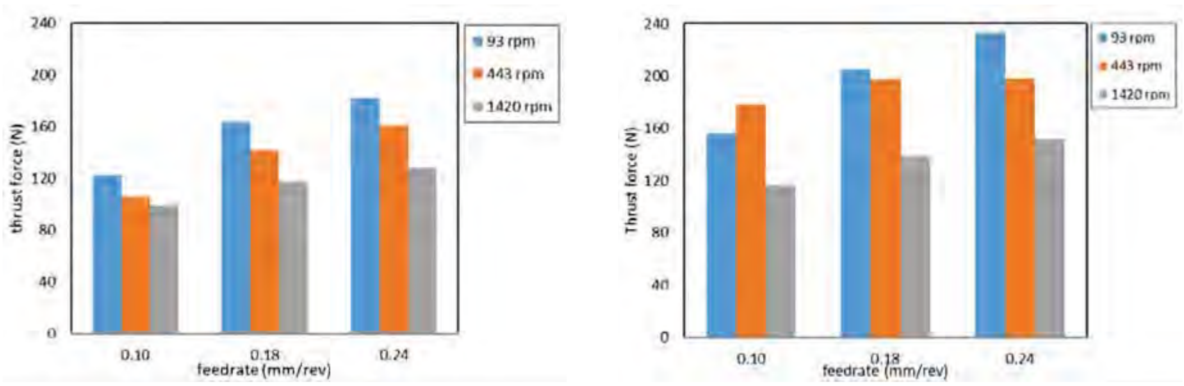
(a) (b)

(c)

Figure 9. Thrust force over drilling cycle of tools diameter 10 mm at spindle speed of (a) 93 rpm, (b) 443 rpm and (c) 1420 rpm.



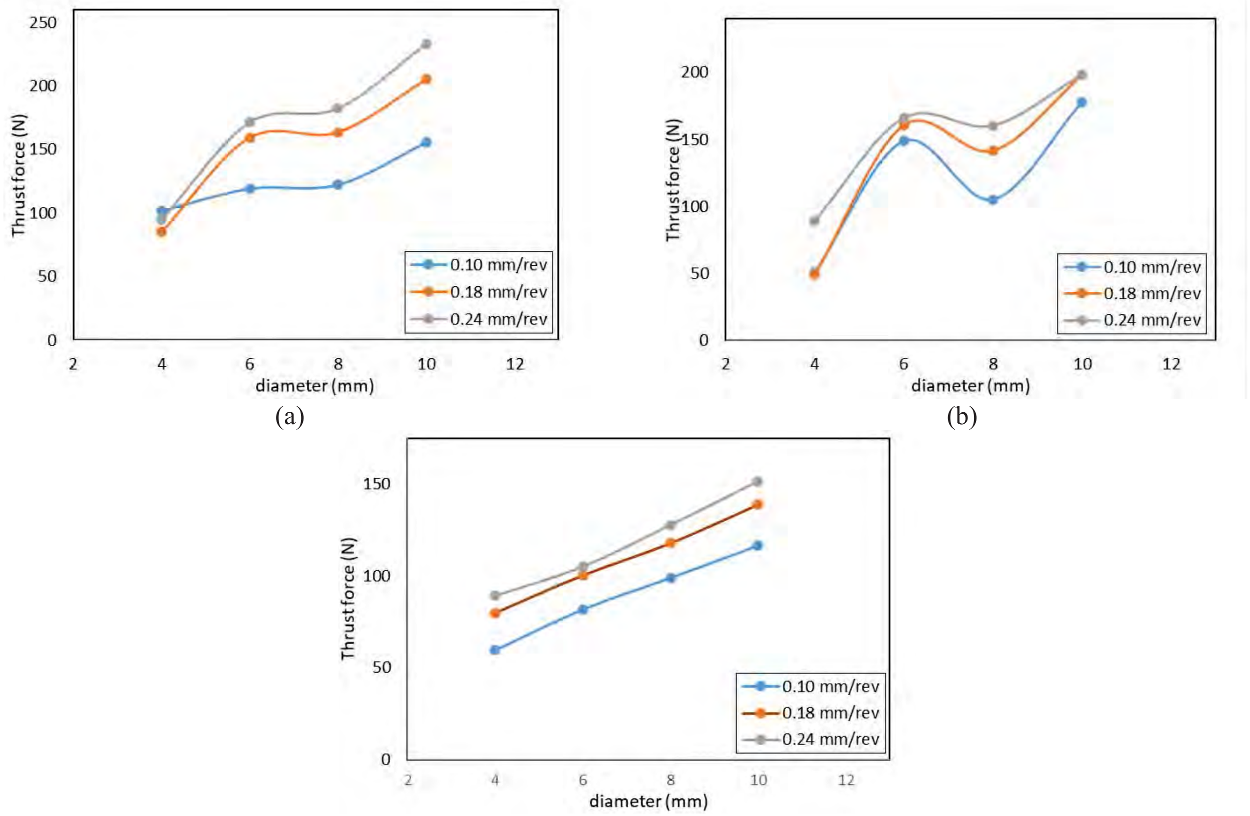
(a) (b)



(c) (d)

Figure 10. Correlation between thrust force and feed rate at the tool's diameter of (a) 4 mm, (b) 6 mm, (c) 8 mm and (d) 10 mm.

Whereas, when examined from the diameter of the drill bit, obtained the lowest thrust force at a smaller diameter, wherein the 4 mm diameter, produces thrust force below 100 N. Then it will increase with increasing tool diameter, as shown in Figure 11. The low thrust force obtained at smaller diameters is likely due to the tool surface area in contact with smaller specimens, causing lower heat dissipation during the drilling process. In line with Shetty et al. [26], said the thrust force could produce higher hardness, wear resistance, thermal conductivity, and high levels of heat dissipation from the drill bit. Because of these factors, the heat generated by the contact between the drills tip and the materials becomes reduced and produces smaller friction. In a previous study, Srinivasan et al.[4], argue that the smallest thrust force is obtained at high spindle speeds, small drill bit diameters, and low feed rates. Furthermore, it is said that the size of the hole is the cause of the development of the thrust force, the larger the hole, the more thrust forces occur.



(a) (b)

(c)

Figure 11. Correlation between thrust force and tools diameter on the spindle speed of (a) 93 rpm, (b) 443 rpm and (c) 1420 rpm.

bserved the factors of damage arising from changes in feed rate and spindle speed. Photographs described and analysed in Figure 12. Two drilling sides observed were the entry and exit side of re 13 and Figure 14, we note the evolution of delamination factors on both sides. At 4 mm n factor on the entry side does not show a significant change due to the feed rate and the spindle on the exit side, there is a tendency enhancement of the delamination factor along with an increasing feed rate. From the tool diameter of 6 mm, the entry side shows a definite increase due to the increase in feed rate and spindle speed. A similar trend also occurs on the exit side even though the difference is not as sharp as the entry side. Delamination factors that arise in 8 mm diameter tools have the same trend on both sides. Feed rate and spindle speed play an essential role in increasing delamination damage in the ramie's woven composite drilled. Likewise, at 10 mm tool diameter, noted that the delamination factor seen to grow with increasing feed rate and spindle speed. The increasing trend is observed on both sides.

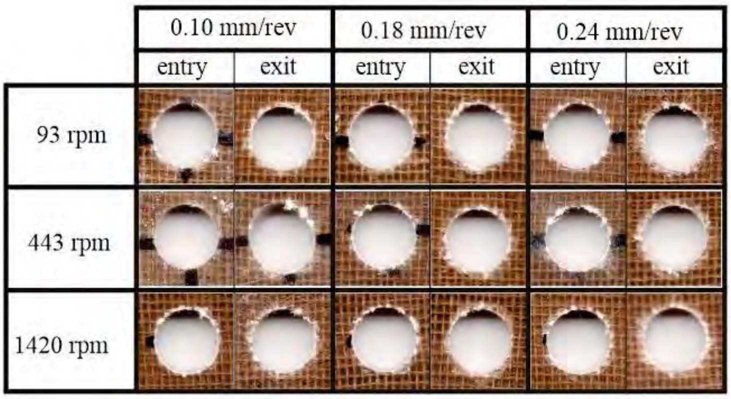
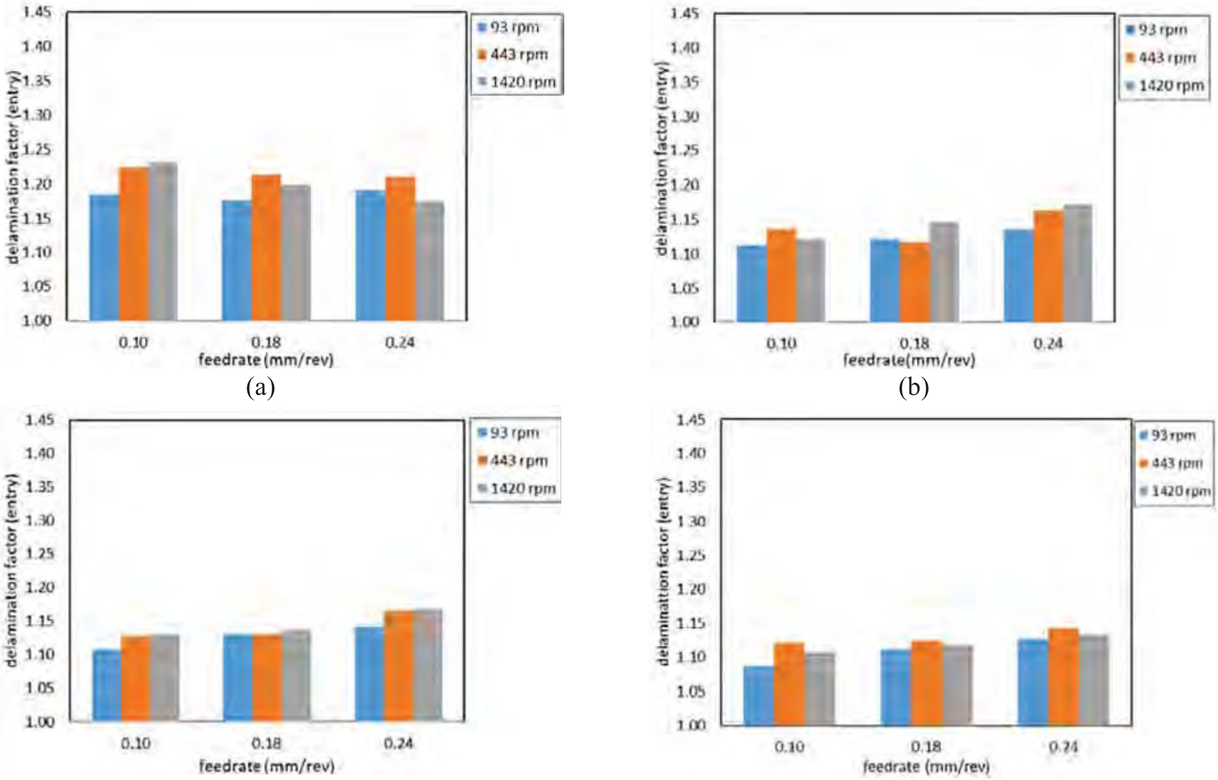


Figure 12. Photographs illustration the delamination in drilled ramie woven composites.



(a)

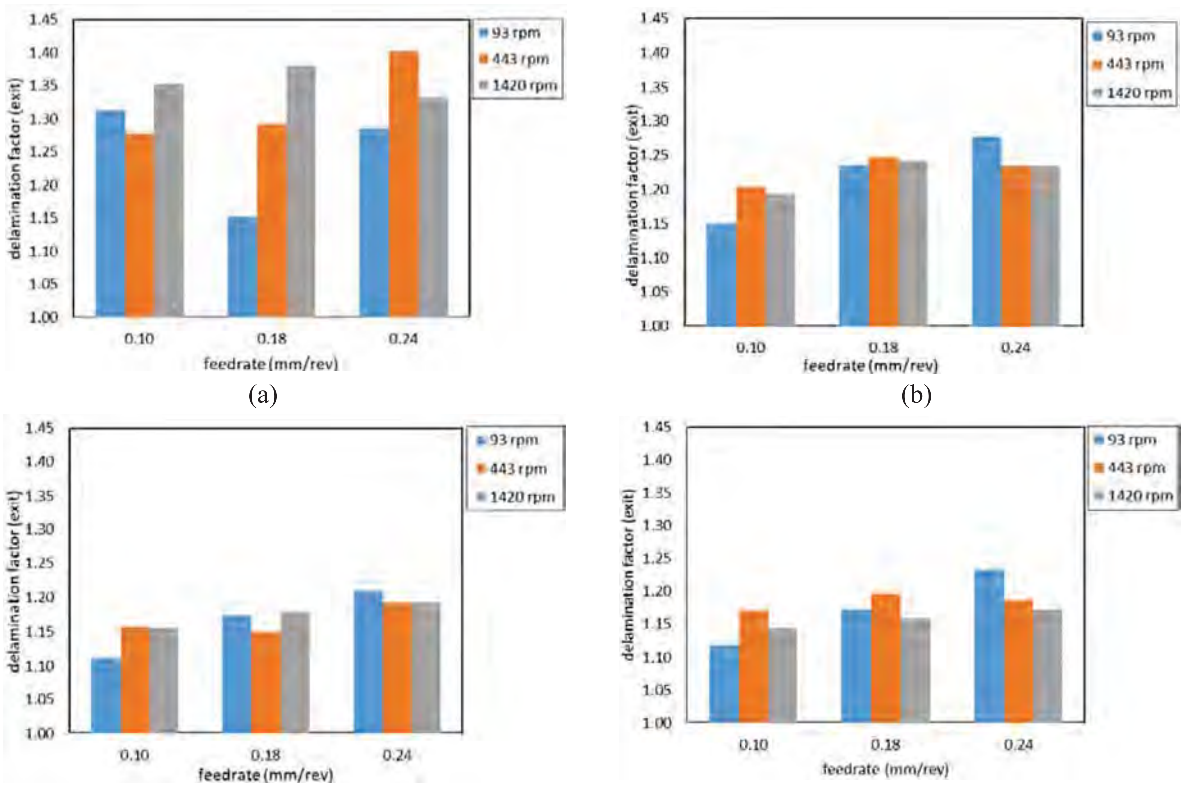
(b)

(c)

(d)

Figure 13. Effect of spindle speed concerning feed rate on delamination factor at the entry side, with the tool's diameter of (a) 4 mm, (b) 6 mm, (c) 8 mm and (d) 10 mm.

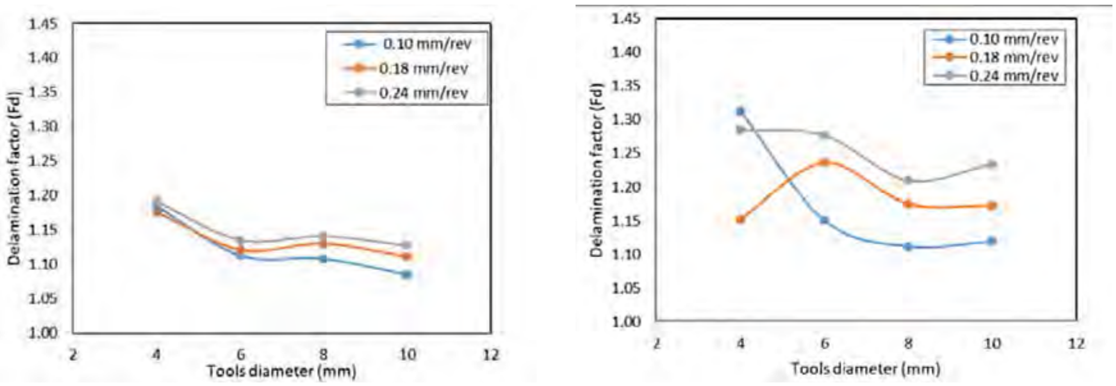
When reviewed from changes in diameter, Figure 15 to Figure 17 shows that the increasing tool's diameter tends to n factor in the machining process for ramie’s woven composites. The same trend can be seen in side and exit side specimens. This outcome is contradictory to previous research, which has f drill bit diameter increases the delamination factor in the drilling of the sandwich's composites, an be caused by differences in specimen material and tool geometry used. As mentioned by and spur drills can reduce delamination factor when compared to twist drill.



(a) (b)

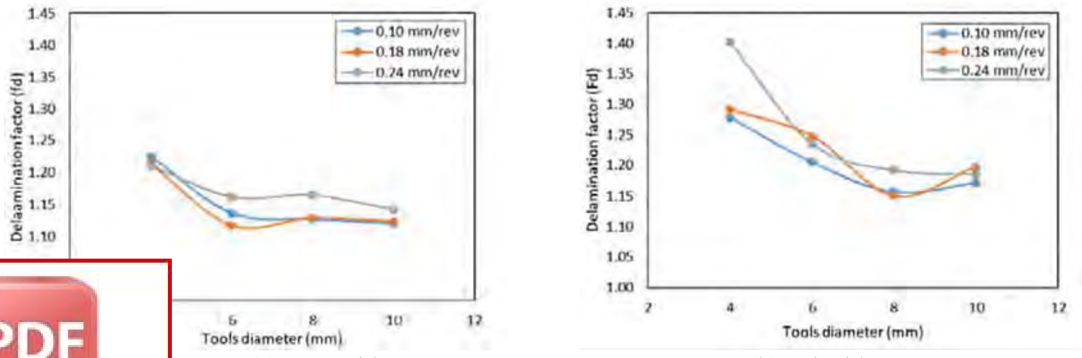
(c) (d)

Figure 14. Effect of spindle speed concerning feed rate on delamination factor at the exit side, with the tool's diameter: a) 4 mm; b) 6 mm; c) 8 mm and d) 10 mm



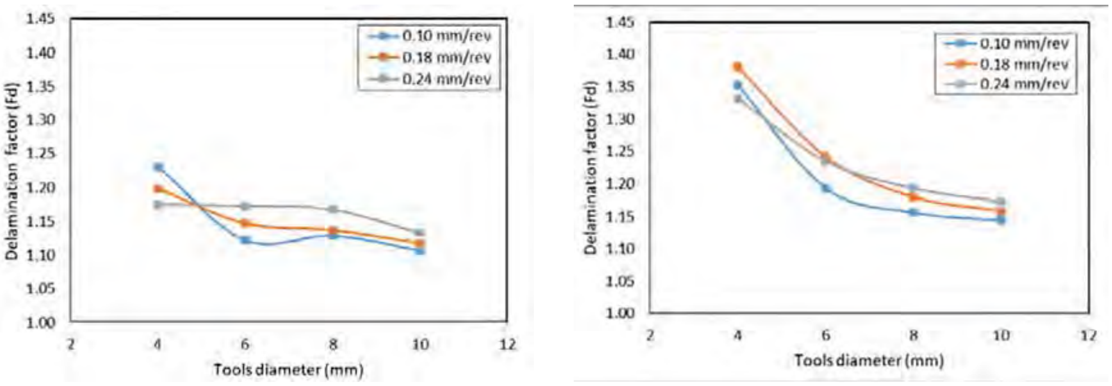
(a) entry side (b) exit side

Figure 15. Correlation between delamination factor and tool’s diameter at spindle speed of 443 rpm.



(a) entry side (b) exit side

rrelation between delamination factor and tool’s diameter at spindle speed of 443 rpm.



(a) entry side (b) exit side

Figure 17. Correlation between delamination factor and tool's diameter at spindle speed of 1420 rpm.

CONCLUSION

The effect of machining parameters on four different diameters of drill bits has been analysed in this study. Composite reinforced by ramie woven with an unsaturated polyester matrix was chosen as the workpiece in this study, and the brad and spur drill type was used as cutting tool. There are several interrelated factors, such as drilling times, thrust force, and delamination damage that affect the surface quality of borehole. Based on the experimental results, some conclusion can be drawn in the following paragraph.

Drilling times affect increasing thrust force while the drilling time is affected by the feed rate and spindle speed. The higher the feed rate, the faster the drilling time occurs. When viewed from the tool's diameter, it can be seen that the tool's diameter increases significantly, followed by the increase in thrust force. When analysed in terms of delamination damage, there was an increase in delamination factor along with an increase in feed rate and increased spindle speed; which can be found on both sides. While the changes in the tool's diameter, it is precisely seen that there is a decrease in the delamination factor as the tool's diameter increases. The same thing happens on both sides of the hole. Moreover, when compared between the entry side and exit drill holes, more significant delamination damage was found on the exit side.

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E. Makalah pada seminar/konferensi ilmiah Nasional dan Internasional

- **Chandrabakty**, S., Renreng, I., Djafar, Z., & Arsyad, H. (2019*). An optimization of the machining parameters on delamination in drilling ramie woven reinforced composites using Taguchi method*. In Journal of Physics: Conference Series (Vol. 1341, No. 5, p. 052005). IOP Publishing. Presented in International Conference on Science (ICOS) 2019 Makassar, Indonesia.