Experimental investigations on hole quality in drilling of Cenosphere reinforced epoxy composite

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Abstract. Cenosphere reinforced epoxy composites are steadily replacing the conventional materials in marine, aerospace and automobile structures owing to their lightweight properties. Drilling is an important conventional machining process essential for assembly of polymer composites using rivets and bolts. Drilling induces damage around the hole which significantly deteriorates composite performance. In the present study, hole quality characteristic such as cylindricity and delamination in drilling of fly ash cenosphere filled epoxy composites are investigated using coated tungsten carbide twist drills. Feed, cutting speed, filler content and drill diameter are considered as the drilling process variables. Samples are fabricated by varying cenosphere content from 10 to 60 by volume % in epoxy resin. Full factorial design (FFD) based experiments are conducted on CNC vertical machining center. Response surface methodology (RSM) based mathematical models are proposed to estimate the characteristics of the hole quality in developed composites. Analysis of variance is used to validate the developed mathematical models. Present study reveals that the cylindricity and delamination decreases with increasing feed. Increasing cutting speed decreases the cylindricity, however delamination is found to be increasing. Results also shows the importance of using high cenosphere content for producing sound quality holes, which is also beneficial from weight saving perspective.

Keywords: Cenosphere, Epoxy, Drilling, RSM, Cylindricity, Delamination

Nomenclature

| Symbol | Description |
|--------|-------------|
| $v$    | Cutting speed (m/min) |
| $f$    | Feed (mm/rev) |
| $D$    | Drill diameter (mm) |
| $R$    | Reinforcement (volume %) |
| $CYL$  | Cylindricity (mm) |
| $F_{d, Enry}$ | Entry delamination factor |
| $F_{d, Ext}$ | Exit delamination factor |
| $D_{\max}$ | Max. diameter of drilled hole (mm) |

1. Introduction

Lightweight features and higher specific strength makes polymer matrix composites to be used extensively in automobile, aerospace, aircrafts and marine structures. Syntactic foam is a particulate composite where in the matrix resin is reinforced with hollow particles called microballoons[1-3]. These closed cell foams are widely used in the field of automotive, marine and aircraft structures because of their higher specific properties and better thermal stability. Cenospheres are the hollow particles of fly ash, which is an industrial waste of thermal power plants. Alumina and silica are the main constituents of cenospheres[4-6]. Cenosphere is reinforced with various matrices like polyethylene, epoxy and cement to develop composite materials for many engineering applications[7-14]. Several researchers conducted studies to evaluate the mechanical, thermal and electrical properties...
of cenosphere reinforced polymer composites[15-18]. Results reveal that incorporating cenosphere particles significantly enhances the properties of the composites. Cenosphere reinforced composites are extensively studied for evaluating the tribological characteristics [10, 19-22]. Results concluded that the addition of cenospheres significantly enhancing the wear resistance of developed composites.

Machining is unavoidable during final stage of production process though the cenosphere-filled epoxy composites can be fabricated to near net shape [23]. Machining plays a vital role in manufacturing process, drilling is a key conventional machining process required for joining several polymer composites using mechanical fasteners like rivets and bolts. Hence, investigations of the drilling characteristics in terms of machinability become significant in many engineering applications. Controlling of machinability characteristics like thrust, circularity, perpendicularity, cylindricity, delamination and surface roughness through the appropriate choice of drilling input parameters like feed, spindle speed, drill diameter, material of drill, drill geometry and reinforcement content are crucial in the drilling process. Many researchers conducted experiments to analyze the influence of process and drill parameters on various machinability characteristics of polymer composites reinforced with glass, carbon and aramid fibers.

Krishnaraj et al. [24] carried out drilling on thin CFRP laminates to optimize the drilling process parameters. An extensive study has been conducted by Ameur et al. [25] in the drilling of CFRP to analyse the dependency of spindle speed, feed, and drill coating on exit delamination and cylindricity error. The results reveal that the feed and tool material significantly affect the thrust force and exit delamination. However, the cylindricity of the hole is highly affected by the spindle speed. Tsao and Hocheng [26] analyzed delamination in the drilling of CFRP laminate, using candlestick, twist and saw drill. Experimental results revealed that the delamination is mainly affected by feed and drill diameter. Shunmugesh and Panneerselvam [27] analysed the influence of feed, drill bit diameter and spindle speed on the circularity and cylindricity during micro-drilling of CFRP. The experimental study revealed that the delamination, circularity and cylindricity can be reduced with the increasing spindle speed and decreasing feed. Salguero et al. [28] conducted drilling experiments on CFRP composites and concluded that the minimum cylindricity error can be obtained by employing lower cutting speeds and highest feeds.

Gaithonde et al. [29] and Karnik et al. [30] conducted high speed drilling experiments to investigate CFRP composites delamination. Experimental results reveal that the decrease in delamination is governed by lower feed rate, higher cutting speed and lower point angle. In and Chen [31] conducted experiments on CFRP composites to study the influence of high speed on hole quality, torque, tool wear and thrust force. Results revealed that cutting force minimizes with increasing the cutting speed which in turn leads to delamination minimization. Sunny et al. [32] conducted investigations on CFRP composites to study the delamination factor using three different types of drills and concluded that the delamination decreases with increasing speed and decreasing feed. Sheth and George [33] observed that the minimum cylindricity in drilling of wrought cast steel can be obtained by decreasing the feed, spindle speed with intermediate depth of Murthy et al. [34] conducted experimentation to analyse the quality of the drilled hole in glass fiber reinforced polymer (GFRP) composites. It is observed that the drilled hole quality is strongly governed by drill geometry. Gowda et al. [35] studied the effect of Si$_3$N$_4$ vol. %, feed, drill diameter, machining time and spindle speed on the surface roughness, circularity and cylindricity in drilling of Si$_3$N$_4$ filled epoxy composites. It is found that Si$_3$N$_4$ vol. % and spindle speed has the least effects on the cylindricity. It is also observed that that increase in the machining time increases cylindricity deviations. Gaithonde et al. [36] studied delamination behavior at entry and exit of a hole in the drilling of medium density fiberboard using Taguchi method. It is noticed that delamination reduces when lower feed and higher cutting speeds are employed. Kumar et al. [37] conducted experimental work in the drilling of GFRP composites using three types of drilling tool showing effectiveness of using eight-facet solid carbide drill towards higher quality hole. Literature survey reveals that extensive work has been carried out to investigate the effect of input variables in fiber reinforced composites drilling. However, evaluation of delamination factor and cylindricity in cenosphere reinforced epoxy resin composites is scarce. Hence, in the present work RSM based mathematical models are proposed based on the experimental data to analyse the effect of
drilling variables on cylindricity and delamination factor.

2. Processing and Experimental plan

2.1. Sample preparation

Epoxy resin of LAPOX L-12 grade and K-6 polyamine hardener is procured from Yuje marketing, Malleswaram, Bangalore, India. Cenosphere fillers are procured from CenosphereIndia Pvt Ltd, Kolkata, India. Cenosphere reinforced epoxy composite specimens are developed by dispersing 10, 35 and 60 volume percent (vol. %) of cenospheres in LAPOX L-12 epoxy matrix. Specimens are prepared by mechanically mixing (stirring) of cenosphere in the epoxy matrix until a homogenous mixture is formed. Subsequently hardener by 10 weight percent is added to cenosphere epoxy mixture prior to pouring into molds. Specimens are cured for 24 h followed by 2 h of post-curing. Molds are applied with releasing agent for easy removal of cast slabs. In total 81 samples are prepared for each filler variation.

2.2. Experimental plan

Design of experiments is an effective tool used to build the regression equations based on response surface methodology. In this study, regression models are developed using RSM to study the influence of drilling variables namely, filler vol. %, feed, cutting speed and drill diameter on drilling characteristics such as cylindricity and delamination factor (entry and exit). In the present work, each variable is considered at three levels for accounting the non-linearity effect among the drilling variables. 81 experiments are planned based on full factorial design by selecting four factors at three levels [27, 28].

Table 1 presents the drilling variables and their respective levels used in the present work. Drilling variables ($A$) and their respective levels ($B$) are represented as $A_B$. For example, $v_{50}$ represents cutting speed of 50 m/min. Proposed plan for experimental work is presented in Table 2.

2.3. Experimental work and drilling characteristics measurement

MaxmillPlus vertical machining center (CNC machine, 9000 rpm max. spindle speed with 7.5 kW power) is employed to conduct the drilling experiments as per full factorial design (Table 2) using tungsten carbide (WC) twist drills (K20) of diameter 8, 12 and 16 mm. Figure 1 shows the coordinate measuring machine (CMM) used to estimate the cylindricity and maximum diameter of the drilled hole. Delamination factor is determined by,

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

Average values of 3 replicates for the responses (CYL and $F_d$) are summarized in Table 3. Finally, RSM based quadratic models are built using the experimental results (Table 3). Figure 2 shows cenosphere epoxy samples post drilling operations.

2.4. Response Surface Methodology (RSM)

RSM is an analytical tool which uses mathematical and statistical techniques to develop a model to assess the real examples in which the response variable is affected by a number of input variables [38, 39]. The models of required response can be proposed by design of experiments (DOE) using several independent input variables. The expression for the response in terms of input parameters can be expressed as [38, 39],

$$Z = \varphi \left( X_1, X_2, X_3, X_4, \ldots, X_k \right) \quad (2)$$

where $Z$ is output variables; $X_1, X_2, X_3, X_4, \ldots, X_k$ are input variables and $\varphi$ response function.
3. Results and discussion

3.1. Response surface modeling for CYL and Fd

The regression models are developed for predicting the drilling characteristic based on the experimental data presented in Table 3. The four drilling process variables along with two-factor interactions are given by the following the regression model [38, 39]:

\[
Z = \left( \begin{array}{c}
0 + a_1v + a_2f + a_3R + a_4D + a_{11}v^2 + a_{12}f^2 + a_{13}R^2 + a_{14}D^2 + a_{15}vR + a_{16}vf + a_{17}vD + a_{18}fR + a_{19}fD + a_{20}Rf + a_{21}RD
\end{array} \right)
\]

(3)

Where \( Z \) is the drilling characteristic and \( a_0, a_1, a_2, \ldots, a_{21} \) are the coefficients of the regression equations which needs to be calculated. The regression coefficients for the mathematical model based on RSM is given by [38, 39],

\[
b = (Y^TY)^{-1}Y^TZ
\]

(4)

Where \( b \) - matrix of parameter estimates; \( Y \) - calculation matrix; \( Y^T \) - transpose of \( Y \) and \( Z \) is the matrix of drilling characteristic. To predict \( CYL \) and \( Fd \) (entry and exit) the following quadratic models have been developed through regression analysis using Minitab 14 statistical software and are given as,

\[
CYL = \begin{pmatrix}
0.0214 + 0.000067v - 0.0047f - 0.000746R + 0.00167D - 0.031v^2 \\
0.000040 + 0.000010D + 0.000019vf + 0.000002vdR + 0.00004vD \\
D + 0.000241f - 0.00509fD + 0.00007\times R\times D
\end{pmatrix}
\]

(5)

\[
F_{d-Entry} = \begin{pmatrix}
0.98862 + 0.000056v - 0.0213f - 0.000056R + 0.003223D - 0.000002v^2 \\
0.0065f^2 + 0.000000R^2 - 0.000147D^2 - 0.000037vdR - 0.000000vR \\
0.000000vdR + 0.0000157f - 0.001107fD + 0.000001R\times D
\end{pmatrix}
\]

(6)

\[
F_{d-Exit} = \begin{pmatrix}
0.98971 + 0.000003v - 0.0387f - 0.000053R + 0.004123D + 0.0000000v^2 \\
0.0587f^2 - 0.000000R^2 + 0.000204D^2 + 0.000053vdR - 0.0000000vRD \\
0.000001vdR + 0.000055f - 0.001837fD + 0.000005RD
\end{pmatrix}
\]

(7)

ANOVA is the statistical tool used to check the acceptability of the proposed models, the results of which are presented in Table 4. Equations 5-7 are used to predict the drilling characteristics namely, \( CYL \) and \( Fd \) by varying the values of drilling variables within the chosen range.

3.2. Discussion on drilling characteristics

Drilling characteristics are studied using interaction effect plots drawn by varying two variables at same time in Equations 5-7 while keeping the other two variables constant at intermediate level.

3.2.1. Analysis of cylindricity

Figure 3 shows the influence of \( v, f, R \) and \( D \) on \( CYL \) for cenosphere reinforced epoxy composites. Figure 3a-c shows the influence of cutting speed on the cylindricity at different feed, filler content and drill diameter. Cylindricity is observed to be decreasing with increasing cutting speed. Increasing cutting speed leads to the softening of the composite material due to raise in machining temperature leading to reduced thrust forces which in turn decreases the cylindricity of the drilled holes [25, 40]. Figure 3a, Figure 3d, and Figure 3e shows the effect of feed on cylindricity of drilled holes. It is seen that the cylindricity is found to be decreasing with increasing feed irrespective of
variations in cutting speed, filler content and drill diameter. Cylindricity is inversely proportional to the feed. Similar effect of feed on the cylindricity in drilling of graphite/bismaleimide composites is observed by Kim and Ramulu\[41\].

The variation of drill diameter on the cylindricity is shown in Figure 3c, Figure 3e and Figure 3f. Cylindricity is observed to be minimum for smaller drill diameter, however increasing drill diameter considerably increases cylindricity of drilled holes. As drill diameter increases thrust force increases owing to higher contact area leading to higher cylindricity values \[40\]. From Figure 3b, Figure 3d and Figure 3f. It is clear that the cylindricity error decreases with an increasing filler content. When the tool comes in contact with cenospheres, it opens up the voids by breaking hollow fillers resulting in reduced uncut material. This uncut material increases with increasing filler content leading to reduced thrust force which subsequently lowers cylindricity\[40\]. Hence, a combination of higher feed, cutting speed and cenosphere content offers minimum cylindricity in drilling of cenosphere reinforced epoxy composites using smaller drill diameter.

### 3.2.2. Analysis of delamination factor

The influence of \( v, f, R \) and \( D \) on \( F_{d,\text{Entry}} \) and \( F_{d,\text{Exit}} \) for developed composites is plotted in Figure 4 and Figure 5 respectively. The effect of cutting speed on the \( F_{d,\text{Entry}} \) is shown in the Figure 4a-c at different feed, filler content and drill diameter. The graphs clearly indicate that the \( F_{d,\text{Entry}} \) increases as the cutting speed. It is known that increasing cutting speed raises the work-tool interface temperature due to the friction and poor thermal conductivity of polymer composite. This results in the heating of epoxy resin leading to reduced stiffness of the composite material which subsequently increases the \( F_{d,\text{Entry}} \) of the drilled holes\[24, 42\]. Davim and Reis \[43\] reported a similar effect of cutting speed on delamination in drilling of CFRP composites. Cutting speed effect on \( F_{d,\text{Exit}} \) is found to be the same as observed from Figure 5a-c. Figure 4a, Figure 4d and Figure 4e shows the influence of feed on \( F_{d,\text{Entry}} \) irrespective of variations in filler content, drill diameter and cutting speed. Decreased machining temperature due to reduced contact time between drill and work material at higher feed aids to retain the stiffness of the polymer matrix resulting decline in trend of \( F_{d,\text{Entry}} \). Figure 5a, Figure 5d and Figure 5e shows the influence of feed on \( F_{d,\text{Exit}} \) for cenosphere-epoxy composites. It is found that the feed is having the same influence on exit delamination as that of delamination on the entry side.

The effect of drill diameter on the \( F_{d,\text{Entry}} \) and \( F_{d,\text{Exit}} \) is presented in Figure 4c, Figure 4e and Figure 4f and Figure 5c, Figure 5e and Figure 5f respectively. Increasing drill diameter up to \( D_1 = 12 \) increases both entry and exit delamination and later it is found to be decreasing. Delamination depends on the thrust force and cutting temperature generated during the process \[44, 45\]. Increase in delamination is attributed to the increased thrust forces due to the increased contact area \[45, 46\]. However, increasing drill diameter also reduces the rotational speed of the tool (\( N = 1000 v/\pi D \)) at the same cutting speed \[47\]. Decreased rotational speed of the tool increases the stiffness of the composite material due to reduced working temperature resulting in lower values of delamination factor with larger diameter drills \[24, 42\]. The addition of cenospheres in the composites leads to reduction in the entry and exit delamination factor as observed from Figure 4 and Figure 5 respectively. Increasing cenosphere content decreases thrust force generated during the process leading to lower \( F_{d,\text{Entry}} \) values. Combination of higher feed, lower cutting speed, higher cenosphere \% and larger drill diameter helps to minimize the \( F_{d,\text{Entry}} \) in drilling cenosphere/epoxy composites.

### 4. Conclusions

Cenosphere/epoxy composites materials are prepared by dispersing 10, 35 and 60 vol. \% of cenospheres and drilling experiments are carried out based on FFD using coated WC drills. Effect of cutting speed, feed, cenosphere content and drill diameter are analysed on drilling characteristics, namely, CYL and \( F_{d,\text{Entry}} \) (Entry and exit) using RSM based mathematical models. On the basis of experimental investigations, the following conclusions are drawn.

- With increase in cutting speed, cylindricity is decreased and delamination is observed to be
increased.  
- Increasing feed and cenosphere content decreases both cylindricity and delamination (entry and exit) of the drilled holes.  
- With increasing drill diameter, cylindricity is increased. However, increasing drill size increases delamination up to D12 and later shows a declining trend.  
- ANOVA results show that drill diameter has a significant effect on cylindricity followed by cenosphere content and cutting speed. Feed has a negligible effect on the cylindricity of drilled holes.  
- Delamination is strongly governed by drill diameter followed by feed and cenosphere content. However, the effect of cutting speed is found to be insignificant.  
- Minimum cylindricity and delamination (entry and exit) are obtained at a combination of $v_{10}f_{0.16R_{60}D_{8}}$ and $v_{50}f_{0.16R_{60}D_{16}}$ respectively.

Acknowledgments
The Authors acknowledge the facilities provided by B. V. B College of Engineering and Technology, Hubballi, Karnataka, India. The Authors are also grateful to Management, Dr. Ashok Shettar, Vice Chancellor, K L E Technological University, Hubballi, Dr. P. G. Tewari, Principal, B V B College of Engineering and Technology, Hubballi and Dr. Basavaraj G. Katageri, Principal KLE Dr. M. S. Sheshgiri College of Engineering & Technology, Belagavi, for their encouragement and support. The authors thank Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, India for the facilities support.

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### Table 1. Drilling variables and their levels.

| Input drilling variable | Levels |
|-------------------------|--------|
| \( v \) (m/min)         | 50     |
|                         | 75     |
|                         | 100    |
| \( f \) (mm/rev)        | 0.04   |
|                         | 0.1    |
|                         | 0.16   |
| \( R \) (vol. %)        | 10     |
|                         | 35     |
|                         | 60     |
| \( D \) (mm)            | 8      |
|                         | 12     |
|                         | 16     |

### Table 2. Proposed plan of experimentation.

| Expt. No. | Process variable settings | Expt. No. | Process variable settings | Expt. No. | Process variable settings |
|-----------|---------------------------|-----------|---------------------------|-----------|---------------------------|
|           | \( R \) \( v \) \( f \) \( D \) |           | \( R \) \( v \) \( f \) \( D \) |           | \( R \) \( v \) \( f \) \( D \) |
| 1         | 8 28 8 55 8              | 2         | 0.04 12 0.04 12 56 0.04 12 | 3         | 0.10 8 60 16 60 16      |
| 4         | 8 31 8 58 8              | 5         | 50 0.10 12 0.10 12 59 0.10 12 | 6         | 12 33 16 63 16 63 16   |
| 7         | 8 34 8 61 8              | 8         | 0.16 12 0.16 12 62 0.16 12 | 9         | 16 36 16 66 16 66 16   |
| 10        | 8 37 8 64 8              | 11        | 0.04 12 0.04 12 65 0.04 12 | 12        | 16 39 16 69 16 69 16   |
| 13        | 8 40 8 67 8              | 14        | 10 75 0.10 12 75 0.10 12 68 75 0.10 12 | 15        | 16 42 16 70 16 70 16   |
| 16        | 8 43 8 70 8              | 17        | 0.16 12 0.16 12 71 0.16 12 | 18        | 16 45 16 73 16 73 16   |
| 19        | 8 46 8 74 8              | 20        | 0.10 12 0.10 12 74 0.10 12 | 21        | 0.04 12 0.04 12 75 0.04 12 |
| 22        | 8 49 8 76 8              | 23        | 100 0.10 12 100 0.10 12 77 100 0.10 12 | 24        | 16 51 16 78 16 78 16   |
| 25        | 8 52 8 79 8              | 26        | 0.16 12 0.16 12 80 0.16 12 | 27        | 16 54 16 81 16 81 16   |
Table 3. Measured values of \( CYL \) and \( F_d \) (entry and exit level).

| Expt. No. | Drilling characteristics | Expt. No. | Drilling characteristics | Expt. No. | Drilling characteristics |
|-----------|--------------------------|-----------|--------------------------|-----------|--------------------------|
|           | \( CYL \)               |           | \( F_{d,\text{entry}} \) |           | \( F_{d,\text{exit}} \)  |
| 1         | 0.029                    | 1.008     | 1.010                    | 28        | 0.020                    | 1.005     | 1.009                    | 55        | 0.015                    | 1.004     | 1.006                    |
| 2         | 0.034                    | 1.008     | 1.009                    | 29        | 0.029                    | 1.007     | 1.011                    | 56        | 0.023                    | 1.007     | 1.007                    |
| 3         | 0.049                    | 1.005     | 1.005                    | 30        | 0.034                    | 1.004     | 1.004                    | 57        | 0.030                    | 1.003     | 1.003                    |
| 4         | 0.024                    | 1.005     | 1.009                    | 31        | 0.014                    | 1.005     | 1.006                    | 58        | 0.019                    | 1.004     | 1.004                    |
| 5         | 0.035                    | 1.006     | 1.008                    | 32        | 0.027                    | 1.007     | 1.007                    | 59        | 0.018                    | 1.007     | 1.007                    |
| 6         | 0.046                    | 1.003     | 1.003                    | 33        | 0.040                    | 1.003     | 1.003                    | 60        | 0.032                    | 1.003     | 1.002                    |
| 7         | 0.026                    | 1.004     | 1.003                    | 34        | 0.018                    | 1.002     | 1.003                    | 61        | 0.014                    | 1.004     | 1.005                    |
| 8         | 0.031                    | 1.005     | 1.008                    | 35        | 0.019                    | 1.007     | 1.007                    | 62        | 0.014                    | 1.007     | 1.006                    |
| 9         | 0.032                    | 1.003     | 1.002                    | 36        | 0.027                    | 1.003     | 1.003                    | 63        | 0.032                    | 1.004     | 1.002                    |
| 10        | 0.023                    | 1.005     | 1.008                    | 37        | 0.018                    | 1.005     | 1.009                    | 64        | 0.013                    | 1.005     | 1.006                    |
| 11        | 0.029                    | 1.007     | 1.010                    | 38        | 0.030                    | 1.004     | 1.010                    | 65        | 0.027                    | 1.007     | 1.009                    |
| 12        | 0.036                    | 1.004     | 1.004                    | 39        | 0.035                    | 1.004     | 1.006                    | 66        | 0.029                    | 1.004     | 1.003                    |
| 13        | 0.026                    | 1.005     | 1.009                    | 40        | 0.014                    | 1.006     | 1.006                    | 67        | 0.016                    | 1.005     | 1.004                    |
| 14        | 0.032                    | 1.006     | 1.009                    | 41        | 0.022                    | 1.007     | 1.008                    | 68        | 0.020                    | 1.007     | 1.008                    |
| 15        | 0.034                    | 1.004     | 1.004                    | 42        | 0.031                    | 1.004     | 1.004                    | 69        | 0.028                    | 1.003     | 1.003                    |
| 16        | 0.019                    | 1.005     | 1.006                    | 43        | 0.017                    | 1.004     | 1.002                    | 70        | 0.020                    | 1.004     | 1.004                    |
| 17        | 0.036                    | 1.013     | 1.008                    | 44        | 0.027                    | 1.007     | 1.008                    | 71        | 0.017                    | 1.007     | 1.006                    |
| 18        | 0.034                    | 1.002     | 1.002                    | 45        | 0.026                    | 1.004     | 1.002                    | 72        | 0.036                    | 1.004     | 1.002                    |
| 19        | 0.013                    | 1.007     | 1.009                    | 46        | 0.010                    | 1.008     | 1.009                    | 73        | 0.011                    | 1.006     | 1.006                    |
| 20        | 0.030                    | 1.008     | 1.010                    | 47        | 0.022                    | 1.006     | 1.010                    | 74        | 0.018                    | 1.008     | 1.009                    |
| 21        | 0.033                    | 1.006     | 1.005                    | 48        | 0.031                    | 1.004     | 1.005                    | 75        | 0.036                    | 1.004     | 1.005                    |
| 22        | 0.020                    | 1.006     | 1.010                    | 49        | 0.015                    | 1.006     | 1.008                    | 76        | 0.008                    | 1.005     | 1.005                    |
| 23        | 0.026                    | 1.005     | 1.009                    | 50        | 0.019                    | 1.007     | 1.009                    | 77        | 0.014                    | 1.007     | 1.008                    |
| 24        | 0.035                    | 1.006     | 1.005                    | 51        | 0.026                    | 1.004     | 1.003                    | 78        | 0.029                    | 1.003     | 1.003                    |
| 25        | 0.019                    | 1.005     | 1.007                    | 52        | 0.007                    | 1.005     | 1.005                    | 79        | 0.010                    | 1.004     | 1.005                    |
| 26        | 0.024                    | 1.005     | 1.009                    | 53        | 0.017                    | 1.007     | 1.008                    | 80        | 0.021                    | 1.004     | 1.002                    |
| 27        | 0.024                    | 1.003     | 1.004                    | 54        | 0.026                    | 1.004     | 1.003                    | 81        | 0.027                    | 1.004     | 1.003                    |

Table 4. ANOVA Results for \( CYL \) and \( F_d \) (entry and exit).

| Drilling characteristic | Sum of squares | Degrees of freedom | Mean square | \( F \)-ratio | \( p \)-value | \( R^2 \) |
|-------------------------|----------------|-------------------|-------------|--------------|---------------|---------|
| CYL                     | 5.18×10^{-03} | 14                | 8.79×10^{-04} | 14           | 66            | 3.70×10^{-04} | 3.70×10^{-04} | 27.77     | <0.001 | 85.49  |
| \( F_{d,\text{entry}} \) | 1.46×10^{-04} | 14                | 1.22×10^{-04} | 14           | 66            | 1.00×10^{-05} | 1.00×10^{-05} | 2.00×10^{-06} | 5.66    | <0.001 | 54.56  |
| \( F_{d,\text{exit}} \)  | 4.90×10^{-04} | 14                | 7.40×10^{-05} | 14           | 66            | 3.50×10^{-05} | 3.50×10^{-05} | 1.00×10^{-06} | 31.42   | <0.001 | 86.95  |

* Significant at 99% confidence level
Figure 1. Coordinate measuring machine used for measuring cylindricity and drilled hole diameter.

Figure 2. Cenosphere/epoxy composite samples post drilling.
Figure 3. Interaction effects of (a) $v$-$f$, (b) $v$-$R$, (c) $v$-$D$, (d) $f$-$R$, (e) $f$-$D$, and (f) $D$-$R$ on CYL.
Figure 4. Interaction effects of (a) $v-f$, (b) $v-R$, (c) $v-D$, (d) $f-R$, (e) $f-D$ and (f) $D-R$ on $F_{d\text{-Entry}}$.
Figure 5. Interaction effects of (a) $v-f$, (b) $v-R$, (c) $v-D$, (d) $f-R$, (e) $f-D$ and (f) $D-R$ on $F_{d, Exit}$. 