Surface roughness analysis in the drilling of carbon fiber/epoxy composite laminates using hybrid Taguchi-Response experimental design

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Abstract

The carbon fiber reinforced polymer composite has made a substantial impact on the manufacturing sectors owing to its excellent mechanical, thermal and corrosion resisting properties. The surface roughness mainly depends on the machining parameters while drilling of carbon fiber reinforced polymer composite laminates. The study concentrates on the impact of uncoated and titanium nitride coated solid carbide drills on minimizing the roughness that is generated while making holes in bi-directional carbon fiber reinforced polymer composite by optimizing the drilling constraints [spindle speed (A), feed rate (B), point angle (C) and drill diameter (D)]. Experimental studies are carried out using Taguchi L27 orthogonal array. The investigation discloses that the drill diameter is one of the most influencing cutting parameters followed by spindle speed and feed rate. The response surface methodology is chosen as a tool for predicting and optimizing the process parameters. The investigation also discloses that the experimental and the predicted results of surface roughness are closely matching with each other. The surface morphology illustrates that titanium nitride coated solid carbide drills minimize the surface roughness compare to that of uncoated solid carbide drills.

1. Introduction

Drilling is one of the most tirelessly used machining processes to form bolted or riveted assemblies exclusively for automobile and aircraft industries. Nowadays, the manufacturers have generally preferred the carbon fiber reinforced polymer (CFRP) composite materials over the conventional materials for different structural applications owing to their excellent mechanical properties such as the higher value of stiffness, lightweight, resistance to corrosion and high specific strength [1, 2]. It was reported that more than 50% of the structural components in Boeing 787 were made up of composites [3].

It is well known that the surface roughness is one of the important parameters normally considered for measuring the surface quality of the products. Since the surface finish of the drilled holes is a main concern in the structural components, the surface roughness (Ra) has received serious attention amongst all the performance characteristics. Further, surface roughness also considered as one of the most serious limitations for the choice of machines and machining parameters in process planning [4–6]. Because of this reason, development in research has been carried out for optimizing the cutting conditions in the drilling of composites to get a precise surface roughness. The proper selection of tool and its geometry and cutting parameters also has a considerable impact on surface roughness.
2. Literature review

To improve the drilling effectiveness of composites, it is important for knowing the drilling performance by conducting a series of drilling experiments and by creating drilling models of composite laminates for optimizing the cutting parameters for minimizing the since it is directly linked to cutting forces [7–11]. Furthermore, during the drilling operation, the superiority of the hole on the surface finish being obtained which exclusively affects the dominance of the end product [12–16]. The drilling experiment on glass fiber reinforced polymer (GFRP) composite was conducted by Ogawa et al and found that there was a drastic reduction in the thrust force, while the hole was pre-drilled to 0.4 mm and above and they also found that the surface roughness generated during drilling of composites was greatly influenced by the tool feed rate [14]. Davim et al have conducted a drilling experiment for studying the effect of cutting velocity and feed rate on surface roughness and thrust force while drilling of GFRP composite material using cemented carbide drills. The investigation showed that thrust force and surface roughness have a direct correlation with feed rate and an inverse relationship with the cutting velocity [7].

Hole quality in drilling of CFRP depends on various factors such as tool edge geometry, tool coatings, cutting force, feed rate and cutting environment [17–21]. Similarly, 50% increase in tool life was observed with coating on the cutting tool during drilling [22]. Giasin et al investigated the surface roughness and burr formation in drilling of fiber metal laminate (GLARE) by using tungsten carbide as cutting tool with three different types of coatings (TiAlN, AlTiN and TiN). Titanium nitride (TiN) coated drills displayed best results with minimum surface roughness and burr formation, whereas TiAlN coated drills exhibited maximum surface roughness and burr formation at higher spindle speed [23]. According to Ozkan et al during milling of CFRP’s with TiAlN and TiN coated carbide tools, maximum surface roughness was observed at lower cutting speed and feed rate in TiN coated carbide tool. However, at higher cutting speed and feed rate, TiAlN coated tool displayed better results [24].

Palanikumar established a mathematical model for surface roughness to study the impact of cutting parameters (cutting speed, fiber orientation angle, depth of cut, and feed rate) while drilling of GFRP composites. The rotatable central composite design was employed for the experimental plan. The author concluded that surface roughness has an inverse relationship with the cutting speed and depth of cut and it has a direct relationship with feed rate and fiber orientation angle [15]. Zipoyne et al have conducted various drilling experiments on a composite of aluminium stacks consisting of 4.2 mm of CFRP laminates with 3 mm layer of Al-2024 using uncoated tungsten carbide drills. They concluded that the surface roughness values between 4 and 8 μm were noticed with the feed rates ranging from 0.05 to 0.15 mm/rev while drilling of CFRP composite [16]. Tsao and Chiu, performed experiments for analysing the influence of process parameters on thrust force while drilling CFRP by using compound core-special drills. The study showed that minimum cutting force and damage-free surface could be produced with a high negative velocity and low feed rate [25]. Hamzeh et al conducted experiments by drilling of CFRP using cemented carbide drills as a tool to predict the influence on surface roughness by process parameters (i.e. spindle speed, feed rate, and tool point angle). It was concluded from the investigation that an increase in tool feed rate increases the surface roughness, whereas, the increase in cutting speed decreases the roughness generated during drilling of composites. The conclusion was made from the experimental results that, it is possible to have a better surface finish with larger cutting speed and a lower feed rate [26].

It is observed from the literature review that optimizing the cutting parameters for minimizing the surface roughness in the drilling of the composite to have better structural integrity is the primary concern of the researchers. With this aim, the present research work is carried out to effectively analyze the feed rate, spindle speed, point angle and drill diameter effect on surface roughness during drilling of bi-directional (BD) CFRP using different solid carbide drills. Since BD CFRP composite has higher strength and stiffness in all directions as compared to uni-directional (UD) CFRP composite, the authors have chosen this material for conducting a study.

3. Experimental procedure

3.1. Fabrication of BD CFRP composite laminate and drilling experimental setup

The T300 type of bi-directional carbon fiber has been chosen for experimental work. The thickness of a single ply of bi-directional carbon fiber is 0.18 mm with a 4 mm thickness of BD CFRP composite as shown in figure 1. The stacking sequence of bi-directional [0/90]12 was processed by hand lay-up method, latterly by a compression moulding technique. The areal density of the specimen fabricated is 200 g m−2. Bisphenol A based epoxy resin L-12 and Amino K-6 is used as a hardener for the preparation of the matrix. Brush and a roller being used for applying the resin mixture (50 wt%) onto each layer of the carbon. The hydraulically pressed matrix resin infused fiber at 0.5 MPa of pressure for 24 h, followed with a post-curing treatment at a temperature of 80 °C for about 8 h. The mechanical properties of BD CFRP composite were determined by using Universal Testing Machine (UTM). Allowable tensile strength 427 MPa and Young’s modulus of 6 GPa were found during the
experimentation. Vickers’s hardness number (VHN) of 19 for BD CFRP composite specimen was found using Matsuzawa micro-hardness testing machine. TRIAC vertical machining center figure 2 is used for conducting the drilling experiments and figure 3 shows the drill bits of different sizes (4, 6, 8 mm) selected for the study.

3.2. Measurement of surface roughness
Taylor-Hobson Surtronic 3+ instrument was used for measuring the surface roughness of the drilled holes as shown in figure 4. $R_a$ is the average value of eight roughness measurements made on the surface of the hole and it is calculated using the equation (1).

$$R_a = \frac{1}{8} \sum_{i=1}^{8} |x_i|$$  \hspace{1cm} (1)

where, $x_i$ is the measured values of surface roughness.

3.3. Statistical tools
$L_2^7$ orthogonal array (OA) from Taguchi’s Design of Model is employed for formulating the experimental layout. The analysis of the means and signal-to-noise (S/N) ratio, smaller the better given in equation (2) are recommended by Taguchi for detecting the parameters that look to be significant (19). The analysis is made using the MINITAB 16 software.

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

In the above equation (2), $n$ represents a number of observations made and $y$ represents the observed data. Table 1 demonstrates the different process parameters, levels selected for the present study. As observed from table 1, for 4 process parameters and their 3 levels, the total degree of freedom (DOF) is 8. But in the present work, interaction effects also considered. Hence, the total DOFs are 26. Therefore, an experimental layout is prepared for Taguchi $L_{27} (3^4)$ orthogonal array (OA) has been shown in table 2.

In the present work, response surface methodology (RSM) is used for modeling and analyzing the data. An empirical relationship is established between the process parameters by selecting the central composite design (CCD) of RSM. The correlation between the surface roughness $y$ and the process parameters ($A$, $B$, $C$, and $D$) is
established, given in equation (3).

\[
y = \beta_0 + \beta_1A + \beta_2B + \beta_3C + \beta_4D + \beta_5A^2 + \beta_6B^2 + \beta_7C^2 + \beta_8D^2 + \beta_9AB + \beta_{10}AC \\
+ \beta_{11}AD + \beta_{12}BC + \beta_{13}BD + \beta_{14}CD + \epsilon
\]  

(3)

Where, \(\beta_0, \beta_1, \beta_2, \ldots, \beta_{14}\) are the regression coefficients and \(\epsilon\) is the random error.

### 3.3.1. RSM optimization

The desirability function method is generally used for optimizing the multi-output variable [27, 28]. According to this approach, a product or process having one of its quality characteristics beyond the desirable limits is completely unacceptable. It aims at finding the process parameters that provide the most desirable output variables. In this study, the desirability function approach is used for optimizing the surface roughness using RSM.

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*Figure 3.* Drill bits, (a) uncoated solid carbide and (b) TiN coated solid carbide.

*Figure 4.* Surface roughness measuring instrument.
In this work, the desirability function transforming the surface roughness into a dimensionless variable called desirability index $d_i$. The desirability index cascades in the close interval range of $(0, 1)$. A higher value of the desirability index for surface roughness implies a higher contribution to the product performance by the particular output variable. The desirability index $d_i$ is a function of the surface roughness $y_i$. An individual desirability function $d_i$ assigns a number between 0 and 1; 0 being a completely undesirable and 1 being a completely desirable or ideal output variable value. For minimization of the surface roughness, $d_i$ can be defined as [27].

$$d_i = \left( \frac{y - y_{\text{min}}}{y_{\text{target}} - y_{\text{min}}} \right)^q ; y_{\text{min}} < y < y_{\text{target}}$$  

(4)

In the above equations, $y$ is the surface roughness, $y_{\text{min}}$ the lowest and $y_{\text{target}}$ being the target values respectively, and $q$ is the weight. The weight $q$ can take low values ($0 < q < 1$) or high values ($q > 1$), according to the effect desired [29]. The value of one generates a linear ramp function among the low, target and high values. The result can be moved towards the goal by increasing the weight [30]. The inclusive calculation of the product performance is achieved by ingressing the geometric mean of all the desirability indices to perceive an aggregate (global or composite) desirability index $D$. i.e.,

$$D = (d_1 \times d_2 \times d_3 \ldots \ldots d_m)^{\frac{1}{m}}$$  

(5)

Table 1. Process parameters and their levels.

| Process parameters | Levels | A     | B     | C     | D     |
|--------------------|--------|-------|-------|-------|-------|
|                    | 1      | 1200  | 10    | 90    | 4     |
|                    | 2      | 1500  | 15    | 104   | 6     |
|                    | 3      | 1800  | 20    | 118   | 8     |

Table 2. Taguchi $L_{27}$ ($3^4$) orthogonal array.

| Trial | (A) Spindle speed (rpm) | (B) Feed rate (mm min$^{-1}$) | (C) Point angle (degree) | (D) Drill diameter (mm) | Conditions |
|-------|-------------------------|-------------------------------|-------------------------|-------------------------|------------|
| 1     | 1200                    | 10                            | 90                      | 4                       | A$_1$B$_1$C$_1$D$_1$ |
| 2     | 1200                    | 10                            | 90                      | 6                       | A$_1$B$_1$C$_1$D$_2$ |
| 3     | 1200                    | 10                            | 90                      | 8                       | A$_1$B$_1$C$_1$D$_3$ |
| 4     | 1200                    | 15                            | 104                     | 4                       | A$_1$B$_1$C$_2$D$_1$ |
| 5     | 1200                    | 15                            | 104                     | 6                       | A$_1$B$_1$C$_2$D$_2$ |
| 6     | 1200                    | 15                            | 104                     | 8                       | A$_1$B$_1$C$_2$D$_3$ |
| 7     | 1200                    | 20                            | 118                     | 4                       | A$_1$B$_1$C$_3$D$_1$ |
| 8     | 1200                    | 20                            | 118                     | 6                       | A$_1$B$_1$C$_3$D$_2$ |
| 9     | 1200                    | 20                            | 118                     | 8                       | A$_1$B$_1$C$_3$D$_3$ |
| 10    | 1500                    | 10                            | 104                     | 4                       | A$_1$B$_2$C$_1$D$_1$ |
| 11    | 1500                    | 10                            | 104                     | 6                       | A$_1$B$_2$C$_1$D$_2$ |
| 12    | 1500                    | 10                            | 104                     | 8                       | A$_1$B$_2$C$_1$D$_3$ |
| 13    | 1500                    | 15                            | 118                     | 4                       | A$_1$B$_2$C$_2$D$_1$ |
| 14    | 1500                    | 15                            | 118                     | 6                       | A$_1$B$_2$C$_2$D$_2$ |
| 15    | 1500                    | 15                            | 118                     | 8                       | A$_1$B$_2$C$_2$D$_3$ |
| 16    | 1500                    | 20                            | 90                      | 4                       | A$_1$B$_2$C$_3$D$_1$ |
| 17    | 1500                    | 20                            | 90                      | 6                       | A$_1$B$_2$C$_3$D$_2$ |
| 18    | 1500                    | 20                            | 90                      | 8                       | A$_1$B$_2$C$_3$D$_3$ |
| 19    | 1800                    | 10                            | 118                     | 4                       | A$_1$B$_3$C$_1$D$_1$ |
| 20    | 1800                    | 10                            | 118                     | 6                       | A$_1$B$_3$C$_1$D$_2$ |
| 21    | 1800                    | 10                            | 118                     | 8                       | A$_1$B$_3$C$_1$D$_3$ |
| 22    | 1800                    | 15                            | 90                      | 4                       | A$_1$B$_3$C$_2$D$_1$ |
| 23    | 1800                    | 15                            | 90                      | 6                       | A$_1$B$_3$C$_2$D$_2$ |
| 24    | 1800                    | 15                            | 90                      | 8                       | A$_1$B$_3$C$_2$D$_3$ |
| 25    | 1800                    | 20                            | 104                     | 4                       | A$_1$B$_3$C$_3$D$_1$ |
| 26    | 1800                    | 20                            | 104                     | 6                       | A$_1$B$_3$C$_3$D$_2$ |
| 27    | 1800                    | 20                            | 104                     | 8                       | A$_1$B$_3$C$_3$D$_3$ |
Where, \( m \) is the surface roughness. In this work, a relationship is attained between the surface roughness and the process factors or machining factors by adding a second-degree polynomial regression equation into the experimental data. Then, the desirability of surface roughness is calculated for estimating the overall desirability. The univariate search method is employed to search the optimum overall desirability from different combinations of machining factors within the experimental range.

4. Results and discussion

4.1. Examination of surface roughness

It is well known that surface roughness one of the key parameters that decide the quality of the drilled holes and the cost of production. It is largely depending on the kind of material to be drilled, the type drills to be used and its point angle, cutting speed, and the cutting force produced in drilling. Figure 5 represents the surface roughness outcomes produced during drilling with uncoated and TiN coated solid carbide drills on BD CFRP. It is witnessed in figure 5 that uncoated solid carbide drills \( R_a \) values are relatively higher than the obtained \( R_a \) values of TiN coated solid carbide drills. This may be ascribed that, TiN coating performs as a lubricant during drilling \([31,32]\), by reducing the friction between the tool and the workpiece.

Figure 6 and table 3 represent the results of surface roughness gained from experimental and predicted values using RSM. From figure 6 and table 3, it is seen the roughness values deduced from the experiment and from RSM are in good agreement. Hence, the RSM can be used as one of the best tools for predicting the surface roughness during drilling. While comparison, it can be observed from table 3, the average error obtained of solid TiN coated solid carbide drills is lower (4.06) than that of uncoated solid carbide drills (4.54) in the drilling of the composite laminate.

For uncoated and coated solid carbide drills figure 7 exhibits the main effect plots for different values of the mean S/N ratio. Figure 7 demonstrate, that drill diameter is the factor that affects substantially to the surface roughness followed by spindle speed and feed rate as their gradients are more steeper. However, the point angle has a negligible effect on surface roughness as the slope of the graphs is nearly flat. The optimum cutting conditions suggested by the main effect plots for conducting experiments for minimum surface roughness will be spindle speed of 1800 rpm, drill diameter of 4 mm, feed rate of 10 mm min\(^{-1}\) and point angle of 90°. Results of analysis of variance (ANOVA) for 95% reliability level are shown in table 4.

Analysis of variance (ANOVA) has been carried out by using the data of S/N ratio for determining the significant cutting parameters on surface roughness. From table 4, the conclusion can be made that there is no interaction effect of machining factors on surface roughness while drilling of the composite. However, Drill diameter and the feed rate and spindle speed have considerable influence on surface roughness \([33–35]\). From the study it is witnessed that there is a significant correlation between the results deduced from ANOVA and the results determine the main effect plots for S/N ratios for surface roughness in drilling using solid carbide drills.

The influence of cutting parameters on surface roughness is also assessed using 3D response plots of RSM which is shown in figure 8. It is observed from figure 8 that the values of surface roughness decrease with increasing effect of spindle speed. The decrease in roughness with increase in spindle speed is due to the fact that...
at higher speed, built-up edge (BUE) developed during low speed disappears and chip fracture decreases, and thus, the roughness decreases [36]. It is also observed from figure 8 that the values of surface roughness increase as the drill diameter increases while drilling of composite. Increasing the drill diameter may promote the BUE formation due to high normal pressure which results in a seizure on the rake face. Hence, it is concluded that by increasing the diameter of the cutting tools, surface roughness increases [33, 36].

The surface roughness versus feed rate and point angle demonstrated in figure 9. It is evident from figure 9 that the surface roughness has a direct correlation with the tool feed rate. The reason for this is at high feed rate,
crack is more vicious and less controllable due to the high strain rate [15]. A higher tool feed rate is also responsible for increasing the thrust force during drilling, resulting in higher chips, poor surface finish [37]. It is also evident from figure 9 that the point angle shows negligible effect on $R_a$ while performing drilling of BD CFRP. From the analysis of the 3D response plots, it is confirmed that the minimum surface roughness can be achieved with minimum drill diameter, maximum spindle speed, minimum feed rate. Also, the point angle can be set at a suitable value as there is no influence of it on the surface finish.

4.2. Surface morphology

Figure 10 illustrate the SEM images of the surface of the hole drilled using solid carbide tools. It is interesting to observe from the SEM images that the hole drilled by uncoated tool shows severely damaged surfaces while comparing to that drilled with TiN coated drill. This may be attributed to the reason that fiber pull-out, debonding, and delamination are more with uncoated solid carbide drills, during drilling of CFRP. These multiple defects are due to ploughing action which dominates over cutting action. The ploughing action may be the result of the heating effect which creates friction in the drilling of composite laminate [38]. TiN coating acts as a lubricant while drilling using TiN coated tool, by reducing the friction which also reduces the defects caused [39]. This in fact produces more uniform surface in case of TiN coated solid carbide drills.

Figure 11 depicts the surface contour for the hole drilled having a drill diameter of 8 mm with the point angle of 118° using uncoated and TiN coated carbide drill at the feed rate of 20 mm min$^{-1}$ and spindle speed of 1200 rpm. From figure 11, it is confirmed that the surface contour deduced from the TiN coated carbide drill is more uniform and homogeneous compared that obtained from uncoated solid carbide drill. This also clearly shows that TiN coated solid carbide tools can be effectively used during drilling of composites for structural assemblies.

![Figure 7. Mean S/N ratio versus cutting conditions for $R_a$ (a) uncoated and (b) TiN coated solid carbide drills.](image)

| Table 4. ANOVA for surface roughness of BD CFRP composite. |
|------------------|------------------|------------------|
| Source           | Uncoated solid   | TiN coated solid |
|                  | carbide          | carbide          |
| Source           | F                | P (%)            | F                | P (%)            |
| A                 | 296.17           | 0.000            | 116.34           | 0.000            |
| B                 | 136.43           | 0.000            | 82.50            | 0.000            |
| C                 | 1.29             | 0.341            | 1.33             | 0.332            |
| D                 | 351.59           | 0.000            | 238.81           | 0.000            |
| A*D               | 6.30             | 0.024            | 6.70             | 0.021            |
| B*D               | 0.31             | 0.865            | 4.68             | 0.047            |
| C*D               | 0.31             | 0.864            | 0.43             | 0.781            |
| R$^2$             | 99.6%            | R$^2$(adj) = 98.4% |
| R$^2$             | 99.4%            | R$^2$(adj) = 97.2% |

F- Variance ratio; P- Smallest level of significance; P (%) - Percentage of contribution; A- Spindle speed in rpm; B- Feed rate in mm/min; C- Point angle in °; D- Drill diameter in mm.
4.3. Confirmation test
To verify experimentally a confirmation test is performed for the minimum surface roughness obtained at predicted optimal process parameters. The results of confirmation tests conducted for optimum cutting

Figure 8. Surface roughness versus spindle speed and drill diameter for (a) uncoated and (b) TiN coated solid carbide drills.

Figure 9. Surface roughness versus feed rate and point angle for (a) uncoated and (b) TiN coated solid carbide drills.

Figure 10. SEM image of the sidewall of a hole drilled using (a) uncoated and (b) TiN coated solid carbide drills.
conditions are exhibited in table 5. By analyzing the experimental and predicted values from table 4, it is concluded that values of surface roughness deduced for ideal cutting conditions ($A_3 = 1800 \text{ rpm}$, $B_1 = 10 \text{ mm min}^{-1}$, $C_1 = 90^\circ$, $D_1 = 4 \text{ mm}$) are in good agreement with a deviation of less than 3%. The confirmation test is also confirmed that the roughness values obtained here are less than the minimum values obtained from the Taguchi experimental results shown in table 5.

| Drill bit                  | Optimum cutting parameters | Experimental $R_a (\mu m)$ | Predicted $R_a (\mu m)$ | % of Agreement |
|----------------------------|-----------------------------|-----------------------------|-------------------------|----------------|
| Uncoated solid carbide    | $A_3B_1C_1D_1$              | 0.617                       | 0.628                   | 99             |
| TiN coated solid carbide  | $A_3B_1C_1D_1$              | 0.368                       | 0.366                   | 99             |

$A_3$ - Spindle speed of 1800 rpm; $B_1$ - Feed rate of 10 mm min$^{-1}$; $C_1$ - Point angle of $90^\circ$; $D_1$ - Drill diameter of 4 mm.
Optimization of surface roughness is performed using the desirability function approach of RSM and its plots drawn for optimum cutting conditions (spindle speed 1800 rpm, feed rate 10 mm min⁻¹, point angle 90° and drill diameter 4 mm) for both uncoated and TiN coated tools are illustrated in figure 12. The merit of these optimization plots is that any values surface roughness can be obtained by varying the values of input parameters within the experimental range.

5. Conclusions

1. For uncoated carbide drills, ANOVA results show the impact of drill diameter, spindle speed and feed rate on surface roughness being 44.37%, 37.38% and 17.22. Conversely, the effect of drill diameter, spindle speed and feed rate with TiN coated carbide drills on surface roughness is 52.98%, 25.81%, and 18.30%. The point angle has a negligible impact on surface roughness. Similar results are also shown by the main effect plots of Taguchi.

2. The 3D surface plots of RSM identify the minimum and maximum surface roughness in drilling of BD CFRP. Also demonstrating that Rₖ has a direct relationship with drill diameter, spindle speed, and feed.

3. The optimization of surface roughness has been obtained by the desirability function approach. The models predict the lowest and highest value Rₖ for BD CFRP. From the optimization plots of RSM, one can determine any values of Rₖ by redefining the input parameters within the inner of the investigational range. The study proves that RSM can be effectively used for optimizing the cutting conditions for minimum surface roughness.

4. The investigation showed that experimental results of Rₖ closely matches with Rₖ of predicted results signifying, RSM is one of the important tools for forecasting Rₖ while drilling of composites.

5. The confirmation test proves that the minimum surface roughness is attained for optimum cutting conditions. A microscopic level of investigation reveals that more damage and surface roughness in BD CFRP composite is observed while drilling using uncoated carbide drills.

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