Response surface methodological evaluation of drilling for the optimization of residual compressive strength of bio-based RPUF composite

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Abstract
Present study investigates the impact of process parameters on the residual compressive strength of bio-based rigid polyurethane foam (RPUF) composites incorporated with copper powder. Formulation of the samples was optimized by performing compressive strength, thermo-gravimetric analysis (TGA) and flammability experiments. It was concluded that incorporation of 8% metallic filler showed up to 116% increase in the compressive strength and T5% was also found to increase from 192 °C to 257 °C. Furthermore, peak heat-release rate (PHRR) was found to decreased from 118 kW m$^{-2}$ to 93 kW m$^{-2}$ and total heat release (THR), smoke production rate (SPR) as well as total smoke release (TSR) also demonstrate a significant decrease on the incorporation of 8% copper powder in the RPUF. Polynomial mathematical model reliant on the Response surface method (RSM) employing Central composite design has been developed. It was concluded that density is the most influential factor for maximizing the residual compressive strength. The optimized process parameters for maximizing residual compressive strength were attained as high spindle speed and low feed rate. Furthermore, equations designated as the coded factors are also presented to identify the relative impact of factors.

1. Introduction

During past few decades, rigid polyurethane foams (RPUFs) have been the subject of intense research due to a wide range of applications in construction & refrigeration industry, prototypes and industrial patterns [1–3]. Commercially, polyurethane (PU) foam is prepared by the reaction of a polyol with a polyisocyanate, both of them are the petroleum-based raw materials. A lot of studies have been executed for the preparation of PU foam using the polyols derived from different vegetable oils and reinforced with different natural and synthetic fillers [4–6]. Of these vegetable oils, only castor oil possesses the hydroxyl group naturally and consequently conversion of castor oil into polyol is comparatively easy and cost efficient process. Although various researchers investigated on the castor oil-based polyurethanes reinforced with different fillers and reported the enhanced mechanical and thermal properties [7–9], still the literature is devoid of investigations on castor oil-based RPUF reinforced with metallic fillers such as copper, iron, and others. Of these, the copper powder may be used to impart good mechanical and thermal properties in castor oil-based RPUF [10] but for the commercialization of this RPUF, some machining operations such as milling, drilling, countersinking, grinding, boring and trimming are required for obtaining desired geometrical shapes [11–13]. Of these, drilling is an important operation required for fastening and riveting structural components in various applications such as aircraft and automobile [14–16]. Drilling of polymer composite is considerably different from that of metals & alloys and require deliberations owing to their some unique characteristics of inherent inhomogeneity, anisotropy, and abrasiveness [17]. Quality of drilled holes, specified by the dimensional tolerances, accuracy, and precision,
influences the load-carrying capacity of the products prepared from polymer composites, consequently ascertains the structural integrity as well as long term reliability of the product. Previous researches on drilling damages in composites have concluded that the peel-up and push-out are two distinguishable modes of delamination mechanisms, commencing when the thrust force surpasses the critical thrust force (CTF) [18]. Analytical studies reveal that cutting parameters such as feed rate, depth of cut, spindle speed and others control the thrust force, which is required to be minimized to reduce the delamination. So, an optimized selection of these parameters administers the delamination-free drilling [19, 20].

To correlate the thrust force and other drilling parameters in composite materials, variety of empirical mathematical models have been established and it was concluded that thrust force and delamination increase with feed rate while spindle speed showed specific behaviours for distinct materials [21–23]. Mechanical properties of polymer composites are also influenced by the delamination, so the impact of delamination on the residual mechanical strength also needs attention. Several studies have been conducted to ascertain the effects of delamination on residual mechanical strength [22, 24]. Diaz Alvarez et al [25] studied the drilling-induced damages in aramid composites and analyzed the influence of the drill geometry (Twist drill, Brad & Spur drill) on the torque, damage and thrust force. Some mechanistic models were developed to ascertain the relation between process parameters and the quality of the final product. It was observed that the Twist drill showed better performance with high feed rate and cutting speeds, while with the Brad & Spur drill, higher speed and lower feed rate provides better results in terms of delamination.

Zarif Karimi et al [24] investigated the effect of drilling-induced delamination on the compressive strength of epoxy composites reinforced with woven glass fiber. The feed rate and spindle speed were considered as process parameters to optimize the delamination and residual compressive strength. It was observed that the extent of damage due to delamination or interlaminar cracking is governed by the cutting forces. Results showed that the feed rate was the most influential factor to optimize the residual compressive strength and the optimized value of residual compressive strength was attained at a spindle speed of 1000 rpm and feed rate of 31.5 mm min \(^{-1}\).

Xu et al [26] studied the severity of drilling-induced damage such as burrs, tearing and delamination in CFRP composites using three different types of specialized drill bits (twist drill, brad spur drill, and dagger drill). The ultrasonic C-scan showed that initially, delamination takes place inside the composite layer and then transmits through plies on increasing the drill thrust load. The feed rate was identified as the most significant factor to generate defects during drilling of the composite. It was concluded from the damage analysis that the brad spur drill provides the least damage in the course of the drilling of CFRP.

Heidary et al [22] investigated the drilling performance of epoxy composites reinforced from E-glass fiber and multi-walled carbon nanotubes (MWCNT) and analyzed the effect of drilling-induced damage on the residual flexural strength. Feed rate (0.04–0.1 mm rev \(^{-1}\)), drill diameter (4 and 5 mm), spindle speed (315 and 630 rpm), and the weight % of carbon nanotubes (0%–1%) were considered as process parameters. Taguchi method in association with grey relational analysis (GRA) was employed for the multi-objective optimization of the drilling process. Results showed that the feed rate was the most influential factor for the optimization of the delamination and thrust force, followed by spindle speed while residual flexural strength was greatly affected by the concentration of the MWCNT, followed by feed rate. It was also reported that feed rate of 0.04 mm rev \(^{-1}\), MWCNT concentration of 0.5%, a drill diameter of 4 mm and spindle speed of 630 rpm are the optimized values of process parameters.

Silva et al [27] studied the effect of tool geometry (twist, brad, step), feed rates (0.12 and 0.30 mm rev \(^{-1}\)) and cutting speeds (1120 and 1800 rpm) on the bearing load and fractal dimension of the carbon fibre reinforced epoxy composite plates. According to their results, the better bearing load was achieved by using step geometry bit with higher cutting speed and lower feed rate. It was also observed that higher feed rate provides lower bearing load, higher delamination, and higher fractal dimension.

Numerous research work has been conducted on the machinability of glass fibre reinforced epoxy composites but polyurethane foam, which is being used in a variety of structural applications, has not been explored yet and necessitates an investigation of all operational aspects. Furthermore, compressive strength is crucial for RPUF, as the applications of RPUF require good compressive strength. But it is evident from the literature that there are immense possibilities of delamination growth under compressive loading [24].

This study investigates the influence of drilling parameters (feed rate, drill diameter, spindle speed and density of RPUF) on the residual compressive strength, thrust force and delamination of copper powder reinforced RPUF. Response surface method-based approach has been employed to accomplish the optimized parameters for the drilling of RPUF. Additionally, experimental investigations have also been performed to optimize the concentration of the copper powder in RPUF employed for drilling analysis.
2. Experimental procedure

2.1. Preparation of RPUF composite
The rigid polyurethane foams were obtained by the method as reported in the literature \cite{28, 29}. In brief, the procedure is as follows:

The copper powder was surface treated with 1% solution of 3-aminopropyl triethoxysilane (APTES) in acetone/water 1:1 (v/v). The predetermined quantity of the surface-treated Electrolytic copper powder (325 mesh size) was added to the modified castor oil (polyol). Then a calculated amount of other ingredients such as catalyst (Dabco 33-LV), blowing agent (n-Pentane), surfactant (Silicon Oil) was added to the polyol and thoroughly mixed to form polyol-premix. A calculated amount of MDI was then added to the beaker. The resulted reaction mixture was poured into a metal mould (100 mm × 100 mm × 10 mm) and kept at room temperature for 72 h to ensure complete curing.

2.2. Characterization

2.2.1. Mechanical strength measurement
The Compressive strength, flexural strength and density of the castor oil-based RPUFs have been determined by standard measurement techniques. Testing was conducted on three specimens of each concentration and the average value was reported. Compressive strength of the prepared RPUFs was measured at room temperature using Instron (model No. 3369) universal testing machine (UTM) according to the ASTM D-1621. Specimens of dimensions 25 mm × 25 mm × 25 mm were cut from foam in the in-plane direction and tested for 10% compression. Flexural strength was measured according to the ASTM D-790 using specimen with dimensions 80 mm × 10 mm × 4 mm. Density of the foam samples was determined according to the ASTM D-1622. The rate of crosshead movement was fixed at 5 mm min^{-1} for each sample.

2.2.2. Thermogravimetric analysis (TGA)
Thermogravimetric analysis (TGA) was performed employing a thermogravimetric analyzer (Perkin Elmer 4000) in a nitrogen atmosphere. The heating rate was kept 10 °C min^{-1} and temperature ranging from 50 °C to 700 °C.

2.2.3. Cone calorimeter testing
The anti-flammability performance of RPUF samples was analyzed with a Cone Calorimeter (Jupiter Electronics, Mumbai, India) according to ISO 5660-1 standard at an incident heat flux of 35 kW m^{-2}. The size of the samples was 100 mm × 100 mm × 20 mm.

2.3. Plan of experiments
In the present study, Response Surface Method (RSM) is used to establish the mathematical relation between responses and drilling parameters using Central Composite Design. The design matrix was created by the employment of statistical analysis software, Design Expert. Foam density, feed rate, diameter of the drill bit and spindle speed, at five levels were selected as input parameters, and the delamination, thrust force and residual specific compressive strength were considered as the responses. Input parameters and their levels were selected based on intensive literature survey and drilling test parameters are summarised in table 1. Computer numerical control (CNC) vertical machining center (VMC) employed with standard high-speed steel (HSS) twist drills was used to perform drilling experiments and each experiment was replicated thrice. Consequences of drilling-induced delamination on the residual compressive strength were determined by performing compression tests as per ASTM D-1621.

| Symbol | Control factor | Unit | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|--------|----------------|------|---------|---------|---------|---------|---------|
| $\rho$ | Density        | Kg m^{-3} | 260   | 302.5   | 345    | 387.5    | 430     |
| $f$   | Feed rate      | mm rev^{-1} | 0.12 | 0.34   | 0.56   | 0.78  | 1       |
| $v$   | Spindle speed  | Rpm  | 56     | 342    | 628   | 914   | 1200   |
| $d$   | Drill diameter | Mm   | 4      | 6      | 8      | 10    | 12    |
3. Results and discussion

3.1. Mechanical strength measurement

Figures 1 and 2 show the changes in mechanical strength, specific mechanical strength, and density on the incorporation of metallic fillers. The unique material characteristics shown by the metallic filler are the result of strong ionic interatomic bonds. Copper powder reinforced RPWF showed an increase in compressive strength up to 3.83 MPa and flexural strength up to 4.72 MPa on the addition of 8% copper powder as compared to 1.77 MPa and 0.79 MPa, respectively for unreinforced polyurethane foam. As the strength of the copper powder filler is higher than that of the RPWF matrix, so the copper powder filler can dissipate the load of the polymer matrix and act as a barrier for the growth of the fracture. When a growing fracture meets a copper powder particle, the dissipation of the energy at the filler site prevents the fracture converting into an unstable one, consequently increasing the toughness of the RPWF [30, 31]. APTES treated metallic fillers have better interaction with the polyl due to the presence of a terminal amino group. APTES also helps in the stabilization of the copper powder by reducing the prospects of oxidation. Increasing the concentration of copper powder filler beyond 8% deteriorates the cell structure which is associated with the agglomeration of metallic fillers after a certain concentration due to the high viscosity of the matrix-filler premix.

Figure 1. Plots of (a) Compressive strength versus Concentration of filler, (b) Flexural strength versus Concentration of filler, (c) Specific compressive strength versus Concentration of filler and (d) Specific flexural strength versus Concentration of filler.

Figure 2. Plots of Density versus Concentration of filler.
Density of the copper powder reinforced RPUF increases slightly on increasing the concentration of copper powder. This behaviour is attributed to the fact that reinforcement of foam with copper powder increases the nucleation site which consequently increase the number of cells. Additionally, density of copper powder is greater than the matrix rigid foam material, which increases the density of the composite.

3.2. Thermo-gravimetric analysis (TGA)

To evaluate the thermal stability of these foams, TGA is conducted under the flow of nitrogen. Figure 3 demonstrates the experimental set-up for the thermo-gravimetric analysis. Results show that thermal properties enhanced on the incorporation of copper powder. Maximum char residue is observed for the copper at 10% filler concentration. Usually, the thermal stability of RPUFs is characterized by the temperatures of 5% weight loss (T5%) considered as the temperature for onset of degradation [33]. It shows that 5% weight loss temperature increases from 192 °C to 257 °C by the incorporation of copper powder. This behaviour of the metallic filler reinforced RPUF may be accredited to the better thermal properties and high temperature performance of the copper powder filler. The TGA analysis of the metallic filler incorporated RPUF are illustrated in figure 4 and the results are summarized in table 2.
3.3. Cone calorimeter testing

Figures 6(a)–(d) shows the plots of the cone calorimeter experiment performed on RPUF containing a varied concentration of metallic filler and data are summarized in table 3. Experimental set-up for cone calorimeter is shown in figure 5. Conventionally, the intensity of the fire is correlated with the heat release rate (HRR) and total heat release (THR) [34, 35]. Figure 6(a) shows that peak heat-release rate (PHRR) is decreased from 118 kW m$^{-2}$ to 93 kW m$^{-2}$ on the incorporation of 8% copper powder in the RPUF. Figure 6(b) shows that total heat release (THR) also decreases from 29.8 MJ m$^{-2}$ to 17.0 MJ m$^{-2}$ on the incorporation of copper fillers. Figure 6(c) shows the smoke production rate (SPR) and the first peak of SPR denotes that the smoke production decreased from 0.008 to 0.004 m$^2$ s$^{-1}$ for the introduction of 8% copper powder. The total smoke release (TSR) also decreases from 302 m$^2$ m$^{-2}$ to 141 m$^2$ m$^{-2}$ for 8% copper powder (figure 6(d)). Properties of composite RPUF starts to deteriorates again on increasing the concentration beyond 8% due to the high viscosity of polyol-filler premix and agglomeration of filler particles. The results are accredited to the fact that the formation of metallic protective layer hinders the flame spread, release of flammable by-products and toxic smoke. It concluded that RPUF with 8% copper powder shows the best mechanical, thermal and flame retardant properties among all the formulations and this is used for the drilling experiments to ascertain the machining ability of the foam. Figure 7 shows the images of samples employed for drilling test.

3.4. Drilling performance test

Drilling-induced damages and consequently residual compressive strength is controlled by the thrust force, which is believed to have a threshold value after which delamination occurs. According to the literature, the exit side of drilled specimen presents more severe delamination in the composite materials, so the images of the holes were obtained at the exit side of the specimen. After that, the maximum diameter and the nominal diameter were measured using an image processing software image j. Figure 8 shows the images of the drilled holes after performing a drilling test at various factor levels.

Residual compressive strength was determined as the force per unit section area remaining after drilling,

$$
\sigma_r = \frac{F}{(l - d)t}
$$

where $F$, $t$, $d$, and are $l$ the force applied at 10% compression, specimen thickness, hole diameter, and specimen width, respectively. To conduct the experiment central composite design model was used, details of experiment design and obtained experimental results of the thrust force, delamination and residual compressive strength are presented in table 4.

The efficiency of the developed regression models has been established by assessing the level of significance for the model, as well as, lack of fit. It was concluded from the fit summary that the quadratic model is the most efficient model for anticipating the effect of the drilling parameters on the residual compressive strength of the
RPUF composite. The ANOVA and the fit statistics for the thrust force, delamination and residual compressive strength are shown in tables 5–7 respectively and the effect of the drilling on the responses is summarized in the subsequent sections.

3.4.1. Thrust force analysis
ANOVA of the reduced quadratic model for the thrust force is summarized in the table 5. The significance of the model is established by the F-value of the model, as well as, the lack of fit, which are 93.32 and 0.72 respectively. The p-value for the model is less than 0.01, which establishes the highly statistical significance of the model at more than 99% confidence interval. The p-value shows that the density, drill diameter and the spindle speed have shown significant effects on the thrust force generated in the course of the drilling, while, the feed rate is insignificant in determining the thrust force. Among these factors, the density is the most influential factor whereas, the influence of the spindle speed is the least significant. It was also noticed that the interaction of the density with the drill diameter, the spindle speed with the feed rate or the drill diameter, the feed rate with the drill diameter and the second order term of density, also have shown significant effect on the developed thrust force.

Figure 9 shows the 3D response surfaces of the developed quadratic model for the thrust force. It was concluded that density, drill diameter, and spindle speed have shown a significant effect on the thrust force generated in the course of drilling, while feed rate is insignificant in determining thrust force. Among these factors, density is the most influential factor whereas, the influence of spindle speed is least.

The higher value of thrust force is accredited to the resistance to cut the polyurethane composite materials with an increase in density which results in higher drilling forces. It was also observed that the thrust force increases slightly on increasing the spindle speed or drill diameter while the feed rate shows no effect on the
thrust force. A similar increase in thrust force was obtained by Debnath et al\cite{15, 36} for thrust force at a higher feed rate.

3.4.2. Delamination analysis
The drilling parameters, as well as the characteristics of matrix and filler, ascertain the extent of delamination during drilling. ANOVA of the reduced quadratic model for the delamination is summarized in the table 6. the F-value of the model and its lack of fit values are 80.69 and 0.42 respectively, which ascertain the significance of

Figure 6. (a) HRR (Heat Release Rate), (b) THR (Total Heat Release), (c) SPR (Smoke Production Rate) and (d) TSR (Total Smoke Release) of RPUFs incorporated with copper pow der.

Figure 7. Samples used for drilling test.
the developed quadratic model. The p-value for the model is less than 0.01, which establish the highly statistical significance of the model at more than 99% confidence interval.

The p-value shows that the density, spindle speed and the drill diameter have shown significant effect on the delamination generated during the drilling, while the feed rate is insignificant in causing the delamination. Among these factors, the drill diameter is the most influential factor whereas, the influence of the density is the least amongst all. It was also noticed that the interaction of the spindle speed with the feed rate, second order of density, feed rate and drill diameter also have shown significant effects on the generated delamination. Figure 10 shows the 3D response surfaces of the developed quadratic model for the delamination. It was observed that the delamination decreases on increasing the spindle speed or density while the feed rate shows no effect on the delamination. Density, spindle speed, and drill diameter have shown a significant effect on the delamination generated during drilling, while feed rate is insignificant in causing delamination. Among these factors, drill diameter is the most influential factor whereas, the influence of density is least amongst all. The similar result was observed by Xing et al[37] while drilling carbon fibre reinforced carbon and silicon carbide composites.

Miguel Silva et al[27] also observed that drilling with high spindle speed and step geometry drill bits provides higher bearing strength in carbon/epoxy cross-ply composite plates. Additionally, increasing drill diameter shows a slight decrease in delamination. It is concluded from these plots that variability in delamination is little affected by the drilling parameters.

3.4.3. Residual compressive strength analysis
ANOVA of the reduced quadratic model for the residual compressive strength is summarized in the table 7. The F-value of the model and the lack of fit values are 97.20 and 0.22 respectively, while the p-value for the model is less than 0.01, which establish the highly statistical significance of the model at more than 99% confidence interval.
The p-value shows that the density, spindle speed and the drill diameter have shown significant effect on the residual compressive strength of the drilled RPUFs. Among these factors, the density is the most influential factor whereas, the influence of drill diameter is least amongst all. It was also noticed that the interaction of the density with the spindle speed or the drill diameter and the interaction of the spindle speed with the feed rate,
second order terms of density, spindle speed, feed rate and the drill diameter also have shown significant effects on the residual compressive strength.

Figure 11 shows the response surfaces of the developed quadratic model for the variation of residual compressive strength with the drilling parameters. It was observed that density, spindle speed, and drill diameter have shown a significant effect on the residual compressive strength of the drilled RPUFs. Among these factors, density is the most influential factor whereas, the influence of drill diameter is least amongst all. An increase in the residual compressive strength was observed on increasing spindle speed. This behaviour is accredited to the lower impact of spindle speed on the generation of delamination which consequently increases the residual compressive strength of the drilled RPUF. Miguel Silva et al [27] also observed similar conclusions while drilling carbon/epoxy cross-ply composite plates.

3.4.4. Optimization employing desirability function

Numerical optimization of the process parameters was performed by employing desirability function. Aim of the optimization was to maximize the residual compressive strength with minimized delamination. Desirability function of 1 is required to achieve the goal of optimization. Some best solutions with desirability function 1 are

Table 6. ANOVA and Fit Statistics for Delamination of RPUF Composite.

| Source       | Sum of Squares | df | Mean Square | F-value | p-value |
|--------------|----------------|----|-------------|---------|---------|
| Model        | 0.1873         | 8  | 0.0234      | 80.69   | <0.0001 |
| p-Density    | 0.0160         | 1  | 0.0160      | 55.20   | <0.0001 |
| v-Spindle Speed | 0.0468      | 1  | 0.0468      | 161.36  | <0.0001 |
| f-Feed Rate  | 0.0003         | 1  | 0.0003      | 0.9191  | 0.3486  |
| d-Drill Diameter | 0.0748      | 1  | 0.0748      | 257.87  | <0.0001 |
| \(V_f^2\)    | 0.0036         | 1  | 0.0036      | 12.41   | 0.0020  |
| \(\rho^2\)   | 0.0364         | 1  | 0.0364      | 125.57  | <0.0001 |
| \(f^2\)      | 0.0027         | 1  | 0.0027      | 9.31    | 0.0061  |
| \(d^2\)      | 0.0140         | 1  | 0.0140      | 48.08   | <0.0001 |
| Residual     | 0.0061         | 21 | 0.0003      |         |         |
| Lack of Fit  | 0.0035         | 16 | 0.0002      | 0.4198  | 0.9149  |
| Pure Error   | 0.0026         | 5  | 0.0005      |         |         |
| Cor Total    | 0.1934         | 29 |             |         |         |

 Std. Dev. 0.0179 R² 0.9685
 Mean 1.15 Adjusted R² 0.9565
 C.V.% 1.48 Predicted R² 0.9484
 PRESS 0.0100 Adeq Precision 32.2324

Table 7. ANOVA and Fit Statistics for Residual Compressive Strength of RPUF Composite.

| Source       | Sum of Squares | df | Mean Square | F-value | p-value |
|--------------|----------------|----|-------------|---------|---------|
| Model        | 56.14          | 11 | 5.10        | 97.20   | <0.0001 |
| p-Density    | 34.01          | 1  | 34.01       | 647.74  | <0.0001 |
| v-Spindle Speed | 5.66        | 1  | 5.66        | 107.70  | <0.0001 |
| f-Feed Rate  | 0.0651         | 1  | 0.0651      | 1.24    | 0.2801  |
| d-Drill Diameter | 4.60        | 1  | 4.60        | 87.66   | <0.0001 |
| \(V_f\)      | 1.51           | 1  | 1.51        | 28.70   | <0.0001 |
| \(F_d\)      | 2.39           | 1  | 2.39        | 45.61   | <0.0001 |
| \(V_f\)      | 0.8789         | 1  | 0.8789      | 16.74   | 0.0007  |
| \(\rho^2\)   | 4.30           | 1  | 4.30        | 81.98   | <0.0001 |
| \(\nu^2\)    | 1.76           | 1  | 1.76        | 33.61   | <0.0001 |
| \(f^2\)      | 2.29           | 1  | 2.29        | 43.52   | <0.0001 |
| \(d^2\)      | 1.37           | 1  | 1.37        | 26.13   | <0.0001 |
| Residual     | 0.9451         | 18 | 0.0525      |         |         |
| Lack of Fit  | 0.3483         | 13 | 0.0268      | 0.2245  | 0.9861  |
| Pure Error   | 0.5968         | 5  | 0.1194      |         |         |
| Cor Total    | 37.08          | 29 |             |         |         |

 Std. Dev. 0.2291 R² 0.9834
 Mean 4.08 Adjusted R² 0.9733
 C.V.% 5.62 Predicted R² 0.9664
 PRESS 1.92 Adeq Precision 35.7390
presented in table 8. It was concluded from the results that high spindle speed and low feed rate are the optimized drilling parameters to obtain maximum residual compressive strength for varied density or drill diameter.

The developed quadratic model to predict responses (thrust force, delamination and residual compressive strength) for the factor levels at which experiment is performed, are presented in the form of coded equations (1)–(3) respectively. The relative impact of the drilling factors can be identified by comparing the factor coefficients provided by these equations.

\[
\text{Thrust force (N)} = +30.10 + 8.97\rho + 3.91\nu + 0.4850f + 4.55d - 1.69\rho d \\
- 1.59\nu f + 1.56\nu d + 2.27fd + 1.30\rho^2
\]  
\[
\text{Delamination} = +1.09 - 0.0258\rho - 0.0442\nu + 0.0033f - 0.0558d \\
- 0.0150\nu f + 0.0361\rho^2 + 0.0098f^2 + 0.022d^2
\]  
\[
\text{Residual compressive strength (MPa)} = +3.15 + 1.19\rho + 0.4854\nu - 0.0521f \\
- 0.4379d + 0.3069\rho\nu + 0.3869\rho d - 0.2344\nu f + 0.3961\rho^2 + 0.2536\nu^2 \\
+ 0.2886f^2 + 0.2236d^2
\]

4. Conclusion

Rigid PU foams were prepared by incorporating copper powder to enhance the mechanical, flame retardant and thermal properties of foams and drilling experiments were performed to assess the machining ability of composite foams. Four drilling parameters, namely foam density, feed rate, drill bit diameter, and spindle speed, at five levels based on central composite design were studied. Conclusions drawn from the present investigation are as follows:

Figure 9. Response surface for the effect of drilling on thrust force.
Incorporation of copper filler enhances the compressive strength of the vegetable oil-based foam from 1.77 MPa for unreinforced RPUF to 3.83 MPa and 5% weight loss temperature increases from 192 °C to 257 °C for the 8% copper powder filled RPUF.

Cone calorimeter test demonstrates that peak heat-release rate (PHRR) is decreased up to 93 kW m$^{-2}$ and total heat release (THR) decreased up to 17.0 MJ m$^{-2}$ on the incorporation of 8% copper powder in the RPUF. Furthermore, 50% decrease in smoke production rate (SPR) and 53% decrease in total smoke release (TSR) was observed in RPUF reinforced with 8% copper powder.

It was noticed that density is the most influential factor for the optimization of residual compressive strength, while the feed rate shows a negligible effect on the responses. It is also observed that residual compressive strength increases with an increase in spindle speed.

After numerical optimization, the optimal process parameters were selected as spindle speed 914 rpm and feed rate 0.34 mm rev$^{-1}$ to maximize the residual compressive strength.

A polynomial regression model showing the impact of density, feed rate, spindle speed and drill diameter on the responses was presented in the form of coded equations.

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Conflict of interest

The authors declare that they have no conflict of interest.
Table 8. Optimized values of factors and responses after numerical optimization.

| S.no. | Density (kg m\(^{-3}\)) | Spindle speed (rpm) | Feed rate (mm rev\(^{-1}\)) | Drill diameter (mm) | Thrust force (N) | Delamination | Residual compressive strength (MPa) | Desirability function |
|-------|--------------------------|--------------------|-----------------------------|--------------------|-----------------|-------------|-----------------------------------|----------------------|
| 1.    | 387.5                    | 914                | 0.34                        | 10                 | 47.534          | 1.049       | 6.530                             | 1                    |
| 2.    | 387.5                    | 914                | 0.34                        | 6                  | 43.240          | 1.160       | 6.632                             | 1                    |
| 3.    | 302.5                    | 914                | 0.34                        | 10                 | 32.974          | 1.100       | 2.762                             | 1                    |
| 4.    | 302.5                    | 914                | 0.34                        | 6                  | 21.90           | 1.212       | 4.411                             | 1                    |

Figure 11. Response surface for the effect of drilling on residual compressive strength.

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