Experimental investigation on the machinability characteristics in drilling of syntactic foams

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Abstract. Syntactic foams (SFs) finds its application in automobiles, aircrafts and underwater vehicles. Drilling is most frequently used machining operation for assembly of these composite structures. In the present investigation, an effort is made to analyse the effect of cutting speed ($C_s$), feed rate ($f_r$), drill diameter ($D$) and filler content ($F$) on machinability characteristics in drilling glass microballoon (GMB) reinforced epoxy SFs. Machinability characteristics analyzed includes thrust force ($T_f$) and surface roughness ($S_r$). SFs are fabricated by dispersing 25, 35 and 45 vol.% of GMBs in epoxy resin. Experiments are carried out based on full factorial design (FFD) using TiAlN coated carbide drills. Experimental results show that $T_f$ and $S_r$ increases with increasing $C_s$. As $f_r$ increases, $T_f$ increases but decreases the $S_r$. Increasing GMB content significantly reduces the $T_f$ and $S_r$ of developed SFs.

1. Introduction
Lightweight materials synthesized by dispersing hollow microballoons in matrix material are called syntactic foams [1]. SFs are widely used for structural and buoyancy modules of submerged vehicle structures, where drilling holes is essential for installing various components. The quality of the drilled hole strongly depends on the input factors and their levels. Nearly 60% of composite parts are rejected due to poor hole quality which in turn substantially increasing the overall production cost [2].

Several researchers evaluated the effects of different input factors on drilling polymer composites. Studies have focused only on understanding the drilling process of fiber reinforced polymer composites (FRPC). Results shows that the increase in $C_s$, leads to increased $T_f$ in drilling FRPC and the twist drills performed better than multifacet drills [3]. Basavarajappa et al. [4] analysed the influence of $C_s$ and $f_r$ on $T_f$, $S_r$, and specific cutting coefficient in drilling of FRPC with and without silicon carbide filler. Results indicate that $f_r$ has a significant influence on $T_f$ and $S_r$. A study on the impact of $C_s$, drill geometry and $f_r$ on $T_f$, hole diameter and circularity error found that the optimum conditions were different in drilling of unreinforced and reinforced polyamides [5].

Even though a comprehensive literature on drilling of FRPC is available, drilling of syntactic foams is less explored, which is the focus of current study. In the current investigation an effort has been made to examine the influence of $C_s$, $f_r$, $F$ and drill diameter ($D$) on $T_f$ and $S_r$ in drilling of GMB/epoxy SFs using CNC vertical machining center and using coated carbide twist drills.
2. Materials and methods

2.1. Constituent materials
Epoxy resin (LAPOX L-12) and hardener (K-6) obtained from Atul Ltd., India is used as resin. Hollow GMBs (SID-350 grade) procured from Trelleborg Offshore, USA are used as fillers.

2.2. Sample preparation
SFs are prepared by dispersing 25, 35 and 45 by vol.% of GMBs. GMBs are added to the resin matrix and stirred slowly until homogeneous slurry is formed. Hardener by 10 wt.% is then added to the slurry, which is then stirred for additional 5 minutes followed by a degassing period of 5 minutes prior to pouring to the molds (ϕ 35×16 mm). Silicone gel is smeared to the mould surfaces. Specimens are cured for 24 h at room temperature.

2.3. Experimentation
In the present investigation, \(T_f\) and \(S_r\) are chosen as responses. Input process parameters (\(C_s\), \(f_r\), \(F\) and \(D\)) and their levels are chosen based on previous investigations (Table 1). Overall 27 experiments with three trials are performed for each drill diameter based on FFD (Table 2).

| Table 1. Input factors and levels |
|----------------------------------|
| Parameters | Level |
|           | 1     | 2     | 3     |
| Cutting speed (\(C_s\), m/min) | 25    | 75    | 125   |
| Feed (\(f_r\), mm/rev)          | 0.04  | 0.08  | 0.12  |
| Filler content (\(F\), %)       | 25    | 35    | 45    |

| Table 2. Experimental layout plan and measured value of responses |
|----------------------------------|
| Exp. No. | \(F\) | \(C_s\) | \(f_r\) | \(D_8\) | \(D_{16}\) |
|----------|------|--------|--------|--------|--------|
|          |      |        |        | \(T_f\)| \(S_r\)| \(T_f\)| \(S_r\)|
| 1        |      | 25     | 0.04   | 42.294 | 2.367 | 112.46 | 2.264 |
| 2        |      | 25     | 0.08   | 57.373 | 2.559 | 138.99 | 2.033 |
| 3        |      | 0.12   | 62.641 | 2.670  | 155.70| 1.961  |
| 4        | 25   | 0.04   | 39.683 | 3.248  | 113.12| 2.748  |
| 5        | 75   | 0.08   | 58.576 | 3.152  | 143.46| 2.452  |
| 6        | 0.12 | 67.659 | 3.102  | 163.99 | 2.374 |
| 7        | 0.04 | 40.341 | 3.261  | 117.05 | 2.911 |
| 8        | 125  | 0.08   | 63.050 | 3.445  | 151.20| 2.670  |
| 9        | 0.12 | 75.948 | 3.543  | 175.55 | 2.587 |
| 10       | 0.04 | 33.983 | 2.711  | 99.56  | 2.271 |
| 11       | 25   | 0.08   | 50.742 | 2.538  | 124.45| 1.982  |
| 12       | 0.12 | 54.375 | 2.324  | 139.53 | 1.851 |
| 13       | 0.04 | 34.006 | 3.211  | 99.54  | 2.695 |
| 14       | 35   | 0.08   | 51.264 | 3.081  | 128.25| 2.401  |
| 15       | 0.12 | 58.712 | 2.962  | 147.14 | 2.265 |
| 16       | 0.04 | 37.298 | 3.585  | 102.79 | 2.919 |
| 17       | 125  | 0.08   | 55.056 | 3.445  | 151.20| 2.670  |
| 18       | 0.12 | 66.320 | 3.320  | 158.02 | 2.479 |
| 19       | 0.04 | 34.210 | 2.603  | 88.57  | 2.200 |
| 20       | 25   | 0.08   | 44.859 | 2.439  | 111.83| 1.852  |
| 21       | 0.12 | 48.017 | 2.673  | 125.27 | 1.663 |
| 22       | 0.04 | 30.236 | 3.107  | 87.87  | 2.625 |
| 23       | 75   | 0.08   | 46.018 | 2.981  | 114.94| 2.272  |
| 24       | 0.12 | 51.673 | 2.914  | 132.20 | 2.078 |
Drilling experiments are performed according to FFD with coated carbide twist drills ($D_8$ and $D_{16}$) fitted on a vertical CNC machining centre (MAX MILL PLUS+, MTAB, Chennai, India). Strain gauge type of dynamometer (Syscon Instruments Pvt. Ltd., India) is used to measure the $T_f$ and $S_r$ of hole is examined using Mitutoyo surftest (SJ 301, Japan). Input factors ($I$) and their levels ($L$) are coded together as $I_L$. For example, $C_{s25}$ represents 25 m/min cutting speed.

3. Result and discussion

3.1. Analysis of thrust force

![Figure 1](image1.png)

**Figure 1.** Effect of (a) $C_s$ and $f_r$, (b) $F$ and $C_s$ and (c) $f_r$ and $F$ on $T_f$ for $D_8$.

![Figure 2](image2.png)

**Figure 2.** Effect of (a) $C_s$ and $f_r$, (b) $F$ and $C_s$ and (c) $f_r$ and $F$ on $T_f$ for $D_{16}$.

Experimentally measured values of $T_f$ are presented in Table 2. The variation of $T_f$ with $C_s$ at different $f_r$, for $D_8$ and $D_{16}$ are shown in Figure 1a and Figure 2a respectively. $T_f$ increases with increasing cutting speed and feed. Increased tool wear at higher $C_s$ might result in such an observation [3]. $T_f$ as a function of $F$ and $C_s$ for $D_8$ and $D_{16}$ are shown in Figure 1b and Figure 2b respectively. $T_f$ decreases with increasing $F$, while increases with increasing $C_s$. Decrease in $T_f$ is due to the increased brittle behaviour of the SFs and also the presence of void inside GMBs. Figure 1c and Figure 2c shows the increasing $T_f$ with increasing $f_r$, while decreases with increasing $F$ for $D_8$ and $D_{16}$ respectively. As $f_r$ increases resistance offered by the SFs increases leading to increased friction between tool and SFs resulting higher $T_f$ [4, 6].
3.2. Analysis of surface roughness
Surface roughness increases with increasing cutting speed for both $D_8$ and $D_{16}$ as shown in Figure 3a and Figure 4a respectively. Heat increases at the drill and SFs interface with increasing $Cs$ leading to rough surface [7, 8].

![Figure 3a](image-url)

**Figure 3a** Effect of $Cs$ and $fr$, (a) $F$ and $Cs$ and (c) $fr$ and $F$ on $Sr$ for $D_8$.

![Figure 3b](image-url)

**Figure 3b** and **Figure 4b** shows decrease in $Sr$ with increasing $F$, while increasing trend is observed with increasing $Cs$. Decrease in $Sr$ with increasing $F$ is owing to the burnishing and honing effect produced by abrasive fillers [4]. Additionally, lower $T_f$ with increased $F$ results in reduced $Sr$ [7, 9]. The variation of $Sr$ with $fr$ and $F$ for $D_8$ and $D_{16}$ are shown in Figure 3c and Figure 4c respectively. $Sr$ decrease with increasing $F$ and $fr$. At higher $fr$, temperature decreases due to reduced contact time between tool and SFs leading to lower $fr$ [8].

3.3. Influence of drill diameter on responses

![Figure 4a](image-url)

**Figure 4a** Effect of (a) $Cs$ and $fr$, (b) $F$ and $Cs$ and (c) $fr$ and $F$ on $Sr$ for $D_{16}$.

![Figure 4b](image-url)

![Figure 4c](image-url)

**Figure 4b** and **Figure 4c** shows decrease in $Sr$ with increasing $F$, while increasing trend is observed with increasing $Cs$. Decrease in $Sr$ with increasing $F$ is owing to the burnishing and honing effect produced by abrasive fillers [4]. Additionally, lower $T_f$ with increased $F$ results in reduced $Sr$ [7, 9]. The variation of $Sr$ with $fr$ and $F$ for $D_8$ and $D_{16}$ are shown in Figure 3c and Figure 4c respectively. $Sr$ decrease with increasing $F$ and $fr$. At higher $fr$, temperature decreases due to reduced contact time between tool and SFs leading to lower $fr$ [8].

![Figure 5a](image-url)

![Figure 5b](image-url)

**Figure 5** Influence of drill diameter on (a) $T_f$ and (b) $Sr$ at different filler content.
Figure 5a shows the effect of increasing $D$ at different $T_f$ on the $T_f$ developed in drilling GMB/epoxy SFs. It is observed that the $T_f$ increases by 2.5 times with increasing $D$ from $D_8$ to $D_{16}$. As $D$ increases, the contact area of the drilled hole increases leading to higher $T_f$ [10, 11]. Increasing $D$ from $D_8$ to $D_{16}$ decreases the $S_r$ of the drilled hole as shown in Figure 5b. $S_r$ decreases by 17.84 and 26.88% with increasing $D$ for $F_{25}$ and $F_{45}$ respectively. At any given $C_s$, $D_{16}$ has a lower spindle speed than $D_8$ which results in lower $S_r$ [7, 12].

From experimental investigation it is confirmed that GMB content strongly impacts machinability characteristics of SFs. Higher filler percentage is preferred in the SFs from drilling operations perspective, which is also beneficial for weight sensitive applications.

Conclusions

GMB/epoxy SFs are studied for drilling characteristics, such as $T_f$ and $S_r$. $C_s$, $f_r$, and $F$ are varied at different levels to measure the responses. The effect of each variable on machinability characteristics are analyzed and presented. The following conclusions are drawn based on the experimental investigation:

- Increase in $C_s$, $f_r$, and $D$ increases $T_f$ while decreasing trend is obtained with increasing GMB content.
- Minimum $T_f$ is observed at a combination of $C_{25F_{10}D_8}$.
- $S_r$ increases with increasing $C_s$ but decreases with the increase in $f_r$, $F$ and $D$.
- $S_r$ is found to be minimum at a combination of $C_{25F_{10}D_{16}}$.
- Increasing GMB content from $F_{25}$ to $F_{45}$ reduces $T_f$ and $S_r$ by 20.92 and 3.92% respectively.
- SFs with high GMB content exhibits better machinability in terms of $T_f$ and $S_r$.

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