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Machinability Study of Syntactic Foams

Ashrith H S[1]1, Mrityunjay Doddamani[1], V N Gaitonde[2], Nikhil Gupta[3]

[1]Advanced Manufacturing Laboratory, Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, 575025, INDIA

[2]Industrial and Production Engineering, BVB College of Engineering and Technology, Hubli, Karnataka, INDIA

[3]Composite Materials and Mechanics Laboratory, Mechanical and Aerospace Engineering Department, Tandon School of Engineering, New York University, Brooklyn, NY 11201, USA

Abstract

In the present study thrust force during drilling of glass microballoon/epoxy syntactic foams is investigated. Syntactic foams are prepared using 20, 40 and 60 vol.% glass microballoonfillers in epoxy matrix.The microballoons have an average 45 µm diameter and 1.09 µm wall thickness. The drilling experiments are performed as per full factorial design using solid carbide drills on vertical machining center. The response surface methodology (RSM) based models are developed for analyzing the effects of cutting speed, feed, drill diameter and filler content on thrust force. With increasing speed, feed and drill diameter the thrust force is observed to increase. With increasing filler content thrust force is found to decrease by 37.73%. The RSM analysis reveals that addition of glass microballoons in epoxy resin considerably decreases the thrust force during drilling of developed syntactic foam composites.

Keywords:Glass microballoon, syntactic foams, response surface methodology, thrust force.

1. INTRODUCTION

Lightweight composite material developed by embedding stiff shell hollow particles in a matrix resin is called syntactic foam (SF)[1]. These closed cell foams are widely used in automobile, aerospace and marine sectors owing to their unique properties like, low density, high compressive strength, low moisture absorption, low coefficient of thermal expansion and dimensional stability at elevated temperatures [2].Glass microballoons (GMB) and cenospheres are commonly used fillers in the fabrication of syntactic foams. But in cenospheres due to the presence of defects such as surface irregularities, wall porosityand non-uniform wall thickness, high quality engineered GMB are preferred in SF fabrication [2].

Drilling of SF is quite different as the tool has to pass through matrix and fillers having different properties[3].Also, the presence of highly abrasive fillers and poor thermal conductivity of composite materials leads to high tool wear and poor surface finish.Further material removal is complex too due to thevariable resistance offered by SF constituents.Even though the composites are produced to near net shapes, an additional machining operation like drilling is essential for partassembly [4]. Drilling is inevitable in assembly operations specifically in lightweight structures.Several researchers investigated the effects of different process parameters on polymer composites drilling and are briefly discussed herewith.

Basavarajappa et al.[4]studied the effect of different process parameter on machinability characteristics duringdrilling of glass epoxy and silicon carbide filled glass epoxy composites using thefull factorial design (FFD) of experiments. Gaitonde et al.[5]investigated the effect of spindle speed and feed on machinability and hole quality in drilling of polyamides. In this, the experiments are conducted using FFD and RSM based models are generated to analyze the effects of process parameters. Krishnaraj et al.[6]used cemented carbide twist drills to analyze the effect of spindle speed and feed on hole quality in drilling thin CFRP and found feed is having more influence on thrust force than spindle speed. The effect of spindle speed, feed and drill diameter on thrust force and surface roughness in thedrilling of glass fiberepoxy composites is analyzed by Palanikumar et al.[7].From the above literature, it is revealed that the feed is the most influential process parameter affecting the thrust force followed by drill diameter.

From the existing literature, it is found that the machinability characteristics of polymer matrix composites are extensively studied. But the machinability characteristics of syntactic foam during drilling are unknown. Hence, an attempt has been made to investigate the effect of process parameters namely cutting speed (V), feed (f), drill diameter (D) and filler content (R) on thrust force (F_t) in drilling of glass microballoon/epoxy syntactic foam. Experiments are performed based on FFD using Maxmill plus vertical machining center. Based on the experimental results, second order mathematical model of the response has been developed using RSM to analyze the effect of different process parameters. Analysis of variance (ANOVA) is used to check the adequacy of the developed mathematical model.

2. RESPONSE SURFACE METHODOLOGY

RSM is used for building the mathematical model to optimize an output response which is influenced by several input parameters. Design of experiment (DOE) is used to develop the model of the required response with minimum number of experiments. The model in terms of input parameters can be written as [8],

$$Y = \varphi(x_1, x_2, x_3, ...x_x) \quad (1)$$

where Y: response, x_1, x_2, x_3,……x_k: input variables and φ:response function

3. MATERIALS AND FABRICATION

[1]Ashrith H S, Email: ashuhiriyal@gmail.com

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SF'sare fabricated using epoxy matrix (LAPOX L-12) and polyamine hardener (K-6), both procured from Yuje Marketing, Bengaluru.GMB fillers of grade SID-350 are procuredfrom Trelleborg, USA and are used in the asreceived condition.

Samples arecastusing 20, 40 and 60 vol.% GMB. A measured quantity of epoxy resin is taken in a beaker to which GMB is added and stirred gently. Hardener is added to the mixture and stirred to getuniform slurry. The slurry is cast into molds of dimension Φ35×16 mm and allowed to cure for 24 hours at room temperature. Silicone releasing agent is applied on molds prior to sample casting for easier removal of coupons.

4. EXPERIMENTAL DETAILS

4.1. Planning of Experiments

A careful planning of experiments is required to develop the mathematical models based on RSM, which reduces the number of experiments [8]. In this investigation, V, f, D,and R are considered as drilling process parameters. Three levels are selected for each of the process parameters for theinitial study. Based on FFD81 experiments are planned. Process parameters and their levels are listed inTable 1.

Table 1:Process parameters and their levels for syntactic foams

Parameters	Levels		
	1	2	3
Spindle speed (V), m/min	25	75	125
Feed (f), mm/rev	0.04	0.08	0.12
Drill diameter (D), mm	8	12	16
Filler content (R), %	20	40	60

4.2. Experimentation

Experiments are conducted using a Maxmill plus vertical machining center. The CNC machining center is equipped with a maximum spindle speed of 9000 rpm with 7.5 kW of power. SF samples are rigidly fixed to the fixture.Coated tungsten carbide twist drills of diameter 8, 12 and 16 mmare used to conduct the drilling experiments. Drilling dynamometer is used to measure thrust force during thedrilling process.Average of three samples is reported for analysis. The measuredvalue of the response at different filler content ispresented in Table 2.

4.3. Development of Mathematical Models

Cutting speed, feed, drill diameter and filler content are independent variables while thrust force is considered as adependent variable in the present investigation. Multiple levels for each process parameter are selected for investigation. Second order mathematical model based on RSM is generatedto findthe effects of process parameter on thrust force. Mathematical model based on RSM is developed using [8],

$$Y = b_0 + b_1 V + b_2 f + b_3 D + b_4 R + b_{11} V^2 + b_{22} f^2 + b_{33} D^2 + b_{44} R^2 + b_{12} Vf + b_{13} VD + b_{14} VR + b_{23} fD + b_{24} fR + b_{34} DR \quad (2)$$

where Y is the desired response and b_o, b_1,… b_{34} are the regression coefficients to be determined. The regression coefficients of the quadratic model are determined by[8],

Table 2: Experimentally measured F_t for different V, f, D and R

Process parameters			F_t (N)		
V (mm/min)	f (mm/rev)	D (mm)	20 vol%	40 vol%	60 vol%
25	0.04	8	29.43	29.43	19.62
		12	58.86	58.86	39.24
		16	117.72	78.48	68.67
	0.08	8	49.05	39.24	29.43
		12	78.48	58.86	49.05
		16	147.15	107.91	88.29
	0.12	8	58.86	49.05	29.43
		12	98.1	78.48	58.86
		16	156.96	117.72	88.29
75	0.04	8	29.43	29.43	19.62
		12	68.67	49.05	29.43
		16	107.91	68.67	58.86
	0.08	8	49.05	39.24	29.43
		12	98.1	68.67	58.86
		16	137.34	107.91	98.1
	0.12	8	58.86	49.05	39.24
		12	98.1	78.48	58.86
		16	166.77	127.53	107.91
125	0.04	8	39.24	19.62	9.81
		12	78.48	49.05	39.24
		16	107.91	78.48	68.67
	0.08	8	58.86	39.24	29.43
		12	78.48	68.67	58.86
		16	166.77	117.72	98.1
	0.12	8	88.29	49.05	39.24
		12	98.1	88.29	68.67
		16	176.58	147.15	107.91

$$B = \left(X^T X\right)^{-1} X^T Y$$

(3) where B is amatrix of parameter estimates, X is calculation matrix, which includes linear, quadratic and interaction terms, X^T is thetranspose of X and Y is amatrix of response. The mathematical models determined by regression analysis to predict thrust force in drilling of syntactic foam is given by

$$F_t = 16.48 - 0.22 \times V + 513.20 \times f - 0.084 \times R - 2.65 \times D + 1.90 \times V \times f - 1.36 \times 10^{-3} \times V \times R + 8.17 \times 10^{-3} \times V \times D - 4.08 \times f \times R + 35.76 \times f \times D - 0.09 \times R \times D + 6.54 \times 10^{-4} \times V^2 - 3065.62 \times f^2 + 9.53 \times 10^{-3} \times R^2 + 0.51 \times D^2 \quad (4)$$

where, V is expressed in m/min, f in mm/rev, D in mm, R in vol.%, F_t in N.

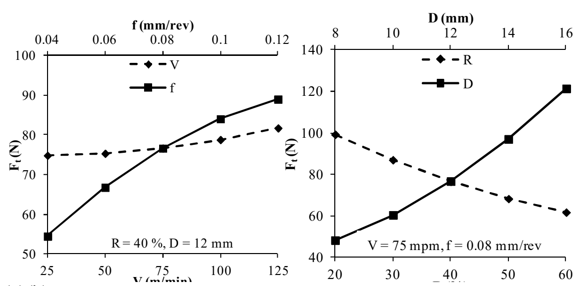
5. RESULTS AND DISCUSSIONS

5.1. Adequacy Checking of Machinability Models

Adequacy of the developed mathematical of thrust force is tested using ANOVA. As per ANOVA, the calculated value of F-ratio of the model should be more than the F-table of the model. The summary of the ANOVA results of the developed model is presented in Table 3.The comparison between the experimental and predicted values of thrust force shows that a close relationship exists between both the values and the average error is found to be 0.70%. Hence, the developed mathematical models can be used to predict the thrust force during drilling of syntactic foams.

Table 3: Summary of ANOVA results and coefficient of determination (CoD) values of the regression model.

Responses	Sum of squares		Degrees of freedom		Mean square		F-ratio	CoD
	Regression	Residual	Regression	Residual	Regression	Residual		
Thrust force	1.1408×10^5	3285	14	66	8148.56	49.78	163.70[a]	0.9720
[a]F-table = 2.36. Significance at 99 % confidence interval.								



(a)(b)

Fig. 1. The trend of F_t with respect to individual parameters estimated by the model: (a) V and f and (b) R and D

5.2. Parametric Analysis on Thrust force

5.2.1. Effect of Individual Parameters:

The regression equation is used to predict thrust force during drilling by substituting the values of V, f, D,and R to identify the parameter that has the most dominant influence on the response. This is achieved using the regression equation by varying one parameter at a time and keeping the otherparameters at the middle level. The result of this parametric study is presented in Fig. 1. These graphs can be used as a quick reference to understand the general trends between various parameters.

It is observed fromFig. 1(a) that the thrust force marginally increases with increasing Vwhile rapidly increases with the higherf. This indicates that the feed has a greater influence on thrust force than cutting speed in drilling SF composites. Fig. 1(b) shows thrust force increases with increasing D and decreases with increasing R. With increasingR thrust force is found to decrease by 37.73%.

5.2.2. Effects of Two-Parameter Interactions:

The regression equation is used to develop the interaction plots as presented in Fig. 2. These graphs are drawn considering two parameters at a time, whereas the other two parameters are kept at the middle value. The matrix used to study the twoparameter interaction effects in drilling SF's is given in Table 4.

Table 4: Two-way interaction parameters used to study thrust force in drilling syntactic foams.

Interaction	
Parameter 1	Parameter 2
V	D, f, and R
f	D and R
R	D

Fig. 2 shows the interaction effect of process parameters on thrust force during the drilling process.

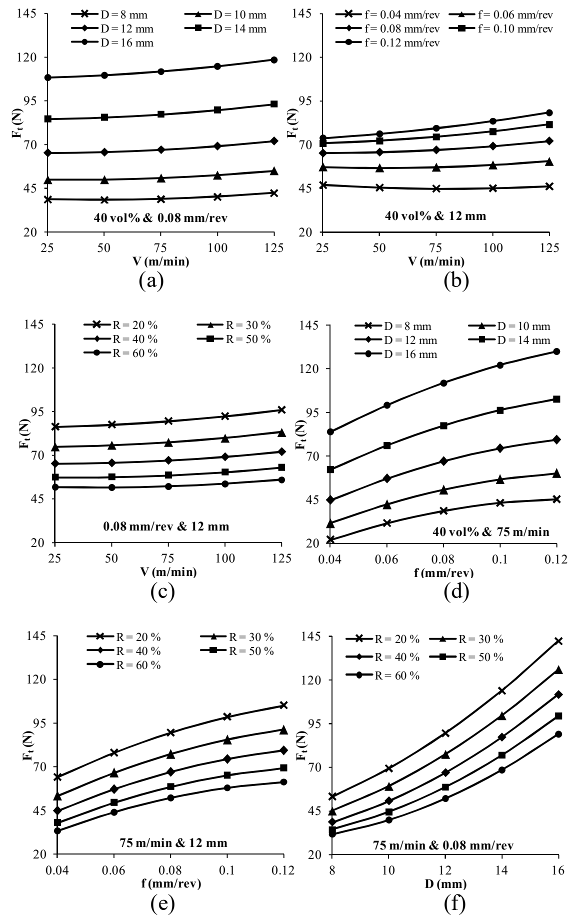


Fig. 2. Variation of $F_t$with respect to V for different (a) D, (b) f and (c) R. F_t with respect to f at different (d) D and (e) R. (f) F_t with respect to D at different R.

Fig. 2(a)-2(c) shows the variation of thrust force with V at different D, f and R respectively. The thrust force increases with increasing V. Increasing V accelerates tool wear, which in turn increases the thrust force [9]. Increasing speed increases the strain hardening of workpiece and hence increases the deformation resistance of shear area, which leads to the increased thrust force[10]. Increasing the V from 25 – 125 m/min, increases thrust force by 9.48 and9.41% for 8 and 16 mm diameter drills respectively. From these values, it is clear that parameter V is having negligible influence on thrust force.

The variation of thrust force with f at differentV, D, and R is presented in Fig.2(b), 2(d) and 2(e) respectively. Thrust force increases with the increasing f at any given value of V, D and R.Low feed rate the workpiece is subjected to low strain rates[11]. At low strain rates more mechanical energy is converted into heat leads to increased temperature of syntactic foams assisted by poor thermal conductivity of foams[12]. The heat generated softens the matrix material resulting reduced thrust forces[11].Also, at high feed rates the material removal rate increases because of the increased contact area between tool and SF, which in turn leads to high thrust forces[4]. Increasing the feed from 0.04 - 0.12 mm/rev, the thrust force increases by 57.59 and 91.70 %for 25and 125 m/min cutting speed respectively.

Fig. 2(a), 2(d) and 2(f) shows the variation of thrust force with D at different V, f, and R respectively. Thrust force is observed to be increased with increasing D at all levels of V, f and R. As the drill diameter increases from 8 to 16 mm, cross-sectional area of undeformed chip (A=D×f/4) increases. Increase in cross-sectional area increases the resistance of chip formation resulting increased thrust forces [13].

Fig. 2(c) andFig. 2(e)-2(f) shows the variation of thrust force with R. The thrust force decreases with the increasing R.Increasing glass microballoon content increases the brittle behaviour of the syntactic foam resulting reduced thrust forces [14]. Also increasing filler content decreases the strength of syntactic foam which may reduce the thrust force generated during drilling [15].

From above discussion on thrust force, it is seen that increasing filler content significantly reduces thrust force in drilling syntactic foams.

6. CONCLUSIONS

Syntactic foams are fabricated with 20, 40 and 60 vol.% of GMB and machinability characteristics are analyzed using FFD of experiments. Effect of each variable and interaction between two variables are studied using RSM based mathematical models. The results show that

- Thrust force increases with the increase in feed and drill diameter but decreases with the increase in the filler content.
- At given feed, drill diameter and filler content, the variation of thrust force with the increase in cutting speed is very less.
- Minimum thrust force (9.82 N) is observed at high speed, low feed, small drill diameter and high filler content.
- Syntactic foams with high filler content (60 vol.%) provides better machinability.

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