Evaluation of Thrust force in Drilling Woven roving Glass fibre reinforced Aluminium Sandwich laminates with TiAlN coated drill using Taguchi analysis

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Abstract: TiAlN is a high-performance coating which outshines in coarse and hard-to-machine materials like cast iron, aluminium alloys, tool steels, and nickel alloys. This paper presents the prediction and evaluation of thrust force and Torque in drilling of Woven roving Glass Fibre Reinforced Plastic and Aluminium sandwich laminate. The Prediction is based on Taguchi method. The experimental results specify that the feed rate and the drill diameter are the most significant factors affecting the thrust force, while the feed rate and spindle speed contribute the most to the surface roughness. In this study, the objective was to establish a correlation between the feed rate, spindle speed and drill diameter with the induced thrust force and Torque in drilling sandwich laminate.

Keywords: Thrust force measurement; Sandwich Laminate; Fibre metal laminates; Drilling; Taguchi analysis

1. INTRODUCTION

Fibre metal laminates are well known for their fatigue resistance and damage tolerance properties. After its successful utilization in Fuselage of Airbus A380, it attracted many researchers world-wide to study its characterisation in various application fields. Drilling is a primary machining operation for assembly of these fibre metal laminates for structural applications. Reducing thrust force and torque reduces the delamination. Therefore it is more essential to reduce thrust force and torque to improve the quality of hole produced. Palanikumar analysed the models of comparable nature made of carbon fiber composites where the size of the delamination region has been revealed to be associated to the thrust force developed during the drilling process and the value of critical thrust force is also observed[1]. Mohan et al diagnosed that speed and drill diameters are the more significant parameters on thrust force than the specimen thickness and the feed rate. Highest speed on the lowest specimen with the smallest drill size and lowest feed rate are the best combination that produces lowest thrust force [2]. There have been many research developments are going on for optimizing the cutting parameters to get the better productivity in drilling process, For these reasons there have been research developments with the objective of optimizing the cutting conditions to obtain a better productivity in drilling process. Ghani et al. used a same approach using Taguchi’s method in end milling to optimize the cutting parameters. Thrust force of Core drill made of diamond is
experimentally investigated in drilling carbon fiber reinforced plastic by Tsao [4], the result shows that the large grit size of diamond, minimum thickness of core drill, lower speed and feed produced minimum thrust force. Wu [5] employed the multifaceted drills to minimize thrust force induced in drilling operation. Mathew et al investigated the thrust force and torque developed while trepanning tool is used for drilling glass fibre reinforced plastic [6]. Julian et al studied the impact of workpiece constituents and cutting speed on the forces induced in drilling CFRP made of three different combinations of resins and two types of woven carbon fibre fabrics [7]. Davim et al investigated the impact of cemented carbide drill geometry, cutting speed and penetration rate on the thrust force in drilling glass fibre reinforced plastic. The result proved that spur geometry of cemented carbide drill exhibited less thrust force compared with 118º point angle. From ANOVA data analysis it is proved that cutting pressure gets reduced with increasing penetration speed and it becomes highest significant factor among the other factors considered to affect both the cutting pressure and thrust force developed during drilling [8]. Basavarajappaa et al discussed the effect of spindle speed, feed rate on feed force developed in drilling hybrid metal matrix composites, the composite is made by stir casting. The effect of these cutting parameters on burr height and surface finish is also studied, the Taguchi analysis is employed to analyse the datas and it is revealed that the output is greatly influenced by the feed rate that the speed [9] Many adverse damages like delamination, fibre pull outs produced during drilling reduce the fatigue strength of composite laminates thereby reducing its durability,[10] Davim et al. [11,12,13], Sardinas et al. [14] observed that cutting speed has more effect on delamination during conventional drilling of composite laminates. All the structures in metallic materials respond in a same manner under machining loads and conditions, whereas composite laminates having anisotropic structures behave in a different manner at different locations of its structure based on the application of load. This variation may lead to defects like delamination. The thrust force produced during drilling is one of main indexes to define machinability of composite laminates due to the fact that it directly affects the quality of drilled holes, especially delamination [15]. There is a critical value for thrust force which is believed to exist below which no delamination occurs [16]. In this paper, the sandwich laminate of 5 layers is made with alternating layers of aluminium and glass fibre mat and its drilling characteristics are studied and analysed using Taguchi method.

2. METHODS AND MATERIALS

The metal used for the current study is Aluminium 1050 which is a popular grade of aluminium for all-purpose sheet metal work where moderate strength is required. Alloy 1050 has excellent corrosion resistance, high ductility and highly reflective finish. WRM mat of GFRP is selected for its excellent flexural strength. The sandwich laminate is fabricated by Hand-Layup process. The Aluminium sheet of grade AA 1050 H14 of 1.2mm thickness is used in this study, for making the sandwich laminate with Glass fiber of Woven roving mat. The sandwich laminate consists of 5 layers in which the Aluminium forms the top, middle and bottom layers. Glass fibre mat are placed in between the aluminium sheets. The Aluminium sheets are uniformly roughened on both sides using a very fine emery paper. Woven Roving mats (WRM) made of E-Glass fibre are also cut to the specimen shape. The Epoxy resin (LY 556) and hardener (Aradur HY951) are mixed in the ratio of 10:1 by weight respectively. The mould on which the layers are to be placed is coated with wax. Aluminium sheet is placed on the wax coating, resin mixture is applied over the roughened Aluminium surface. Woven Roving mat is placed over the coating. The above steps are repeated for next three layers. Now the mould is closed by a wax coated acrylic sheet. Weights are placed over it to get a uniform pressure while curing. Excess resin oozed out is wiped. The hybrid laminate is taken out of the mould and epoxy paste sticking on the sides is cleaned. The fabricated Sandwich laminate is cut to a size of 100mmX50mm for so that it can be fit into the fixture provided experimental setup. The thrust force is measured using the Kistler dynamometer which is placed just below the fixture. The prepared specimen for the measuring the thrust force is shown in figure 1.
The drill bit selected for this study is Titanium Aluminum Nitride (TiAlN) coated drill of 6mm, 8mm and 10mm diameters, which is shown in Figure 2. TiAlN coating is applied where heat resistance and extra hardness is required for machining abrasive materials. Aluminium oxide layer formed gives better tool life. This coating is mainly selected where no coolant or little coolant is being used for machining; TiAlN has a high surface hardness with a coefficient of friction less than Titanium Nitride (TiN). TiAlN is a high-performance coating which outperforms in drilling materials like cast iron, aluminum alloys, tool steels, and nickel alloys.

### 3. EXPERIMENTAL SETUP

Drilling process is carried out in a SIEMENS CNC Vertical Machining Center using TiAlN coated drill of 3 different diameters 6mm, 8mm and 10mm. The machining parameters such as speed and feed are varied and their ranges are shown in Table 1. The thrust forces during drilling were measured using a Kistler type piezoelectric dynamometer and the signal was transmitted and converted by a Kistler type controller unit and recorded on a personal computer. Each test was repeated twice and the average is taken for discussion. The experimental setup is shown in the figure 3.

| Input Parameters for Drilling Operation |
|----------------------------------------|
| A:Diameter (mm) | B:Feed (mm/min) | C:Speed (rpm) |
| 6          | 100            | 1000          |
| 8          | 200            | 2000          |
| 10         | 300            | 3000          |

**Figure 1. GFRP/Al Sandwich Laminate Specimen**

**Figure 2. TiAlN Coated drills**

**Figure 3. Experimental Setup**

**Table 1. Drilling input parameters**
After the drilling operation is done for each set of input variables, the chips are removed and the workpiece is removed from the fixture. The thrust force and torque developed during the drilled are analysed.

4. RESULTS AND DISCUSSION

Drilling of sandwich panels is different than drilling of monolithic materials as drill passes through alternate fibre and metal layers which have different properties. The variation in the properties of the constituents of composite materials makes difficult in understanding the mechanism of the material removal rate. During drilling of sandwich laminates the uneven load distribution between the fibre and metal layers leads to series of fractures. The thrust force and torque developed in the drilling operation influence much on the size of the delamination. There is also a critical value for the thrust force below which damage does not occur. Drilling induced damages are mainly due to these forces. Torque is associated to the feed rate, higher the value of feed rate higher will be the torque and high torque may also reduce the tool life.

Response Surface Methodology is used to analyse the effect of drilling parameters on thrust force and torque. Design Expert software is used to check the significant factors. Orthogonal array of $L_{27}$ is used to design the experiments. The fig. 4 shows clearly the ANOVA table for the Thrust Force, it denotes the model is significant. The parameters $A$ and $C$ are the most significant on thrust force. Value of ‘Prob>F’ less than 0.05 denotes the factors are significant which is shown in the fig. 4. In this case, $A$, $B$, $C$, $A^2$, $C^2$ and $AC$ are significant model terms. Values greater than 0.1 indicates the non-significant factors, i.e., the parameters, Drill Diameter, Spindle Speed and Feed rate and the interaction between Diameter and Feed rate affects the thrust force developed.

| Source  | Sum of Squares | DF  | Mean Square | Value | F       | Prob>F |
|---------|----------------|-----|-------------|-------|---------|--------|
| Model   | 7.745E+005     | 9   | 86056.18    | 124.92| < 0.0001| significant |
| A       | 1.700E+005     | 1   | 1.700E+005  | 259.78| < 0.0001|
| B       | 1.169E+004     | 1   | 1.169E+004  | 16.50 | 0.0007  |
| C       | 4.987E+004     | 1   | 4.987E+004  | 725.97| < 0.0001|
| $A^2$   | 1.498E+004     | 1   | 1.498E+004  | 21.00 | 0.0002  |
| $B^2$   | 1.294E+003     | 1   | 1.294E+003  | 12.01 | 0.0007  |
| $C^2$   | 3.922E+003     | 1   | 3.922E+003  | 14.40 | 0.0004  |
| $AB$    | 8.72E+002      | 1   | 8.72E+002   | 0.56 | 0.3146  |
| $AC$    | 3.907E+002     | 1   | 3.907E+002  | 36.62 | < 0.0001|
| $BC$    | 9.235E+001     | 1   | 9.235E+001  | 7.742E+005| 0.9931 |
| Residual| 1.1711.07      | 17  | 88.18       |       |         |
| Cor Total| 7.862E+005   | 26  |             |       |         |

The Model F-value of 124.92 implies the model is significant. There is only a 0.01% chance that a “Model F-value” this large could occur due to noise.

Figure 4. ANOVA generated by the Design Expert software for the response ‘Thrust Force’
Figure 5. ANOVA generated by the Design Expert software for the response ‘Torque’

The fig. 5 shows clearly the ANOVA table for the Torque, the effects are almost same as that of thrust force, the parameters drill dia and feed are more significant on Torque. Value of ‘Prob>F’ less than 0.05 denotes the same in the table of fig 5, the interaction between Diameter and Feed rate also affects the torque.

The surface plot can help to visualize the response surface. These are used to promote the required response values and working conditions. The surface plots displays how a thrust force and torque relates to two factors based on model equation. The surface plot shows only two variables, the third variable is kept as constant.

The 3D surface plot generated by the Design Expert software showing the interactions between the parameters affecting Thrust Force is shown in the fig. 6 which denotes that the higher the feed rate and diameter the higher will be the thrust force value, where on the other hand higher the spindle speed lower will be the thrust force. Fig 6 [a] shows the interaction between feed rate and diameter affecting thrust force, fig 6[b] shows the interaction between feed and spindle speed and fig 6[c] shows the interaction between spindle speed and diameter.

The three dimensional surface plot shown in fig. 7 is the interaction between parameters that is affecting torque. It is clearly visible that torque is most affected by feed rate and it increases with the increase in feed rate and drill diameter, whereas it decreases slightly with the increase in speed. Therefore feed rate and drill diameter have high influence on the thrust force and torque. Fig 7 [a] shows the interaction between feed rate and diameter affecting thrust force, fig 7[b] shows the interaction between feed and spindle speed and fig 7[c] shows the interaction between spindle speed and diameter.
Figure 6. 3D surface plot between the parameters affecting Thrust Force
[a] Interaction between feed rate and diameter  [b] Interaction between feed and spindle speed  
[c] Interaction between spindle speed and diameter

Figure 7. 3D surface plot between the parameters affecting Torque
[a] Interaction between feed rate and diameter  [b] Interaction between feed and spindle speed  
[c] Interaction between spindle speed and diameter
Scanning Electron microscopy of drilled surface is shown in fig. 8, the surface roughness of the drilled portion is clearly visible in fig. 8[a], it shows the fibres which are uncut during drilling operation, the broken resin particles are also spread over the surface wrecks the surface finish of the hole produced, higher the spindle speed, the finer the surface finish, this is due to the reason that at higher speed the thrust force produced is less. Fig. 8[b] shows traces of the initiation of delamination of the layers, but the surface finish of the hole produced at low feed is comparatively better compared with surface produced at high feed.

![Figure 8: Scanning Electron Microscopy of Drilled portion of Sandwich panel](a) Surface produced at high feed and low speed (b) Surface produced at low feed and high speed

5. CONCLUSION

An experimental and Taguchi based analysis for thrust force and torque associated with various input parameters in drilling of sandwich laminate is presented in this paper. The following conclusions are drawn from the above analysis:

- 10mm drill offers the highest drilling thrust force compared with other drills.
- The two major cutting parameters affecting thrust force is the diameter and feed rate.
- The thrust force increases with increase in diameter and feed rate.
- Within the selected cutting range, the combination of high diameter (6 mm), low feed rate (100 mm/min) and high speed (3000 rpm) would be the best experimental conditions when drilling laminates.
- Scanned Electron Microscopy images show that uncut fibres occurs in hole produced at high feed rate and low spindle speed.
- 6mm diameter hole surface quality is better than the 10mm diameter hole surface due to the fact that the thrust force experienced is more, which indicates that the thrust force has more effect on the hole surface.

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