Evaluation of delamination damage and surface roughness in end milling flax fibre composites

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Abstract. Flax fibre reinforced composites have been very attractive in numerous applications such as wall and automotive panels. With chemical treatments and modifications, their mechanical competent can be at par with the existing synthetic fibre composites. The flax fibre composites are normally fabricated to near-net shape, but very often these composites require a secondary cutting process such as milling to attain final geometrical and dimensional tolerances. Due to the continuous contact of the milling tool on the composite material during cutting process, several undesirable damage such as delamination, matrix cracking, fibre pull-out; existed which may lead to deterioration of their mechanical strength. In this study, parametric effects of milling parameters, namely: feed rate, spindle speed, and number of end mill flutes on delamination damage and surface roughness, were investigated. Taguchi L18 orthogonal array was used to design the experimental plan. Signal to Noise (S/N) ratio and response tables were implemented to analyse the experimental data. It was found that spindle speed and feed rate had equal effects on delamination damage and surface roughness, whereas the number of end mill flute had a marginal influence on the aforementioned machining outputs.

1. Introduction
Natural fibres are substances which are derived from plants and animals. These fibres can be spun into filament, thread or rope and further weaved into woven, knitted, matted or bound types. In recent years, natural fibres have been widely used as reinforcement materials in many types of polymer matrices [1]. Apart from having competitive mechanical properties, these fibres are 100% sustainable compared to their synthetic fibre counterparts. Hence, the application of these natural fibres for polymer composites have been increasing and becoming as an alternative or substitute for the conventional composite materials made from synthetic fibres such as E-glass and carbon fibres. Among many types of natural fibres, the use of flax fibres as reinforcement in polymer composites has gained popularity due to their high lignocellulosic contents [2]. This characteristic leads to decent mechanical properties that are comparable to that of the synthetic fibre reinforced composites.

It is widely known that the fabrication technique for the natural fibre composites follows the same approach as to that of synthetic fibre composites. Very often, these composites are fabricated near to the final shape, i.e. close to the finished product and as different assembly parts [3]. Due to this, machining operations are commonly employed to meet dimensional, design tolerance and
assembly requirements. End milling is one of the machining practices highly employed as integral parts for composite manufacturing sequences. However, due to the continuous contact of the milling tool on the composite material during cutting process, several undesirable damage such as delamination, matrix cracking, fibre pull-out; existed [4]. Delamination is failure in a laminated material due to the separation of the layers of fibre reinforcement or fibre plies. Delamination failure that is due to machining process can be of several types, such as, fracture within the adhesive or resin, fracture within the reinforcement or debonding of the resin from the reinforcement. A number of factors govern the extent of end milling-induced damage in fibrous composite materials, which include cutting parameters, geometry and diameter of the tools, and also their material types [5]. Some studies in milling of natural fibre composites existed and recommended a low feed rate and a high cutting speed for reduction of delamination [6]. However, due to variations in the mechanical properties of natural fibre composites, inconsistent results were reported with respect to the milling induced delamination damage on the natural fibre composites in the prior experimental studies [6-7]. Therefore, in this paper, the main effects of end milling parameters such as cutting speed, feed rate and end mill flute on the delamination and surface roughness are studied through statistical analyses. Wide range of milling parameters were employed to distinguish the parametric effects of the aforementioned control factors.

2. Experimental method

2.1 Material details
In this study, woven type flax fibres and epoxy resins were used to fabricate the composite workpiece. Initially, the workpiece had a size of 300 x 300 mm at the fabrication stage. Later, machining samples of 94 mm x 70 mm as depicted were trimmed from that bigger plate. Each samples have a thickness of approximately 5 ± 0.5 mm. This thickness was achieved using five layers of woven flax fibres. Fabrication was carried out using vacuum assisted resin transfer moulding. The flax fibre reinforced composites were tested for their following mechanical properties. It was found that the tensile strength and modulus were in the range of 60–80 MPa and 4.00–5.00 GPa, respectively.

![Figure 1. The flax fibre reinforced epoxy composite.](image)

2.2 Machining setup, cutting tool and experimental procedure
End mill slots were cut using a three axis CNC milling machine, by Tongtai EZ-5A model with FANUC controller. A high speed steel (HSS) end mill was used due to the fact that the effect of abrasive wear and friction from the flax fibres on the end mill can be very minimal. Two types of flutes were 2 and 4 number of flutes, in which these number of flutes are commonly used in research studies and also industries. Each sample of flax fibre reinforced epoxy composite was mounted on a vise prior to the machining experiments. End milling was performed under dry environment. After the milling experiments have completed, there were several distinguishable delamination damages that can be observed on top of the end milled slot. Xoptron XST60 stereomicroscope, was used to quantify these delamination damage zones (via delamination factor) around the milled slots. Meanwhile, the surface roughness of the end mill slots was determined using a Mitutoyo surface roughness measurer. Measurement was carried out on five positions along the slot and average value of surface roughness was calculated for subsequent experimental analyses.
2.3 Design of experiment
Taguchi method was implemented for execution of this experimental study. As mentioned in section B, there were 3 controlled factors such as number of flutes, feed rate and spindle speed, which were important for the parametric analysis. Table 1 shows these parameters and their levels.

| Parameter               | Level 1 | Level 2 | Level 3 |
|-------------------------|---------|---------|---------|
| (A) Number of flutes    | 2       | 4       | −       |
| (B) Spindle speed (rev/min) | 1000   | 2000    | 3000    |
| (C) Feed rate (mm/rev)  | 0.1     | 0.2     | 0.3     |

Based on parameter and level shown above, Taguchi $L_{18}$ orthogonal array was used to apply the experiment layout. Taguchi $L_{18}$ orthogonal array is a special type of array that allows the implementation of mixed level of experimental parameters. For the data analysis, signal-to-noise (S/N) ratios were calculated in order to identify the quality characteristics that were either nearing or deviating from desired value. The lower the better characteristic was chosen for the determination of S/N ratio. The formula is given by:

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

Where, $y =$ experimental value; $n =$ no. of experiment.

Apart from the S/N ratio, statistical analyses were used to identify the significant factors that affect the experimental response. These analyses are presented in term of response tables.

3. Results and Discussion

3.1 Delamination factor and surface roughness
The outputs for both and delamination factor and surface roughness were obtained from experiment and tabulated in Table 2. The values for surface roughness were obtained through measurement of $R_a$ using surface roughness measurer on the milled surface, whereas the delamination factors were obtained based on ratio between damage width to the required width, $F_d = \frac{W_{\text{max}}}{W}$, Figure 1. It is apparent that the highest surface roughness value, $R_a$ for the experiment was 4.82 µm and the lowest value, $R_a$ is 2.33 µm for experiment number 7 and number 16, respectively. As for the delamination factor, $F_d$ the highest value of delamination factor for top side is 1.08 mm whereas 1.01 mm is the lowest value of delamination factor.

![Figure 2. Schematic of delamination factor measurement.](image)
Table 2. Delamination factor and surface roughness values from Taguchi L_{18} experiments

| Exp | Number of Flute | Spindle Speed (RPM) | Feed rate (mm/rev) | S/N Ratio for F_d | Surface Roughness, R_a (µm) | S/N Ratio for R_a |
|-----|----------------|---------------------|--------------------|------------------|-----------------------------|------------------|
| 1   | 2              | 1000                | 0.1                | -0.29            | 3.51                        | -10.91           |
| 2   | 2              | 1000                | 0.2                | -0.47            | 2.83                        | -9.03            |
| 3   | 2              | 1000                | 0.3                | -0.10            | 2.65                        | -8.47            |
| 4   | 2              | 2000                | 0.1                | -0.52            | 2.76                        | -8.82            |
| 5   | 2              | 2000                | 0.2                | -0.23            | 3.23                        | -10.18           |
| 6   | 2              | 2000                | 0.3                | -0.51            | 3.79                        | -11.58           |
| 7   | 2              | 3000                | 0.1                | -0.67            | 4.82                        | -13.66           |
| 8   | 2              | 3000                | 0.2                | -0.37            | 3.76                        | -11.49           |
| 9   | 2              | 2000                | 0.3                | -0.32            | 2.94                        | -9.37            |
| 10  | 4              | 1000                | 0.1                | -0.37            | 3.22                        | -10.17           |
| 11  | 4              | 1000                | 0.2                | -0.22            | 3.62                        | -11.16           |
| 12  | 4              | 1000                | 0.3                | -0.29            | 4.15                        | -12.35           |
| 13  | 4              | 2000                | 0.1                | -0.19            | 4.30                        | -12.68           |
| 14  | 4              | 2000                | 0.2                | -0.10            | 3.23                        | -10.19           |
| 15  | 4              | 2000                | 0.3                | -0.10            | 2.87                        | -9.15            |
| 16  | 4              | 3000                | 0.1                | -0.41            | 2.33                        | -7.35            |
| 17  | 4              | 3000                | 0.2                | -0.25            | 2.43                        | -7.69            |
| 18  | 4              | 3000                | 0.3                | -0.42            | 2.85                        | -9.09            |

3.2. Response table

Table 3 shows the response table for S/N ratio of surface roughness at each factor level. It can be seen that spindle speed and feed rate contributed equally on the surface roughness based on the calculated delta values (the difference between maximum and minimum value of each factor level). The lowest delta value in this table is 0.41 corresponding to the number of flute factor. This implies that this factor has the smallest influence on the surface roughness measurement as compared to the other two drilling factors. Consistent results were depicted for the delamination factor output as depicted in Table 4.

Table 3. Response table for S/N ratio of surface roughness.

| Factors             | Level 1     | Level 2     | Level 3     | Delta   | Rank |
|---------------------|-------------|-------------|-------------|---------|------|
| Number of flutes    | -10.3909    | -9.9809     | -           | 0.4100  | 3    |
| Spindle speed       | -10.3491    | -10.4323    | -9.7763     | 0.6561  | 1    |
| Feed Rate           | -10.5974    | -9.9580     | -10.0023    | 0.6394  | 2    |

Table 4. Response table for S/N ratio of delamination factor.

| Factors             | Level 1     | Level 2     | Level 3     | Delta   | Rank |
|---------------------|-------------|-------------|-------------|---------|------|
| Number of flutes    | -0.3864     | -0.2616     | -           | 0.1247  | 3    |
| Spindle speed       | -0.2897     | -0.2760     | -0.4062     | 0.1302  | 2    |
| Feed Rate           | -0.4072     | -0.2728     | -0.2919     | 0.1344  | 1    |
The aforementioned results appeared to be consistent with the reported study by Celik et. al. when the authors end milled jute fibre reinforced polymer composites [7]. According to the authors, at high feed rates, the end mill had insufficient time to cut most of the fibres and the uncut fibres remained intact due to softer nature of the flax fibres and also failure of the polymer metrics [7]. As a result, delamination damage occurred on each side of the cutting slot. At the same time, the increase in cutting speed also deteriorated the delamination on flax fibre composites. This was mainly attributed to the elevated cutting temperature due to friction at the contact surfaces of the tool and the flax fibre composite. Polymer matrix failed due to the increased cutting temperature, and hence the bond strength between the fibre and the matrix was reduced that lead to severe delamination [7]. Summaries of percentage contribution of $R_a$ and $F_d$ are shown in Figure 3.

![Figure 3](image_url)

**Figure 3.** Pareto ANOVA for percentage contribution of experimental parameters on (a) $R_a$ and (b) $F_d$.

4. **Concluding Remarks**

In this study, the effects of cutting parameters such as cutting speed and feed rate on delamination factor and surface roughness were evaluated in end milling process using two and four number of flutes end mill tools. The results can be summarised as following; delamination factor and surface roughness on the milled flax fibre composites were equally affected by the feed rate and spindle speed. The number of end mill flute had a marginal influence on the aforementioned machining outputs. The results were successfully analysed by using response table and Taguchi L18 orthogonal array.

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