Analysis cutting forces and surface roughness of fibre reinforced polymer for end mill processes

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Abstract. This study aims to determine the cutting force characteristics when cutting composite workpieces material. Cutting force is one of the cutting conditions that can determine the machinability of the workpiece. Composites have different mechanical properties from metals thus the machinability characteristics of composites will also be different compared to metals. In this research, cutting force of two GFRP workpieces consisting of chopped strand mat and woven roving type glass fibers with resin matrix was measured using a dynamometer and recorded using DAQ then the surface quality of the workpieces was analyzed. The cutting force and surface roughness characteristics are then compared to the cutting force of Perspex and Aluminium workpieces. The results show that the average cutting force measurement (Ftm) of GFRP Chopped strand mat, GFRP woven roving, Aluminium, and Perspex were 146.8845 N, 103.3915 N, 97.6002 N and 65.33 N resulting in surface roughness of 3.8511 µm, 5.2733 µm, 6.127 µm, and 6.23 µm respectively.

1. Introduction
Nowadays, the composite material is one of the most widely studied materials. Composites have taken an important role in replacing metal materials. This is because the composite has several advantages over metal material. The composite weight that is much lighter, cheaper prices, and beneficial mechanical properties make composite materials as an alternative solution in the area of engineering. Applications from diverse materials require a lot of research to improve material capabilities and gain greater benefits.

Furthermore, machining of composite materials has become increasingly important in the engineering industry especially in the prediction of cutting strength. The composite material has a structure consisting of two constituent components namely matrix and reinforcement. The matrix can be in the form of metal, ceramic, or polymer material, while reinforcement can be in the form of fiber, particles, or crystalline filament [1].

Cutting force measurement is used to obtain machinability of process parameters. Knowledge of the effect of cutting parameters on cutting force can be used to determine the cutting mechanism including machinability of the material, surface quality, the form of chips, friction and heat of cutting tool [2].

GFRP (glass fiber reinforced polymer) is a composite material that uses a matrix of resin and glass fiber as its reinforcement. GFRP fiber consisted of two types, namely a chopped strand mat (fine fiber) and woven roving (coarse fiber). The milling process on GFRP will have different characteristics with the metal milling process. The low melting point of the GFRP can cause the workpiece to melt due to
friction arising during the milling process. Therefore GFRP can produce different characteristics with metal workpieces.

There have been many studies of the cutting strength of the machine tool in machining composite materials. Jahromi and Bahr (2010) [3] developed an energy method for predicting the strength of machining for orthogonal machines in unidirectional matrix (PMC) composites. Kumar et al. (2014) [4] improved the method by investigating the effect of cutting conditions and tool geometry on cutting strength on the replacement of unidirectional glass reinforced plastic composites (UD-GFRP) using multiple regression models. This model proved to be very popular for predicting cutting strength. Guo et al. (2011) [5] proposed a model for predicting the thrust and torque forces produced in drilling composite materials using a rotating drill. Then a finite element model was developed by Li et al. (2014) [6] to simulate the final pressure of fiber tension wrinkles and fiber compression bucking, the main stress of the longitudinal tensile matrix and shear damage. The cutting strength obtained from the FE simulation matches the experimental observations.

Important criteria in the parameters of the composite processing selection process are the value of cutting strength. Rychkov and Yanyushkin (2016) [7] developed a method for determining the cutting strength with a comparative evaluation of the calculated value and the actual value of the cutting force of the composite material machining.

In conducting machining of the composite, besides cutting force, the relationship between cutting parameters and cutting temperature is also as a consideration in looking at cutting characteristics. Wang et al. (2015) [8] considered the effect of glass transition temperature, the effect of cutting force and cutting temperature on CFRP surface quality. The analysis results show that spindle speed is a key parameter that affects the cutting temperature while the feed rate is a key parameter that affects the cutting force in CFRP milling. If the cutting temperature exceeds the glass transition temperature (Tg), the matrix cannot provide sufficient support for the fiber, and the composite material's machining quality is poor.

2. Experiment

Cutting force occurs due to the thrust force tool when cutting workpieces. The cutting force value is influenced by several parameters including cutting speed, feed rate, cutting depth, cutting tool geometry, type of workpiece material and collant [9]. The dynamometer is used to measure cutting force. This dynamometer can read three directions of forces, namely the thrust force (Fy), axial force (Fz), and cutting force (Ft).

In the experiment, the preparation of workpiece and the dynamometer were carried out. Preparation of GFRP begins with the manufacture of box-shaped molds. Then the resin is weighed and mixed with a catalyst with a ratio between catalyst and 1: 100 resin. The mixture is stirred evenly with a stirring time of about 5 minutes so that the catalyst is completely evenly distributed. Then the liquid that has been mixed is poured into the mold until the mold is half and insert a sheet of chopped strand mat which has been cut to the size of the workpiece with a ratio of about 10% of the total resin and catalyst mixture. The remaining resin is then added over the fiber until it is embedded in the resin. GFRP liquid is left to room temperature until it hardens. The same process is carried out for GFRP woven roving. For comparison, cutting forces of Perspex and Aluminium alloy is also measured so that the differences in characteristics with GFRP material can be seen.

The workpiece is placed in the tool holder and locked with a thread. The milling machine used is a universal milling machine with the same machining parameters for both workpieces, namely the end milling process with HSS tool, spindle rotation speed (n = 283 rpm), number of tool flutes (z = 4), feed-rate (Vf = 104 mm / min), cutting depth (a = 4 mm), and cutting time (t = 4 s).

Cutting forces measurement consists of three components, namely the sensor component dynamometer loadcell, amplifier, and DAQ. Figure 1 shows the setup of recording data for the milling processes of Aluminium, Perspex, GFRP chopped strand mat and GFRP has woven roving. Dynamometer will measure cutting force and display measurement results. The recording process is carried out by NIDAQ and Labview software.
Cutting force measurements were carried out three times experiments for each workpiece. The surface roughness was measured on the workpieces using Mitutoyo SJ-301 Surface Roughness Tester. For each experiment, the measurement of surface roughness was carried out at three points along the chosen area, then the arithmetic roughness value (Ra) was averaged. The results of surface roughness measurements were then correlated with the results of cutting force. Thus the influence of cutting force on the surface roughness of the workpiece can be obtained.

3. Results and discussion

3.1 Cutting Force Analysis

The cutting force obtained from the measurement has three direction forces, namely axial force (Fz), thrust force (Fy), and cutting force (Ft). The axial force for the workpieces GFRP chopped strand mat occurred at 5N and for GFRP woven roving was in the range of 6N to 8N can be seen in Figure 2.

All of these results show that during the three times validation of the experiment, the force acting in the axial direction was seen to be constant in each experiment. This is because the end milling process does not give much pressure in axial direction if the depth of the cut is equal. Thrust force (Fy) results of dynamometer measurements for three times experiments. It has values that are close to each other with fluctuating force, as seen in Figure 3 for GFRP chopped strand mat, which has a range of 100 N to 200 N, for GFRP woven roving, which has a range of 0 to 180 N. Aluminium has a range of 0 to 200 N and Perspex has a range of 10 to 140 N. Fluctuations occur due to the position of each tool flute. The top of the chart that marks the highest force occurs when the feed-rate moves push the tool blade to slash the workpiece, and the chips begin to form. While the graph valley marks the lowest force even zero because at this position the workpiece has been cut off and the chips have finished forming, but the tool hasn't arrived at the new surface of the workpiece that will be cut due to the effect of a small feeding speed. Both of these processes occur in a very short time interval.

![Dynamometer and data acquisition system](image1)

**Figure 1.** Dynamometer and data acquisition system

![Axial force (Fz) for each workpiece.](image2)

**Figure 2.** Axial force (Fz) for each workpiece.
For GFRP chopped strand mat which has a graph valley reaching 100 N, can be caused by fiber which is not directly cut but the fiber is first attracted and covers the new surface of the workpiece to be cut so that the formation of chips becomes slower and the tool always encounters a new surface that is driven by thrust force. Cutting force (Ft) obtained from measurement results has the same pattern as thrust force in Figure 4. GFRP chopped strand mat has a range of 60 N to 220 N, and GFRP woven roving has a range of 10 N to 200 N. Perspex has a range of 30 to 110 N, and Aluminium has a range of 40 to 180 N. Fluctuations in the graph of cutting force (Ft) is caused by the position of each tool flute when cutting the workpiece. The top of the graph occurs when the tool flute slashes the workpiece where the chips begin to form, while the graph valley occurs when the tool flute has finished cutting, and the chips have finished forming, but in a short time another tool flute follows and comes into contact with the workpiece so that the smallest force is not read up to zero.

In GFRP woven roving, when hardened by resin, the edge side of woven fibers are attracted and stretched, not as tight as the middle area of the woven fiber. This causes a decrease in cutting force on the GFRP woven roving. The composition of the fiber where the chopped strand mat is tighter than the woven roving causes the cutting force of the GFRP chopped strand mat larger than the GFRP woven roving.

3.2 Surface roughness analysis

After the milling process, the surface roughness is measured on the workpiece. Then the results of surface roughness are correlated with the average cutting force. The average cutting force (Ftm) of GFRP Chopped GFRP strand mat is 146.8845 N resulting in surface roughness of 3.8511 μm. For the average cutting force (Ftm) of GFRP woven roving is 103.3915 N resulting in surface roughness of 5.2733 μm. The average cutting force on Aluminium is 97.6002 N resulting in surface roughness of 6.127 μm and on Perspex, the average cutting force is 65.33 N resulting in surface roughness of 6.23 μm. This relationship can be seen in Figure 5.
Figure 5. Average Cutting Force (Ftm) vs. Surface Roughness of 4 Workpieces

The average cutting force (Ftm) in Figure 5 consists of several different materials that produce different surface roughness due to the different material composition. The smallest cutting force produces the roughest surface roughness, while the largest cutting force produces the most subtle surface roughness. This is due to differences in a material having different cutting resistance. The greater the specificity of the average cutting resistance of a material, the greater the cutting force occurs. Large surface roughness is also affected by the large feed-rate (fz) as well. The greater the fz the thickness of the resulting chips (Hm) is also getting bigger. Furthermore, the greater the chip thickness, then the specific cutting resistance will be smaller where the smaller the specific cutting resistance can lead to a smaller cutting force.

The theoretical cutting force (Ftm) on Aluminium workpieces can be calculated as follows: the feed-rate is 104 mm/min, spindle rotation is 238 rpm (1495.3981 rad/min), the number of flutes is 4, and then the feeding movement is:

\[
F_{tm} = \frac{V_f}{(n \cdot z)} = \frac{104 \text{ mm/min}}{(1495.3981 \text{ rad/min} \cdot 4)} = 0.0173866 \text{ mm/flute}
\]  
(1)

The main cutting angle \(kr\) and the average position angle \(\phi_m\) max is 90o, so the average thickness of the chips (hm) is:

\[
h_m = f_z \cdot \sin \phi_m \cdot \sin \phi_m = 0.0173866 \text{ mm} \cdot \sin 90^\circ \cdot \sin 90^\circ = 0.0173866 \text{ mm}
\]  
(2)

The specific cutting force of Aluminium alloy for the turning process is 370 N / mm2, so the specific cutting force references in the milling process are:

\[
K_{rt \cdot lathe} = 1.40 K_{rt \cdot flute} = 1.4 \cdot 370 = 518 N/mm^2
\]  
(3)

The power of average chip thickness is 0.25 so that the specific cutting resistance is:

\[
K_m = K_{rt \cdot h_m} = 518 N/mm^2 \cdot (0.0173865)^{0.25} = 1426.514 N/mm^2
\]  
(4)

The width of the chips before cutting at the end mill is 4 mm, so the average cross-sectional area of the chips is:

\[
A_m = b \cdot h_m = 4 \text{ mm} \cdot 0.0173866 \text{ mm} = 0.06954 \text{ mm}^2
\]  
(5)
Finally, the average cutting force per flute is:

\[ F_{\text{tm}} = A \cdot K = 0.06954 \ mm^2 \cdot 1426.514 \ N/mm = 99.1997 \ N \]  \hspace{1cm} (6)

By using the same method, the empirical cutting force is obtained for each workpiece as shown in Table 1.

| Workpieces    | \( F_{\text{tm}} \) Experiment (N) | \( F_{\text{tm}} \) Empirical (N) | Correction Factor |
|---------------|-------------------------------------|-----------------------------------|-------------------|
| Aluminium     | 97.6002                             | 99.1997                           | 1.01638           |
| Akrilik       | 65.3338                             | 50.9404                           | 0.77961           |
| GFRP strand mat | 146.8845                           | 140.773                           | 0.95839           |
| GFRP woven roving | 103.3915                           | 140.773                           | 1.36155           |

The correction factor is used to see the closeness of the experimental results with the results of the theory. If the experimental results are closer to the theoretical results, the correction factor value approaches one. The results of the experimental cutting force cannot be the same as the empirical calculation results. In Table 1 the values that are close to each other are Aluminium and GFRP chopped strand mat. But on the results of Perspex and GFRP woven roving workpieces, there is a considerable difference. The thin Perspex can cause this, when mounted on the clamp, the surface is slightly curved so that the depth of the cut is slightly increased, if the depth of the cut increases, the cross-sectional area of the chips increases and the cutting force increases. In GFRP woven roving, when hardened by resin, the woven fiber edge is attracted so that it stretches as not tightly as the center of the webbing.

4. Conclusions
Based on the results of cutting force experiments and the results of workpieces Surface Roughness on the milling process it can be concluded:

a. GFRP cutting force has fluctuating force characteristics caused by the movement of tool flutes during the milling process.

b. Cutting force average (\( F_{\text{tm}} \)) GFRP Chopped Strand Mat is larger than GFRP Woven Roving.

c. Based on experimental, the surface roughness of the workpiece can be reduced by increasing the average cutting force (\( F_{\text{tm}} \)).

Acknowledgments
Publication of this article is supported by Engineering Faculty of Andalas University grant contract no.: 050/SP2H/LT/DRPM/2018.

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