Effects of machining conditions on the specific cutting energy of carbon fibre reinforced polymer composites

A I Azmi 1, A Z Syahmi 1, M Naquib 1, T C Lih 2, A F Mansor 1 and A N M Khalil 2

1 Faculty of Engineering Technology, Universiti Malaysia Perlis (UniMAP), UniCITI Alam Campus, Padang Besar, 02000 Perlis, Malaysia
2 School of Manufacturing Engineering, Universiti Malaysia Perlis (UniMAP), Pauh Putra Campus, Pauh, 026000 Perlis, Malaysia

Abstract. This article presents an approach to evaluate the effects of different machining conditions on the specific cutting energy of carbon fibre reinforced polymer composites (CFRP). Although research works in the machinability of CFRP composites have been very substantial, the present literature rarely discussed the topic of energy consumption and the specific cutting energy. A series of turning experiments were carried out on two different CFRP composites in order to determine the power and specific energy constants and eventually evaluate their effects due to the changes in machining conditions. A good agreement between the power and material removal rate using a simple linear relationship. Further analyses revealed that a power law function is best to describe the effect of feed rate on the changes in the specific cutting energy. At lower feed rate, the specific cutting energy increases exponentially due to the nature of finishing operation, whereas at higher feed rate, the changes in specific cutting energy is minimal due to the nature of roughing operation.

1. Introduction
Machining operations in manufacturing industries generate a number of waste resources that contribute toward a substantial environmental impact and manufacturing costs. Among waste resource issue that attracted significant attention in both academia and industries is energy efficient machining through optimization and reduction strategies. These strategies are highly challenging due to the complexity of cutting mechanics; the interrelationships among efficiency, energy, speed, cost, and quality; and the diversity of energy-consuming units of a machine tool and its auxiliaries [1]. In addition to that, it has been well reported that energy efficiency in machining operations is often very low. Zhao et al. [2] and Jun et al. [3] have reported that the energy used during actual machining only accounts approximately 15% - 30% of the total energy requirement. Yet, it should be emphasized that more energy is consumed due to the poor machinability of the material. The increase of machining forces and localized heat generation near the cutting zone have a major influence on the growth of tool wear, accelerates the power and energy demand for the machining operation. Among poor machinability metallic materials include titanium alloys, nickel based alloys, stainless steels, whereas for polymer composites such as fibre reinforced composites (FRPs) are also classified as difficult-to-cut materials. In recent years, the development and application of carbon fibre reinforced composites (CFRPs) are occurring at an increasingly fast pace to replace the conventional metallic materials in in various application parts such as automobile, aerospace, and marine. Superior properties of CFRPs include low density, high strength, high stiffness, good toughness, good fatigue, creep, wear and
corrosion resistance, low friction coefficient and good dimensional stability [4]. Despite of these superiorsities, the fibre reinforcements of the CFRP composites are highly abrasive that accelerate the wear on cutting tool and hence probably requires high force and energy to shear or machine them. Furthermore, previous understanding of machining CFRP is that, it involves brittle fractures and lack of plastic deformation which make them difficult to obtain the required quality and strict final dimensional accuracy in machining. Thereby, proper selection of machining parameters and tools are inevitable in ensuring efficient cutting process for excellent surface finish and qualities, subsequently help to achieve minimal energy usage. From the literature, there is abundant amount of research works focusing on the characterising, optimising and predicting the machinability of CFRP composites. Among the pioneering work was reported by Sakuma and Seto [5] that studied the performance of different tool materials and geometries during machining of FRP composites. Later around 2002-2010, major research works of machining via turning process for CFRP composites and glass fibre reinforced composites (GFRP) can be found through the work of Davim et al [6-8], Palanikumar et al. [9-11] and others. Various solutions are proposed among which statistical, analytical and experimental were employed to determine effective and efficient machining of those composites. However, the limitation of those works is that the aspects of energy and power consumption were not taken into account.

Only until recently, Marathe and Javali [4] reported the effects of machining parameters on the specific cutting energy and delamination damage of glass fibre-polyester reinforced composites in drilling operation. The authors showed that the specific cutting energy for this type of composite is approximately 0.81-0.83 J/mm². Feed rate was the main factor that contributed to the lowest cutting energy per unit volume or material removal. It is to note here that the value of specific cutting energy for polymer composite is relatively low as compared to that of metal [12]. In another earlier work, Rosario et al. [13] studied the energy required during the dry drilling of PEEK GF30, a thermoplastic material, polyetheretherketone, reinforced with glass fibre. An analysis of variance (ANOVA) showed that the type of drill is a more influential factor and the optimum conditions are with the tool made of tungsten carbide (WC) with diamond point under the higher cutting conditions of speed and feed rate [4].

From the aforementioned review, it can be concluded that rarely efforts have been made towards understanding the effects of cutting parameters on the specific cutting energy of CFRP composites via turning process. Through this study, it enables the identification of process parameters and evaluation of the process efficiency at which the different cutting mechanisms occurred.

2. Experimental setup and methodology

2.1. Materials and cutting inserts

Two types of CFRP composites were used in this experimentation, Figure 1(a-b). The first is a 12 mm diameter of 2 m length pultruded CFRP composites, made from uni-directional carbon fibres with epoxy matrix. Another one is a CFRP hollow pipe of 60 mm outer diameter and 57 mm inner diameter. This CFRP pipe is made of 3K 2/2 twill weave type carbon fibres with epoxy matrix. The length of the tube is also 2 m. It is to note that the fibres used are of standard modulus fibres. For both of the samples, its diameter has a tolerance of ± 1 mm. All of these CFRP composites were supplied by EasyComposites UK Ltd. For machining test purposes, both of the CFRP composites were trimmed to the length of 75 mm. For the cutting inserts in turning process, PVD cemented coated carbide insert from SUMITOMO was used with a tool holder ETJNR-2020K16, Figure 1(c). A cutting length of 50 mm was carried out on the workpiece for each of the cutting conditions. During each condition, a new side of cutting edge insert was used in order to alleviate any effect of worn tool on the measurement of machining force. All cutting process was carried out in a dry condition. This is due to the recommendation from previous reported research that dry condition is much preferable and the use of cutting fluids has insignificant effect on the cutting performance.
2.2. Machining Conditions
The workpiece specimens were machined at the cutting speeds ranging from 20 m/min to 100 m/min for the pultruded CFRP composites, whereas 50 to 250 m/min for the composite pipes. The feed was varied from 0.15 mm/rev to 0.60 mm/rev corresponding to every cutting speed for the pultruded CFRP composites. As for the composite pipes, feed was varied from 0.10 mm/rev to 0.50 mm/rev. Depth of cut was 0.2 mm for the pultruded CFRP and 0.1 mm for the CFRP pipes, respectively. Details of cutting conditions are shown in Table 1.

| Depth of cut, $a_p$ (mm) | feed, $f$ (mm/rev) | $V_c$ (m/min) | Condition |
|--------------------------|-------------------|---------------|-----------|
| 0.2                      | 0.15, 0.30, 0.45, 0.60 | 20, 40, 60, 80, 100 | Dry       |
| 0.1                      | 0.10, 0.20, 0.40, 0.50 | 50, 100, 150, 200, 250 | Dry       |

2.3. Machine Tools and Data Acquisitions
All straight turning process was performed on Chevalier FCL-608 CNC turning machine. The machine is capable of handling a maximum spindle speed up to 6000 RPM, maximum cutting diameter of 260 mm and maximum cutting length of 290 mm. Figure 2(a) depicts the CNC turning machine used in this study. Since the main objective of this study is to determine the specific cutting energy, the cutting force profile of the workpiece was measured with a 3-channel dynamometer (Kistler® 9129) as depicted in Figure 2(b). Kistler Dynoware software with Kistler® 5070 charge amplifier and data acquisition module were used to acquire and sample the cutting force data at appropriate sampling frequency of 2kHz.
2.4. Determination of specific cutting energy

According to Zhao et al. [2], energy consumption of a machining process can be evaluated at different levels, namely; machine tool, spindle, and process levels. Based on these three levels, it was decided that the energy consumption at the process level is being evaluated. In this level, only the energy consumed by actual material removal is considered, which is machine tool independent. As the energy consumption at the level governs the chip formation process and surface generation, therefore, this energy is considered when selecting process parameters where the objective is to balance energy consumption with surface integrity [2]. It is well known that specific energy is widely used to evaluate the energy consumption for a machining process. It is defined as energy consumption to remove a unit volume of work material. The formula for the specific cutting energy is given as:

\[ k = \frac{P_m}{MRR} \]  

Where
- \( k \) – specific cutting energy in J/mm³
- \( P_m \) – Cutting Power (J/s or Watt), given by:
  \[ P_m = F_c \times V_c \]
- \( F_c \) – cutting force
- \( V_c \) – cutting velocity
- \( MRR \) – Material Removal Rate (mm³), given by:
  \[ MRR = \pi \cdot \frac{D_i^2 - D_f^2}{4} \cdot \frac{f \cdot V_c}{D_{ave}} \cdot \frac{1000}{60} \]  

Where
- \( D_i \) – initial diameter
- \( D_f \) – final diameter
- \( f \) – feed
- \( V_c \) – cutting speed
- \( D_{ave} \) – average diameter

3. Results and discussion

Figure 3-4 show the relationship between cutting power and material removal rate during turning of pultruded CFRP composites and CFRP composite pipes, respectively. From these graphs, it is apparent that there is a positive linear relationship between cutting power and the MRR. In fact, the linear fitting of the experimental data shows a good relationship between cutting power and MRR since the \( R^2 \) is in the range of 0.95 – 0.99 (which is very close to 1.0) regardless of the type of CFRP composites used.

**Figure 3**: Power-MRR relationship at different feed when machining pultruded CFRP composite
Figure 4: Power-MRR relationship at different feed when machining CFRP composite pipe

It is important to highlight here that the specific cutting energy constant, \( k \), is represented by the slope of cutting power-MRR trend line. For both of the material, the values of \( k \)'s are tabulated in Table 2. It can be observed that the specific cutting energy constant reduces from 0.264 J/mm\(^3\) to 0.153 J/mm\(^3\) for the pultruded CFRP composite. Meanwhile, the specific energy constant also reduces with respect to the feed rate particularly for the CFRP composite pipe. The changes are from 0.974 J/mm\(^3\) to 0.370 J/mm\(^3\). The relationships of this specific cutting energy with the feed rate are plotted in graph shown in Figure 5. It can be seen that relationship can be curved-fitted well with a power law function. The value of \( R^2 \) for the pultruded CFRP composite is 0.851, whereas for the CFRP composite pipe is 0.949. As apparent, the specific cutting energy is initially high at lower feed but reduces exponentially and almost plateau when feed is at higher level. This result is consistent with the findings of Balogun and Mativenga [14] when machining AISI 1045 steel alloy and titanium 6Al-4V alloys. The authors asserted that fairly plateau specific cutting energy at higher feed is due to a higher un-deformed chip thickness, which represent typical of roughing operations (high feed rate). Whereas, exponentially higher at low feed (typical of finishing operations) is due to low un-deformed chip thickness [14]. The finding of our study also confirms that the specific cutting energy is significantly influenced by the feed. It is also in agreement with the theoretical specific cutting force model [14].

Figure 5: Effect of feed on the specific cutting energy for (a) pultruded CFRP composites and (b) CFRP composite pipe
Table 2. Specific cutting energy of the tested material at different feed

| Pultruded CFRP composite | CFRP composite pipe |
|--------------------------|---------------------|
| feed (mm/rev) | $k$ (J/mm$^3$) | feed (mm/rev) | $k$ (J/mm$^3$) |
| 0.15 | 0.264 | 0.1 | 0.9741 |
| 0.30 | 0.190 | 0.2 | 0.491 |
| 0.45 | 0.132 | 0.3 | 0.396 |
| 0.60 | 0.153 | 0.4 | 0.370 |

4. Conclusion

This paper has discussed the power, MRR and specific cutting energy of pultruded CFRP composites and CFRP composite pipes during turning process at different parameter settings. Based on the experimental results, the effects of turning parameters on the MRR and specific cutting energy of CFRP composites have been determined. The increase in cutting power was due to the MRR since the experimental data shows a positive linear relationship and $R^2$ was very close to 1.0 regardless of the type of CFRP composites used. The experimental results also revealed that the specific cutting energy of the both CFRP composites were strongly influenced by the feed rate. The specific energy constant can be reduced with respect to the feed rate particularly for the pultruded CFRP composite and CFRP composite pipe. Lastly, the relationships of specific cutting energy with the feed rate in this present study were good agreement with the theoretical specific cutting force model.

5. References

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