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Shredding energy consumption of GFRP composite waste

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Shredding energy consumption of GFRP composite waste

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Abstract. This work investigated effect of glass fibre fabric structures, feedstock feed rate and screen size on specific shredding energy of glass fibre reinforced plastics (GFRP) waste via a two-level factorial design of experiment study. Four types of fabric structure, i.e. unidirectional (UD), biaxial (BIAX), triaxial (TRIAX) and chopped strand mat (CSM), were impregnated separately with unsaturated polyester resin to manufacture GFRP plates. The shredding energy was measured using a two-wattmeter approach. During shredding, CSM demonstrated a relatively flat power consumption curve compared to other fabric types. It was also noticed that the GFRP plate reinforced with more complex woven structure, i.e. TRIAX, required higher energy for shredding, especially with a combination of high feed rate and small screen size. It was found that mechanical efficiency was only around 8.2-15.7% and 0.8-2.2% for shredding at feed rate of 60 kg/hr and 10 kg/hr respectively. It was also found that adopting a larger screen size and lower feed rate could reduce the specific shredding energy.

Keywords: Glass Fibre Reinforced Composites; Mechanical Recycling; Shredding; Energy Consumption

1. Introduction

A summary of fibre reinforced plastics (FRP) annual production in China is shown in Figure 1. Also, it is well known that majority of those FRP composites are GFRP. A total of 3.35 million tons of FRP was produced between 1975-2000 and over 1 million tons had been produced since 2004. In 2017 alone, 4.44 million tons was produced in China, which covered over 60% of the global production. FRP composite generally has a service life between 15-20 years and thus a significant amount of end-of-life FRP parts has already been discarded and more is anticipated in the near future. Together with waste created during the manufacturing process, the urgency of finding feasible recycling and reuse options for GFRP waste is imminent.

Owing to an irreversible 3-D cross-linked structure, GFRP composites containing thermosetting matrix are more difficult to be recycled compared to thermoplastic composites. A series of recycling technologies has been suggested, such as mechanical shredding, chemical degradation, thermal combustion, electrical approach and biotechnology [1]. However, unlike carbon fibre, commercial value to be recovered from GFRP waste is relatively low, thus many thermosetting GFRP waste are directly treated via combustion or simply disposed of via landfill. Mechanical shredding is the only widely used technology to recycle GFRP waste because it requires the lowest capital investment and has low energy consumption requirement. GFRP waste can be shredded into small pieces to be reused as a low-cost filler. It was reported that specific shredding energy is about 0.14-0.31 MJ/kg at a shredding rate of 400 tons/year [2].

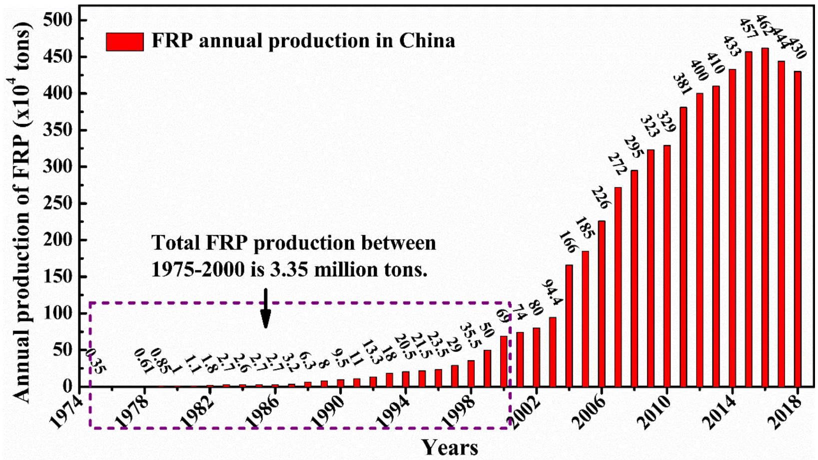


Figure 1. Annual FRP production in China from 1975-2018[3-6].

Mechanical recycling refers to size reduction by a physical process, then follows with size classification via sifting [7]. Primary apparatus for mechanical recycling is granulating machine, which can be divided into roller crusher, jaw crusher, impact crusher and shearing crusher [8]. The shearing crusher is usually considered as one of the least energy consumption option for polymer composite waste. In addition, the shredded parts final size distribution can be controlled via screen aperture selection [9]. It has been reported that shredded part dimension depends on shredding process parameters, for example, a larger gap between fixed and rotating blades would produce thinner particulates, due to higher layer peeling force [10]. On the contrary, smaller clearance resulted in finer pieces to the produced with higher energy consumption [11]. It had been reported that sieve with a larger open area would save more energy due to higher crushing rate and shorter residence time [12]. Further energy saving can be realized by opting for a higher feed rate. Woldt et al. reported that 50–90% of shredding energy were dissipated for fragments undergoing secondary milling before leaving the shredding chamber [13].

Past researches on shredding energy investigation were mostly done on GFRP waste reinforced with chop strand mat for its isotropic mechanical properties. Effect of other fabric structures on shredding energy investigation has not been reported. In this study, GFRP plates reinforced with four types of glass fiber fabric structure i.e. UD, TRIAX, CSM and BIAX, were manufactured individually. These plates were used as feedstock for the shredding energy investigation. The study also investigated the effect of feedstock feed rate and screen open area on shredding energy consumption.

2. Materials and methods

2.1. GFRP feed preparation

Four types of glass fibre fabric structures (UD, TRIAX, CSM and BIAX), were purchased from Jushi Group Co. Ltd, China. TRIAX is a triaxial non-crimp fabric with orientation 45°/0°/-45° and BIAX is a biaxial non-crimp fabric in ±45°. UD and TRIAX had nearly the same areal density of around 1200 grams per square meter (gsm) but BIAX and CSM are lower, i.e. 800 and 300 gsm respectively. VP2 unsaturated polyester resin and MEKP catalyst were both purchased from Easy-Composite (Beijing) company with ratio of catalyst to VP2 resin at 2 wt.%. Vacuum infusion process was selected as the method to manufacture 300 mm x 300 mm GFRP plates [14]. Different number of fabric layers were used in order to achieve a mould plate with an average thickness of 4 mm, i.e. 5, 5, and 14 layers of TRIAX, UD, BIAX and CSM fabrics respectively. The impregnated plates were cured at room temperature for around 24 hours, followed with 3 hours of post-curing at 80 °C. The plates were later cut into 50 mm x 50 mm pieces [15].

2.2. *Process and design of experiments (DOE)*

2.2.1. Shredding. A single-motor NPCY 50J shredder, with a rotation speed of 400 rpm, was supplied by DongGuan Naser Machinery company, as shown in Figure 2(a). Inside the cutting chamber, there are three rows of evenly distributed cutting blades installed on a shaft. Each row has five cutting blades. The chamber also contains two fixed horizontal blades, as shown in Figure 2(b). A sieve is installed underneath the cutting chamber and its aperture dimension controls the size distribution of shredded GFRP pieces. The shredded pieces are conveyed to the cyclone pneumatically by two centrifugal fans, which also create a constant draught cooling the cutting chamber. The shredded pieces are separated from the outgoing air via a swirling action inside the cyclone.

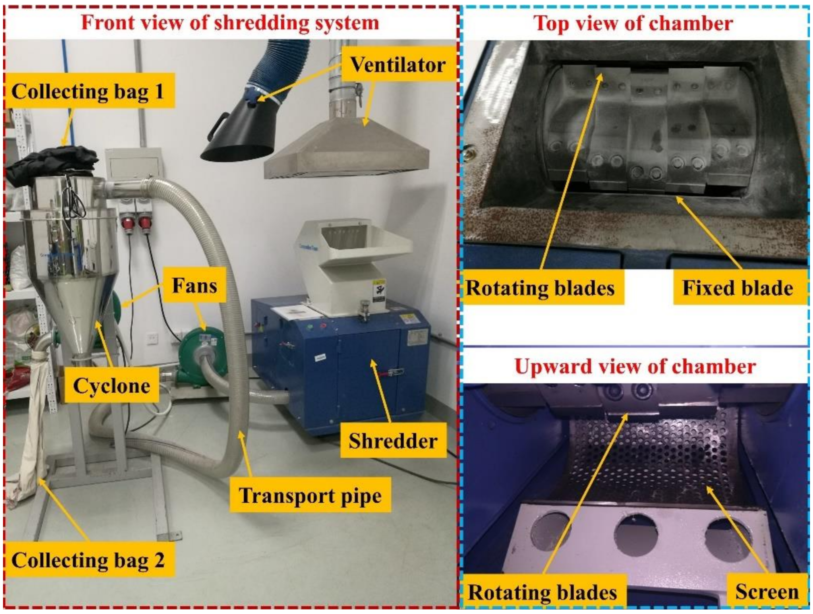


Figure 2. (a) The single-motor shredder plus sucking fans & cyclone and (b) shredder chamber.

The maximum feeding capacity of the shredder is 100-160 kg/hr. A feed rate of 100 kg/hr was chosen as a high level initially. However, severe blockage to the screen aperture was observed. Thus, the high feed rate was later set to 60 kg/hr, which was closer to a value recommended by Shuaib et al. [16]. The low-level value feed rate was set to 10 kg/hr. Two sieves of different aperture diameter were used, i.e. 6mm and 20mm.

2.2.2. DOE for tests. A Minitab 17 software was used to create an experiment matrix for the DOE test. The DOE tests were undertaken with fabric structures marked in high level “1” for TRIAX and low level “-1” UD[17]. Further trials with fabric structure BIAX taken as higher “1” and CSM for lower “-1”, are shown in Table 1. With respect to the screen size and feed rate, low values were defined as “-1” and high value were defined as “1”. A designation was applied to aid labelling the test under different test conditions, for example, TRIAX-6-60 indicates GFRP piece was reinforced by TRIAX fabric, and was shredded via a 6 mm aperture screen at a feed rate of 60 kg/hr. Each run was repeated at least one time.

Table 1. Experimental design via DOE for UD (CSM) and TRIAX (BIAX).

Designations	Std. order	Exec. order	A (GF fabric structure)	B (Screen aperture)	C (Feed rate)
UD-6-60	2	1	-1	-1	1
UD-20-60	4	2	-1	1	1
TRIAX-20-60	8	3	1	1	1
TRIAX-6-10	5	4	1	-1	-1
TRIAX-20-10	7	5	1	1	-1
UD-20-10	3	6	-1	1	-1
TRIAX-6-60	6	7	1	-1	1
UD-6-10	1	8	-1	-1	-1

2.3. Shredding power measurement and calculation

A two wattmeters method is adopted to measure power consumption of the shredding process [18]. This setup allows average current and voltage to be measured to determine apparent power via equation (1):

$$S = \sqrt{3} \times \overline{U} \times \overline{I} \tag{1}$$

Where, S is the apparent power (VA), $\overline{U}$ and $\overline{I}$ are three-phase average voltage (V) and current (A) respectively.

Instantaneous apparent power and active powers were plotted against time using Origin 8.5 software. The apparent basic power of the shredder means working in an idle state and active power indicates mechanical work consumed. The plotted power profile can be used to identify the start and ending of the shredding process and thus the whole process can be divided into idle, major cutting and minor cutting states. Small fluctuation in the basic power was noticed between experiments and this was probably due to slight variation in main power supply. Active shredding power was determined by subtracting the average value of the basic power from the total measured power consumption. Shredding energy was obtained by integrating the active power profile over the whole shredding period. Specific shredding energy was then determined with the known mass of the shredded GFRP parts.

After obtaining the specific shredding energy, E_s (kJ/kg) and total specific energy consumption, E_t (kJ/kg), the mechanical efficiency (η) can be calculated, as shown in Equation (2):

$$\eta = (E_s/E_t) \times 100 \tag{2}$$

3. Results and discussion

3.1. Shredding power profiles

From the Figure 3, at 10 kg/hr feed rate and with a 20 mm aperture, it can be seen that among these four types of fabric, the TRIAX-20-10 test gets the highest instantaneous power, close to 4200 VA, which is around 800 VA more than the basic power. Whereas the peak power in BIAX-20-10 is the lowest with merely 400 VA above the basic value. UD and CSM hold a close peak distribution while generally UD-20-10 owns a higher peak value than the CSM-20-10.

Figure 4 shows the power plots obtained from tests using a smaller screen size of 6 mm. It could be seen that the highest single peak is obtained from the TRIAX fabric again and its value reaches around 5400 VA, which is 2100 VA more than the basic power. For the cases of BIAX-6-10 and UD-6-10, their peak power values are both around 3500 VA. CSM-6-10 displays a quite even power consumption distribution but a longer minor milling duration.

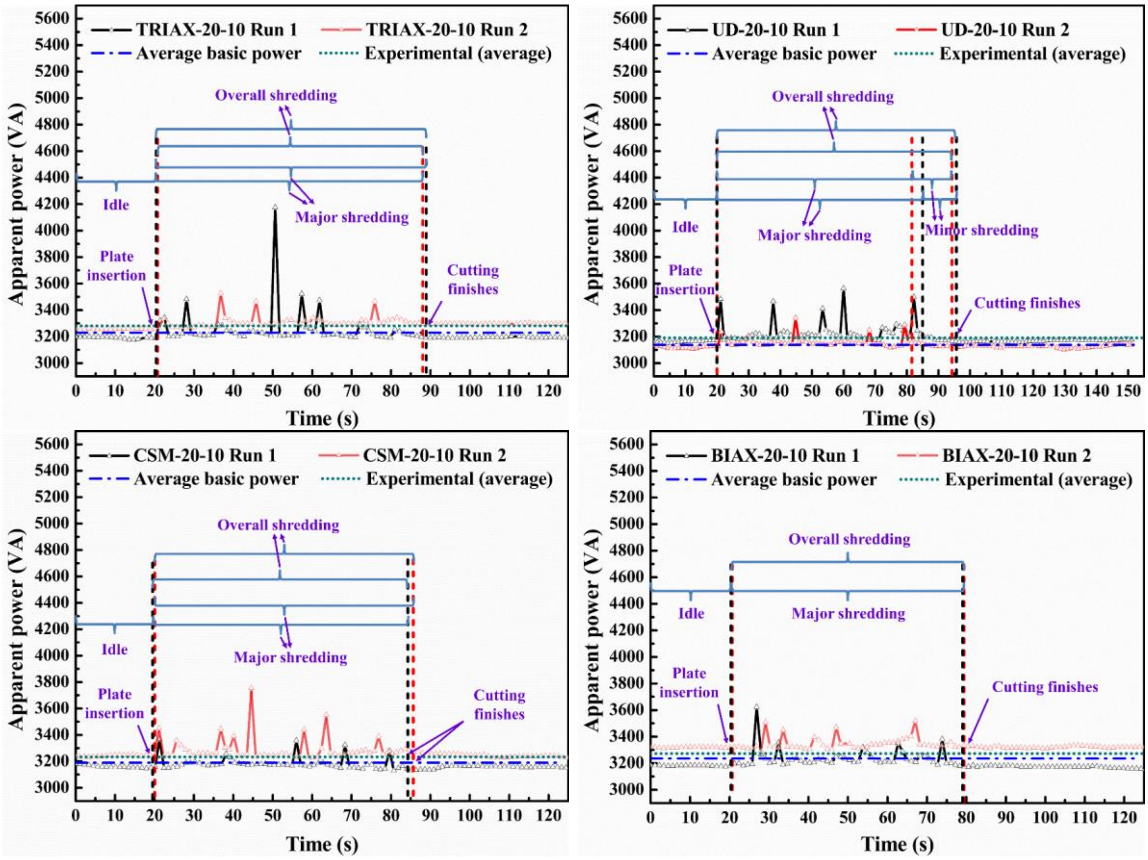
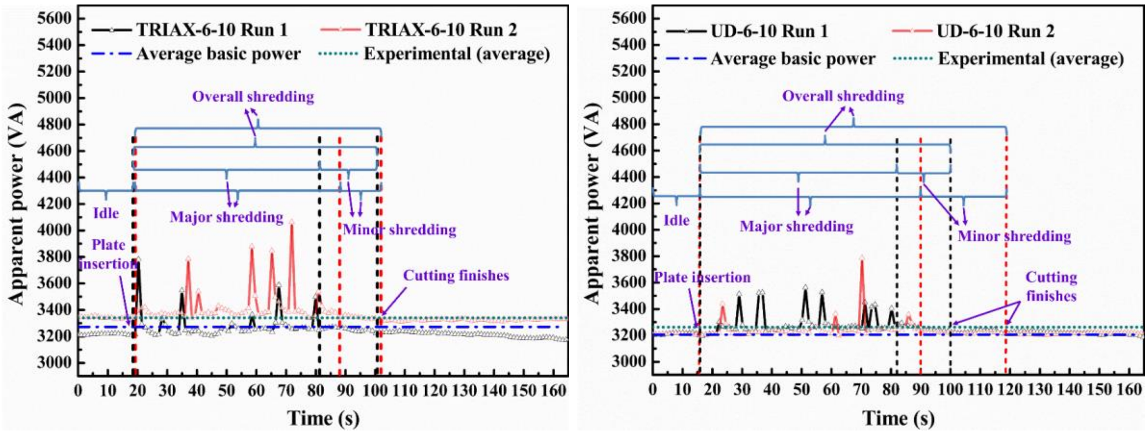


Figure 3. The instantaneous apparent power of TRIAX, UD, CSM and BIAX GFRPs shredding at feed rate 10 kg/hr & 20 mm screen size.



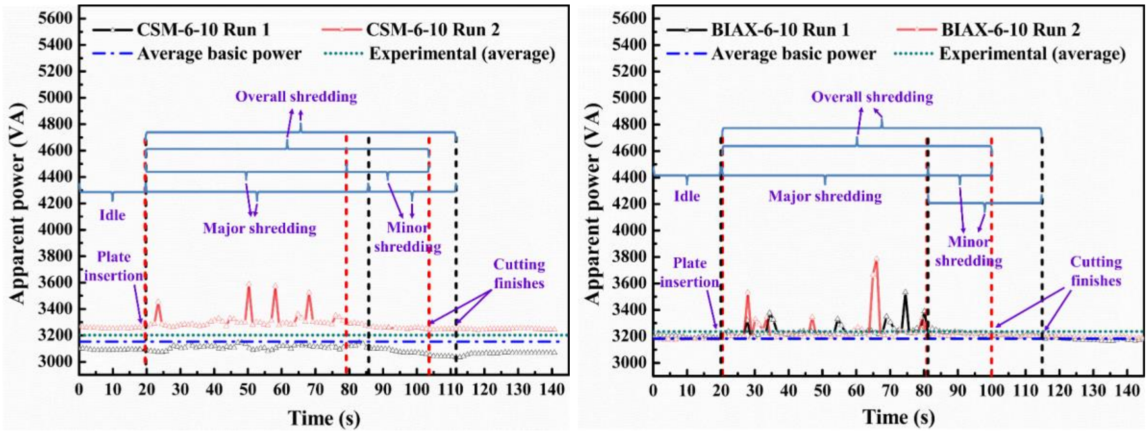


Figure 4. The instantaneous apparent power of TRIAX, UD, CSM and BIAX GFRPs shredding at feed rate 10 kg/hr & 6 mm screen size.

As shown in Figure 5, with a feed rate of 60 kg/hr and a screen size of 20 mm, the BIAX-20-60 gets the highest peak instantaneous power near 5700 VA, which is around 2400 VA above the basic power. The lowest instantaneous power is registered from the TRIAX-20-60 run, which only has 2200 VA above the basic value. The overall peaks distribution of UD and CSM are relatively homogeneous, while CSM's distribution seems flatter than that of UD's.

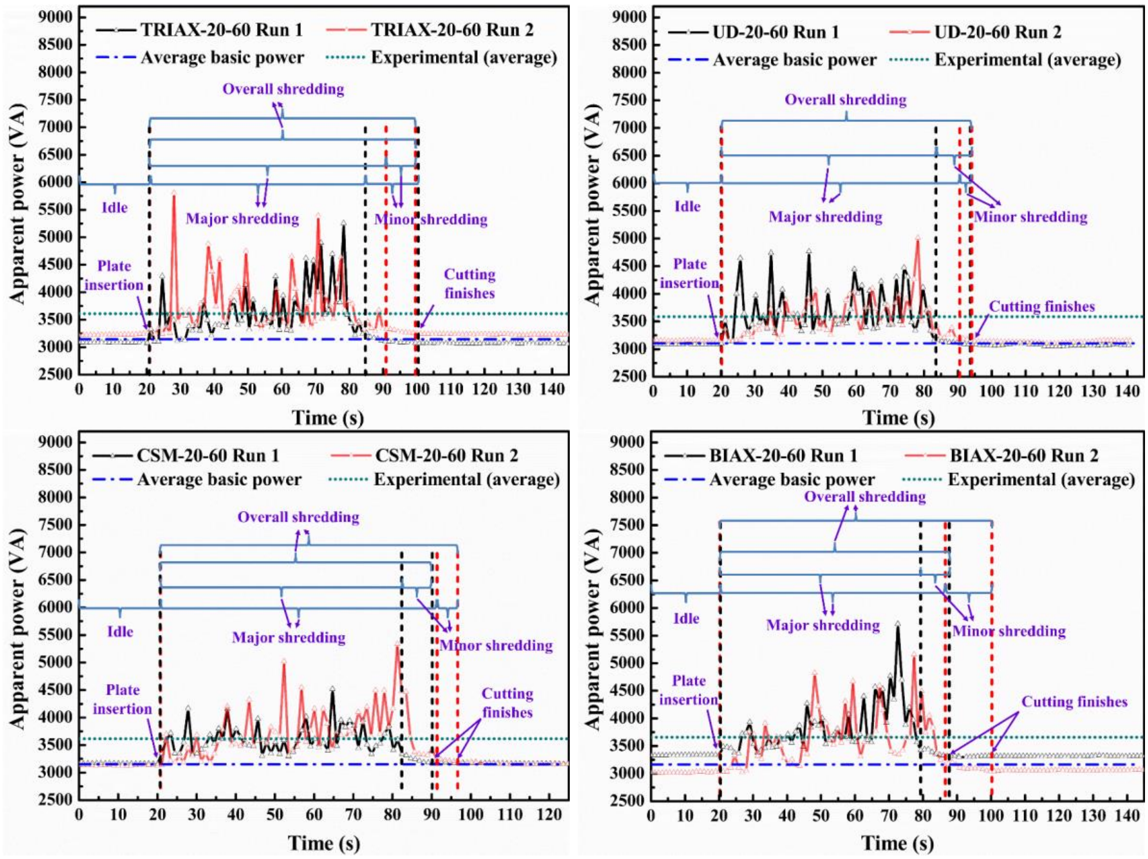


Figure 5. The instantaneous apparent power of TRIAX, UD, CSM and BIAX GFRPs shredding at feed rate 60 kg/hr & 20 mm screen size.

By reducing the screen size to 6 mm, the instantaneous peaks, as shown in Figure 6, can be seen becoming sharper. It can be known that there is also a single peak in the TRIAX-6-60 operation with more isolated peaks and gained a highest value of around 6300 VA, which is 3200 VA more than the basic power. BIAX-6-60 and UD-6-60 both get the highest peaks more than 6000 VA, but BIAX seems contains more overlapped bands. CSM-6-60 still shows a rather smoother curve and shorter shredding duration than other fabrics.

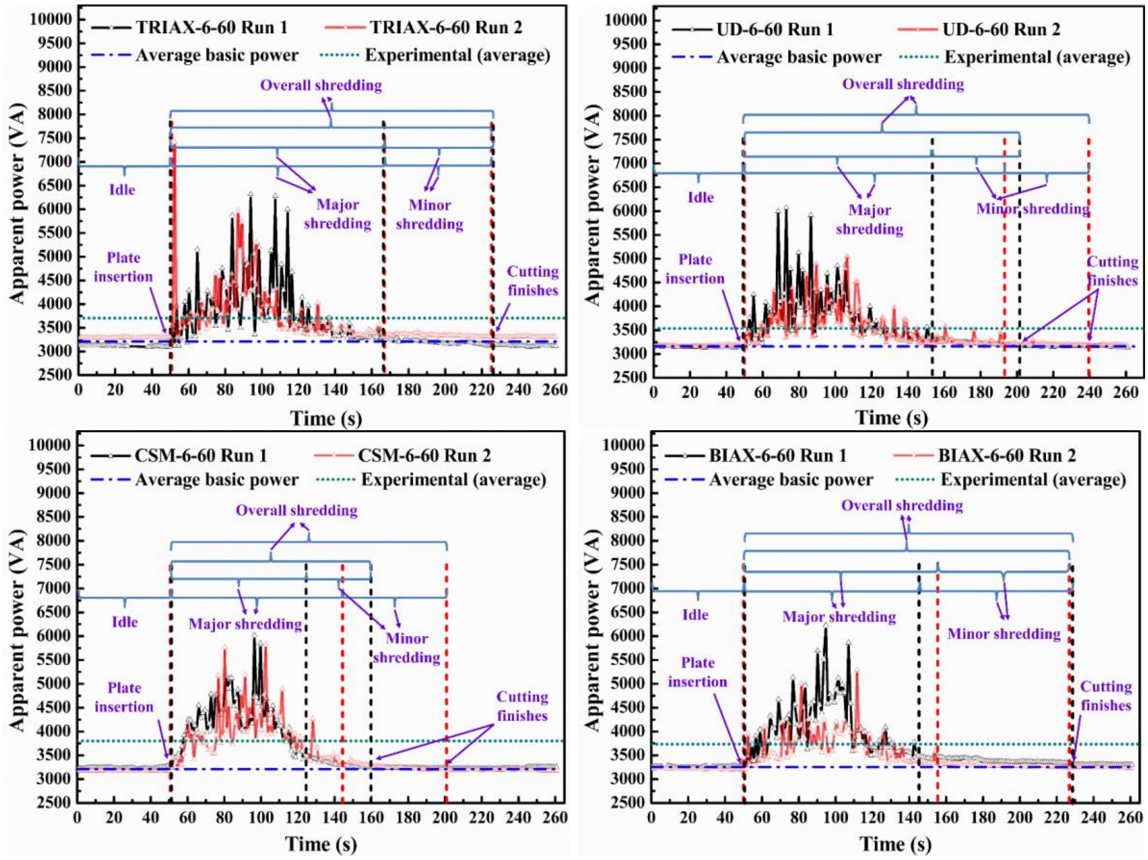


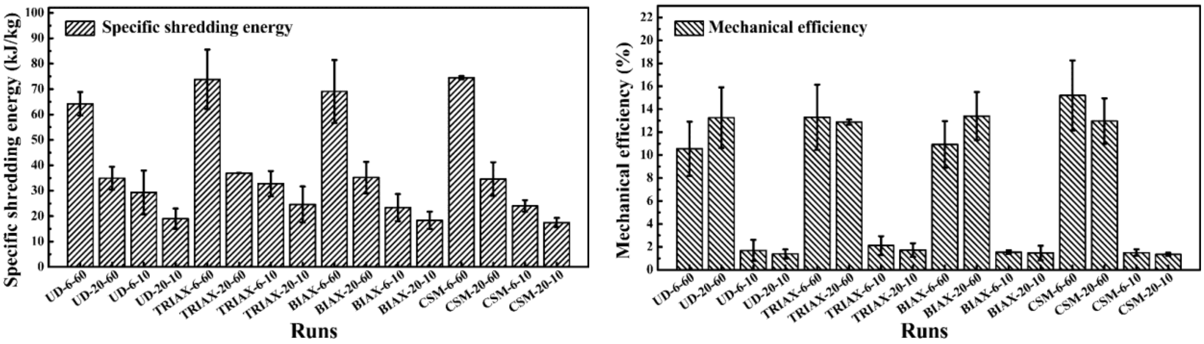
Figure 6. The instantaneous apparent power of TRIAX, UD, CSM and BIAX GFRPs shredding at feed rate 60 kg/hr & 6 mm screen size.

3.2. Specific shredding energy & mechanical efficiency

Figure 7 (a) shows specific shredding energy consumption of the GFRP materials. It should be noted that by sifting and resin burning-off test, those GFRP recyclates demonstrate almost a consistent distribution in particle yield and resin content. Both TRIAX and BIAX structures reveals similar energy consumption close to 83 kJ/kg when the feed rate and screen size were 60 kg/hr and 6 mm respectively. Then, a slightly lower energy consumption was observed from the CSM structure. Among them, the lowest energy consumption was obtained from the UD structures, i.e. around 70 kJ/kg. However, when operated in the other three conditions, namely, 60 kg/hr & 20 mm, 10 kg/hr & 6 mm and 10 kg/hr & 20 mm, the TRIAX and UD structures generally required more shredding energy than the CSM and BIAX structures. In this shredding study, wear to the cutting blade was not considered.

Figure 7 (b) shows the mechanical efficiency obtained from the current study. Large difference in efficiency was observed between BIAX-6-60 and BIAX-20-60, suggesting positive effect of screen size on reducing active power consumption. The CSM reinforced GFRPs that had been shredded in the same conditions also demonstrated the same positive results. At 60 kg/hr, the mechanical efficiency is around

8.2-15.7 %, but dropped to 0.8-2.2 % at lower feed rate of 10 kg/hr. These values are in consistent with the data presented by Woldt et al [13]. Based on our results, it can also be concluded that higher feed rate would benefit for higher mechanical efficiency.



(a) (b)

Figure 7. (a) Specific shredding energy and (b) mechanical efficiency under different conditions.

4. Conclusion
It was found that CSM reinforced GFRPs seemed to require a rather flat power supply than other structures, namely BIAX, TRIAX and UD, but required a longer secondary shredding period. For the specific shredding energy, TRIAX and BIAX structure required about 83 kJ/kg at 60 kg/hr feedrate & 6 mm screen aperture but CSM & UD are both around 70 kJ/kg. It can be concluded that GFRP reinforced by triaxial fabric, would consume higher specific shredding energy, especially at high feed rate and with a small screen size. Meanwhile, it was found that only 8.2-15.7 % power was used for shredding when feed rate was 60 kg/hr but the mechanical efficiency dropped significantly to about 0.8-2.2 % at a lower feed rate of 10 kg/hr. When adopting a larger screen size, both the shredding energy and total energy consumption could be reduced. While increasing the feed rate would increase specific shredding energy, but cutting down total energy demand due to its large scale.

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