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Influences of Main Machining Process Parameters and Tool Wear on The Machining Damage Generated During Edge Milling CFRP Composites

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ABSTRACT

Machining Carbon Fibre Reinforced Plastics (CFRPs) composites are typically accompanied by the appearance of machining damage which strongly impacts the structural integrity of composite parts during their service lives. Studying the correlation between machining damage and its affected factors has still been an open issue. Hence, it is necessary to do more research. This study focuses on investigating the influences of main process parameters and tool wear phenomenon in terms of machining length on the machining quality which was characterized by the surface roughness criterion, the ten-point max, Rz. A full factorial design of experiments was conducted including three levels of feed speed and two degrees of spindle speed. The results revealed that machining damage was mainly influenced by process parameters at a small machining distance, whereas at a longer machining distance, tool wear had a dominant effect on the machining quality than machining parameters. These findings could provide guidelines for selecting suitable machining parameters to enhance the machining quality of CFRP.

Keywords: *CFRPs; Machining Quality; Edge Milling; Cutting Condition; SEM*

Introduction

In recent decades, CFRP composites have been widely accepted in several

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important industries such as automotive, shipping, aircraft, and sports equipment because of their advantages including dimensional stability, high specific strength, and low density. Composite parts are frequently fabricated to near-net shapes to suit certain applications [1], but excess materials in the edge of moulded CFRP parts must be removed to get the required dimensions for assembly by secondary operations like milling, drilling and trimming processes [2]-[4]. There have been the fact machining processes of CFRP composites are frequently associated with the occurrence of machining defects in the machined surfaces [5]-[6] such as matrix cracking, matrix fibre interface debonding, matrix degradation, fibre pullout [7]-[9]. The induced machining defects may harmfully impact the machined surface integrity and the mechanical properties of CFRP structures during their service lives [5], [10]. For this reason, it is necessary to clearly know and suitably select the factors which influence the generation of defects, including machining parameters, tool geometries, and the wear phenomenon of cutting tools [11]-[13].

El-Ghaoui et al. [14] showed that the combination of high cutting speed and low feed speed induces better quality of machined surface when machining composite materials generates a smaller level of theoretical chip thickness or volume of cut materials, hence machining process is easy to perform. Similar results were also observed in the studies of other researchers [15]-[16]. However, other studies [17] revealed that machining at low feed speeds and high cutting speeds can result in severe defects due to the effects of tool wear. This finding is also identically documented in the study of Haddad et al. [18]. In machining CFRP laminates, because of the low thermal conductivity of the matrix component and the highly abrasive nature of carbon fibre, the contacting areas occur friction phenomenon making the cutting edge become quickly worn out. The evaluation of tool wear can be conducted by flank wear [19]-[21], and the radius of the cutting edge [22] or by machining length [23]. Almost studies in the literature have concluded that cutting speed and feed rate have strong influences on the generation of flank wear [21]-[24]. Elgnemi et al. [25] detailed that an increase in cutting speed or an increase in feed rate leads to augmenting the average tool wear. Moreover, feed rate has more impact on tool wear than that of cutting speed. This result is consistent with those documented by [26]. However, in the study of [27], the authors showed that cutting speed has a stronger impact on tool wear compared with those feed rates because cutting speed is the major factor influencing cutting temperatures.

It is clear that there have been contradictory results on the machinability of composite materials given by researchers. Despite numerous recent studies on machining composites, it remains a challenging task due to the material behaviour depending on non-homogeneity, anisotropy, and diverse reinforcement and matrix properties. The responses between cutting tools and different workpiece materials can be completely different.

Therefore, results in an experimentally particular study are not always fully applicable to those of another specific study. In order to answer the gaps which, contain the ambiguity in the machining composite study, the impacts of machining parameters and tool wear on machining quality when carrying out edge trimming of CFRP composites were experimentally studied in this research. Average surface roughness was selected to characterize machining quality. Six new carbide-cutting tools with three-helix flutes were used for testing. A full experimental design showing the combinations between three levels of feed speed and two levels of spindle speed was used to investigate the impact of machining parameters on machining quality. The effects of tool wear on the machining quality were conducted based on the evolution of machining length.

Experimental Procedure

The specimens used in this study were fabricated by laminating P2352 prepregs according to the stacking sequence of $[90°/90°/-45°/0°/45°/90°/-45°/90°/45°/90°]_s$, where each ply has a thickness of 0.26 mm. The total theoretical dimension of each plate is 300 x 300 x 5.2 mm. Before the milling test, each plate was cut into the size of 300 x 150 x 5.2 mm with the cutting direction along 150 mm length. The CFRP properties are further described in Table 1. A Mazak vertical centre smart 530C (Yamazaki Mazak Corporation, Japan) was utilized to perform the edge milling tests. Six cutting conditions were carried out, with the combination of three feed speeds V_f, (500 mm/min, 1000 mm/min, and 1500 mm/min) and two spindle speeds N, (8000 rpm, and 10000 rpm). All tests were performed without coolant (dry machining). Each cutting condition was carried out with the machining length of 3.0 m or 3000 mm, and the feed direction parallel to the dimension of 150 mm of CFRP plate. This corresponds to twenty tool paths of the edge milling process (20 x 150 mm=3000 mm). Six new carbide tools (three-helix flutes, 6 mm shank diameter, helix angle of 45°, rake angle of 11°, and clearance angle of 9° - Figure 1) were used in edge milling. The machined surface was unfixed and quantitatively evaluated by measuring surface roughness, R_z, and its average values were calculated by three measurements. A roughness tester namely SJ-210 Mitutoyo (Mitutoyo Corporation, Japan) with a cut-off length of 0.8 mm and transverse length of 5.0 mm was employed to test the machining quality. The optical images of the cutting tool were taken by KEYENCE VHX-6000 digital microscope to state the tool wear phenomenon (Figure 2). In order to quantify the state of machining damage induced, the microstructure of machined surfaces was investigated by Scanning Electron Microscope (SEM) referenced under “JEOL-JSM 5410 LV” (Figure 3).

Figure 1: Carbide milling cutter with three-helix cutting edges

Table 1: Mechanical properties of P2352 prepreg

Density (g/cm^3)	Longitudinal shear modulus (GPa)	Longitudinal Young's modulus (GPa)	Compressive strength (MPa)	Tensile strength (MPa)	Poisson's ratio
2.63	6.21	162	1552	2844	0.34

Figure 2: Keyence VHX-6000 digital microscope

Figure 3: SEM machine referenced under JEOL-JSM 5410 LV

Results and Discussion

Analysis of induced defects observed in machined surface

After machining, the microstructures of the machined surface were analysed by using SEM observation. Three positions of machining length (*Lc*) were considered for each cutting condition, e.g. *Lc*=15 cm, 150 cm, and 300 cm. Figure 4 presents SEM images of the machined surface obtained at a spindle speed of 8000 rpm and feed speed of 500 mm/min. The results indicated that there was no significant difference in machining defect levels between those at machining lengths of 15 cm and 150 cm where small levels of machining defects were visualized at the fibre direction of -45°. However, at a machining length of 300 cm, a higher level of machining damage in the form of craters or valleys sited at the fibre direction of -45° was observed when using the magnification of 400 µm. The dominant type of damage observed in this case was fibre pullout. The nature of fibre pullout is due to the fact that the advance of cutting edges causes the severe out-of-plane displacement and deformation of the fibres which generate the induced defects in the forms of fibre pullout, and delamination intralaminar shear along fibre–matrix interface [28]. The machining defects dominantly observed at the position of the fibre angle of -45° as previously mentioned are attributed to the chip formation [29]. Consequently, the machined surface at fibre locations of -45° was more irregular than that at other fibre locations [30]. It was observed that the worst quality of the machining surface was obtained at a longer distance when machining with a small feed speed. This is due to the increase in contact areas between the workpiece and the cutting edge, leading to a higher level of friction, higher machining temperatures and quicker wear of the cutting edge, accordingly [18]. Wang et al. [31] suggested that materials are pushed instead of being sheared at a short cutting distance, and trimming is more difficult due to wider contact between the cutting edge and the workpiece. In this case, the springs back caused by elastic recovery after the tool passer over are experimentally observed. The bouncing back region is twice bigger than the radius of the cutting edge in the fibre locations of -45°, resulting in rougher machined surfaces at longer machining lengths. This information was confirmed by the SEM images in Figure 5 which shows the wear process of cutting edge for different distance cutting with the same machining condition previously mentioned. The wear patterns of the tool in terms of the nose radius of the cutting edge were crucially influenced by the machining distance. Indeed, from Figures 5(a) and 5(b), after a machining distance of 1.5 m, the radius of the cutting edge was importantly modified, namely worn cutting edge, and bigger compared with that before machining (sharp cutting edge). Moreover, in this case, the microchips in the form of dust stuck in the rake face of the cutting edge were visualized. When the cutting distance reached 3.0 m, the modification of the cutting edge was a higher level, and more adhered chips in the rake face were also visualized. A similar observation was also documented in the research of Haddad et al. [18]. They explained that the machining temperatures reached the glass transition temperature (T_g) of the matrix which favours the adhesion of the broken chips on the active surface of the tools. At higher cutting distances the bigger cutting edge radius led to an increase in temperatures. This was why more adhered chips were seen in Figure 5(c).

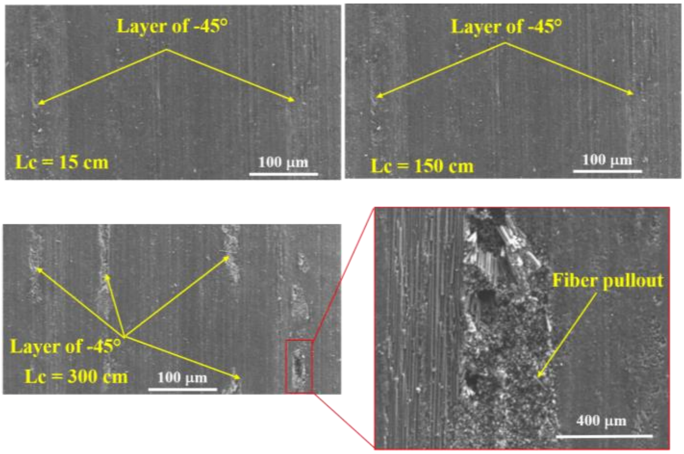

Figure 4: Machining damage observed with a feed speed of 500 mm/min and spindle speed of 8000 rpm

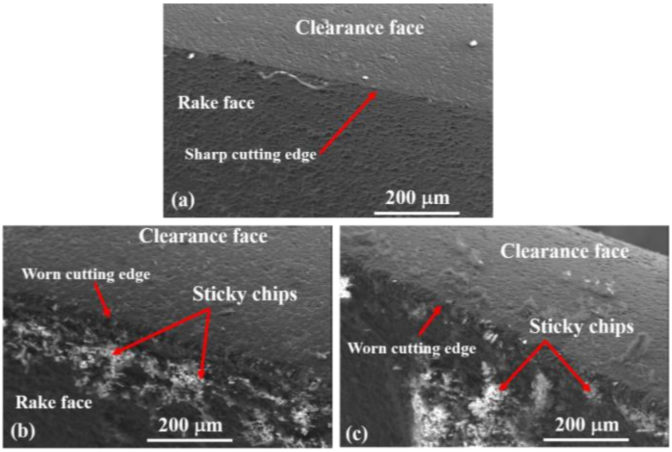

Figure 5. SEM images of cutting edges; (a) before machining and after machining distance of; (b) 1.5 m, and (c) 3.0 m for a spindle speed of 8000 rpm with a feed speed of 500 mm/min

At the cutting condition of 1000 mm/min feed speed and 8000 rpm spindle speed, the results depicted in Figure 6 showed that the machining damage level was almost identical regardless of machining length. This was explained as the cutting length is small, i.e. the cutting tool can be considered as new, and the machining damage of the surface is mainly influenced by the theoretical thickness of the chip [32]. However, as the cutting length increases, the radius of the cutting edge also increases, and the wear of the cutting edge becomes more significant, which leads to a more difficult machining process [33]. This is the wear phenomenon of cutting tools. Nevertheless, the tool wear in this cutting condition was insignificant due to the short contacting time between the workpiece and the cutting edge, in comparison with the case of a feed speed of 500 mm/min. Consequently, the degree of machining defects increases slightly as the machining length increases [11]. The variation of machining damage level with machining length at a feed speed of 1500 mm/min was similar to that given by a feed speed of 1000 mm/min. These results are consistent with those documented by Nguyen-Dinh et al. [17]. Moreover, it was observed that the machined surface exhibited similar characteristics when the spindle speed increased to 10000 rpm, regardless of the feed speed. Thus, the results obtained under this condition were not discussed in this text.

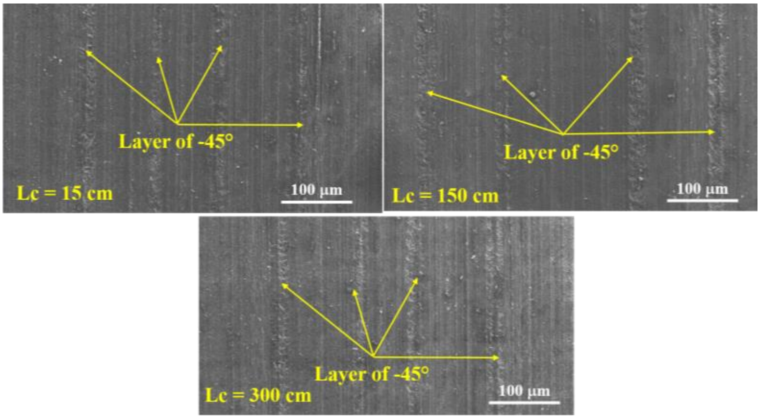

Figure 6: Machining damage observed with a feed speed of 1000 mm/min and spindle speed of 8000 rpm

Influence of process parameters on the machining quality

In this section, machining damage was quantitatively estimated to check machining quality by using ten-point mean (*Rz*) instead of using average surface roughness (*Ra*). This is according to the recommendations by the authors in the literature [11] where it was concluded that *Rz* is more responsive to machining parameters than *Ra* and hence is more suitable for representing surface roughness of composite materials. Figure 7 shows the evolution of surface roughness as a function of machining parameters. The results showed that surface roughness decreases when feed speed varies from 500 mm/min to 1000 mm/min, but increases when feed speed changes from 1000 mm/min to 1500 mm/min. These tendencies were similarly observed in both cases of spindle speed. Regarding the first case, e.g. feed speed varies from 500 mm/min to 1000 mm/min, surface roughness (*Rz*) reduced from 8.46 µm to 7.56 µm corresponding to the reduction of 10.7% for a spindle speed of 8000 rpm, while the per cent reduction by 23.3% was for a spindle speed of 10000 rpm. Considering the second case, i.e. feed speed varies from 1000 mm/min to 1500 mm/min, it was noticed that surface roughness increased by 88.3% (from 7.56 µm to 14.24 µm) and by 63.9% (from 7.16 µm to 11.73 µm) for spindle speed of 8000 rpm and 10000 rpm, respectively. Moreover, it was realized that the effect of spindle speed on the surface roughness in this was less profound, likely due to the selected range of sufficient spindle speed to generate the different machining damage levels [34].

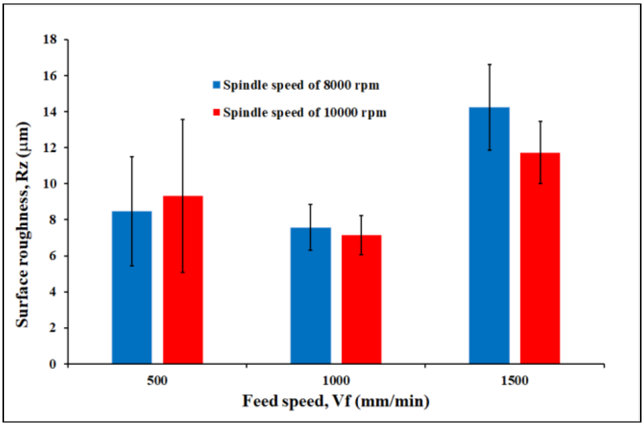

Figure 7: Influences of machining parameters on ten-point mean (*Rz*)

The results in Figure 7 can be interpreted that when the feed speed increases and/or the spindle speed decreases the theoretical thickness of the material to be cut also increases [2]. However, at low feed speed, tool wear increases rapidly [18], which makes the effect of cutting tool wear relatively more dominant than that of cutting condition on surface roughness [34]. This was why the surface roughness varies in opposite directions for the first and second branches of Figure 7. To be more specific, when the feed rate increased from 500 mm/min to 1000 mm/min, the surface roughness decreased mainly due to the influence of wear. Conversely, in the remaining case, the surface roughness increases due to the important influence of the machining parameters (or chip thickness). The variations of surface roughness for the cutting condition are consistent with the variation of the degree of surface defects for the cutting mode, as presented in the previous part of this study. Notably, the results in this study differ from those reported by [2], [32] where the authors revealed that machining with low feed speed and high cutting speed can generate a good quality machining surface.

Influence of radius cutting edge on the machining quality

Figure 7 displays the average surface roughness values for each cutting condition. The values of the standard deviation were observed to be considerably high, with the highest value of 4.23 μm given by the machining condition of spindle speed of 10000 rpm and feed speed of 500 mm/min. The reason is because of the large dispersion between the measured values at the 20 tool paths of each cutting condition. In particular, it was seen that at the feed speed of 500 mm/min (in both cases of spindle speed), the standard deviation of the surface roughness was maximum. This was another clear reflection of wear on the surface quality of CFRP composite machining surfaces. The influence of wear in terms of machining length on surface roughness was able to see in Figure 8 for a spindle speed of 8000 rpm. The largest increase in roughness with the machining length was observed for a feed speed of 500 mm/min, increasing from 3.33 µm to 15.33 µm corresponding to 203.1%. Surface roughness increased with increasing in cutting distance by 62.2% and 61.7% for feed speeds of 1000 mm/min and 1500 mm/min, respectively. This increase in surface roughness is due to an increase in the radius of the cutting edge, making the cutting process more difficult as presented in Figure 5 [31]. The cutting-edge radii could be measured by Keyence VHX-6000 Digital Microscope as shown in Figure 9. The increase of cutting-edge radii at two cutting distances of 15 cm and 300 cm with a feed speed of 500 mm/min and spindle speed of 8000 rpm were shown in Figure 10. The results showed that at a cutting distance of 15 cm, the radius of the cutting edge is 9 μm, while at a cutting distance of 300 cm, the one was 22 μm. The dependence of surface roughness on machining length was similarly observed in the case of 10000 rpm spindle speed as shown in Figure 11. The highest augmentation of surface roughness with increasing cutting distance was observed at a feed speed of 500 mm/min. For example, surface roughness increases by 360.3% when cutting distance reaches 3.0 m at a feed speed of 500 mm/min, while the relative increases at a feed speed of 1000 mm/min and 1500 mm/min are 54.7% and 52.5%, respectively.

The machining case with a feed speed of 500 mm/min exhibits the highest increase (360.3%) in surface roughness compared to other cutting conditions. Nguyen-Dinh et al. [33] explained that when machining with a high spindle speed, if a spiral is developed, the contact surface between the tool and the workpiece is larger than at lower spindle speed. When combined with numerous contacts per unit time at low feed speeds, this results in increased friction and heat, leading to faster tool wear [11]. The wear rate of the cutting tool directly affects the quality of the machined surface, results in many types of defects, leading to the higher value of surface roughness. The cutting edge radius given by Keyence for this machining condition was 28 µm.

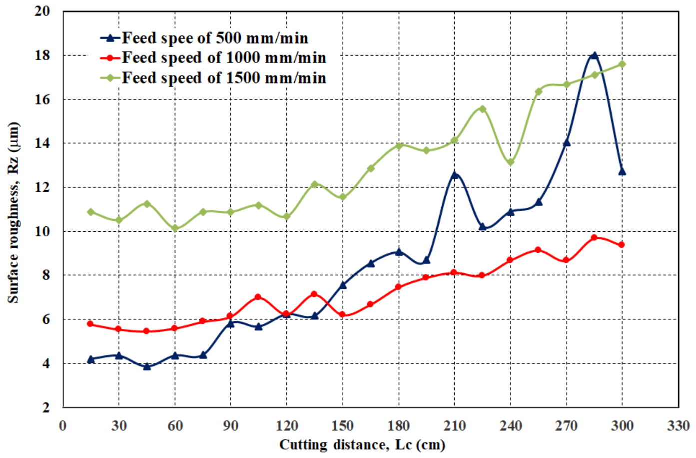

Figure 8: Evolution of *Rz* vs machining length for spindle speed of 8000 rpm

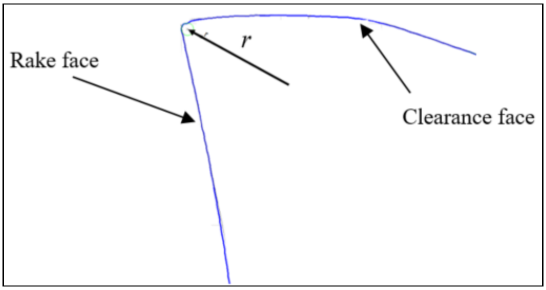

Figure 9: Profile of cutting edge radius measured from the software available in Keyence VHX-6000 digital microscope

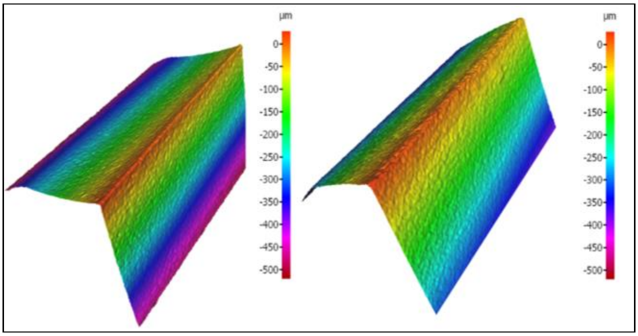

Figure 10: Cutting edge form after machining at the length of; (a) 15 cm, and (b) 300 cm with feed speed of 500 mm/min and spindle speed of 8000 rpm

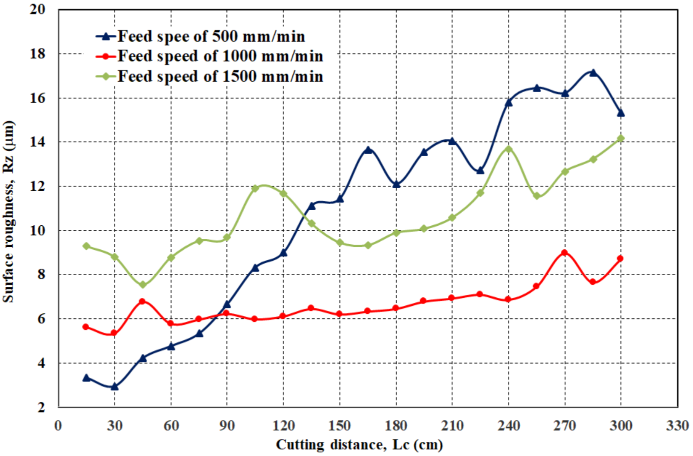

Figure 11: Evolution of *Rz* vs machining length for spindle speed of 10000 rpm

Conclusion

Experimental method was applied in this study to investigate the influence of machining parameters and tool wear on the quality of the machined surface when dry milling of CFRP composite plates. The quality of the machined surface was evaluated quantitatively using the surface roughness criterion. The conclusions about the research results of this study are summarized by the main results as follows:

i. The results of qualitative assessment of the surface quality of CFRP composite panels were shown through SEM observations. Machining defects are found to be dependent on cutting conditions when cutting length is small. However, when the cutting length increases, wear significantly influenced the formation of machining defects (observed through SEM), especially when machining with a small feed speed.

ii. The surface roughness measurement results accurately reflected the machining quality when correctly describing the evolutions in the occurrence of machining defects observed by SEM. That is, when the machining length increased, the machining with a small feed speed, due to the large contact between the cutting tool and the workpiece, increases the friction and cutting heat, leading to the rapid wear of the cutting edge.

iii. The machining length, characterized by the increase of the cutting-edge radius, had a great influence on the quality of the machined surface. Machining with a large feed speed, due to the small contact length, resulted in slower increase in the wear rate of the cutting edge, leading to little change in the quality of the machined surface in terms of evaluation. Meanwhile, machining with a small feed speed increases the contact length between the cutting edge and the workpiece, causing friction and heat to increase, leading to a rapid increase in the tip radius. As a result, the surface roughness increases rapidly by 203.1% and 360.3%, respectively when machining at the spindle rotation speed of 8000 rpm and 10000 rpm.

Contributions of Authors

All authors discussed the original idea. N.T.H carried out the experimental tests and analyzed the results, wrote the original manuscript with support from N.D.N. All authors provided critical feedback and helped shape the research, analysis, and manuscript. Finally, N.D.N supervised this work and revised the article. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interests

The author declares that they have no conflicts of interest.

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