Cutting Forces and Flank Wears Analysis for End Mill Processes Using HSS Tools Cryogenic Treatment When Cutting PFRP Material

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Abstract. This study aims to characterize the wear and cutting forces of cryogenically treated and non-treated high-speed steel (HSS) tools when milling PFRP work piece. Pineapple fibre mixed with unsaturated polyester resin was prepared for the work piece. While three levels of cryogenic treatment were applied to the HSS tools with time immersion parameters in liquid nitrogen and time duration. The end mill process using the tools was applied to examine wear and cutting forces. Significant improvement of flank wear ensued on the first tool variation with average flank wear of 90 µm where the tool was treated cryogenically with the immersion of 48 hours and raising the heat up to 150o then normalized and repeating twice. Severe flank wears arisen on a non-treated cryogenic tool with 115 µm. The axial force, cutting force, and thrust force the tool variation varied in the range of 0.4 N to 2.5 N, 40 N to 210 N, 5 N to 28 N, respectively. It can be concluded that cryogenic treatment on HSS employing cryogenic treatment on the first variation of the tool is recommended to be applied in workshops.

Keywords: Cutting forces; Flank wear; Treated cryogenic HSS tool, PFRP, End mill

1. Introduction

Products made from natural fibre-reinforced composites are increasingly becoming an industrial concern due to their advantages such as low cost, biodegradability, relatively good mechanical properties, chemical reactions, and corrosion resistance. It is not as easy as metal machining. Machining difficulties due to irregular fibre structure are a challenge to be investigated. The lay-up of fibre would impact cutting forces, tool wear, chatter, and work piece surface deterioration when improper machining parameters are applied.

The literature shows many of the experimental works that have been conducted on cutting forces, tool wear, and selection of appropriate machining parameters. End-milling experiments of GFRP composite to examine their machinability have been carried out by Azmi [1]. Offered ANFIS models have shown the relationship between cutting force and the growth of tool wear. Experiments show that better machinability and higher surface finish in the machining of GFRP has been achieved by selecting the right tool insert [2]. Moreover, the machinability tests were conducted through different cutting conditions. Many studies on improvement in surface roughness, cutting force, cutting temperature, and tool flank wear in machining composite by selecting the proper cutting speed, feed-rate, and depth of cut has been reported [3-7] in literature. On the other hand, research of the HSS tool in the machining of FRP has become attractive since this tool material has been widely used in the manufacturing industry because of its useful properties at a reasonable cost. Indeed, the HSS tool was not reliable enough to cut...
FRP material; therefore, many researchers made improvements to the HSS tool's performance by cryogenic treatment. Details reviews of the cryogenic treatment of the HSS tool were conducted, concluding the effectiveness of heat treatment that could widely be applied to various cutting tools and reduced production costs [8-10]. The deep cryogenic treatment has been carried out to improve HSS tool performance [11-13].

Despite many studies on machinability, cutting forces and tool wear for FRP machining are seen in the literature, very few have focused on HSS treated cryogenic tools affecting machinability, cutting forces and wear. This is a problem for the workshop industry to get references in increasing productivity. The purpose of this research is that the characterization of wear and cutting forces has been assessed using four different HSS tools, namely three types of high speed steel (HSS) tools which are cryogenically processed and not processed when milling PFPR work pieces. This study's results are expected to be used as a reference by the workshop industry in reducing production costs and increasing productivity.

2. Preparation of HSS Tool
The purpose of this process is to achieve a better steel microstructure and obtain the most desirable properties. The complete process in sequence consists of austenitizing, quenching, cryo processing, and tempering [8]. In this research, three types of cryogenic tools were prepared by adopting three cryogenic treatment methods [8, 14, 15] and a cryogenically non-treated HSS tool.

2.1. Temperature Variation of the Cryogenic Treatment Process
In the first variation, the cryogenic treatment was applied using shallow and deep cryogenic treatment at a cooling rate of 0.5 °C/min to prevent potential damage in the tools' microstructure. The treatment is the immersion process using cryogenic liquid (liquid nitrogen) at a temperature of -196 °C for 48 hours, then raising the heat up to 150 °C for 10 hours, then normalized and repeating twice. The second variation of cryogenic treatment is a cryogenic process at a temperature of -196 °C for 24 hours and raising the heat up to 204 °C for 1 hour, then normalized and repeating three times. The third variation of cryogenic treatment is a cryogenic process with a temperature of -196 °C for 24 hours and raising the heat up to 200 °C for 2 hours then normalized. The graph of immersion time for each variation can be seen in Figure 1.
Figure 1. (a) The first variation of cryogenic tools [8], (b) The second variation of cryogenic tools [14], (c) The third variation of cryogenic tools [15], and (d) Cryogenically treated HSS tools.

The PFRP work piece material was fabricated using Unsaturated Polyester Resin BQTN-157, Yukalac, and pineapple fibers as reinforcement. The fiber was blended and sizing into 25 µm by screen level. The resin was poured into a box-shaped mold and followed by the fiber to get the work piece’s rigid shape. The mixture was stirred repeatedly for 5 minutes so that the resin catalyst was evenly distributed. The size of the work piece can be seen in Figure 2.

Figure 2. PFRP work piece material.

3. Experimental Setup
The PFRP work piece material was mounted on end-milling and orthogonally cut using four different HSS tools. The experiment was conducted at a spindle speed of 283 rpm, feed-rate of 104 mm/min, cutting depth of 1 mm, and cutting length of 40 mm. The cutting force, axial force, and thrust force were acquired with strain gauges based dynamometer. For validation purposes, three cutting experiments were applied. The measurement setup can be seen in Figure 3. Summary of used tools are summarized in Table 1.
4. Results and Discussion

4.1. Axial Force, Cutting Force, and Thrust Force
The axial force, Fz results for A, B, C and D tools can be seen in Figure 4, Figure 5, Figure 6, and Figure 7, respectively. The cutting force, Ft of A, B, C and D tools can be seen in Figure 8, Figure 9, Figure 10, and Figure 11, respectively. A, B, C, and D thrust, Fy force can be seen in Figure 12, Figure 13, Figure 14, and Figure 15, respectively.

| HSS Tool Variation | Cryogenic treatment | Adopted |
|--------------------|---------------------|---------|
| A First            | A deep cryogenic treatment temperature of -196°C for 48 hours, then raising the heat up to 150°C for 10 hours, then normalized and repeating twice | [8] |
| B Second           | A cryogenic process at a temperature of -196°C for 24 hours and raising the heat up to 204°C for 1 hour, then normalized and repeating three times | [14] |
| C Third            | A cryogenic process with a temperature of -196°C for 24 hours and raising the heat up to 200°C for 2 hours then normalized | [15] |
| D Forth            | Non-treated HSS tool |         |

Figure 3. Setup measurement device and PFRP work piece material on the dynamometer.

Table 1. Summary of tools treatment.

![Figure 4. Axial force of the first tool variation.](image1)

![Figure 5. Axial force of the second tool variation.](image2)
Figure 6. Axial force of the third tool variation.

Figure 7. Axial force of the fourth tool variation.

Figure 8. The cutting force of the first tool variation.

Figure 9. The cutting force of the second tool variation.

Figure 10. The cutting force of the third tool variation.

Figure 11. The cutting force of the fourth tool variation.
Figure 12. The thrust force of the first tool variation.

Figure 13. The thrust force of the second tool variation.

Figure 14. The thrust force of the third tool variation.

Figure 15. The thrust force of the fourth tool variation.

Figure 8 shows the axial force (Fz) of tool A (the first variation of the HSS tool cryogenically treated) with three times experiments and a depth of cutting of 1 mm each where the axial forces vary in the range of 1 N to 2.5 N. While, Figure 9 shows the axial force (Fz) of tool B (the second variation of cryogenically treated HSS tool) with three times experiments and a depth of cut of 1 mm each where the axial forces ensue in the range of 0.4 N to 2 N. Furthermore, Figure 10 shows the axial force (Fz) of tool C (third variation of cryogenically treated HSS tool) with three experiments and a depth of cut of 1 mm each where the axial forces transpire in the range of 1 N to 2.5 N. Finally, Figure 11 shows the axial force (Fz) of tool D (cryogenically non-treated HSS tool) with three experiments and a depth of cut of 1 mm each where the axial forces occur in the range of 1 N to 2.5 N.

The average axial forces (Fz) in each tool range from 0.4 N to 2.5 N. This force is relatively small. It is natural because, according to the axial force theory (Fz), the end milling does not make any axial motion. Still, the axial force may arise due to vibrations during the cutting process so that the work piece goes up and down.

Average cutting force (Ft) is obtained from the summation of the maximum cutting force divided by the data amount. The average cutting force (Ft) on the first cryogenic tool variation is 42.0127 N, the average cutting force (Ft) on the second cryogenic tool variation is 119.2925 N, the average cutting force (Ft) on the third cryogenic tool variation is 135.157 N. The average cutting force (Ft) on the fourth tool variation cryogenically non-treated is 133.5846 N. It can be seen that the smallest cutting force (Ft) occurs in the first cryogenic tool variation. In contrast, the most extensive cutting force ensues in the third cryogenic tool variations and the fourth tool. The cryogenic process in the first tool allows the tool to be tougher, thus increasing the tool's cutting speed, which results in reduced cutting forces [12].

The average cutting forces (Ft) are fluctuated in the range of 40 N to 210 N. Fluctuations arise due to the spread of fibre in resin, which has different strengths at each point. Consequently, when the tool
cuts the soft part, the cutting force ensues low, and when the tool touches the hard part, cutting forces goes high. Fluctuating cutting force \((F_t)\) can also be analysed because of the wear on the tool when cutting the pineapple fibre composite material so that the cutting force occurs quite large. However, the cutting force in the first tool variation is quite low compared to other tool variations. It happens because the wear rate of the first tool variation is lower than other tool variations.

The average thrust forces \((F_y)\) arising in each tool is in the range of 5 N to 28 N. The thrust force \((F_y)\) also fluctuates, but not as much as the fluctuation of the cutting force \((F_t)\). High fluctuations ensue when the cutting edge starts to touch the PFRP work piece’s surface, and the smallest fluctuation occurs when the cutting has finished. Fluctuations also happen due to PFRP work pieces' unevenness at each point, so the tool reacts provides resistance when cutting, resulting in vibrations in the work piece

### 4.2. Tool Wear Measurement Results

Figure 16 shows the wear measurements of four HSS tools in which three tools with three variations of cryogenic treatment and untreated tools. After the milling process, the wear of the cut tool edges was observed using an Olympus SZX10 stereo microscope. The HSS tool is positioned perpendicular to the microscope. The way to see the wear is taking 10 points perpendicular to the line drawn along the cutting edge and then averaging the wear. The measurement uses the Olympus SZX10 stereo microscope. Flank wear measurement calculation method by drawing a 10-point line can be seen in Figure 16.

![Flank Wear (Vb)](image)

**Figure 16.** Wear the calculation method by drawing a 10-point line.

**Figure 17.** Flank wear graph \((V_b)\) of the four HSS tool variations.
It can be seen in Figure 17 that by three experiments, the graph trend remains consistent for each trial where the flank wear increases with increasing tool variation. The average flank wear (Vb) ensues in the first tool variation is 90 μm, in the second tool is 101 μm, in the third tool variation is 110 μm, and in the fourth variation is 115 μm.

The smallest flank wear (Vb) occurs in the first cryogenic tool variation, an immersion treatment into cryogenic liquid (liquid nitrogen) at -196 ℃ for 48 hours. It then raises the heat up to 150 ℃ for 10 hours, then normalized and repeating two times. In contrast, the most significant wear arises in the fourth tool variation. Thus, it can be concluded that an efficient cryogenic treatment with toughness and reliability for cutting composites occurs in the first variation HSS tool followed by the second variation HSS tool then the third tool variation HSS tool. Whereas the flank wear (Vb) of the fourth variation, HSS tool without treatment, is extensive compared to the cryogenically treated-HSS tool. Figures 18-21 show snapshots of the flank wear (Vb) captured using the SXZ10 stereo Olympus microscope.

Figure 18. Flank wear (Vb) of the first cryogenic tool variation in the second experiment.  
Figure 19. Flank wear (Vb) of the second cryogenic tool variation in the second experiment.

Figure 20. Flank wear (Vb) of the third cryogenic tool variation in the second experiment.  
Figure 21. Flank wear (Vb) of the fourth cryogenic tool variation in the second experiment.

The treatment of various cryogenic methods on the HSS tool provides better machining performance for increased productivity and decreased production costs. Information on the results of this experiment can be used as a workshop industry to improve machine performance. Application in the workshop industry will provide several advantages, including; longer tool life increased productivity and ultimately will reduce production costs.
5. Conclusions
Experimental results have shown a comparison between HSS tools with cryogenic treatment and an untreated HSS tool. The first variation HSS tool provided good performance by giving the smallest flank wear of 90 µm with the axial force, cutting force, thrust force component values of 2.5 N, 42.0127 N, and 17.5 N, respectively. The tool's cryogenic treatment was by immersing into cryogenic liquid (liquid nitrogen) at -196°C for 48 hours, then raising the heat up to 150°C for 10 hours, then normalized and repeating twice. Severe flank wears arisen on a non-treated cryogenic tool with 115 µm. The axial force, the cutting force, and the thrust force fluctuated in the range of 0.4 N to 2.5 N, 40 N to 210 N, 5 N to 28 N, respectively. The cutting force will increase with increasing feed-rate. Increasing the feed-rate will result in high friction and impact loads, thereby increasing the cutting temperature. As a result, there are abrasive and adhesion mechanisms that cause expansion and erosion of the main cutting edges. The greater the feed-rate used, the greater the flank wear and cutting force occurring in the milling process of pineapple fibre-reinforced composite work piece. Information on experimental data on cryogenic treatment on HSS can be used as a recommendation to the workshop industry for better productivity.

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