Characterization of Surfaces Generated in Milling and Abrasive Water Jet of CFRP Using Wavelet Packet Transform

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Abstract. Polymer matrix composites find extensive application in aerospace and automotive industry. Although composites are molded to a near net shape, secondary machining such as hole-drilling and edge trimming is unavoidable. Conventional milling and Abrasive water jet are widely employed processes to cater the machining needs. Because of the nature of material-tool interaction, both the processes have their limitations resulting in machining induced damages such as matrix cracking, exit-delamination, fiber pull-outs, spring-back, interply delamination, striations, abrasive embedment, and kerf taper.

Surface roughness plays a pivotal role in determining the damage induced during the machining processes. Traditionally roughness parameters – average roughness (R_a) and ten-point average (R_z) are used to characterize the surfaces. Often, the use of cut-off wavelengths, governed by standards, result in poor distinguishability for machined surfaces of anisotropic materials such as polymer matrix composites (PMC). The insensitivity and poor distinction in certain cases leads to unsound judgment in characterizing the machining induced damage, and also in the selection of process parameters. This necessitates other methods and indicators that better identify the surface signature and correlate with the process parameters. In this study, a novel approach is proposed in which wavelet packet transform (WPT) is applied to the machined surface profiles. An indicator (ratio of wavelet packet energy and entropy) is defined to characterize the surface and better predict the surface quality as a function of machine tool, material and process variables. Regardless of the type of CFRP and machining process (AWJ and conventional milling), WPT indicator proved to be a better predictor of the machining process (R^2 > 80%) when compared with R_z (R^2 < 67%).

1. Introduction

Although composite materials (CFRP) are molded to a near net shape, secondary machining is often required to meet the dimensional tolerances and attain desired functional performance [1,2]. Two primary processes in practice are conventional trimming and abrasive water jet (AWJ) machining. The anisotropy of CFRP laminates decide the resistance offered to the machine tool, which in turn governs the surface quality. In conventional milling, because of the abrasive nature of fibers, tool wear is prominent. Besides, matrix cracking, exit-delamination, fiber pull-outs, spring-back and interply delamination limits the process speed and affects the process viability [3]. Abrasive Water jet is a high speed alternative to conventional milling, but striations due to jet energy loss, abrasive embedment, exit delamination and kerf taper are a few limitations [4–6].

The damages and defects introduced in CFRP during machining could be reflected on the surface or sub-surface. If unaccounted in the component design, these defects could severely affect the static and dynamic mechanical properties [7]. The relationship between the surface features reflecting these
defects and process parameters is important for a defect free machining. Traditionally, gaussian filter is
used to calculate roughness parameters, however the technique is computationally expensive and often,
more than one parameter is required for wholesome characterisation of the engineering surfaces.
Wavelet analysis is has proven to be an effective tool in signal analysis. Lee et. al. [8] were among the
first to propose the morphological characterisation of engineering surfaces using Wavelet transform.
Kim et. al studied correlated the surface quality of steel with wavelet energy signatures [9]. Wang et. al.
[10] used Wavelet Packet transform for feature extraction and roughness evaluation. There is a dearth
of literature in studying the surfaces machined with Abrasive Water Jet (AWJ), especially for
challenging materials such as prepreg-based CFRP. Pahuja et al. [11] used discrete wavelet analysis to
study the surfaces of AWJ machined carbon foam.
In this study, a novel approach is proposed where wavelet packet transform (WPT) alongwith a surface
feature indicator – energy-entropy coefficient is used to characterize the machined surfaces of prepreg-
based, random chopped discontinuous fiber composite – HexMC. The random and inhomogeneous
nature of the material results in localised damage, necessitating effective techniques to identify these
damages [12,13]. Upon comparison with traditional roughness parameters, WPT energy-entropy
signature was found to be superior in describing the surface texture, and its correlation with the
machining process used to generate those surfaces.

2. Materials, Methods and Equipment
In this study, random chopped discontinuous fiber composite (DFC), commonly known as HexMC®
was used. HexMC is made up of prepreg chips of size 50.8 mm x 8 mm chopped, randomly distributed
and consolidated through molding process. The nominal thickness of HexMC laminate was 11 mm, and
mechanical properties are given in Table 1. The SEM micrograph in Figure 1 shows the random nature
of prepreg chips in the laminate.

| Property             | Value          |
|----------------------|---------------|
| Tensile Strength     | 300 MPa       |
| Tensile Modulus      | 38 GPa        |
| Flexural Strength    | 500 MPa       |
| Flexural Modulus     | 30 GPa        |
| Compression Strength | 290 MPa       |
| Compression Modulus  | 38 GPa        |
| Interlaminar shear strength | 250 MPa |
| Interlaminar shear modulus | 15 GPa |
| Poisson’s ratio      | 0.3           |

Figure 1. SEM micrograph of HexMC (a) Top view, (b) Side view.

The conventional milling experiments were performed using a 3 axis Haas milling machine DFC
laminate was edge trimmed using a two-flute carbide tool of diameter 6.35 mm and helix angle 30°.
Tool was advanced 1 mm radially into the material and through-the-thickness in axial direction. The
length of cut (straight) was 50 mm. The Abrasive Water Jet experiments were performed using Flow
International® water jet machine equipped with 400 MPa intensifier. Details about the experimental
conditions can be found in the previous work [12]. The process variables and their levels for
conventional milling and AWJ are given in Table 2.

| Conventional milling | Abrasive Water Jet |
|----------------------|--------------------|
| Spindle speed        | 1000 and 6000 rpm  |
| Feed rate            | 5, 10, 15, 20, 25 mm/ |
| Pressure             | 250, 275, 350 MPa  |
| Abrasive flow rate   | 5.3, 6, 6.8 g/s    |
| Traverse speed       | 5, 10, 15, 19 mm/s |
The surface roughness profile was measured using contact type roughness measuring equipment (Mahr XR20). With a skidless probe of 2 μm diameter. The profile evaluation length was 5.6 mm with sampling length of 0.8 mm. Gaussian filtering with cut-off length 2.5 μm was used to calculate the ten point average roughness parameter. Several roughness profiles were measured for each machined surfaces, with a distance of h=1,2,…k mm (8 and 11 for conventional and AWJ respectively) from the top edge. Multiple measurements were made to increase the probability of capturing severe localized damage, if present. Overall, 376 profiles were evaluated in this study.

3. Analysis methodology

Wavelet packet transform (WPT) decomposes the signal onto time and frequency scales. Starting with a mother wavelet, the signal is decomposed such that it is downsampled by 2, resulting in two subbands—approximation and detailed coefficients. The successive decomposition(s) is carried out by scaling and translation of the wavelet function, on both approximation and detailed subbands. If the original sampling frequency of the signal is \( f_s \), the first level decomposition will result in 2 subbands with

![Figure 2. (a) Shape of mother wavelets, (b) Wavelet Packet Transform (WPT) analysis algorithm.](image-url)
frequency ranges \([0, 0.25f_s]\) and \((0.25f_s, 0.5f_s]\). At \(j\)th decomposition level, \(2^j\) subbands (or wavelet packets) are generated. The surface profiles were evaluated using Wavelet packet transform (WPT). Usually, mother wavelets are used based on their phenomenonological significance as reflected in the signal. A wavelet which best describes the nature of the signal, will extract the signal features in the most effective manner. In this study, 35 mother wavelets have been selected for the analysis, as in [14] and depicted in Figure 2(a). The first step is the wavelet packet transform of the roughness profile. For a given decomposition level, the wavelet packets were calculated and arranged in ascending frequency order. Energy of each wavelet packet at the given decomposition level is given computed. The total energy at each decomposition level is given by the summation of energy of all packets at that level. Next, Shannon entropy was calculated. Further, the ratio of packet energy and total Shannon entropy was determined as given by equation (1).

\[
\eta(i, j) = \frac{E_i}{En_T}
\]  

(1)

This energy-entropy coefficient (\(\eta\)) was then plotted against the frequency ordered wavelet number, and dominant peaks were identified. The summation of the absolute values of these peaks identified as a unique classifier for a given profile. This WPT-indicator, \(I\), is given by equation (2).

\[
I = \sum \eta_{\text{peaks}}
\]  

(2)

The optimal class and order of mother wavelet was identified as given in Figure 2(b). Upon selection of optimum wavelet and decomposition level, the profiles were correlated with the process variables. The wavelet packet analysis algorithm is summarized in Figure 2(b).

4. Results and Discussion

4.1. Conventional milling

**Figure 3.** \(R^2\), Adjusted \(R^2\) and Standard deviation (\(\sigma\)) for 35 wavelets at decomposition level (a) Level 5 and (b) Level 10 for conventionally milled HexMC.

Figure 3 shows \(R^2\), adjusted \(R^2\) and standard deviation for regression between WPT Indicator \(I\) and \(R_z\). The Biorthogonal wavelets outperformed other wavelets for nearly all decomposition levels. Bior3.3 at decomposition level 7 was selected with \(R^2\), adjusted \(R^2\) and standard deviation of 72.25%, 71.78% and 0.9169 respectively. Although \(R^2\) is low, it was the best that was achieved using any wavelet and
decomposition level. As shown in Figure 3(a), the performance at level 5 was poor and many cases were eliminated in calculation due to non-existence of the Indicator $I$. At the selected level (Level-7), the wavelets – db2, coif1 and sym2 were better among their respective families of wavelet. However, $R^2$ was less than 40% for these mother wavelets. The maximum value of log $I$ for Bior3.3 at level 7 is 5.4128 which is 18.9%, 20.6% and 18.9% higher than db2, coif1 and sym2 respectively. Figure 4 shows a strong positive correlation between $R_z$ and $I$ for Bior3.3 wavelet among others.

![Image](Figure 4: Relationship between $I$ and $R_z$ on a log-linear scale for conventionally milled HexMC profiles analyzed using mother wavelet – (a) Bior3.3, (b) Db2, (c) Coif1 and (d) Sym2 at level 7 decomposition.)

Figure 5 shows the correlation between WPT indicator $I$ and process parameters. In general, a positive trend between feed and $I$ was observed. At high spindle speed (6000 rpm), the magnitude of indicator $(I)$ increased from 3x10$^4$ to 9.3x10$^4$ for specimens machined with feed ranging from 5-20 mm/s. A sudden reduction in $I$ was observed at 25 mm/s feed. At 1000 rpm spindle speed, the resistance to cutting was higher and resulted in high $I$ value. The magnitude of $I$ ranged between 8 x10$^4$ and 25.9 x10$^4$. 
4.2. Abrasive Water Jet machining

The abrasive process involves jet-material interaction in such a way that the energy of the jet is dissipated as the jet penetrates through the workpiece. If the power of the jet (i.e. abrasive velocity) is low or the exposure time of the jet is small, the jet may deflect back due to the loss of energy and hence its cutting ability. The beginning of the curving of jet cutting front is usually specified as the beginning of rough cutting region (RCR) and often needs to be minimized to meet the tight surface roughness and dimensional tolerances.

The wavelet analysis, similar to conventional milled surfaces, resulted in optimal wavelet– Bior3.3 and decomposition level 8. Next, the relationship between process parameters and WPT indicator $I$ was studied. The relationship between the process parameters water pressure ($P$), speed ($u$), Abrasive Flow rate ($AFR$) and response variables – $R_z$ and $I$ was developed using Analysis of Variance (ANOVA). A cubic polynomial model was implemented with F-value of 36.24. Backward elimination procedure was used to eliminate the insignificant factors by comparing the f-values with the critical f-ratio at alpha = 0.05 level. Pressure and feed were the most contributing parameters in the model. A high pressure resulted in high jet power and hence a smoother surface was obtained. A high feed rate resulted in low exposure time, low jet energy per unit area and hence rougher surface. Figure 6 shows the effect of pressure and feed rate at abrasive flow rate 6 g/s. When measured near jet entry side ($h=1$ mm), the maximum $R_z$ was 28 $\mu$m at $u=19$ mm/s and $P=200$ MPa, which was 62.3 $\mu$m near jet exit side ($h=8$ mm) and at the same process conditions. Figure 6(c) and (d) shows the effect of pressure and feed rate on $R_z$ at $h=1$ mm and $h=8$ mm respectively. The maximum value of $I$ was $3.3 \times 10^5$ at jet entry side ($h=1$ mm) at $u=19$ mm/s and $P=19$ mm/s as shown in Figure 6(a). The WPT indicator $I$ was increased to $2.36 \times 10^6$ when measured at $h=8$mm which is an indicator of striated geometry. In comparison, the increment in $R_z$ and $I$ from $h=1$mm to $h=8$mm was 122.1% and 617.1% respectively. This indicates that the poor surface quality is more accentuated by $I$ as opposed to $R_z$, making $I$ to be a better indicator to represent surface quality.
Figure 6. Effect of pressure (P - MPa) and jet feed rate (u-mm/s) on $R_z$ at jet penetration distance (a) $h=1$ mm, (b) $h=8$ mm, and on $I$ at jet penetration distance (a) $h=1$ mm, (b) $h=8$ mm.

5. Summary and Conclusion
In this study, Wavelet Packet Transform (WPT) was used to identify characteristic features of surface profiles generated by different machining processes and parameters. HexMC, a random chopped discontinuous fiber composite (DFC) was machined using surface conventional milling and Abrasive Water jet machining process. Wavelet coefficients were calculated after decomposing the surface profiles at different scales. A novel approach was proposed to characterize the process using the ratio of energy and entropy of dominant wavelet packets ($I$). The selection of mother wavelet and decomposition level was carried out by comparing the WPT indicator ‘$I$’ with ten-point roughness parameter ($R_z$). For both AWJ and conventional milling, WPT indicator $I$ proved to be a better predictor of process conditions when compared to $R_z$. Irrespective of the type of composite material and process used to generate the surface profile, higher value of $I$ indicated poor surface quality. Mother wavelet Bior3.3 was found to be optimal for both machining processes. Decomposition levels 7 and 8 resulted in a reasonable correlation for conventional and AWJ milling respectively. A low spindle speed and high feed resulted in high $R_z$ and $I$ values. The surfaces generated by Abrasive Water jet showed higher value of $R_z$ and $I$. Low pressure and high speed resulted in high $R_z$ and $I$. Predictive models were developed to correlate $I$ and process parameters. A comparison between WPT indicator $I$ revealed high correlation of $I$ with the process parameters ($R^2>80\%$) as opposed to $R_z$ ($R^2<67\%$).
WPT method along with the proposed indicator—ratio of packet energy to Shannon—was developed as an ideal procedure to define and characterize the surface quality; identify machining-induced damage in composites; and correlate the surface integrity with process conditions.

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