Characterization of Fiber Pull-out in Orthogonal Cutting of Glass Fiber Reinforced Plastics

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1. Introduction

The reliability of machined fiber reinforced composites (FRC) in high strength applications and the safety in using these components are often critically dependent upon the quality of surface produced by machining since the surface layer may drastically affect the strength and chemical resistance of the material [1,2,3,4]. Current study will discuss the characterization of fiber pull-out in orthogonal cutting of a fiber-matrix composite materials. A sparsely distributed idealized model composite material, namely a glass reinforced polyester (GFRP) was used as workpiece. Analysis method employs a force sensor and the signals from the sensor are processed using AR time series model. The experimental correlation between the fiber pull-out and the AR coefficients is examined first and effects of fiber orientation, cutting parameters and tool geometry on the fiber pull-out are also discussed.

2. Spectral Analysis Based on Autoregressive (AR) Time Series Model

A time series model that approximates many discrete time deterministic and stochastic processes in engineering problems represents the stationary time correlation of the process. An AR process of order *r*, in particular, is given by

$$x(n) = -\sum_{i=1}^{r} a_i x(n-i) + u(n) \tag{1}$$

where *x(n)* is the output sequence of the filter that models the observed data. (is a filter gain,*u(n)* is a zero mean, unit variance Gaussian input driving noise sequence and *a0=1*. Model parameter *ai* comprises a pattern vector.

One way of quantifying the distortion between a random signal *x(n)* and a predefined pattern vector ***A*** is to use the discrimination information defined in terms of Itakura-Saito distortion measure[5]. Suppose *q* and *p*signify the probability densities associated with processes *x(n)* and ***A***, respectively. The discrimination information functional for Itakura-Saito distortion measure is given by:

$$H[q,p]=\frac{1}{\sigma^2}\left\{r_x(0)r_a(0)+2\sum_{s=1}^{S}r_x(s)r_a(s)\right\}+\log(\sigma^2) \tag{2}$$

where

$$r_a(s)=\begin{cases}\sum_{i=0}^{S-s}a_i a_{i+s}, & s\le S\\ 0, & otherwise\end{cases} \tag{3}$$

*rx(s)'*s are the autocorrelation functions of *x(n)* for lags *s=0,1,...,S*. The signal distortion measure in the form of discrimination information in Eq(2) and Eq(3) are known to be particularly useful in real-time application due to their simplicity in computation.

3. Experiment and Results

A series of orthogonal cutting experiments were conducted for both CuFRP and GFRP composite materials. The GFRP plate were 4.0mm thick with glass yarns of 0.4mm diameter arranged approximately 0.8mm apart. The reinforcement was arranged in the middle of the plate. Constituents of GFRP are given in Table 1.The workpieces were mounted on a Rockfort Shaper-Planer equipped with modified hydraulic system to provide a steady cutting motion. About 25mm of the material was exposed for machining each time. Multi-purpose C2 grade carbide inserts were used in dry cutting of GFRP. Schematic diagram of data acquisition and experimental setup is given in Figure 1. Schematic of the workpieces and relative angles between the cutting direction and fiber orientation is also shown in Figure 1. Detailed description of signal processing procedure is given elsewhere [1,2,3].

The cutting stress distribution in the machining zone of material dictates not only the type of chip produced and but also the quality of the surface finish. Fiber pull-out from the matrix material by fiber-matrix debonding and matrix stripping significantly affect the surface quality in cutting GFRP. Specifically, poor surface results from the fiber pull-out. Depth of fiber pull-out as a function of fiber orientation angle, tool rake angle and cutting parameters has been previously observed experimentally [1]. Depth of fiber pull-out observed in our experiments ranged approximately from 0.1mm to 0.5mmfor fiber orientation from 60 to 150, rake angle from 20 to 20, and 0.051mm depth of cut. For the rest of fiber orientation, pull-out depth was minimal.

The d[redacted]tion measure in Equation (2)is plotted for fiber "Pull-out" case and "No pull-out" case in Figure 2. Since the spectral distortion defined in terms of Itakura-Saito distortion measure tends to track more accurately the spectral peaks than the spectral valley, good sensitivity is seen when fiber pull-out is present. Moreover, different level of fiber pull-out may be attributed to the chip formation mechanism (cutting mechanism). The decision on the quality of surface can then be made by quantitatively analyzing the AR coefficients of cutting force model for both cutting mechanism and depth of fiber pull-out.

Typical side view of the GFRP machined surface using the back light technique was given in [1]. A distinct back spot was observed in the glass roving that corresponds to fiber pull-out when the fiber orientations exceed 60o. In case of 135ofiber orientation, fiber pull-out was maximized. Figure 1(b) shows all force components acting on the tool and workpiece. The cutting force, *Fc*, and the thrust force, *Ft*, are

$$\begin{bmatrix} F_t \\ F_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} F_b \\ F_p \end{bmatrix} \tag{4}$$

Fb is the force components perpendicular to the fiber, and *Fp* is the tangential component of force. As shown in Figure 3, the fiber pull-out was due to fracturing of the glass roving in a plane perpendicular to the roving axis and roving-matrix debonding [1]. Therefore, the fiber pull-out length, l, can be written as

$$l = \left(\frac{F_p}{r^* \tau_{\max}} + \frac{n\sigma_u \pi (2r)^4}{16 F_b} \right) \tag{5}$$

where n is the number of the fibers, and r is the radius of a fiber. $r*$ is the contact length between fibers and matrix. $\sigma_{\max}$ is the maximum interfacial shear stress. σ_u is the tensile stress of the fiber. This model was verified with the FEA and the photo-elastic investigation performed by Wern et al [1]. Incase of 135ofiber orientation, the predicted fiber pull-out length equals to 232 μm, while the actual fiber pull-out average length was 270 μm.

References

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2.C.W. Wern, M. Ramulu and A. Shukla, "Preliminary Investigation of Stresses in the Orthogonal Cutting of Fiber Reinforced Plastics", Experimental Mechanics , Vol. 36, No.1, 1996, pp.33-41.

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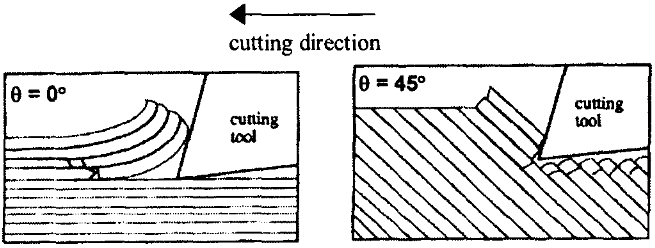
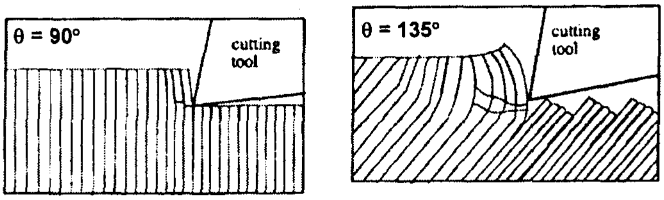
Table 1 Constituents of GFRP used in this study

	GFRP
Resin	Unsaturated polyester polymal 6304, 6320F at a ratio of 1:1
Reinforcement	ECG-75-11/2 3.3 S NA glass yarn of 0.4mm diameter
Reinforcement Volume Fraction (%)	0.85%
Post Curing	120C for 2 hours



Delamination

Fiber Cutting



Deformation

Fiber Pull-outs

Figure 1 Designation of angles and schematic diagram of experimental setup

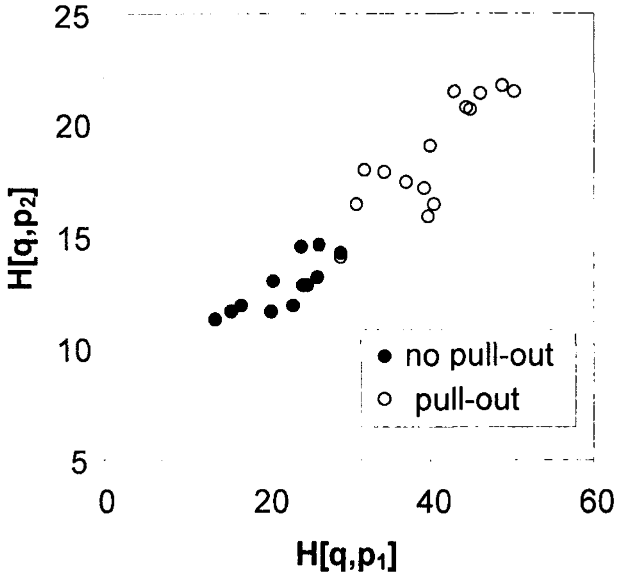


Figure 2 Two dimensional plot of $H[q, p]$ for fiber "Pull-out" and "No fiber pull-

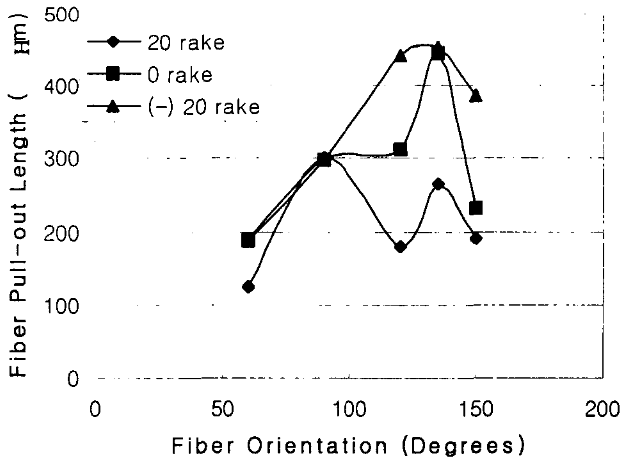


Figure 3 Effect of tool rake angle on the fiber pull-out length
(Cutting conditions: cutting speed of 3 m/min and depth of cut of 0.051 mm).