Identification of Cutting Mechanisms in Orthogonal Cutting of Glass Fiber Reinforced Composites

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1. Introduction

In recent years, composite materials such as fiber reinforced plastics (FRP) have gained considerable attention in the aircraft and automobile industries due to their light weight, high modulus and specific strength. In practice, control of chip formation appears to be the most serious problem since chip formation mechanism in composite machining has significant effects on the finished surface [1,2,3,4,5]. Current study will discuss frequency analysis based on autoregressive (AR) time series model and process characterization 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 different chip formation mechanisms and model coefficients are established

2. Orthogonal Cutting of GFRP

Depending on the fiber orientation, cutting mechanisms can be categorized into the following 4types:

(1) Type I (0° fiber orientation): Cutting mechanism is characterized by Mode I loading and fracture along the fiber-matrix interface, Mode II loading through tool advancement, and fracture perpendicular to the fiber direction under bending load

(2) Type II (15°-75° fiber orientation): In this positive fiber orientation, cutting mechanism is composed of fracture from compression induced shear across the fiber axis and interfacial shearing along the fiber direction which eventually causes

fiber-matrix debonding.

(3) Type III (75°-90° fiber orientation): Cutting mechanism is characterized by compression induced fracture perpendicular to the fibers and inter-laminar shear fracture along the fiber/matrix interface.

(4) Type IV (beyond 90° fiber orientation): Cutting mechanism in this type is basically similar to Type III.

3. Autoregressive Modeling

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 *p*, in particular, is given by

$$x(n) = -\sum_{i=1}^{p} a_i x(n-i) + \sigma u(n) \qquad (1)$$

where $x(n)$ is the output sequence of the filter that models the observed data, $a_0=1$, σ is a filter gain and $u(n)$ is a zero mean, unit variance Gaussian input driving noise sequence. Model parameter ai comprises a pattern vector $A=\{a_0, a_1, ..., a_p\}$. In the present case, $x(n)$ is the measured discrete force signal sequence.

4. Feature Selection

M pattern vectors $A(k)$; $k=1,...,M$ resulting from M measurements under different combinations of cutting parameters and tool geometry may be represented by a centroid $\hat{A}$. $\hat{A}$ is determined to minimize the average distance D_c $(\hat{A})$, i.e.,

$$\hat{A} = \min\left[D_c(\hat{A})\right] = \min\left[\frac{1}{M}\sum_{k=1}^{M} D[A^{(k)}, \hat{A}]\right] \qquad (2)$$

The minimum of $D_c(\hat{A})$ is achieved simply by the components of $A(k)$ each being the arithmetic mean of the components of $A(k)$. For any cutting mechanism specified by a subscript "1", an i-th parameter mean can be defined for the i-th model coefficient as

$$[a_{i,1}]_{mean} = \frac{1}{M}\sum_{k=1}^{M} a^k{}_{i,1} \qquad (3)$$

where M is the number of sample data. A discrimination index $J_i[1,2]$ between two cutting mechanisms "1" and "2" based on i-th coefficient can then be obtained by normalizing $Q_i[1,2]$ with $S_{i,1}$ and $S_{i,2}$. That is

$$J_i[1,2] = \frac{Q_i[1,2]}{[S_{i,1}S_{i,2}]^{1/2}} \qquad (4)$$

Features are selected based on the their discrimination indices. The most important coefficient is the one that maximizes the discrimination index.

5. Experiment

A series of orthogonal cutting experiments were conducted for GFRP composite. 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. Detailed experimental procedures are described elsewhere [1,2,3].

6. Results

The sensitivity of AR coefficients to the fiber orientation-dependent cutting mechanisms was examined. Table 2 summarizes the experimental conditions and trends observed in orthogonal cutting of GFRP. AR coefficients for 3 different classes, i.e., "CLASS 1", "CLASS 3" and "CLASS 5" (or types of cutting mechanisms, i.e., TYPE II, TYPE III and TYPE IV) were, for example, plotted on the feature spaces in Figure 2. The figure clearly indicates that there are overlaps among model coefficients. Since the boundaries of a2 and a5 are not clearly distinguished, examining all AR coefficients does not necessarily provide the discriminatory information on the cutting mechanisms. The discrimination indices for different combinations of cutting mechanisms and cutting parameters summarized in Table 3 were then calculated for each model coefficient. The results of this test show that the separation attributed to changes in cutting parameters (J[1,2], J[3,4] and J[5,6]) is low, whereas the separation resulting from different cutting mechanisms (J[1,3], J[1,5] and J[3,5]) is comparatively high.

Next, all data under condition 1 and 2 (3 and 4, 5 and 6) were combined into a single class, i.e., "CLASS 1+2" ("CLASS 3+4" and "CLASS 5+6"), and the discrimination indices were calculated. Results summarized in Table 4 show lower discrimination indices compared to the cases where classes for varying cutting parameters are not combined (i.e., J[1,3], J[1,5] and J[3,5]). Based on the discrimination indices, a1 and a4 were selected to be the most important features in terms of characterizing the cutting mechanisms while maintaining insensitivity to changes in cutting parameters. Shown in Figure 3 is the feature space for combinations of model coefficients that are selected to maximize the discrimination index. It is observed that three classes were reasonably separated in the feature space so that correlation with the cutting mechanism can be established by quantitatively analyzing the AR coefficients of force model.

7. References

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Table 1 Constituents of GFRP used in this study

	GFRP
Resin	Unsaturated polyester polymal 6304, 6320F (ratio: 1:1)
Reinforcement	ECG-75-11/2 3.3 S NA glass yarn of 0.4mm diameter
Reinforcement Volume Fraction	0.85%
Post Curing	12℃ for 2 hours

Table 2 Experimental conditions for machining GFRP. Depth of cut is 0.051 mm.

Class	Fiber Orientation Angle(degrees)	Cutting Mechanism	Fiber Pull-out	Cutting Parameters	
				Cutting Speed	Rake Angle
1	45	II	N	3 (m/min)	20 (degrees)
2	45	II	N	6	20
3	90	III	Y	3	20
4	90	III	Y	6	20
5	135	IV	Y	3	20
6	135	IV	Y	6	20

Table 3 Discrimination index J for different combinations of cutting mechanisms and experimental conditions

	Characteristics to be correlated	A 1	a 2	a 3	a 4	a 5	a 6
J[1,3]	Cutting Mechanism (CM)	23.28	6.81	11.5	85.72	10.65	32.61
J[1,5]	CM	19.83	5.96	21.53	62.32	49.02	52.22
J[1,2]	Cutting Parameter (CP)	2.68	3.63	5.55	3.79	0.78	4.23
J[3,4]	CP	1.51	0.74	4.05	23.14	0.54	17.80
J[5,6]	CP	2.88	2.18	11.78	2.61	6.84	6.00

Table 4 Discrimination index J for different combinations of cutting mechanisms and experimental conditions

	Characteristics to be correlated	a 1	a 2	a 3	a 4	a 5	a 6
J[1+2, 3+4]	Cutting Mechanism	2.4	0.642	0.544	1.665	2.584	0.163
J[1+2, 5+6]	Cutting Mechanism	7.781	0.76	2.604	2.289	1.937	2.792
J[3+4, 5+6]	Cutting Mechanism	3.775	0.001	2.705	0.528	0.586	1.924

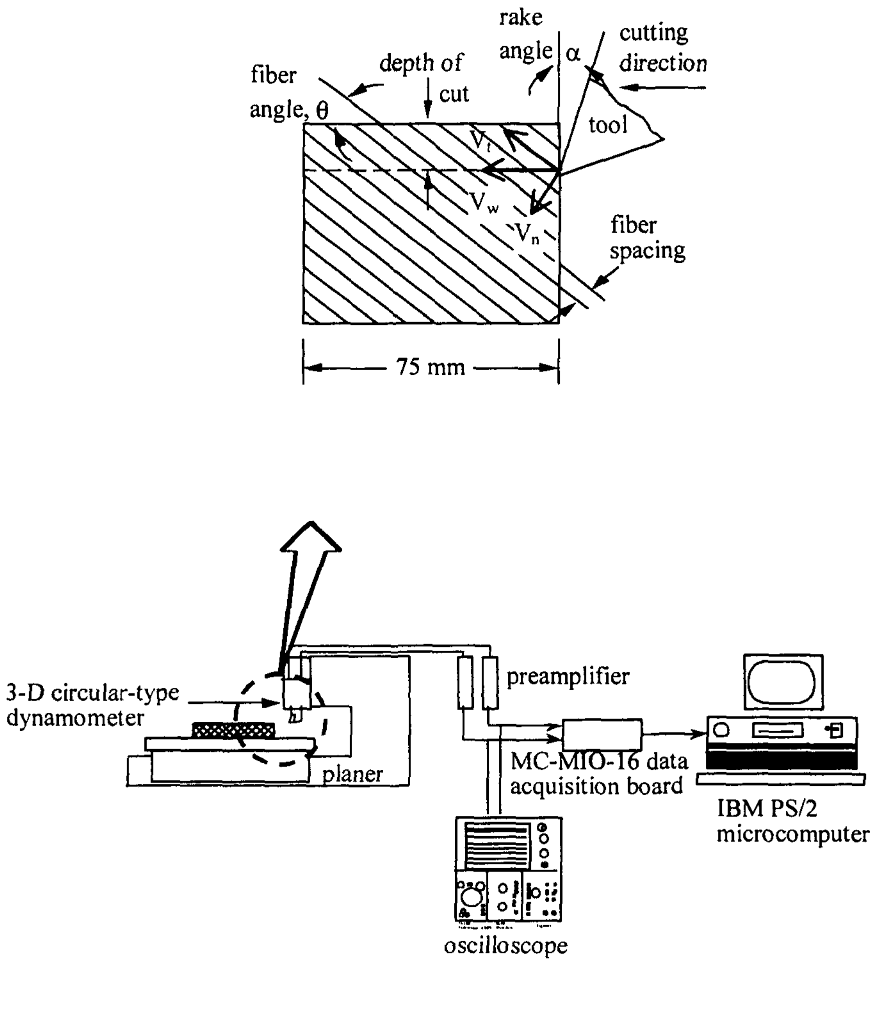

Figure 1 Designation of angles and schematic diagram of experimental setup

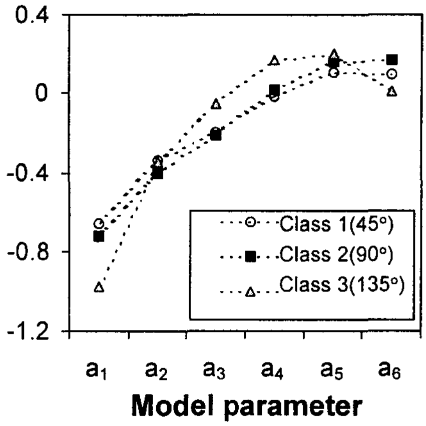

Figure 2 Model coefficients for CLASS 1, 3 and 5.

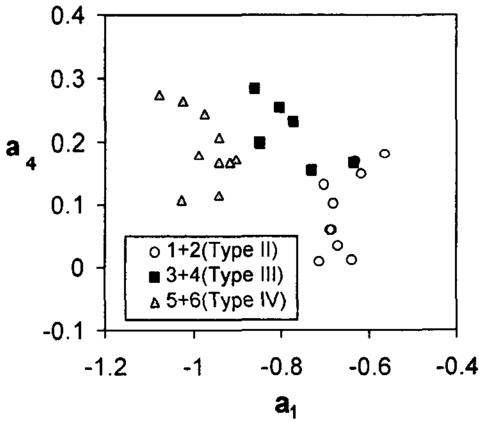

Figure 3 Feature spaces for discriminating types of cutting mechanism.