FREQUENCY ANALYSIS AND PROCESS MONITORING IN DRILLING OF COMPOSITE MATERIALS

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ABSTRACT

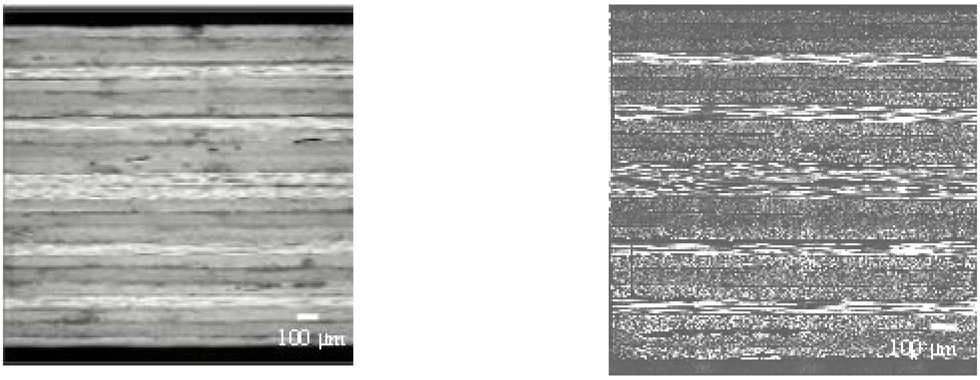
Drilling experiments were conducted using carbide and cryogenic treated carbide drills into carbon fiber-reinforced thermoplastic composites, namely Graphite/PIXA-M (PIXA-M) composites. Drilling force signals were collected from all conditions and analysed using fast Fourier transformations and autoregressive (AR) time series models. Power spectrums were used to examine the cutting characteristics in the drilling process. AR coefficients were used to distinguish the cutting signals of autoclaved and induction heated PIXA-M composites, and conventional and cryogenic treated carbide drills.

Keywords: Thermoplastic composites; Drilling; Frequency analysis; Hole quality; Surface textures

1. INTRODUCTION

Fibre reinforced plastic composites (FRPs) are now one of the most important classes of engineered materials, as they offer several outstanding properties such as high strength-to-weight ratio, stiffness-to-weight ratio, fatigue resistance, and corrosion resistance. Since the early 1970s, a great deal of effort has been directed to the drilling of FRPs and a new challenge has been found [1-5]. Improper drilling causes the defects on the drilled hole. Because machined surface quality determines the fatigue strength of the component's service life, producing a quality hole is essential in drilling FRPs. One of the ways to prevent the defects on the drilling process is to monitor the change in the quality of the hole on-line to decide when defects would occur. The availability of such model-based control schemes would be a large advancement in the efficient drilling of FRP parts [6,7].

However, most of all damage detecting techniques are based on average thrust force data. It was observed in graphite/epoxy composite cutting experiments that tool clearance angle has limited effect on the average cutting force level [8]. The first effort was made by Radhakrishnan and Wu to correlate between the cutting forces in frequency domain and hole surface quality using the Dynamic Data System (DDS) technique [7]. Recently, Ramulu et al [9] conducted frequency analysis to characterise the orthogonal cutting process of idealized glass fibre reinforced plastic (GFRP) composite materials. The analysis method employed a force sensor and the signals from the sensor were processed using either the fast Fourier transform (FFT) technique or AR time series model. This worked in 0.85% by volume GFRP, but may need to find relevance in real composites with 60% fibre volume composites. In this study, frequency analysis and characterisation methodology are applied into drilling of PIXA-M thermoplastic composites with 60% fibre volume. The experimental observations are examined on two different consolidation processed (autoclaved and induction heated) composites. Frequency characterisation links the composite cutting mechanisms and the signal characteristics. The correlations between the different cutting characteristics and AR model coefficients are then established. Effects of consolidation process, drilling conditions and tool material on the cutting characteristics and surface quality are also discussed. While this study addresses the problem of frequency characterisation in drilling thermoplastic composites,



(a) Autoclaved (b) Induction heated

Fig.1: Photomicrograph of PIXA-M thermoplastic composite panel.

it also develops an approach to find the relationship between the sensor signal and the characteristics of drilled composite hole quality.

2. EXPERIMENTAL PROCEDURES

2.1 Workpiece material system

PIXA-M thermoplastic composites are used in this series of experimental studies. The PIXA-M composite has graphite fibres embedded in a PIXA-M engineering thermoplastic and polyamide polymer matrix. 24 ply quasi flat panels were used in the experiment, with the following fibre lay-up: {(45, 0, -45, 90, 45, 0, -45, 90, 45, 0, -45, 90)$_2$}, where the ply thickness was about 140 μm. Materials were consolidated by autoclave and induction heating methods. This detailed consolidation methods are given elsewhere [11]. Fig. 1 shows the photograph of the PIXA-M composites.

2.2 Drilling experiments

Drilling experiments were performed on a commercial vertical mill, which was retrofitted with a CNC control and drive unit. C2 grade carbide drills with a standard drill geometry were selected for this investigation based on their availability and widespread use in industry. Cryogenic treated carbide tools were also used in the drilling process. Cryogenic treatment was performed commercially at 300 Below Company. The flow chart of the experimental procedures with quality assessment is introduced in Fig. 2.

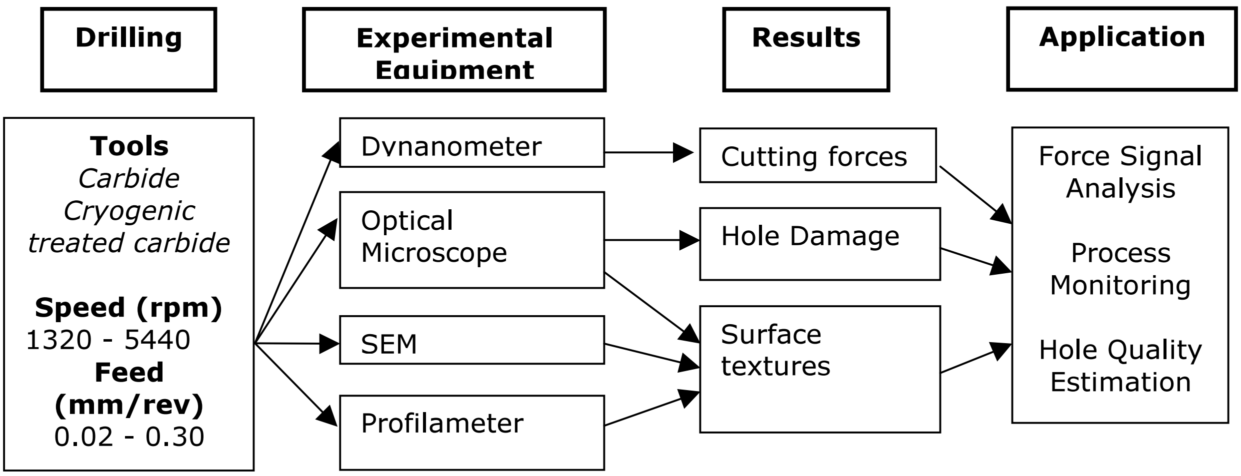
2.3 Frequency analysis methods

Two signal processing methods, power spectrum and autoregressive time series model were used, and their performances are compared. The detailed frequency analysis technique can be found in Ref. 9. Fig. 3 shows the overall technique used in this study.

3. RESULTS AND DISCUSSIONS

3.1 Composite cutting characteristics and hole quality

Fig. 2: Experimental procedures.



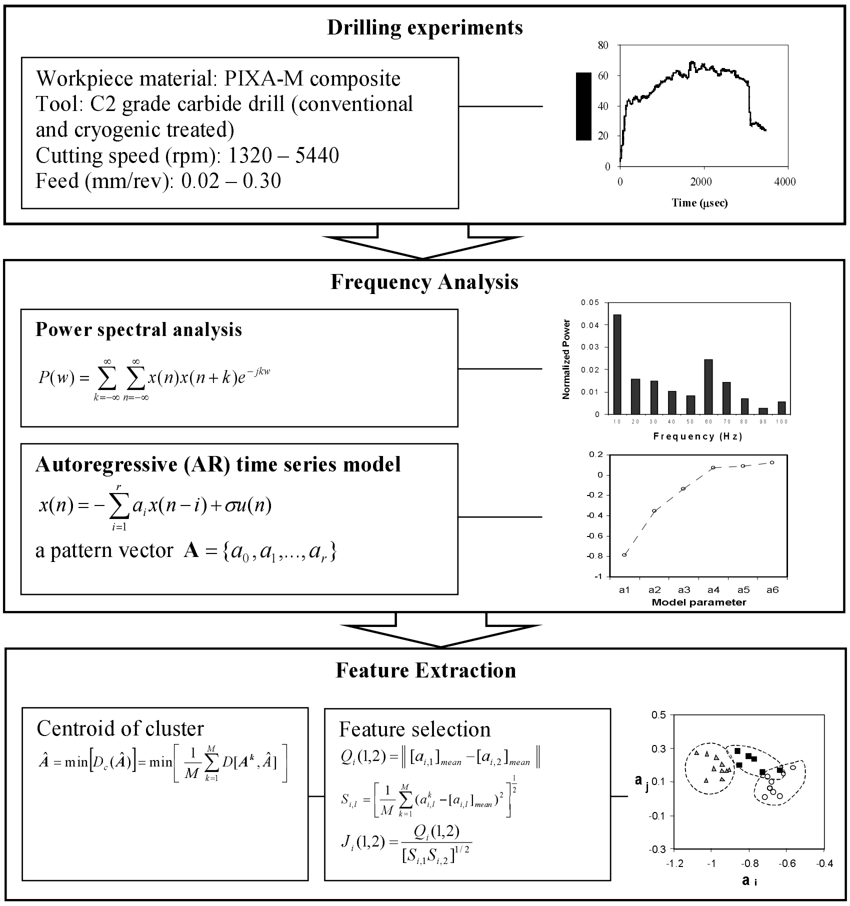


Fig. 3: Frequency analysis in drilling of PIXA-M composites.

Table 1: Classifications of experimental conditions in drilling of PIXA-M composites.

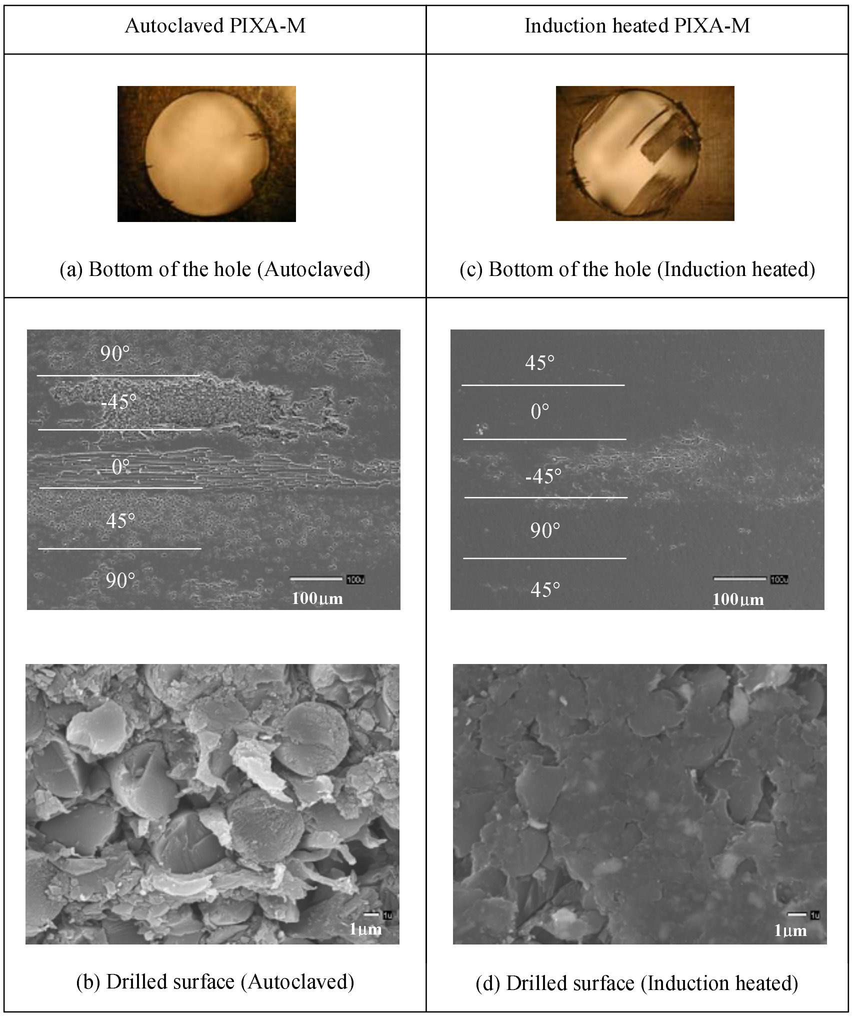
CLA-SS	**Workpiece materials**	**Drilling conditions**			**Maximum Thrust/** N	**Maximum Torque/** Nm	**Ra/** μm
		Tools/ carbide	**Feed/** mm/rev	**Speed /** rpm			
1	Autoclaved	Conventional	0.03	2230	68.9	0.163	1.29
2	Autoclaved	Conventional	0.03	5440	57.0	0.140	1.36
3	Induction heated	Conventional	0.03	2230	74.3	0.241	0.53
4	Induction heated	Conventional	0.03	5440	60.1	0.141	0.81
5	Induction heated	Cryogenic treated	0.03	2230	79.0	0.280	0.85
6	Induction heated	Cryogenic treated	0.03	5440	68.0	0.170	0.60

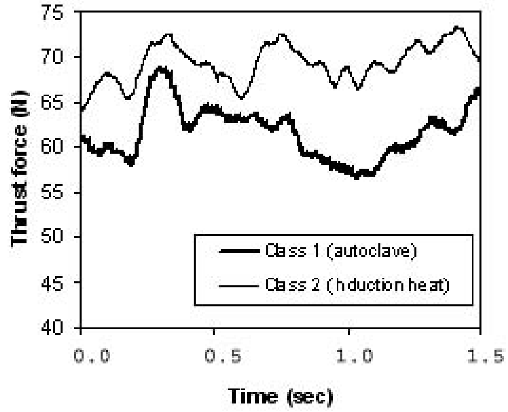
Machining of multi-directional composites involves shearing and cracking of matrix material, brittle fracture across the fibre, fibre pull-out and matrix-matrix debonding, and delamination prior to final fracture both in the chip and below the cutting plane depending on the fibre orientation and cutting conditions [9]. Typical thrust force signal is shown in Fig. 3. Fig. 2 shows the typical record of cutting force profiles captured during machining. The cutting force fluctuations were found regardless of cutting conditions, tool materials, and fibre contents. Due to the point angle, drill bits and chisel edge cut multiple laminates with multi-oriented fibres. The nature of the force fluctuations in drilling is because of the various cutting force magnitudes due to different fibre orientations. The effect of machining conditions on oscillations of the cutting forces will be elaborated in the next section. Fig. 4 presents machined holes and surface topography for autoclaved and induction heated PIXA-M composites. Roughness and surface defects are one of the major hole quality parameters in thermoplastic composite material [12]. The effect of consolidation processing on surface quality can be clearly seen in Fig. 4 (b) and (d). There is a large area of pitting on the autoclaved PIXA-M composite surface while the induction heated PIXA-M composite has a smoother surface because of matrix smearing at the same drilling conditions. In Fig. 4 (d), the surface of the induction heated PIXA-M composites is almost covered entirely by the matrix, therefore the small pockets are rarely seen. This means that deeper fibre pullouts occurred in autoclaved PIXA-M composite drilling, hence more surface damage. Table 1 contains average surface roughness values for both autoclaved and induction heated PIXA-M composites. In Table 1, the surface roughness values of autoclaved PIXA-M composites are twice as large as those of induction heated PIXA-M composites.

3.2 Frequency analysis

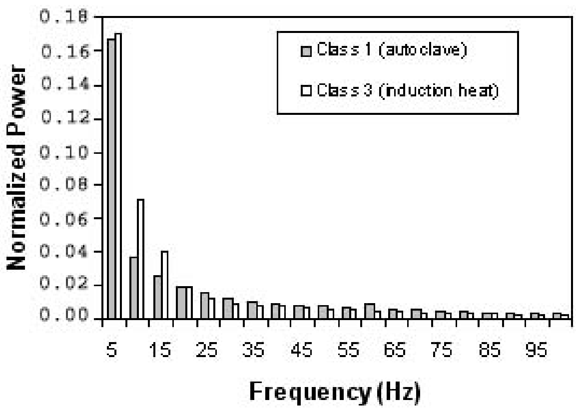
In order to characterise the cutting performances in drilling of PIXA-M composites, the frequency analysis was examined. Table 1 summarizes the experimental conditions and consolidation processes of the workpiece materials in drilling of PIXA-M composites. Based on reported literature and also our extensive experimental work, low feeds and high speeds are desirable for drilling graphite composites [2,5,12]. As a result, the feed rate of one fourth of laminate thickness (0.03 mm/rev) and the spindle speed of 2230 rpm and 5440 rpm were chosen for the drilling conditions. The experimental conditions were classified with 6 different classes to investigate the effect of consolidation processing, drilling conditions, and tool material. CLASS 1 is defined as autoclaved PIXA-M composite drilling at 0.03 mm/rev and 2230 rpm, while CLASS 2 is the same as Class 1 but the drilling speed is 5440 rpm. CLASS

Fig. 4: Effect of consolidation processing on hole quality of the PIXA-M composites drilled at 0.02 mm/rev and 3500 rpm (Angles indicate the angle between the fibres and the cutting direction).

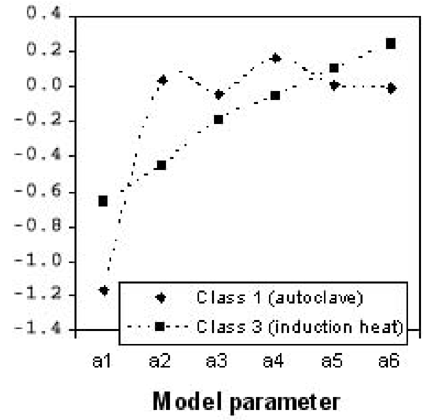




(a) Thrust force signals



(b) Normalised power spectrum



(c) AR model coefficients

Fig. 5: Force signals in time domain, power spectrum, and model coefficients for CLASS 1 and CLASS 3.

3 and 4 are defined as induction heated PIXA-M composites at the feed of 0.03 mm/rev and the speed of 2230 rpm and 5440 rpm, respectively. AR coefficients for induction heated PIXA-M composite drilling by cryogenic treated carbide tools are classified as CLASS 5 and 6.

Typical drilling force signals during the process are shown in Fig. 5 (a). Power spectrums for CLASS 1 and 3 are introduced in Fig. 5 (b). Model coefficients are saturated for an order of 6 or higher, the order of the AR model was set to 6 for all cases [9]. For example, AR coefficients for two different classes (CLASS 1 and CLASS 3) are plotted on the feature spaces in Fig. 5. This figure clearly shows the overlaps and discrepancies among model coefficients.

According to Radhakrishnan and Wu [7], the "lamination frequency" was defined as the number of laminations per unit length over time taken by the drill to penetrate per unit length. This lamination frequency is unique for composite materials and it constitutes the waviness aspect of the hole surface. In this study, this value is computed to be 8 Hz for 0.03 mm/rev and 2230 rpm speed. In Fig. 5 (b), there is a significant difference of normalised power magnitudes between autoclaved and induction heated composites. As mentioned in the previous section, consolidation processing effects mostly on cutting characteristics and hole surface.

In order to find the differences between each class, the comparisons were made with respect to the reference class, CLASS 3. According to Table 1, CLASS 3 is induction heated PIXA-M with carbide drills. In Figure 6, the relative variation of normalised power with different workpiece and tool material is represented by the signal to noise ratio (ratio of the power at frequency ω to the power at frequency ω_r with CLASS 3) in dB scale as:

$$SNR = 20\log\left(\frac{w}{w_r}\right) \quad (dB)$$

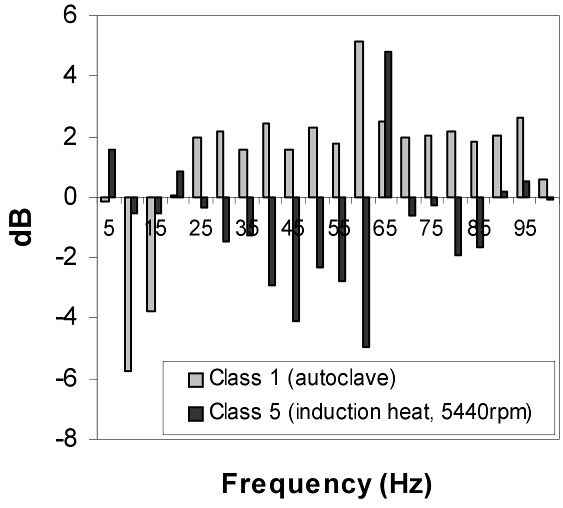


Fig. 6: Effect of material processing and tool material on the normalised frequency spectrum in drilling of PIXA-M composites. Reference is CLASS 3 in Table 1.

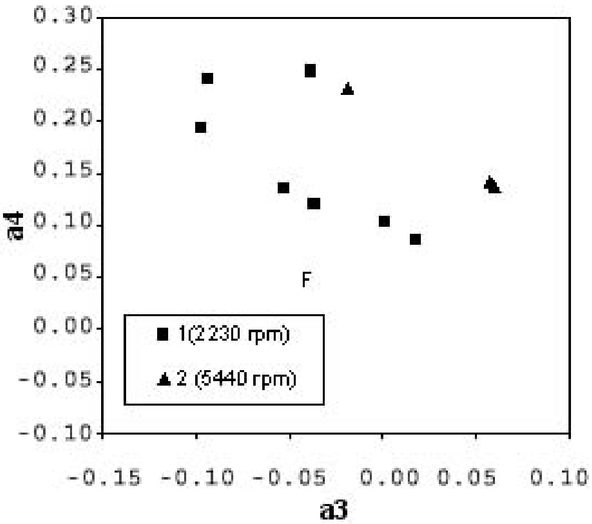


Fig. 7: Sensitivity of AR coefficients to drilling speed for CLASS 1 and CLASS 2.

Table 2: Discrimination index J for different combinations of drilling conditions.

	Characteristics to be correlated	a_1	a_2	a_3	a_4	a_5	a_6
J(1,2)	Speed	0.080	0.397	0.410	0.044	0.214	0.017
J(3,4)	Speed	0.332	0.194	0.690	0.212	0.166	0.527
J(5,6)	Speed	0.121	0.076	0.550	1.209	0.686	1.267
J(1+2,3+4)	Consolidations	3.377	2.763	1.226	1.251	1.306	2.366
J(3+4,5+6)	Tools	0.063	0.068	0.257	0.466	0.646	0.201
J(1+2,5+6)	Consolidations+tools	4.861	5.175	1.487	1.060	0.003	2.737

As shown in Fig. 6, there is an appreciable amount of energy above 20 Hz with CLASS 1. This frequency range is higher than the lamination frequency, which is 8 Hz. Burst type cutting signals for autoclaved PIXA-M composites may lead the intermittent inter-laminar fracture that causes a high contribution to the total power at a high frequency range. Fibre pull-out also contributes to the high frequency contents of the force signal. However, it is hard to find the difference between CLASS 3 and CLASS 5. This indicates that the cryogenic treated carbide tools provide the same pattern of force signals as do the conventional carbide tools.

The discrimination indices for different combinations of workpiece materials and cutting conditions, i.e. CLASS 1 to 6, summarized in Table 1, are then calculated for each model coefficient. The sensitivity of AR coefficients to the process conditions is examined. In drilling autoclaved PIXA-M composites, AR coefficients for two different spindle speeds, 2230 rpm and 5440 rpm, are plotted on the feature spaces in Fig. 1. Even though AR coefficients a_3 and a_4 have the highest values in the discrimination indices, the boundaries of a_3 and a_4 are not clearly distinguished in Fig. 7. The separation attributed to changes in drilling speeds (J(1,2), J(3,4), and J(5,6)) is low. That means that speed does not have much affect on drilling force signals in the frequency domain. These results are expected from the fact that speed is not a major contributing factor to the cutting characteristics in PIXA-M composite materials.

The sensitivity of AR coefficients to the consolidation processes in Table 2 indicates that consolidation processes are well distinguished. All data under CLASS 1 and 2 (3 and 4) are combined into a single class, i.e. "CLASS 1+2", ("CLASS 3+4"), and discrimination indices are calculated. Discrimination index J(1+2,3+4) has much higher values than J(1,2) or J(3,4), even though the combined class has a higher with-in class variation. It is noted that AR coefficients are more sensitive to consolidation processes than drilling speeds. As mentioned in previous sections, there are discrepancies between cutting characteristics for autoclaved and induction heated PIXA-M composites. Through the hole quality assessments, matrix smearing and elastic recovery are dominant in induction heated PIXA-M composites. Two separate cutting characteristics with two different consolidation processed materials lead to high sensitivity for the AR coefficients.

In order to characterise the drilling force signals by cryogenic treated carbide tools, discrimination index J(3+4,5+6) is examined. In Table 2, J(3+4,5+6) has low values. This result indicates that the separation attributed to changes in cutting tools is not significant. It is also expected that cutting characteristics are not changed much by using cryogenic treated carbide drills. Note that conventional carbide drills and cryogenic treated carbide drills have same tool geometry and material. As shown in Figure 8, the feature space for combinations of model coefficients, a_1 and a_2, are selected to maximize the discrimination index. It is clearly shown that CLASS 1+2 and CLASS 3+4 or CLASS 1+2 and CLASS 5+6 are clearly separated, whereas CLASS 3+4 and CLASS 5+6 are not. Therefore, examining AR coefficients does not provide the discriminatory information if cutting characteristics are identical.

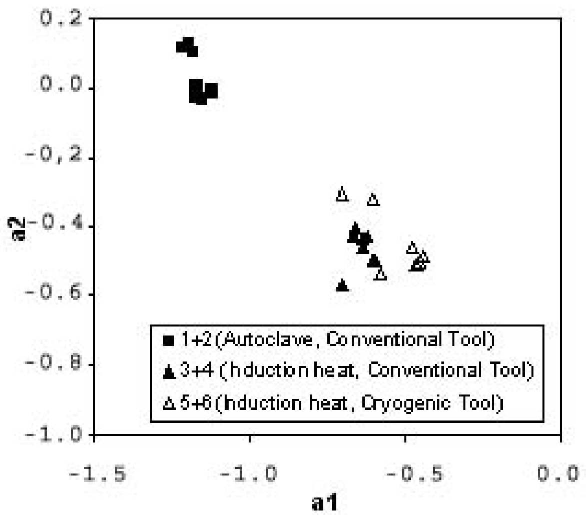


Fig. 8: Feature spaces for discriminating drilling conditions.

4. CONCLUSIONS

Drilling experiments and frequency analysis were conducted for carbon fiber-reinforced thermoplastic composites, namly PIXA-M composites. Based on the results the following conclusions were made:

- Composite consolidation process affects cutting characteristics and surface quality of PIXA-M composites. In drilling of autoclaved PIXA-M composites, deeper fibre pullouts on the machined surface are observed, while matrix smearing is dominant in induction heated PIXA-M composites.
- Drilling force signals of PIXA-M composites are characterised using power spectrums. High frequency components of the force signal can be found in drilling of autoclaved PIXA-M composites, and it exhibits high sensitivity to burst type cutting force signal and fibre pull-out in the process.
- A strong correlation between AR coefficients and the cutting characteristics was found. Combinations of model coefficients that maximize the discrimination index seem to depend more strongly on the consolidation processes, rather than on cutting conditions such as drilling speeds and cryogenic treatment of carbide tools.

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