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Moisture effects and acoustic emission characterization on lap shear strength in ultrasonic welded carbon/nylon composites

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Carbon/nylon composites were ultrasonically welded under controlled welding pressure and time. The optimized pressure and time for the highest joining strength are found by conducting the lap shear test. The acoustic emission (AE) technique used during the test is able to detect the first-damage load (FDL) and identify the damage mechanisms. Fiber breakage contributes to higher lap shear strength of the specimen, while debonding and pull-out lead to lower strength. Furthermore, the configurations of the AE curves provide the judgment of the magnitude of lap shear strengths of composites. The moisture absorption in welded composites follows Fick's law of diffusion; and lap shear strength of the composite decreases with increasing moisture content, the correlation of which follows an exponential decay function. The reduction of the strength is due to weaker hydrogen bond in the matrix connected between water and amide groups, and damage caused by the swelling of the matrix. *© 2000 Kluwer Academic Publishers*

1. Introduction

The joining technique used on a particular composite depends on the application and composition of the material [1]. The category of typical joining techniques for composites include (1) mechanical fasteners, (2) adhesive bonding, (3) polymer-coated material (PCM) welding, (4) hot gas welding, (5) resistance welding, and (6) ultrasonic welding.

The mechanical fastener is a fast joining technique for the composite and can provide satisfactory strength; however, major problems of the technique include thermal expansion mismatch between bolts and composites, stress concentration at the drilling holes that causes delamination under loading, and reduction of structural integrity. For adhesive bonding, it preserves structural integrity by the elimination of the holes and can easily join all composites and dissimilar materials; but the joining usually can not sustain large amount of stress and is affected by moisture, temperature and other environmental factors. PCM welding is able to bond aluminum alloy with carbon/PEEK composite as strong as using adhesives only in less than a minute. To prepare the welding, a layer of amorphous PEI was comolded onto one surface of the carbon/PEEK composite and a thin thermoplastic layer was applied to the surface of the pretreated aluminum alloy. The resistance implant used was a piece of unidirectional carbon fiber prepreg tape wrapped by PEI and PES films. During welding, because of the lower glass-transition temperatures of PEI and PES films than that of PEEK matrix, PEI and PES films on implant and carbon/PEEK and thermoplastic coating on the metal all melted together to form the weld.

Hot gas welding is one of fusion bonding techniques, which include three categories: thermal welding, frictional welding, and electromagnetic welding. For thermoplastic composites, the fusion bonding techniques heat the polymer to a viscous state and physically cause polymer chains to inter-diffuse and form a weld. The hot gas welding applies heat directly to the surfaces to be joined. The surfaces are quickly brought into contact, held under pressure, and allowed to cool down and form a bond. Resistance welding, a method in second category of fusion bonding techniques, puts a metal insert between two parts to be joined and then increases the temperature of the insert by the induction or resistance heating so that the thermoplastic matrix around the insert fuses to form a joint. The conductive insert remains within the joint and as such affects the final strength of the weld.

Ultrasonic welding is a bonding process in third category of fusion bonding techniques, which uses high frequency mechanical vibrations, that is, ultrasonic vibrations, as a source of energy. Heat is generated by both intermolecular and surface friction. The most important factors are to provide smooth contact and an energy director between welding parts. During the welding process, pressure is applied to the parts being joined, and a welding horn is applied to the area to be bonded. The horn delivers high-frequency (20 to 40 kHz) and low amplitude (20 to 60 Mm) vibrations which are concentrated by the energy directors to localize heat and join the thermoplastic composites. Total welding cycle time was only 10 to 15 s (second) and satisfactory strength was achieved for Gr/PEEK composites [2].

Control of the welding pressure and time is very important that influences the properties of the joint. A theoretical model was proposed [3] to completely analyze the process for ultrasonic welding of APC-2/PEEK composites, which includes five sub-models: mechanics and vibration, viscoelastic heating, heat transfer, flow and wetting, and intermolecular diffusion. Although a zigzag energy director is usually used for transmitting the heat, flat tie layer was successfully used [4] to join aluminum alloy and PP by ultrasonic welding. Anodizing of aluminum alloy and adding amorphous PP into semi-crystalline PP were two major factors that improve lap shear strength significantly.

Strength of welded thermoplastic composites is closely related to their damage mechanisms. However, to in-situ identify the damage mechanism needs special instrument such as acoustic emission (AE) apparatus. Finite element method associated with AE were used [5] to identify damage mechanism for thermoplastic composites under tensile load. The damage modes for thermoplastic composites under tensile load before and after soaking into hot water were found by AE to be matrix cracking and debonding, respectively [6]. It is expected that damage modes in ultrasonic welded thermoplastic composites under lap shear test are different.

Therefore, this paper presents failure analysis of ultrasonic welded carbon/nylon composites using acoustic emission (AE). The prime objective is aimed at investigating the effect of welding pressure, time, and moisture absorption on lap shear strength of ultrasonic welded composites. The correlation between strengths and damage mechanisms is analyzed.

2. Experimental procedure

2.1. Materials and ultrasonic welding

Carbon/nylon composites (Phoenixx TPC Inc., USA) with configuration of $[0]_{16}$ and fiber volume fraction of 53% were used for ultrasonic welding and following tests. The composite panel was cut as the specimen with dimension of 107 × 25.4 × 2 mm according to ASTM standard for lap shear test (D3163-73). Before welding, the specimen must be well cleaned.

A nylon energy director was inserted into the overlapped region (25.4 × 12.7 mm) between two welding specimens. The energy director with small triangular ridge was made from a nylon film via a mold. The angle between two ridges is 90°. The processing of the energy director was conducted under a hot-press machine at the temperature of 220°C and pressure of 100 N/cm^2 for 20 min. The width and depth of the ridge on the energy director are 0.9 and 0.2 mm, respectively. The energy director concentrates the applied power to provide rapid melting of the material contained in the director. Molten material from the energy director flows across the joint interface and fuses with the two components to form a weld.

Two carbon/nylon specimens with energy directors inserted into the overlapped region (12.7 × 25.4 mm) were gripped on the anvil of the ultrasonic welding machine (MECASONIC OMEGA-MPXII, France). The specification for the machine is as follows: input voltage 220 V, output power 2000 W, output frequency 20 kHz, and magnification of amplitude 2.67. The horn for the machine is made from titanium alloy with geometric shape as an exponential function. To weld composites, the horn is applied to the overlapped region of specimens and a controlled pressure in a certain period of time is transmitted to the specimens being joined. The horn delivers 20 kHz frequency and low amplitude (20-Mm) vibration to specimens, which is concentrated by the energy director to localize heat and join the composite parts.

2.2. Water immersion experiment

To study the effect of moisture absorption on the lap shear strength of carbon/nylon composites, the specimens were immersed into water according to the designed procedure. All the test specimens were dried in an oven at 60°C, and were then placed into a still water trough kept at a constant room temperature (25°C). The moisture absorption specimens were weighed periodically on a Buehler Analytic Balance. The weight was measured until it remains unchanged. This is the saturated specimen and the moisture content is 100%. The weight change as a function of time was recorded.

Upon the weight gain and time curve was plotted, five different specimens that absorb different amount of moisture were prepared using the time data from the curve, that is, 20%, 40%, 60%, 80%, and 100% (saturated specimen). The bonding strengths of five specimens were then measured by the lap shear test.

2.3. Testing

The lap shear test was conducted according to ASTM standard for lap shear test (D3163-73). The schematic of the test set-up and dimension of the specimen were shown in Fig. 1a and b, respectively. Aluminum end-tabs were attached to two ends of specimens via epoxy to protect specimens and transfer the load from MTS testing machine to specimens. The crosshead speed was 0.5 mm/min. The load displacement diagram was recorded during the test and the damage evolution of the specimen was observed.

An acoustic emission apparatus (1200A crack detector, made by Physic Acoustic Corp., U.S.A.) is used to conduct the acoustic emission (AE) test. As shown in Fig. 1a, a 9R-ISI-8 sensor of the acoustic emission apparatus must be closely attached to the specimen during the lap shear test. Therefore, vacuum grease was spread at the interface between sensor and composite that were tied up together by an elastic ribbon to prevent separation. During the lap shear test, when the damage emerges in the specimen, acoustic waves transmit to the surface and the sensor can detect high amplitude waves. The number of those waves corresponds to the count in the AE curve. During the test, both the load-displacement curve and the AE count-time relationship were recorded, and two curves were matched in order to investigate the damage evolution. The parameters for AE machine were set as window time of 1 s, delay time

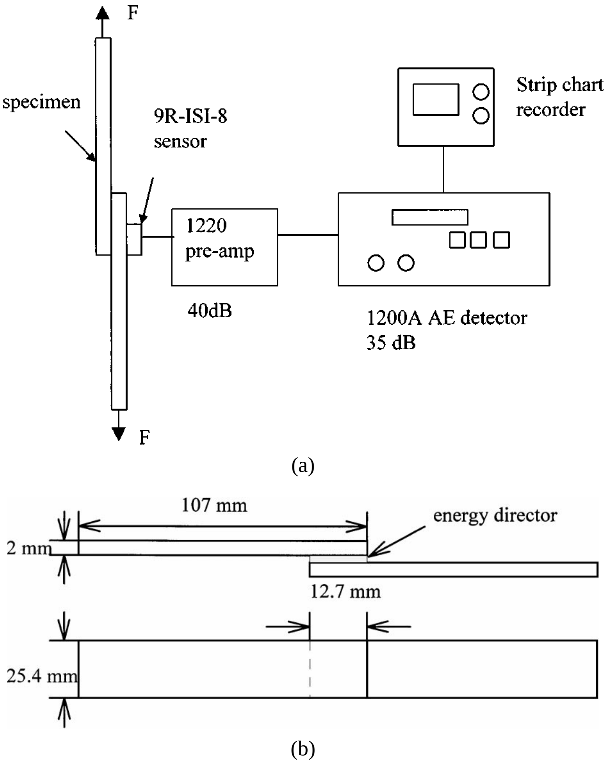

Figure 1 (a) Dimension of specimens, and (b) schematic of set-up for lap shear test and acoustic emission test.

of 0.005 s, and total amplitude of 75 dB. Using the chart recorder, the relationship for count number and time can be completely recorded.

3. Results and discussion

3.1. The effect of welding time and pressure

Fig. 2 shows the influence of welding time on lap shear strength of the joint for carbon/nylon composites. Under welding pressure of 0.25 MPa, the lap shear strength increases with the increase of welding time. The results indicate that under this welding pressure the longer the welding time, the more complete the interdiffusion of the nylon matrix at the joint. While for higher welding pressures of 0.3 MPa and 0.35 MPa, the lap shear strengths increase with increasing welding time from 1.8 s to 2.5 s, but reduce when the welding time is 3.0 s. Observation of damage mechanisms of 12 welded specimens under various conditions is shown in Fig. 3. Longer welding time results in lower strength because it degrades the nylon matrix (Figs 3k and 1). Nevertheless, shorter welding time also leads to lower strength because it can not supply enough heat to melt the nylon (Fig. 3a, b, and d). In addition, due to the zigzag shape of energy director, shorter welding time traps air inside the energy director and reduces the strength (Fig. 3b and e).

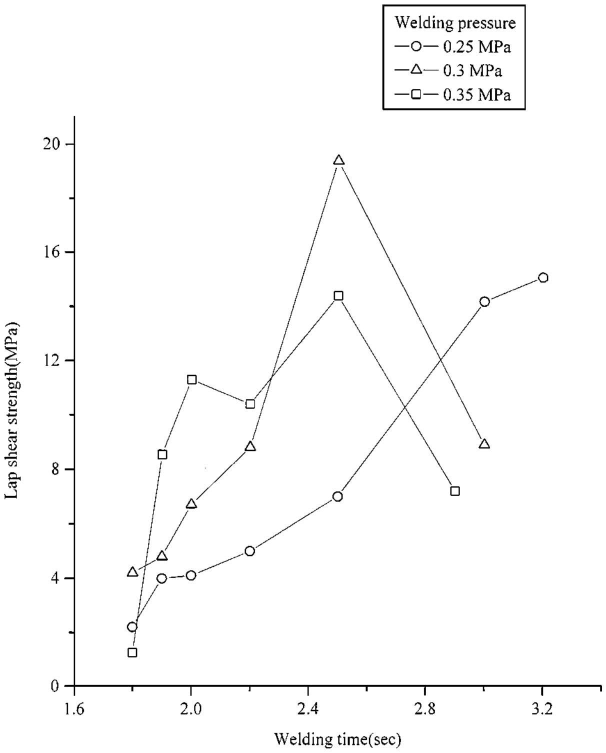

Figure 2 Influence of welding time on lap shear strength of the joint of carbon/nylon composites.

Fig. 4 shows the influence of welding pressure on lap shear strength of the joint for carbon/nylon composites. For welding times of 1.9 s, 2.0 s, and 2.2 s, the lap shear strengths of specimens increase with welding pressure from 0.25 MPa to 0.35 MPa. The tested specimen (welding time 2.2 s, welding pressure 0.35 MPa) has a good lap shear strength of 10.38 MPa, and corresponding damage modes are fiber breakage, debonding, and pull-out as shown in Fig. 5. Similar damage modes are found in Fig. 3j for the specimen with strength of 14.25 MPa. However, further increase of welding pressure up to 0.4 MPa reduces the strength of the specimen welded by welding times of 2.0 s. For welding time of 2.5 s, the maximum lap shear strength is 19.4 MPa under welding pressure of 0.3 MPa. Due to better matrix flow at the joint during welding process, fibers in one specimen can move to another specimen through the joint. Therefore, the failure mode is fiber breakage, as shown in Fig. 3h, which contributes to higher lap shear strength. Incontrast, higher or lower welding pressures lead to lower strengths (Fig. 3g and i). Higher welding pressure of 0.4 MPa squeezes out the energy director and carbon fibers at the joint (similar to Fig. 3l). The squeeze out of energy director releases the heat out of the joint and reduces the inter-diffusion between two joining specimens. Furthermore, the squeeze out of carbon fibers reduces the amount of fibers at the joint and bends the aligned fibers out of loading direction (Fig. 3b, c, f, i, k, and l). Both reduce lap shear strength.

However, lower welding pressure also leads to lower lap shear strength. For thermoplastic nylon matrix, the mechanism of heat generation in the ultrasonic welding process is via viscoelastic dissipation. Energy dissipation can be calculated from [7]

$$P = \frac{1}{2} {e_0}^2 \omega E \sin\delta \qquad (1)$$

in which P is the energy dissipation [W/m^3], e_0 is strain, ω is angular frequency of the driving force [rad/s], E is the modulus of the plastic [Pa]. The dissipation energy is proportional to the square of the local strain, and the strain is proportional to the applied welding pressure if the modulus E remains constant. Therefore, lower

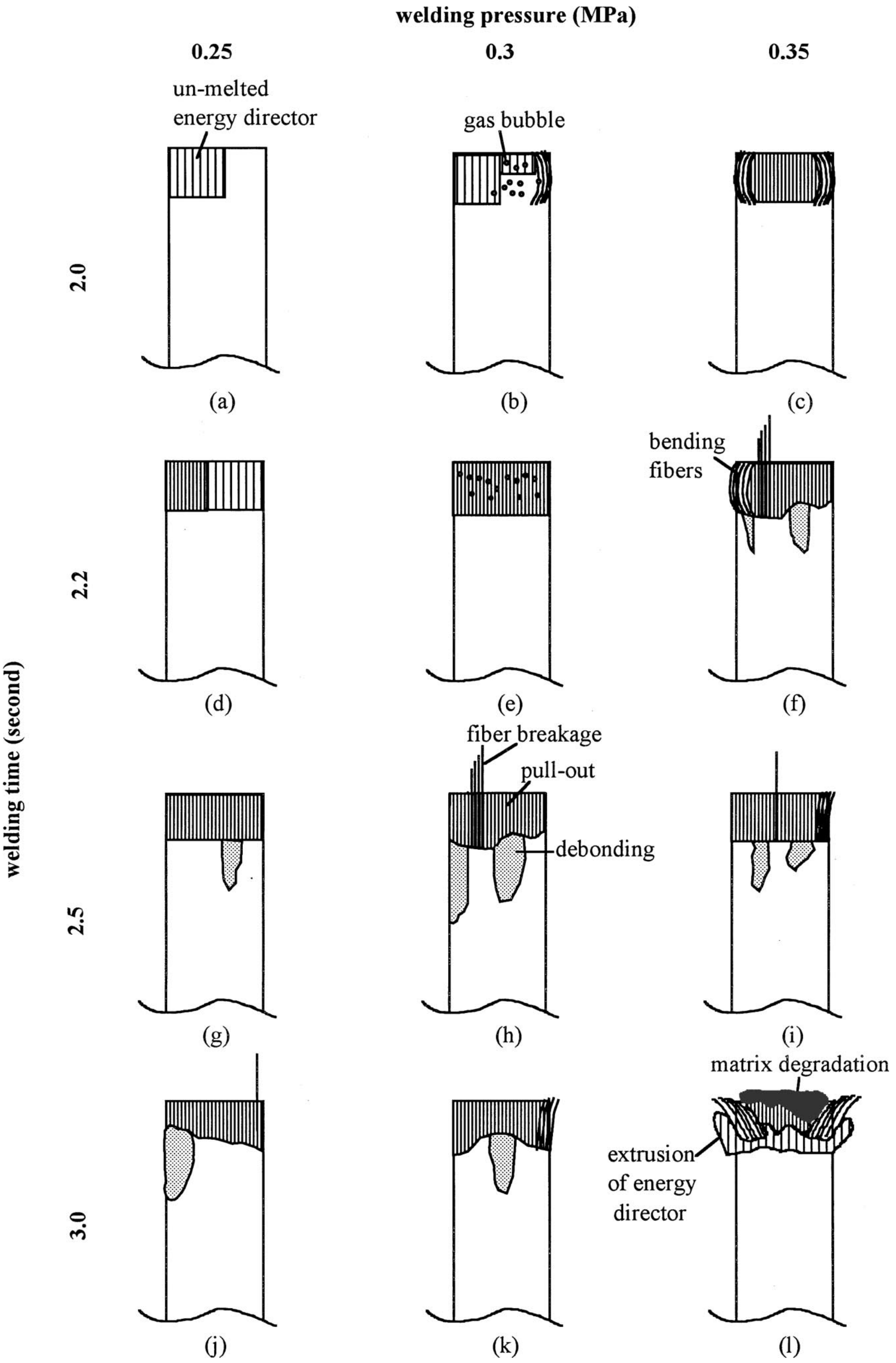

Figure 3 Damage mechanisms of 12 welded carbon/nylon composites under various welding pressures and times.

welding pressure may not generate enough energy dissipation (heat) to completely melt the nylon at the joint, which results in lower lap shear strength.

3.2. AE characterization and failure modes

Figs 6 to 11 show six acoustic emission (AE) count-time curves combined with corresponding load-displacement curves. Figs 6–9 compare the effect of welding time on the lap shear strength using AE analysis, while Figs 9–11 compare the effect of welding pressure. Generally, for those figures, three main stages can be found in the AE curve: stage I, increasing count stage; stage II, maximum count stage; stage III, decreasing count stage. In stage I, the corresponding load-displacement curve increases up to maximum load; in stage II, the corresponding load-displacement curve is narrow and declines sharply; in stage III, the corresponding load-displacement is gradually declined and approaches to zero. However, there is variation among those figures because their strengths are different. Therefore, each stage for those figures is discussed as follows.

Fig. 6 shows the AE count-time relationship and corresponding load-displacement curve under welding pressure 0.35 MPa and welding time 2.0 s. The specimen has the lowest lap shear strength of 5.12 MPa

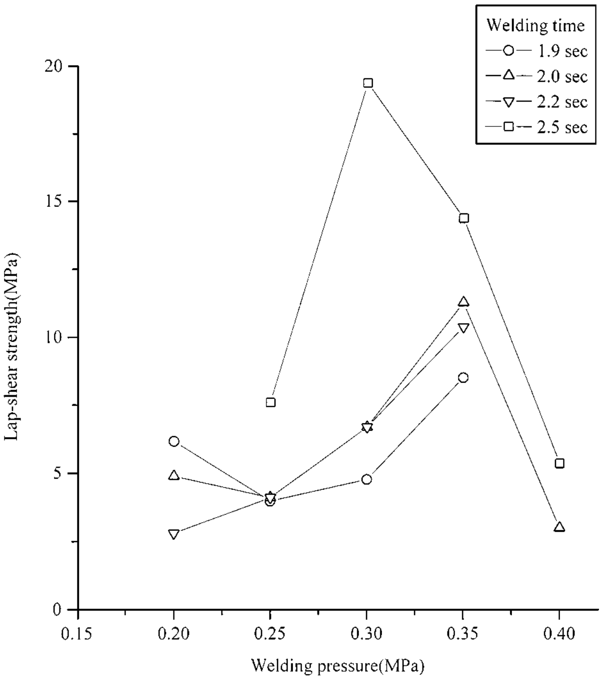

Figure 4 Influence of welding pressure on lap shear strength of the joint of carbon/nylon composites.

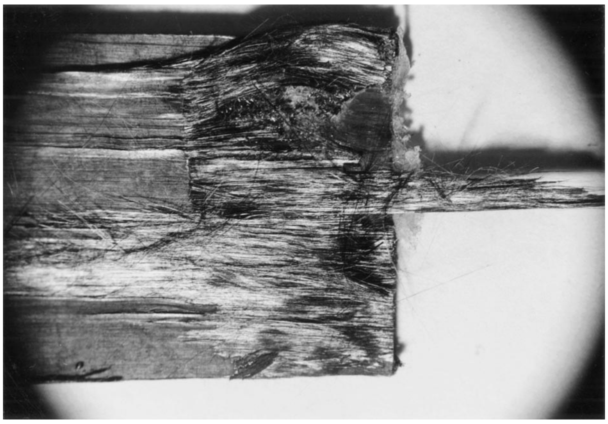

Figure 5 Fiber breakage, debonding, and pull-out in the tested specimen under welding pressure 0.35 MPa and time 2.2 s.

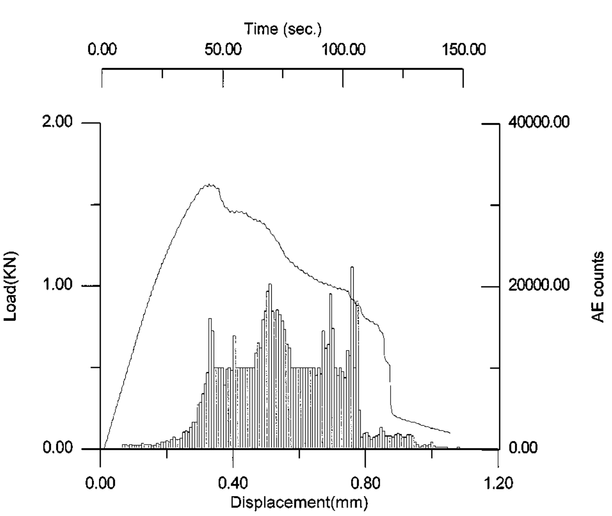

Figure 6 The AE count-time relationship and corresponding load-displacement curve under welding pressure 0.35 MPa and welding time 2.0 s.

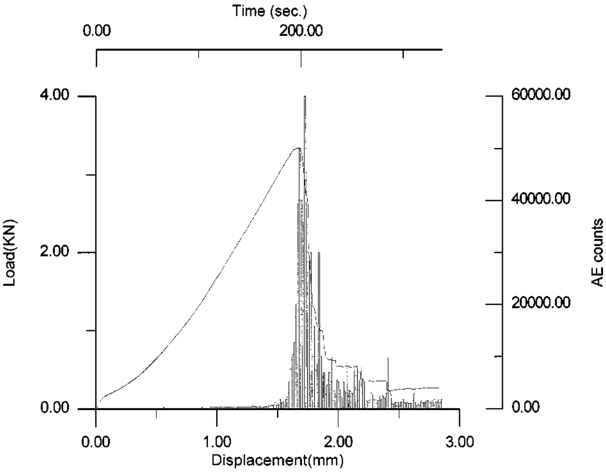

Figure 7 AE count-time relationship and corresponding load-displacement curve under welding pressure 0.35 MPa and welding time 2.2 s.

among the specimens welded under same welding pressure but different welding times. In the stage I for AE curve, slightly increasing count is found. Local damage mode such as matrix micro-cracks occurs at the joint. Four major damage modes in composites possess different count levels, the lowest being matrix cracks, the second lowest being fiber pull-out, the third being debonding, and the highest being fiber breakage [5]. Fiber breakage emits stress waves with the highest frequency (count level) because fibers are brittle and have high modulus. Usually, the shorter duration events at the stage I (lower stresses), the lower the lap shear strength. This can be seen in Fig. 6. In the stage II for AE curve, maximum count occurs and corresponds to the region right after the maximum load in the load-displacement diagram. Matrix cracks extend to whole joining region. The curve for count-time in this stage shows a plateau shape but the value for the maximum count is not very high. The major damage mode that contributes to maximum count may be debonding instead of fiber breakage. This results in the lower strength of the specimen. In the stage III for AE curve, debonding and fiber pull-out occur, but both damage modes can not sustain high shear stress. Eventually the extension of the two damage modes causes two welded specimens to split. Through the AE curve, the damage mechanism for the specimen is clarified.

Figs 7–9 show the AE count-time relationships and corresponding load-displacement curves for specimens under same welding pressure 0.35 MPa, but different welding times of 2.2 s, 2.5 s, and 3.0 s, respectively. These figures are compared to Fig. 4 in order to evaluate the effect of welding time. The lap shear strengths for specimens under welding time 2.0 s, 2.2 s, 2.5 s, and 3.0 s are 5.12 MPa, 10.38 MPa, 14.4 MPa, and 7.22 MPa, respectively. The specimens welded under 2.0 s and 3.0 s show shorter duration events than those under 2.2 s and 2.5 s at lower stresses. Note that the scale for AE curves in the four figures is different. Therefore both specimens show lower lap shear strength. As shown in Fig. 9 (3.0 s), a few high count peaks are found in the stage III, which are not seen in Fig. 6 (2.0 s). Therefore the specimen welded under 3.0 s is stronger

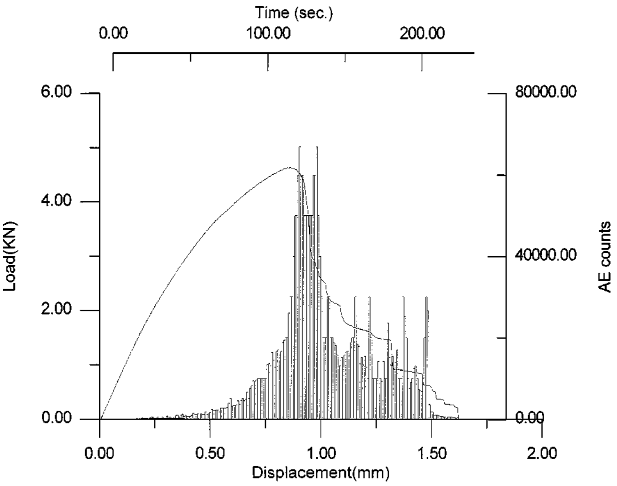

Figure 8 AE count-time relationship and corresponding load-displacement curve under welding pressure 0.35 MPa and welding time 2.5 s.

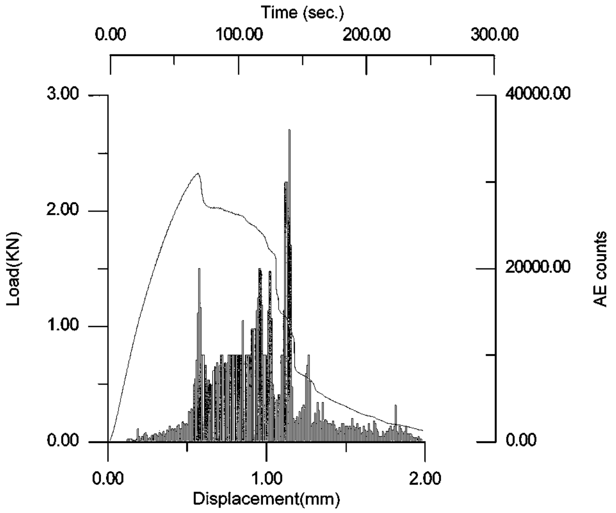

Figure 9 AE count-time relationship and corresponding load-displacement curve under welding pressure 0.35 MPa and welding time 3.0 s.

than the specimen under 2.0 s. As shown in Fig. 8 (2.5 s), some extremely high count peaks are found in stage II, which are induced by fiber breakage. This leads to its highest strength among the four specimens.

Figs 10 and 11 show the AE count-time relationships and corresponding load-displacement curves for specimens under same welding time 3.0 s, but different welding pressures of 0.25 MPa and 0.3 MPa, respectively. Both figures are compared to Fig. 9 in order to evaluate the effect of welding pressure. Lap shear strengths of specimens decrease with increasing welding pressures. Two features in the AE curve contribute to higher lap shear strength for the specimen behaves in Fig. 8. First, long duration events in the first stage indicate that gradual matrix crack propagation occur in the joint due to less defects. Second, extremely high and intensive count peaks exist right after the peak load, which demonstrate that fiber breakage occurs to provide higher strength. Specimens which show either one or neither of the two modes result in lower strengths, as shown in Figs 9 and 11.

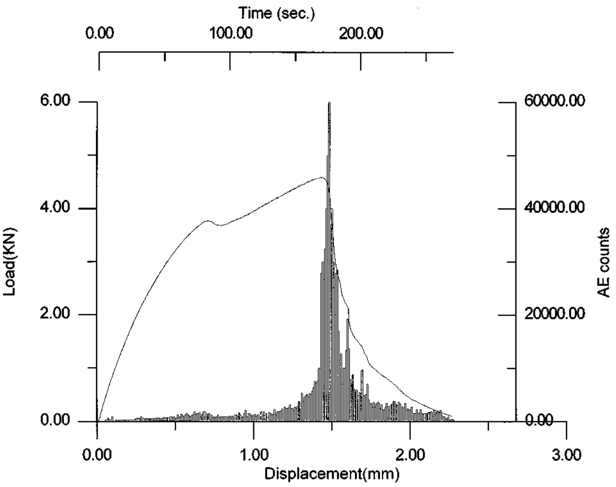

Figure 10 AE count-time relationship and corresponding load-displacement curve under welding time 3.0 s and welding pressure 0.25 MPa.

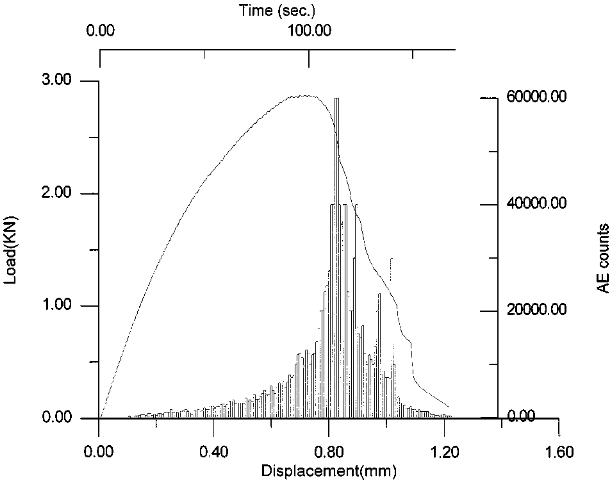

Figure 11 AE count-time relationship and corresponding load-displacement curve under welding time 3.0 s and welding pressure 0.3 MPa.

Acoustic emission (AE) technique not only depicts damage mechanisms of ultrasonic welded carbon/nylon composites under various conditions, but also predicts their lap shear strengths. Table II shows the first damage load (FDL), first signal in the AE curve, and maximum load (from load-displacement curve) of specimens welded under various pressures and times. It is found that the FDL occurs early before the existence of maximum load and the first damage load is approximately one quarter of maximum load. This means that the FDL is approximately proportional to the lap shear strength because the strength is derived by maximum load divided by the welded area. Therefore, the FDL can be used to predict the lap shear strength, that is, the larger the FDL, the higher the lap shear strength indicating fewer defects in the welded region. The advantage of using AE curve to pick up the FDL is that it resembles to a non-destructive method.

3.3. The effect of moisture absorption

The measured weight change of carbon/nylon composites welded under pressure 0.35 MPa and time 2.2 s as a function of time is plotted in Fig. 12. This welding condition results in good lap shear strength of 10.4 MPa. The absorption of moisture is diffusion controlled,

Figure 12 The influence of welding pressure and time on lap shear strength

Welding pressure Welding time	0.2 MPa	0.25 MPa	0.3 MPa	0.35 MPa	0.4 MPa
1.8 s.	5.121 (MPa)	2.226	4.228	1.25	
1.9 s.	6.178	3.977	4.78	8.534	
2.0 s.	4.75	4.103	6.686	5.12	2.9698
2.2 s.	2.767	5.069	8.842	10.378	
2.5 s.		7.52	19.39	14.396	5.376
3.0 s.		14.245	8.9125	7.22	

TABLE II First damage load (FDL) versus maximum load detected by acoustic emission technique during the lap shear test

Specimen	First damage load (kN)	Maximum load (kN)
0.25 MPa/3.0 s	1.06	4.596
0.3 MPa/3.0 s	0.75	2.875
0.35 MPa/2.0 s	0.294	1.627
0.35 MPa/2.2 s	0.727	3.348
0.35 MPa/2.5 s	0.91	4.644
0.35 MPa/3.0 s	0.51	2.33
0.4 MPa/2.0 s	0.24	0.958
0.4 MPa/2.5 s	0.642	1.734

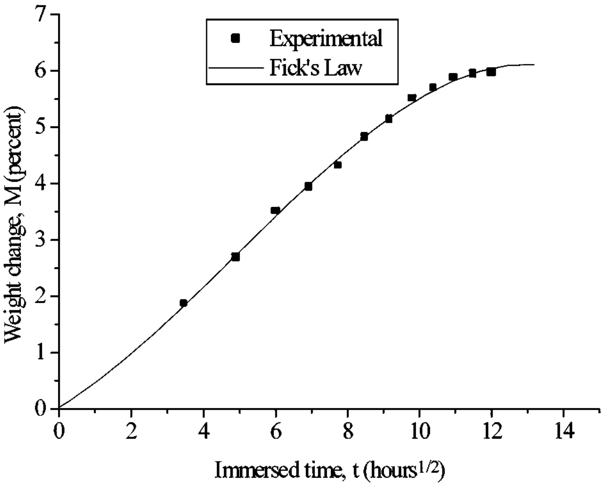

Figure 13 Weight gain of welded carbon/nylon composites under pressure 0.35 MPa and time 2.2 s. Solid line computed by Fick's law.

which can be described by Fick's second law of diffusion. For welded carbon/nylon composites absorbing moisture through both surfaces the initial moisture uptake is proportional to the square root of time, as given below

$$\frac{M}{M_{\mathrm{m}}} = \left(\frac{4}{h}\right)\left(\frac{Dt}{\pi}\right)^{1/2} \tag{2}$$

where M is the moisture uptake at time t, M_{m} the saturated moisture content and h the plate thickness. The weight change calculated by Fick's law is also included in Fig. 12 (solid line) using suitable diffusivity values [8]. Experimental data well fit the Fick's law. According to the law, specimens absorb moisture quickly at initial stage. As the moisture content increases the rate of absorption decreases and approaches a maximum. The maximum weight gain seems to be higher than the typical value for APC-2 composites [9]. This difference may be due to more moisture absorption via capillary effect in the joint or to the fact that materials exposed to water and humid air behave differently.

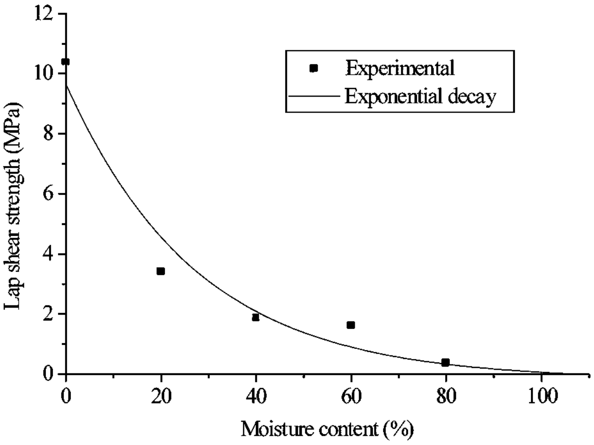

Figure 14 The lap shear strength versus degree of water saturation for carbon/nylon composite welded under pressure 0.35 MPa and time 2.2 s.

Fig. 13 shows lap shear strength versus degree of moisture absorption of carbon/nylon composites welded under pressure of 0.35 MPa and time 2.2 s. It is observed that the strength decreases exponentially with increasing moisture content in specimens. For nylon matrix without moisture absorption, there are hydrogen bonds connecting amide molecular chains in nylon structure. Due to intrinsic hydrophilicity of nylon, when moisture diffuses into nylon, intermolecular hydrogen bonding either connects between water molecules or between water and amide groups; therefore, bonding strength decreases. Moisture absorption also lowers the glass transition temperature of nylon, and enhances plasticization [10]; therefore, it reduces the matrix strength. Therefore, the more amount of moisture absorption, the lower the lap shear strength of the welded composite. Furthermore, the moisture absorption in the matrix, but not in the fibers, usually leads to swelling of the matrix. The differential strain between matrix and fibers results in matrix microcracking, debonding, blistering or delamination. Those damage modes also reduce the lap shear strengths of welded specimens.

4. Conclusions

Acoustic emission (AE) characterization and moisture effects on lap shear strengths in ultrasonic welded carbon/nylon composites were investigated. With a control of either welding time (ranging from 1.8 to 3.0 s) or pressure (ranging from 0.2 to 0.4 MPa), a medium value is proved to have the best effect. Meanwhile, higher welding pressure leads to lower strength due to extrusion of an energy director and bending of fibers; longer welding time results in lower strength due to degradation of nylon. Composites welded under pressure of 0.3 MPa and time of 2.5 s have the highest lap shear strength of 19.4 MPa.

AE characterization is able to detect the first-damage load (FDL) early before the failure of the joint. An interesting finding is that the FDL is approximately proportional to maximum failure load of the joint; therefore, FDL is allowed to predict the lap shear strength of the joint. The configuration of AE curve can further depict the damage mechanism of welded composites under the lap shear test. The longer the duration event in stage I (increasing count stage) and the higher the peak count in stage II (maximum count stage), the higher the lap shear strength of the joint is. The longer duration event implies that there are fewer defects in the joint after ultrasonic welding; therefore matrix cracks extend gradually without the stress concentration caused by the defects. The higher peak count indicates that there is fiber breakage in the joint that emits stress waves with high frequency. In consequence, failure mode of fiber breakage contributes to higher lap shear strength.

Moisture absorption in the joint for carbon/nylon composites obeys Fick's law of diffusion, that is, the weight change of composites is proportional to square root of immersed time. The lap shear strength of the joint decreases exponentially with increasing moisture content. Three reasons lead to reduction of the strength. First, the water molecules connect to the amide molecules and reduce the strength of hydrogen bonding in the nylon matrix. Second, moisture absorption in the nylon matrix lowers glass transition temperature and promotes plasticization. Third, the swelling of nylon matrix due to moisture absorption induces strain mismatch between fibers and matrix; therefore, more damage emerges in the composite and lowers its joint strength.

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