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A Method for Bond Strength Evaluation for Laminated Structures with Application to Ultrasonic Consolidation

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A push-pin type test is proposed as a general approach for bond strength evaluation normal to bonded areas for laminated structures. The evaluation method includes experiment and finite element (FE) simulation. The method has been successfully applied to evaluation of the bond strength of laminated structures made with ultrasonic consolidation (UC). Bond strength varying with UC process parameters has been studied. Based on the results of the simulation and the experiment, a quantitative correlation has been identified between the percent of bonded area and bond strength for UC.

Keywords bond strength, finite element, laminated structure, test method, ultrasonic consolidation

1. Introduction

The overall strength of a laminated structure depends critically on the bond strength between laminated layers. Bond strength measurement has been widely employed to evaluate strength for thin film coating, dental adhesion, and composite fabrication. There are several methods to experimentally evaluate the bond strength for laminated structures. These methods can be broadly classified into five categories depending upon the debonding mode: (a) tensile test (pull-off test), (b) bending test, (c) peel test, (d) scratch test, and (e) ultrasonic test.

The tensile test (Ref 1) is the most commonly used method for the bond strength measurement of thin layers. An increasing tensile force is applied perpendicular to the bonding interface until the interface fails. Some criteria, such as the maximum force or area of detachment, are measured and used to evaluate the bond strength. Two requirements of this method include: (1) the interface bond strength must be lower than the strength of the adhesive media with which an extension can be joined to the thin layer for gripping and (2) a uniform load should be applied across the interface. Two drawbacks for the direct tensile test are: (a) tensile test involves a complex mixture of tensile and shear forces that make the results difficult to interpret and (b) tensile test is limited by the strength of adhesive media.

In the bend test (Ref 2, 3), a load is applied to a sample fixed in a support. Crack nucleation and propagation are detected from the disruption of the load-deflection curve or by an acoustic emission detector. In the peel test (Ref 4, 5), a layer is peeled from a substrate by a peeling load. For both the bend and peel tests, alignment of the specimen with the axis of the testing machine is not required, but both tests are limited to soft coatings or films. The peel test has less substrate distortion resulted in the test than the tensile and bend test. However, the results of peel tests are difficult to interpret, and are not directly comparable with the other bond strength testing methods, unless a layer can be completely debonded from the substrate. This limits the peel test to be suitable for layers with poor bond strength.

In the scratch test (Ref 6-8), an increasing load is applied to scratch a layer by an indenter tip. The critical load for failure is recorded for the analysis of bond strength. In the ultrasonic test (Ref 9-13), the ultrasonic wave is reflected from the interface when a bond is not perfect. The amplitude of the reflected wave is measured and correlated with the bond strength. The difficulty with these two methods is the interpretation of results and qualitative correlation to the bond strength. The difficulty arises from the many variables involved in the measurement and analysis procedures. Some other methods, such as lateral force-sensing microindentation, and laser spallation tests have also been developed for the evaluation of the bond strength (Ref 14, 15).

We propose a new method for bond strength measurement—the push-pin experiment and finite element simulation (PEFE) for laminated structure. PEFE has the following advantages: (a) It is simple to set up, and efficient to test. (b) No adhesive is required for specimen extension, therefore there is no limitation due to the adhesive media or interface strength. (c) For multilayer structures, it has the capability of performing the bond strength measurement of each layer. (d) It is straight forward to interpret the experimental results by decoupling the shear force and obtaining the bond strength, with the help of finite element analysis. (e) A master calibration curve can be prepared to identify bond strength.

Ultrasonic consolidation (UC) is a new manufacturing process that performs a solid-state surface bonding between metals and has many inherent benefits over other joining technologies. Ultrasonic consolidation is designed to continuously weld layers of metal foil to previously deposited material, during which the profile of deposited layers is created by contour milling, to build-up a 3D structure (Fig. 1). Some applications of UC are to: form fiber-reinforced metal matrix composites from engineering material matrices, form dissimilar metal devices with optimized thermal expansion and

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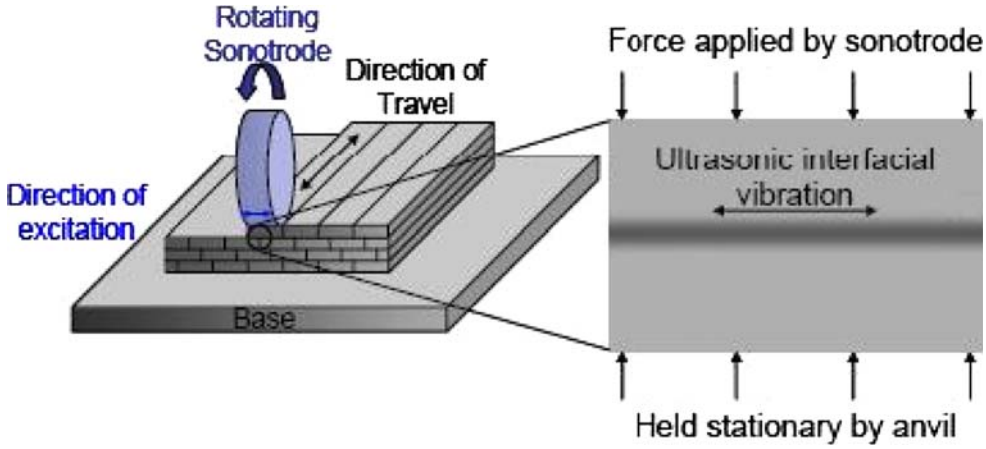

Fig. 1 Schematic of ultrasonic consolidation process (Ref 16)

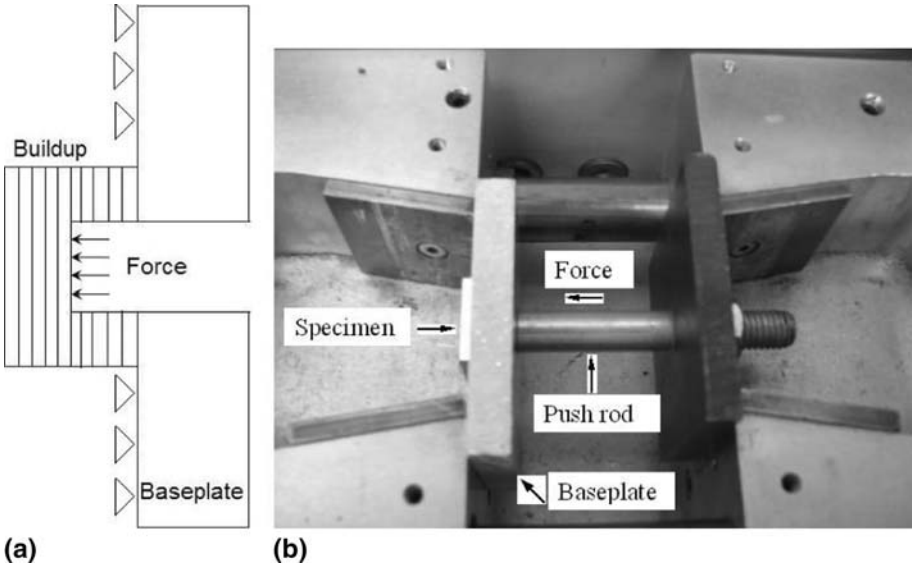

Fig. 2 (a) Schematic of the push-pin experiment; (b) setup for the push-pin experiment on the Gleeble

conductivity, form complex components with embedded functionality, and has the potential to provide design breakthroughs for the electronics, aerospace and transportation industries.

Bond strength is a critical issue that can greatly influence the development of UC and its expansion in existing and new fields. However, there have been no bond strength data from direct measurements on UC consolidated structures. The reason seems to be the lack of a suitable method to evaluate the bond strength between bonded layers. Attempts to conduct tensile testing for the bond strength have not been successful, because the specimen fails at the grips, and it is difficult to control the failure location to a specific bond interface. The motivation for the current work, as well as the first application, has been to measure the bond strength of structures built by UC.

2. Methodology of PEFE

PEFE is defined as push-pin experiment and finite element simulation to determine the bond strength measurement for laminated structures. PEFE involves the following steps: (1) conduct the push-pin experiment and record the force and displacement data; (2) develop a layer-structured FE model with the same dimensions to simulate the push-pin experiment; (3) try different property coefficient for the bond zone until the curve of force versus displacement from the simulation match those from the experiment; and (4) pick the maximum stress normal to bonded areas from simulation results as the bond strength.

3. Push-Pin Experiment

3.1 Experiment Setup

Figure 2 shows the schematic and setup of push-pin experiment on the Gleeble™ 1500D thermal-mechanical simulator. In the push-pin test, the left surface of the baseplate is fixed and a hole is machined from the right surface of the baseplate along the direction normal to the bond areas. The depth of the hole is determined by the depth of interface of

which the bond strength is to be measured. A uniform load is applied with a given strain rate on the specimen by a push rod until the specimen fails. The history of force and displacement is recorded.

3.2 Specimen Design and Test Procedure

The push-pin experiment is designed to study the bond strength of UC, as influenced by process parameters in UC. The controlled process parameters include the sonotrode vibration amplitude, normal pressure, and sonotrode's travel velocity. For this study, four levels are chosen for each process parameter (Table 1), while keeping other process parameters constant. Samples are built on the Solidica™ Formation UC system. The geometry of the multilayered buildup for the process parameter study is 22.9 mm wide, 25.4 mm long, and 16-layers high. The raw material in foil format is Al3003-H18 aluminum strip 0.1 mm thick, and 23.9 mm wide. A hole with 12.4 mm diameter was machined into the specimen. The diameter of push rod is 12.3 mm. The displacement rate used in the push-pin test is 0.42 mm/s. The tests are conducted on the Gleeble™ 1500D thermal-mechanical simulator. To provide the necessary data for simulation, the mechanical properties and coefficient of friction of the raw aluminum foil Al3003-H18 have also been measured on the Gleeble.

Table 1 Process parameters for ultrasonic consolidation

Parameters	Level 1	Level 2	Level 3	Level 4
Sonotrode vibration amplitude, μm	12	16	20	24
Sonotrode normal pressure, N	800	1000	1400	1800
Sonotrode travel velocity, m/min	1.02	1.27	1.42	1.53

Note: The pressure and velocity are 1800 N and 1.42 m/min for the study of amplitude; the amplitude and velocity are 16 μm and 1.42 m/min for the study of pressure; the pressure and amplitude are 1800 N and 16 μm for the study of velocity

PEFE allows bond strength measurement on all bond interfaces through different depths of the hole machined into the substrate. This unique character of PEFE provides a reliable way to perform bond strength measurement for parts with a very small number of layers. One layer buildup is able to be tested, with a backup metal plate glued to the top surface of the layer to prevent the push through by the push pin.

3.3 Experimental Results

The results of push-pin experiments for the study of UC process parameters are shown in Fig. 3. It can be seen that applied force increases nonlinearly with displacement. The force reaches its peak value and drops down quickly. Parts built by UC show brittle fracture normal to bonded areas with low ductility. A typical tested push-pin specimen is shown in Fig. 4. Most of the specimens fracture along the bond line by separation of the foil interface. A fractography with porous features can be observed, indicating only a fraction of the bond interface has been bonded. The slopes and peak values on these curves of force versus displacement are revealing the real

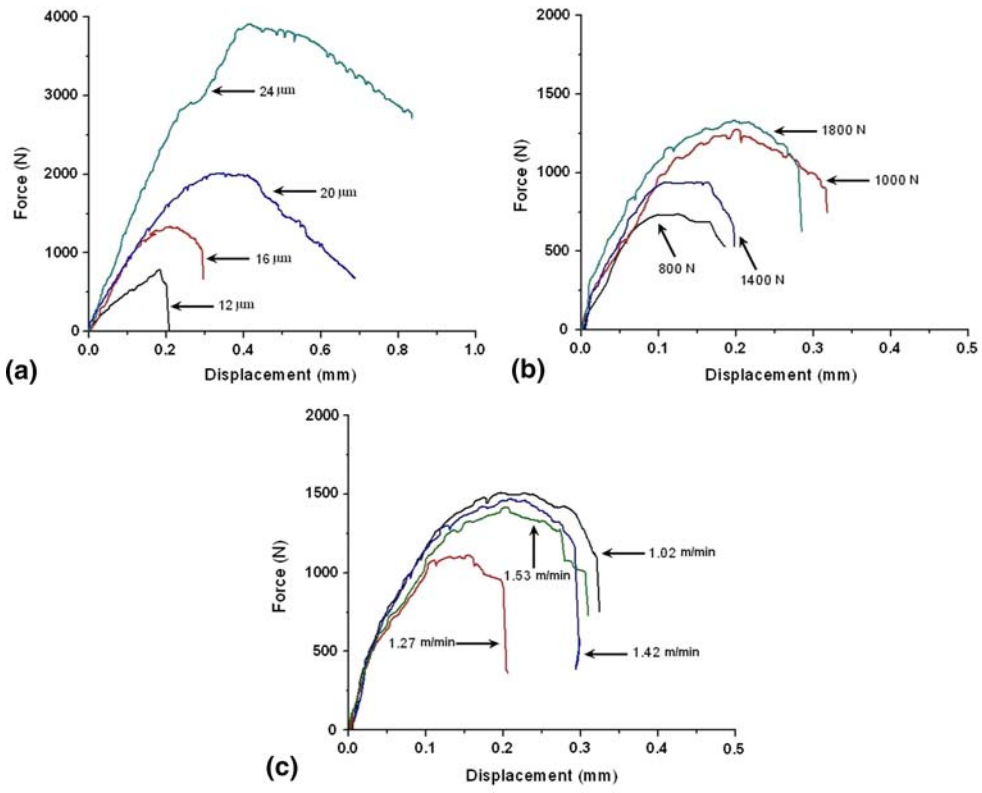

Fig. 3 Force versus displacement curves from push-pin experiments on specimens made with varying UC process parameters: (a) vibration amplitude; (b) normal pressure; and (c) sonotrode's travel velocity

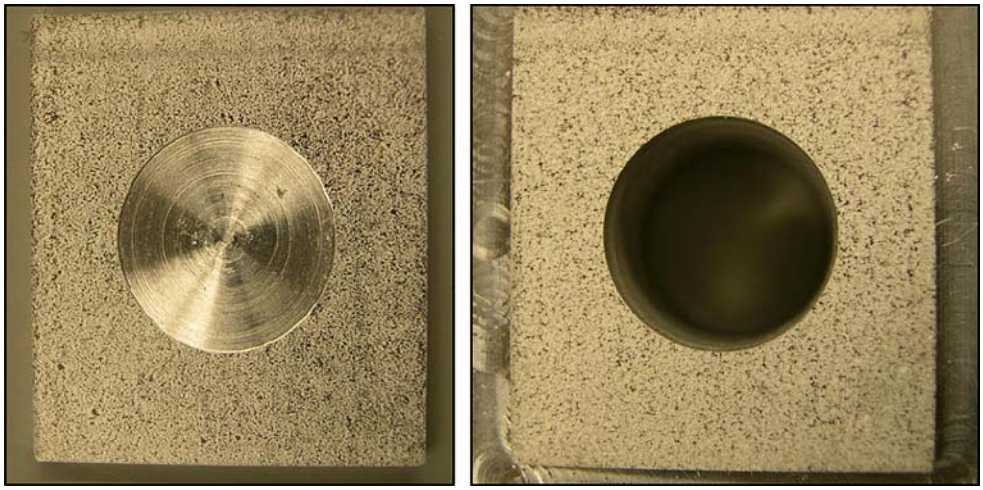

Fig. 4 Typical tested push-pin specimen

property differences among samples. Higher slope and peak value represent greater material stiffness and fracture strength. These results indicate that the push-pin experiment is a sensitive method for bond strength measurement.

The push-pin experiment also improves the understanding of process parameters on bonding strength. Among the selected process parameters, vibration amplitude has the most significant influence on the slope and peak value of force versus displacement curve. That means vibration amplitude is a critical factor that determines properties of parts built by the UC process. Larger vibration amplitude resulted in a stronger UC bond, which is shown by the slope and peak value increasing with vibration amplitude. In the selected range of normal pressure and sonotrode's travel velocity, the curves of force versus displacement show similar slopes, but different peak values. This implies that the major effect of normal pressure and travel velocity is on the fracture strength, not the structure stiffness. The peak values showed a nonlinear relation with parameters of normal pressure and travel velocity. Experiment and simulation of UC process showed that too large or too small of a normal pressure, and too high of a travel velocity will produce a defective UC bonding. On the other hand, too slow of a velocity will reduce the efficiency of manufacturing process (Ref 17). That is shown in the results (Fig. 3b-c). It is seen that the peak force values for 800 N pressure and 1.53 m/min velocity are smaller than the optimized process parameters, which are 1800 N and 1.42 m/min, respectively.

3.4 Finite Element Simulation

3.4.1 The Finite Element Model. Due to the symmetry of specimens, a 2D FE model with layered structure has been developed, based on the commercial ANSYS software, to simulate the push-pin experiment. Figure 5 shows the layered and meshed models. In the layered part, narrow strips are located between layers to simulate the bond zones. The layered part and bond zones have been finer meshed. The dimensions and number of layers are the same as those in push-pin specimen in order to match the experimental and simulation results. The bond zone has been estimated to be 10-20 μm thick based on microstructure observation. Since the bond zones are not as strong as the layers, they are assumed to have a proportion of the properties of raw material. Proportional coefficients of properties are used to correlate the unknown properties of the bond zones with those of the raw material. The measured mechanical properties of the raw foil material Al3003-H18 are shown in Table 2.

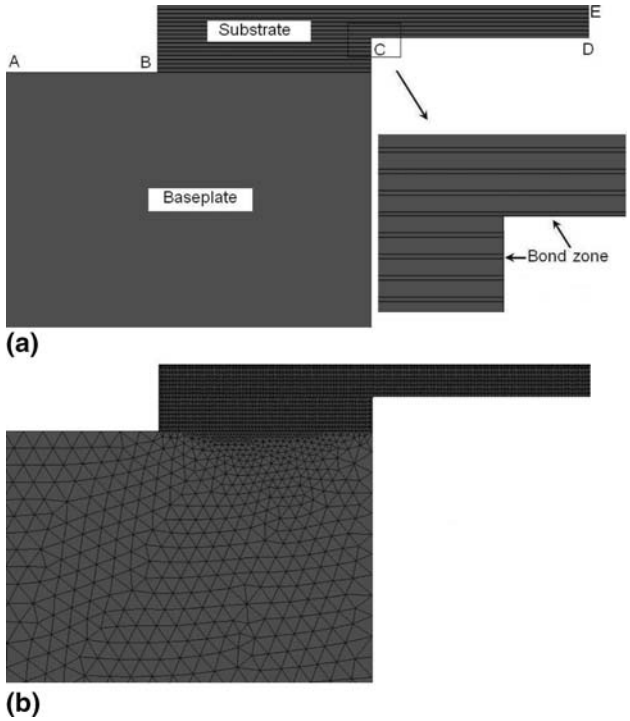

Fig. 5 (a) Finite element model of the push-pin specimen and (b) meshed model

Table 2 Measured mechanical properties of matrix material Al3003-H18

Modulus of elasticity, GPa	Yield strength, MPa	Ultimate tensile strength, MPa
53.2	227.3	244.2

Table 3 Coefficients of elastic modulus for the bond layer

Vibration amplitude, μm	12	16	20	24
Coefficient, $\times 10^{-4}$	1.1	2.8	3.3	5.0
Normal pressure, N	800	1000	1400	1800
Coefficient, $\times 10^{-4}$	1.9	2.4	2.5	2.8
Travel velocity of sonotrode, m/min	1.02	1.27	1.42	1.53
Coefficient, $\times 10^{-4}$	2.9	2.4	2.8	2.5

In simulation, the fixed and axial symmetric boundary conditions are used on the edges of AB and DE, respectively. Bilinear kinematic hardening rule has been used to simulate the nonlinear material behavior. A load with the same loading rate as in the push-pin experiment is uniformly applied on the edge of CD (Fig. 5). Different combinations of property coefficients of elastic modulus, yield stress, and work hardening for the bond zones were tested until the curve of force versus displacement from FE simulation matches that from push-pin experiment. Therefore, the bond strength can be identified by this FE-based "experiment."

3.4.2 Simulation Results. Simulations of push-pin experiments have been conducted for all parameter sets in Table 2. From the FE simulation results, the stress distribution along the edge CD is calculated for each displacement. Then multiplying the cross section area of the push rod, the average force on edge CD is calculated for all the displacement levels. The coefficients of elastic modulus used in simulations for different parameter sets are shown in Table 3, which is found to be the most sensitive in changing the shape of the force versus displacement curve. Figure 6 shows the comparison of force versus displacement from experiment and simulation for all the parameter sets. It is clearly seen that, when the appropriate bond strength properties are fed to the FE model, a matching curve can be achieved. The simulation stops at the peak force, based on the assumption that the peak force is the onset of failure. After the peak force is reached, the crack will propagate quickly and the resistance will decrease.

The von-Mises yield criterion is used in this nonlinear simulation of FE model and the typical distribution of von-Mises strain is shown in Fig. 7(a). The maximum von-Mises strain is located at the corner of the machined inner hole. In the push-pin experiment, all specimens fail from the corner of the machined inner hole. Therefore, the depth of the hole can accurately determine the location of the failure. The distribution of von-Mises strain confirms this experimental observation.

The debonding process entails the foils is a complicated effects of normal and shear stresses on the fracture plane. However, these effects can be simplified by PEFE, because the stress normal to the bond areas weighs more importantly than the other stress components. This means that this stress will most likely dominate the crack propagation process. It can be proven by the stress distribution normal to the bond areas, shown in Fig. 7(b). This stress distribution is similar to that of von-Mises plastic strain, and the maximum tensile stress is also located at the corner bonding interface. Therefore, the stress data obtained from the FE simulation, which match the push-pin experiment data, can be used to evaluate the bond strength. The influence of meshing element size has been studied and shown in Fig. 8 for the case of 16 μm vibration amplitude, 1800 N pressure, and 1.42 m/min velocity. The results are not very sensitive to mesh size. When the meshing element number is 16 times that of used in this study, the result of bond strength decreases by 8.5%. The mesh size that gives higher bond strength was chosen in this study.

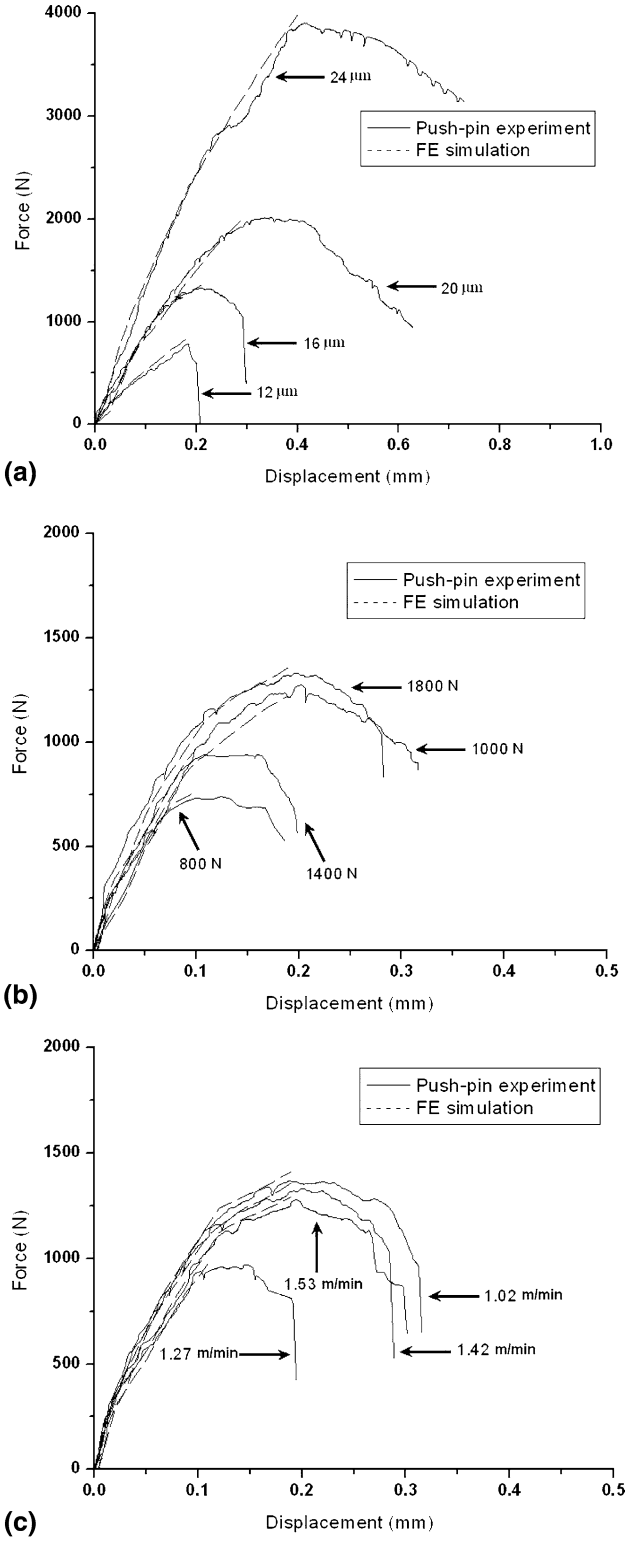

Fig. 6 Comparison of force versus displacement curves from the push-pin experiment and from the FE simulation for specimens made using various process parameters: (a) vibration amplitude; (b) normal pressure; and (c) sonotrode's travel velocity

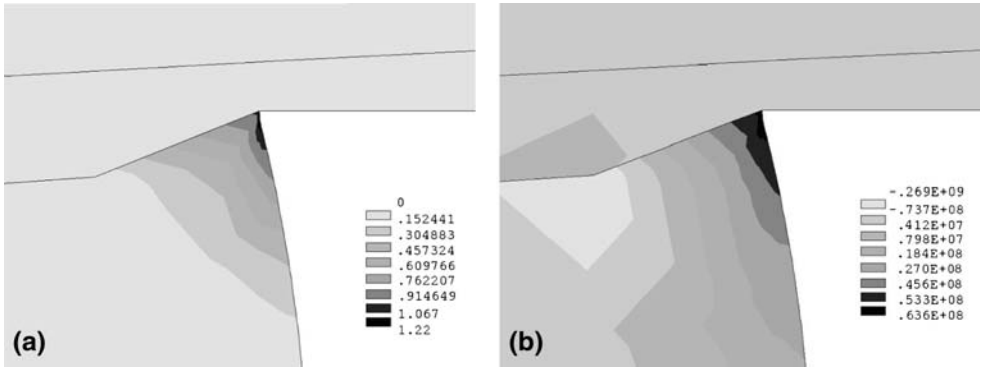

Fig. 7 (a) A typical von-Mises strain distribution near the corner of the push-pin hole and (b) a typical *z*-direction (specimen height direction) stress σ_{zz} distribution at the same location (Unit: Pa)

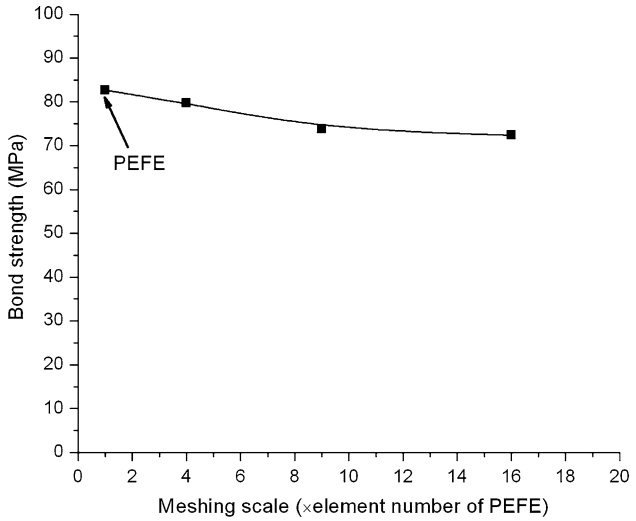

Fig. 8 Meshing study for the case of 16 μm vibration amplitude, 1800 N pressure and 1.42 m/min velocity

3.5 Determination of Bond Strength by PEFE

The debonding at the interface involves the coupling of stresses that make the failure analysis for layered structure difficult. Brewer and Lagace (Ref 18) proposed a general criterion, the quadratic delamination criterion (QDC), for the prediction of interface debond that takes the coupling effect of normal and shear stresses into account. Based on QDC, the onset of interfacial failure can be predicted with

$$\left(\frac{\bar{\sigma}_{xz}}{Z^{sx}}\right)^2+\left(\frac{\bar{\sigma}_{yz}}{Z^{sy}}\right)^2+\left(\frac{\bar{\sigma}^t_{zz}}{Z^t}\right)^2+\left(\frac{\bar{\sigma}^c_{zz}}{Z^c}\right)^2=1 \qquad \text{(Eq 1)}$$

where $\bar{\sigma}_{ij}$ is average of a stress component; Z^t is tensile interlaminar normal strength; Z^c is compressive interlaminar normal strength; Z^{sx} is interlaminar shear strength for σ_{xz} stresses, and Z^{sy} is interlaminar shear strength for σ_{yz} stresses.

When one stress component, normal or shear stress, is dominant in the failure process, Eq 1 can be significantly simplified. We assume that the debond failure in UC specimens is caused mainly by normal tensile stress at the failure interface. Therefore, all terms on the left hand side of Eq 1 can be ignored, except the Z^t term. With this simplification Eq 1 becomes $\bar{\sigma}^t_{zz}=Z^t$, the maximum stress failure criterion. Compared with QDC, the maximum stress failure criterion (Ref 19, 20) is an effective and popular approach for engineering failure analysis. In push-pin experiment, the peak force has been found and taken as the starting point for debonding failure. The maximum stress σ^t_{zz} corresponding to the peak force is calculated from the FE simulation and taken as the bond strength Z^t.

Figure 9 shows the determined bond strength Z^t of UC specimens using the proposed PEFE method. The highest bond strength for parts made with the parameters discussed in this study is identified to be 180 MPa, which is 75% of the UTS of the raw material. For the first time, the bond strength of UC processed components is able to be positively determined using PEFE.

It should be noted that while the bond strength identified by PEFE does seem to be reasonable, PEFE can only be considered as a semi-quantitative method. The process involves inversely identifying, through simulation, at least two bond strength parameters (strength and modulus), therefore, there is always the "uniqueness" question on the parameters identified. However, since there is no better way for evaluating the bond strength for UC, the bond strength identified by PEFE is better than other qualitative methods, such as the peeling test. One way to overcome this semi-quantitative limit of PEFE method is to calibrate the bond strength identified by another direct measurement method.

Based on Fig. 9(a), an increasing vibration amplitude increases the bond strength and it has more significant effect on bond strength/formation than the other two parameters (pressure and travel velocity). In the actual manufacturing process of UC, the optimum parameter set used were 16 μm vibration amplitude, 1800 N normal pressure, and 1.42 m/min travel velocity. In Fig. 9(b), normal pressure of 1800 N resulted in the best bond strength, while the lowest pressure of 800 N resulted in the worst bond strength. Based on our understanding of UC process, to a high normal pressure will decrease bond strength, because the vibrational motion of the parts is constrained, and not enough friction heat will be generated. Thus, intermediate normal pressure, in the range of 1800 N, is the optimal for higher quality UC bonding. Figure 9(c) shows that the lowest travel velocity has the highest bond strength. Although the lowest moving velocity is optimal for bond formation, it also reduces the working efficiency. Therefore, considering the bond strength and working efficiency, 1.42 m/min is the optimal choice for the range of parameters considered in this study.

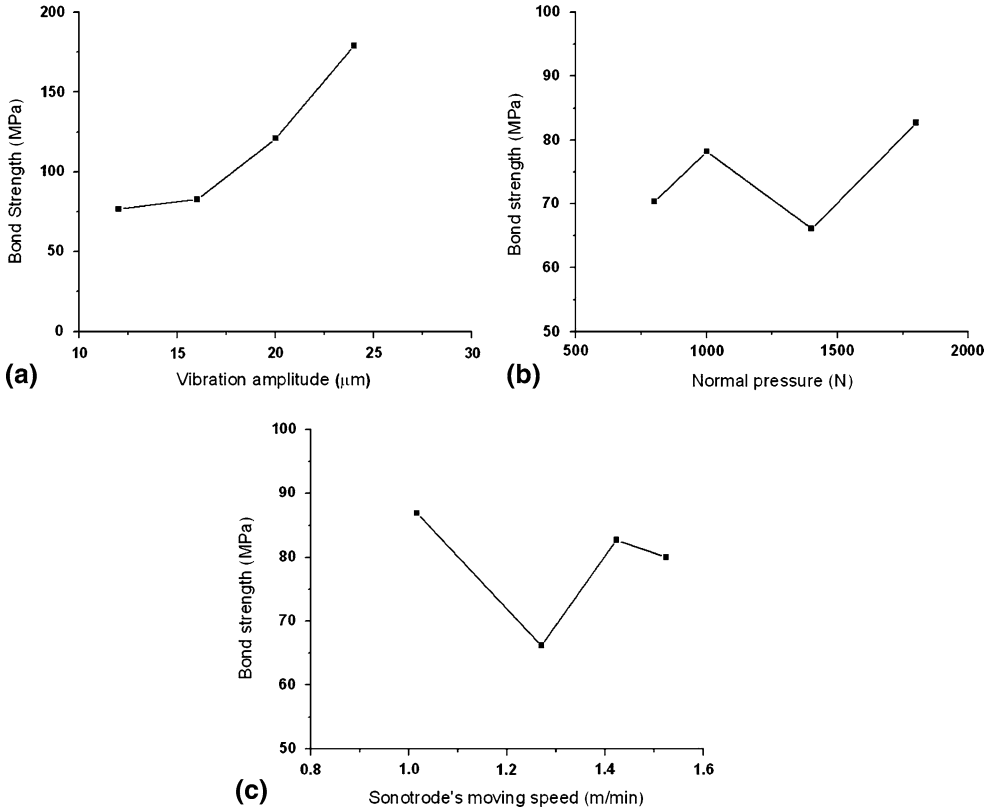

Fig. 9 Bond strength evaluated by PEFE varies with process parameters: (a) vibration amplitude; (b) normal pressure; and (c) sonotrode's travel velocity

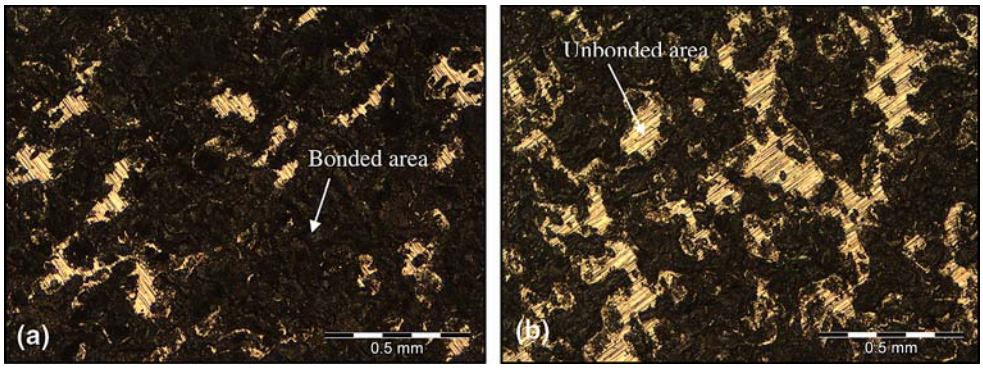

Fig. 10 Typical feature of fractured surfaces: (a) 91.6% bonded area and (b) 74.9% bonded area

3.6 Correlation of Bond Strength by PEFE with Percentage of Bonded Area

Figure 10 shows the typical morphology of fractured surfaces for both high and low quality UC bonding conditions discussed in this study. A difference in the percentage of bonded area exists for these two bonding conditions. Most of the area is bonded for the better UC bonds, while large un-bonded areas exist in the low quality UC bonds. The percentage of bonded area is a reliable way of evaluating the bond formation and bond strength. The bulk bond strength can be predicated by the averaged percentage of bonded area of the entire bonded surfaces. The bond strength in a local region can also be evaluated from the percentage of bonded area of that local region. The bulk averaged percentage of bonded areas have been measured with digital images of fractured surfaces, and converted to bond strength. The bond strength from area measurements is defined as the averaged percentage of bonded area times raw material's UTS. The results of bond strength evaluated by percentage of bonded areas are plotted in Fig. 11. Comparing Fig. 9 and 11, the bond strength provided by these two approaches are showing the same trend for all three process parameters. The similarity between these two sets of results is a strong validation for the PEFE method. The bond strength is probably over-evaluated by the percentage of bonded area method. It should be recognized that the UTS of the raw material used in the bond strength calculation from area is higher than the real bond strength.

Figure 12(a) shows the relation between the bond strength by PEFE and percentage of bonded area. With this curve, an

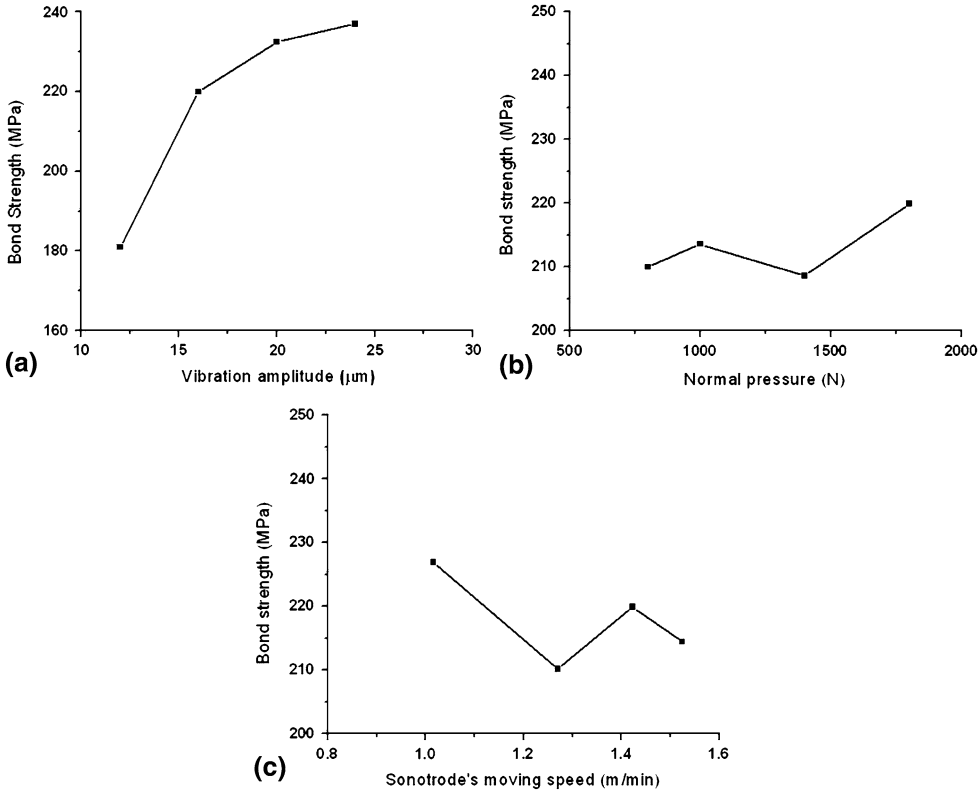

Fig. 11 Bond strength evaluated by bonded area to total area ratio varying with process parameters: (a) vibration amplitude; (b) normal pressure; and (c) sonotrode's travel velocity

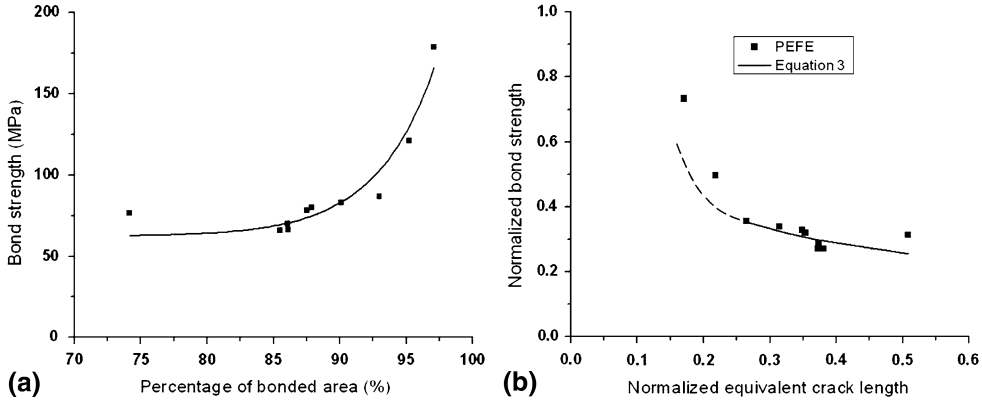

Fig. 12 (a) Bond strength by PEFE versus percentage of bonded area and (b) bond strength as a function of the equivalent crack length, with a comparison between strength obtained using PEFE and strength predicted using Eq 3

estimate of bond strength can also be obtained by conducting a bonded area measurement of UC specimens. The bond strength increases rapidly when the percentage of bonded area is over 90%. This trend can be explained by a basic fracture mechanics analysis. The general form of the Griffith (Ref 21) equation is $s_f = \sqrt{2Ew_f/\pi a}$, where s_f is failure stress, E is elastic modulus, w_f is fracture energy, which could include plastic, viscoelastic, or viscoplastic effects, depending on materials, and a is half of the crack length. The failure stress is proportional to $\sqrt{1/a}$, when assuming that E and w_f are constants for a given material. In PEFE, the un-bonded area can be considered as a crack, so an equivalent crack length (a_{eqv}) is calculated from the percentage of bonded area by

$$a_{eqv} = \frac{1}{2L}\sqrt{A(1 - r_b)} \quad \text{(Eq 2)}$$

where A is total cross section area, r_b is percentage of bonded area, and L is width of cross section.

Substituting the crack length a in the Griffith equation with a_{eqv}, the equivalent fracture strength for the defect-containing UC specimens can be written as

$$s_f = \sqrt{\frac{2Ew_f}{\pi a_{eqv}}} \quad \text{(Eq 3)}$$

If a constant fracture energy w_f is assumed, the curve of s_f (i.e., bond strength) versus a_{eqv} can be fitted to correlate with

the bond strength determined by PEFE (Fig. 12b). When the normalized equivalent crack length is longer than 0.25, the bond strength governed by Eq 3 matches well with that by PEFE. Although assumed as a constant, the fracture energy w_f should be viewed as a parameter, which may affect the bond strength.

4. Conclusions

1. A push-pin type, combined experimental and numerical method for evaluation of bond strength of laminated structures has been developed. The new method has been validated by experimental bonded area data, and has been successfully applied to laminated structures produced using UC.
2. Bond strength for different UC parameter combinations has been evaluated. The best bond strength produced using the set of ultrasonic process parameters in this study is 75% of the UTS of the base material. An increase of vibration amplitude of the sonotrode will increase the bond strength. There is an optimized sonotrode pressure level for bond strength; both low and high pressures will cause a decrease in bond strength. Lower travel velocity of the sonotrode will generate higher bond strength.

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