ULTRASONIC SPECTROSCOPY OF STAINLESS STEEL SANDWICH PANELS

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ABSTRACT

Enhanced, lightweight material systems, such as 17-4PH stainless steel sandwich panels are being developed for use as fan blades and fan containment material systems for next generation engines. In order to improve the production for these systems, nondestructive evaluation (NDE) techniques, such as ultrasonic spectroscopy, are being utilized to evaluate the brazing quality between the 17-4PH stainless steel face plates and the 17-4PH stainless steel foam core. Based on NDE data, shear tests are performed on sections representing various levels of brazing quality from an initial batch of these sandwich structures. Metallographic characterization of brazing is done to corroborate NDE findings and the observed shear failure mechanisms.

KEY WORDS: Ultrasonics, Non-Destructive Evaluation, Sandwich Construction

1. INTRODUCTION

Work under the Ultra Safe Project at NASA Glenn Research Center encompasses research and development of advanced materials and structural concepts to improve the state of the art for fan blades and engine containment. The goal of the project will ultimately contribute to safer, lighter-weight, lower cost and more robust engine materials. Stainless steel sandwich panels consisting of two thin plates adhered to a metallic foam core are being investigated to address these needs. In particular, aerospace grade 17-4PH stainless steel is chosen due to its attractive mechanical properties and its ease of making foam.

Cellular materials, such as metallic foams, are an attractive class of low-density materials with an outstanding combination of mechanical, thermal and acoustic properties (1). They offer a large potential for lightweight structures, energy absorption and thermal management. Their extraordinary property combinations make them interesting for applications where more than one function must be met, such as high stiffness and acoustic damping.

In order to take advantage of the properties of metallic foams, sandwich-like structures are created with the foam acting as the core. The stiffness of the sandwich structure is increased by

separating the two flat sheets by the foam layer. The resulting structure has a high stiffness and lighter weight in comparison to the same thickness of the solid material. The face sheets carry the applied bending moment via longitudinal tensile and compressive stresses, while the core carries the transverse shear stresses (2).

Although methods to produce metal foams are not new, the difficult process control and high costs have prevented the spread of their use. However, advances in production techniques and cost reduction have created a new interest in the technology. The different production methods can be classified into four groups: from melts, from powders, by sputtering, and by deposition. Each production method covers a characteristic range of density, cell size and cell topology. The powder metallurgy route, utilized to manufacture the panels of the current study, provides a low cost technique for producing large complex shape panels (3).

The aim of this investigation is to analyze the brazing quality of a 17-4PH foam core to 17-4PH face sheets. The bond strength between the core and face sheets is crucial to maintain the structural integrity of the sandwich structure. Hence, NDE techniques, such as ultrasonic spectroscopy, are being utilized to evaluate the brazing quality between the stainless steel face plates sandwiching a metallic foam core.

Ultrasonic spectroscopy is a NDE technique for material characterization and defect detection. The typical approach involves the transmission of a wide bandwidth ultrasonic pulse into a component. After the time domain response is converted to the time domain via fast Fourier transform (FFT), the frequency domain response is evaluated based on known parameters, such as thickness and acoustic velocity. Previous approaches to ultrasonic spectroscopy demonstrated effectiveness in evaluating attenuation, velocity, delaminations, and degradation in composite materials; detecting and classifying discrete flaws, cracks, and corrosion; and analyzing multiple layered structures (4-6). Fitting and Adler (5) produced an extensive review of these approaches to ultrasonic spectroscopy and their applications.

Recently, Tucker (7) developed and patented a swept-frequency approach to ultrasonic spectroscopy, which exhibited advances in detecting hidden corrosion in aluminum plates (8) and evaluating bond quality in multiple layered structures (9). The method also demonstrated capabilities for evaluating polymer matrix composite material rings and rims from flywheels (10, 11). Additionally, the technique exhibited delamination detection and monitoring capabilities in a polymer matrix composite ring (12). This method was further established as a scanning technique (13).

The current study further investigates the capabilities and limitations of the swept-frequency approach to ultrasonic spectroscopy. An ultrasonic c-scan image, acquired with 10 MHz transducers in a pulse-echo immersion scan, suggested that different regions of the sandwich panel had various levels of brazing quality between the outer face plates and the foam core. Although the ultrasonic c-scan provided valuable information, complete immersion in water may cause steel panels to rust. Therefore other NDE techniques, such as swept-frequency ultrasonic spectroscopy, are being investigated for inspection of these types of panels. Four regions representing different levels of brazing quality were investigated with ultrasonic spectroscopy. Then the sandwich panel was sectioned to create four shear specimens incorporating the various

levels of brazing quality in the gauge region of each specimen. The results of a mechanical shear test are compared to the ultrasonic spectroscopy results to describe the capabilities and limitations of ultrasonic spectroscopy in characterizing the brazing quality.

2. BACKGROUND

2.1 Ultrasonic Resonance The fundamental resonant frequency results from a localized ultrasonic standing wave in a plate. An ultrasonic transducer coupled to a plate induces resonance when the wavelength of the transmitted frequency is twice the thickness of the plate. The fundamental resonant frequency can be calculated from an equation relating frequency to thickness of a plate, d, and the acoustic velocity in the plate. The relationship (6) between the frequency, f, wavelength, λ, and acoustic velocity, c, is

$$c = f\lambda . \quad (1)$$

At the fundamental resonant frequency, f_R, there is a half wavelength in the plate thickness and

$$\lambda = 2d . \quad (2)$$

The resulting equation for the fundamental resonant frequency is

$$f_R = \frac{c}{2d} . \quad (3)$$

Equation (3) is then used to evaluate the material under investigation given the acoustic velocity of the material, thickness of the component, or fundamental frequency produced by ultrasonic spectroscopy.

3. EXPERIMENTAL

3.1 Material and Specimens The 17-4 PH stainless steel foam sandwich panel measuring 15.24 cm (6 in) wide by 25.4 cm (10 in) long by 1.30 cm (0.51 in) thick was obtained from Porvair Inc., Hendersonville, NC. First, a 17-4 PH stainless steel foam panel with dimensions of 15.24 cm (6 in) wide by 25.4 cm (10 in) long by 0.99 cm (0.39 in) thick, 32 pores per cm (80 pores per inch), and a relative density of 6 percent was produced by proprietary powder metallurgy technique. Then, the foam and rolled sheets of 17-4PH steel, approximately 1.6 mm (0.062 in) thick, were brazed together using BNi-6 at 971°C (1780°F) for 30 minutes and argon quenched to produce the sandwich panel. Finally, the sandwich panel was heat treated at 552°C (1025°F) for 90 minutes and argon quenched.

The panel was investigated on both front and back sides using ultrasonic spectroscopy and ultrasonic c-scans (figures 1 and 2). The darker regions indicate good bonding conditions and the lighter indicate poor bonding. Based on the results four shear test samples were cut from the panel such that the gauge regions of each sample consisted of either well-bonded or poorly-bonded areas. The front of samples A and B represented regions of poor and intermediate brazing. The back of these two samples appeared to have good brazing quality from the ultrasonic c-scan. The front and back of samples C and D exhibited regions with good brazing. The specimen dimensions were 15.24 cm (6 in) by 2.54 cm (1 in) by 1.30 cm (0.5 in) as shown in figure 3. Each gauge region had dimensions of 2.54 cm (1 in) by 2.54 cm (1 in) and was sized such that the gauge was completely composed of either good or bad bonded areas.

3.2 Ultrasonic Spectroscopy System The commercially available ultrasonic system (4)

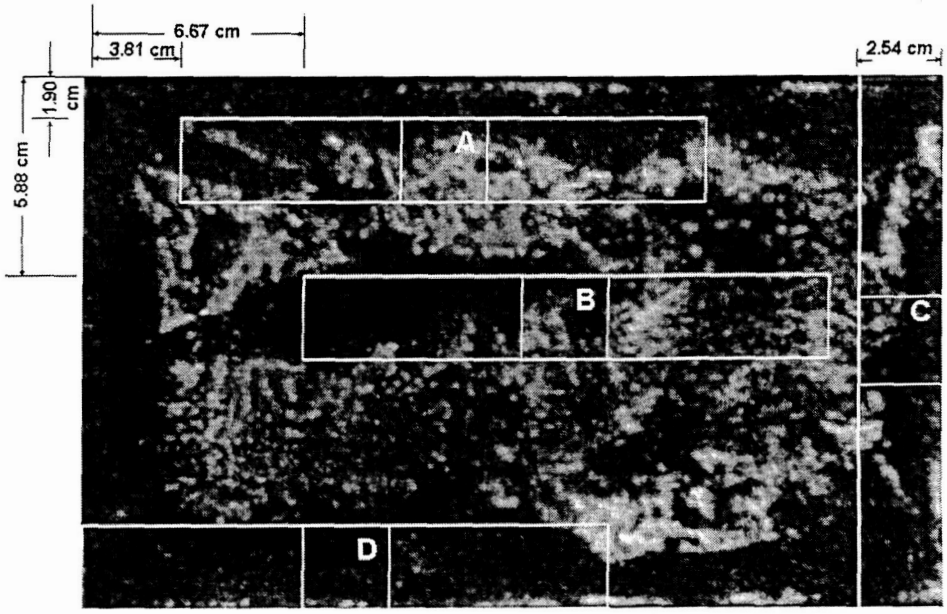


Figure 1. Ultrasonic c-scan of the front of the sandwich panel illustrating the four regions of the sandwich panel tested with ultrasonic spectroscopy and machined for shear testing.

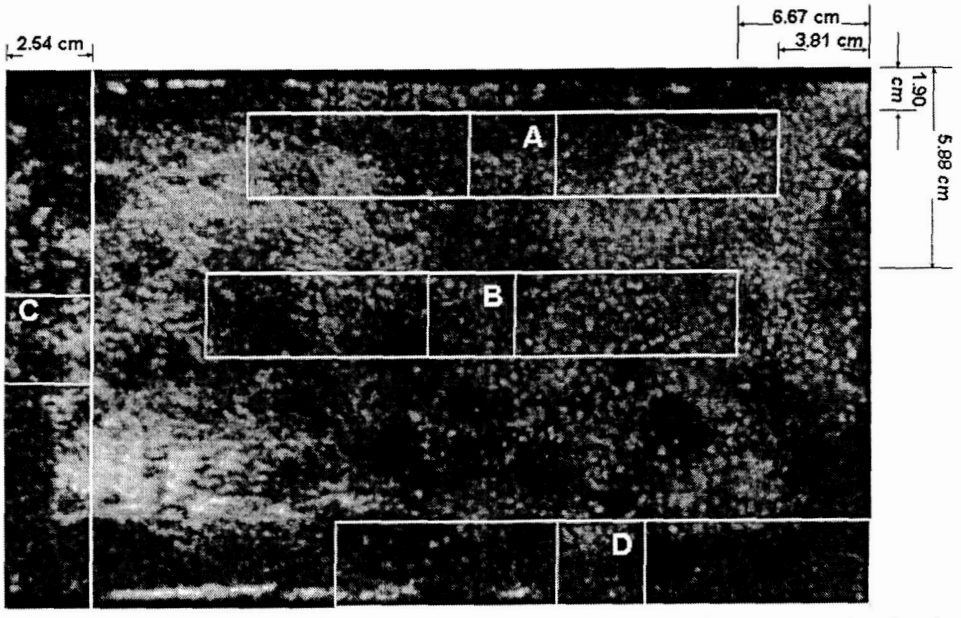


Figure 2. Ultrasonic c-scan of the back of the sandwich panel illustrating the back side of the regions tested with ultrasonic spectroscopy and sectioned for shear testing.

includes a digital processing oscilloscope, amplifier, digital to analog converter, and computer software. The software generates a continuous swept-frequency acoustic wave and captures the ultrasonic response of a test specimen. The frequency sweep or interval is user defined with capabilities from the audible range to approximately 12 MHz. The current study utilized two frequency intervals to illustrate the capabilities of the system. The first interval, employed prior to sectioning the sandwich panels, was from 1 to 5 MHz. The second interval, utilized after

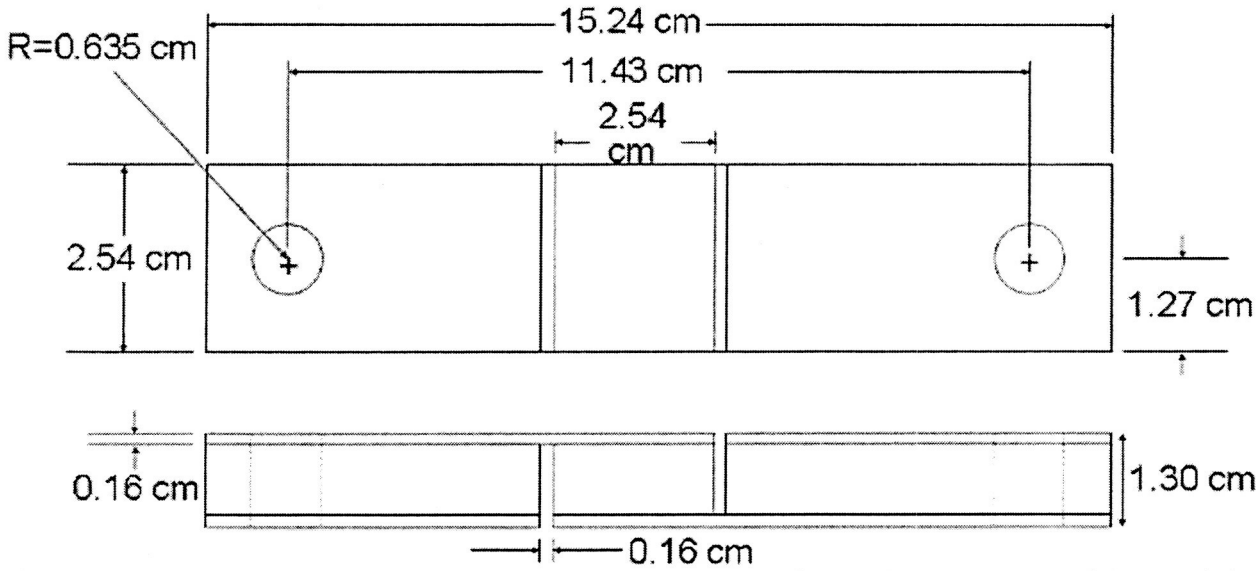
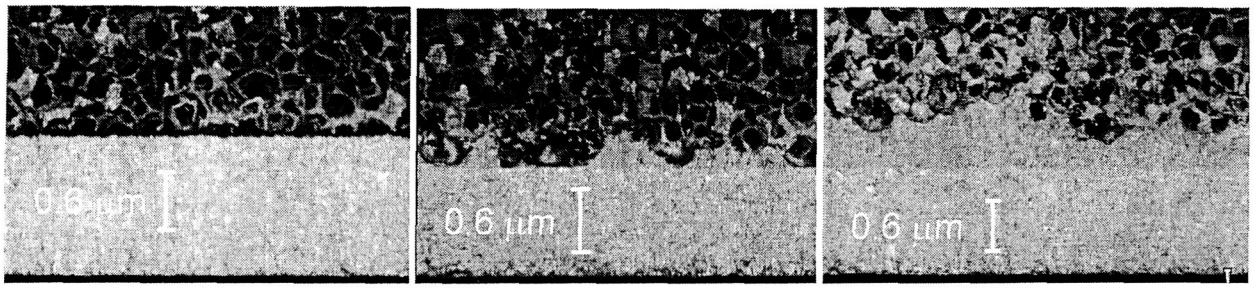


Figure 3. Typical specimen dimensions of the samples sectioned from the sandwich panel for shear testing.

sectioning the panel, was from 1.5 to 10 MHz. The pulser generates a digital input waveform, which is converted to an analog signal and transmitted into the test specimen with an ultrasonic transducer which is coupled to the specimen surface. The ultrasonic time domain response is received by a second transducer. For the initial sweep of 1 to 5 MHz two 5 MHz medium-damped direct-contact ultrasonic transducers were utilized. For the second sweep of 1.5 to 10 MHz a 5 MHz dual-element direct-contact transducer was utilized. To eliminate the effects of a nonlinear transducer response and achieve a truer broadband signal, the system has the capability of equalizing the amount of energy distributed to each frequency. A digital spectrum analyzer converts the received ultrasonic wave from the time domain to the frequency domain via FFT. If the frequency sweep includes the fundamental frequency, it may appear in the frequency domain. However, the resulting frequency spectrum typically contains higher order resonance peaks or harmonics as exhibited by the material system under investigation. Since the value of each harmonic is an integer multiple of the fundamental frequency, the spacing between resonance peaks represents the fundamental frequency. Consequently, the performance of a second FFT on the spectrum produces a peak representing the spectrum resonance spacing, or the fundamental resonant frequency. The existence of such a resonance peak indicates an impedance mismatch either due to the back face of the specimen or a planar crack type flaw. In this particular study, the fundamental resonant frequency is produced when the outer plate is separated from the metallic foam.

4. RESULTS

4.1 Ultrasonic Spectroscopy Figure 4 illustrates the three braze conditions initially interrogated in this study. Figure 4a shows the poor brazing condition where no braze wet the surface of the outer face plate. This photo is of the edge of the gauge region of shear specimen A. Figure 4b exhibits the intermediate brazing condition from shear specimen B. Some braze wet the surface of the plate and adhered to the foam core. Figure 4c depicts the good brazing condition where the braze adhered to both the face plate and the foam core. This image came from the gauge



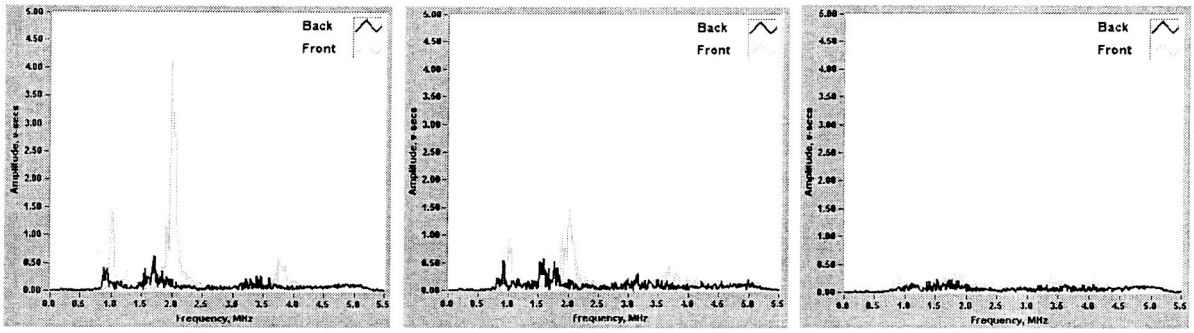
(a) (b) (c)

Figure 4. Optical photo of three brazing conditions investigated in this study: (a) shear specimen A with poor brazing, (b) specimen B with intermediate brazing, (c) specimen D with good brazing between the outer face plate and the foam core.

region of specimen D.

Prior to sectioning, four regions from the front and back of the panel were tested with ultrasonic spectroscopy to determine how to section the panel. These signals also verified results from the ultrasonic c-scans, illustrated in figures 1 and 2. The dark regions of the ultrasonic c-scan represent areas with good braze conditions. Four regions were chosen to represent different levels of brazing. The front side of the area labeled A in figure 1 is a region with no braze between the face sheet and the foam core. The front side labeled B in the figure represents an intermediate region with some brazing between the face sheet and the foam core. The majority of the front side of region C represents a good brazing condition with a section of intermediate brazing. Good brazing conditions on the face sheets are exhibited by the remaining regions; the back side of regions A, B, and C, depicted in figure 2, and both the front and back sides of region D, depicted in figures 1 and 2.

The initial ultrasonic spectroscopy data was collected with the two medium-damped 5 MHz transducers and the frequency sweep input of 1 to 5 MHz. The transducers were placed on the same side of the specimen with gel couplant in a send-receive mode of transmission. The resulting frequency spectra for the front and back of regions A, B, and C are shown in figure 5. The ultrasonic spectroscopy responses from C and D had the same features. Therefore, the results for the front and back of region C only are presented in the figure. Contrary to the ultrasonic c-scan, the ultrasonic spectroscopy response indicates that region C has as good of brazing conditions as region D. Only the frequency spectra were acquired as a single harmonic, the fundamental frequency of the outer face sheet was excited. Hence, the spectrum resonance spacing did not offer any new information. The comparison of responses from the front and back of region A represents the comparison of a region with poor brazing (front) versus a region presumed to have good brazing (back). The comparison of the front and back of region B represents the comparison of intermediate brazing (front) versus presumed good brazing (back). The responses from the front and back of region C represent results typical of two regions with good brazing compared to the ultrasonic c-scan results that indicated some intermediate braze for the front of region C. For the region with poor brazing quality, the front of region A, a frequency peak of 2.0 MHz appears in the frequency spectrum. Based on the acoustic velocity of steel, 5.9 mm/μsec (6), this frequency corresponds to the fundamental frequency of the outer face plate with a thickness of approximately 1.5 mm (0.06 in). For the region with intermediate brazing, the front of region B, a frequency peak of 2.0 MHz also appears in the frequency spectrum corresponding to the thickness of the outer face plate. However, this peak has an amplitude



(a) (b) (c)

Figure 5. Frequency spectra from the front and back of three regions of the sandwich panel: (a) region A with poor brazing on the front face plate and presumed good brazing on the back face plate, (b) region B with intermediate brazing on the front face plate and presumed good brazing between the back face plate and the foam core, and (c) region C with good brazing conditions between both face plates and the foam core.

approximately 60 percent lower than the peak for the region with poor brazing. For the region with good brazing, both sides of region C, no frequency peak appears as the ultrasound was attenuated by the braze and the foam core. This response is identical for region D as well. In all the responses, a slight peak appears at approximately 1 MHz. This frequency peak at the beginning of the frequency sweep of 1 to 5 MHz is an artifact of the FFT.

Although the response for the back regions of A and B have a weak response, there is a signal with very low amplitude and a slight shift in frequency to approximately 1.75 MHz. The shift in frequency is attributed to the increased thickness due to the presence of the braze. Comparison of the response from the back sides of regions A and B to the responses from C helps to explain the results as well. Figure 6 plots the response from the front of region C with good brazing

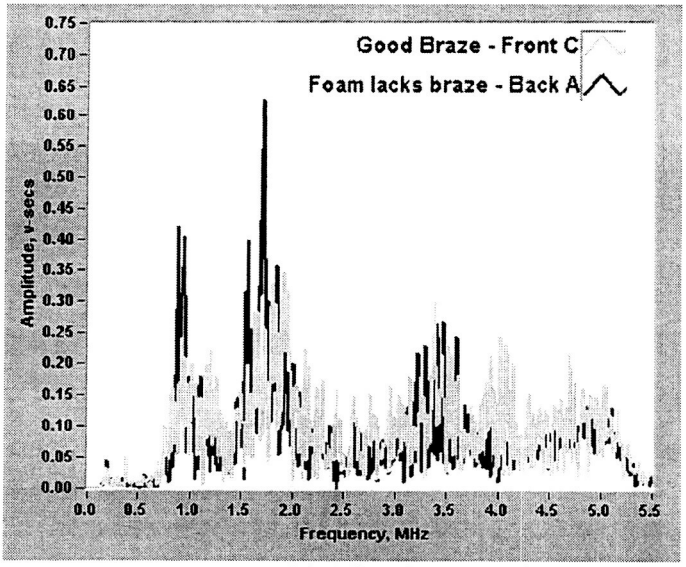
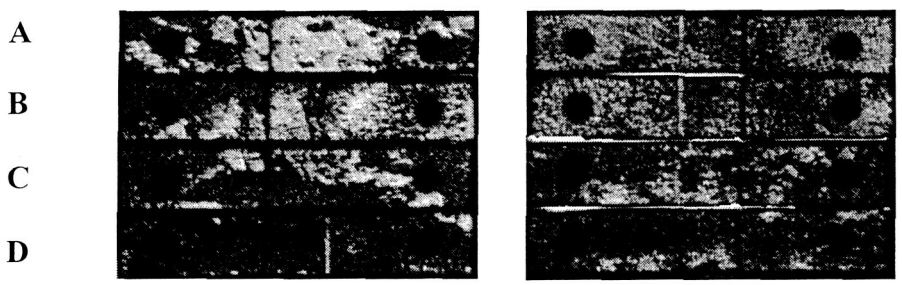


Figure 6. Ultrasonic spectroscopy response highlighting the difference in amplitude between the frequency spectrum from a region with good braze versus a region where the braze wet the surface of the plate but not the foam.

conditions and the response from the back of region A. The amplitude of region A was greater than the response from region C. This was identical to the response from the back of region B as well. This difference in amplitude was credited to a condition which exists near the interface of the metallic foam and the braze. On the back side of regions A and B there is either cracking in the metallic foam or lack of braze at the foam-braze interface. It appears that the braze wet the surface of the face plate only. Some ultrasound returned from the back face of the braze. Much of the ultrasound was scattered by the rough surface of the braze. The interface condition was evident visually after the panel was sectioned for shear testing as will be shown later in the text.

Figure 7 shows an ultrasonic c-scan of the front and back of each shear specimen. Each specimen was designated according to the region it was sectioned from. For example, the shear specimen taken from region A of the sandwich panel is referred to as shear specimen A. From the c-scan image in figure 7a it is evident that there was a lack of braze on the front of specimen A, an intermediate brazed condition on the front of specimen B, good braze conditions for the majority of the front of shear specimen C, and good braze conditions for specimen D. The c-scan image shown in figure 7b implies that the back of all four specimens had relatively good brazing conditions.



(a) (b)

Figure 7. Ultrasonic c-scan images of the (a) front and (b) back of each shear sample acquired after sectioning from the sandwich panels.

Figure 8 shows optical photos of the gauge region for each shear specimen. The top of each picture represents the front of each specimen. It is evident from these photos that there is either cracking or a lack of braze adhering to the metallic foam surface on the back of shear specimens A and B. In these two specimens the braze appears to have wet the surface of the back face plate but not the surface of the metallic foam core. Hence, there is a very weak bond, if any, between the braze and the foam core.

To illustrate some of the capabilities of the ultrasonic spectroscopy system, the data was collected from the sandwich panel shear specimen sections in a slightly different manner than the initial ultrasonic spectroscopy data. A longer frequency sweep of 1.5 to 10 MHz was utilized with a 5 MHz dual-element transducer to acquire signals from the front and back of the 2.54 cm by 2.54 cm (1 in by 1 in) gauge region of the sandwich specimens. The dual-element transducer was utilized to increase the amount of ultrasonic energy received in a smaller, more exact region. Since the spacing between the transducers decreased, the amount of ultrasonic energy lost due to the angle of the ultrasonic path decreased. The longer frequency sweep combined with more ultrasonic energy allowed more harmonics to be excited in the frequency spectrum. Hence,

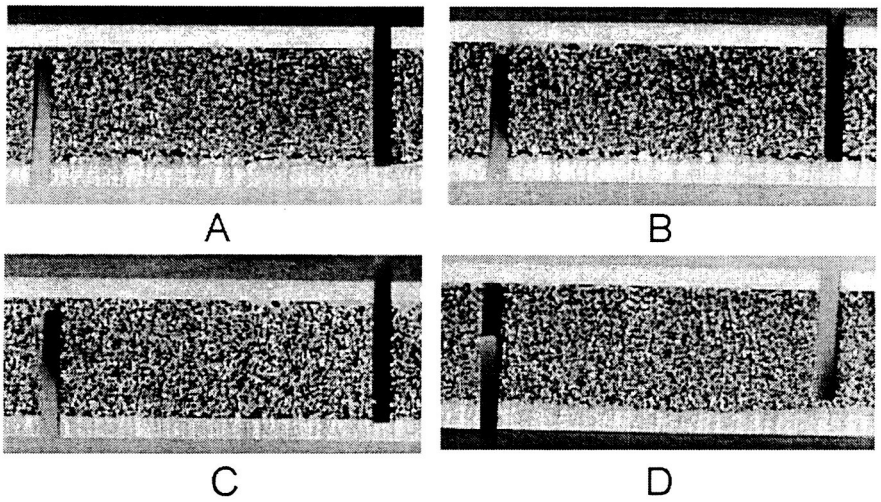
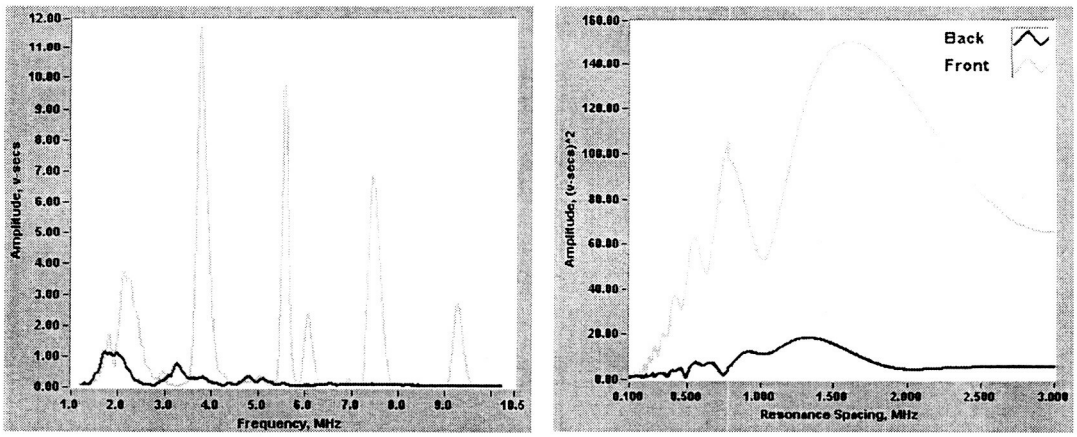


Figure 8. Optical photos of the gauge regions of each shear specimen prior to testing with the top of each specimen representing the front as referred to in the text.

when a second FFT is performed on the frequency spectrum, the spectrum resonance spacing domain provides the fundamental frequency.

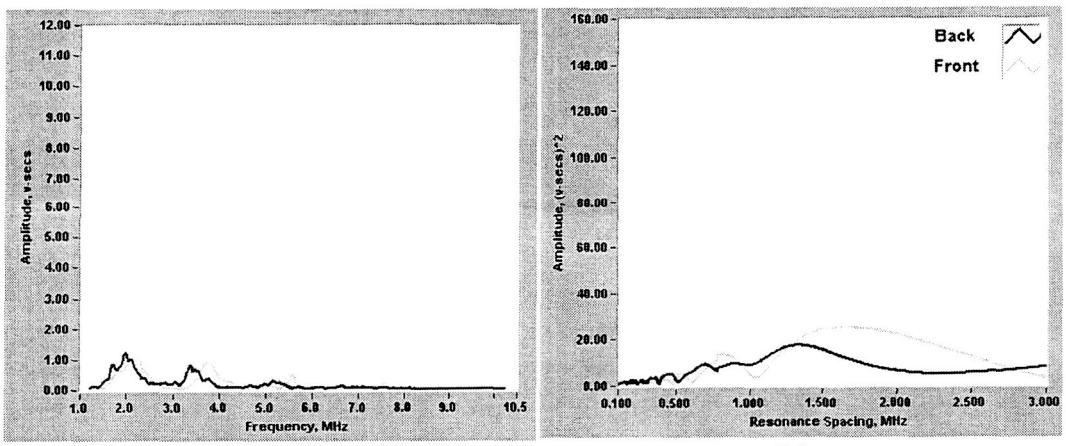
Figure 9 illustrates the spectrum and spectrum resonance spacing domains for the front and back of shear specimen A. The spectrum exhibits the harmonics excited in the frequency range 1.5 to 10 MHz. The spectrum resonance spacing shows the spacing between the harmonics in the spectrum. For the front of the specimen, a peak in the spectrum resonance spacing domain appeared at 1.62 MHz. This frequency was shifted from the 2.0 MHz acquired with the two individual transducers. The shift in frequency was due to a delay line in the dual-element transducer. The response from the back of specimen A has a lower amplitude, just as it did in the response from the two individual transducers. The strong ultrasonic signal from the front surface of shear specimen A is indicative of lack of brazing on the face sheet.



(a) (b)

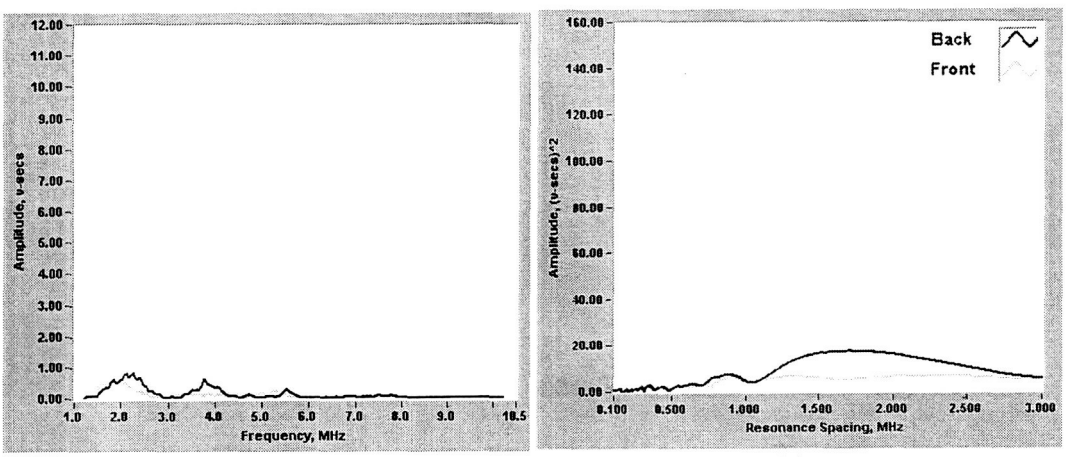
Figure 9. Ultrasonic spectroscopy responses from the front (poor brazing) and back (good brazing) of shear specimen A illustrating the fundamental frequency of the stainless steel face sheet in the response for the poorly-brazed region.

The responses from both sides of specimens B and C are shown in figures 10 and 11. The response for specimen B does not appear to indicate the same quality of brazing as it did prior to sectioning from the panel. Prior to sectioning, the response from region B represented an intermediate level of braze quality. An explanation for the poor response with the dual-element transducer may be that the dual-element transducer did not cover as wide of an area as the two individual transducers. The center to center spacing was 18.0 mm for the sending and receiving transducers utilized prior to sectioning compared to 8 mm for the dual-element transducer. Hence, a much smaller area was being interrogated with the dual-element transducer. Another explanation is that the specimen and panel alignment was different than expected. The specimen was sectioned 1.6 mm (0.0625 in) to the left of the region desired. This slight shift may have shifted the gauge region enough to miss the region with intermediate braze quality and change the ultrasonic spectroscopy response. For these material systems, the data collected with the two individual transducers prior to sectioning seemed to be more helpful than the data collected with the dual-element transducer. This may be due to the larger center-to-center spacing. The



(a) (b)

Figure 10. Ultrasonic spectroscopy responses illustrating the spectrum (a) and the spectrum resonance spacing (b) from the front (intermediate brazing) and back (presumed good brazing) of shear specimen B.



(a) (b)

Figure 11. Ultrasonic spectroscopy responses illustrating the spectrum (a) and the spectrum resonance spacing (b) from the front (good brazing) and back (good brazing) of specimen C.

ultrasonic response may be a more average response for the bulk region between the two transducers, while the dual-element transducer is interrogating a more precise location. As with the response prior to sectioning, the responses from shear specimen C and shear specimen D gave an identical response. Therefore, only the response from shear specimen C is depicted.

4.2 Mechanical Shear Test

Shear tests were conducted in a double-pinned clevis similar to that recommended in ASTM C273. The cross-head rate was 2.54 mm/min (0.1 inches/min). The samples were 15.24 cm (6 in) by 2.54 cm (1 in) by 1.30 cm (0.5 in) as shown in figure 3. The maximum loads for each sample are given in table 1. The two specimens with good braze joints had nearly a factor of three larger ultimate load than the two with poor brazing. This is also reflected in the higher shear modulus for the specimens where the face sheets are well-bonded to the foam core. Note that the values for the shear modulus are lower than expected based on the approximation (14):

$$G=3E/8 \qquad (4)$$

where E is Young's modulus and measured to be approximately 220.63 MPa (32,000 psi). The reason for this is believed to be due to the small length of the shear specimen. The specimen dimensions used in this study violate the conditions in ASTM C273. However, the goal was to investigate differences between NDE indications of ostensibly good-bonded vs. poorly-bonded face sheets. These areas were often confined to approximately a one square inch area. Therefore, using samples with a larger shear area would have prevented this comparison.

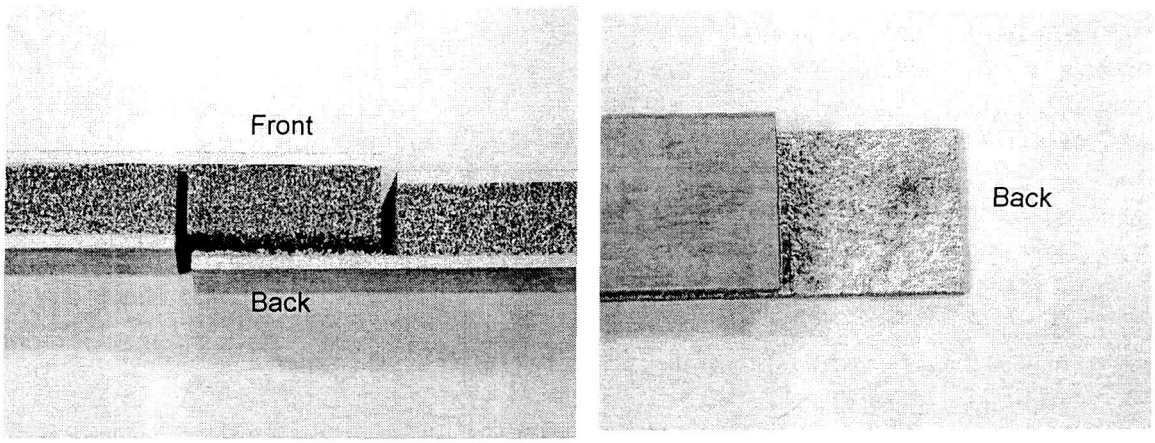
Specimen ID	Ultimate Load kg (lbs)	Shear Strength MPa (psi)	Shear Modulus MPa (psi)	Failure Mode
A	45.6 (100)	0.69 (100)	16.26 (2359)	Bond line
B	62.6 (138)	0.95 (138)	18.57 (2693)	Bond line
C	158.3 (349)	2.41 (349)	21.05 (3053)	Core
D	131.5 (290)	2.00 (290)	21.26 (3083)	Core

Table 1. Shear Test Data for 17-4 PH Foam Sandwich Structures.

Specimens A and B with poor brazing on the front side failed along what was presumed to be the good bond line on the opposite face (figure 12) and resulted in one of the face sheets having little foam connected to the surface. Failure was expected to occur where there was no braze on the face sheet at the bond line of the poorly bonded regions. Figure 8 shows that there may have been a lack of braze or cracking at the location of failure. Contrary to this, shear specimens C and D with good bonding (and sound NDE indications) failed through the foam thickness as shown in figure 13. There was a layer of foam still bonded to each of these face sheets after the test.

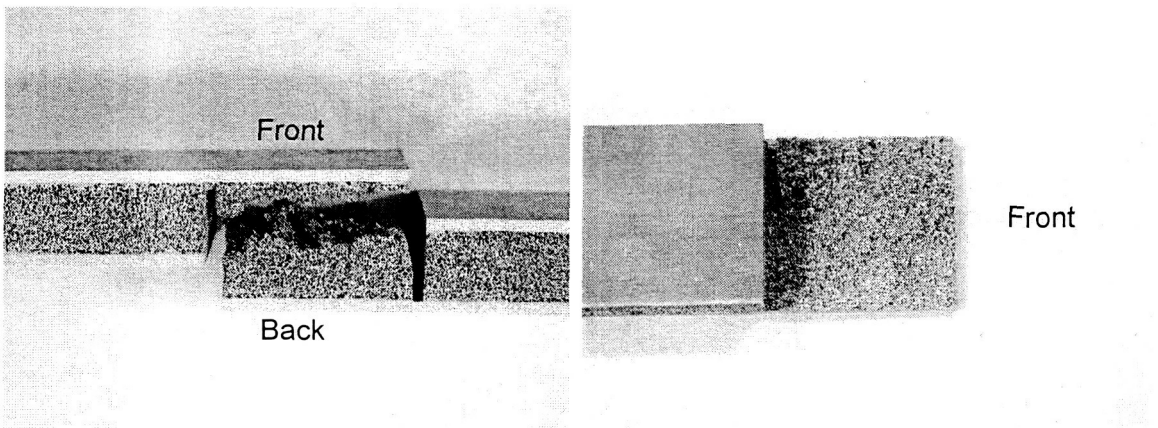
5. DISCUSSION

For use as a structural material, sandwich foams will need to carry tensile and shear loads which necessitates that there is good bonding between the face sheets and the foam core. As part of quality control of this bond, as well as the core itself, will need to be characterized by some sort



(a) (b)

Figure 12. Photo of the failure interface of shear specimen A illustrating the failure near the bond line (a) and the failure surface (b).



(a) (b)

Figure 13. Photo of the failure interface of shear specimen C illustrating the failure through the foam thickness (a) and the failure surface (b).

of inspection technique. In this study, ultrasonics was chosen as the inspection medium based on material composition, mode of interrogation from the surface of this structural material, and the techniques available. Ultrasonic spectroscopy was used to characterize areas of good and bad bonding, as shown in figure 5. The poor braze condition (i.e., areas of no wetting of the face sheet by the braze) produced a strong ultrasonic spectroscopy response with the fundamental frequency corresponding to the thickness of the outer face plate. This condition was easily recognizable using ultrasonic techniques where all of the ultrasound was reflected from the back surface of the face sheet. The intermediate braze condition produced a fundamental frequency corresponding to the thickness of the outer face sheet at a lower amplitude than the poor braze condition. Some ultrasound was scattered by areas of brazed foam while some ultrasound reflected at the back surface of the face sheet. Finally, ultrasonic spectroscopy characterized the good braze condition as a signal that was completely attenuated. The ultrasound was scattered at the braze-foam interface so that very little to no ultrasound returned.

For shear specimens C and D, failure occurred within the metallic core, as expected from the NDE results which indicated good brazing conditions between the outer face sheets and the foam

core. For shear specimens A and B, the initial assumption from the NDE results was that failure would occur at the bond line interface between the front outer face sheet and the metallic foam core. This assumption was based on the NDE indication, and later on microscopic investigations (figure 4a) that the braze did not wet the surface of the outer plate for shear specimen A and did not completely wet the surface of the plate for specimen B. Therefore, these interfaces were considered to be weak. However, the failure actually occurred on the opposite (back) sides having what was initially assumed to be good brazing conditions for both specimens. In hindsight, the initial ultrasonic spectroscopy responses shown in figure 5 may have indicated this weakness. Although the ultrasonic spectroscopy response from the back of regions A and B were weak, there was a signal with a shift in resonant frequency. This may be due to some ultrasound returning from the surface of the braze whereas most of the signal was attenuated by either the roughness of the braze or the few bits of foam connected to the braze. The initial ultrasonic spectroscopy responses were able to discriminate between the well-brazed condition and the bond condition which actually failed at the foam-braze interface, as shown in the comparison in figure 6. The response from the well-brazed bond condition had a lower amplitude than the response from the bond condition that actually failed.

It is possible that the front of regions A and B, with a lack of braze and intermediate brazing, may have small regions within the gauge region with better brazing between the foam and the face sheet. The ultrasonic spectroscopy response represents the response in the particular region of interrogation, which is the region between the transducers. Although the transducers cover most of the gauge region with a 18 mm center to center spacing between transducers and transducer face diameters of 12.7 mm, areas of good brazing outside this region may have gone undetected. A small area of good braze may have been enough to prevent failure at the interface especially if the conditions at the braze-foam interface were very poor. Scanning electron microscopy will be performed on two regions of specimen A to investigate this explanation. The crack or lack of brazing that appeared on the back side of the gauge region of specimen A extended outside the gauge region even prior to shear testing. So, a region just outside the gauge region will be tested to examine the foam-braze interface on the back side of the specimen. The second region of interest is at the front of shear specimen A. The gauge region will be sectioned through the center to confirm there is a lack of brazing between the face sheet and the foam core at this interface.

To summarize, ultrasonic spectroscopy successfully characterized braze conditions at the surface foam-face sheet interface. When the braze did not wet the surface of the plate a resonance corresponding to the thickness of the face sheet was produced. With the presence of braze the ultrasonic spectroscopy signal was attenuated. However, the ultrasonic spectroscopy response was able to detect a difference between the condition where braze existed on the face sheet only versus the condition where the braze adhered to both the face sheet and the metallic core. This difference was indicated by a difference in amplitude. When the braze wet the surface of the face plate only, the ultrasonic spectroscopy signal was larger in amplitude than the signal produced when the braze adhered to both the metallic foam core and the face sheet.

6. SUMMARY AND CONCLUSION

The braze quality between 17-4PH stainless steel sandwich face sheets and the 17-4PH foam

core were examined using ultrasonic techniques. Four regions from a sandwich panel representing various levels of brazing quality between the outer face plates and a metallic foam core were investigated with ultrasonic spectroscopy. Each region represented a different level of brazing quality ranging from well-brazed to poorly-brazed conditions. Based on the NDE results, four shear specimens sectioned from the sandwich panel to contain each of these regions were mechanically tested. Optical photos from the gauge region of each specimen confirmed that ultrasonic spectroscopy successfully characterized the braze quality existing on the outer face plate better than ultrasonic c-scan. When the braze did not wet the surface of the plate a resonance corresponding to the thickness of the face sheet was produced. Intermediately brazed conditions, with some braze adhering to both the face sheet and the metallic foam produced a resonance with much lower amplitude. With the presence of good braze between the face sheet and the metallic foam the ultrasonic spectroscopy signal was attenuated so that no resonance was produced. When the braze wet the surface of the face plate only, the ultrasonic spectroscopy signal was slightly larger in amplitude than the signal produced when the braze adhered to both the metallic foam core and the face sheet.

The results of the shear tests indicated that the condition where small amounts of braze or foam adhered to the surface of the face plate was a more critical manufacturing defect than having very little or no braze wet the surface of the plate since the actual failure occurred on the opposite side of the specimen where the braze wet the face sheet and not the foam. The non-wetted surface may have contained some areas of good bonding. Scanning electron microscopy will aid in the explanation of these results.

Given the limited data, ultrasonic spectroscopy demonstrated great potential for examining bond quality between foam cores and the face sheets. Ultrasonic spectroscopy identified various levels of braze quality between the face sheet and metallic foam core at the panel level. These results can be extended to the evaluation of engine components made from these stainless steel sandwich structures as ultrasonic spectroscopy signals corresponding to certain levels of brazing quality have been identified. The signals acquired here can be compared to signals acquired from newly manufactured components to evaluate bond quality. However, the technique is limited with respect to evaluating the condition of the metallic foam. To further improve the manufacturing and inspection methods, a better understanding of the failure mechanisms occurring in these sandwich structures is necessary. Scanning electron microscopy will further corroborate the results indicated by ultrasonic spectroscopy. Depending on the type of defects and failure, a higher (above 20 MHz) ultrasonic frequency regime may be investigated to evaluate the more critical bond conditions. In addition, other NDE techniques are being investigated to further understand these sandwich structures and their failure mechanisms.

7. ACKNOWLEDGEMENT

This work was funded under the Ultra Safe Technology Project at NASA Glenn Research Center.

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