MEASUREMENT OF STRENGTH OF ADHESIVE BONDS

G. A. Alers and R. K. Elsley
Science Center, Rockwell International
Thousand Oaks, California 91360

and

P. L. Flynn
General Dynamics
Fort Worth, Texas 76101

ABSTRACT

In order to predict the strength of an adhesive bond between two metal sheets, it is necessary to measure the physical state of the adhesive layer that mechanically joins the two pieces of metal. This requires rapidly performing a detailed analysis of the ultrasonic echoes reflected from the entire structure when it is immersed in a water bath for a normal ultrasonic pulse-echo inspection. To achieve this result, computer-operated ultrasonic inspection systems have been assembled and equipped with special signal processing routines so that particular features of the ultrasonic echo in both the time domain and the frequency domain can be extracted in a time short enough to meet the requirements of a production inspection system. Such features as the relative amplitude of the signals reflected from the top and bottom of the adhesive layer and the frequencies for which standing waves are excited in the adhesive and in the metal adherends are of particular interest for making the strength predictions. It is also important that the interrogating ultrasonic pulse be of very short time duration so that the echoes from the various interfaces in the sandwich-like joint can be resolved in the time domain display. This requires the use of special high frequency pulse generators coupled to broad band transducers and amplifiers. Special procedures are also needed to insure the accuracy of the analog-to-digital conversion at the input to the computer and the subsequent transformations to and from the frequency domain.

The measurement of the strength of a completed adhesive bond between two pieces of metal stands as one of the most important NDE problems in the aerospace industry. Without such a test, this very light, inexpensive and efficient method of joining two metals can only be used in secondary structures. Two aspects of the problem must be attacked because the bonds can fail both by cohesive failure within the bulk adhesive itself and by adhesive failure at the interface between the metal and the polymer used as the adhesive. The detection of both of these basic failure modes has been the subject of the current program being carried out at the Rockwell International Science Center and at General Dynamics.

In both laboratories, the approach has been to utilize extensive digital processing on the ultrasonic signals reflected from a metal-adhesive-metal joint purposely prepared with either poor cohesive bond strength or with poor adhesion at the metal interface.

Figure 1 shows the ultrasonic data acquisition system used. It consists of a transducer in a water bath directing its beam at normal incidence against a sandwich structure consisting of two relatively thick metal sheets on each side of a thin adhesive layer. Also shown are the broad band (narrow time duration) echo signals reflected by the structure. Signal R_1 is large and arrives first because it is reflected from the top surface of the first metal adhered. Signal R_2 is much smaller and arises from the reflection at the top metal to adhesive interface. Immediately thereafter, the reflection from the bottom of the adhesive layer (signal R_3) appears followed by the reverberations of signals reflected more than once by all of the interfaces in the joint. In order to separate these reverberations and extract quantitative information from them, the echo train is put into digital format and a Fourier transform is calculated by the computer.

Figure 2 shows the results of such transformations. The smooth, bell shaped amplitude versus frequency curve in the upper left is the transform of the front surface echo alone and is used to define the band pass characteristics of the transducer and electronics. The transform of the entire echo train is shown in the lower left where many well defined dips can be seen to be superimposed on the band pass curve of the transducer. The dips correspond to the frequencies at which standing acoustic waves can be established within the various layers. By correcting the wave train transform for the transducer response, the reflection spectrum shown in the upper right can be obtained. It represents the experimental reflection coefficient of the adhesive bond sandwich that would be obtained if a truly flat frequency response transducer had been used. Fortunately, the reflection of plane acoustic waves by a layered medium is a soluable mathematical problem, and the theoretical reflection amplitude versus frequency curve is shown in the lower right for comparison. The excellent agreement between theory and experiment shows that a detailed comparison between the observed and calculated responses can be used to find abnormalities which may correlate with the mechanical strength.

Figure 3 shows photographs of the computerized ultrasonic adhesive bond inspection systems which have been assembled at the Science Center and at General Dynamics. The block diagrams show that different individual pieces of ultrasonic and data processing equipment were used at each laboratory even though the results of the analysis are very similar.

Figure 4 shows the possible methods that can be used to measure the strength of a completed adhesive bond. For the present program, most of the mechanical strength data was obtained from the small compression shear type of specimen obtained by cutting small coupons out of larger bonded strips or plates of aluminum. Examples of the peel specimen and the compression shear specimen after failure are shown on the right.

In order to control separately the cohesive and adhesive bond strength of the specimens during the sample preparation cycle, two methods were used as described on Fig. 5. For the cohesive bond strength tests, two 6-inch square aluminum plates were bonded together using a commercial adhesive, FM 400, with different curing temperatures. After ultrasonic scanning, these plates were cut up into many small compression shear specimens and their shear strengths measured destructively. The different curing temperatures resulted in different degrees of crosslinking and hence a systematic variation in cohesive strength of the adhesive material itself. For the adhesive interface bond tests, both lap shear and peel type specimens were prepared with a thin layer of contamination applied to the aluminum surfaces prior to bonding. By changing the thickness of the layer of contamination, samples exhibiting differing strengths of adhesion were prepared.

Figure 6 shows the results of correlating the measured cohesive bond strength with two physical properties of the bulk adhesive deduced from the ultrasonic measurements in the frequency and time domains shown in Figs. 1 and 2. The two physical properties of the adhesive layer were the attenuation and the sound velocity in the adhesive. For a model adhesive, which contained no scrim cloth and very little bubble type porosity, the correlation was excellent as shown on the left-hand side of the figure. For the commercial adhesive which contained a scrim cloth and had bubbles formed by the evolution of volatiles during the cure process, the correlation is poor because of the large scatter in the data. Much of this scatter has been traced to the fact that the scrim cloth and the porosity dominate the attenuation and, to a lesser extent, the velocity so that the measured physical properties are not closely related to the condition of the adhesive material itself.

Figure 7 shows the results obtained for the samples with thin layers of stop-cock grease at the metal to adhesive interface. For these tests, lap shear specimens were used and an obvious difference in the Fourier spectra of the echo signals can be seen in four specimens whose strengths were different. The different strengths of these samples are recorded in the upper left-hand corner of each spectrum. A graph correlating the measured shear strength with the highest frequency at which splitting was observed in the dips of the reflection amplitude versus frequency graphs show a promising technique of predicting the strength of adhesion in a completed bond. Theoretical analysis of the spectra shows that the splitting arises from the fact that the upper and lower metal plates can be considered as separate oscillators whose thickness resonant modes are coupled together through the adhesive layer. The absence of splitting can be interpreted as showing that no high frequency acoustic energy is transmitted through the interfaces from the top metal sheet to the bottom sheet, and a standing wave is set up only in the top plate at high frequencies.

Acknowledgement

This research was sponsored by the Center for Advanced NDE operated by the Science Center, Rockwell International, for the Advanced Research Projects Agency and the Air Force Materials Laboratory under contract F33615-74-C-5180.

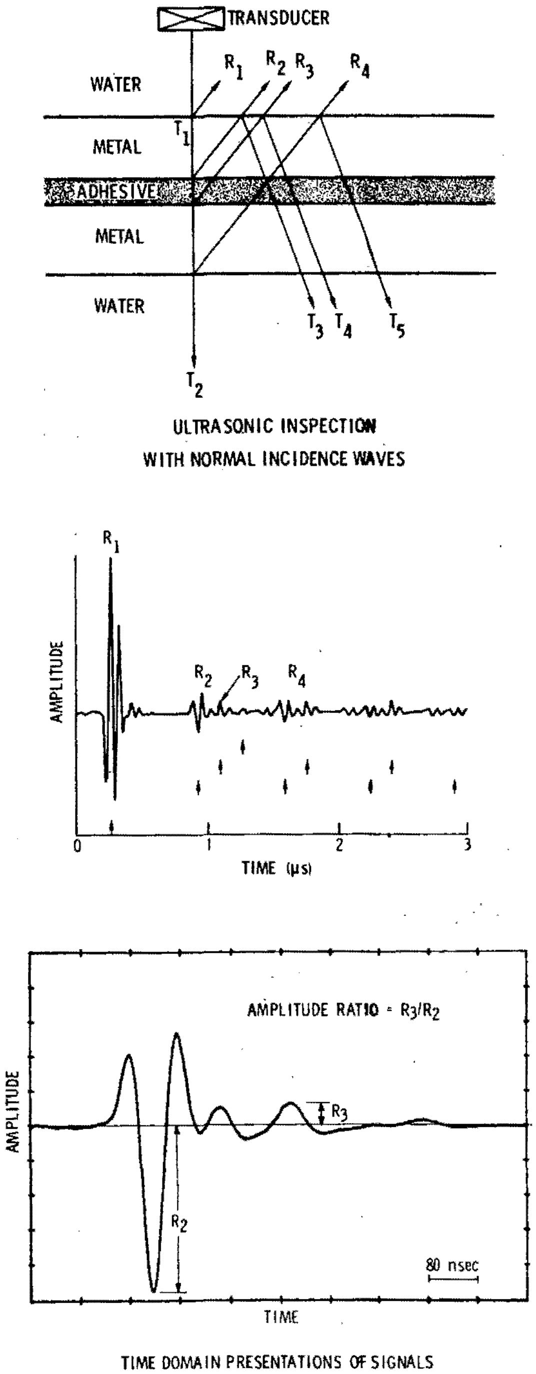

Figure 1. Data acquisition.

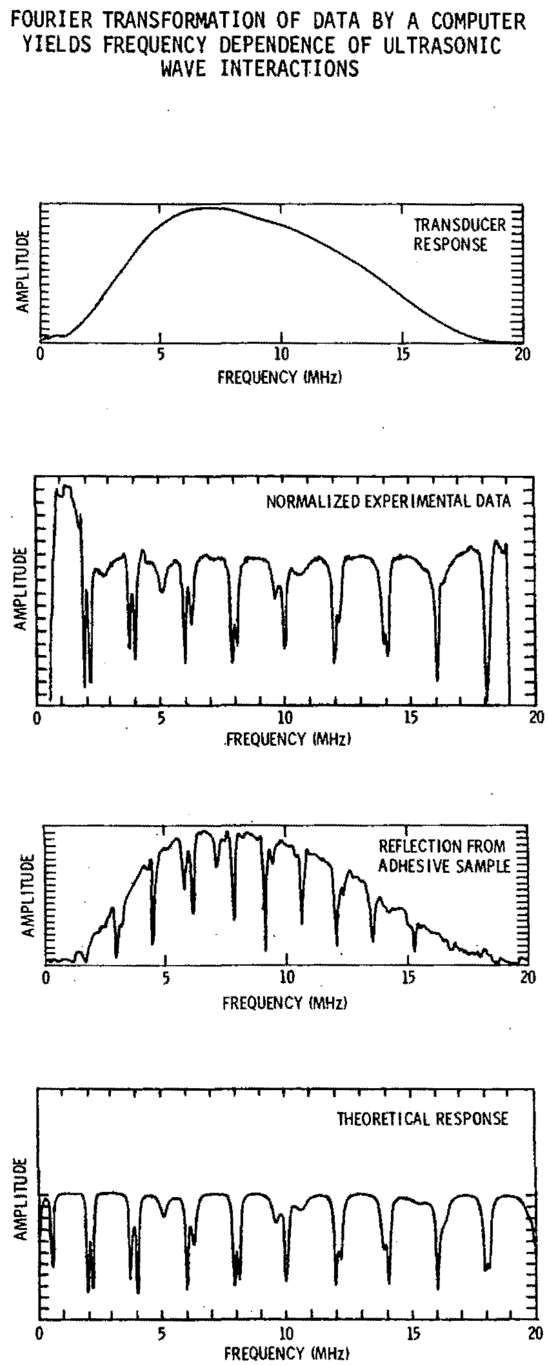

Figure 2. Signal processing.

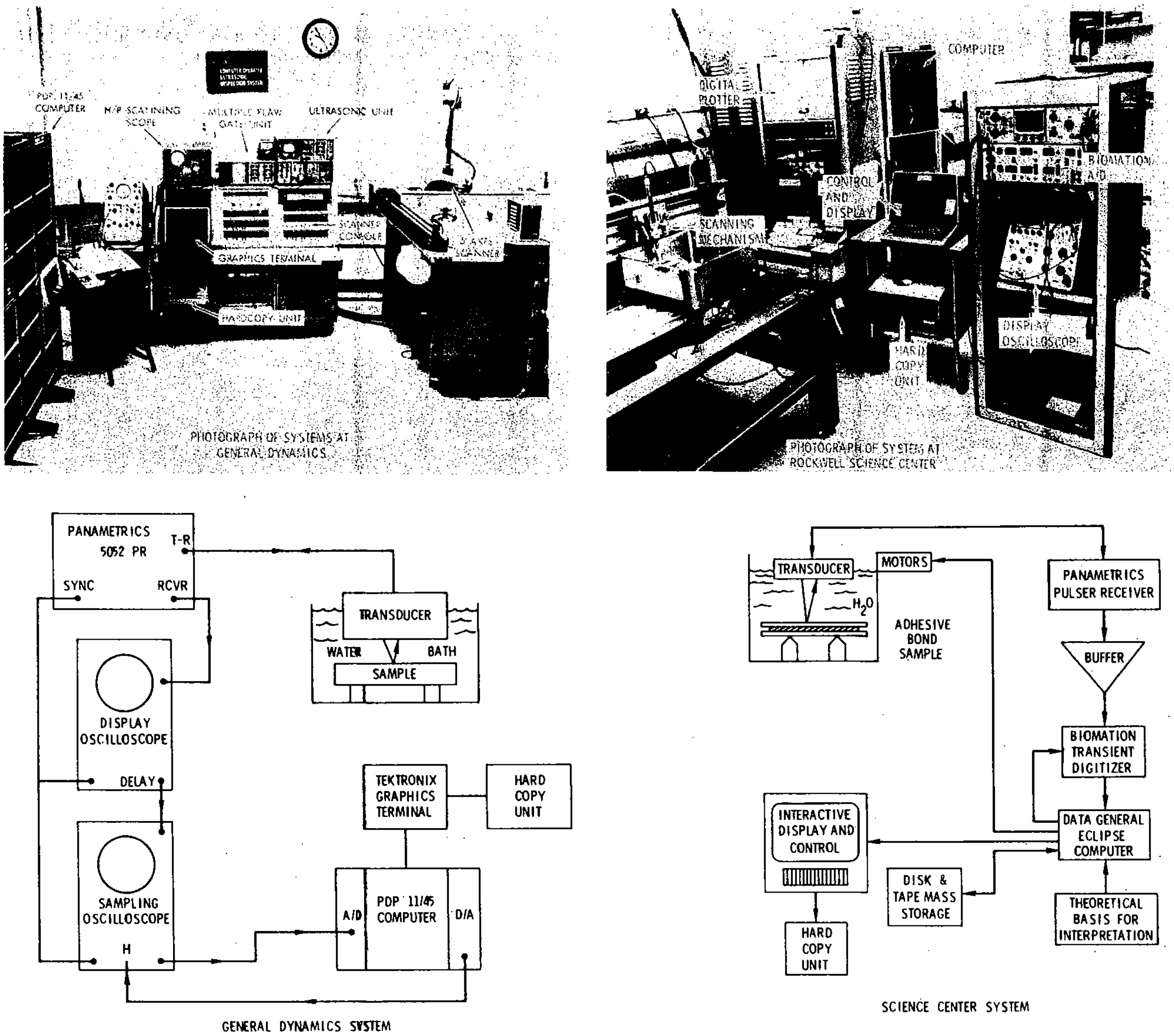

Figure 3. Automated inspection system.

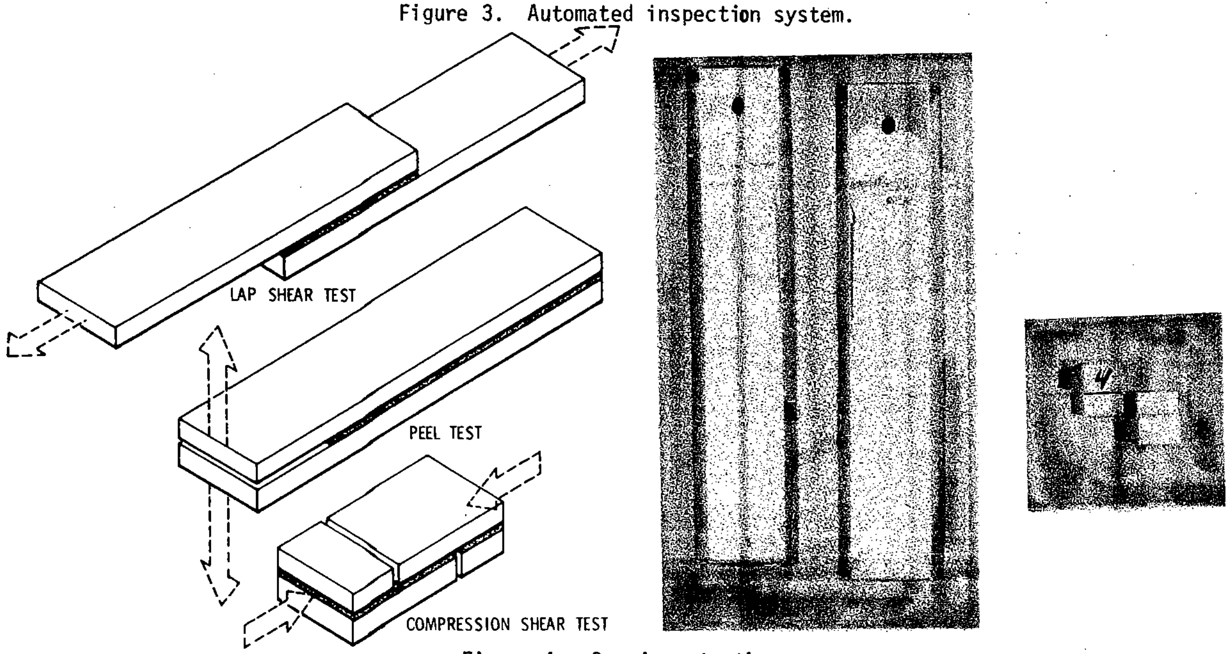

Figure 4. Specimen testing.

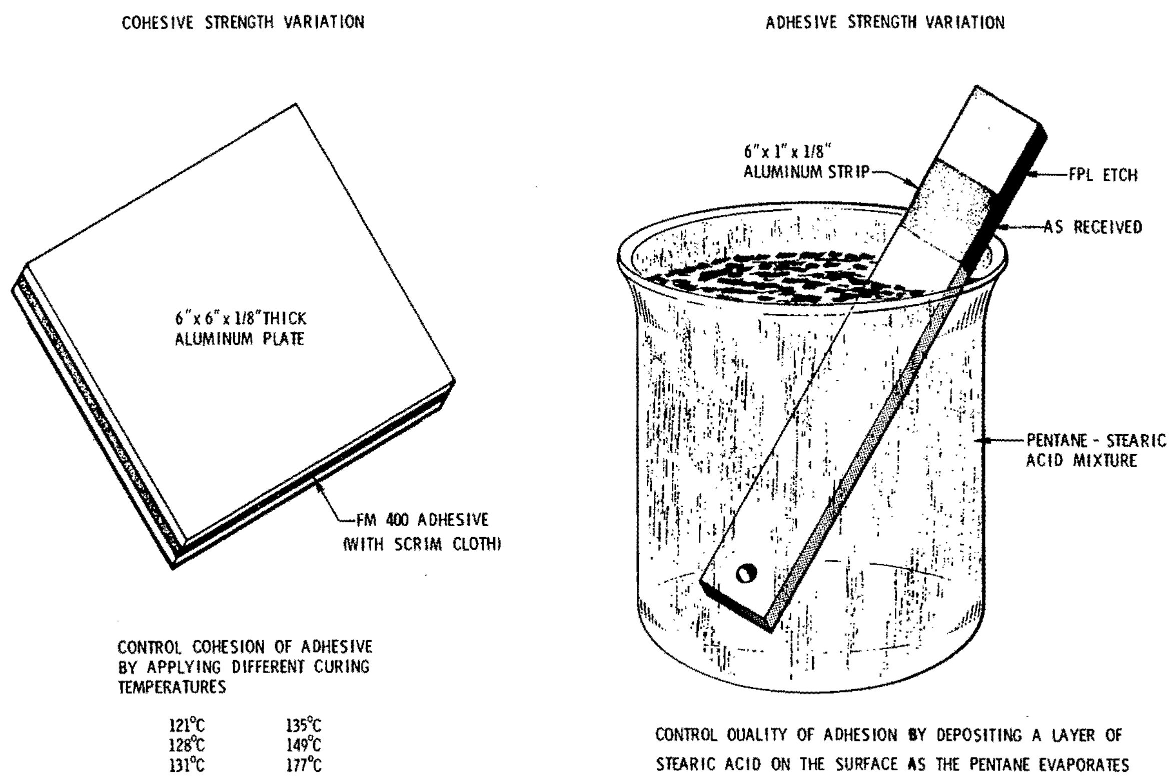

Figure 5. Specimen fabrication.

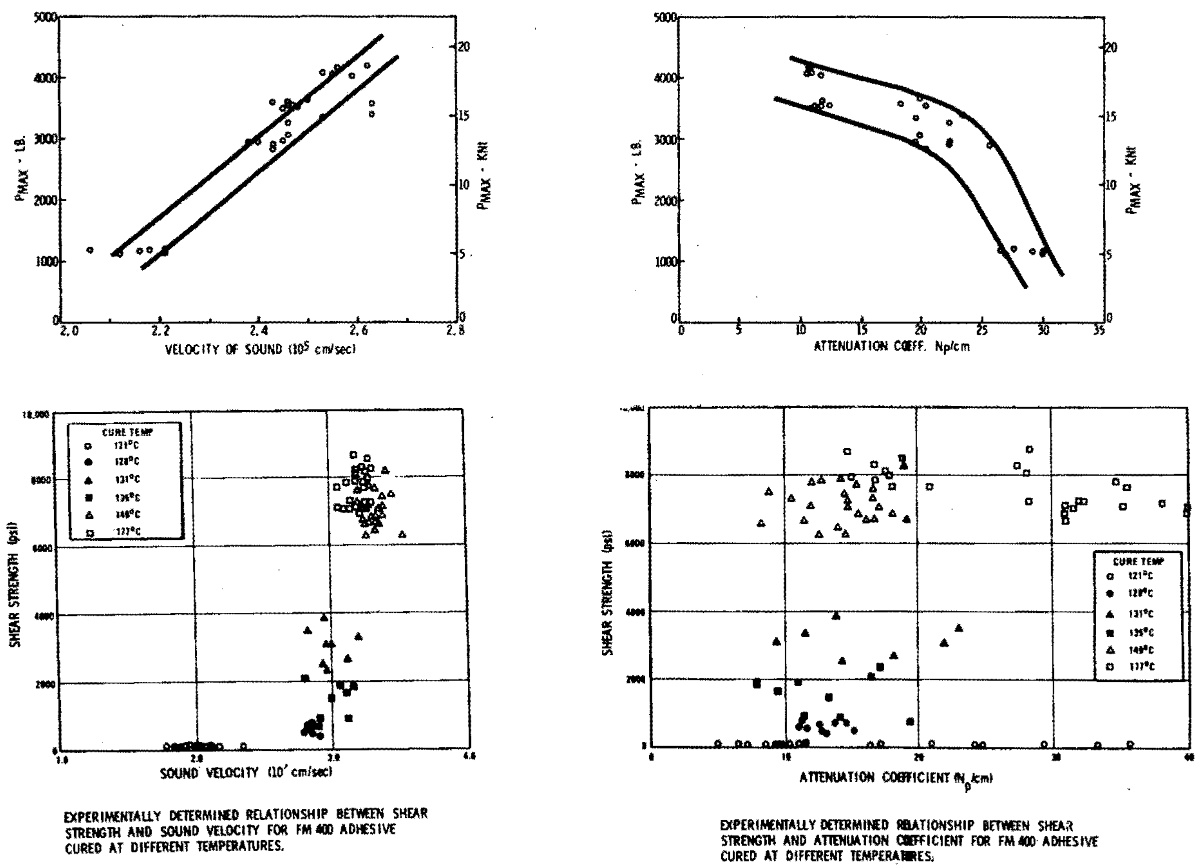

Figure 6. Cohesion strength measurement.