NON-DESTRUCTIVE EVALUATION OF RESISTANCE SEAM WELDS BY ACOUSTIC EMISSION

by

Karl R. Markey

Submitted to the Department of
Mechanical Engineering
in Partial Fulfillment of the
Degree of

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Mechanical Engineering Department Committee

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ABSTRACT

The problem was to develop a fixture for stressing resistance seam welds in low carbon steel cans as part of an AE weld evaluation system. The challenge is in that the fixture cannot emit any mechanical or electrical noise that cannot be filtered and therefore prevented from interfering with the AE signal. Four possible methods of stressing the weld are discussed. They are: the use of a pressurized bladder inside the can, the use of magnetic fields, mechanically pulling on the weld, and thermally stressing the weld. The thermal stressing concept was chosen for experimental investigation. It was found that the clamping forces and heat of the fixture were damaging to paint on the exterior of the can. No real correlation between AE signals and weld quality was found.

Thesis Supervisor: Ming-Kai Tse

Title: Assistant Professor of Mechanical Engineering

ACKNOWLEDGEMENTS

I would like to thank the following people their aid during the course of this thesis:

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INTRODUCTION

Acoustic emission is a nondestructive evaluation technique based on the detection of crack growth in a material under stress. Using piezoelectric transducers, it is possible to detect stress waves caused by the sudden extension of cracks. The transducers typically produce a so called "ring down" signal, i.e. damped oscillatory output, at frequencies characteristic to the transducer. These frequencies usually range from 25 khz to several Mhz. The amplitude and duration of the signal are, however, directly related to the amplitude of the stress waves, which in turn relates to the crack parameters such as crack size, orientation, velocity of extension. In this study, acoustic emission is of interest for evaluating the quality, or strength, of resistance seam welds in three piece cans. (See fig. 1, following page.) More specifically, the scope of this thesis is to propose various methods for stressing the welds and to carry out experiments which will determine the ability of a chosen method for producing acoustic emission signals.

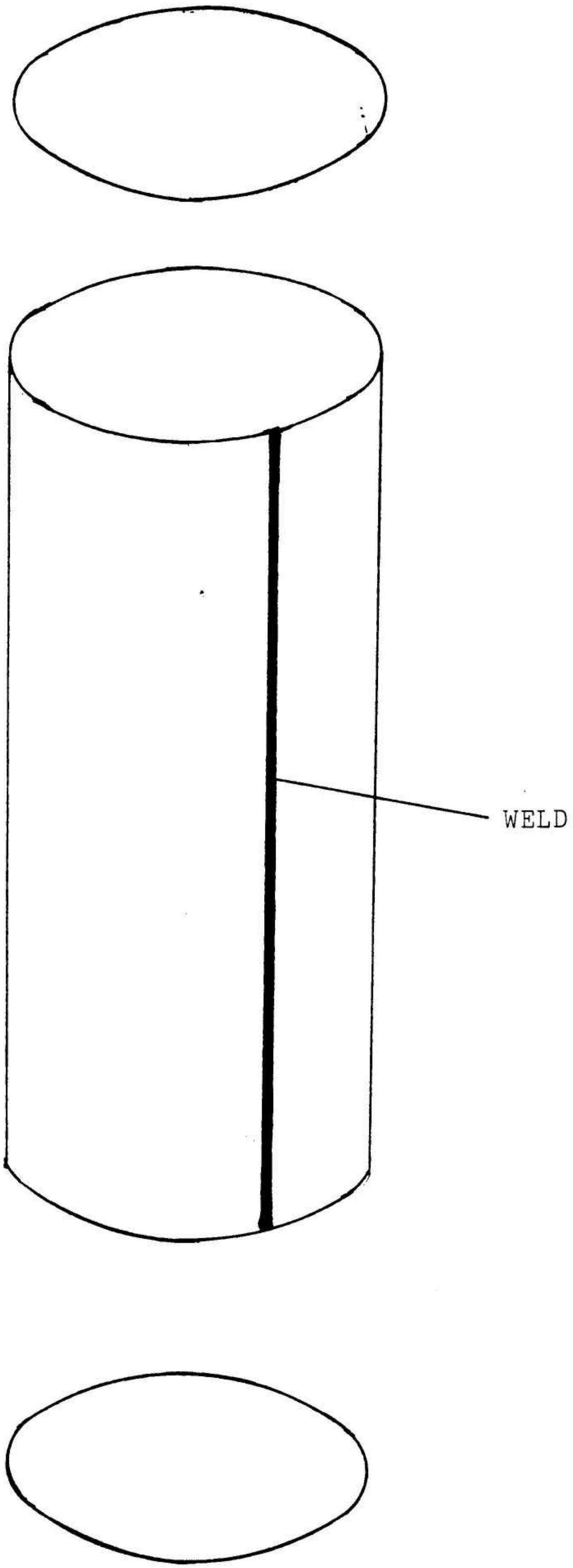

Figure 1. Three-piece can.

GENERATION OF ACOUSTIC EMISSION

Before a detailed discussion of the different methods considered for stressing welds to generate acoustic emission, it would be useful to establish some background on the mechanisms of AE generation. As already mentioned, crack propagation is a major source of AE. However, in the material other mechanisms such as phase transformations or dislocation movements also produce detectable stress waves.

In order to acheive crack growth, one must apply either tensile, mode I, or shear stresses, mode II or III, to the area of interest - cracks will not grow under compression. The level of stress applied and the strain rate are major factors in determining the amount of crack growth. For h.c.p. or b.c.c. materials, temperature also plays a role in that the brittle-ductile transition of the fracture mechanism requires higher strain rates at higher temperatures in order to achieve crack growth. The welded cans considered in this thesis are low carbon steel with b.c.c. structure both before and after welding.

These few facts are the basics of how stress and crack growth are related as far as the realm of a.e testing is concerned.

NOISE VS. ACOUSTIC EMISSION

To design a reliable AE test system, careful considerations must be given to discriminate against extraneous noise. Noise refers to both mechanical and electrical noise superimposed on the stress wave signals from the transducer. Though neither source of noise can be completely eliminated by the proper test system design, there are methods to reduce this problem. For noise of frequencies lower than say, 25 khz where a.e. typically starts, electrical filtering through the use of high-pass band filters generally suffices. For most types of mechanical noise, a mechanical filter can be the solution. The filter works on impedance mis-matching between adjacent components just as an electrical filter does. Acoustical impedance is a function of the Young's modulus. At the interface between two materials with very different acoustical impedances, most of the incident wave is reflected instead of transmitted. Hence, to minimize unwanted mechanical disturbances, a soft material such as rubber is placed to serve as a filter between the noise source and the test specimen or the object to which the piezoelectric transducer is attatched. For the reader interested in a more detailed analysis of this type of filtering, this author refers him to an article by G. G. Martin in the May, 1983 Ultrasonics Journal. An alternate solution to the mechnical noise problem is to employ multiple transducers for the purpose of spatially filtering the signal.

Low frequency mechanical and electrical noises have been covered. For high frequency electrical noise, if the frequency and content of the noise is known, one may try to eliminate the noise in the frequency domain. However, if the noise is very broad band, spectral filtering may not be feasible. The only other solution known to this author is to carefully ground and/or rearrange surrounding electrical equipment and shield any cables necessary to eliminate the source of noise. One may find white noise to be a particular problem because of the high gains generally used in an AE system to amplify the transducer's signal.

METHODS OF STRESSING THE WELD

Four possible methods of stressing the weld in the cans will now be discussed. The first three were not investigated in this thesis and are described only briefly only. The last method was found unsuitable to our needs after experimental investigation described in following sections.

Pressurized Bladder Method

The basic idea here is to insert a bladder made of flexible material, such as rubber, into the can. The bladder would then be pressurized either pneumatically or hydraulically causing it to expand against the inner walls of the can. This would apply a hoop stress in the can. Using the thin-walled approximation formula for hoop stress:

$$\sigma = \frac{pr}{t} \qquad (1)$$

where σ = tensile stress in the material

p = pressure against the interior of the can

t = wall thickness of the can = .010" (typical),

it is found that only 200 psi would induce a 20 ksi stress in a two inch diameter can.

An advantage of this method of stressing over that of thermal stressing, to be discussed, is in the type of stresses that are generated. Figure 2 depicts the stresses on the weld line for both methods.

Bladder Method

Thermal Method

Figure 2. Comparison of bladder and thermal stress situations (end view).

With the bladder method, the forces on the weld are such that both tensile and shear forces rather than compressive and shear forces are acting on the weld. Intuitively, this set of applied stresses would be more favorable for propagating an existing crack.

Some of the issues and problems that might be associated with bladder stressing are:

1) Designing the bladder in such a manner that all parts of the weld are equally stressed. This would include items like constraining the bladder's tendency to balloon out the ends of the can as in figure 3.

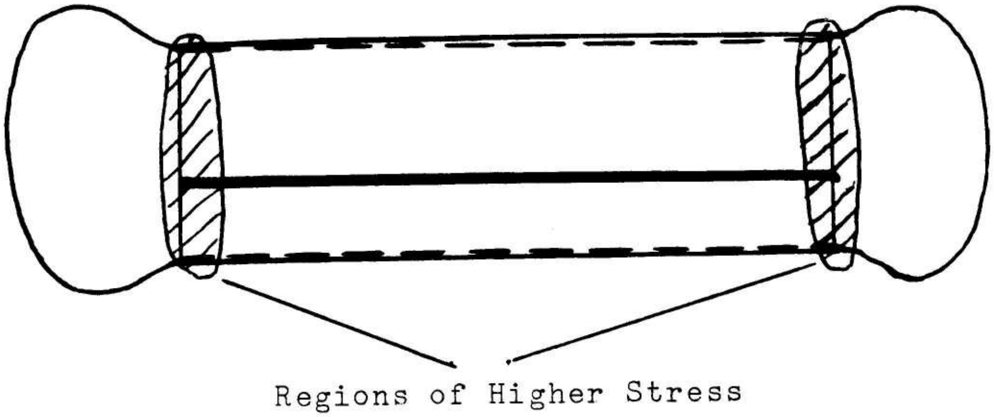

Figure 3. Improperly constrained bladder

2) Choosing the bladder material and dimensions so that the bladder does not slip against the inner walls of the can and create noise during the stressing cycle. This would not be a problem if one felt that listening for acoustic emission could be done once the can has reached full stress rather than listening during the time of increasing stress.

3) All of the weld would be stressed at once with this design so that one would have to use multiple transducers and spatial filtering to determine where on the weld acoustic emissions were coming from. Spatial filtering determines an emission's origin through analyzing the relative times at which the emission reaches each transducer.

An alternative to the bladder concept is the use of air-tight seals over the end of the can and feeding compressed air into the can rather than inserting a bladder.(4) Preliminary work indicated that the configuration in figure 4a resulted in leaks past the seals at 50 psi, but the configuration in figure 4b has held tight up to 200 psi. The maximum pressures have not yet been tested. There is not yet conclusive evidence as to whether or not the signals generated are actual a.e. or noise from the pneumatic system. Further testing is in progress.

Magnetic Method

Magnetic fields could also be used to stress the weld. The concept of using magnetic forces has been applied to the metal forming area. A bachelor's thesis by F.J. Williams achieved simple deformations of metal pipes such as reduction in diameter.(2) To accomplish this, he used a 9 kJ bank of 20 kV capacitors to generate fields of 300,000 gauss for six micro-seconds. Though for a.e. testing of cans lower fields and longer pulses would be what are required, the r.f.i. associated with such a system would likely prove an insurmountable noise problem. Also, the induced currents in the can would wreak havoc on electrical components if the transducer were not electrically insulated from the workpiece.

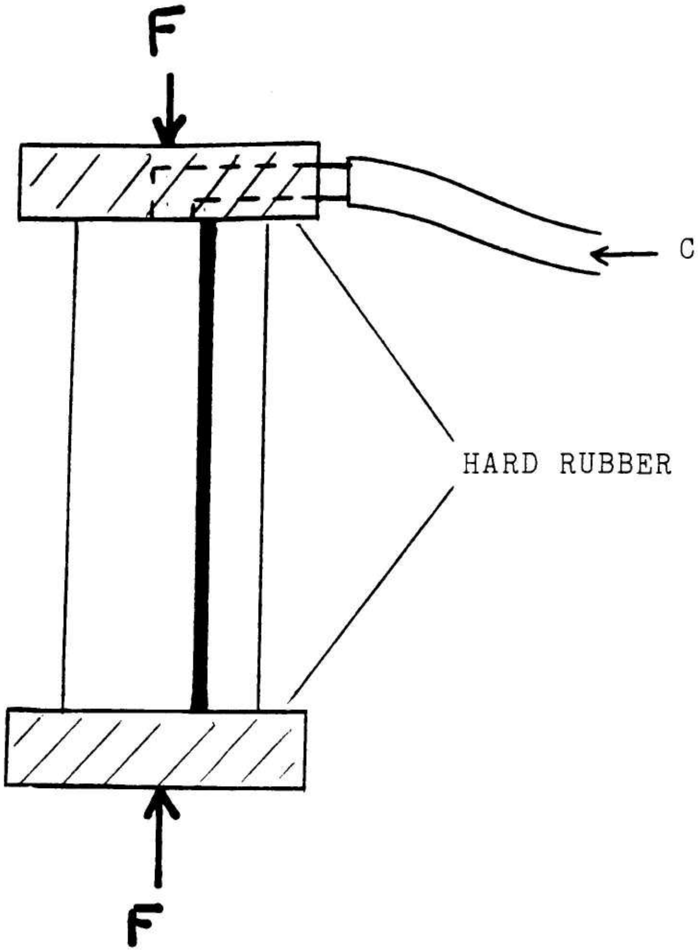

Figure 4a. Hard rubber end seals.

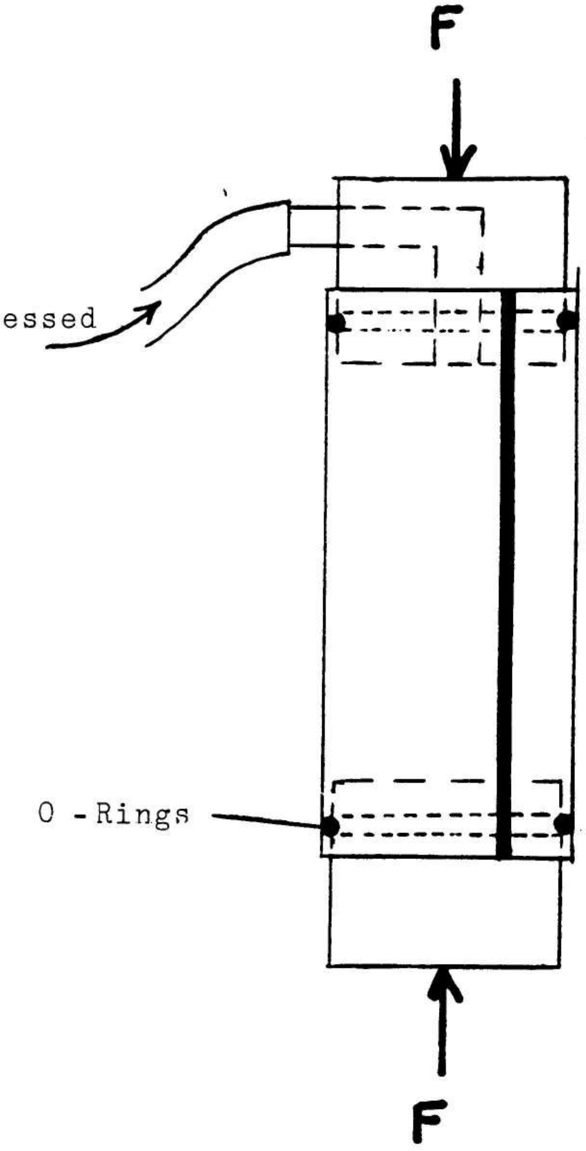

Figure 4b. O-ring seals

Mechanical Pull Method

This is perhaps the most obvious method for stressing the weld. The basic idea here is to take a cylinder of material such as aluminum that is slightly smaller in diameter than the can and slice it in half along its axis of length. The two halves may then be placed inside the can with some sort of mechanical noise between the can and cylindrical halves. By pulling the halves apart, a force will be distributed across the section equal to half of the pulling force on the two halves. Figure 5 depicts this set-up

This was actually done as a first attempt by the members of this research group to generate a.e. Work was only carried far enough to discover that the Instron used to supply the pulling force was a source of r.f.i. at about 1 khz. Later testing related to another stressing method showed that this problem can easily be solved with electrical filters.

Such a method of stressing the weld, however simple it may be, could actually turn out to work well if the proper material is chosen as a mechanical noise filter. As with the bladder system, the main problems now become slippage of the insulator against the can and the use of spatial filtering to determine where the source of the emission is.

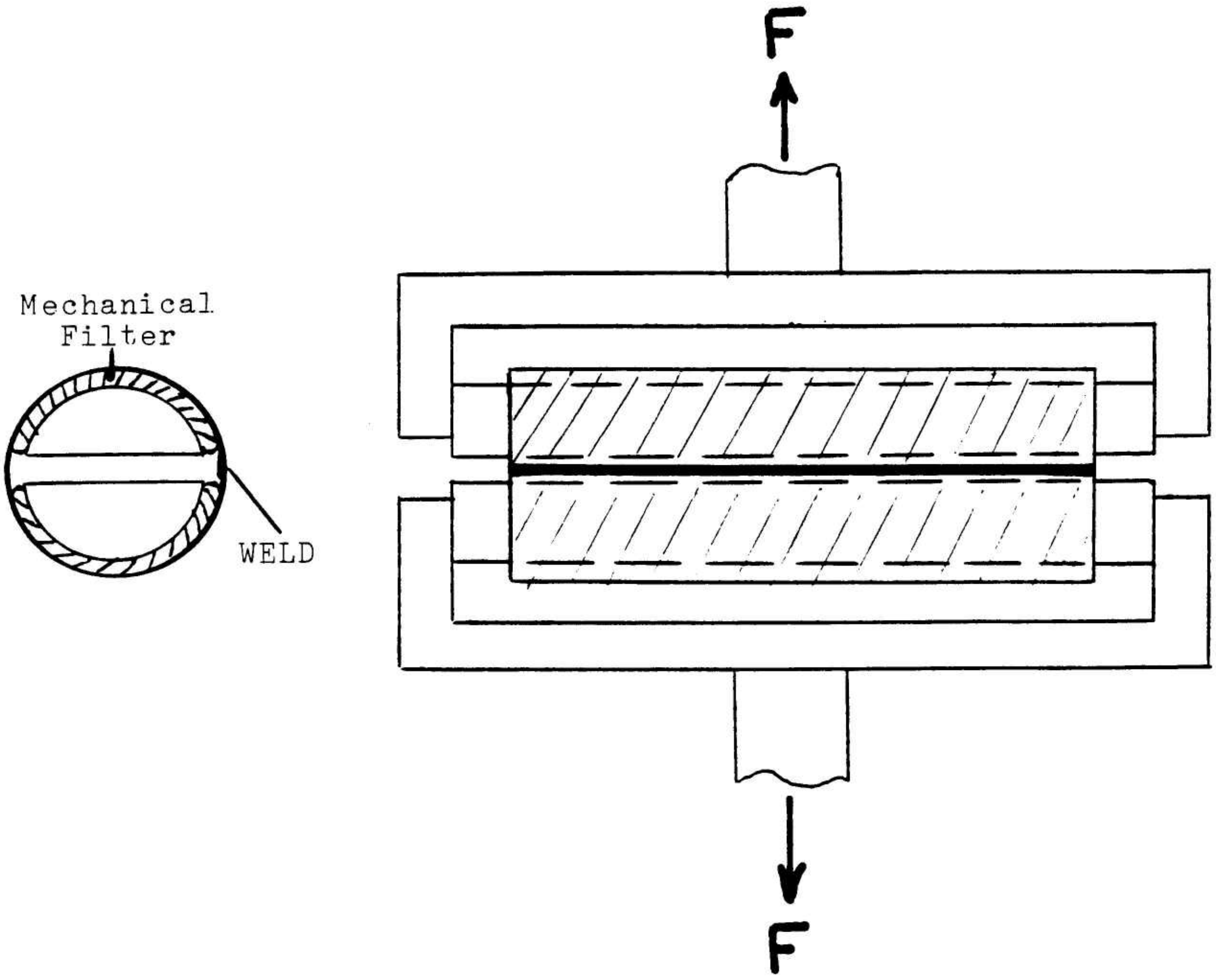

Figure 5. Mechanical Pull method of weld stressing.

Thermal Method

a. Theory

This is the method that was chosen to be investigated experimentally as a means of producing a.e. The concept is rather straight forward. A piece of material will try to expand when heated but will become stressed if it's is expansion constrained. The thermal stressing method uses clamps on either side of the weld to constrain expansion in the 1 direction as figure 6 shows.

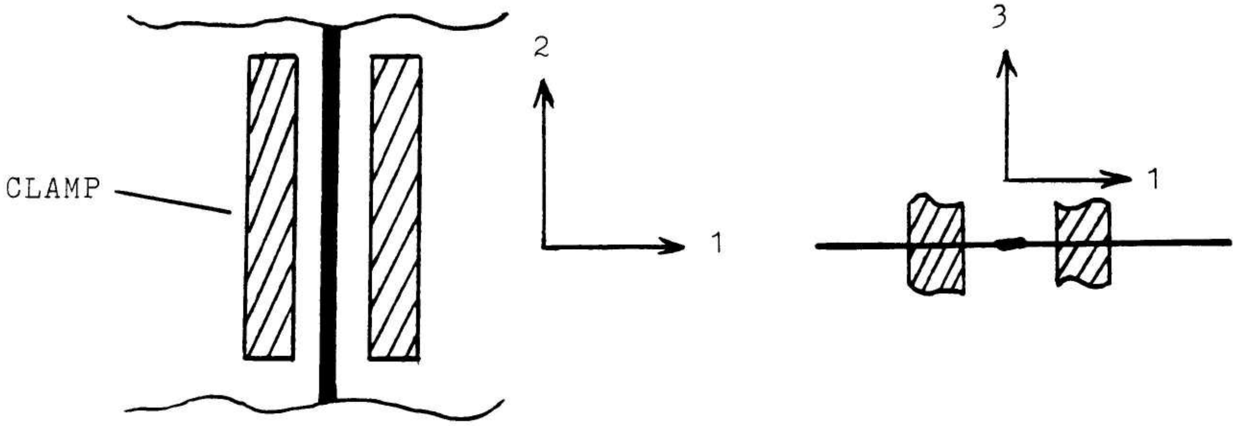

Figure 6. Clamp placement for the thermal method.

Expansion in the 3 direction, as shown by figure 6, experiences no stress. Expansion in the 2 direction is yet to be determined from strain gage testing as it is not possible to easily say how much the clamp and the surrounding can material will constrain this.

One problem that comes to mind here is that the stresses being generated here are primarily compressive and that this will not result in crack growth. However, a more careful look at the weld cross-section as shown in figure 7 reveals that shear stresses are also being generated across the weld joint.

Figure 7. Stresses created by clamping and heating.

The actual levels of stress on the weld line, particularly shear stress, are strongly dependent upon the geometry of the weld. Figure 8 shows three situations in which the shear stresses are clearly different.

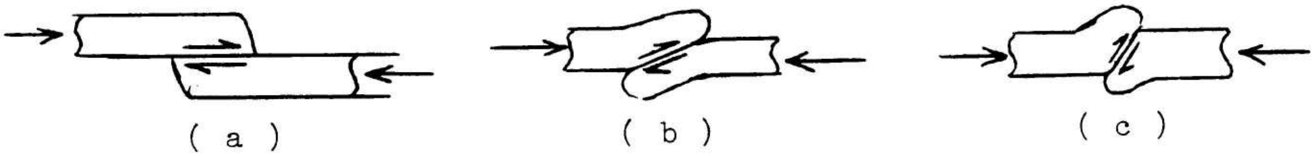

Figure 8. Various weld geometries and stresses.

Case (b) is closest to the actual situation.

One can start an analysis of the weld stresses by first considering a homogeneous metal plate and analyzing the effects of clamping on an element as shown in figure 9.

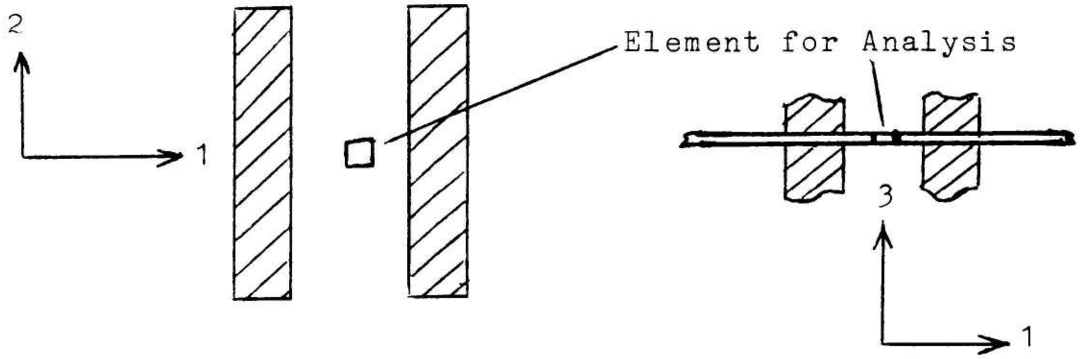

Figure 9. Clamped plate and element for analysis.

All shear components are zero as well as strain in the 1 direction and stress in the 3 direction. Using the thermo-elastic stress-strain relations:

$$\epsilon_{ij} = \frac{1}{E}\left\{(1+\nu)\sigma_{ij} - \nu\sigma_{kk}\delta_{ij}\right\} + \alpha\Delta T \qquad (2)$$

one can solve for σ_1 and σ_2 as:

$$\sigma_1 = \frac{E(\nu\epsilon_2 - \alpha\Delta T(1+\nu))}{1+\nu^2} \qquad (3)$$

$$\sigma_2 = E\epsilon_2 - E\alpha\Delta T + \nu\sigma_1 \qquad (4)$$

Strain gages and thermocouples could could be used to measure ϵ_2 and ΔT so that σ_1 and σ_2 may be determined using the above relations.

Returning now to the situation with a weld as shown in figure 10, we can calculate F from σ_1 in eq. (3) above.

Figure 10. Situation from which weld stresses may be determined.

σ_2 in eq. (4) above corresponds to the compressive stress normal to the page for figure 10. If the geometry of the weld is known, one can then determine the stresses acting on the weld using the information on F and σ_2.

Using this simple analysis, the magnitude of thermally induced compressive stress for a temperature rise of 80°F is approsimately 20 ksi.

b. Clamps

Two types of clamp design were investigated for the thermal stressing method: a clamp with an external heat source and a hot clamp. Figure 11 shows the clamp used with external heaters.

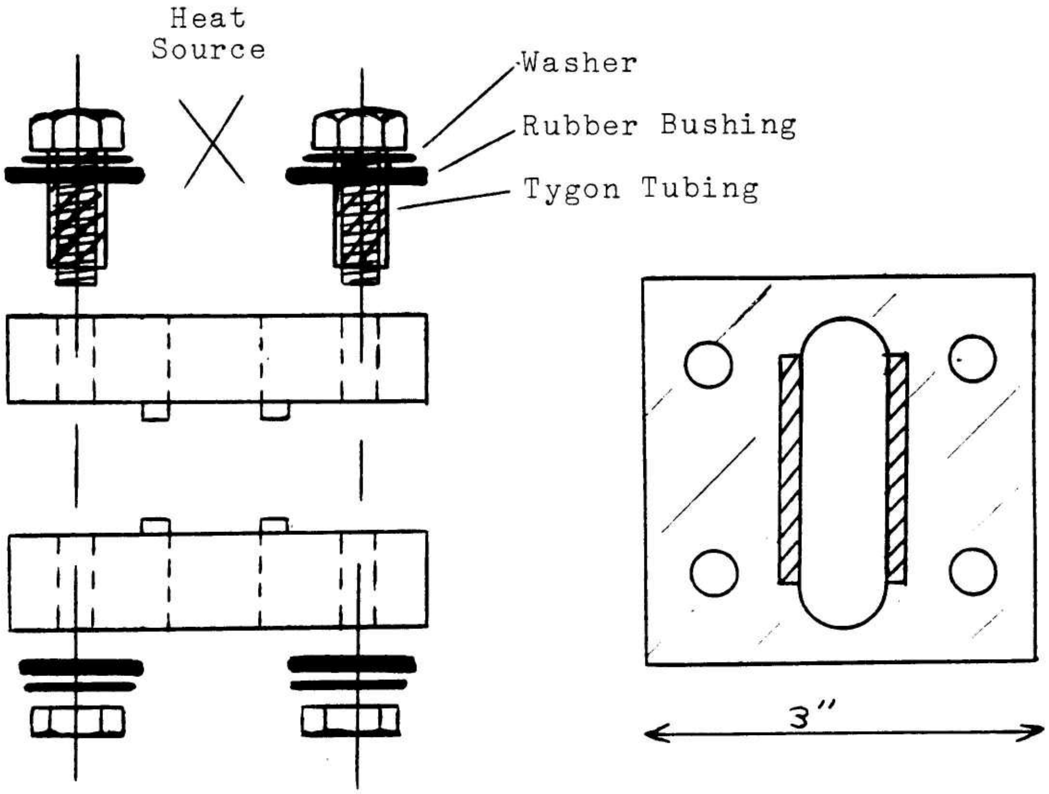

Figure 11. Clamp for external heat source

The rubber bushings and tygon tubing were used to eliminate metal to metal contact which might serve as noise sources if any slippage at these faces occured. The two halves of the clamp were mirror images so that both would stress equally against the heated test section of can. This was done with the hope of eliminating the possibility of slippage between the two clamp halves and the test piece.

To operate this prototype, the test piece was placed between the two clamp halves, and tightening down the four bolts shown in figure 11 supplied the clamping force. Heat was then applied to the test section. Three methods for externally heating the clamped section and the performance of the clamp itself are discussed in the results section.

The internally heated clamp is shown in figure 12.

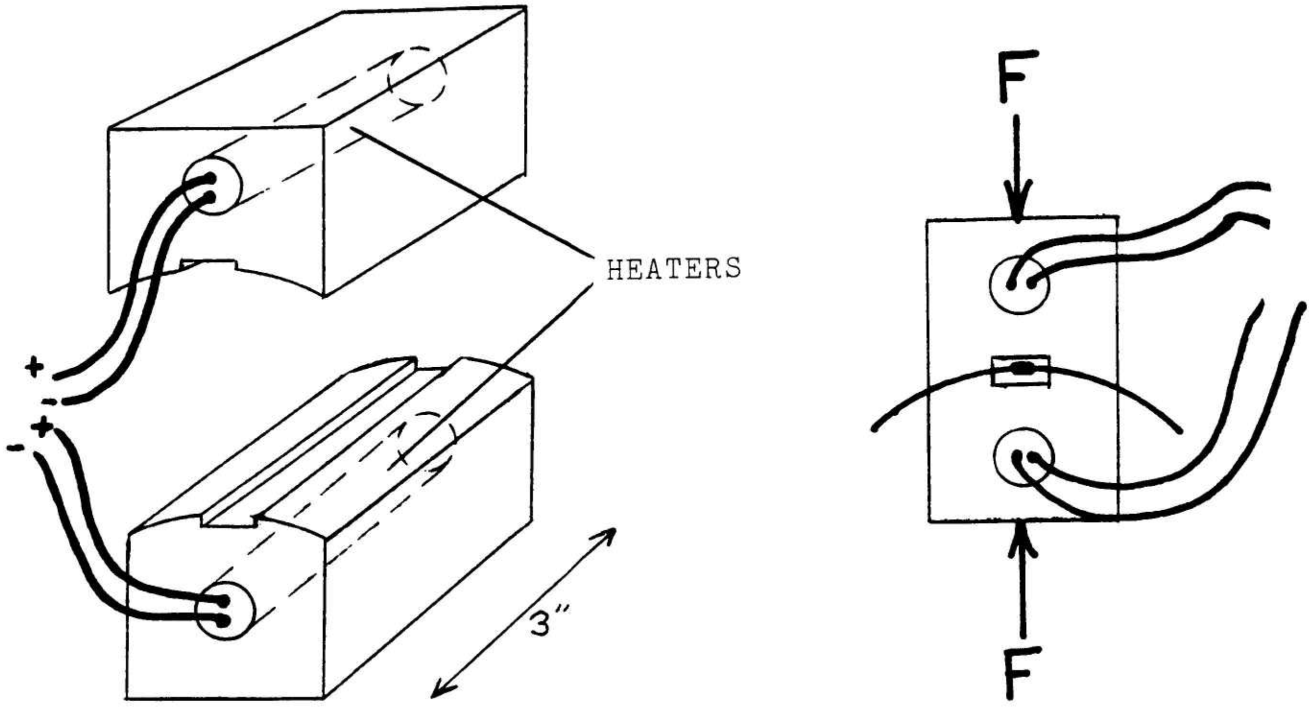

Figure 12. Hot (internally heated) clamp.

One 500 watt immersion heater is mounted in each half of the clamp via a shrink fit technique. A blowtorch was used to expand the aluminum block forming the clamp. The heaters were then placed in their holes which were enlargened by the heating. The aluminum then shrunk around the heaters as it cooled. Both pieces now expand together when the clamp is heated for operation so that the fit stays tight.

The faces of the clamps were milled to a two inch radius so that all diameter cans could be tested without causing any permanent deformation to the can. A channel was milled in each clamp half so that the weld would not contact any part of the clamp (figure 12).

To operate the clamp, a voltage was applied across the heaters so that the clamp halves were heated prior to use. Once the desired temperature was reached, the hot clamps were quickly clamped to the test piece which then heated via conduction from the clamps to the test piece. Heating of the clamps prior to clamping was necessary because the clamps would merely expand with the test if both were heated together. As figure 13 shows, a vice borrowed from a milling machine supplied the clamping force for the initial experiments with this clamp. In later experiments an Instron model 1125 replaced the milling vice. The two nylon pieces serve as mechanical noise insulators.

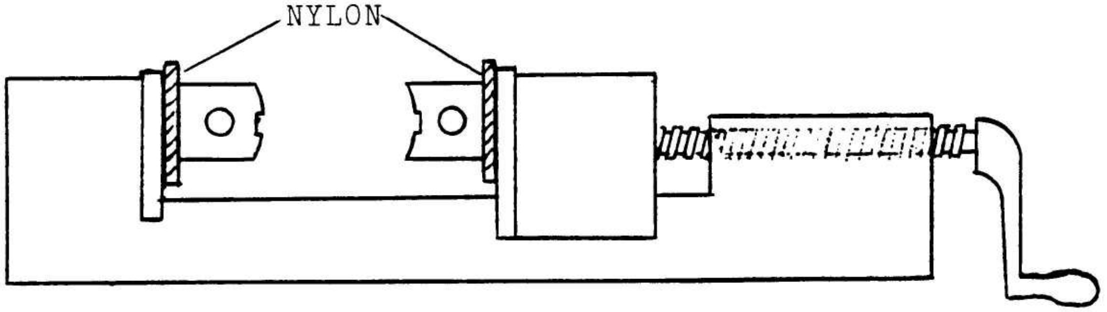

Figure 13. Milling machine vice to supply the clamp force.

THERMAL STRESSING METHOD - EVALUATION PROCEDURES

Stress Relief by Buckling

One question that comes to mind when evaluating the proposed thermal stressing method is whether or not the stressed section is going to buckle and relieve some or all of the stress. If the clamps were applied right next to the weld on both sides, this would not be a problem because the stress would be across a short length relative to the thickness for buckling. However, for ease of operation, it would be better to have some leeway in positioning the weld in the clamp. This means having distance between the weld and the clamp which might result in the stressed section becoming buckled. In order to test for this, strain gages were placed as indicated in figure 14. These strain gages were also telltales as to whether or not the clamp was constraining the piece being heated.

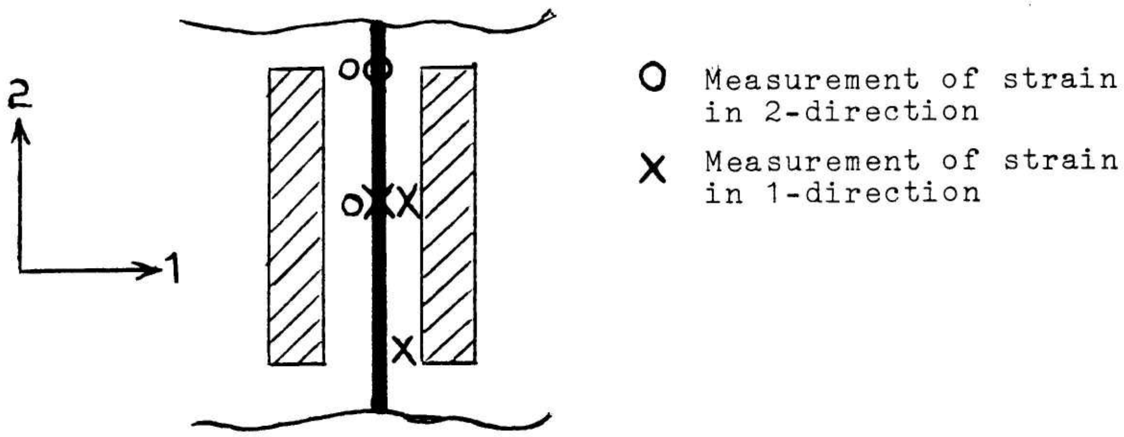

Figure 14. Strain gage placement for stress relief testing

As was mentioned in the section describing the analysis of thermal stress, the amount of stress relaxation parallel to the weld is also of interest. In order to test for this strain gages were placed at the edge of the clamp in the 2-direction as shown in figure 14.

Testing for AE Generation

After the feasibility of the thermal stressing concept was established, the clamp and heater configurations were tested for their ability to produce a.e:

a. Testing of Heating

The procedure here was very straightforward. It consisted of using chromel-constantan thermocouples to measure the rate of heating and the final temperature at various points around the clamped section. This allowed evaluation of various types of heating on the basis of speed and uniformity. Knowing temperature also gave insight to the stress levels being introduced. The various methods of heating are discussed in the results and discussion section.

b. Ability to Produce A.E.

This is the bottom line in whether or not the thermal stress concept will work. Sections of can to be tested were clamped and heated. Figure 15 on the following page depicts a schematic of the AE test equipment system.

A Panametrics AE1003 resonant piezoelectric transducer with a 1 Mhz characteristic frequency was used to detect acoustic emission. The transducer was held with rubber bands to a section of the test piece external to the clamped region. Vaccuum grease was used as a couplant between the transducer and the test piece. Signals from the transducer were sent through a Physical Acoustics 1220A AE preamplifier with a band pass of 25 Khz to 1.25 Mhz. The amplifier's gain was set at 60 db.

This signal was then input to a Tektronix 7D20 oscilloscope capable of digitizing waveforms at sampling rates of 50 ns per point. The digitized signals were then sent to an IBM personal computer so that they could be reproduced and analyzed at a later time. This particular arrangement does not permit a continuous time monitoring of the transducer's output spanning the entire stressing process. To work around this, software for the computer was written to 1) arm the scope trigger 2) read the digitized version of the signal that triggered the scope and then 3) re-arm the scope's trigger to repeat the process. Because the computer had to read in the data from the scope's memory before it could re-arm the trigger, there was a dead zone

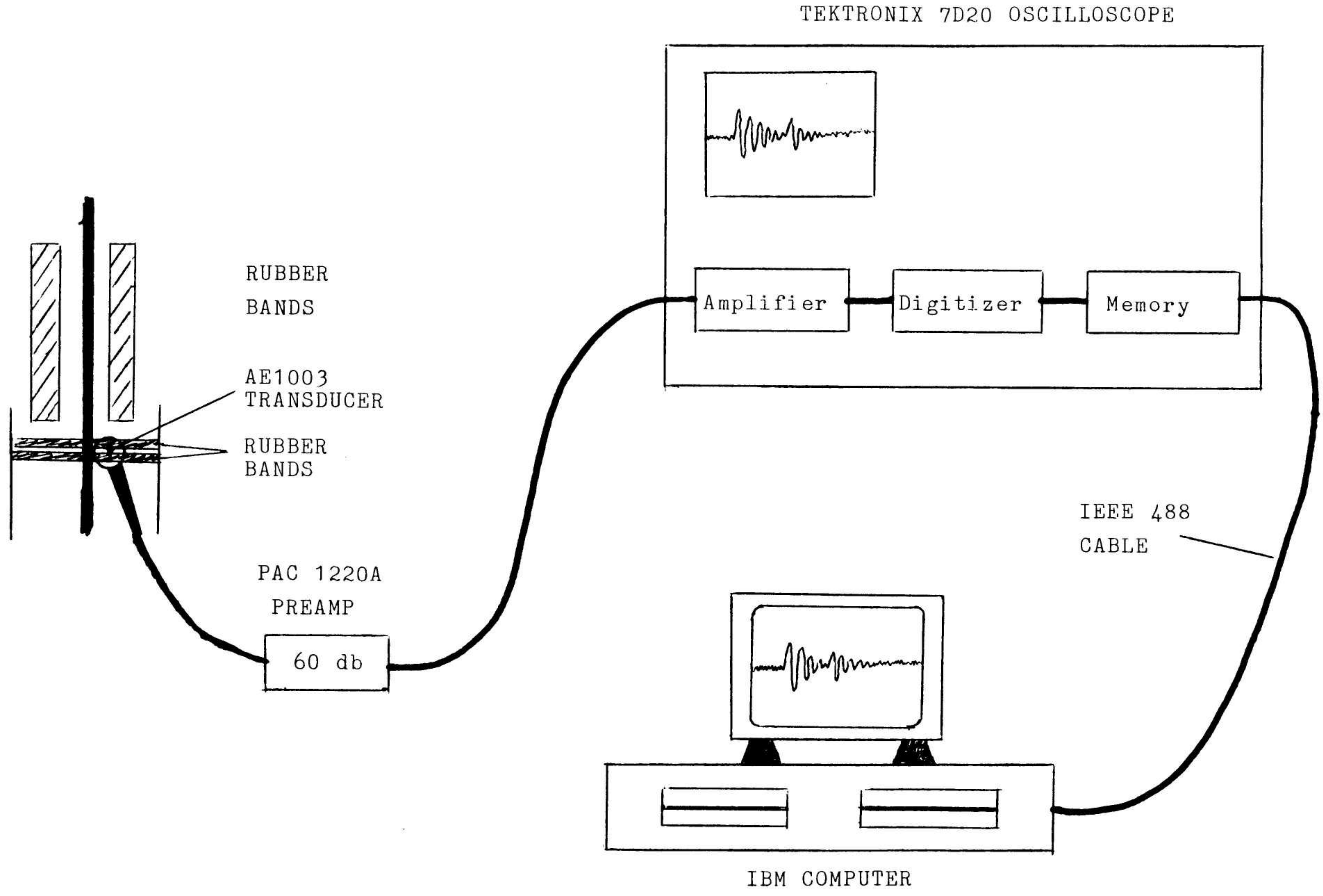

Figure 15. AE data acquisition system.

between triggering and re-arming of approximately 80 ms during which the transducer's signal could not be monitored

In order to determine whether or not any signals produced were actually acoustic emission from the weld, both sections with welds and sections without welds , i.e. blanks, were tested. If signals were obtained from welded sections but not from the blanks, then it would have been likely that the source of the trigger was from within the weld. Various levels of heat and/or heat rate were applied for each clamp in an attempt to produce a.e.

Clamp Force Measurement

As a design parameter, one should know the clamping force required to ensure that the can does not slip and expand when heated. This would lead to stress relaxation and probably a generation of signals that would be mistaken as a.e.

To determine the clamp force needed, the clamp arrangement was placed on an Instron Model 1125. The Instron was run in compression mode, and a 5,000 lb reversible load cell was used. A blank was clamped and stressed. The same signal detecting equipment as shown in figure 15 was connected to the blank being tested. The initial clamping force supplied by the Instron was set to be higher than needed to prevent slippage, 1,500 lb, as found by preliminary testing. The clamping force was then gradually decreased by moving the Instron crosshead away from the clamp at a rate of .002 in/min. This resulted in a clamp force reduction rate of about 100 lb/min. As the clamp force was reduced, the loads at which signals were obtained from the transducer were recorded and taken to be points of slippage.

RESULTS AND DISCUSSION

Stress Relief by Buckling

The strain gage testing revealed that there was no buckling of the clamped section and no problems constraining the piece against slippage. In the direction parallel to the weld the material was constrained enough by the surrounding can material and the clamps so that σ_1 was only reduced by 5%-10% of what it would be for the plane stress case with $\epsilon_2 = 0$. In all, clamping works well in as far as constraining the test pieces is concerned.

Evaluation of External Heat Sources

Three types external heating techniques and one cooling technique were evaluated. The first type,direct flame heating, was done with a hobbyist's torch from Radio Shack. Though the flame heat could easily heat the test piece to several hundred degrees farenheit within a couple of seconds, two problems were encountered. The heating was irregular and the physical action of the flame against the test section was enough to trigger the oscilloscope when testing for a.e. Both of these problems are probably solveable with several less intense flames arranged in a row rather than passing the blowtorch back and forth.

Rather than trying to solve the flame heat problems, a second approach to heating was investigated. An immersion heater was placed at varying distances to the clamped section and supplied with varying voltages. See figure 16.

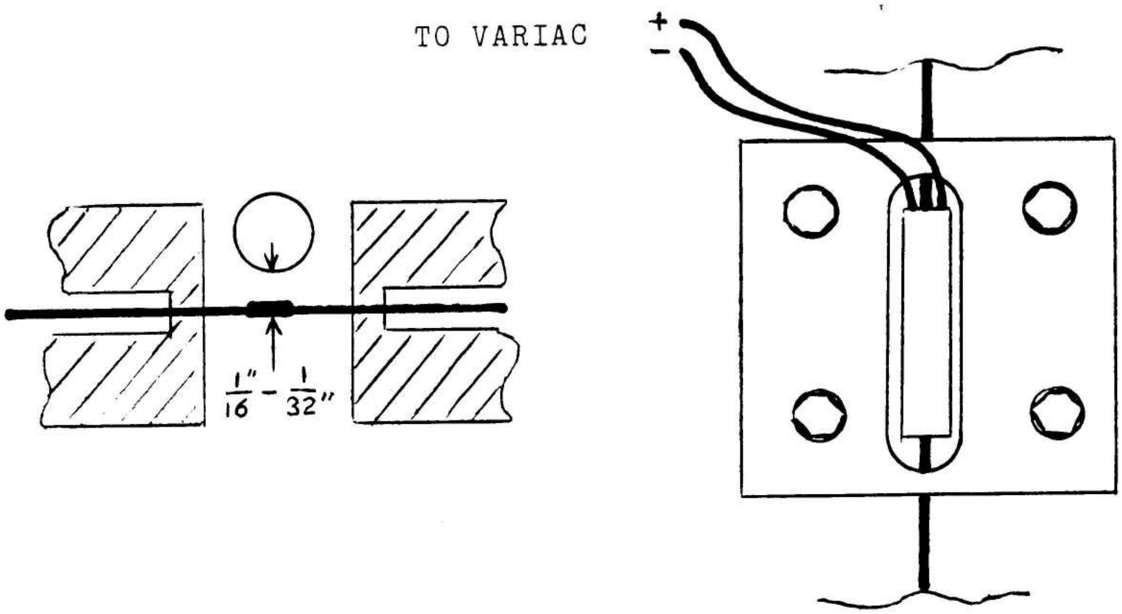

Figure 16. Immersion heater as an external heat source.

This type of heating proved to be rather inefficient and slow. With the immersion heater glowing red hot, the quickest heating was approximately a first-order exponential rise with a rise time on the order of a minute to raise the weld about 100°F above room temperature. Distances of approxiamately 1/16" to 1/32" had to be used for this. Also, the test piece temperature was very sensitive to the distance of separation. A change of height from about 1/32" to 1/16" changed T from 240°F to 195°F. This sensitivity could give problems in repeatability of temperature. This type of heating also led to a temperature gradient across the weld as shown in figure 17.

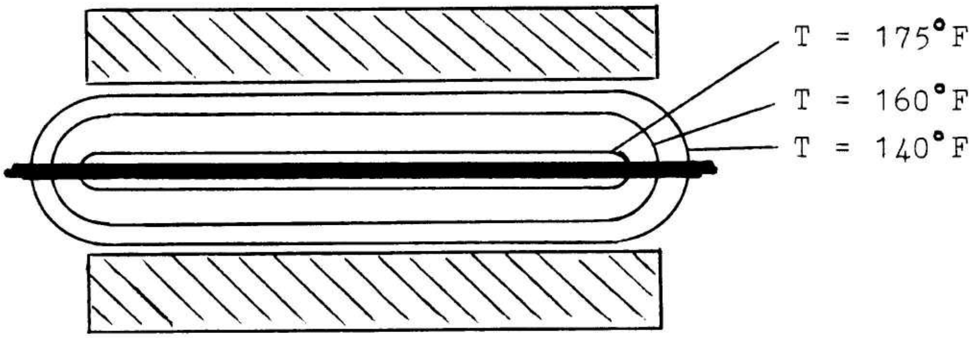

Figure 17. Typical temperature distribution for external immersion heating

One final type of heating for externally heated clamps which was never implemented involves using flashtubes to heat the can. Xenon Corp., Wilmington, MA was the manufacturer for the particular flashtube in consideration here. Flashtubes come in various shapes and sizes. They operate in pulses on the order of micro-seconds long and may be pulsed seversal times a second. Energy outputs range from hundreds to thousands of joules per pulse in the form of light energy. The feature that makes them attractive for heating such as in heat treatment is the bandwidth of light emitted which allows much of the energy to be absorbed by the specimen. According to Xenon, approximately one-third of the energy input to a flashtube would be absorbed by the can, although some reflectors to guide the flash would have to be constructed.

Flashtubes were never used in this study because the electrical and mechanical noise each pulse generates would severely interfere with the transducer's signal. Each time the tube pulses, the quick rise and drop of voltage across the tube emits electrical noise. Typical operating voltage is 2000 V. Mechanical noise is also a problem because the rapid heating of gas in the tube results in a shockwave transmitted through the glass tube to the surrounding environment. It was because of these problems and the time involved to set-up the flashtube circuitry that this type of heating was never implemented experimentally.

Rather than heat the weld to produce stress, it was also considered to cool the weld. This would result in tensile stresses such as those produced by the mechanical pull method. The lower temperature would also produce greater crack growth than when hot. To cool the weld, Radio Shack Component Cooler was used. This is a freon spray capable of cooling objects to -32°F. Unfortunately, the action of spraying the weld and the action of the freon boiling off of the weld as it cooled the weld was a noise problem.

Problems With Externally Heated Clamps.

This type of clamp was never able to produce reliable a.e. data. The major problem was that after running several tests, the clamp itself started to heat. It is believed that this was a source of spontaneous triggering as one half of the clamp exposed to the heat source expanded or contracted relative to the other. If testing were continued long enough, the clamps might have eventually warmed to the point that they would heat the test piece before the external heater is applied which could affect the test results.

Evaluation of Hot Clamps

This type of heating was by far superior to any type of external heating tried. The clamped section rose to to the temperature of the clamps within several seconds. Figure 18 shows a typical temperature pattern in the test piece revealing only a small temperature gradient over most of the clamped piece.

Unfortunately, as far as use in an a.e. test system is concerned, this type of clamp must also be considered unacceptable. It was found that the combination of temperatures and clamping forces required to produce any signal are high enough to blister the paint off of the test

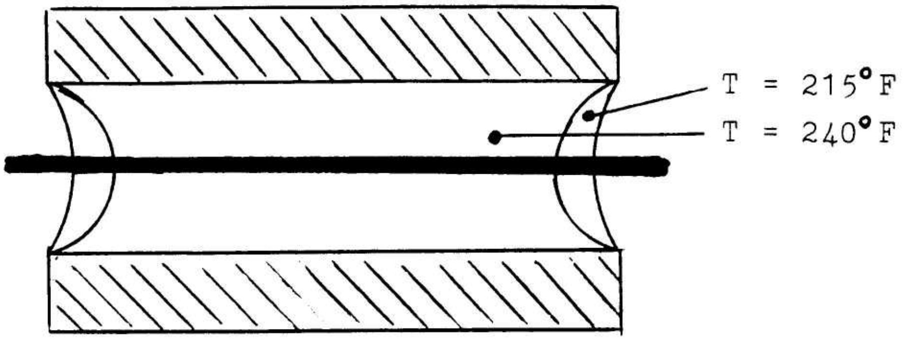

Figure 18. Temperature distribution for hot clamp.

pieces. In effect , this starts to become a destructive evaluation process for cans painted with customers' product labels.

Another bad aspect of this clamp arrangement lies in the data obtained. Testing a mix of twenty-four welded sections and thirteen blanks made the clamp appear to be working as intended. Figure 19 on the following page shows a typical signal obtained by the oscilloscope and plotted using the IBM computer with a Hewlett Packard plotter. Unfortunately, similiar testing done with the clamps set-up on an Instron after determining the clamping force required to overcome slippage revealed no discernible difference between the AE data obtained from the blanks and that from the welds. Since the Instron offered better control of the clamping over that of the milling machine vice, considerable doubts were cast on the validity of the previous AE data. Also, quantification of the data at this point would not be

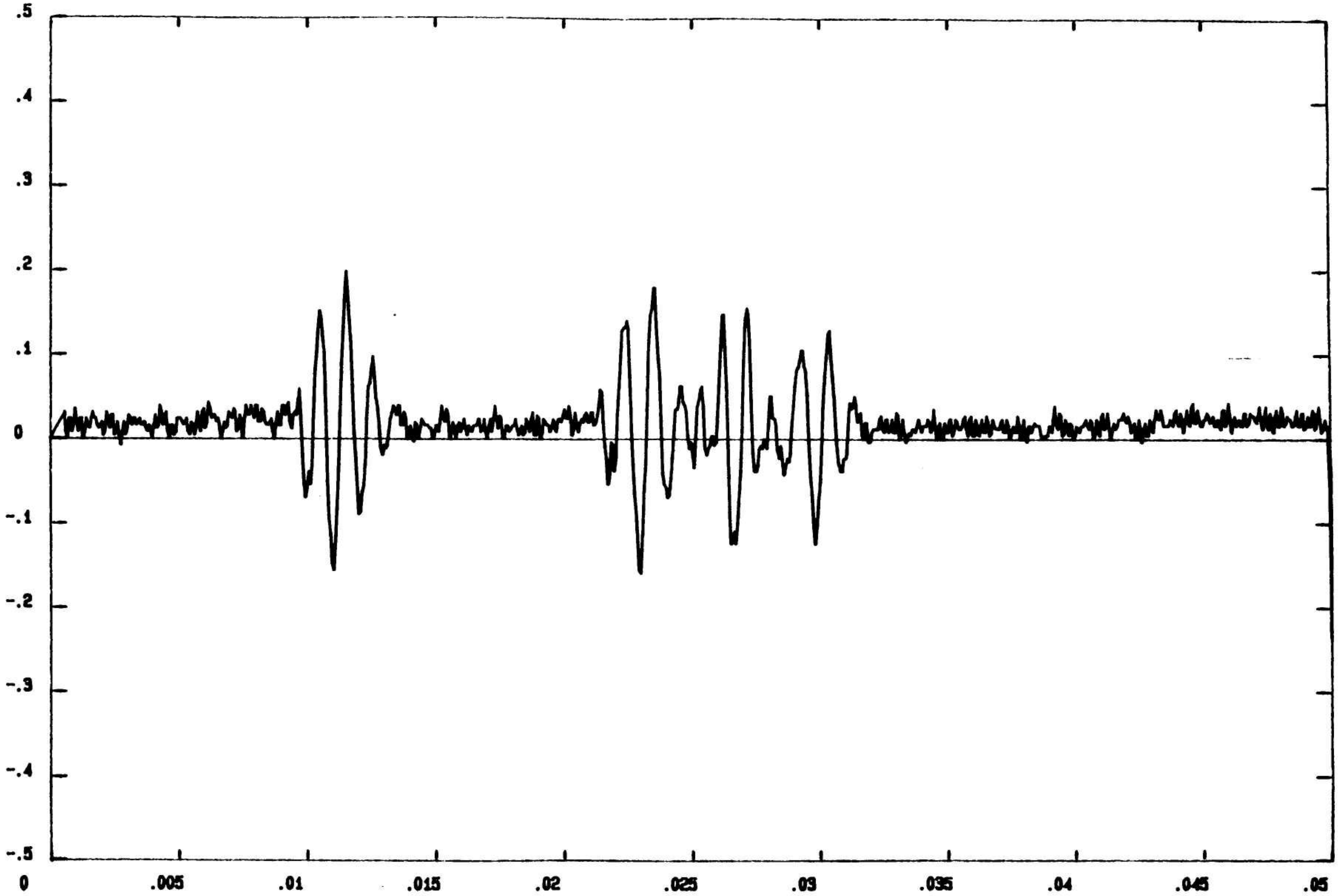

Figure 19. Sample of a.c. test data taken with system of figure 15.

meaningful because of the deadzones during monitoring of the stress process. Improvement is clearly needed in this reguard.

Other doubts arise if one considers when the a.e. is produced. From the existing theory on a.e. generation, a.e. should be produced mainly during the period of increasing stress. However, the signals here were produced well after final stress was reached. By temperature measurements, the steady-state thermal stress should be reached well within five seconds of clamping whereas the signals obtained occured anytime between fifteen seconds and three minutes after clamping. A majority of the signals detected, however, fell within thirty to ninety seconds after clamping. Further investigation to clarify the origin of the detected signals is necessary.

This time duration also poses a problem considering implementation of this in a production environment. The time required to run a test on a can with this thermal method is simply too long based on the results of this investigation. The process already runs too hot for the paint so that it would not be acceptable to use even hotter clamps to quicken the process.

Clamp Force Measurement

Eight trials were run. Based on the signals generated it was concluded that the force required to prevent slippage ranged from 400 lb to 1000+ lb. It was also observed that slippage occured randomly either all at once or in multiple slips. The overall behavior of the slippage, which is seemingly random, may be attributable to the paint layer and how it interacts with the test piece and the clamp when it is hot enough to blister.

CONCLUSIONS AND RECOMMENDATIONS

This research shows that the thermal stressing technique is not suitable for use as part of an a.e. test system. The reasons for this are as follows:

1) The combination of heat and clamping forces required to generate any a.e., or what appears to be a.e., is enough to blister the paint off of the can making the process destructive.

2) Any a.e signals that have been generated so far are produced irregularly. No clear correlation between AE characteristics and weld quality have been obtained by this technique. Although further experimentation may lead to more consistent and valid a.e., in light of the other drawbacks of this method, this approach is not recommended.

3) Stressing by heating is not ideal for a.e. generation because of the compressive nature of the applied force.

Recommendations for designing a system by which to generate a.e. from resistance seam welds are:

1) Apply tension across the weld rather than compression as shown in figure 20.

Figure 20. Good vs. not good stress cases.

2) Avoid designs which require clamping on painted surfaces as shown in figure 21 to avoid damaging paint or running into problems of clamp slippage.

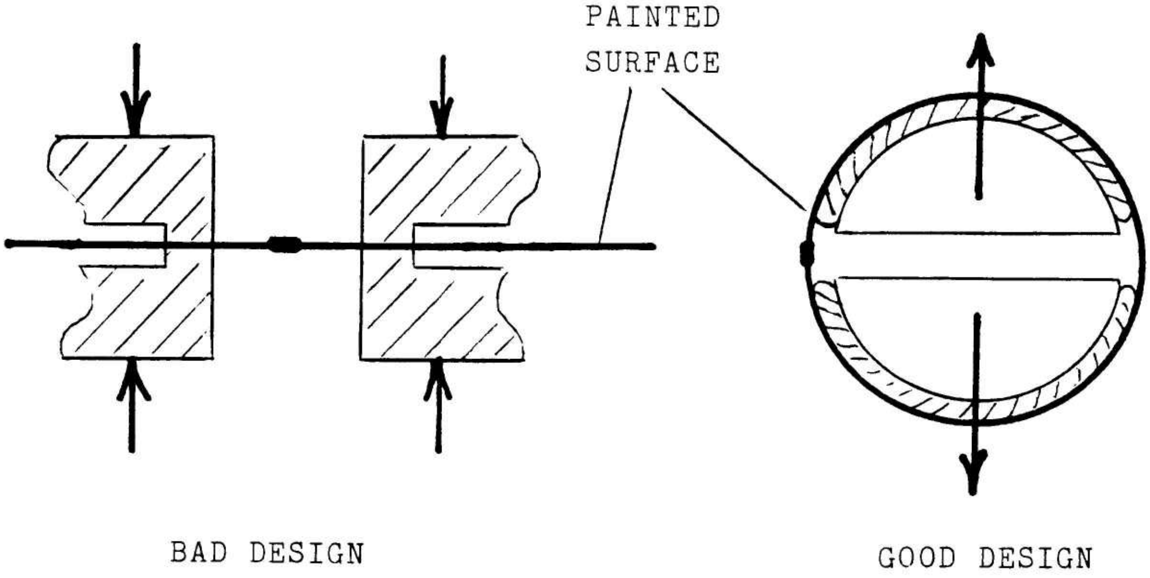

Figure 21. Avoid clamping onto painted surfaces.

3) Avoid using equipment that generates broad band white noise as this is by far more difficult to handle than any other type of noise.

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