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THE APPLICATION OF ACOUSTIC EMISSION TO IN-PROCESS WELD INSPECTION

By

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ABSTRACT

Acoustic emission is evaluated as an in-process nondestructive test for welds. Experimental results show that cracks and porosity in welds emit acoustic emission during and following joint fusion. Automatic machine welds in 1/2 in. plate and hand welds in 1/2 in. thick coupons of stainless steel are discussed.

A correlation is shown between acoustic emission rate, radiography, and metallographic sections of a number of welds. Some defects not detected by radiography are indicated by acoustic emission and verified by metallographic sections. Acoustic emission rate from weld defects is shown to be a function of weld defect temperature.

Practical applications and problem areas are discussed.

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MASTER

INTRODUCTION

Welding is one of the most commonly used methods of joining metal parts. The structural integrity of buildings, submarines, bicycles, and skateboards depends on welded joints. The integrity of a welded joint depends primarily upon precise control of the welding process.

Quality of the joint can be verified, in most cases, by one of several nondestructive techniques. Internal weld defects such as cracks, porosity, or inclusions can be detected either ultrasonically or radiographically. Since either of these techniques is applied after the fact, a certain amount of guess work is involved in determining the dynamic conditions leading to the occurrence of defects in the weld joint. With such a handicap, establishing reliable welding procedures and maintaining quality in production can be expensive and time consuming.

The obvious solution to this dilemma is a real-time nondestructive test which will indicate the occurrence of cracking, porosity, or inclusions during the fabrication of a weld joint. It occurred to us and others[1] that acoustic emission, which results from the fracture of a material under stress, should be produced by the growth of a crack in a weld joint. As the weld metal cools stress can be sufficient to cause plastic deformation of the material as well as cracking in the weld metal or along the fusion line. Weld flaws such as inclusions or porosity should also cause acoustic emission because of the stress concentration around a discontinuity. If so, acoustic emission would provide an immediate indication of the quality of the weld. Since acoustic emissions are essentially omnidirectional, a transducer located conveniently on the base metal would indicate flaws in a weld joint several feet long.

COUPON WELDS

The success of initial experiments is demonstrated graphically in Figure 1. The correlation between real-time acoustic emission data and subsequent radiography is readily apparent. The two welds represented here were approximately two inches long in half inch stainless steel plate. They were made with a hand held gas-tungsten arc torch using filler metal. The defective weld shown in the upper trace was caused to crack by the addition of titanium on the second and fourth weld passes. The numbered bars beneath each trace represent individual weld passes. Acoustic emission from each weld was monitored for approximately 9 minutes. Acoustic emission from the two welds was essentially the same during the first weld pass but the defective weld appeared to begin cracking as soon as the titanium was melted into the weld metal on the second pass. The radiograph of this defective weld shows a number of cracks and some porosity in the weld metal while the radiograph of the second weld gives no indication of a defect. The emission signals were initially stored on magnetic tape. The rectified signals shown here represent the acoustic energy in a pass band of 50 KHz to 300 KHz.

Data Correlation

The next step was to generate a calibration curve relating acoustic emission to the number and size of defects in the weld. For this purpose 24 butt welds were made in both 304L SS and 316 SS.[2] A water cooled restraining fixture shown in Figure 2 was used to insure high stress buildup in the weld metal. All welds were 2 inches long in 1/2 inch thick material. The welding process was manual gas-tungsten arc using filler metal. A number of tricks were employed to obtain a variation in weld quality. These include the use of incompatible filler metal such as titanium, tantalum and mild steel; occasional high current wash passes; longer than normal arc length; and bubbling the cover gas through water. Acoustic emission signals from the 24 weld coupons was stored on magnetic tape for later analysis.

The welds were radiographed and this information used to select 3 transverse metallographic sections for each coupon. Figure 3 shows a typical weld section. Each metallographic section was divided into 3 regions, as shown here, in order to obtain a crack length factor which could be related to the acoustic emission data.

The assumption here was that the total visible crack length should be related to the number of acoustic emissions recorded. Visible cracks in the center region of each section were measured and their lengths added to obtain the crack length factor for each weld coupon. Figure 4 shows the result of plotting this crack length factor against the number of acoustic emissions from the center region of each coupon. The correlation obtained in this manner is rather crude, but at least a trend is shown.

We feel that the point spread shown here is largely due to the inherent errors in measuring the relative crack length. An example of one such error is shown in Figure 5. Longitudinal cracks were observed visually during welding of all four of the weld specimens shown here. However, in the two lower specimens the cracks were apparently fused by subsequent weld passes. Figure 6 demonstrates another possible source of error in the crack length measurement. Each of the three weld specimens shown here generated in excess of 400 acoustic emissions, which were attributed to the extensive porosity since the measureable crack length in these specimens was small.

Radiographic examination of the two weld specimens shown in Figure 8 indicated no defects; however, random metallographic sectioning exposed defects which correlate with the observed acoustic emissions. Weld #14 appears to be cracked extensively corresponding to an acoustic emission total in excess of 10,000 while Weld #11 exhibits one major crack corresponding to a total of 400 acoustic emissions.

The acoustic emission rate for three of the weld specimens is shown in Figure 9 along with representative photomicrographs of the three welds. Horizontal bars beneath each trace represent individual weld passes. It is interesting to note that the acoustic emission rate from the three specimens is similar until the contaminating material is added on the third pass to Specimens #27 and 23. As the photomicrograph shows, the addition of tantalum to the weld specimen does not produce as extensive cracking as the addition of titanium. The addition of titanium to Specimen #23 caused such an increase in the acoustic emission rate that a change in scale on the graph was necessary. Comparison of the photomicrographs from Specimens #27 and 23 further demonstrates the difficulty encountered in measuring the crack length from these micrographs. The relative crack lengths recorded for these two specimens are 5.8 for

Specimen #27 and 6.9 for Specimen #23, but the defect in Specimen #23 appears to be several times more extensive than that in Specimen #27. The difficulty of physically measuring the extent of defectiveness in a weld specimen is probably responsible for the poor correlation shown in the relationship between relative crack length and acoustic emission.

SINGLE PASS WELDS

A series of long single pass welds were made in 1/8 inch 304 stainless plate using an automatic welding machine.[3,4] Welding parameters can be closely controlled on a welding machine to insure the weld to weld repeatability. Figure 9 shows the acoustic emission data obtained from one of these single pass welds. The weld seam was 36 inches long and required approximately 8 minutes to complete. In this weld two short pieces of titanium wire were laid in the weld groove and subsequently welded over. Very localized cracking occurred in the region where the titanium was added, as indicated on the graph by the bar directly above the acoustic emission trace. A time delay between the welding of the defective region and the occurrence of acoustic emission from that region is readily apparent on this data trace. This time delay is not surprising since, for cracking to occur, the weld metal must cool from a liquid state until the thermally induced stress exceeds the strength of the weld in that region. A segment of the radiograph from each defective region is inset above the acoustic energy trace. Close examination of the first defective region shows a number of fine cracks which run across the weld seam. In the radiograph of the second defect there appears only one large crack directly across the weld seam but it has changed direction at least twice. The data shown here is no more quantitative than that shown for the coupon welds, but in this case one can make a direct comparison between the acoustic emission from a long segment of the weld seam which contains no cracks with that from the region where cracks did occur. The data shown here was also converted electronically to an acoustic emission rate plot which is shown in Figure 10. This is the acoustic emission rate in pulses per minute as a function of time from the beginning of welding. The time at which the two defective regions were passed over by the welding arc is indicated on the graph. The high emission rate at the beginning of the weld is attributed to the interference of the alternating exciter current from the welding machine. The exciter current stops automatically when the arc is stabilized. The point of interest here is that the emission rate from the isolated defects is well above the background level from the normal portions of the weld. The time delay between welding a potential defect and the onset of acoustic emission from the defect in this series of welds varied from 20 seconds to 1 minute.

Temperature Dependence

To gain further insight into this time delay between welding and cracking the weld joint temperature was recorded along with the acoustic emission data. Assuming that any point along the weld seam would have essentially the same cooling rate from the melt as that recorded, the acoustic emission rate for 4 different defects was converted from a function of time to a function of temperature, as shown in Figure 11. The emission rate from the four defects was normalized and then averaged to produce the smooth curve shown in this figure. The emission rate begins to rise sharply at about 600 °C and peaks at approximately 400 °C. Of course, the relationship shown here applies only to the particular welding conditions and the materials involved in this series of tests. One would not necessarily expect naturally occurring defects to exhibit the same emission rate versus temperature relationship as shown here, but the point is made that acoustic emission rate is a function of weld temperature.

Experimental Equipment

For this series of welds, acoustic emission, weld temperature, and welder position data were recorded on magnetic tape for later analysis. A block diagram of the acoustic emission monitoring system used is shown in Figure 12. This block diagram also schematically represents the equipment used in the weld tests discussed earlier. The transducers used for all these tests were developed at Battelle-Northwest especially for acoustic emission applications. They exhibit high sensitivity in several radial and diameter modes ranging from 150 KHz to 650 KHz. The pass band used for all these weld tests was limited to between 50 KHz and 300 KHz, the upper limit being imposed by the bandwidth of the Ampex tape recorder and the lower limit by mechanical and electrical interference encountered during the weld tests.

RESISTANCE WELDS

We have also applied acoustic emission monitoring to other types of welding. Figure 13 shows the results obtained from monitoring a series of spot welds in 6061 aluminum. The welds were made to join a strip of 1/8 inch aluminum to a strip of 1/16 inch aluminum. The acoustic emission was received by attaching a standard acoustic emission receiver to one end of the 1/8 inch strip. The welding parameters were varied to generate the variation in nugget diameter shown on the graph. The acoustic emissions plotted here are those which occurred as the welder electrodes released the joint after the weld is completed. These emissions are mechanically generated as the electrodes separate from the metal surface. This is admittedly an indirect measurement resulting from the surface deformation produced when the joint is made. In most cases, the surface deformation is directly related to the nugget diameter. This is demonstrated by one point which does not fit the curve. This weld produced a large surface deformation with accompanying acoustic emission but no joint. This was caused by shunting the current through a nearby joint.

Acoustic emission from a spot weld is divided into three discrete groups. The first group of emissions occur when the electrodes are clamped to the metal. Emissions again occur on the follow-through when the metal becomes plastic and the electrodes compress the metal. The third group, as previously mentioned, occurs as the electrodes release the joint. The first group of emissions was found to correlate very well with the electrode condition. A smooth, clean electrode surface produced very little acoustic emission upon closure of the electrodes while an electrode which had become pitted produced a large number of acoustic emissions. The second group of emissions correlated roughtly with the extent of plastic flow and also indicate the expulsion of material at the electrode or the weld interface. Although the scope of this experiment was limited it does demonstrate the feasibility of

SUBMERGED ARC WELDS*

Acoustic emission can also be applied to industrial welding. One application which we have demonstrated applies the technique to monitoring the quality of submerged arc welds. One of the major problems involved with this type weld is the inclusion of slag. The submerged arc weld is protected from the atmosphere by applying a granulated silicate flux which melts in the arc to form a glassy cover over the weld bead. The slag inclusions referred to are pieces of this glassy cover which are trapped beneath a weld bead. We found that the acoustic emission rate during submerged arc welding correlates well with the conformation of the bead surface. Thus, we were able to detect conditions leading to the formation of slag inclusions. Figure 14 shows the acoustic emission rate from a series of submerged arc weld beads. The emission rate can be seen to change drastically as the bead conformation progressively changes from a normal bead to what is called a roped bead. The normal bead presents a smooth surface so that slag cannot be trapped. The roped bead, as the name implies, has raised edges and pockets along its sides which can trap slag on the next weld pass, thus causing a slag inclusion. The correlation found here stems from the fact that the glassy cover over a normal bead lifts smoothly away as it cools and solidifies, while the glassy cover from a poorly formed bead is partially trapped and fractures extensively as it separates from the weld bead surface. The ability to detect variations in bead quality can lead to considerable reduction in re-work time because defects can be located and easily repaired on the weld surface. Repair time can be reduced from days to minutes.

*This investigation sponsored by NORTEC, Inc., Richland, Washington.

Experimental Equipment

A portable acoustic emission monitoring instrument was used to obtain data from the submerged arc welds and the resistance welds. This instrument presents, on a strip chart, a voltage proportional to the rate of acoustic emissions.

CONCLUSIONS

The favorable results obtained on three different types of welding (gas-tungsten-arc, resistance, submerged arc) lead to the conclusion that acoustic emission can be successfully applied to nondestructive weld inspection. Defects can be detected as they occur without detrimental interference with the welding equipment. A single sensor will detect cracking in a weld several feet long. The occurrence of cracking can be related to other dynamic conditions in a weld. These results suggest that acoustic emission monitoring could be used to advantage in the development of new welding procedures as well as on the production line. Another promising application is the training of welders. The almost immediate response of a defective weld should be a great help in the development of welding technique.

Used as an on-line quality control, acoustic emission monitoring shield complement established final inspection methods in many welding applications. Of course, much more experience on a wider range of applications is necessary to validate these conclusions, but the initial experiments were very encouraging.

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1. Kenneth Notvest. "Effect of Thermal Cycles in Welding D6Ac Steel", The Welding Journal, Vol 45, Research Suppl., p. 173-s, 1966.

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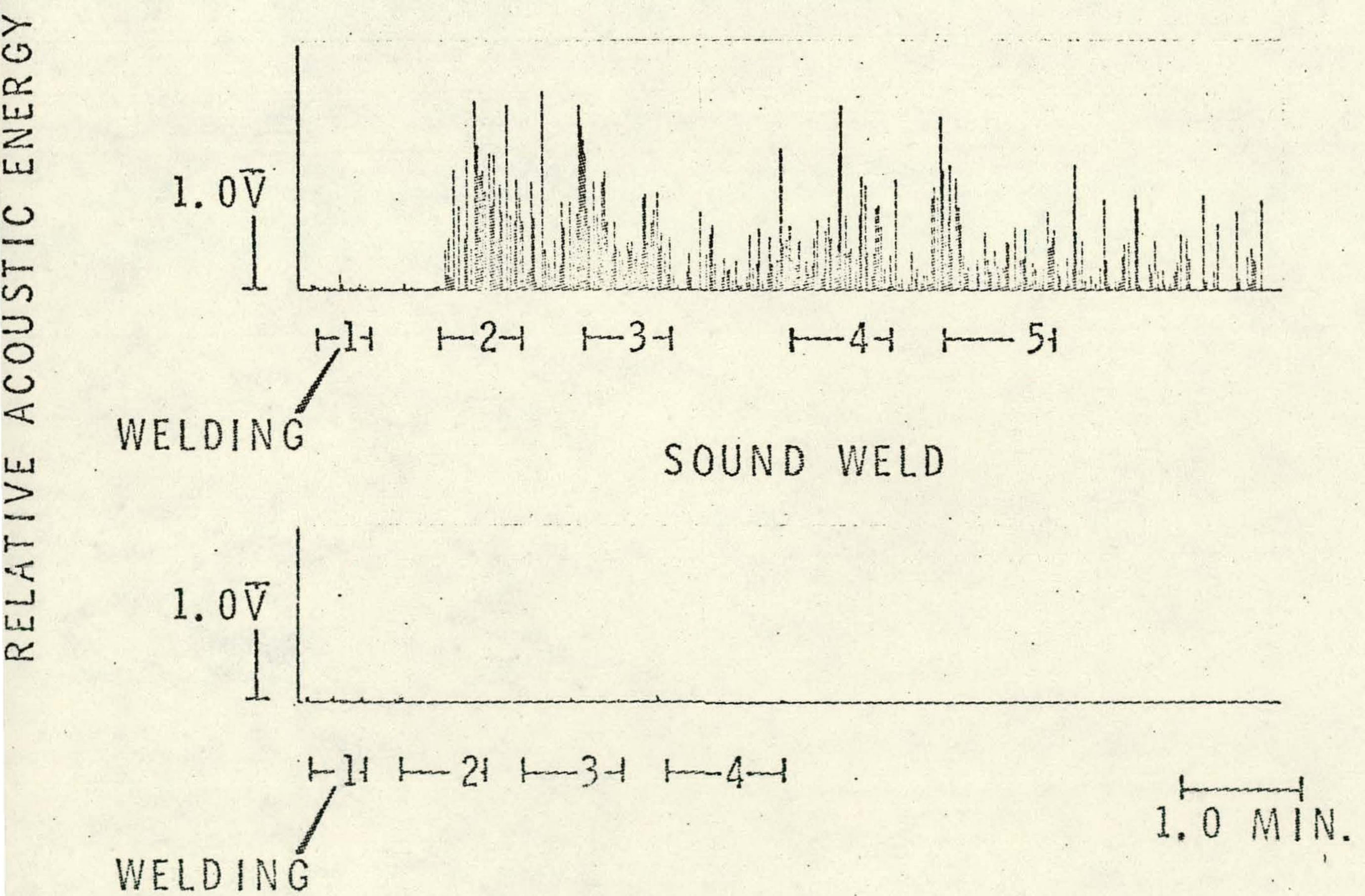
ACOUSTIC EMISSION RESPONSE FROM SOUND AND DEFECTIVE WELDS IN STAINLESS STEEL

DEFECTIVE WELD (TITANIUM ADDED IN THE SECOND AND FOURTH WELD PASSES TO PRODUCE CRACKING)



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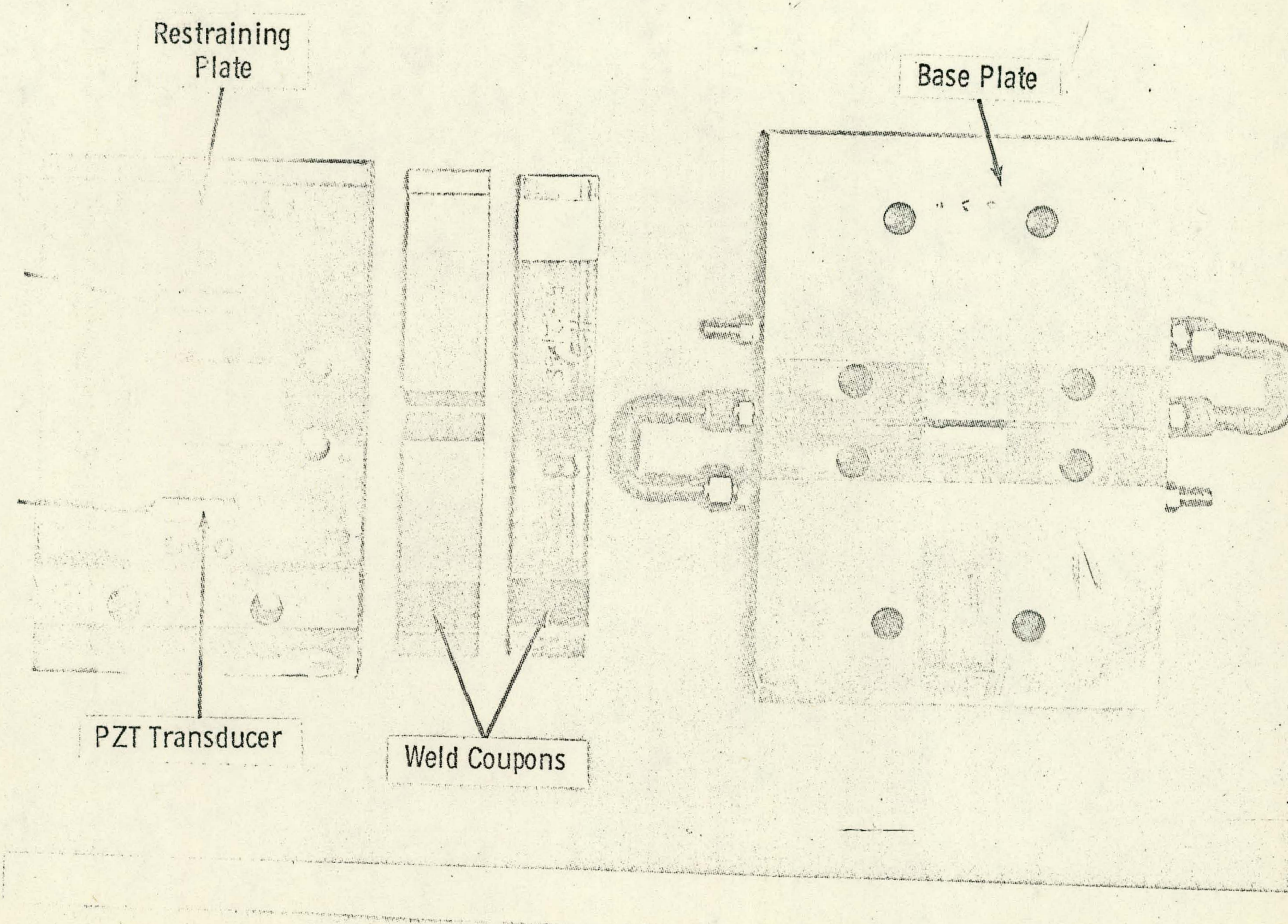

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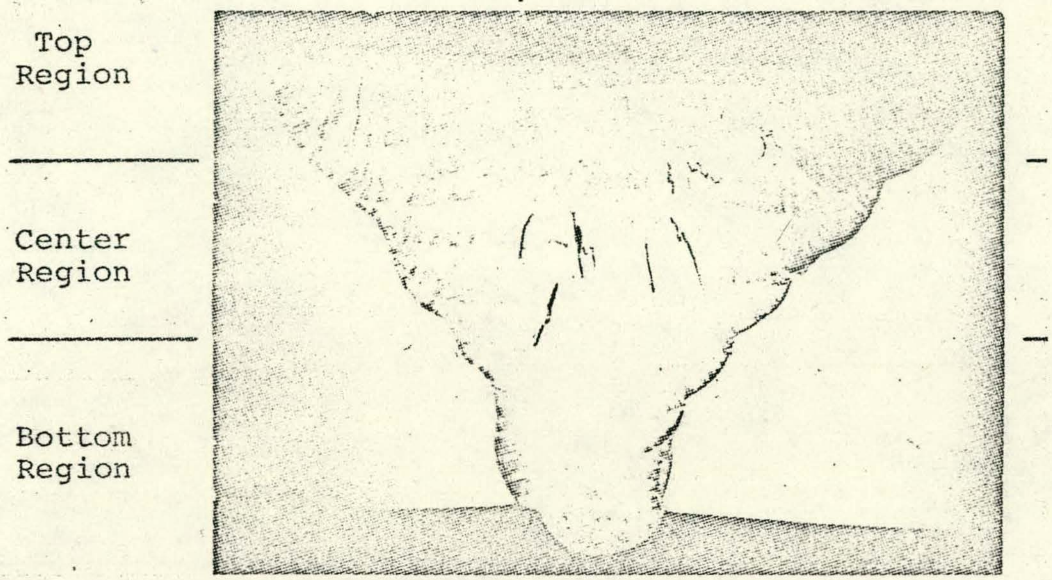

FIGURE 8. Transverse Metallographic Section of a Weld Divided into Three Regions for Crack Length Determinations and Correlation Studies

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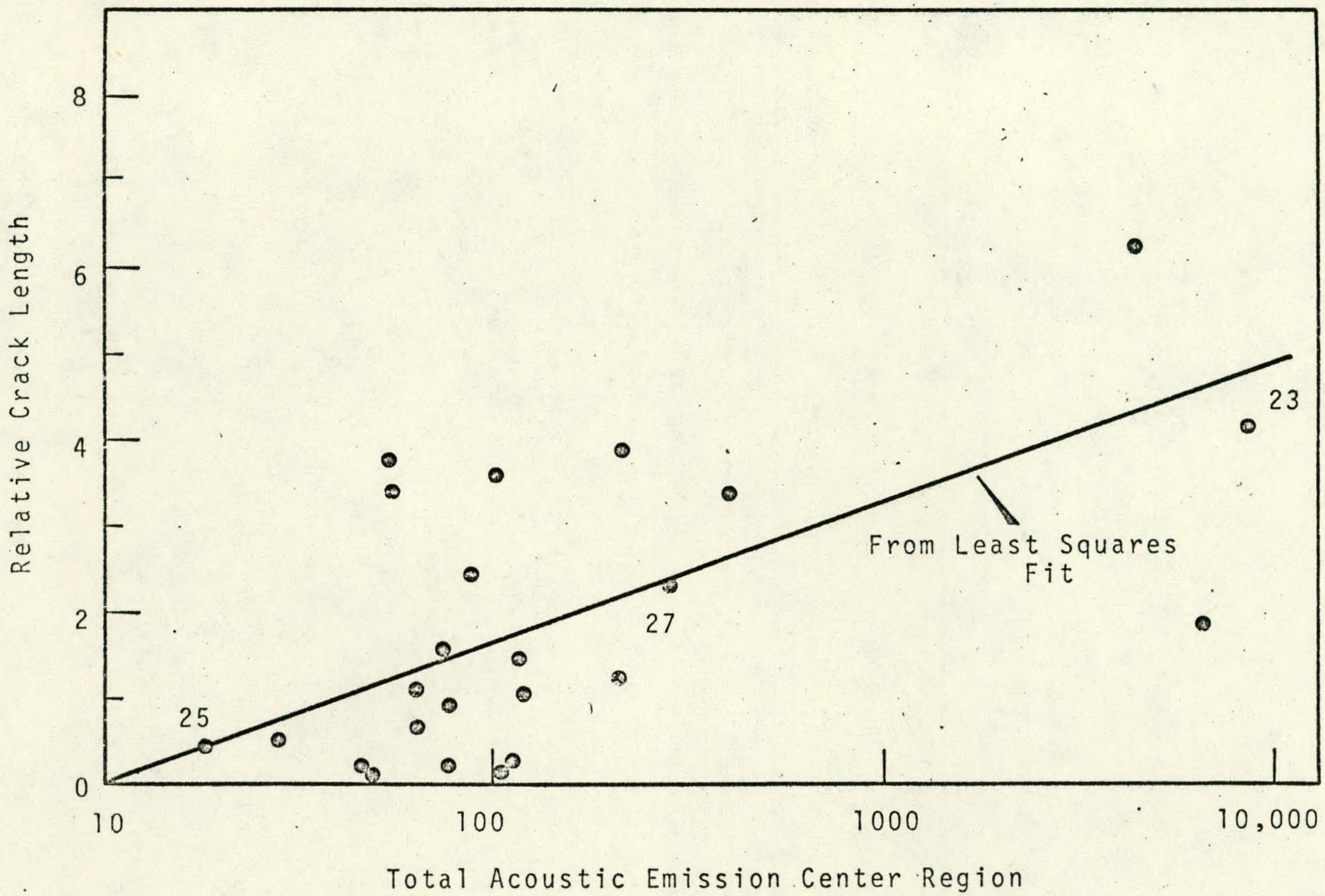

FIGURE 9. Acoustic Emission Versus Crack Length (as Measured from Three Metallographic Sections Each) for the Center Region of 24 Welds. (The Numbered Welds Correspond to those Samples for Which Data Are Shown in Figure 10 and 11.)

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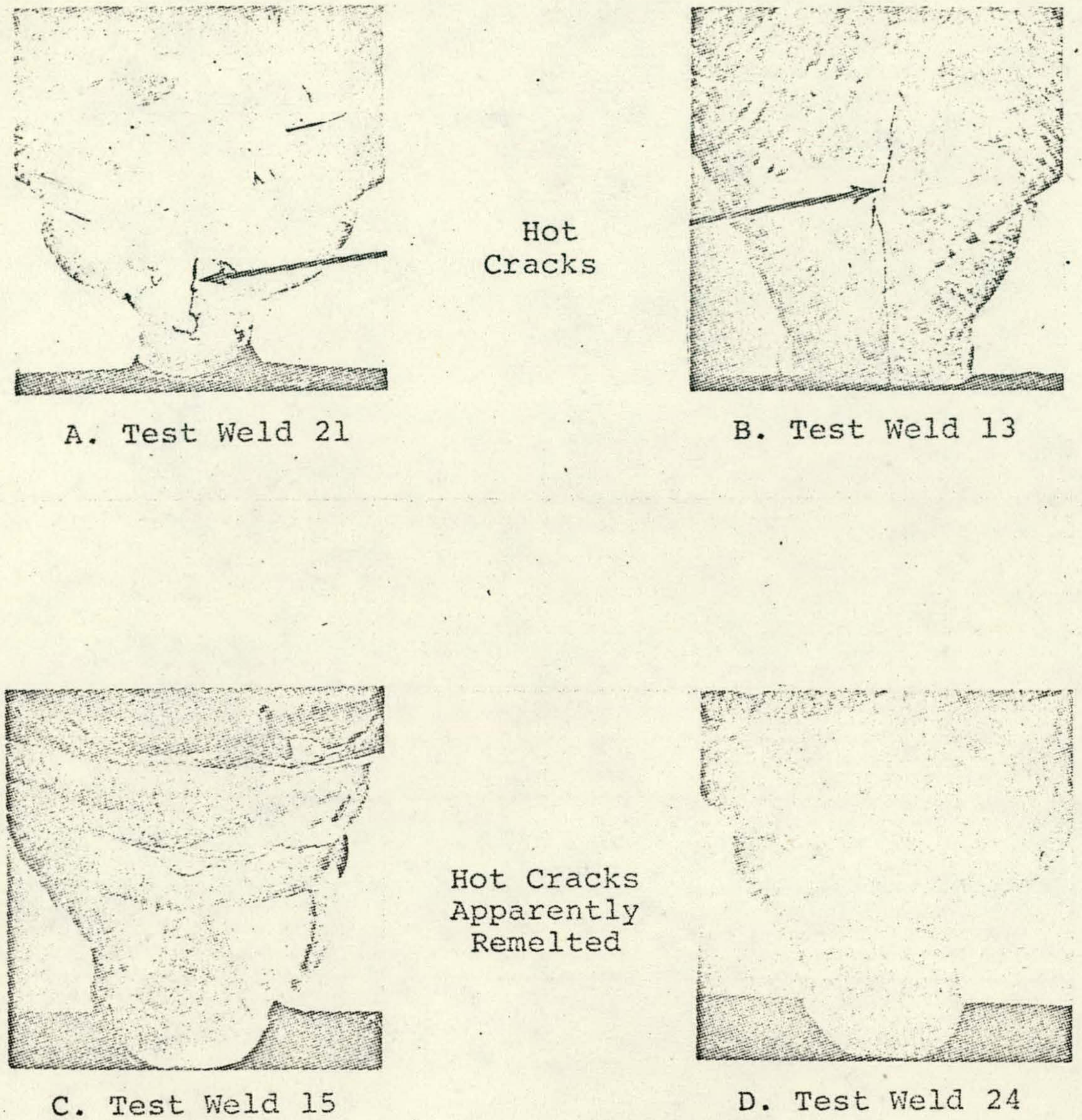

FIGURE 13. Bottom Region of Weld Samples Where Hot Cracks Formed and Were Detected Visually During the Welding Operation

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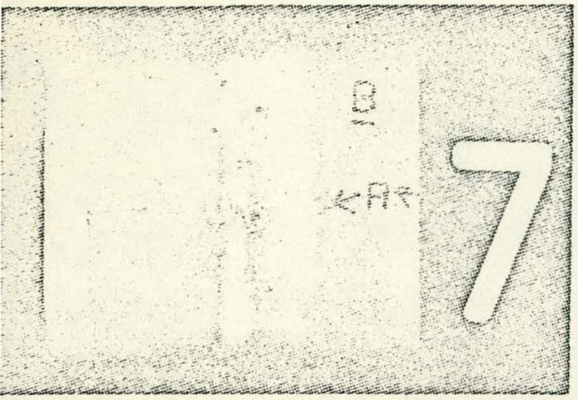
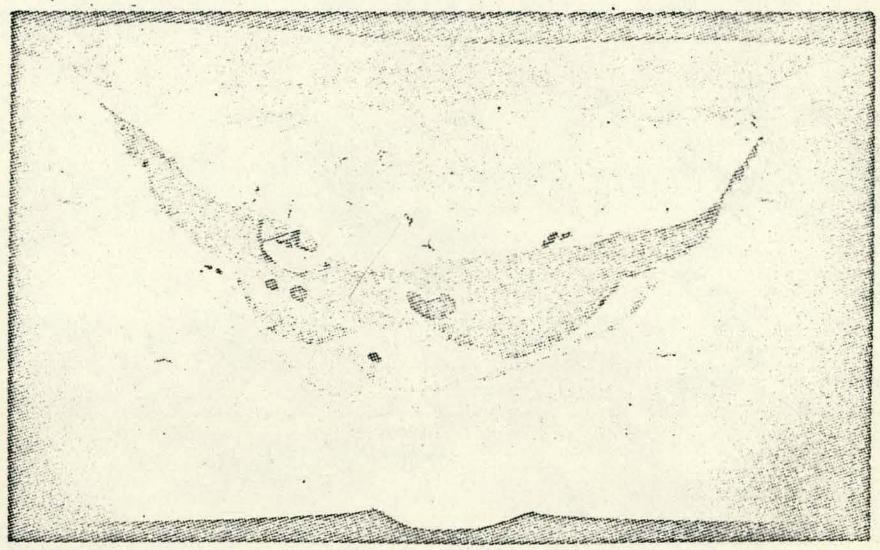
Fig. 14

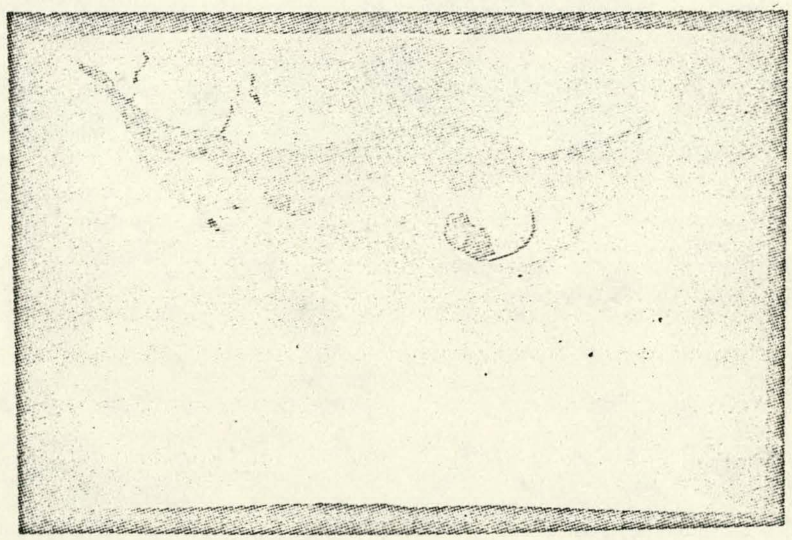
Radiographs

Photomicrographs

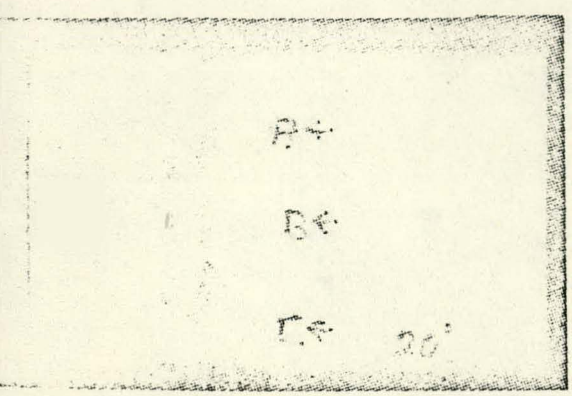


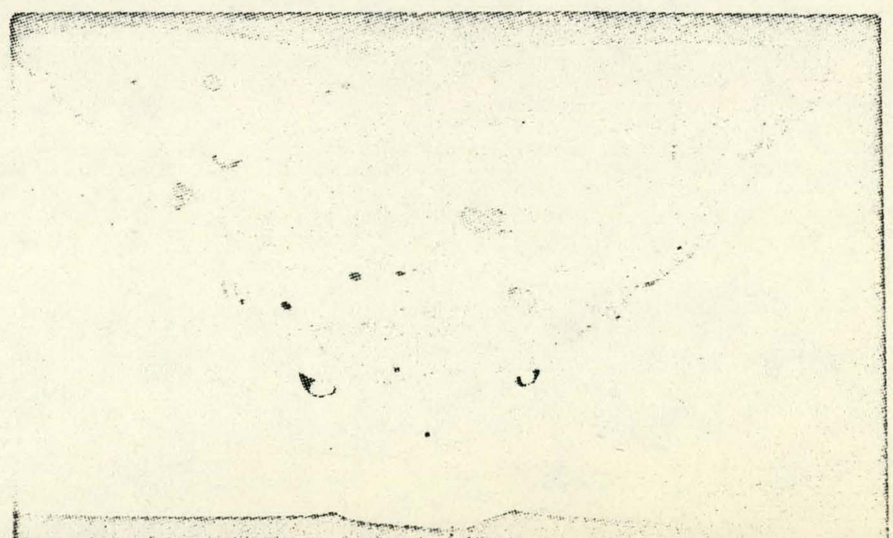


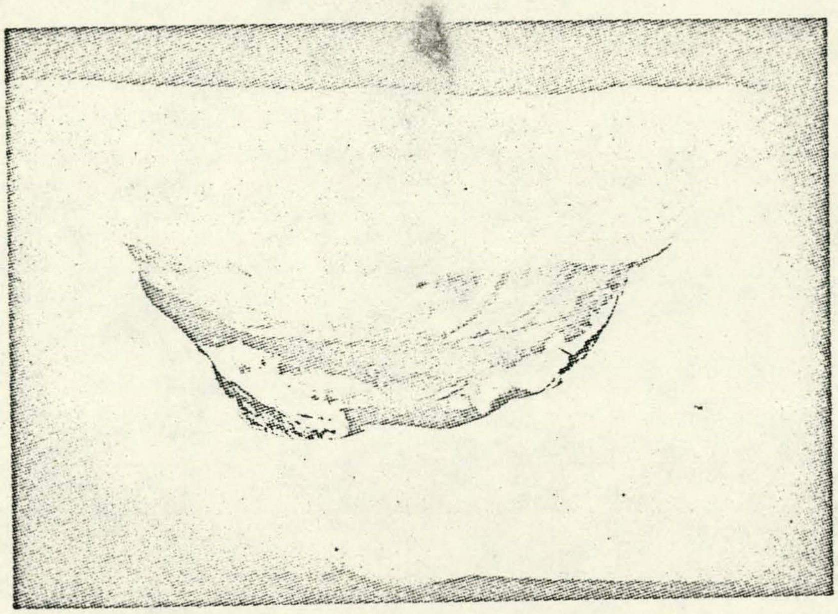
A. Test Weld No. 7
Total Acoustic Emission 426



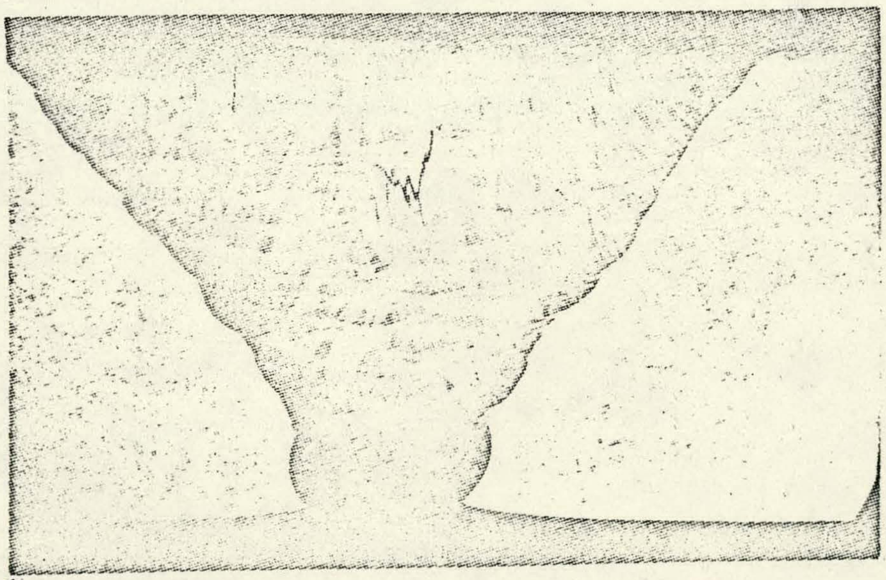
B. Test Weld No. 9
Total Acoustic Emission 466







A. Test Weld No. 14
Total Acoustic Emission 10300



B. Test Weld No. 11
Total Acoustic Emission 200

FIGURE 15. Welds Producing Acoustic Emission from Cracks that Were Not Detected by Conventional Radiographic Techniques.

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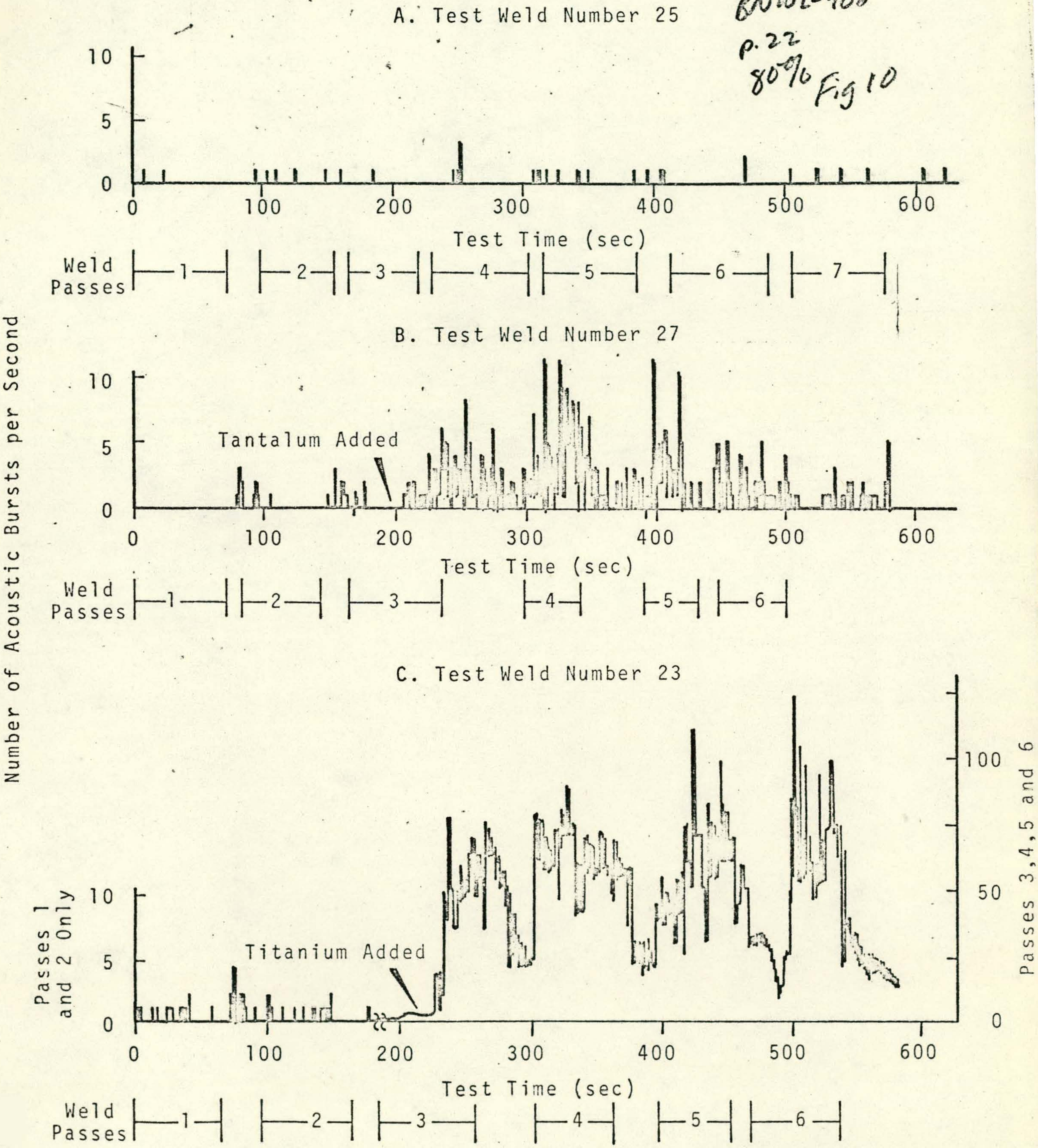
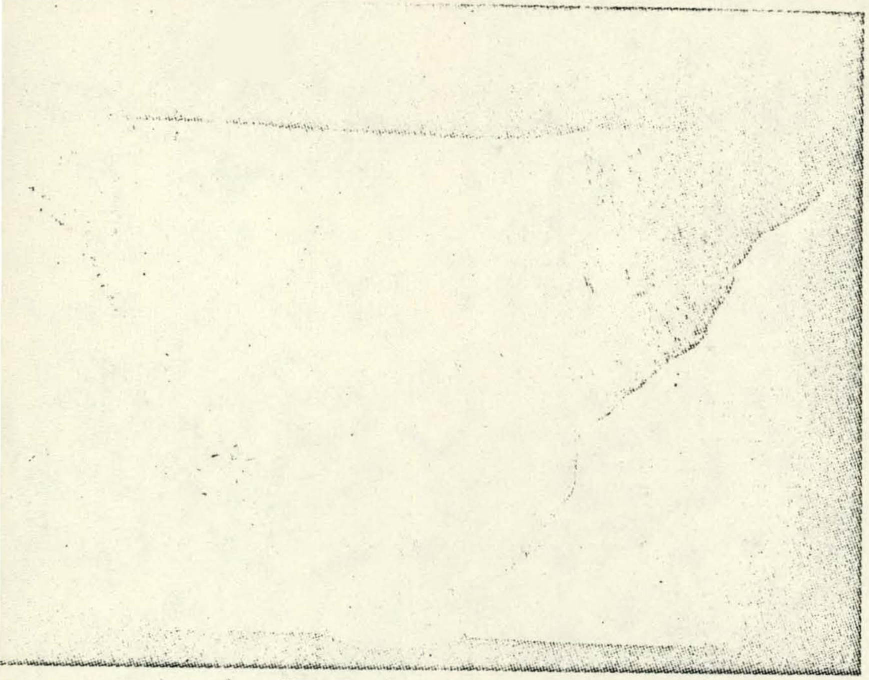
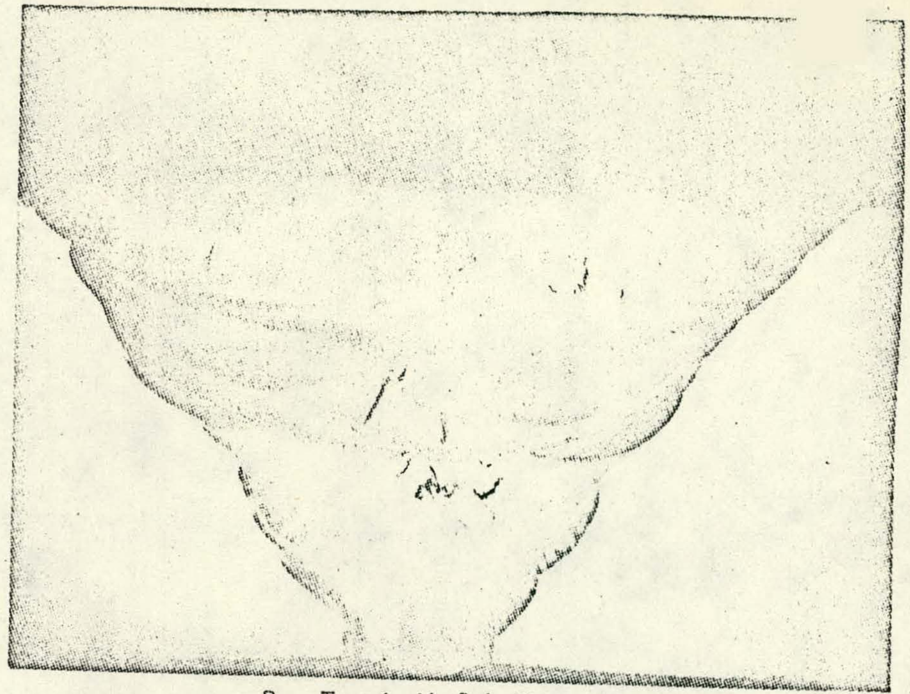
80%
Fig 10

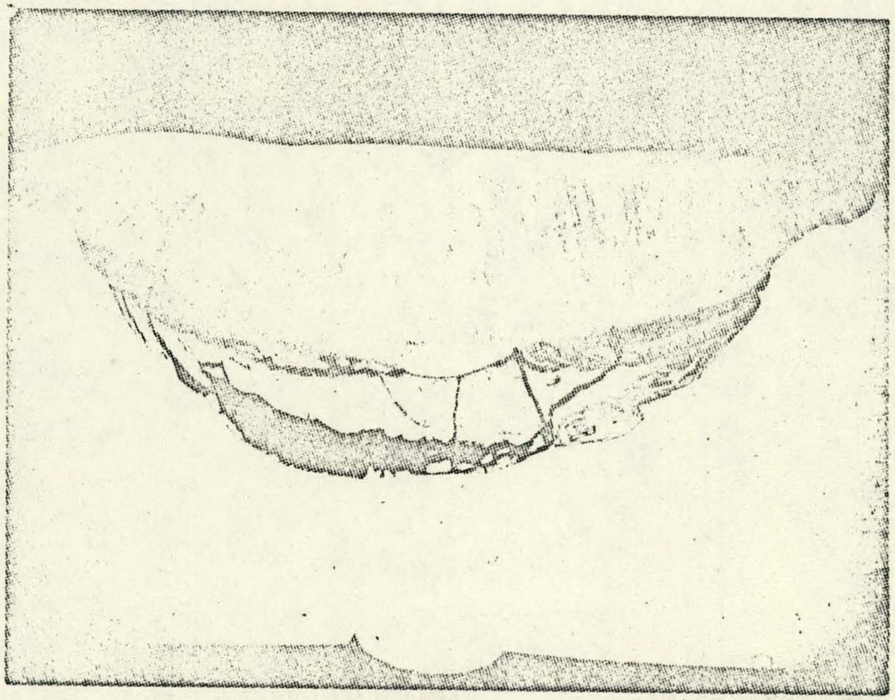




A. Test Weld No. 25



B. Test Weld No. 27



C. Test Weld No. 23

Fig 11
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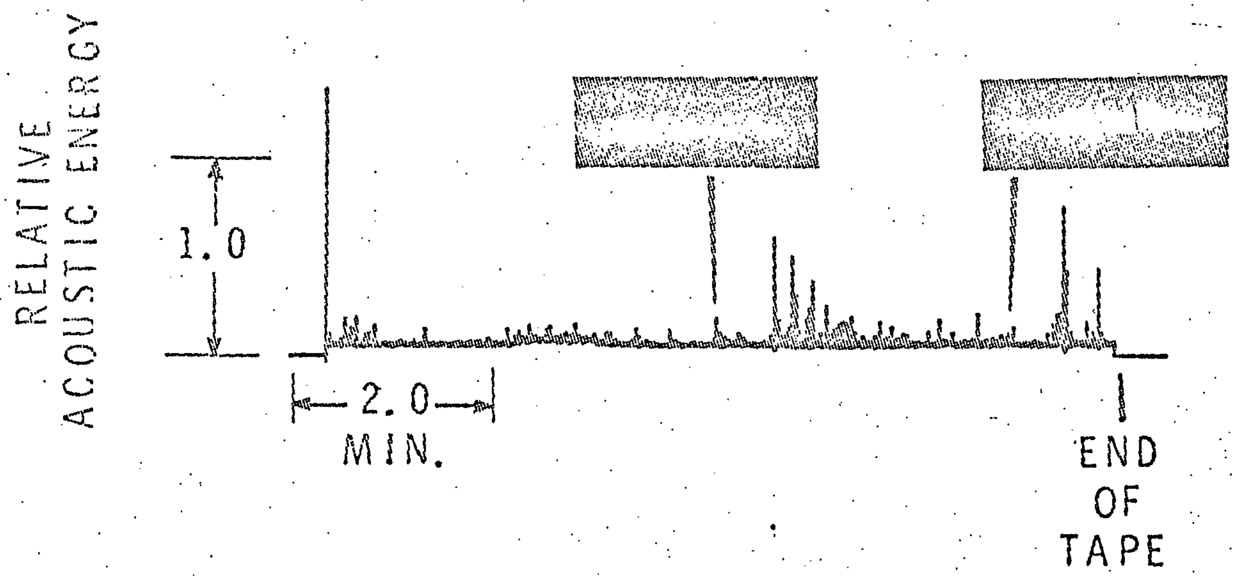
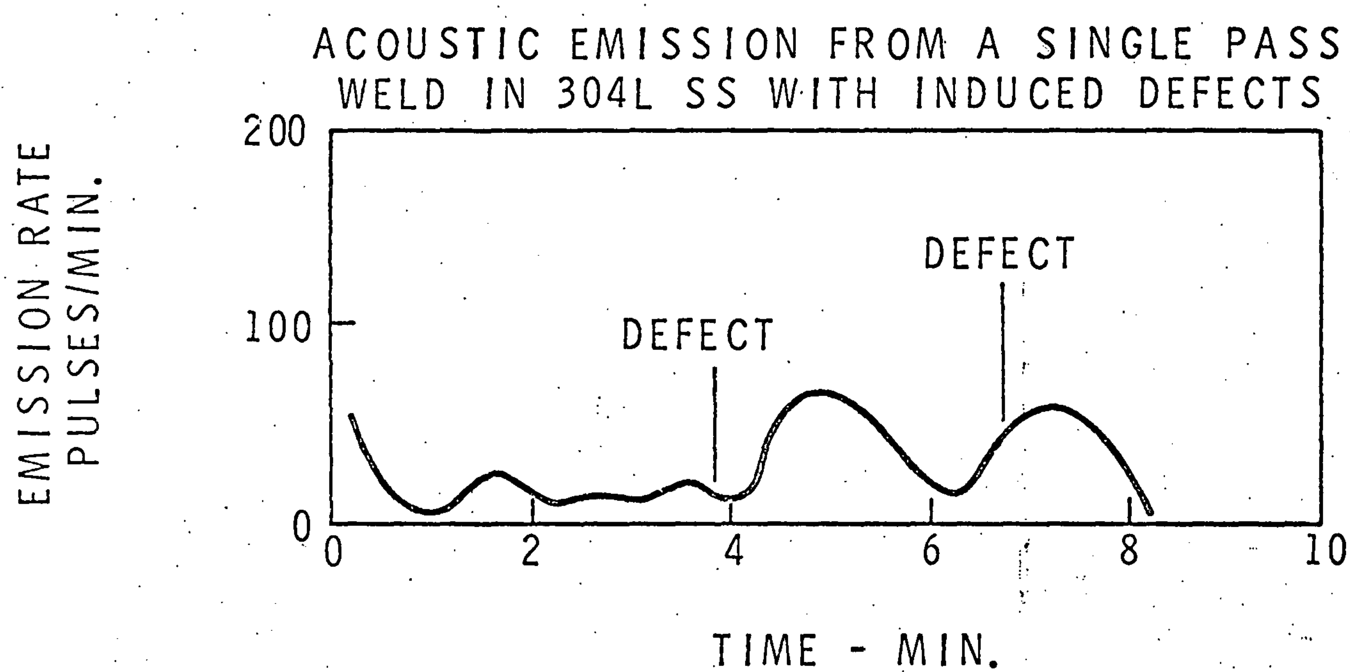
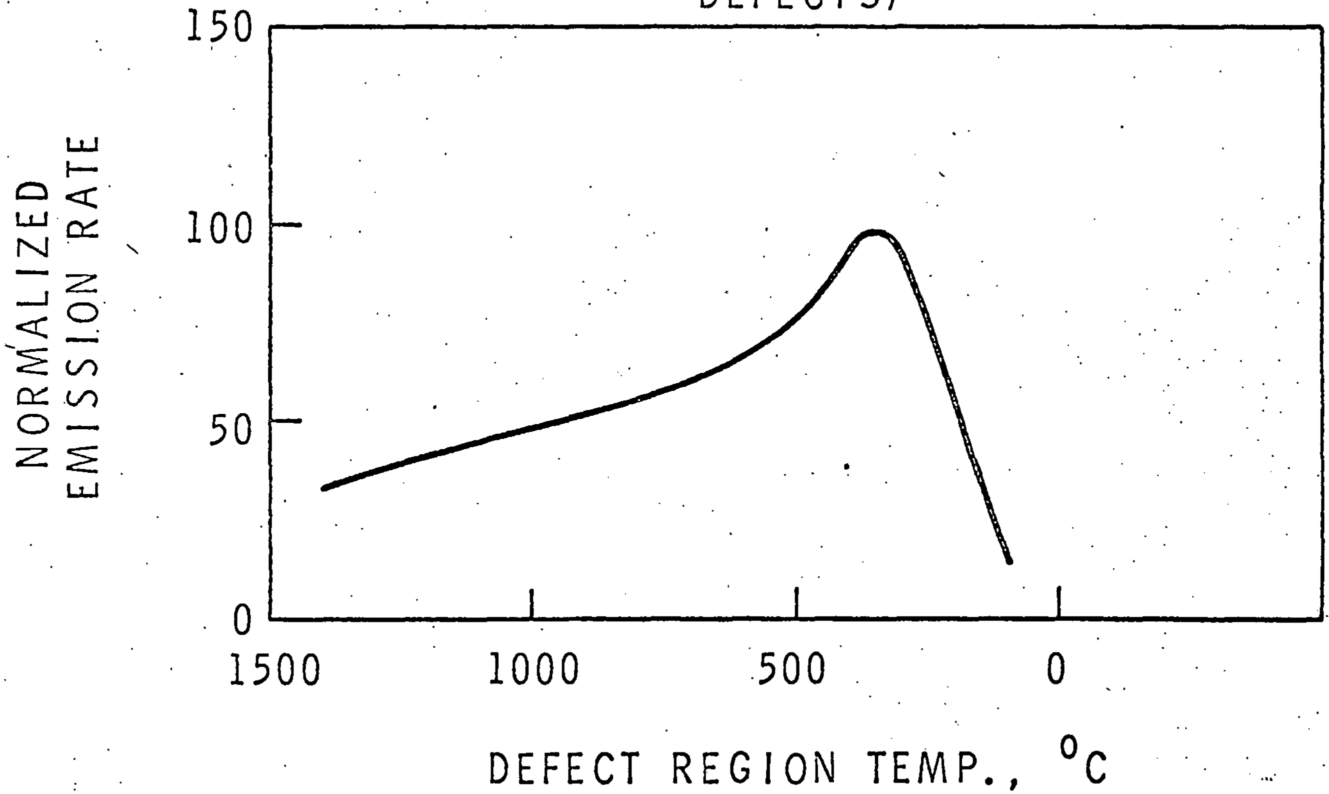
ACOUSTIC EMISSION FROM A SINGLE PASS WELD IN 304L SS WITH INDUCED DEFECTS

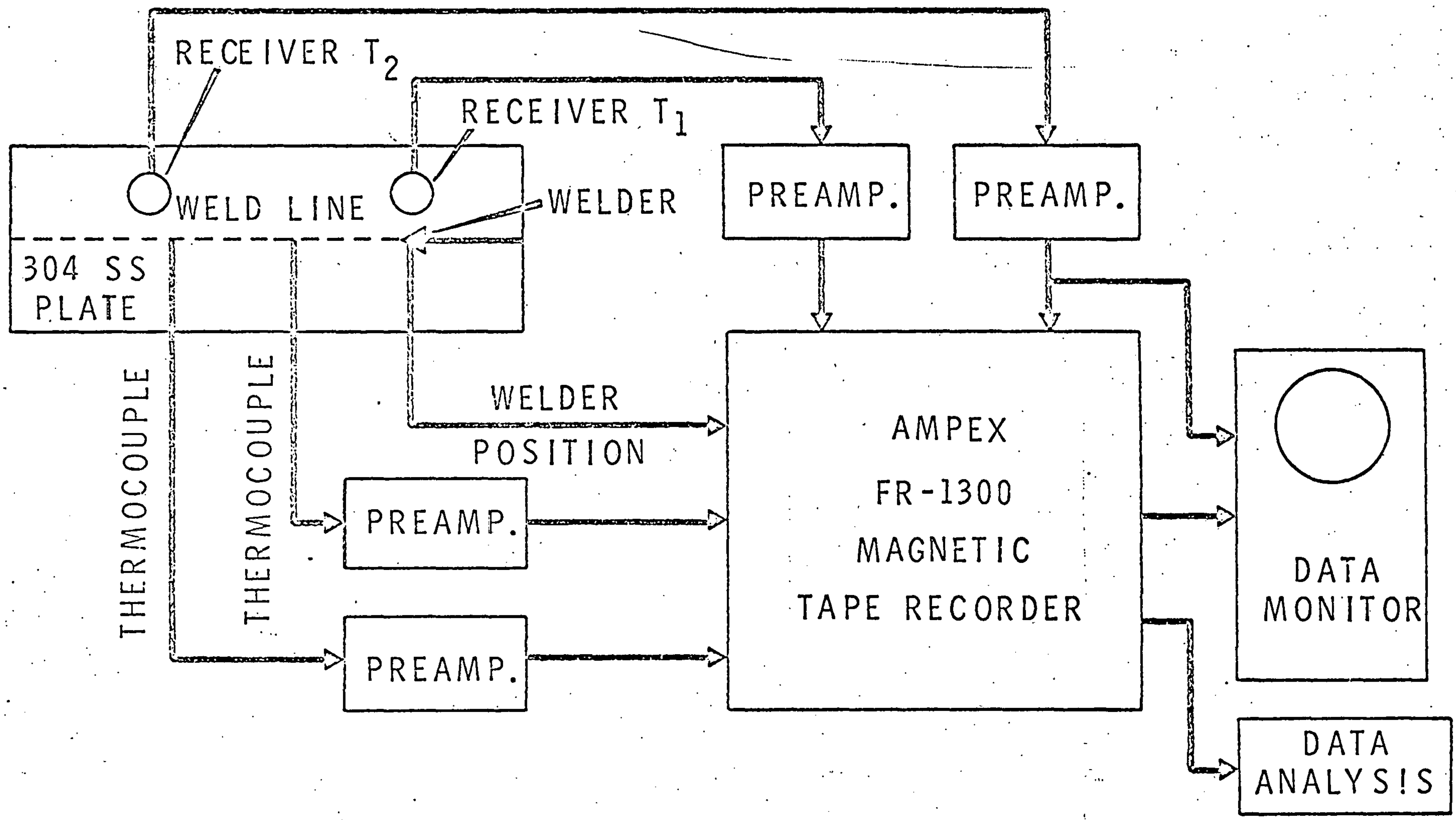



ACOUSTIC EMISSION FROM A SINGLE PASS
WELD IN 304L SS WITH INDUCED DEFECTS
EMISSION RATE
PULSES/MIN.
200
100
0
DEFECT
DEFECT
0
2
4
6
8
10
TIME - MIN.

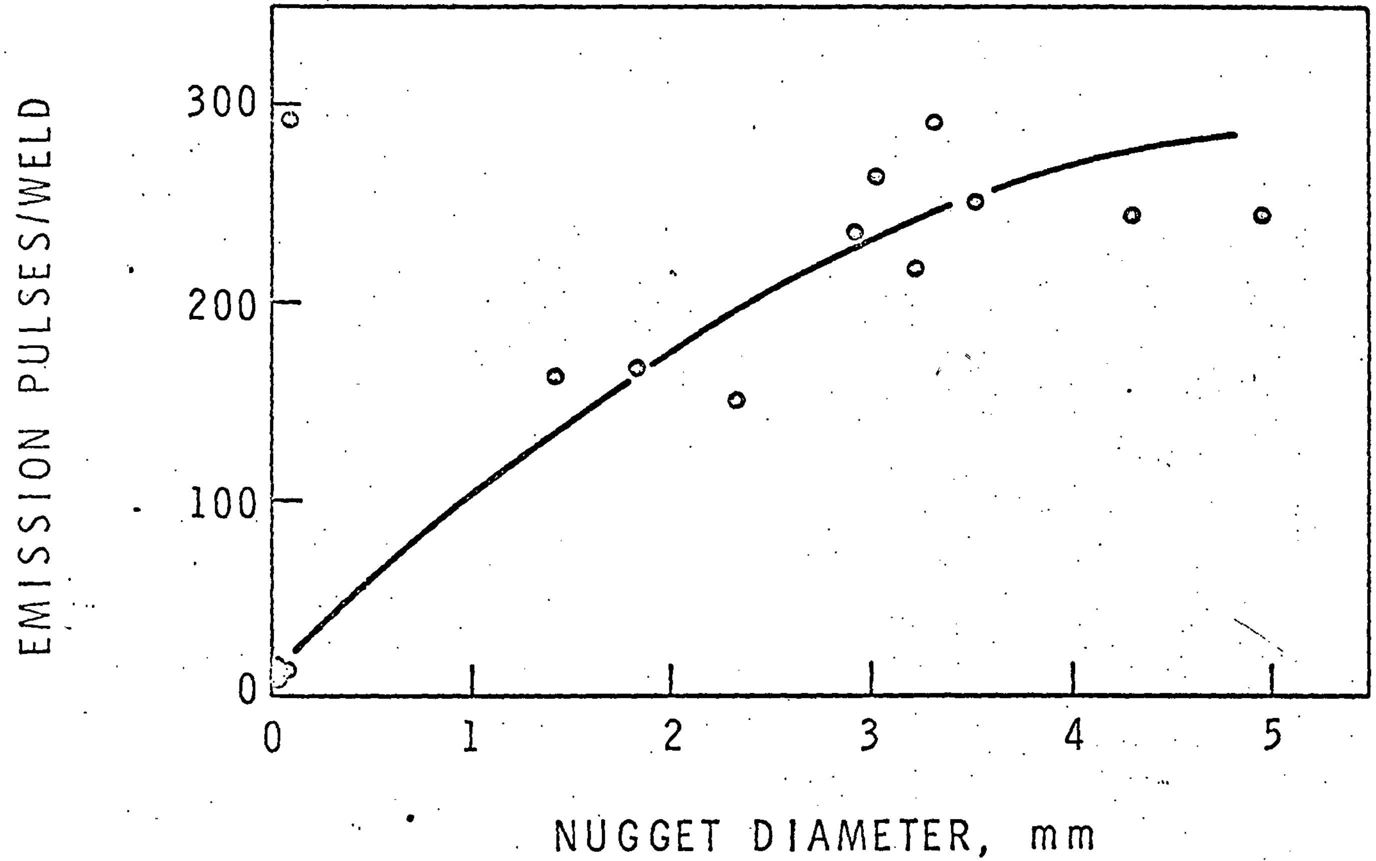
ACOUSTIC EMISSION RATE AS A FUNCTION OF DEFECT TEMPERATURE (AVERAGE OF 4 INDUCED DEFECTS)



ACOUSTIC EMISSION MONITORING SYSTEM



ACOUSTIC EMISSION AS A FUNCTION OF NUGGET DIAMETER - SPOT WELDS IN 6061 ALUMINUM



ACOUSTIC EMISSION RELATED TO BEAD CONFORMATION IN SUB-ARC WELD