In-Process Quality Detection of Friction Welds Using Acoustic Emission Techniques

Correlation is shown between total acoustic emission counts and weld strength

BY K. K. WANG, G. R. REIF, AND S. K. OH

ABSTRACT. A feasibility study was conducted to investigate the use of acoustic emission (AE) techniques for detecting the quality of friction welds during processing. For ferrous metal welds, it was observed that two distinctive bursts of acoustic emission took place, one occurring during the welding cycle and the other upon cooling of the welded specimen. A correlation between the total number of AE counts and the weld strength appears to exist. It seems likely that extension of this study could lead to the development of an in-process quality monitoring system based on the acoustic emission events.

Introduction

Friction welding is a solid state welding process. It makes use of the frictional heat generated at the rubbing surfaces to raise the temperature at the interface high enough to cause the two surfaces to be forged together under high pressure. Friction welding has been shown to have significant economic and technical advantages (Ref. 1). However, one of the major concerns in using friction welding is the reliability of the weld quality. No reliable nondestructive test method is available at present for detecting weld quality, particularly in a production environment. Efforts have been made to detect weld strength nondestructively using ultrasonic methods (Ref. 2). Unfortunately, the results were difficult to interpret; also, applications were limited to a certain weld geometry where side reflections of the ultrasonic wave were not significant.

This paper presents a new approach which attempts to develop an in-process quality monitoring method for friction welds by using acoustic emission (AE) techniques. In this investigation, the acoustic emission counts were measured during the welding process to correlate the weld strength for friction welds over a wide range of process conditions. Some preliminary results from an exploratory study are presented (Ref. 3).

Source of Acoustic Emission from Friction Welding

Acoustic emission is a phenomenon arising from a rapid release of strain energy within a material. Part of the energy radiates from the source in the form of elastic waves which can be detected at the material surface (Ref. 4). The major sources of acoustic emission can be mechanical, thermal, and metallurgical processes acting upon the material (Ref. 5, 6).

Friction welding takes place under heavy pressure and high temperature which result in large-scale plastic flow of material from the interface to form a flash. The frictional heating and subsequent forging and cooling stages of the welding cycle also cause changes in microstructure at the weld region. In this regard, it is well known that not only mechanical and thermal stresses (Ref. 7) but also microstructural changes may generate acoustic emissions; these include dislocation movement, creation and annihilation of vacancies and interstitial sites, development of slip lines and twins, initiation and running of cracks, and phase transformations.

The possible sources of acoustic emission activities described above apparently take place in friction welding as evidenced by a typical AE count rate trace (Fig. 1) generated during friction welding of two carbon steel rods. The AE bursts represented by zone "A" in Fig. 1 are primarily attributable to the large amount of plastic deformation during the welding process.

Figure 2 shows the typical processing characteristics of inertia welding (one type of friction welding) which was used for this investigation. In the initial stage I, the axial displacement increases rapidly as the surface asperities are quickly deformed and compacted under high pressure. The displacement continues to increase in stage II; however, it continues at a much slower rate until the temperature at the interface reaches such a high level that a large amount of material flows out of the weld region by the forging action taking place in stage III. The plastic deformation generates a burst of acoustic emission as a result.

As the welding process ends, the material at the weld interface typically reaches a maximum temperature of over 1,300°C (Ref. 8) i.e., 2,372°F; however, it is subjected to immediate cooling, primarily through heat conduction. A second burst of acoustic emission takes place after a brief pause of a few seconds. This AE activity as indicated by zone "B" in Fig. 1 lasts much longer than the previous one.
Fig. 1 — A typical acoustic emission trace obtained from inertia friction welding of steel bars

Fig. 2 (right) — Characteristics of the process parameters in inertia friction welding

Since all mechanically induced sources of stress waves are halted at this stage, the acoustic emission events presumably originate from thermal and metallurgical property changes. Upon cooling, the high temperature gradient around the weld and the heat-affected-zone results in thermal stresses. For carbon steels, it is known that an active acoustic emission could emerge if martensitic transformation takes place (Ref. 9, 10).

Experimental Setup and Procedures

The welding experiments were carried out on a flywheel-type inertia friction welding machine. Figure 3 is a block diagram showing all major components used in the experimental setup. The welding machine is driven by a hydraulic motor having a maximum speed of 4,500 rpm.

The rotating speed can be preset on an analog speed control dial on the machine control panel. In the meantime, a digital readout displays a more accurate spindle speed from a digital tachometer using a magnetic pickup. An analog tachometer-generator is also attached to the rotating chuck to provide a continuous speed trace recorded on an oscillograph. A linear variable differential transformer (LVD) and a piezoelectric load cell are used to monitor the axial displacement and thrust force, respectively; both traces, along with the speed, are recorded simultaneously on a Honeywell Model 1858 graphic data acquisition system.

The blocks exhibited at the bottom part of Fig. 3 represent a Dunegan/Endevco model 3000 acoustic emission analyzing system. The signals, coming from a transducer mounted, either on the stationary chuck or directly on the workpiece, are recorded on an X-Y plotter.

Fig. 3 — Block diagram for the experimental setup including all major components of instrumentation
The plot could be either in the form of the rate of AE counts or accumulated total number of counts. The instrument also has a digital readout which could be used for displaying either number. Since the acoustic emissions originated from a large variety of sources covering a wide spectrum of frequency range, a Dunegan Model 9203 high sensitivity transducer was selected along with a Model 801P preamplifier to provide a system gain of about 75 dB.

Two sets of workpiece materials and joint configurations of the weld were selected, as shown in Fig. 4, for most of the experiments. The hexagonal section bar was used to prevent the workpiece from slipping over the jaws on the chuck which may generate additional but undesirable acoustic emissions. On the other end of the weldment, a square bar was chosen for the convenience of mounting the AE transducer. However, both ends to be welded were faced and turned down to the same diameter of % in. (9.5 mm) to ensure consistency of the mating surface geometry.

In the case of tube-to-tube joint, the tube ends were machined before welding. For tensile test, weld flashes were first removed and a narrow groove with a radius of 0.025 in. (0.64 mm) was machined at the weld interface so that fracture would occur at the interface to reflect the real weld strength.

To ensure proper measurement of AE events, a thin layer of Dow-Corning's high vacuum grease was applied to the transducer surface for good coupling. Another set of experiments was performed to determine the effect of the location where the AE transducer was mounted.

As shown in Fig. 5, the location testing indicated that the general characteristics of the AE events during welding with the transducer mounted at two different locations remains essentially the same. The transducer was first mounted on the stationary workpiece (1.5 in., i.e., 38.1 mm, from the weld interface) and then moved to the holding jaw, 2.12 in. (53.8 mm) away from the weld interface. The apparent net effect was that the overall magnitude of the total AE counts (presented by the area under the curve) was slightly smaller. This is presumably due to the acoustic impedance of the material when the stress wave has to travel through a longer path and across an interface between the workpiece and the jaws.

Approximately 200 sample welds were made at a variety of welding conditions to aid in selecting proper materials, test conditions, frequency window for the AE monitoring system, and selection of suitable AE transducer. To help identify the sources of acoustic emission, six grades of plain carbon and alloyed steels were used as workpiece material with carbon content varying from 0.0% to 0.38%.

Two nonferrous materials, aluminum and copper, were also included in the experiments in order to see the different effect of ferrous and nonferrous metal welds on acoustic emission. Further, a set of quenching experiments was performed on all six ferrous metals and two nonferrous metals to examine AE events. Specimens were heated to over 900°C (1652°F) using an oxyacetylene torch on one end with an AE transducer mounted on the other; they were immediately quenched in water, oil, or cooled in the air to see the effect of different cooling rates on acoustic emission.

Results and Discussion

The initial weldments were made with mild steel bar stock to aid in establishing
The total kinetic energy decreases as the initial rotating speed increases. For a constant amount of inertia and thrust force applied, the area of B-zone decreases as shown in Fig. 7.

Figure 8 is a plot of all data obtained from the SAE 4140 to 1215 cold-drawn steel bar-to-bar welds. In the experiments, the inertia and the thrust force were kept unchanged at 5.6 lb-ft² and 2,000 lb respectively, while spindle speed varied from 1,200 to 2,200 rpm. Each set of conditions was repeated five times for the purpose of examining the experimental error and gathering statistics.

From the plot of Fig. 8, it seems evident that a definite correlation exists between the total AE counts resulting from B-zone and the tensile force required to break the weld. However, the spread of data, particularly at the spindle speed of 2,000 rpm, is quite appreciable which accounts for experimental error.

It is interesting to note that a similar trend was reported by Jon et al. (Ref 11, 12) when the AE techniques were applied to test resistance spot welds of nonferrous metals for weld strength. In fact, the spread of data in the case of spot welding was much greater than that obtained in this study. Of course, spot welding causes melting and solidification of the material at the weld; the phase transformation characteristics of nonferrous metals are also different as reflected in acoustic emission activities.

A large number of weldments were made with ferrous and nonferrous metals under various welding conditions in two joint configurations (bar-to-bar and tube-to-tube). The specimens were either pull-tested for tensile strength or examined microscopically. Micrographs and Knoop hardness tests of quenched specimens were compared with those of friction weldments.

Figure 9 is a plot of Knoop hardness measured on the center axis and near the outer radius of the specimen for the quenched and welded specimens, respectively. It can be seen that for the 1117 steel bar, there is no appreciable increase in hardness on the quenched specimen while the hardness at the weld interface is about doubled as a result of strain-hardening. On the other hand, the hardness near the interface of the 4140 steel bar is doubled for the quenched specimen, and almost tripled for the welded specimen. This is apparently attributed to the combined effect of quenching and strain-hardening.

An important finding of this study is that the AE counts represented by the
second distinctive region (B-zone) during friction welding are most likely due to the mechanism of martensitic transformation. This transformation apparently occurs in friction welding of steels when they cool down from the high forging temperature to room temperature a few seconds after welding is completed. Although the mechanisms and conditions for generating acoustic emission during martensitic transformation in steels are much more complex (Ref. 10), the following observations tend to substantiate the interpretation:

1. Neither significant B-zone AE activities have been observed for friction welding of aluminum and copper, nor have AE counts been realized in the case of quenching these materials.
2. The size of B-zone of the steel welds is affected by the carbon content and alloys of the materials used which also dictate the magnitude of AE counts from the welds.
3. Martensitic microstructure is very noticeable throughout the weld region on the 4140 steel side which is also reflected in much higher hardness in this region.

Conclusions

As a result of the exploratory study described in this paper, the following preliminary conclusions can be drawn:

1. For a satisfactory friction welding of ferrous metals, there are two distinctive bursts of acoustic emission; one occurs during the welding cycle (A-zone) and the other (B-zone) starts a few seconds later after the welding is completed. The initial AE burst is primarily attributed to plastic deformation of the material while the second AE event, usually greater in magnitude, is interpreted as a result of martensitic transformation.
2. A definite correlation seems to exist between the total number of AE counts and the strength of friction welds of steels. A quantitative relationship could be established subject to further reduction of the experimental errors.
3. With proper selection of transducers and other components, an acoustic emission monitoring system could be developed for detecting the quality of friction welds of ferrous metals during the process.

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References


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High Temperature Properties of 2-1/4Cr-1Mo Weld Metal
by C. D. Lundin, B. J. Kruse and M. R. Pendley

The determination of the creep rupture properties of 2-1/4Cr-1Mo weld metal is necessary because of the paucity of data available. This document represents the initial reporting on the current efforts at the University of Tennessee.

Stress rupture testing of 2-1/4Cr-1Mo weld metal was conducted at three temperatures: 850, 950 and 1050°F. The weld metals tested were deposited by the submerged arc process and the electroslag process.

Subsequent phases of this program will more fully characterize the influence of welding process-procedure on the elevated temperature properties of 2-1/4Cr-1Mo weld metal.

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