Vibrational Residual Stress Relief in a Plain Carbon Steel Weldment

Vibratory treatment of a welded, symmetrical, mild steel plate specimen significantly reduced residual stresses due to welding. Applications and limitations to real structures are discussed

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ABSTRACT. Residual stress relief of metals by resonant elastic vibrations has been reported to be as effective and more convenient than the customary thermal treatments. In the present work, attempts were made to reduce the residual stresses due to circumferential welding in a disc shaped test sample of a plain carbon steel (AISI 1018). The magnitudes and the distribution of residual stresses in samples that were vibrated and not vibrated were determined by a modified Sachs boring-out technique. Results show that high strain amplitude vibrations do significantly lower the residual stresses in areas of high residual stress. In areas outside the areas of high residual stress, the residual stresses may be reduced or not affected. Implications for the use of vibrational stress relief are discussed.

Introduction

Deleterious residual stresses are introduced into many metal structures and components during their fabrication. Welding produces particularly severe residual stresses, generally of the order of the yield stress in the region of the weld. In many situations removal or at least significant reduction of these stresses is necessary for satisfactory functioning of the structure. Buckling of slender beams, stress corrosion cracking, fatigue failure of some metals, and lack of dimensional stability have often been strongly influenced by welding residual stresses.

The commonly used method of residual stress reduction has been a thermal stress relief cycle. The metal structure is heated to a relatively high temperature where the creep strength of the material is low. Creep relaxes the elastic strains to values much below that characteristic of the high temperature yield stress. This type of stress relief, while usually effective, has several drawbacks. The cost is high, the process is time consuming and frequently it results in deterioration of material properties due to microstructural changes or atmospheric attack. Its use is also restricted to homogeneous structures.

The use of vibrational stress relief techniques (Refs. 1-3) has been reported to be equally effective as that of thermal stress relief with none of the above drawbacks. However, results using these techniques have generally been reported as inconsistent, qualitative in nature, and, more often than not, established by inference. There has been little direct quantitative measurement of the effect of vibration on residual stress. A. L. Esquire and K. R. Evans (Ref. 2) found that residual stresses on a small shot peened specimen (AISI 4130) were reduced moderately after cycling at 50 to 70% of the fatigue limit. Tests were performed on a similar shot peened samples by Wozney and Cramer (Ref. 1). They concluded that for any stress relaxation to occur the combined stress level (residual plus vibrational) would have to exceed the cyclic elastic limit. Applying their techniques to a larger welded structure they found no stress relaxation at the limited number of points of measurement used. Strachan (Ref. 3) reported 80% stress relief by vibration in a low carbon mild steel.

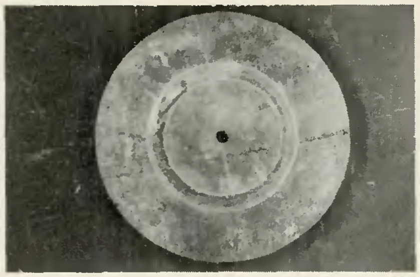

Fig. 1 — As-welded test plate

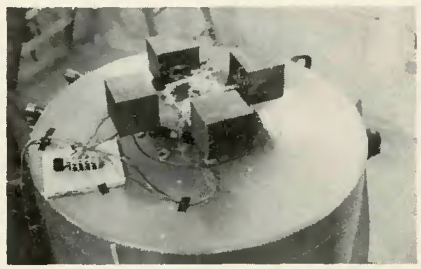

Fig. 2 — Welded sample plate with weights mounted on vibrator

Table 1 — SAW Welding Parameters

Current	285 A, ac
Voltage	50 V
Electrode	1/8 in. Lincoln L-61
Flux	Linde #85
Stickout	1 in. to contact tube
Speed	28.5 ipm
Travel angle	zero (perpendicular)
Penetration	86%

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Table 2 — Mechanical Properties of Base Metal and Weld Metal

Property	Base metal	Weld metal
0.2% yield stress, psi	29,000	34,000
Ultimate tensile stress, psi	49,000	51,000
Hardness (R_B)	84.2	—

Table 3 — Summary of Vibrational Test Data

Plate no.	Frequency hertz	Vibration time, min	Amplitude tangential stress, psi	Vibration[a] radial stress psi
5	137	15	40,100	19,560
	133	15	31,200	14,100
	166	15	24,700	12,300
8	134	30	20,800	13,400
	120	15	17,300	22,600

(a) Assuming completely elastic straining

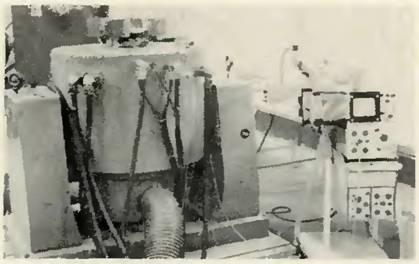

Fig. 3 — Overall view of vibrational test equipment

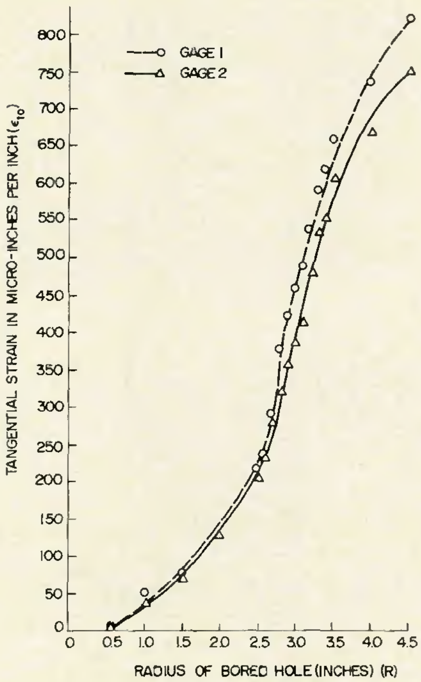

Fig. 4 — Tangential strain (ε_{to}) versus radius of bored hole (R) measured for plate No. 7

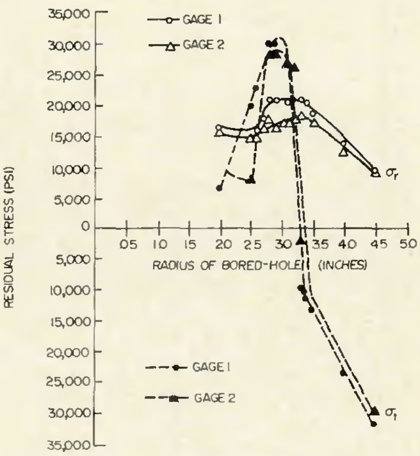

Fig. 5 — Residual stress pattern, measured in plate No. 7, welded and unvibrated

The above investigations do not clearly specify the conditions necessary for effective vibrational stress relief. More quantitative data of the results of measuring the complete stress pattern is needed rather than determination of the stress at only one or a few points. In the present investigation vibrational stress relief was measured on 12 in. diam by 1/2 in. thick mild steel (AISI 1018) plates containing a 6 in. diam circumferential submerged arc bead weld pass. The stress field in the plane of the plate was determined by a modified Sachs boring-out technique (Refs. 4,5).

Experimental Method

Test Samples

Test samples used in this investigation were 12 in. diam by 1/2 in. thick disks of a low carbon steel (AISI 1018). Each disk was flame cut from a plate, a 1/2 in. hole was bored in the center, and the flame cut edge was removed in a lathe. A 1/2 in. wide by 1/4 in. deep "V" groove 6 in. in diam was machined in the plate and filled with a single pass submerged arc weld (See Fig. 1). Welding parameters are shown in Table 1.

Results from tensile tests on weld metal and on base metal are given in Table 2.

Vibration

The samples were vibrated on a large laboratory shaker which allowed continuous variation of frequency and amplitude. The plate was bolted to the shaker table through the 1/2 in. hole in the center. Four 25 lb weights were spaced equally around the perimeter of the disk to lower the resonant frequency in flexural vibrations to one compatible with the frequency range of the shaker (5 to 5000 hertz). Figure 2 shows a sample mounted and ready for vibration; Fig. 3 is an overall view of the shaker and mounted sample.

Dynamic strain amplitude at the weld was monitored by a strain gage mounted on the bottom of the test plate just below the weld. The driving frequency was adjusted to give maximum vibratory stress at the weld. Strain levels obtained and the times of vibration are given in Table 3 for each test disk. The stresses are calculated assuming completely elastic strain with the normal elastic modulus. Obviously the higher reported values represent partial plastic straining and the actual stresses are lower.

Residual Stress Measurements

The residual stresses were measured using a modified Sachs boring-out technique. This method of measurement, first used by Adams and Corrigan (Ref. 4) and refined somewhat by Cepoline and Cananico (Ref. 5) allows continuous determination of the magnitudes of residual stresses as a function of radius in circular plates. Measurement of strains at the perimeter of the plate, as successive circular sections of the disk are removed from the center, allows calculation of the residual stresses in the material removed. Assuming:

1. the material is homogeneous and isotropic,
2. stress components in the thickness direction may be neglected, and
3. the stress system possesses circular symmetry,

the residual stress at a radius R can be related to change in strain ε_{to} at the perimeter of the plate by (Ref. 5):

$$(\sigma_r)_R = \frac{E\varepsilon_{to}}{2}\left(\frac{R_0^2}{R^2} - 1\right) \qquad (1)$$

where:

ε_{to} is the total change in strain reading taken at the outer perimeter when the radius of the bored hole is R.

R_0 is the outer radius of the plate.

E is Young's modulus.

$(\sigma_r)_R$ is the radial component of the residual stress at R.

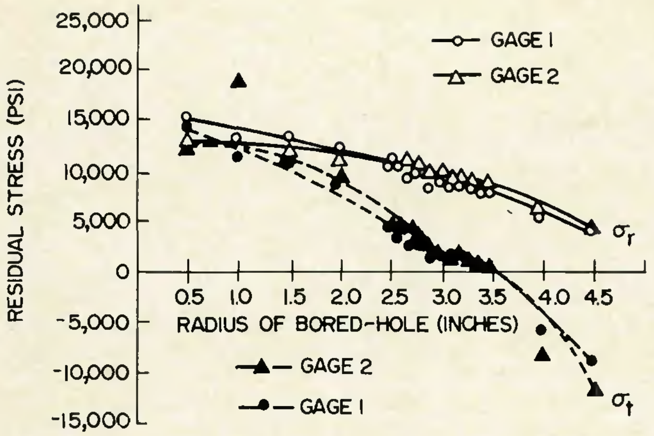

Fig. 6 — Residual stress pattern measured in plate No. 5, welded and vibrated

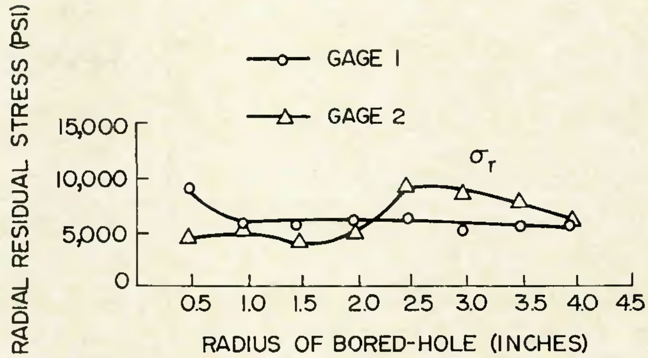

Fig. 7 — Radial residual stress, measured in plate No. 2, unwelded and not vibrated

The tangential component at R is then given by:

$$(\sigma_r)_R = \frac{d(R\sigma_r)}{dR} = \sigma_r + \frac{R\,d\sigma_r}{dR} \tag{2}$$

In this investigation a smooth curve was drawn through the ε_{to} vs R data points and σ_r and σ_t are calculated from the above equations.

Strains on the perimeter of the test plate were measured by means of two strain gages mounted 90 deg apart. Gage 1 was located adjacent to the arc-stop position, and gage 2 at 90 deg from gage 1.

Experimental Results

In all, eight experimental plates were prepared for testing. Disposition of these plates is given in Table 4.

Figure 4 shows the ε_{to} vs R data points for both strain gages on plate No. 7 (welded but not vibrated). Similar data was obtained for all specimens analyzed in Table 4. Values of σ_r and σ_t were calculated from the continuous curve fit to the raw data. Plots of σ_r and σ_t are given in Fig. 5. Data generally below R equal to 2 inches shows considerable scatter and are not reported.

Vibrating a welded plate results in considerable decrease in the residual stress levels. Such vibration completely removes the peak in tangential stress which approached yield stress levels near the weld center line. Figure 6 shows the residual stress pattern for plate No. 5. This plate had been welded and then vibrated for a total of 45 minutes. Results can be compared against a control plate (plate No. 2) which has been neither welded nor vibrated as shown in Figs. 7 and 8. Duplicate specimens were prepared and analyzed in the "welded only" (plate No. 4) and in the "welded and vibrated" (plate No. 8) conditions. Results are presented in Figs. 9 and 10.

A summary of the residual stress

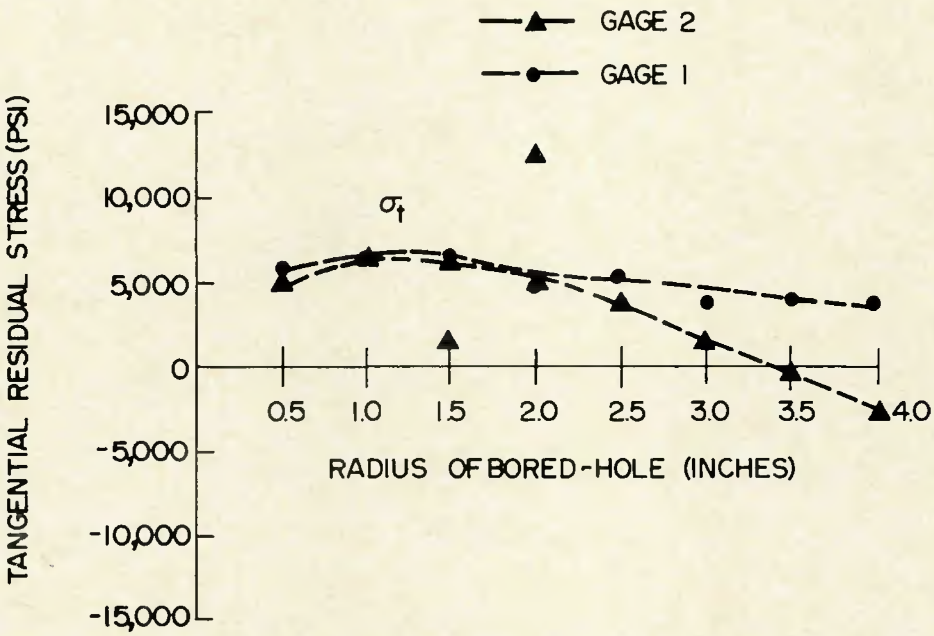

Fig. 8 — Tangential residual stress, measured in plate No. 2, unwelded and not vibrated

patterns of the plates processed in all conditions which were analyzed are shown in Figs. 11 and 12. These summary curves illustrate the effect which vibratory stresses have on reducing welding residual stresses and the excellent reproducibility of the effect.

Discussion of Results

The results of this investigation have demonstrated conclusively that the application of high amplitude vibrations to a low carbon steel weldment significantly reduces peak residual stresses in the weldment. Vibrations smooth out the residual stress distribution, removing the localized high stresses due to welding. Care should be exercised however in extrapolating the results to other materials until further research has been performed.

It is to be expected that not all materials will react to vibratory

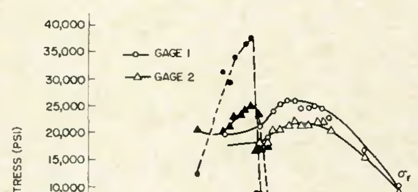

Fig. 9 — Residual stress pattern, measured in plate No. 4, welded only

stresses in a manner similar to low carbon steels. This follows directly from a consideration of the variable effect of residual stresses on fatigue in various materials systems. Clearly, the cyclic stresses present in a high frequency fatigue test are identical in nature to the stresses present in a vibrating sample. One would expect those materials which show a significant effect of residual stress on the fatigue life to exhibit a lesser susceptibility to stress relieving by vibrational techniques. If vibrations could remove the residual stress, the residual stress would be reduced early in the fatigue test and not remain to affect the fatigue strength. Conversely, those materials which show little dependence of fatigue strength on residual stress levels, are good candidates to react to vibrational stress relieving.

Residual stresses are a result of "internal misfit" in the structure, i.e. some area of the structure is too small or too large for the structure. In a weldment, the weld metal, solidifying under zero stress, becomes much too short for the surrounding material as it cools down. Reduction of the "internal misfit" stresses can be accomplished only by changes in the dimensions of the overall structure which then remove the "misfit." Either the "misfitting" part changes dimensions to accommodate the rest of the structure, or the remainder of the structure changes dimensions to accommodate the "misfitting" portion. In either case, plastic deformation in an appropriate region of the structure removes the origin of the residual stress which is the condition of "internal misfit."

Since the "misfits" involved are small (strains are elastic) one needs only small plastic strains ($\varepsilon \approx 10^{-3}$) to significantly lower residual stresses. Baker and Carpenter (Ref. 6) have shown that the application of vibratory stress decreases the flow stress of metals by amounts comparable to the amplitude of the vibratory stress applied. Thus, during the half cycle in which the vibratory stress adds to the residual stress, those areas in which the sum of the residual stress and vibrated stress exceeds the yield stress, the material plastically deforms in a manner that results in lowering of residual stress.

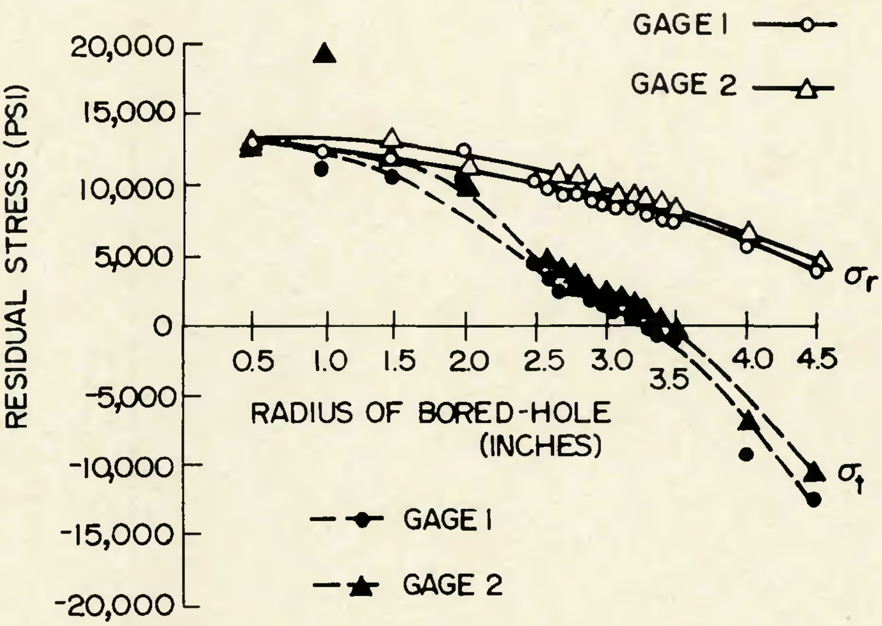

Fig. 10 — Residual stress pattern measured in plate No. 8, welded and vibrated

Conclusions

The application of vibratory stresses to a mild steel weldment has proven effective in substantially reducing the high residual stresses introduced by welding.

Successful industrial application of vibrational stress relieving involves satisfactory compliance with various requirements among which are:

Table 4 — Summary of Testing

Code	Disposition of plate
1	Welded, metallography
2	Not welded, not vibrated, analyzed
3	Welded, metallography
4	Welded, not vibrated, analyzed
5	Welded, vibrated, analyzed
7	Welded, not vibrated, analyzed
8	Welded, vibrated, analyzed
9	Not welded, not vibrated, analyzed

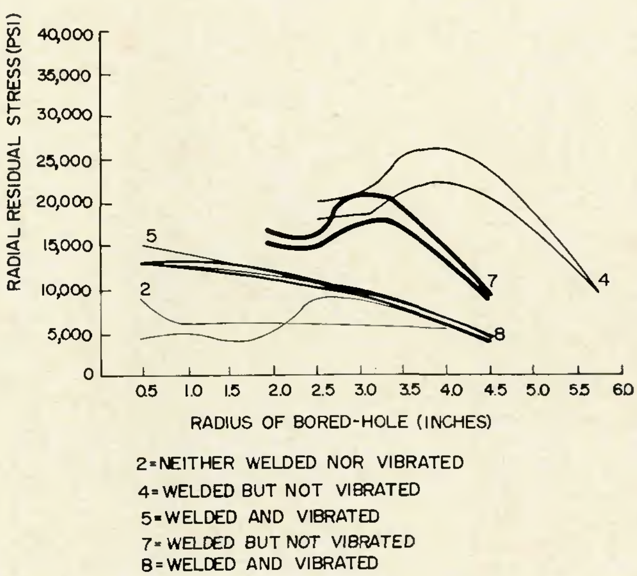

Fig. 11 — Summary of radial residual stress patterns, measured for the three test conditions

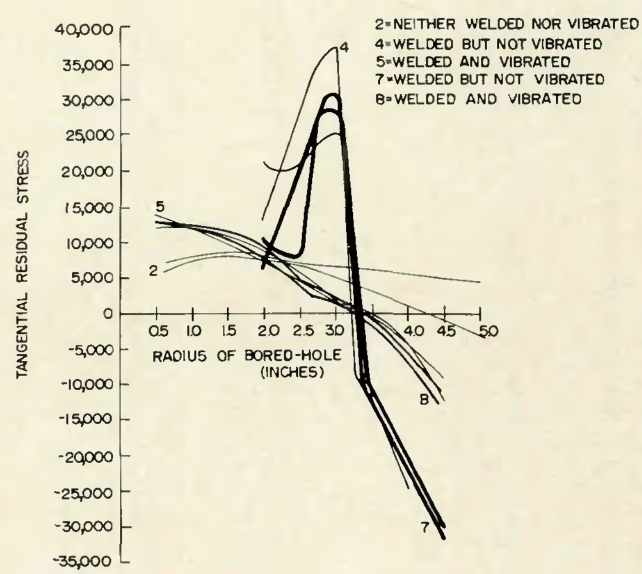

Fig. 12 — Summary of tangential residual patterns measured for the three test conditions

1. A relatively simple geometry and the application of multiple modes of vibration are necessary to allow all areas of the structure to experience high vibrational amplitudes. The use of additional strategically located weights can control nodal patterns and result in resonant frequencies suited to the application.

2. Large amplitudes of vibration with stresses of the order of the fatigue limit of the material appear to be necessary in order to relax the major portion of even the most severe residual stresses.

3. The material must be of a type susceptible to vibrational stress relief. It appears that lower yield strength materials capable of large amounts of microstrain below the yield stress would be most susceptible to vibrational stress relief.

Obviously many industrial candidates for stress relief cannot satisfy all of the required criteria. The structures may be so irregular and complicated that it would be difficult to apply resonant vibrations that will provide high stresses to more than a limited area of the structure. Simple structures possessing uniform cross-sections such as rings, plates and bars are excellent candidates for vibrational stress relieving. As the complexity of the structure increases, successful vibrational stress relief becomes more difficult.

Acknowledgments

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Correction

In the paper starting on page 28-s of the January issue, "Weldability of a New High Strength Low Alloy Cast Steel," the initials for author L. C. Minard are incorrectly given as D. L. in the Table of Contents and as L. D. in the title page; Table 4 which shows silicon as 40 should read .40; the macrographs over the Fig. 4 and Fig. 5 captions were transposed and should be reversed, captions remaining as set.

WRC Bulletin 206 — June 1975

"Effects of Porosity on the Fatigue Properties of 5083 Aluminum Alloy Weldments"

by F. V. Lawrence, Jr., W. H. Munse and J. D. Burk
of the University of Illinois

The current study is an inquiry into the effect of distributed porosity on the fatigue resistance of 5083 double-V butt weldments subjected to a constant amplitude, 0-tension stress cycle. Porosity levels were recorded by normal incidence radiography prior to testing and measured directly on the fatigue fracture surfaces. This study is an extension of a previous study of the effects of porosity on the tensile properties of 5083 and 6061 weldments as published in *WRC Bulletin 181.*

The results of the current investigation indicate that 5083-5183 welds subjected to fatigue are little affected by porosity if the weld reinforcement is left in place. The weld reinforcement itself is the critical and fatigue limiting notch. Most welds tested with their reinforcement removed gave longer fatigue lives than as-welded tests regardless of porosity level. Porosity most influenced the fatigue lives of the reinforcement removed tests at the lowest stress levels. The radiographic standards currently in use by the U.S. Navy were found to be effective in insuring superior results with reinforcement removed welds. Conversely, few reinforcement removed welds which failed these standards gave shorter fatigue lives than porosity-free, as-welded welds.

The publication of this report was sponsored by the Aluminum Alloys Committee of the Welding Research Council.

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