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Effect of Preheat on Residual Stress Distributions in Arc-Welded Mild Steel Plates

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Residual stress distribution in the longitudinal and transverse directions on a 6-mm-thick arc-welded mild steel plate was experimentally examined with and without initial preheat. Stress measurements were completed by monitoring strain changes on mounted strain gauges resulting from successive milling of the welded plate specimens. Machining stresses were also compensated for by carrying out measurements of strain changes due to milling operation of a stress-free unwelded annealed mild steel plate. High tensile residual stresses exist close to the weld line in both longitudinal and transverse stresses. Maximum longitudinal residual stress values existing close to the weld line are reduced (between 50 and 75%) due to the effect of initial metal preheat of 200 °C of the welded steel plate.

Keywords preheat, residual stress, steel, strain gauges, welding

1. Introduction

Several factors, such as welding thermal conditions, weld plate restraint, deposition speed, joint type, material properties, *etc.*, affect residual stress distribution in a welded plate. A quantitative knowledge of the distribution of residual stresses in a welded plate under various welding conditions is essential for controlling and minimizing its value. Various techniques[1] have evolved for assessing the values of residual stresses with their relative advantages and disadvantages; the successive metal removal technique by milling operation[1,2] was used in this study. The relaxed strain values as monitored by strain gauges were converted into their equivalent stress values by application of the biaxial stress-strain relationship.[3] Earlier research work[4] established that postweld stress relief treatment reduced the magnitudes and spatial distribution of longitudinal, transverse, and normal stresses in an arc-welded plate. In this study, the effect of initial metal preheat to 200 °C on the magnitude of longitudinal and transverse residual stresses in a 6-mm-thick arc-welded steel plate was experimentally investigated and discussed using the strain gauge technique of measurement.

2. Experimental Methods

The welding operations were carried out using titania covered electrode (Sapinox RCN (China) 29.10) 2.5 mm in diameter (gauge 10) with an arc-welding machine set at an output current of 110 A on a constructed welding rig with provision for a constant velocity of weld.

Residual stress determinations were monitored by observations of strain changes on mounted resistance strain gauges with a dimension of 5 by 2.5 mm, a nominal resistance of 120 ohms, and a gauge factor of 2.

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Successive millings of the welded plate by taking 1 mm depth per lap caused strain relaxations that were converted into redistributed stresses. This procedure was repeated for the second and third laps. Similar successive milling procedures were carried out on identical annealed mild steel specimens that were used to compensate for the induced machining strains and stresses in the welded mild steel plate during milling operation.

2.1 Work Material and Preparation

The work material used for this investigation was mild steel of approximate chemical composition 0.25%C, 0.05%S, 0.8%Si, 0.75%Mn, and 0.06%P. Pieces, measuring 100 by 63 by 6 mm, were cut from supplied mild steel plates. Each piece was milled along the length with a beveled angle of 45°3 mm deep, and 2-mm root gap was allowed during welding operation.

Mild steel workpieces used were annealed in an electric furnace at a temperature of about 850 °C and were allowed to soak at this temperature for about 30 min in order to make them stress free at the onset of experimentation.

2.2 Welding Procedures

Welding at 200 °C preheat was done by heating workpieces in a furnace to temperatures slightly above 200 °C and then clamping on the rig immediately after. Welding commenced as soon as the temperature dropped to 200 °C. A semiautomatic welding procedure was applied by keeping the electrode arc stationary, while the workpiece moved at the desired welding speed of 1.84 mm/s relative to the stationary arc.[5]

The specimen without a prepared weld groove was dimensionally identical to the as-welded steel plate. This specimen was used to monitor and compensate for residual stresses introduced during the milling process for correct residual stress evaluation. Figs. 1(a) and 1(b) show the HAZ microstructures for the arc-welded mild steel plates without and with metal pre-heat respectively, while Fig. 1(c) shows the annealed base metal microstructures.

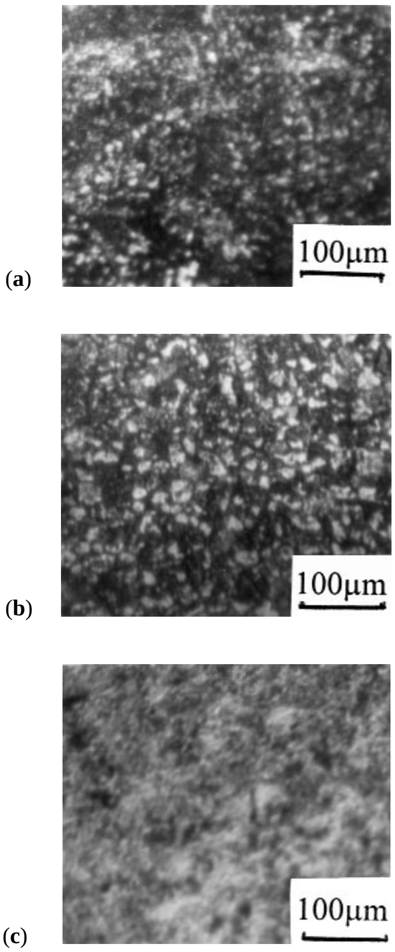

Fig. 1 (**a**) HAZ microstructure (no initial metal preheat). (**b**) HAZ microstructure (with metal initial preheat). (**c**) Annealed base metal microstructure

2.3 Residual Stresses Measurement

A wheatstone bridge with both active and dummy arms made of 120 ohms nominal resistance strain gauges was constructed. The readout consisted of a microstrain meter with the 3000 microstrain range was used throughout the experiment.

The strain gauges were arranged and positioned in the *x* and *y* directions, as shown in Fig. 2. Each location had a pair of strain gauges oriented in longitudinal transverse directions in each of the *x* and *y* directions.

After completion of installation of all strain gauges, the zero shift readings were observed and recorded for 7 days when the zero drift readings remained fairly constant. A waterproof agent such as wax was applied on the strain gauges and the connecting cables carefully soldered to eliminate or reduce moisture absorption by the gauges during milling. A final covering of the strain gauge with foam and nylon was applied to minimize shocks during milling operation.

The relaxed residual strains due to lapping, in longitudinal and transverse directions, were recorded using the wheatstone bridge setup for all the strain gauges installed. Similar milling operations and strain measurements were taken on the annealed stress-free

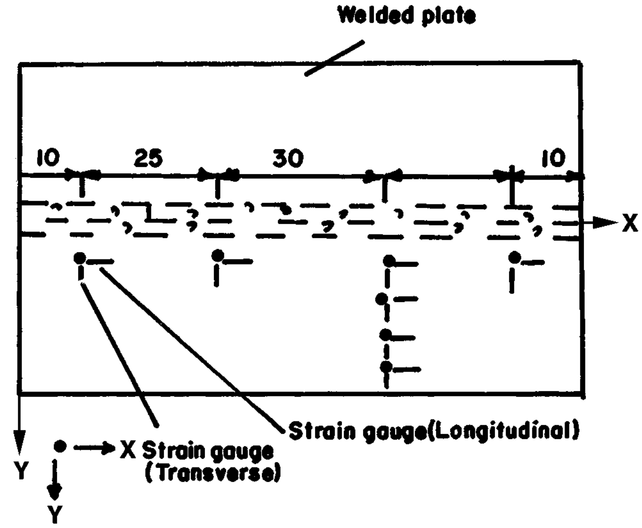

Fig. 2 Strain gauge arrangement and orientation

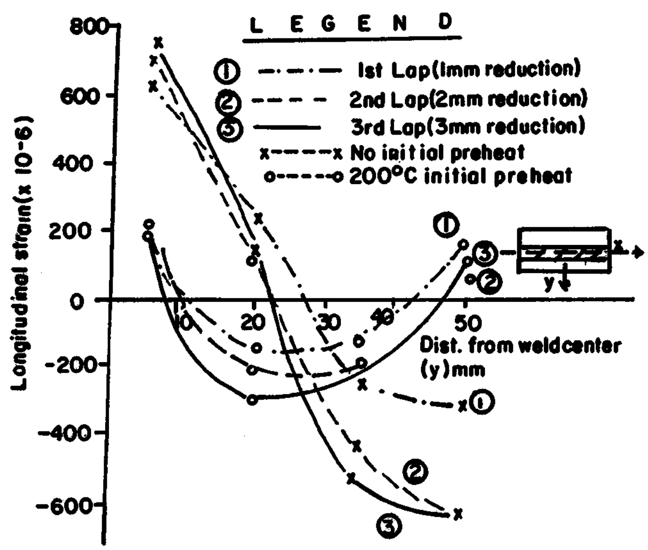

Fig. 3 Typical variation of longitudinal strain in the *y* direction

unwelded steel plate, and the induced strains by milling were used to obtain the corrected strain values[5] for the welded steel plates.

$$\sigma_x = \left(\varepsilon_x + \upsilon\varepsilon_y\right)\frac{E}{1-\upsilon^2} \qquad \text{(Eq 1)}$$

Corrected residual stress value[3] were obtained from the expression given as

$$\sigma_y = \left(\varepsilon_y + \upsilon\varepsilon_x\right)\frac{E}{1-\upsilon^2} \qquad \text{(Eq 2)}$$

where

σ_x is the longitudinal stress at point (x, y);

σ_y is the transverse stress at point (x, y);

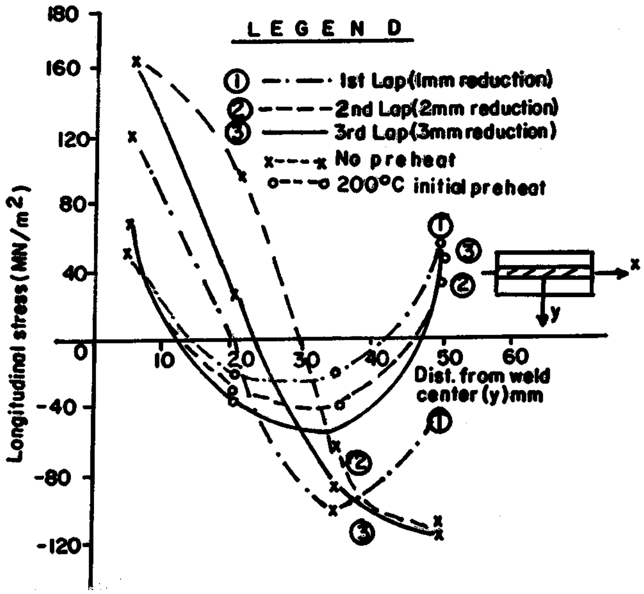

Fig. 4 Variation of longitudinal stresses in the *y* direction

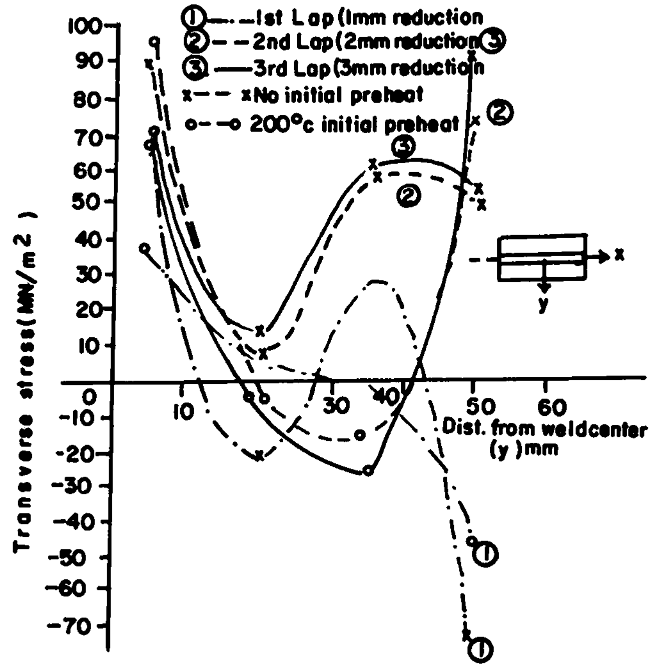

Fig. 5 Variation of transverse stress in the *y* direction

Table 1 Effect of preheat and no preheat on longitudinal and transverse residual strain in the *y* direction

		No initial plate preheat				Initial plate preheat of 200 °C			
		Longitudinal strain (x10^{-6})		Transverse strain (x10^{-6})		Longitudinal strain (x10^{-6})		Transverse strain (x10^{-6})	
Mill stage	Weld plate thickness after mill (mm)	Max.	Mim.	Max.	Mim.	Max.	Mim.	Max.	Mim.
1st mill	5	620.0	0.0	579.0	0.0	224.0	0.0	233.0	0.0
2nd mill	4	707.0	0.0	422.0	18.0	233.0	0.0	371.0	0.0
3rd mill	3	741.0	0.0	431.0	26.0	–311.0	0.0	388.0	0.0

E is the modulus of elasticity (200×10^9 N/m^2);
υ is Poissons ratio, 0.3; and
ε_x, ε_y are longitudinal and transverse strains at point (x, y).

3. Discussion of Results

3.1. Effect of Preheat on Longitudinal and Transverse Residual Strains on a Plane Perpendicular to the Weld Line

Figure 3 shows the longitudinal strain variations, with and without preheat in the welded plate, as given by the strain gauge arrangements shown in Fig. 2. At locations near the weld centerline, both longitudinal and transverse strains observed are tensile under preheat and no-preheat conditions. With 200 °C metal preheat, longitudinal strain reduction by about 70 pct is observed at 5 mm distance from the weld line (Fig. 3). A reduction in transverse strains due to initial metal preheat are more pronounced 30 mm from the centerline. Table 1 gives details of the maximum and minimum values of longitudinal and transverse strains with and without preheat. Reductions in both longitudinal and transverse strains are observed with metal preheat.

3.2 Effect of Preheat on Longitudinal and Transverse Residual Stresses on a Plane Perpendicular to the Weld Line

Figures 4 and 5 show the longitudinal and transverse residual stress variations in the *y* direction. High tensile residual stresses are observed close to the weld line in both longitudinal and transverse stresses. A maximum longitudinal residual stress value of 169.1 MN/m^2 near the weld line was reduced by about 65% due to 200 °C initial metal preheat. A reduction in transverse stresses was also observed due to initial metal preheat.

The as-welded longitudinal stresses were compressive in the base metal and become tensile through the heat-affected zone (HAZ) and into the fusion zone. This trend can be explained in terms of shrinkage of hot metal in the fusion zone against the constraint of the cooler metal, which shrinks less. The metal tends to yield to accommodate local strain gradients that are caused by different thermal contractions.

A magnitude of transverse stresses are generally observed to be lower than longitudinal stresses. Table 2 shows the maximum values of compressive and tensile longitudinal and transverse residual stresses in the *y* direction.

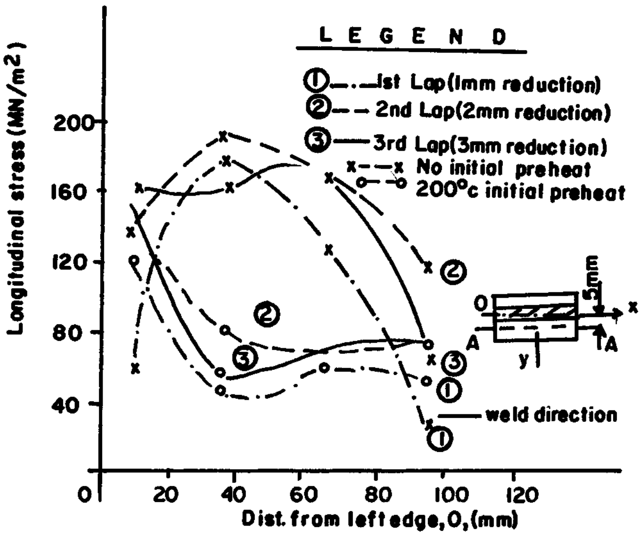

Fig. 6 Variation of longitudinal stresses in the HAZ (along *A*-*A*) in the *x* direction

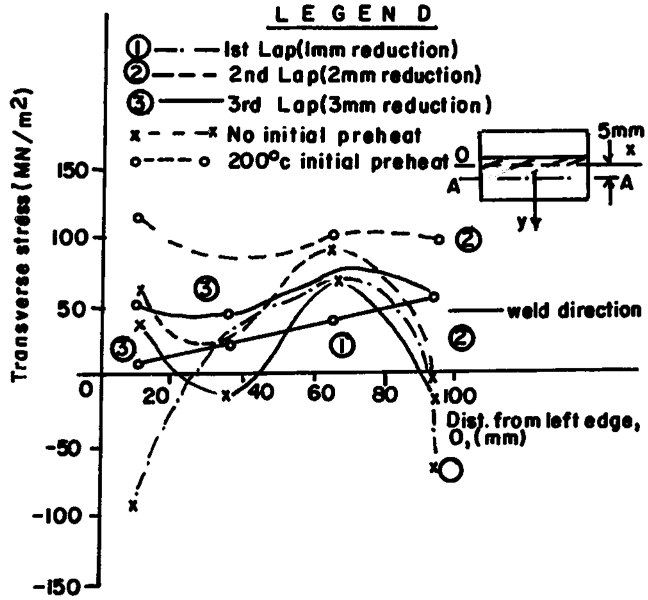

Fig. 7 Variation of transverse stresses in the HAZ (along *A*-*A*) in the *x* direction

Table 2 Effect of preheat and no preheat on longitudinal and transverse residual stresses in the *y* direction

		No initial plate preheat				Initial plate preheat of 200 °C			
		Longitudinal residual stress, MN/m²		Transverse residual stress, MN/m²		Longitudinal residual stress, MN/m²		Transverse residual stress, MN/m²	
Lap stage	Weld plate thickness after mill, mm	Maximum compressive	Maximum tensile	Maximum compressive	Maximum tensile	Maximum compressive	Maximum tensile	Maximum compressive	Maximum tensile
First mill	5	−103.0	+126.0	−73.8	67.0	−22.2	58.7	−48.0	38.0
Second mill	4	−108.4	+169.1	(a)	90.4	41.5	69.0	−17.0	94.6
Third mill	3	−109.3	+170.3	−14.60	69.30	−55.40	69.4	−27.0	94.0

(a) Nil

Table 3 Effect of preheat and no preheat on longitudinal and transverse residual stresses in the *x* direction

		No initial plate preheat				Initial plate preheat of 200 °C			
		Longitudinal residual stress, MN/m²		Transverse residual stress, MN/m²		Longitudinal residual stress, MN/m²		Transverse residual stress, MN/m²	
Lap stage	Weld plate thickness after mill, mm	Maximum compressive	Maximum tensile	Maximum compressive	Maximum tensile	Maximum compressive	Maximum tensile	Maximum compressive	Maximum tensile
First mill	5	0.0	177.0	0.0	+54.0	0.0	121.0	−97.5	+67.0
Second mill	4	0.0	189.0	0.0	+117.0	0.0	151.0	−3.2	+90.0
Third mill	3	0.0	170.3	0.0	+72.0	0.0	155.0	−15.7	+69.3

3.3 Effect of Preheat on Longitudinal and Transverse Residual Stresses on a Plane Distance 5 mm to the Weld Line in the HAZ

Figures 6 and 7 show the effect of 200 °C initial metal preheat on longitudinal and transverse residual stresses. Their values are reduced by between 50 and 75% (Fig. 6). The as-welded plate shows compressive transverse stresses at the edges of the weld plate and tensile transverse stress at the middle. Metal preheat by 200 °C tends to alter the transverse stress distribution along line *A*-*A* toward a uniform value (Fig. 7). Table 3 shows the maximum values of compressive and tensile longitudinal and transverse residual stresses in the *x* direction (*i.e.*, parallel to the weld direction). A comparison of the relative magnitudes of longitudinal and transverse residual stresses shows that longitudinal stresses are greater than transverse residual stresses at a common point.

4. Conclusions

Preheating of steel by 200 °C before arc-welding results in a reduction of longitudinal and transverse residual stresses by as much as 65%, which is similar to the effects of post-weld stress relief of welded structures. Pre-weld treatment is therefore recommended for the weldment of structures, operating at fairly high temperatures, or weldments of structures that are liable to precipitation hardening during post-weld treatment, which can result to higher residual stresses.

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