X-RAY ANALYSIS OF RESIDUAL STRESS DISTRIBUTION IN WELD REGION

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ABSTRACT

Distribution of residual stresses arising after welding is quite complex and inhomogeneous. Many factors have influence on the magnitude and the profile of the stress distribution curve. In the present paper an x-ray technique was used to analyze the residual stress distribution in steel sheets jointed by industrial welding with linear or circular weld seams. Interpretation of experimental results takes into consideration the satisfaction of the equilibrium equation. It has been shown that the equilibrium equation for residual stresses on the surface of a welded sheet, especially for stress components perpendicular to the weld seam, excludes the possibility of homogeneous stress distribution into the depth of the weld region. To confirm this point of view, stress measurements were made after successive removing of surface layers.

INTRODUCTION

Welding is one of the most important technological process used in many branches of industry such as industrial engineering, shipbuilding, pipeline fabrication among others. Residual stresses arising after welding exert a considerable influence on the service characteristics of welded equipment and their control allows to avoid failure of welded joint. The influence of residual stresses on service characteristics of welded equipment is analysed in many original papers and books [1,2]. Different techniques are used to control the stress state in the weld region. X-ray diffraction technique is one of the methods widely used to analyse residual stress distribution in weld seam and near the welded region. However, numerous measurements by X-ray tensometry [3,4] contain contradictory information about weld-induced residual stresses and the analysis of stress distribution is usually carried out without considering of equilibrium conditions.

In this paper, experimental results of residual stress measurements by X-ray tensometry are presented. Both longitudinal and transverse stress components were made in the seam weld, the heat-affected zone (HAZ) and in the base metal near the weld region.
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MATERIAL AND EXPERIMENTAL TECHNIQUE

Two types of samples were used to study the residual stress distribution in the weld region. One of them are made from A106GrB steel plates joined by arc welding with linear weld seam (see figure 1a) Its dimensions are 45cm x 30cm x 13mm. The other type of sample (SAE1020 steel) is a disk shaped plate with a circular weld seam. Two of these samples were made with dimensions 250mm and 150mm in diameter and 25 mm of thickness. Figure 1 shows the structures of the weld seams and indicates the points of stress measurements located in the seam, heat-affected zone and outside the weld region. At each point two stress components were measured; one of them is perpendicular to the weld seam (transverse residual stress or radial for disk shaped sample) and the other is parallel (longitudinal residual stress or tangential for disk shaped sample).

![Figure 1. Scheme of the weld seam structure and points of stress measurements: (a-a), (b-b), (c-c) positions of stress measurements after layer removals.](image)

Stress measurements were made with a portable X-ray apparatus presented at the 48th X-ray Denver Conference [5]. Cr-Kα radiation and (211) reflections were used to study residual stress distribution in weld region. A general view of the apparatus is shown on figure 2. Stress components were measured by the sin²ψ-method, using the double exposure technique, for which the main equation to determine any stress component \( \sigma_\phi \) is [6]:

\[
\sigma_\phi = \frac{E \tan \theta (\theta_{p,\psi 2} - \theta_{p,\psi 1})}{1 + v \sin^2 \psi_2 - \sin^2 \psi_1},
\]

(1)

where E, v are elastic constants, \( \theta \) is diffraction angle, \( \phi \) and \( \varphi \) are azimuth and polar angles.
Figure 2. General view of the portable X-ray apparatus:
1-high voltage source; 2-X-ray tube; 3-collimator–cassette unit; 4-control unit; 5-analysed sample.

Using calibration data from an unstressed material, equation (1) may be written as:

\[ \sigma_{\varphi} = A (L_{50} - L_0), \]  

where \( A \) is a coefficient that includes elastic constants, scale and geometry factors, \( L_{50} \) and \( L_0 \) are distances on the film corresponding to \( \varphi = 50^0 \) and \( \varphi = 0^0 \) degrees between diffraction line and reference; \( L_{50} \) and \( L_0 \) are measured by minidensitometer [5].

**EXPERIMENTAL RESULTS AND DISCUSSION**

Experimental results of stress measurements on the front and back faces of steel plate with linear weld seam are shown in figures 3 and 4. Table 1 shows the experimental results for disk shaped samples. The residual stress state on the surface of the weld region for sample with linear weld seam is characterised by compressive stresses in the weld seam and by tensile stresses in the HAZ and the base metal near the HAZ. Samples with a circular weld seam show a more complex state of stress, which also is different for the large (sample 1) welded disk to the small one (sample 2).

The main purpose of this paper is to analyse the stress state in a weld region considering the equilibrium of residual stresses integrated over any cross-section of a welded plate:

\[ \int_A \sigma_{\text{res}} (x) \, dA = 0, \]  

where \( A \) is the area of the cross-section perpendicular to the analysed stress component.
Figure 3. Residual stress distribution on the front face of the welded plate with linear weld seam:
1-longitudinal stresses; 2-transverse stresses.

Figure 4. Residual stress distribution on the back face of the welded plate with linear weld seam:
1-longitudinal stresses; 2-transverse stresses.
For longitudinal and transverse residual stresses, equation (3) is transformed to the following two equations:

\[ \int \int \sigma_i(x, z) dx dz = 0, \]  

\[ \int \int \sigma_i(y, z) dy dz = 0, \]

where \( Z \) is the coordinate along depth from the sample surface. Figure 5 illustrates the equilibrium conditions, shows the coordinate axes and integration area for longitudinal and transverse residual stresses. It is clear from figure 5 that equilibrium of longitudinal residual stresses can be satisfied by different signs of stresses in the weld seam, HAZ and base metal. For example, compressive residual stresses in weld seam, presented in figures 3 and 4 can be equilibrated by tensile stresses in HAZ and base metal. A different situation occurs with transverse residual stresses. To satisfy the equilibrium of these stresses they must vary along \( Z \) coordinate. That means that compressive transverse residual stress on the outer surface of weld seam can be equilibrated by some tensile stress within the analysed cross-section.

### Table 1. Residual stresses on the surface of disk shaped sample.

<table>
<thead>
<tr>
<th>Point</th>
<th>Region</th>
<th>Sample</th>
<th>Radial</th>
<th>Tangential</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Weld seam</td>
<td>1</td>
<td>-230</td>
<td>-50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>-260</td>
<td>-100</td>
</tr>
<tr>
<td>2</td>
<td>HAZ</td>
<td>1</td>
<td>-50</td>
<td>-60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>+180</td>
<td>+50</td>
</tr>
<tr>
<td>3</td>
<td>Base metal</td>
<td>1</td>
<td>-180</td>
<td>-80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>+100</td>
<td>+90</td>
</tr>
<tr>
<td>4</td>
<td>Base metal</td>
<td>1</td>
<td>-30</td>
<td>-160</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>-250</td>
<td>-30</td>
</tr>
</tbody>
</table>

Figure 5. Equilibrium conditions.
This conclusion means that stress measurements on the outer surface of the welded joint are not enough to examine residual stress states in weld regions and it confirms the need to study stress distribution along the depth. This can be accomplished by means of stress measurements after surface layer removing. It is clear that in the case of layer removal by machining or grinding it is necessary to undertake electropolishing to remove residual stresses introduced by machining. Analysis of equilibrium equations for circular weld seam is more complicated but the importance of knowing the stress distribution along the depth is obvious. Stress measurements after surface removal are presented in figure 6. The stress distributions for the samples with a linear circular weld seams show that the compressive residual stresses at the centre of the weld seams reverse to tensile stresses after removing a surface layers approximately equal to 0,5 mm.

![Figure 6. Depth stress distribution for transverse (radial) components.](image)

The experimental results presented in figures 3,4 and 6 do not contradict to the theory of introduction of residual stresses by welding. According to [4] the principal sources of residual stresses after welding are:

1. shrinkage;
2. quenching;
3. phase transformation.

Shrinkage causes the appearance of tensile stresses, whereas quenching and phase transformation cause compressive stresses at the weld seam. Compressive residual stresses on the surface of the weld seam indicate that they are caused mainly by quenching or phase transformation. The stress distribution presented in figure 6 is typical for residual stresses after quenching; this fact means that the predominant cause of welded residual stresses is quenching.
CONCLUSION

Distributions of residual stresses on the surfaces and along the depth for the welded steel samples have been presented. Stress distribution for the sample with the linear weld seam is characterised by compressive stresses on the surface and by tensile stresses at the HAZ and base metal. Stress distributions for samples with circular weld seam are more complicated. Conclusion about reversing of compressive residual stress on the surface of the weld seam to tensile stress in the depth made by analysis of equilibrium equations have been confirmed experimentally.

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REFERENCES