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Prediction of Residual Stresses Produced by Low Transformation Temperature Weld Wires and its Validation Using Contour Method

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1. Introduction

Controlling the induced residual stresses are most common concerns in the welding of high strength steels. In welded steel structures produced with conventional wires, residual stresses caused by the welding process may significantly influence structural integrity and may also reduce the fatigue strength of the joints. Low transformation temperature (LTT) material has been found to improve the fatigue strength in welded joints. In weld metal formed by LTT weld wire, the tensile residual stress is reduced by taking advantage of martensitic transformation expansion at low temperature which improves the fatigue strength.

The contour method (CM) has become one of the most powerful techniques that provides residual stress measurement. This technique is based on elastic stress relaxation after part cutting. The ability to obtain a full 2D cross-sectional map of residual stresses with a single measurement process makes CM unique. The methodology of CM consists in four major steps: part cutting, contour measurement, data processing and elastic calculations for obtaining stresses from displacements. In order to evaluate induced residual stresses of different weld wires especially LTT wires; CM using the finite element analysis (FEA) can play a significant role as a powerful tool in predicting residual stresses at any plane of interest.

2. Experimental Work

The material used in this investigation was 20 mm thick AH36 high tensile strength steel with yield and tensile stresses as 446 and 543 MPa, respectively. Three different weld wires were used as shown in Table 1, to examine the influence of weld wire properties on residual stresses using CM. Test specimen and joint geometry are shown in Fig.1. Six specimens were used as 2-specimens/weld wire. Welding was performed along specimen length with one pass using GMAW process. Welding heat input for wires A, B and C are 2.77, 2.34 and 2.16 KJ/mm, respectively. After welding, x-ray measurements were conducted at the same cutting position on both welding and back surfaces for all welded specimens. Additionally, CM was implemented experimentally in which cutting, the first and most critical step in conducting CM, was carried out at specimen mid-length using the wire electric discharge machine with 200 μm wire diameter. After that, surface contour was measured using 3D Measuring Macroscope with a repeatability (height measurement) 0.5 μm; allowing for accurate measurement. Measured data were processed before applying it to elastic FEA. Then, reproduced stresses were obtained at any location on cut surface for all specimens.

Table 1 Details of used weld wires.

Wire designation	Wire code	Wire type	T_{Ms}^{*}, ^{o}C
MG-S50	Wire A	Conventional	400~500
10% Cr–10% Ni	Wire B	LTT	200~250
NH18-W2	Wire C	LTT	150~200

* indicates martensitic transformation start temperature.

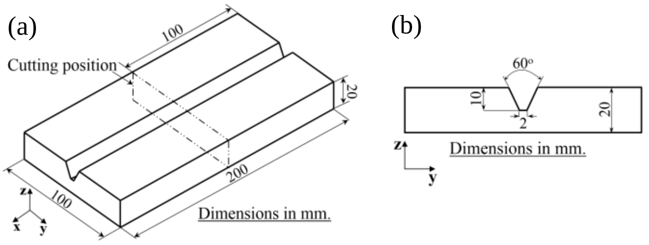

Fig. 1 Schematic drawing of test specimen. (a) test specimen geometry and (b) joint geometry.

3. Numerical Analysis

In a previous study [1] authors validated CM numerically, so based on this study a full FEA consists in welding, cutting and reproducing residual stresses was conducted using the finite element (FE) code JWRIAN in which the iterative substructure method is employed. A 3D model (Fig. 2) was constructed with the same dimensions of welded specimens but without groove. A bead-on-plate weld using the different weld wires (conventional and LTT wires) was performed along the model length; with almost the same welding conditions of experiment. In this analysis, both weld and base metals have martensitic and ferritic mechanical properties respectively after cooling process.

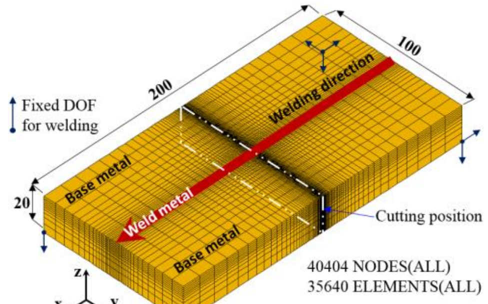

Fig. 2 FE model with locations of welding line and cutting.

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4. Numerical Analysis Approach

Theoretically, stresses due to welding (σ_W) and change in stresses due to relaxation after cutting (σ (U)) must be equal, as in Eq. (1). However in FEA, stresses are calculated in elements not at nodes. Therefore, sum of σ_W and σ (U) does not exactly equal zero, as in Eq. (2). In reproducing stresses step, since calculations represent a linear elastic problem; so reproduced stresses (σ_R) can be obtained by applying the calculated displacements after cutting with an inverse sign (-U) to a stress-free model, as in Eq. (3). Both σ_W and σ_R are equal theoretically, while in FEA both stresses (σ_W and σ_R) are almost equal as in Eqs. (4) and (5), respectively. However, the error due to FEA is shown to be small enough as discussed in [1].

Theory:	$\sigma_W + \sigma\,(U) = 0$	(1)
FEA:	$\sigma_W + \sigma\,(U) \simeq 0$	(2)
General (linear elastic):	$\sigma_R = \sigma\,(-U) = -\,\sigma\,(U)$	(3)
Theory:	$\sigma_W = \sigma_R$	(4)
FEA:	$\sigma_W \simeq \sigma_R$	(5)

where U represents the displacement components (u, v, w).

5. Results and Discussion

In order to validate the numerical CM, two different measurement techniques (i.e. experimental CM and x-ray method) were performed. For each weld wire, numerical CM shows a good agreement with the measurements results on both welding and back surfaces as shown in Fig. 3. CM, numerically and experimentally, successfully shows the behavior of residual stresses for the three weld wires. In other words in case of conventional wire, residual stresses in weld metal are tensile; however, LTT wires introduce compressive residual stresses. By using CM, it became easy to reproduce residual stresses at any location on the cut surface, and obtain a full 2D cross-sectional stress map as shown in Fig. 3. Moreover, both experimental CM and x-ray method showed their reliability for measuring residual stresses at different locations. Additionally, reliability of numerical CM is achieved as shown in Fig. 3, in which it can be used as a predictive tool for determining residual stresses at any plane of interest.

On the other hand, numerical and experimental results show the effectiveness of LTT weld wires in reducing the tensile residual stresses and inducing compressive one in weld metal; which can improve fatigue performance of welded joints. It is also observed that both LTT weld wires do not show a big difference in the induced compressive residual stresses in weld metal, and this may be due the small difference in T_{Ms} for both wires.

6. Conclusions

From this study, both numerical and experimental CMs facilitate the capability to obtain full 2D cross-sectional maps of stresses for various weld wires. Additionally, CM revealed the effectiveness of LTT wires in inducing compressive stresses into the weld metal.

7. Reference

[1] Ramy Gadallah, Hidekazu Murakawa and Seiichiro Tsutsumi, Preprints of the national meeting of Japan Welding Society 94 (2014) 226–227.

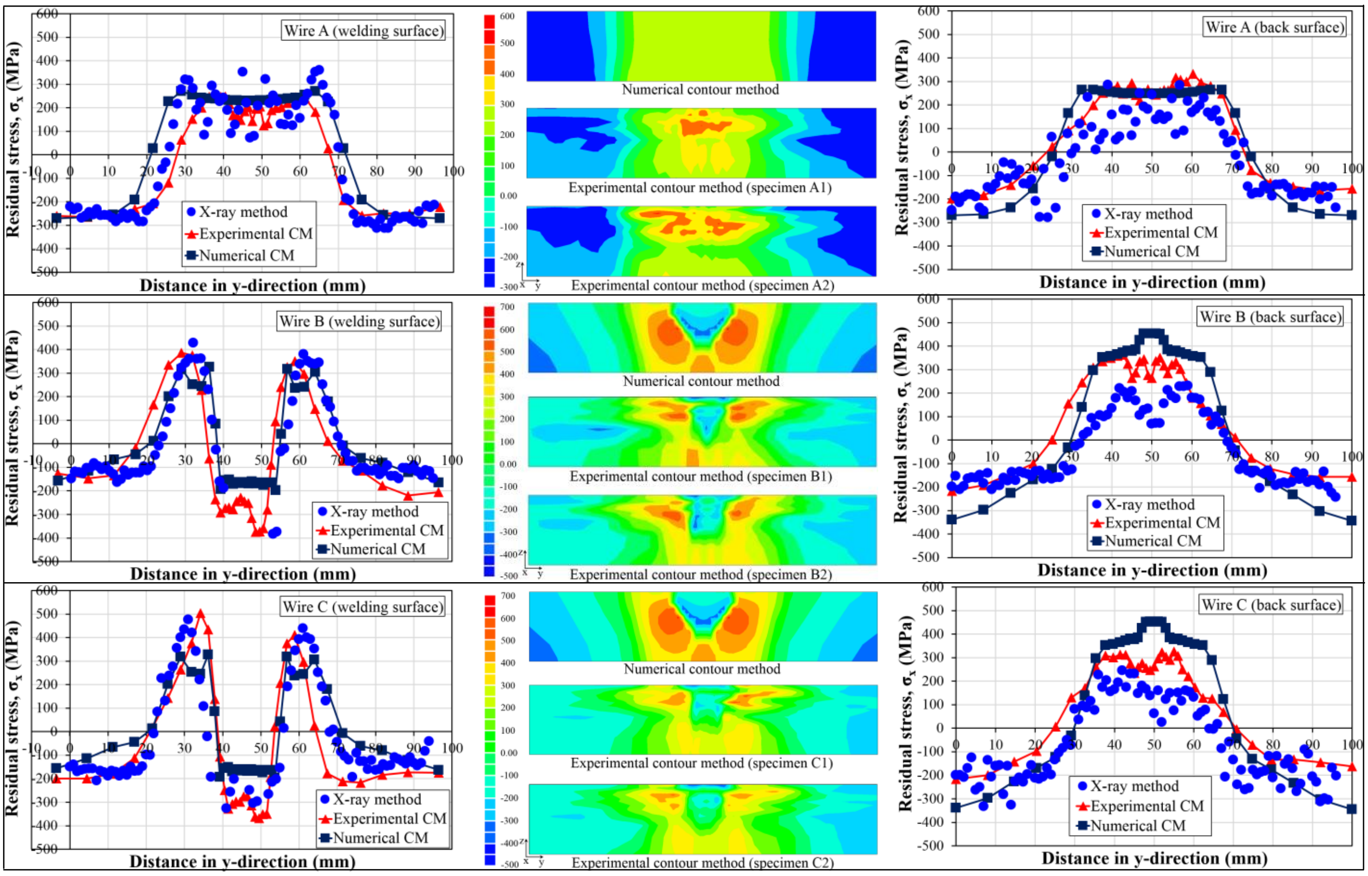

Fig. 3 Validation of residual stresses for the three weld wires with the 2D cross-sectional stress maps.