FEM Analysis of Plasticity-induced Error on Measurement of Welding Residual Stress by the Contour Method

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The contour method relies on deformations that occur when a residually stressed component is cut along a plane. The method is based on the elastic superposition principle. When plasticity is involved in the relaxation process, stress error in the resulting measurement of residual stress would be caused. During the cutting the specimen is constrained at a location along the cut so that deformations are restrained as much as possible during cutting. With proper selection of the constraining location the plasticity effect can also be minimized. Typical patterns of longitudinal welding residual stress state were taken to assess the plasticity effect along with constraining locations.

Key Words: Residual Stress, Contour Method, Plasticity Effect, Stress Error

Nomenclature

E : Young's Modulus
ν : Poisson's ratio
S_y : yield strength
σ_x : Weld-direction component of residual stress
σ_o : Peak residual stress
ξ : Normalized y-coordinate

1. Introduction

Welding residual stresses can substantially affect the mechanical performance of welded components. These stresses are directly responsible for fatigue, fracture and corrosion. The manner in which residual stresses affect these failure processes is often difficult to ascertain because the residual stresses are difficult to measure. The contour method has recently been developed and has the capability to determine a two dimensional map of the residual stress component normal to a plane through an object (Prime, 2001).

The contour method for measuring residual stresses is based on a variation of Bueckner's superposition principle (Bueckner, 1958) and can determine residual stress variations directly from the measured deformations on the surface created by a cut. In order to cut on a path which is as planar as possible and to remove as little as possible, wire electric-discharge machining (WEDM) is typically applied for making the cut. Tosun (2003) thoroughly described the process of WEDM and investigated the effect of cutting parameters on roughness of the cutting surface in WEDM.

The specimen is constrained at a location near the cut in order to hold the plane of the cut from moving during cutting. The method is relatively simpler to apply over the other relaxation methods since the deformation is measured directly on the plane of the cut rather than on other free surfaces. The method is especially effective for measuring a 2-D profile of residual stress such as in a welded plate.

The assumption of elastic relaxation in the contour method is not valid when plastic relaxation occurs during the process. When plasticity is involved during the relaxation process, the residual stress profile measured by the contour

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method no longer would represent the original residual stress state in a body. It is, however, believed that constraining the body during cutting at a proper location can minimize the plasticity effect. Thus, as described above, constraining a specimen during the cut can serve the purposes of not only preventing the plane of the cut from moving but also minimizing the effect of plasticity.

In this paper, the plasticity effect on measuring axial welding residual stress by the contour method is numerically simulated for specific residual stress distributions under different constraining locations from the plane of the cut. These analyses were performed using a commercial FE package, ABAQUS/Standard (2002). A nickel-chromium-molybdenum (Ni-Cr-Mo) Alloy C-22 plate (Fig. 1) was taken as FE models. C-22 alloy has exceptional resistance to a wide variety of chemical process environments, including strong oxidizers such ferric and cupric chlorides, chlorine, formic and acetic acids, and seawater and brine solutions. C-22 alloy resists the formation of grain-boundary precipitates in the weld heat-affected zone, thus making it suitable for most chemical process applications in the as-welded condition. Some of the areas of use for this alloy are nuclear fuel reprocessing, radioactive waste canisters, acid etching, chlorination systems, flue gas scrubber systems, SO_2 cooling towers and tubular heat exchangers.

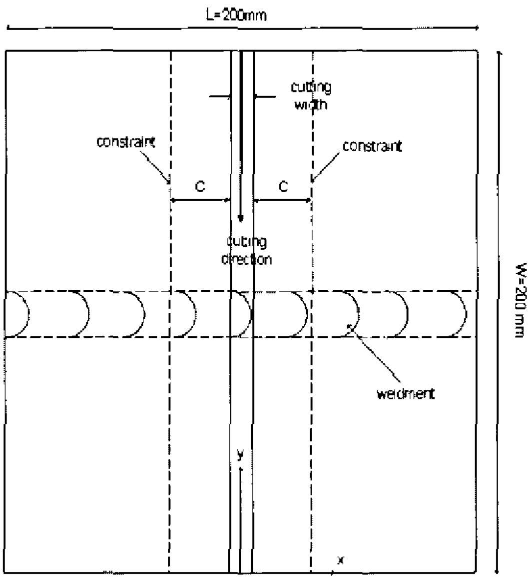

Fig. 1 Schematic of the contour method on an Alloy C-22 welded plate

The Alloy C-22 plate was assumed to have an axial welding residual stress distribution. The axial residual stress distribution was implanted in the FE model of the Alloy C-22 plate as its initial stress state. Then, the plate was constrained at the location C (Fig. 1) by fixing the corresponding nodal points. After constraining the plate each element along the plane of the cut was removed one after another. The displacements along the plane of the cut were read after completing the element removal and releasing the constraint. The displacement field was imposed in an elastic model of the undeformed configuration, as would be done when executing residual stress measurement by the contour method. The induced stress state in the elastic FE model of the undeformed body was compared with the initial stress state, and the stress error due to plasticity was computed.

2. Numerical Model

An Alloy C-22 plate of 200 mm×200 mm was modeled with the material data of; S_y(yield strength) =349 MPa, E(Young's Modulus) =207 GPa, and ν(Poission's ratio) =0.3. The material was assumed to have linear isotropic hardening to a stress level of 377 Mpa at plastic strain of 0.011, and perfect plasticity beyond that region. An approximate axial residual stress distribution (σ_x) was assumed for this case, given by Terada (1976) and Tada and Paris (1983);

$$\sigma_x(\xi) = \sigma_o e^{-0.5\xi^2}(1-\xi^2) \qquad (1)$$

where σ_o is the peak residual stress, and ξ is the normalized y-coordinate. A similar distribution of the axial residual stress of multi-pass welded thick plates was also obtained by an ABAQUS simulation, and compared with experimental results by the hole-drilling technique (Kim et al., 2002).

Given with three different peak values of the

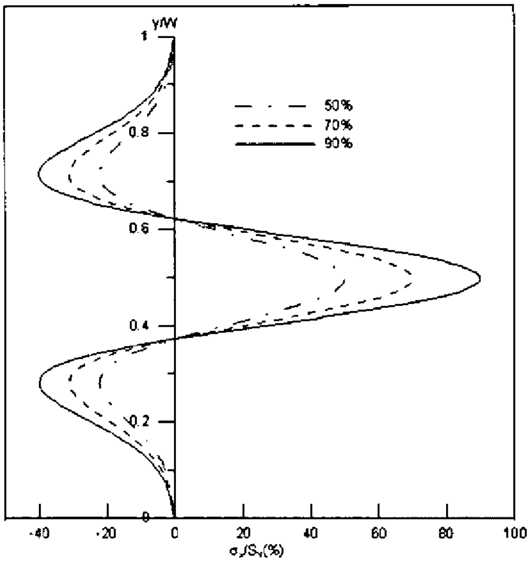

Fig. 2 Original residual stress distributions with peak values of 90%, 70%, 50% of the yield strength

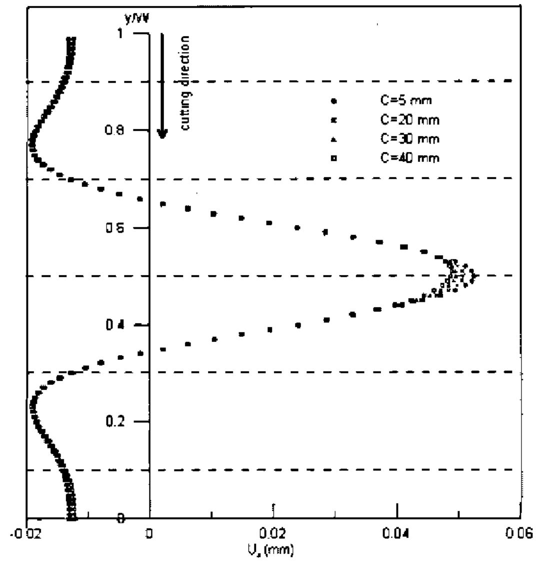

Fig. 3 Displacement distributions after completing the cutting process when the peak value of the original residual stress is of 90% of the yield strength

residual stress distributions such that $\sigma_o/S_y=50$ %, 70% and 90% (Fig. 2), the specimen was cut along the mid-plane perpendicular to the welding bead with a cut width of 0.254 mm. The simulation was performed on one half of the length of the plate to take advantage of the symmetry of the geometry. The half of the plate was modeled using 100 (x-direction) $\times$200 (y-direction) of 4-noded plane strain elements, and the mesh was biased toward the plane of the cut. At each step in the element removal process one element of 1 mm depth was removed, and thus 200 steps were performed to complete the cut. Removal of an element can be achieved by assuming the modulus of elasticity of the element to be about zero.

During each cutting process the model was constrained in x and y-direction at the locations of C=5 mm, 10 mm, 15 mm, 20 mm, 30 mm and 40 mm from the cutting edge, respectively. Convergence analysis was preliminary conducted by increasing the element refinement to ensure the independence of the solution from the mesh.

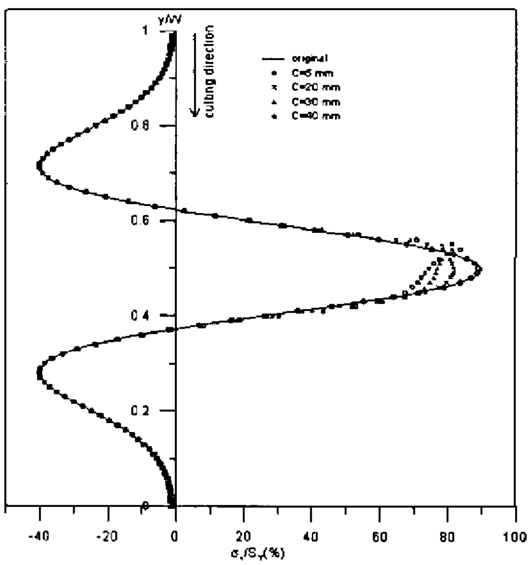

Fig. 4 Recomputed residual stress distributions by the contour method when the peak value of original stress is 90% of the yield strength

3. Results and Discussion

The simulation of the cutting process on the welded Alloy C-22 plate was performed from top to bottom. Fig. 3 depicts the displacement distributions after completing the cutting process with different constraining locations when the peak value of the original residual stress is of 90% the yield strength. For each constraining location the displacements along the plane of the cut were imposed on an elastic model of the undeformed configuration. Fig. 4 shows the recomputed weld-

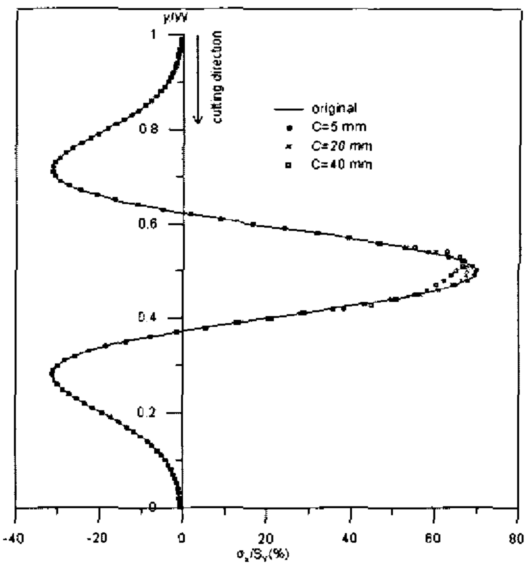

Fig. 5 Recomputed residual stress distributions by the contour method when the peak value of original stress is 70% of the yield strength

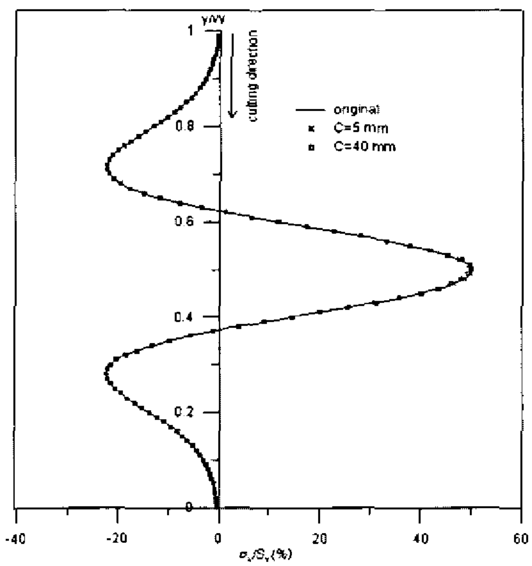

Fig. 6 Recomputed residual stress distributions by the contour method when the peak value of original stress is 50% of the yield strength

direction component of residual stresses along the plane of the cut by the above process i.e. contour method. It was ensured that the residual stress distribution computed under the assumption of no plasticity involved during the cutting is identical with the original residual stress distribution. Figs. 5 and 6 show the same pattern but less degree of plasticity effect when the peak stresses are of 70% and 50% the yield strength, respectively. As can be seen in the figures the stress error *due to the effect of plasticity is confined mainly* in the high tensile residual stress region of the welded plate.

For each peak value and constraining location the Root-Mean-Square (RMS) stress errors averaged through the plane of the cut are shown in Fig. 7, and the greatest stress errors in Fig. 8. For further the location of constraint from the cutting edge, higher stress error due to the plasticity effect is involved. For the peak stress value of 90% of the yield strength the constraint at *C*=*5 mm gives the RMS stress error of less than* 0.2% of the yield strength. For the peak values of 70% and 50% yield strength the RMS stress errors are nearly zero with the constraint at C=5 mm. For the peak value of 90% the yield strength the constraining location C=5 mm gives the maximum stress error of about 1% along the

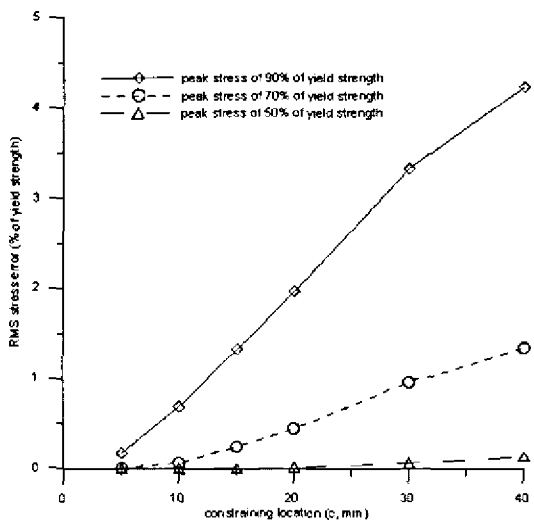

Fig. 7 RMS stress error averaged through the plane of the cut

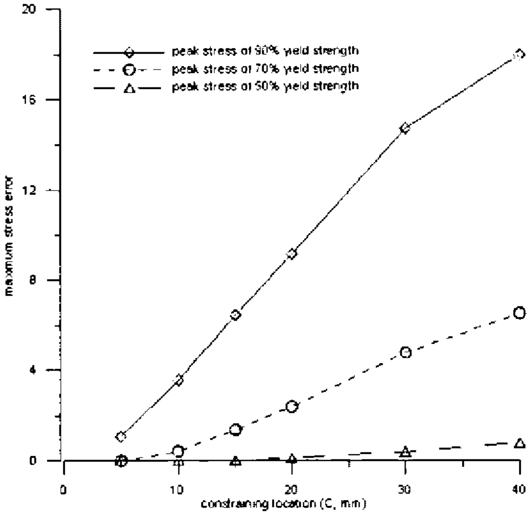

Fig. 8 Maximum stress error along the plane of the cut

plane of the cut. For the peak values of 70% and 50% the yield strength the maximum stress errors are negligible under the constraining location C=5 mm.

According to the Technical Note (Vishay-Measurement Group, 1993), the effect of plasticity in measuring residual stresses by the hole-drilling technique becomes significant due to local yielding caused by stress concentration around the hole when residual stresses are over 60% of the material's yield strength. In measuring residual stress of 70% yield strength by the hole-drilling technique (Beaney, 1976) an overestimation of 15% can be given by the plasticity effect. For residual stresses of 90% yield strength, an error of 20% can be expected in stress calculation (Beghini et al., 1994). Gibmeier (1998) estimated an error of 35% in measuring residual stresses of 95% yield strength by the hole-drilling technique. Obviously, the stress error due to plasticity in the contour method with proper constraining location is much lower than in the hole-drilling method where no constraint is applied.

5. Conclusions

The contour method is based on the principle of superposition in elasticity. When residual stresses are large enough to cause yielding during cutting, the measurement using the contour method may lead to an erroneous result. In the contour method the plasticity-induced error is dependent on the constraining location from the plane of the cut, while the constraining arrangement is to hold the cutting plane from moving during the cut. When the contour method is applied for axial welding residual stress measurement, it is considered that constraining the object at an adequate location from the cutting plane gives negligible stress error due to the plasticity effect.

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