Title	Effect of Welding Residual Stresses on Fracture Toughness Testing : Part 2: Crack Tip Opening Displacements in the Residual Stress Field of Multipass Weldments of Thick Plates(Mechanics, Strength & Structure Design)
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Effect of Welding Residual Stresses on Fracture Toughness Testing†

Part 2: Crack Tip Opening Displacements in the Residual Stress Field of Multipass Weldments of Thick Plates.

Juan C. SUAREZ*, Hidekazu MURAKAWA** and Yukio UEDA***

Abstract

There are several methods of allowing for residual stresses in Elastic-Plastic Fracture Mechanics, but all of the approaches imply such simplifying assumptions that could contribute to the observed scattering in test results. This paper examines the prediction and incorporation of residual stresses in fracture toughness test data evaluation. Part 1 dealt with the Finite Element analysis of Crack Tip Opening Displacement specimens of thick plates, paying special attention to the peculiarities in behavior of deep and shallow cracks. Calculations of stress and strain fields, together with the shape and size of the plastic zones ahead of crack tips, were presented for several loads and crack lengths. Opening displacements in the crack tip, values of rotation factors under bending and J integrals were obtained in order to characterize the different behaviors, when residual stresses were absent from the models. For Part 2, residual stresses were computed using thermal elastic-plastic Finite Element analysis and crack tip opening displacements recalculated to assess any variation with respect to the ideal unstressed specimen. Results point to substantial dissimilarity in behavior for both specimens - with and without residual stresses - and, in addition, such differences are found to be linked to the failure loads. Hence, as the model suggests, actual toughness values could be smeared by the residual stress state in the CTOD test specimens.

KEY WORDS: (Fracture) (Welding) (Toughness) (CTOD) (Residual Stress) (Finite Element Method)

1. Introduction

The importance of residual stresses on the fracture performance of weldments has been acknowledged from long time ago[1)], and some efforts have been made to asses their role in the calculation of stress intensity factors[2)], fatigue life[3)], crack propagation rates[4)], etc.

However, to obtain reliable predictions in actual applications is necessary not only add the residual stresses to the on-service loads but measure accurate values of fracture toughness for the materials involved. The most widely used test for weldments is the Crack Tip Opening Displacement (CTOD) test[5)]. Standards' major difference between test on parent material and those in weldments concerns the fact that high residual stresses are present in as-welded joints. Residual stresses tend to influence the growth of the fatigue precrack, resulting in an uneven growth and, hence, rejection of the test. Two commonly used techniques are local compression of the ligament ahead of the machined notch before fatigue precracking[6,7)] and stepwise high R-ratio fatigue loading[8,9)]. There is not yet an agreement about the possibility that these treatments could affect the toughness of the material tested. Nevertheless, a recent European Round Robin on fracture toughness testing of weld metal[10)] showed a lack of inter-laboratory reproducibility, which undermines the concept of a standard procedure. This contrasts with an earlier project on fracture toughness of parent material[11)], in which inter-laboratory variation was deemed negligible. No

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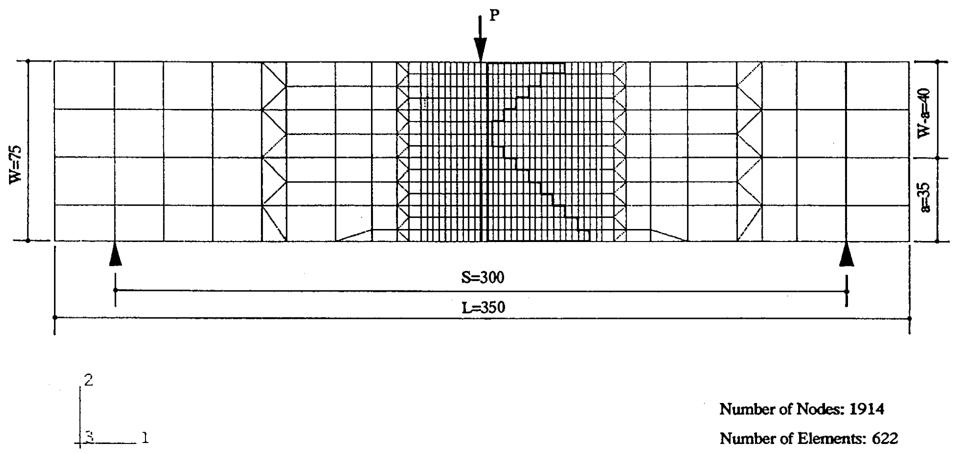


Fig.1 FEM mesh for CTOD specimen with a K weld groove and location of the crack in the HAZ.

consistent reasons have been found for the differences among the twelve laboratories after this largely empirical approach, and more fundamental research was considered essential to improve the fracture toughness testing in weldments.

Besides welding residual stresses, other factors play a role during testing, mainly: mismatching in mechanical properties and microstructural gradients. All of them take place simultaneously and their individual contributions upon the overall toughness values are hard to discern. The Finite Element Method (FEM) is a useful tool to focus just in one of these factors, to ascertain its influence on toughness testing. Part 1 of this paper[12] dealt with the analysis of CTOD specimens of thick plates, paying special attention to the peculiarities in behavior of deep and shallow cracks. Calculations of stress and strain fields, together with the shape and size of the plastic zones ahead of the crack tips, were presented for several loads and crack lengths. Opening displacements in the crack tip, values of rotation factors under bending and J integrals were obtained to characterize the different behaviors, when residual stresses were absent from the models. In part 2, residual stresses have been computed using thermal elastic-plastic FEM analysis[13,14] and crack tip opening displacements recalculated to assess any variation concerning the ideal unstressed specimen. Results point to substantial dissimilarity in behavior for both specimens - with and without residual stresses - and, besides, such differences are found to be linked to the failure loads. Therefore, as the model suggests, actual toughness values could be smeared by the residual stress state in the CTOD test specimens.

2. FEM Model of CTOD Specimens

FEM mesh for the CTOD test specimen of a multipass weldment is shown in **Fig.1**. The K groove was filled with 67 passes. Both the base material and the weld metal have the same mechanical and thermal properties, **Fig.2**. The model considered neither

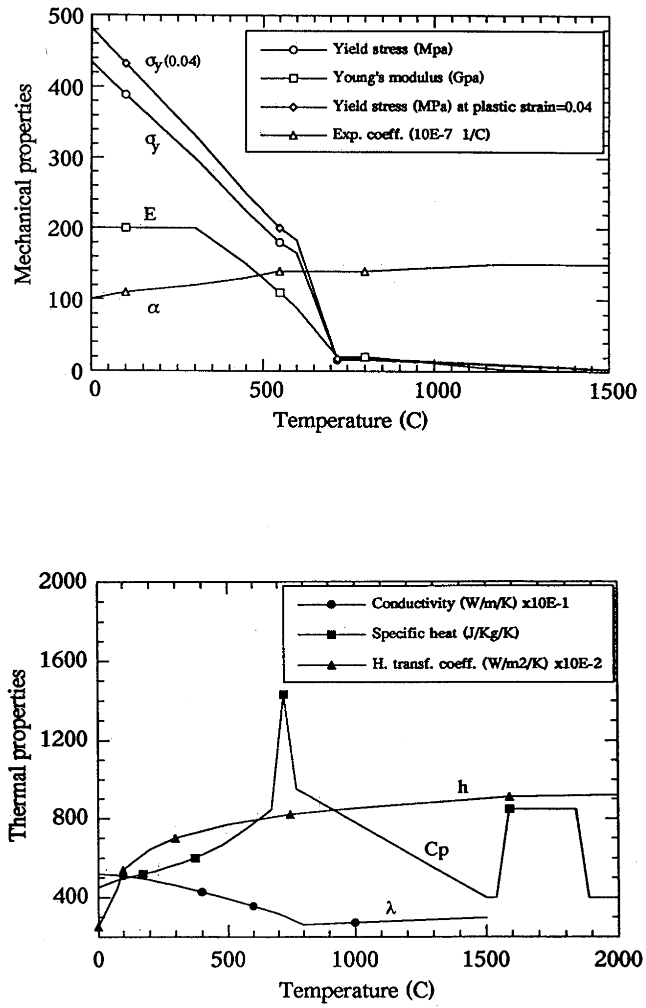


Fig.2 Mechanical and thermal properties used for the FEM analysis.

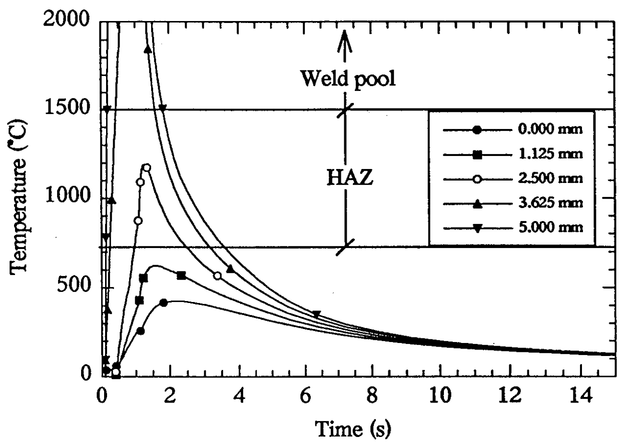


Fig.3 Weld thermal cycles at several distances from the left edge of the groove.

mismatching nor microstructural gradients in the HAZ; only the influence of residual stresses was examined.

Crack location in the HAZ is 2.5 mm from the groove's left edge, as is also shown in **Fig.1**. This distance was selected after a preliminary study to locate the crack just in the border between HAZ and weld pool when a heat input of 2 MJ/m is used, **Fig.3**, which is a usual value for arc welding of these HSLA steels. The crack has to remain closed during the welding residual stress analysis, allowing a perfect transmission of loads through the crack plane. The procedure used to do this with the FEM code (ABAQUS) was defining two surfaces, corresponding two both crack edges, and tying them together as a "contact pair". After completion of residual stress computation, the crack was opened by removing the contact pair definition, and the CTOD analysis continued loading the cracked specimen under three points bending.

Two different FEM analyses are needed for every pass: a thermal analysis to compute the temperature field; an elastic-plastic analysis using the previous temperature distribution as thermal loads. Both thermal and mechanical analyses were assumed to be uncoupled, so was possible to run one after the other. However, all material properties are temperature dependent, and it is necessary to reevaluate them for every step in the analysis. Temperature differences were restricted to 200°C for consecutive steps; thermal and mechanical properties were interpolated when datum was not available for a certain intermediate temperature. Mesh topology was the same for both analyses: 622 isoparametric, rectangular and triangular elements. For the thermal analysis DC2D8 (rectangular, 8 nodes) and DC2D6 (triangular, 6 nodes) elements were used. However, for the stress analysis CGPE10 (rectangular, 10 nodes) and CGPE8 (triangular, 8 nodes) were necessary under the assumption of generalized plane strain. The last two nodes are shared by all the elements but are needed to obtain the strain in axial (welding) direction with a 2D model. Only a linear variation in axial displacements is permitted. The stress analysis used 1914 nodes.

Some problems arose with the time incrementation controls of ABAQUS, due to the high non-linearity in material's properties, and controls were modified to allow a bigger number of equilibrium iteration for each step. A file with all the information about geometry and stresses was saved after calculations for every pass. Following pass used this file as input, and the previous residual stresses were modified according to the new weld thermal cycle. Thus, a comprehensive track of the evolution of residual stresses from pass 1 to 67 was kept for further use.

Every weld bead was introduced in the model activating elements previously defined. Heat flux for every pass was distributed as a gaussian curve - writing a FORTRAN user's subroutine - over the upper faces of the elements forming the bead. Heat input of 2 MJ/m was enough to melt all the material of the bead and partially the others surrounding it, as it is the case in actual weldments. Heat was dissipated by convection through the outside boundaries of the model, with a sink temperature of 20 °C. No preheating was applied.

3. Distribution of Welding Residual Stresses

Figure 4 shows the opening stress distribution ahead of the crack tip, in thickness direction, for pass numbers 1, 2, 15 and 22, respectively. A zone in compression develops at a certain distance in front of the crack tip; a narrow zone of tensile opening stresses moves up as the welding proceeds, with a maximum slightly below the surface for pass 22.

When pass 22 was over, welding continued from the opposite side of the K-shaped groove. For the FEM model that means to modify boundary conditions, changing constrains to the upper edge of the mesh. **Fig.5** shows the opening stress ahead of the crack tip, in thickness direction, for pass numbers 23, 37, 50 and 67, respectively. The redistribution of residual stresses after pass 23 is not only due to one more weld thermal cycle but also to the change in boundary constraints.

Figure 6 shows the opening stress along the crack line (crack not opened yet) after pass 67, together with

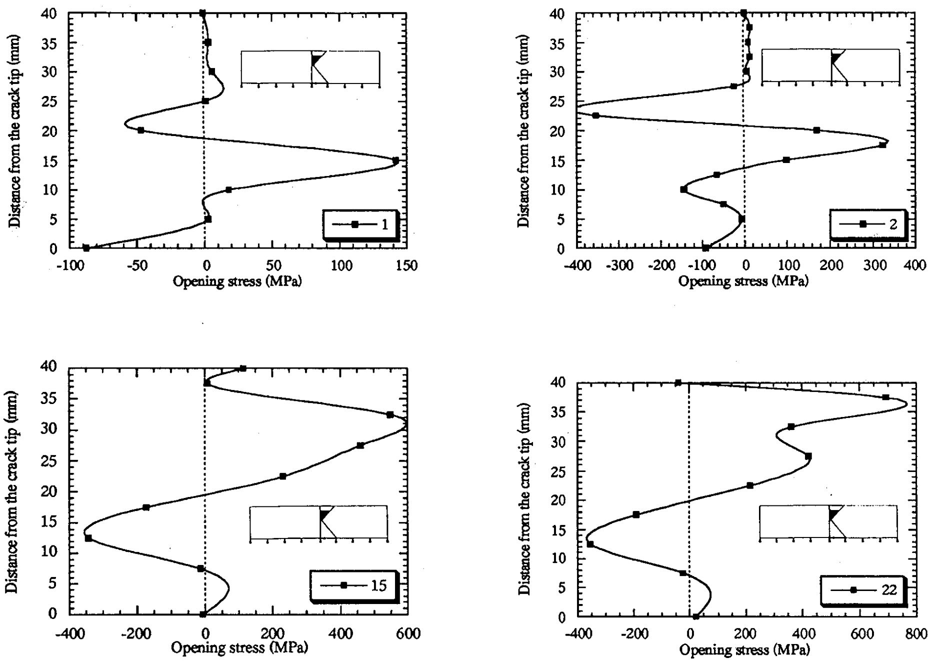


Fig.4 Opening stresses ahead of the crack tip for passes 1, 2, 15 and 22 (half groove filled up).

distributions along two other lines located at ±1.25 mm right and left. There are differences in opening stresses and, therefore, differences in crack location during CTOD testing can yield different toughness values, not related to the sampling of different metallurgical microstructures but to differences in the residual stresses state ahead of the crack tip. This is specially meaningful in elastic-plastic fracture; the aptitude to develop a plastic zone around the crack tip is largely affected by the stress state in a wide region surrounding the crack.

After residual stresses were calculated, the crack was opened removing the contact pair definition that kept both crack flanks tied. Also boundary constraints were changed again and stress distribution recalculated. The inherent strains - the plastic strains produced during welding - are the source of residual stresses; they are unchanged during the crack opening and, hence, the stress distribution changes slightly only. **Fig.7** shows the very similar pattern of opening stresses ahead of the crack tip before and after crack opening.

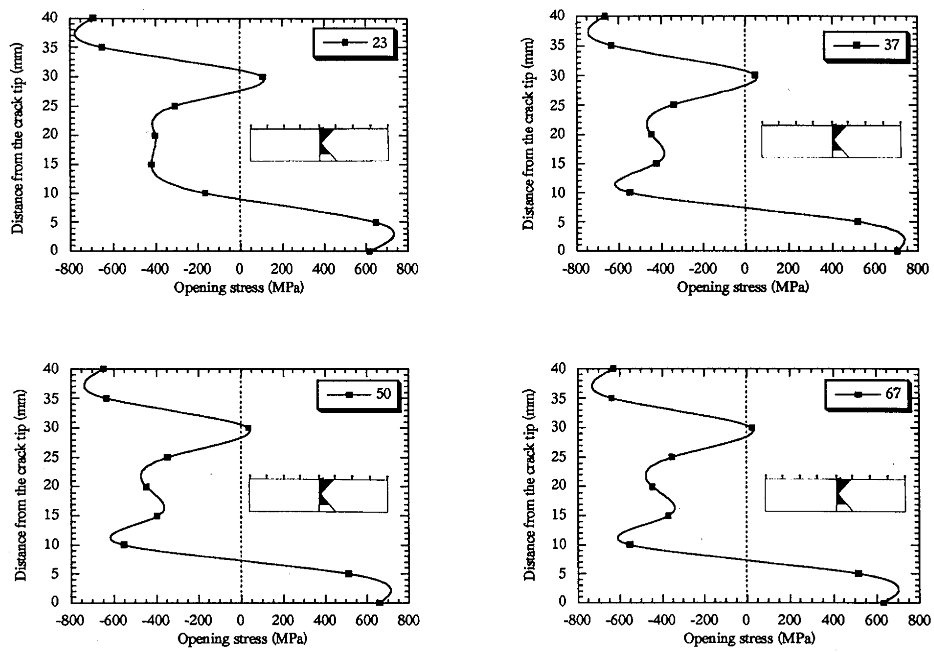


Fig.5 Opening stresses ahead of the crack tip for passes 23, 37, 50 and 67 (complete groove filled up).

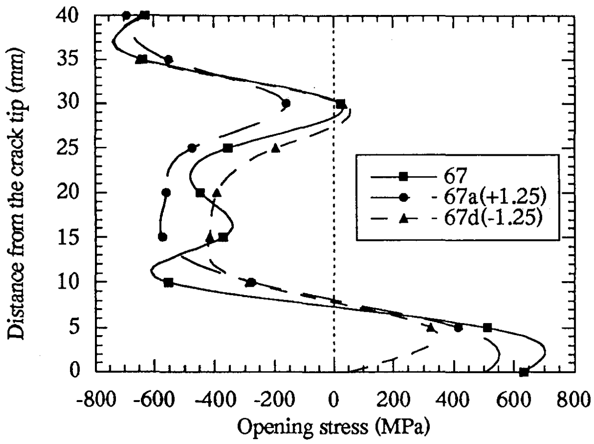


Fig.6 As-welded opening residual stresses ahead of the crack tip and ±1.25 mm left and right from the crack line.

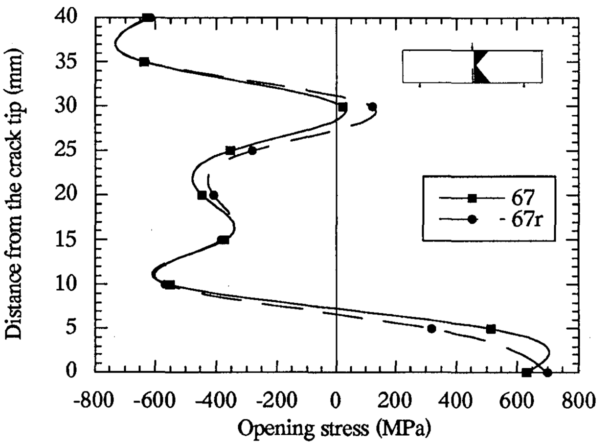


Fig.7 Opening residual stresses ahead of the crack tip before and after the crack is introduced.

4. Three Points Bending of CTOD Specimens With and Without Residual Stresses

CTOD specimens, with and without welding residual stresses, were loaded in bending. The maximum load applied was 1.3 times the limit load for plastic collapse of the remaining ligament (Py)[12].

Figure 8 shows the Load-Deflection and Load-CMOD (Crack Mouth Opening Displacement) curves for both specimens. There is a certain load range, roughly between 0.6 and 1.2 Py, in which the curves diverge. Out of this interval the behavior is closely the same. The relationship between CMOD and deflection of the specimens are shown in **Fig.9**.

Crack Tip Opening Displacements (δ) were calculated from the values of the plastic component of CMOD/Load curve using the standard equation, as is detailed in Part 1[12]. **Fig.10** includes data on δ for several loads, showing both the total value and the elastic and plastic contributions to CTOD. Loads with equal contribution from elastic and plastic components are different for both test specimens: 1.15 Py without residual stress and 1.08 Py with residual stress. Total opening displacements are compared in **Fig.11**.

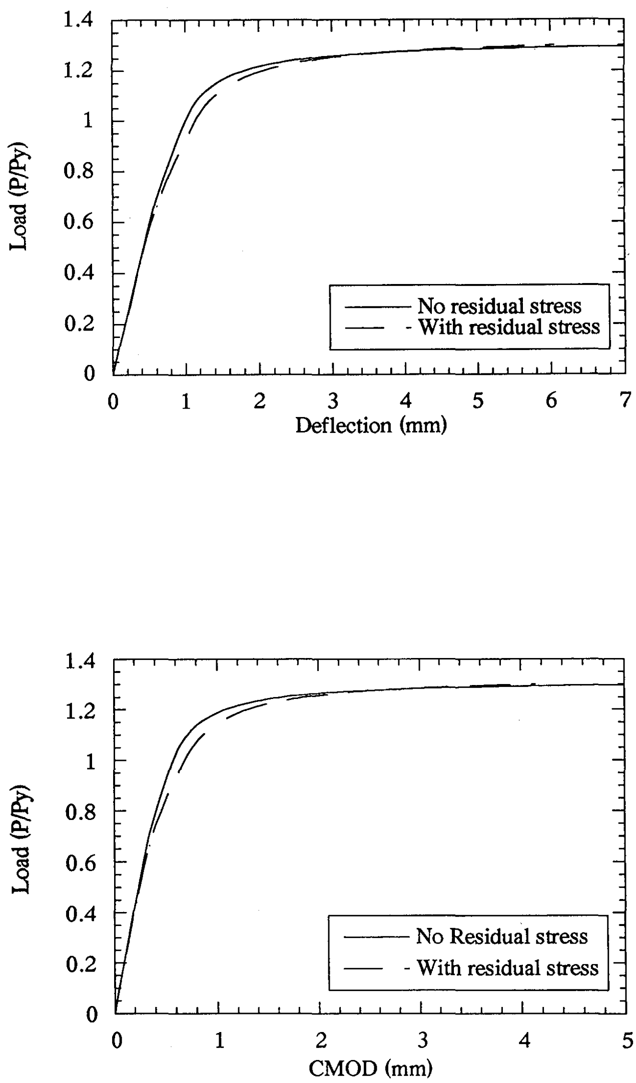


Fig.8 Load-deflection and load-CMOD curves under bending.

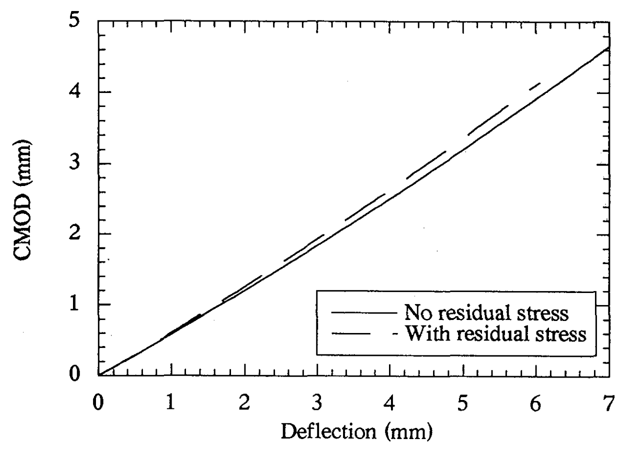


Fig.9 Deflection-CMOD relationship under bending.

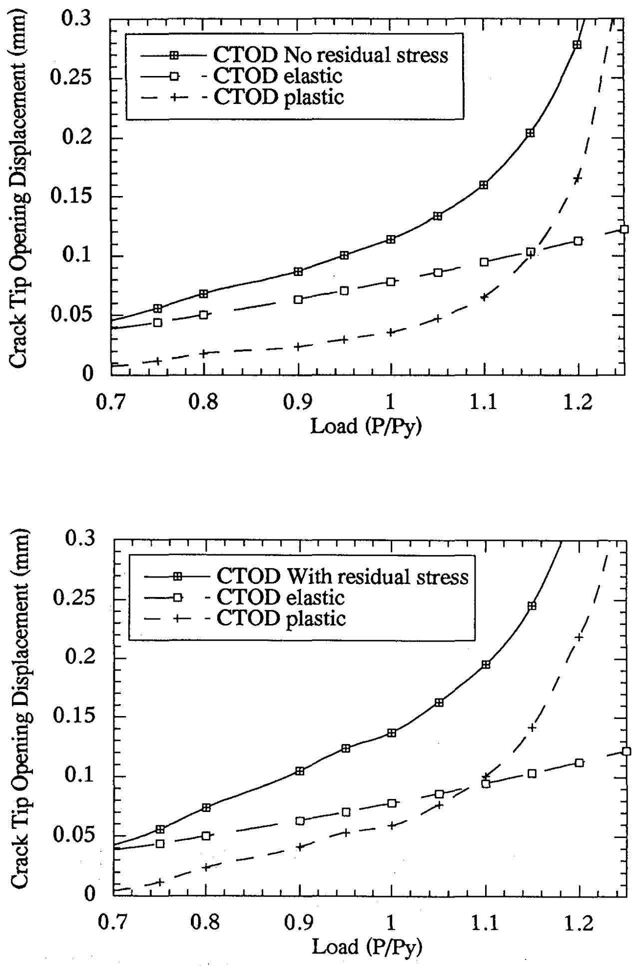


Fig.10 Total CTOD, elastic and plastic contributions for specimens with and without residual stresses.

Differences (in percentage) between CTOD values for the same load in specimens with and without welding residual stress are presented in **Fig.12** (solid line). There is a plateau ranging from 0.9 Py to 1.2 Py that keeps a constant difference of 22%. That means, for the same load, that δ in specimens with residual stress is up to 22% higher than the unstressed specimens.

5. Crack Opening and Plastic Zone Development

For the case including welding residual stresses, crack flank displacements resulted to be unsymmetric, as can be seen in **Fig.13**. For the same load (P=1.00 Py), crack displacements were different for specimens with and without residual stress, **Fig.14**.

The change in behavior when residual stresses are present seems to be related to the early plastic zone development ahead of the crack tip. For the elastic regime both specimens behave closely the same, but at higher loads the residual stresses field around the crack tip modifies the plastic constraint on the material; as the load continues increasing and plastification spreads to the specimen boundaries the behavior resumes again the same trend for both situations. The range of influence of residual stresses on the development of the plastic zone is bound by the extension of the plateau in **Fig.12** (solid line).

When only the plastic contribution to δ is considered, **Fig.12** (dashed line), it becomes clear that maximum difference is obtained for a load of 0.95 Py, with a figure around 80 %. This reinforces the idea that the distinct behavior due to residual stresses derives from the early shaping of the plastic zone and disappears when plastification is generalized.

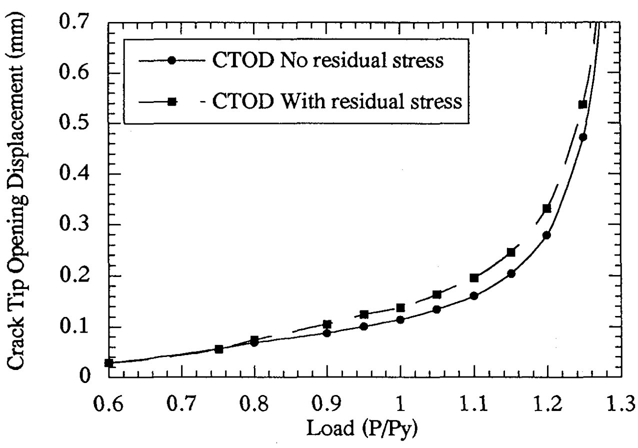


Fig.11 Comparison of total CTOD values for specimens with and without residual stresses.

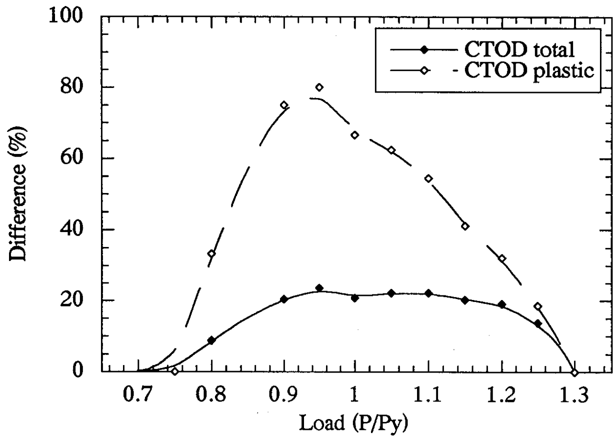
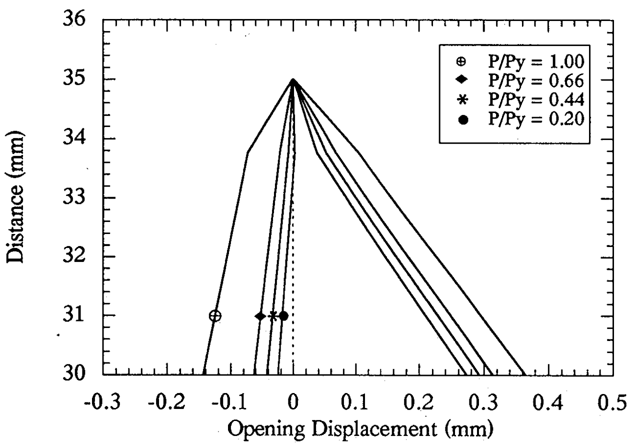


Fig.12 Differences in CTOD calculated values (total and plastic contribution) between specimens with and without residual stresses.



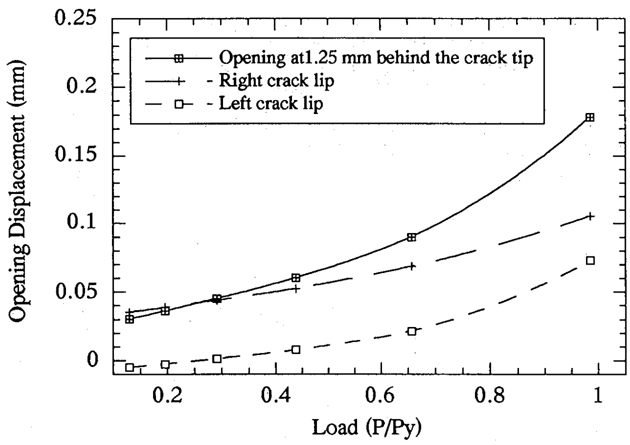


Fig.13 Opening displacements of the crack flanks for the specimen with welding residual stresses.

The conclusion that can be drawn, under the assumptions of this particular model, is that the presence of welding residual stresses modifies the value of δ up to 22 %, when compared with a non pre-stressed specimen. The question arises if differences in toughness for two specimens welded with different heat inputs could be related not only to differences in microstructure but to changes in the residual stress pattern.

Moreover, even when comparing several specimens of the same material, welded in the same conditions and with the crack located in the same position of the heat affected zone, differences in measured toughness could be originated by the residual stresses pattern. Scattering in toughness values due to differences in the microstructure sampled by the crack front may be distorted by the presence of residual stresses: if failure happens at lower loads, without crack extension, the influence of residual stresses could be negligible and a truly material-dependent property is being measured; in the same way, if failure happens at high loads, after substantial stable crack,

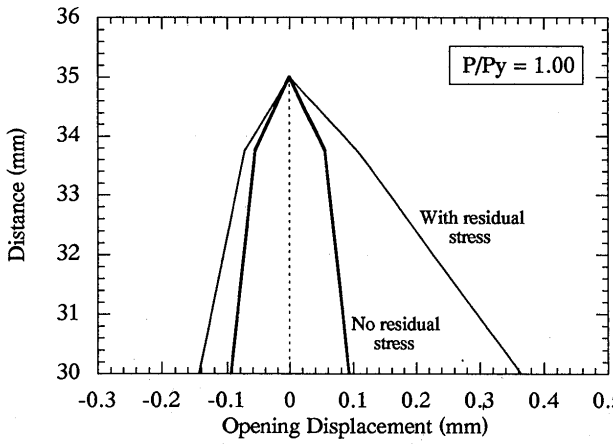


Fig.14 Opening displacements of the crack flanks at limit load for the collapse of the remaining ligament for specimen with and without welding residual stresses.

extension, the model suggest that residual stresses are not modifying the toughness values; but if failure happens at loads straddling the range for which a limited stable crack extension occurs, then residual stresses do play a key role on the development of the plastic zone ahead of the crack tip and measurements can accordingly vary. The differences resulted to reach up to 22%, what is only a meaningful figure in the contest of this particular model. The important point is, however, that variations are linked to the load: for small differences in failure load, deviations in δ could be very important if they are in the slopes (left or right) limiting the plateau; if the load falls inside the plateau the deviation is the biggest, but the differences in δ for specimens with slightly higher or smaller failure loads do not become so meaningful.

The unsymmetrical crack opening also suggests the use of local CTOD values, different for the right (δ_r) and left (δ_l) flanks, in place of the usual total value ($\delta_t=\delta_r+\delta_l$).The failure would happens when any of the local δ's reachs its critical value and not when δ_t does it. This generalized CTOD criterion has been used for joints with weld metal mismatching[15], but also even-matching weldments with high residual stresses should be treated in the same way.

Residual stresses can partially account for both discrepancies in toughness for specimens with different heat inputs, and for the scattering observed in the measurement of identical specimens. Hence, as the model suggests, actual toughness values could be smeared by the residual stress state in the CTOD test specimens.

6. Conclusions

In order to deepen the understanding of the influence of welding residual stresses on fracture toughness test results, a thermal elastic-plastic FEM analysis of CTOD specimens in multipass weldments of thick plates has been conducted. Comparing the crack opening displacements of specimens with and without residual stresses a number of conclusion can be drawn:

(1) The presence of welding residual stresses modifies the value of CTOD up to 22 %, compared with a residual stress-free specimen, when the loads are in the range of 0.9 to 1.2 times the value of the limit load for plastic collapse of the remaining ligament. Differences drop steadily outside this plateau.

(2) The evolution of plastic contribution to CTOD value shows that differences in behavior between specimens with and without residual stresses appear at the early stages of plastic zone development ahead of the crack tip. Both in the elastic regime and when generalized plastification under bending is reached the influence of residual stresses is negligible.

(3) Scattering in test results due to inherent variability of material properties might be smeared by the different significance of welding residual stresses according to the actual failure loads. Further research is needed to assess if this could be related to the lack of reproducibility sometimes reported in the literature.

(4) Unsymmetrical crack opening suggests that the critical values of Local CTOD should be used in place of the total δ value as the fracture criterion, likewise is done for mismatched joints.

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