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Effect of reconstitution on fracture toughness measured with PCCv

prepared for
Tractebel Energy Engineering
Avenue Ariane 7
B1200 Bruxelles

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Abstract

The effect of the heat affected zone resulting from reconstitution on the measured fracture toughness is investigated by finite element analysis. Finite element simulation is performed on two geometries: a standard precracked Charpy size specimen and a reconstituted specimen in which the heat affected zone is such that only 3 mm thick virgin material remains.

The load-displacement curve of the reconstituted sample lies slightly above the curve of the standard specimen: the difference is about 3.5%. The resulting K_J-values are in good agreement, the difference does not exceed 5%. This is confirmed also by the stress distribution ahead of the crack which is identical in both situations.

Introduction

Reconstitution of the base and weld materials of the Doel II reactor pressure vessel steel in the un-irradiated condition resulted in a large Heat Affected Zone (HAZ). As shown in Figure 1, the remaining non-affected material is about only 3 mm in length. Previous metallographic investigations on specimens reconstituted before reveal a HAZ of about 1.5 to 2 mm at each side of the insert. In a 10x10x10 insert, this leaves a 6 mm of unaffected material. The unexpected large HAZ on the Doel base and weld materials was identified as due to an inversion of polarity during the welding process.

The aim of this work is to investigate how this reduction of unaffected material can affect the measured J-values. Indeed, it was found before that a loss of impact upper shelf energy occured when reducing the size of the insert [1]. This is mainly due to the interaction of the plastic zone with the heat affected zone. In the present case, however, the specimen is precracked to a crack length-to-width ratio of 0.5 and further sidegrooved. This decreases the possible effect of the HAZ and promotes plane strain conditions.

Finite element calculations were performed on two PCCv specimens: standard and reconstituted. The material is respectively considered homogeneous in the first situation (one flow curve) while materials of various flow properties were introduced in the second case in order to simulate the HAZ. Metallographic observations supported by hardness measurements were used to define the HAZ in position as well as material properties.

Finite element results allow to compare the load-displacement behaviour of both samples, to determine the evolution of J with the applied loading and to compare the evolution of the stress distribution ahead of the crack tip.

Materials

The reconstitution process results in an increase of the material hardening at the weld joint. On the metallographic photo of the Doel weld sample shown on Figure 1, the hardened zone exhibits a darker aspect. Vickers hardness measurements performed on this sample resulted in the distribution shown in Figure 2. This hardness increase is characterized by a higher yield stress. The weld joint and resulting HAZ being localized, this region is subdivided into 5 zones of various constitutive laws. These flow curves are derived from the reference curve used for the original (unaffected) material (see Figure 3).

A typical flow curve of a reactor pressure vessel steel is taken for the reference material. In the heat affected zone, the yield stress gradually increases from 516 up to 945 MPa. As indicated in Figure 4, the constitutive laws in the various HAZ regions are derived by horizontally shifting the reference flow curve.

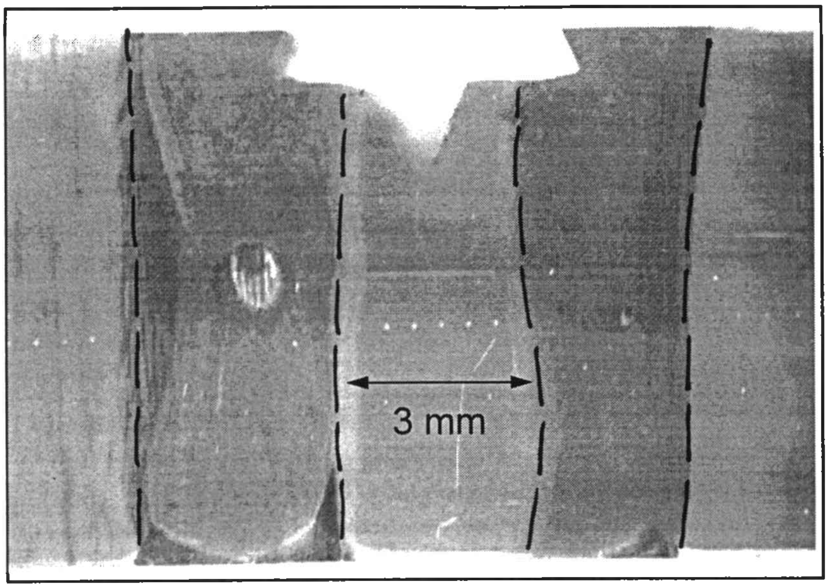

Figure 1. *The heat affected zone is such that the remaining unaffected material is only 3 mm thick (Doel weld baseline specimen 2Z4WB).*

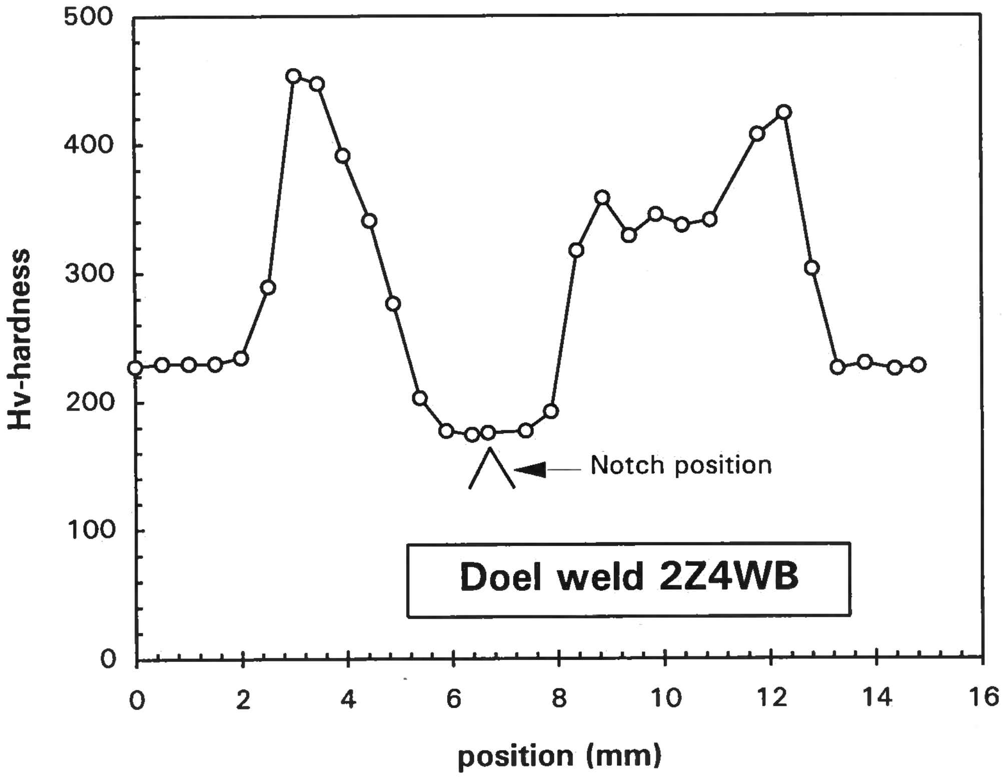

Figure 2. *Measured Vickers hardness along the HAZ and the weld of the specimen 2Z2WB shown on Figure 1.*

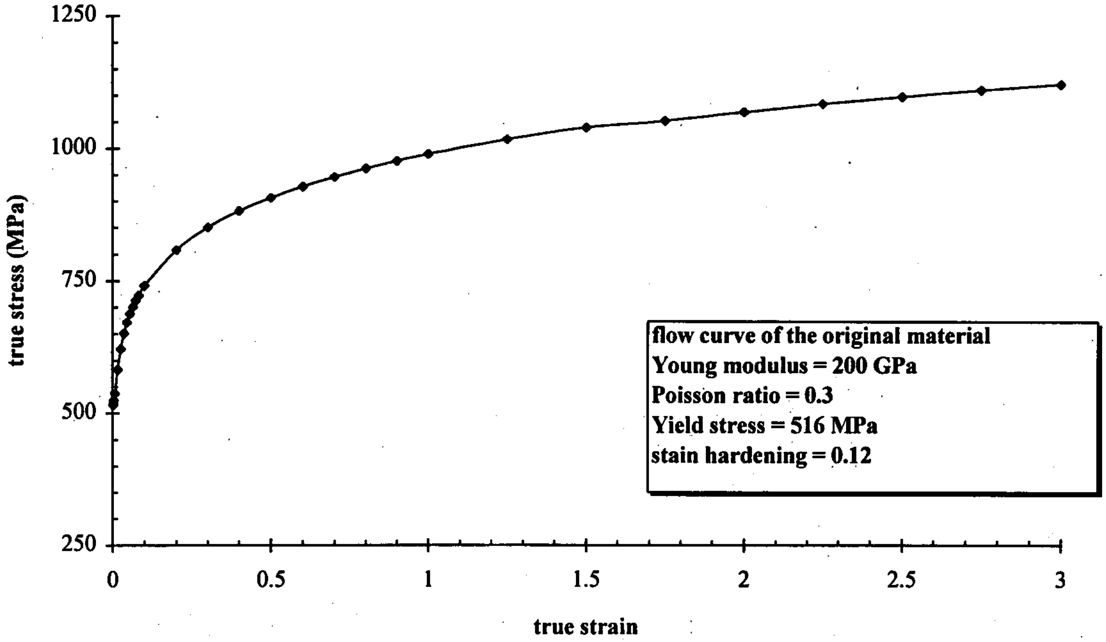

Figure 3. *True stress - true strain flow curve of the reference material.*

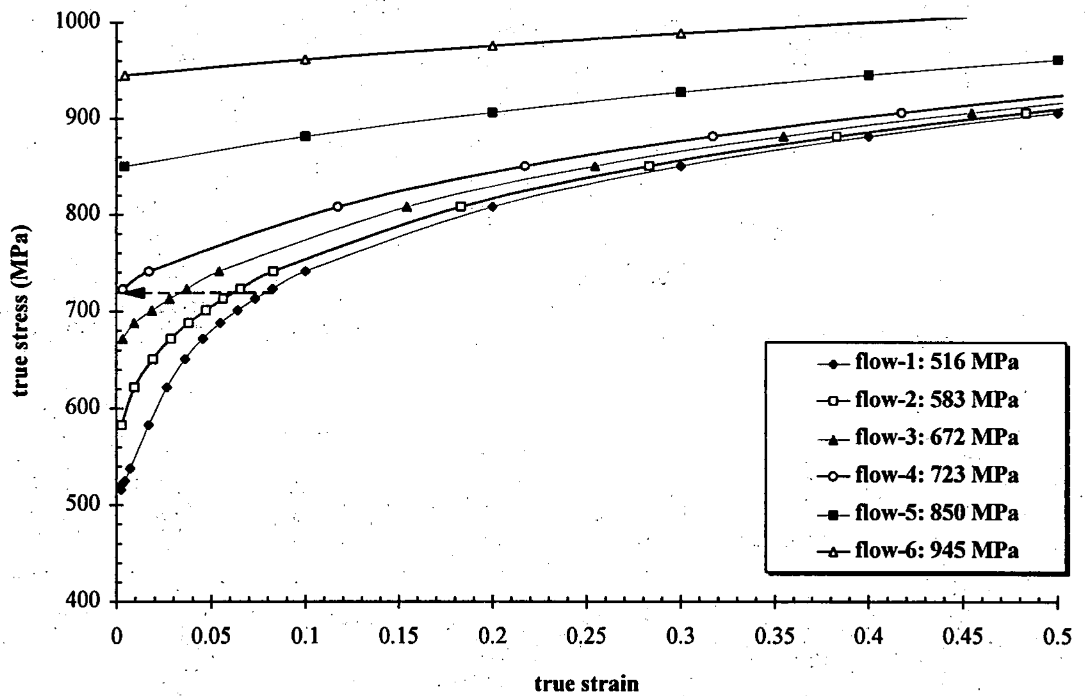

Figure 4. *True stress - true strain curves corresponding to the different regions in the weld and HAZ. The arrow indicates how the flow-4 curve is derived from flow-1.*

Finite element simulation

Due to axial symmetry relative to the crack plane, only half of the Charpy specimen is modeled. Two-dimension finite element calculations were performed assuming a plane strain condition. The finite element meshing is shown in Figure 5. The original notch angle of 45° is modified to simplify the meshing. For both standard and reconstituted samples, the meshing, boundary conditions and modeling are identical except that for the reconstituted specimen the material behaviour law is modified in the weld joint and in the HAZ. In the standard (un-reconstituted) specimen, all meshes are characterized by a unique flow curve given in Figure 3 while the flow properties in the reconstituted specimen were chosen according to Figure 4.

The incremental theory of plasticity is used in combination with an isotropic strain-hardening model based on the Von Mises criterion. The mesh consists of about 841 eight-node isoparametric elements with reduced Gauss integration. Because of large geometry changes, the updated Lagrangian procedure is used to account for large strains and displacements. To avoid large mesh deformation and overlapping at the crack tip, an initial blunted mesh is used (radius of the crack tip = 20 μm). The mesh size and density are chosen to reduce computer time and to keep the solution nearly insensitive to mesh size. The specimen is loaded in three-point bending, the applied load being simulated by a vertical displacement.

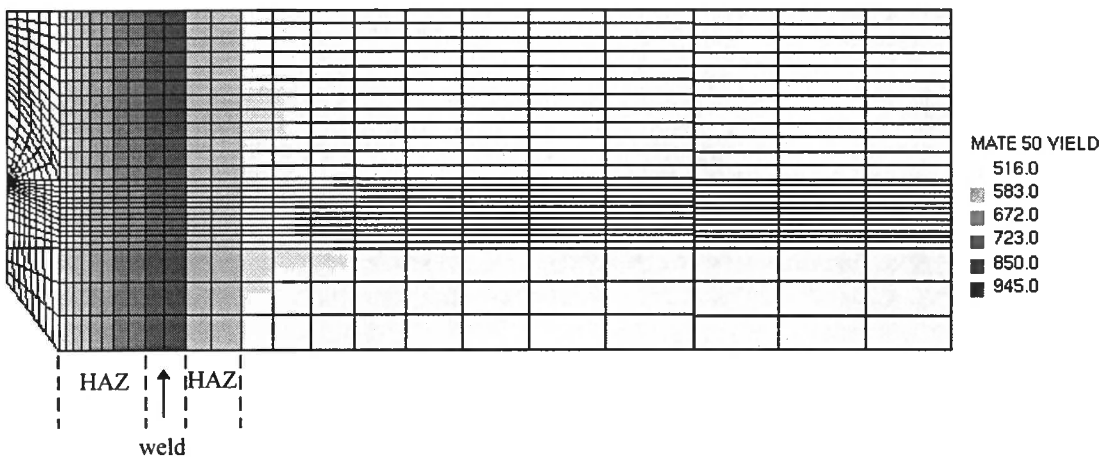

Figure 5. *Finite element meshing of the PCCv sample. Material variability is represented by various yield stresses. In the standard specimen, a unique flow curve is applied for all meshes.*

Results and Discussion

The influence of the weld zone is investigated by comparing both geometries in terms of:
- plastic zone extension,
- load versus displacement behaviour,
- J-integral (or equivalently K_J-level),
- and, stress distribution ahead of the crack tip.

It was already shown in [1] that in the Charpy impact test, the presence of the weld zone primarily affects the plastic zone pattern. The extension of the plastic zone in the standard specimen is shown in Figure 6. The loading corresponds to a 1 mm load line displacement, or equivalently, $K_J = 220$ MPa$\sqrt{}$m. It is clear that this plastic zone interacts with the weld region of the reconstituted sample. However, it is found that in the reconstituted sample, the plastic zone is only slightly smaller that in the standard specimen.

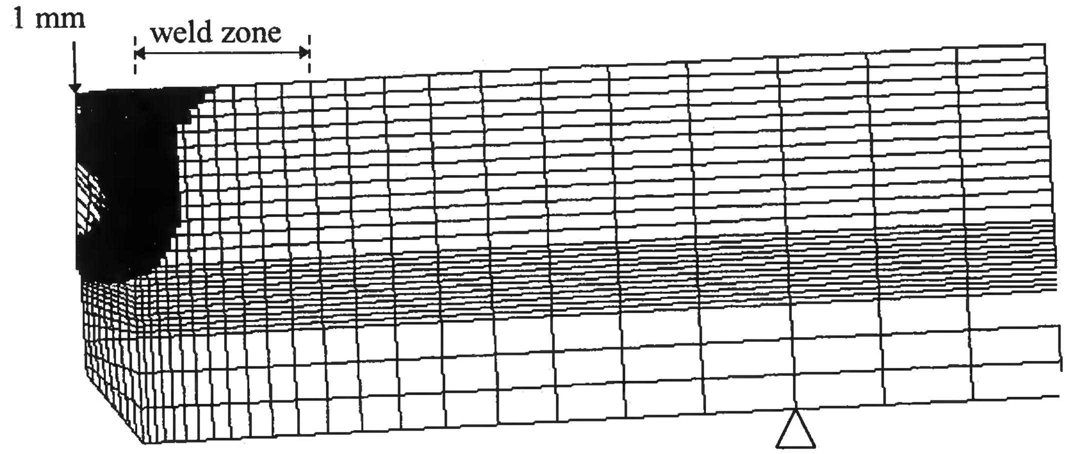

Figure 6. *Plastic zone in the standard (non reconstituted) specimen loaded to 1 mm displacement. The plastic zone interacts with the welded region. Load level corresponding to K_J=220 MPa√m.*

The load-displacement traces for both specimens are compared in Figure 7. No difference is found as long as the plastic zone does not reach the reconstituted zone. For larger load levels, the reconstituted specimen exhibits slightly higher loads (about 3.5% higher). This can be associated with the higher yield stress in the weld region.

To compare the fracture resistance of both situations, the J-integral concept is used. The J-integral is determined by integration along a path surrounding the crack tip and by the energy release rate formulation based on the load-displacement trace. It should be mentioned that the load point displacement is derived from the crack mouth opening displacement (CMOD). These two quantities are plotted in Figure 8: "K from integral" is the reference value that governs the fracture mechanism determined by the local stress-strain conditions, while "K_{rec} and K_0 from CMOD" are determined using the load-displacement trace and the plastic energy formulation. Figure 8 shows that for the standard sample, the measured fracture toughness slightly under-estimates the actual value but remains conservative. The difference between these two values is less than 2.5% for K_J levels up to 220 MPa√m. In the reconstituted situation, the fracture toughness is under-estimated by less that 5% on the conservative side as well. Consequently, the fracture toughness of the reconstituted sample is slightly lower (about 3%) than the value of the standard sample.

In the transition region, cleavage fracture occurs when a critical stress is reached over a characteristic distance ahead of the crack tip. The distribution of the opening stress ahead of the crack tip is determined for each specimen and compared in Figure 9 for two loading levels, K_J = 118 and K_J = 204 MPa√m. No significant difference is found between both cases.

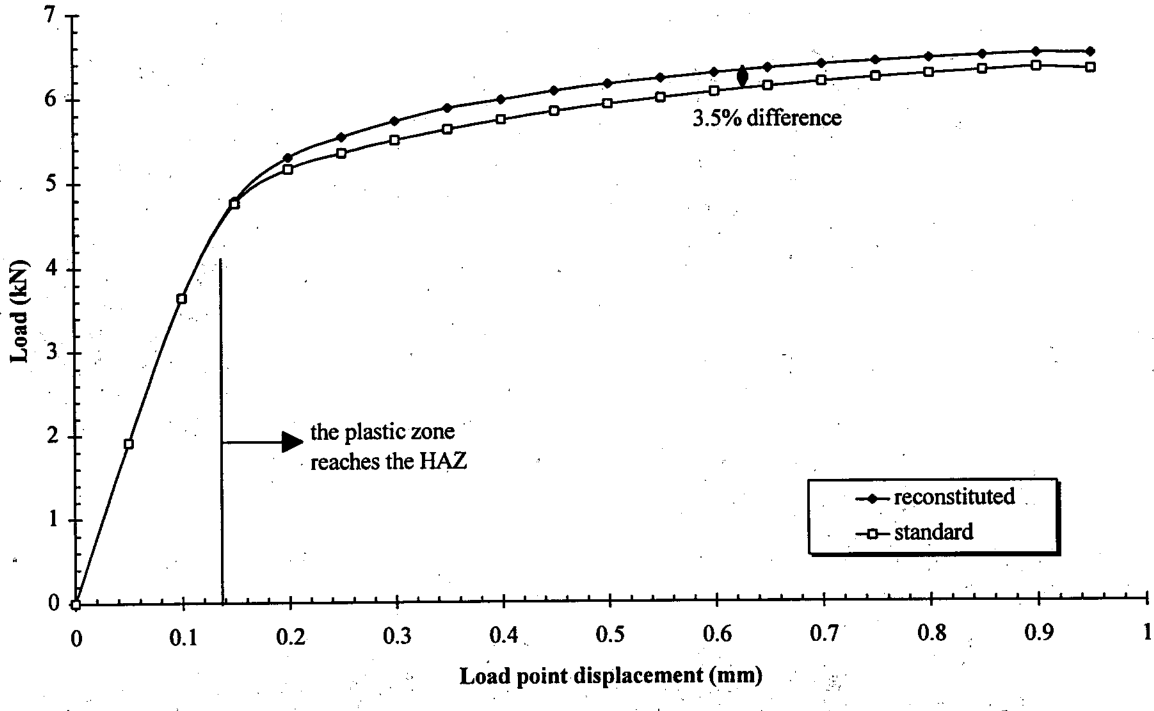

Figure 7. *Load-displacement recordings for both standard and reconstituted specimens. The difference in load does not exceed 3.5%.*

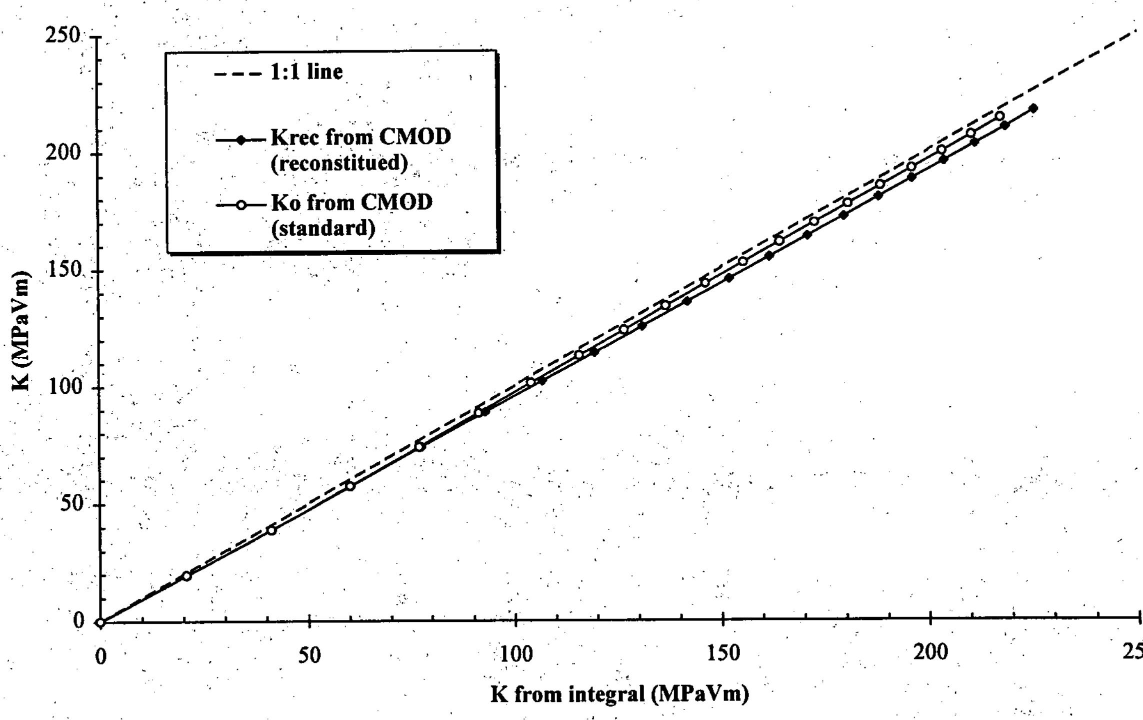

Figure 8. *Very small differences are found between K determined by local integration and K evaluation using the load versus displacement (CMOD) trace: K_0 for standard and K_{rec} for reconstituted sample.*

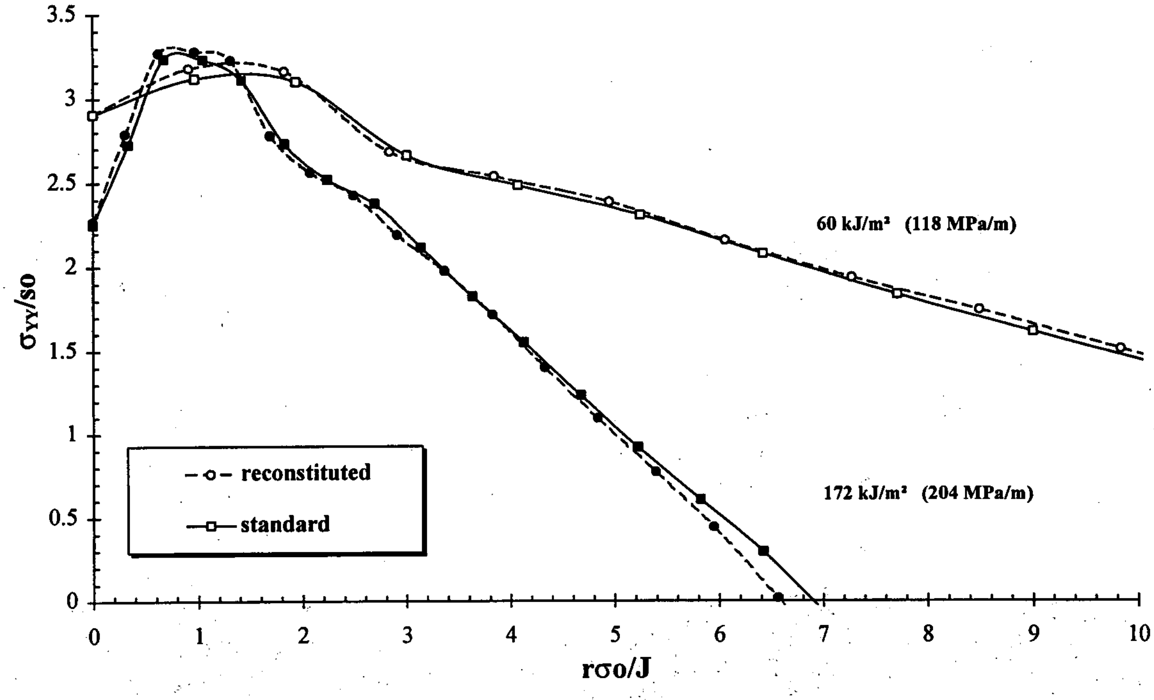

Figure 9. *Opening stress as a function of normalized distance from the crack tip for load levels of J=60 and 172 kJ/m² (σ_0=516 MPa). J is calculated by integration on a path surrounding the crack tip.*

Conclusions

The effect of the heat affected zone (HAZ) resulting from reconstitution is investigated through finite element analysis. Very small differences are found on the load-displacement curves as well as on the resulting K_J-values. This is also supported by the stress distribution ahead of the crack in both situations.

The presence of a hardened zone surrounding 3 mm of original material leads to slightly lower (less than 5%) fracture toughness values, which from the safety viewpoint, are conservative. This conclusion is supported by the stress distribution ahead of the crack tip which is almost unaffected by the presence of the HAZ.

References

[1] E. van Walle, "Reconstitution: where do we stand", Effects of Radiation on Materials, 17th International Symposium, ASTM STP 1270, David S. Gelles, Randy K. Nanstad, Arvind S. Kumar and Edward A. Little, Eds., American Society for Testing and Materials, 1996, pp. 415-441.