A J-INTEGRAL APPROACH FOR EVALUATING THE INFLUENCE OF RESIDUAL STRESSES ON FRACTURE BEHAVIOR

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ABSTRACT

A study has been made concerning the effect of residual stresses on the fracture behavior of structural steels. Appropriate techniques were applied to induce different residual stress fields in the vicinity of fatigue precrack tip in SENB specimens. Measurements of residual stresses were carried out using an X ray diffraction method while the fracture resistance was evaluated on the basis of J-integral approach, at a temperature within the ductile-brittle transition range. A semi-quantitative analysis was then developed in order to estimate the contribution of the residual stress fields to the J-values corresponding to the critical fracture event. This makes it possible to calculate the residual stress fields originally introduced in the crack tip vicinity and to compare them with those measured experimentally.

KEYWORDS

J-integral, unstable fracture, residual stresses, structural steels.

INTRODUCTION

Normally, residual stress fields arise from the fabrication processes or from the elastic loading during the assemblage of structures or from both. Their distribution in mechanical components and structures is a complex function of many variables. While some of these variables are related to the material properties and to the geometry of the components, others depend on the nature and parameters of the fabrication process.

An important problem associated with the presence of residual stress fields is that they can, in many cases, affect the fracture behavior of the component or structure (Ainsworth, 1986; Chell, 1986). For example, surface or near surface compressive residual stresses, introduced by shot peening, appreciably improve the fatigue resistance of structural components (Wohlfahrt, 1987), as the compressive residual stresses reduce the effective tensile stresses acting along the loading direction. On the other hand, the introduction of tensile residual stresses in regions near the crack tip, due to welding for example, may have a detrimental effect on the fracture behavior of structures (Rybicki and Stonsifer, 1980). Premature failure can thus occur, under different loading conditions, at a stress level inferior to what would normally be expected. Further, tensile residual stresses acting in the thickness direction may be high enough to enhance triaxiality of the total stress state and hence promote brittle fracture (Knee, 1990).

This work represents an approach to evaluate the influence of residual stresses on the fracture behavior of high strength low alloy structural steels tested in the ductile-brittle transition temperature (DBTT) range. Following ESIS' recommendation (ESIS, 1991) for toughness testing in this range, a J-integral approach was adopted and critical J-values were determined in the presence and in the absence of residual stress fields, making it possible to assess the effect of these on the fracture resistance. The critical J-values may also permit an estimation of a stress intensity factor K^S associated with the secondary (residual) stress fields. The residual stresses at a given point in the vicinity of the crack tip could thus be calculated from K^S and then compared with those originally introduced in the test specimens.

MATERIALS AND EXPERIMENTAL METHODS

The materials used in this investigation were two high strength low alloy structural steels (namely Weldox 700 and Weldox 900). The steels were received in the form of quenched and tempered 12 mm thick plates, having the following strength levels (determined at -40°C)

	0.2% Yield Limit (MPa)	Ultimate Stress (MPa)
Weldox 700	880	930
Weldox 900	1040	1070

The tensile ductility, expressed by the percentage reduction in area at failure, is 65 and 70% for Weldox 700 and Weldox 900, respectively.

Ten millimeter thick SENB specimens were machined in the L-T orientation and fatigue cracking was carried out according to ESIS (1991). After precracking, all of the specimens were stress relieved at a temperature of 500°C for 2 hours in order to eliminate residual stresses resulting from machining and fatigue precracking. Residual stresses were then introduced in the vicinity of the fatigue precrack. Following Smith *et al.* (1987) and Pereira (1994), compressive residual stresses were generated by preloading, which consisted of loading the specimens to a crack mouth displacement of 0.5 mm, followed by total unloading. Tensile residual stresses,on the other hand, were introduced adopting a local heating procedure, henceforth designated hot spot technique, using a welding simulation device. Details of this technique are described elsewhere (Formby and Griffiths, 1977; Pereira, 1994).

Surface residual stresses were measured by means of an X ray diffraction method. Description of the equipment and details of the experimental procedure are found in Pereira (1994). Following this procedure, the transverse residual stress (perpendicular to the precrack plane) was determined directly ahead of the precrack tip (y = 0) at x = 1, 2, 3, 4 and 5 mm, as well as at points across from the crack plane (x = 1 mm) at y = -4, -2, 0, 2 and 4 mm.

Fracture tests were carried out following ESIS (1991). Critical J-values were determined by monotonically loading the testpieces upto the point of fracture instability at a temperature of -40°C. This test temperature was selected because it belongs to the DBTT range, where both steels are oftenly used.

RESULTS

Transverse residual stresses, σ_t, determined at different points around the precrack tip are presented in Figures 1 and 2 for Weldox 700 and Weldox 900, respectively. These distributions were obtained by averaging measurements made on both sides of the specimens.

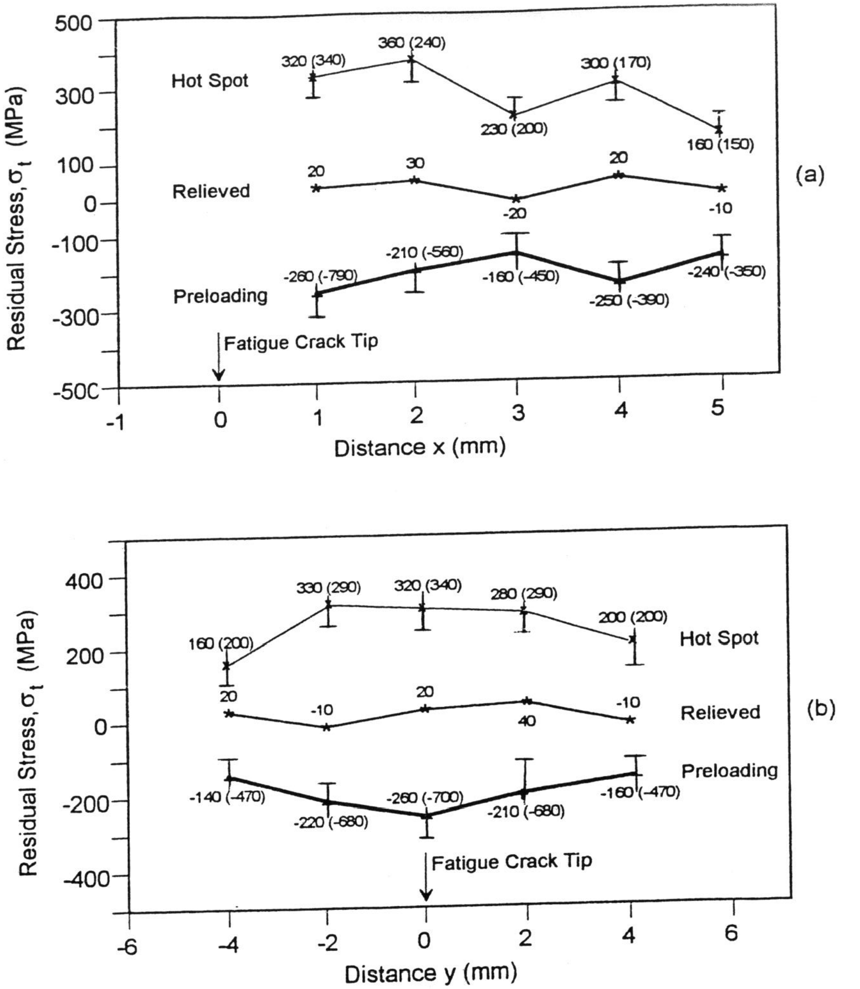

Fig. 1. Transverse residual stress distribution for Weldox 700 steel specimens, (a) ahead of the crack tip (y=0) and (b) across crack plane (x=1 mm)

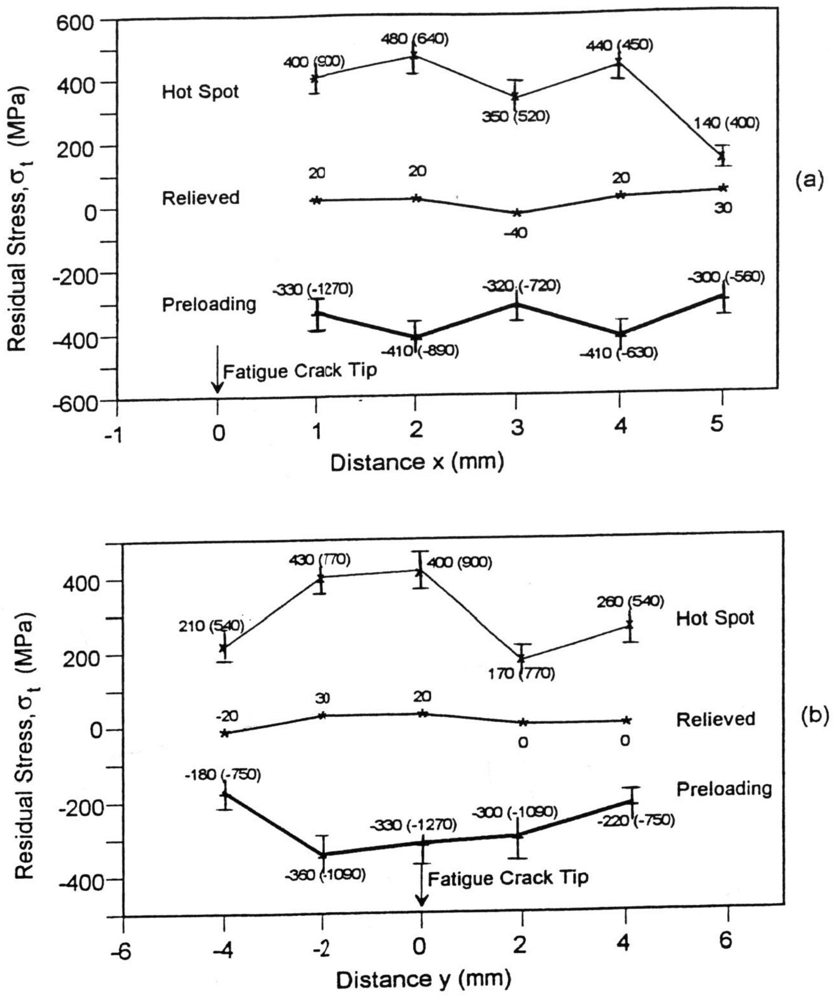

Fig.2. Transverse residual stress distribution for Weldox 900 steel specimens, (a) ahead of the crack tip (y=0) and (b) across crack plane (x=1 mm)

As one may expect, residual stresses are essentially nil for the stress relieved condition, compressive for the preloaded specimens and tensile for the specimens that were subjected to localized heating (hot spot technique). The numbers between brackets in these figures refer to calculated transverse residual stresses, as will be shown later (see Discussion).

Average critical J-values corresponding to fracture instability are listed in Table 1. Each J-value in this table represents the average of at least five fracture test results. At this point it is important to mention that each individual test result was found to satisfy the J_{Ic} validity criteria relative to the specimen dimensions (ASTM, 1988).

TABLE 1 Average J-Integral Values at Fracture for Weldox 700 and Weldox 900 Steels (P refers to preloading, HS hot spot and SR stress relieving)

Steel	Condition	J(MPa.m)
Weldox 700	P	0.098
	HS	0.079
	SR	0.082
Weldox 900	P	0.203
	HS	0.141
	SR	0.162

DISCUSSION

Fracture specimens tested in the DBTT range exhibited a non-linear load-displacement record and fracture resistance evaluation should thus be based on an elastic-plastic fracture mechanics parameter. However, as unstable fracture was not preceded by significant stable crack propagation, the determination of such a parameter did not involve establishing an R curve. Rather, as pointed out earlier, the critical J-values reported in Table 1 were calculated at the point of fracture instability, which was preceded by limited crack extension. In fact, scanning electron microscopy observations of the fracture surfaces have indicated that, whenever it was detected, stable crack extension was always less than 0.2 mm (Pereira, 1994).

Residual stresses measured at points around the precrack tip in the stress relieved condition were found to be essentially nil. Accordingly, the corresponding critical J-value, henceforth designated J_c, is to be considered a material's property. The toughness levels, represented by the J_c values , listed in Table 1 for the two steels, are seen to be consistent with their mechanical characteristics. The Weldox 900, which is the higher strength material, exhibits a better ductility compared to the Weldox 700. As the fracture mechanism in both steels is one of ductile failure, higher strength combined with higher ductility would lead to better toughness (Ritchie and Horn, 1978).

As to the effect of residual stresses on the fracture resistance, the data listed in Table 1 indicate that the critical J-value is higher in the presence of compressive residual stresses. Here the applied and residual stress fields act in opposite senses and compressive stresses are to be overcome before failure can occur, implying in an increase in the fracture resistance. In the presence of tensile residual stresses, on the other hand, the fracture resistance is expected to be lower compared to that determined for the stress relieved condition (Table 1). However, this decrease in fracture resistance could indeed be attributed to residual stresses, only if the local heating (hot spot) technique did not result in significant microstructural changes. In this respect, two aspects are worth noting. First, the steels, received in the quenched and tempered condition, had their tempering treatment performed at 620 and 580° C, for the Weldox 700 and

900, respectively. Accordingly, the stress relief treatment carried out at 500° C is not expected to introduce relevant microstructural or property changes. In fact, plastic properties measured for the two steels in the stress relieved state were essentially equivalent to those determined for the as-received condition. Further, microstructures observed for both steels were not altered by stress relieving, for two hours, at a temperature of 550° C (Pereira, 1994). The second aspect that should be mentioned here is related to the fact that a peak temperature of only 500° C was actually reached, after about of 40 s, by local heating, thus insuring the generation of tensile residual stresses in the crack tip vicinity without introducing significant microstructural changes.

Considering the change in the critical J-value brought about by the residual stress field, one may associate with this field a secondary J-integral, J^S. Accordingly, at the critical fracture event, one can state, to a first approximation, that

$$J_c = J_c' + J^S , \tag{1}$$

where J_c' corresponds to the critical J-integral value at fracture instability in the presence of residual stresses. J_c' can thus be designated as apparent toughness to be distinguished from the real toughness J_c determined for the stress relieved condition, i.e., in the absence of residual stresses.

Knowing J_c and J_c', one can calculate J^S and hence a corresponding stress intensity factor K^S, using the expression

$$K^S = \left[\frac{EJ^S}{1-\nu^2}\right]^{1/2} , \tag{2}$$

where E is the elastic modulus and ν Poisson's ratio. The values of J_c , J_c', K_{Ic} (calculated from J_c) and K^S are listed in Table 2. One may observe that K^S is negative for preloaded specimens, indicating that compressive residual stresses tend to close the crack.

TABLE 2 Average Values of J_c, J_c', K_{Ic} and K^S

Steel	Condition	J_c (MPa.m)	J_c' (MPa.m)	K_{Ic} (MPa.m$^{1/2}$)	K^S (MPa.m$^{1/2}$)
Weldox 700	P	-	0.098	-	-63
	H	-	0.079	-	27
	SR	0.082	-	142	-
Weldox 900	P	-	0.203	-	-101
	H	-	0.141	-	72
	SR	0.162	-	201	-

The residual stress field, σ^S_{ij} , at a point (r,θ) around the crack tip is related to K^S by the expression

$$\sigma^S_{ij}(r,\theta) = \frac{K^S}{\sqrt{2\pi r}} f_{ij}(\theta) \tag{3}$$

where $f_{ij}(\theta)$ are given functions of θ (see Dowling, 1993). Using equation (3), it would be possible to reassess the residual stress fields in the vicinity of the precrack tip. As an example, one can calculate the transverse residual stresses from equation (3) at the points where these stresses were measured (Figures 1 and 2) and, then, compare the calculated values (shown in brackets in Figures 1 and 2) with those determined experimentally. As may be concluded from these figures, the calculated and experimental σ_t values are in fair agreement, for the case where tensile residual stresses were induced by the hot spot technique. A possible source for the observed difference could indeed be related to the through thickness variation in residual stresses, resulting from variation in temperature gradiente along the specimen thickness. Experimental results obtained by Pereira (1994) have indicated that residual stress values measured at points in the central region of the specimen could be as much as 30% lower than those determined for points at the surface. This is seen to be in qualitative agreement with the results shown in Figure 1(a) where the transverse stress, due to hot spot, measured at the surface is consistently higher than the calculated value.

For compressive residual stresses, on the other hand, the estimated stress levels are seen to differ considerably from those measured experimentally. This difference can be attributed, at least in part, to the fact that, while the measurements were made at the specimen surface, the calculated residual stress levels are related to K^S, which should reflect the stress state also along the specimen thickness. The plastic zone formed ahead of the crack tip in the central region of the specimen (plane strain) is smaller than that formed under essentially plane stress conditions, i.e., on the specimen surface. The strain distribution will be correspondingly more diffuse on the specimen surface and the resulting residual stress levels are expected to be lower there compared to the central region. This seems to be borne out by the observation that the calculated stress levels are consistently higher than the measured ones.

Finally, it is worth noting that plastic deformation, as well as possible stable crack extension, preceding fracture instability are expected to alter the residual stress distribution in the precrack vicinity. Accordingly, the secondary stress intensity factor K^S should, in fact, correspond to the residual stresses that do exist in the material at the critical fracture event.

CONCLUSIONS

The J-integral approach seems to be appropriate for evaluating the influence of residual stresses on the fracture behavior of high strength low allow steels in the ductile-brittle transition temperature range.

It has been shown that residual stress fields affect the fracture resistance. The value of J, and correspondingly K, at the point of fracture instability decreases with the action of tensile residual stresses, whilst both parameters increase in the presence of compressive residual stresses.

Based on the difference between the real and apparent toughness values, a reassessment of residual stresses acting along the loading direction can be achieved. However, the calculated values are seen to be in fair agreement with the experimental results only for the case of tensile residual stresses introduced by the hot spot technique .

REFERENCES

Ainsworth, R. A. (1986). The treatment of thermal and residual stresses in fracture assessments. *Eng. Fract. Mech.*, **24**, 65-76.

ASTM (1988). Standard test method for J_{Ic} - a measurement of fracture toughness. ASTM E 813-87. In: *1988 Annual Book of ASTM Standards*. ASTM, Philadelphia.

Chell, G. G. (1986). A J-estimation procedure for combined mechanical, thermal and residual stresses. *Int. J. Pressure Vessels Piping*, **23**, 187-213.

Dowling, N. E. (1993). *Mechanical Behavior of Materials*. Prentice Hall, Englewood Cliffs.

ESIS (1991). Procedure for determining the fracture behaviour of materials. ESIS P2-91D/ Second Draft. *ESIS Publications*, Delft.

Formby, C. L. and Griffiths, J. R. (1977). The role of residual stresses in the fracture of steel. In: *Proc. Conference: Residual Stresses in Welded Constructions and their Effects*, pp. 379-394. The Welding Institute, Cambridge.

Knee, N. (1989). Coping with residual stresses in the integrity assessment of an as welded repair. In: *Proc. European Symposium on Elastic-Plastic Fracture Mechanics*, pp. 173-187. EMAS Publications, Warley.

Pereira, M. (1994). *Effect of residual stresses on the fracture behaviour of steels of different yield limits*. Doctoral Dissertation, University of Kassel. VDI-Verlag, Dusseldorf.

Ritchie, R.O. and Horn, R. M. (1978). Further considerations on the inconsistency in toughness evaluation of AISI 4340 steel austenitized at increasing temperatures. *Met. Trans. A*, **9A**, 331.

Rybicki, E. F., Stonsifer, R. B. and Olson, R. J. (1981). Stress intensity factors due to residual stresses in thin-walled girth-welded pipes. *J. Pressure Vessel Technology*, **103**, 66-74.

Smith, D. J., Bourke, M. A. M., Hodgson, A. P., Webster, G. A. and Webster, P. J. (1991). Residual stresses in cracked specimens subjected to prior loading. *Welding Institute Members Report* 431/1991. The Welding Institute, Cambridge.

Wohlfahrt, H. (1987). Practical aspects of the application of shot peening to improve the fatigue behaviour of metals and structural components. In: *Proc. Third Int. Conf. on Shot Peening*, pp. 563-584. DGM-Verlag, Oberursel.