A SIMPLIFIED METHOD FOR EVALUATING RESIDUAL STRESSES BY MEANS OF CTOD MEASUREMENTS

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The purpose of this paper is to suggest a simplified method for relating residual stresses and fracture resistance. Residual stresses were generated in the crack tip vicinity of SENB specimens and measured using X-ray diffraction technique while the fracture resistance was evaluated on the basis of the Crack Tip Opening Displacement. Then, a semi-quantitative approach was developed in order to evaluate the secondary stress intensity factor. Finally, a possible re-assessment of the residual stresses is presented and discussed.

INTRODUCTION

An important problem associated with strength and toughness evaluation is the presence of residual stress fields. While compressive residual stresses can improve fatigue resistance of structural componentes, the presence of tensile residual stresses may promote brittle fracture, fatigue or stress corrosion cracking (1,2). Evaluation of the influence of residual stresses on fracture events can be adequately solved by simple linear superposition of the stress intensities induced by the primary and secondary stresses. Accordingly, the purpose of this paper is to determine the effect of residual stresses on the fracture resistance of a structural steel by comparing critical CTOD values. This comparison can also permit an estimation of a stress intensity factor K^S due to secondary (residual) stresses (3). The stress fields calculated from K^S are to be compared with those originally introduced in the test specimens.

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EXPERIMENTAL

A high strength low alloy structural steel (namely Weldox 900) quenched and tempered (yield strength and tensile strength of about 880 and 930 MPa, respectively) has been selected for this investigation. Three point bend specimens of 10mm thickness were machined in the L-T orientation, while fatigue precracking was carried out according to (4). After precracking all the specimens were stress relieved at a temperature of 500°C during 2 hours.

Residual stresses were generated in the vicinity of the fatigue precrack tip. Compressive residual stresses were introduced by preloading that consisted of loading the specimens to a total MOD of 0.5mm followed by full unloading (3). Tensile residual stresses were introduced by means of the "hot spot" technique using a welding simulator (3). Measurements of surface residual stresses were carried out by X-ray diffraction method. Description of equipment and details of procedure are found in (3). Transverse residual stresses (perpendicular to the crack plane) were measured ahead of the crack tip ($y = 0$mm) at $x = 1, 2, 3, 4$ and 5mm as well as across crack plane ($x = 1$mm) at $y = -4, -2, 0, 2$ and 4mm.

Fracture mechanics tests were carried out according to reference (4). Critical CTOD (δ) values were determined by loading the test pieces monotonically up to the point of fracture instability at a temperature of -40°C (previously selected according to ductile-brittle transition curves of the steel).

RESULTS

Transverse residual stresses, σ_t, are presented in Fig. 1. These distributions were obtained by averaging measurements made on both sides of the specimens. Average values of the critical fracture parameter are listed in Table 1.

TABLE 1- Average critical δ for Weldox 900 steel specimens at -40°C.

Condition	δ(mm)
Preloading	0.094
"Hot-Spot"	0.065
Stress Relieved	0.075

DISCUSSION

The flow properties in the stress relieved condition were not affected by the heat-treatment, meaning that no significant microstructural changes have occurred (3). So, δ value determined in the stress relieved condition can be considered as inherent toughness of the steel.

It is clearly evident from the data listed in Table 1 that the value of δ is lower in the presence of tensile residual stresses. Residual stresses at the fatigue crack tip induce an initial displacement δ^S. In the case of compressive residual stress fields, the applied and residual stresses act in opposite senses and the compressive residual stresses are to be overcome before the external loading can cause any displacement at the crack tip. For tensile residual stresses, the external and residual fields reinforce each other and this could lead to premature failure of the specimens. To a first approximation, one can, then, state that:

$$\delta_c = \delta'_c + \delta^S \qquad (1)$$

where δ_c is the critical δ, δ'_c is δ related to primary stresses and δ^S is δ related to the presence of residual stresses. Therefore, δ'_c can be designated as an apparent toughness to be distinguished from the real toughness, δ_c, determined for the stress relieved condition. Knowing δ_c and δ'_c, one can calculate δ^S and hence a corresponding K^S using the expression:

$$K^S = \left(\frac{2E\sigma_f\delta^S}{1-\nu^2}\right)^{1/2} \qquad (2)$$

where E is the elastic modulus, σ_f the flow stress and ν Poisson's ratio. Table 2 shows the values of δ_c, δ'_c, K_{Ic} (calculated from δ_c) and K^S. The values of K^S for preloading are negative in the sense that compressive residual stresses tend to close the crack.

TABLE 2- δ and K values for Weldox 900 in different conditions.

Condition	δ_c(mm)	δ'_c(mm)	K_{Ic}(MPa.m$^{1/2}$)	K^S(MPa.m$^{1/2}$)
Preloading	-	0.094	-	-100
"Hot-Spot"	-	0.065	-	73
Stress Relieved	0.075	-	199	-

The residual stress field, σ_{ij}^{S}, at (r,θ) ahead of the crack tip is related to K^S:

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

where $f_{ij}(\theta)$ are given functions of θ. A possible re-assessment of the transverse residual stresses could be achieved using eq. (3). For this purpose, r was replaced by 1, 2, 3, 4 and 5mm and θ was considered equal to zero. Table 3 gives the values of σ_t^S (calculated from K^S) compared to those measured (σ_t) at the surfaces of the specimens (Fig 1a).

A difference between the values of σ_t^S and σ_t is to be expected (3). An argument for this difference is that, while σ_t was measured at the surfaces of the specimens, σ_t^S is relative to K^S which reflects the intensity of stresses at the fatigue precrack tip in the central region of the specimen. The plastic zone ahead of the crack tip due to preloading and "hot-spot"in plane strain (in the mid-thickness of the specimens) is much smaller than in plane stress (at the surfaces of the specimen) because the yielding is restricted. For this

TABLE 3- Comparison between calculated σ_t^S and measured σ_t values of the transverse residual stresses (the numbers 1, 2, 3, 4 and 5 refer to distance in mm ahead of the crack tip).

Condition		σ_t^S (MPa)	σ_t (MPa)
Preloading	1	- 1260	-330
	2	-890	-410
	3	-730	-320
	4	-630	-410
	5	-560	-340
"Hot Spot"	1	920	400
	2	650	480
	3	530	350
	4	460	440
	5	410	160

reason, the strain distribution at the surfaces is correspondingly more diffused whilst in the mid-thickness the strain gradient is steep due to plastic constraint. Consequently, the residual stresses should be higher in the mid-thickness in order to fit a higher strain gradient.

Another possible source for this difference may be the fact that eq. (3) is not sufficiently accurate to provide a re-assessment of the residual stresses of the first-kind (3). This expression evaluates the stresses for an area close to the crack tip only and, therefore, the K values evaluated by means of eq. (3) are relative to a local approach. This limitation seems to apply for δ since this is a quantity determined locally at the site of interest. Its magnitude is a direct measure of the events occurring at the crack tip irrespective of conditions remote from the crack tip. Nevertheless, the residual stresses of the first-kind involve several grains, i.e., a large area. The residual stresses that were evaluated in this research are classified as residual stresses of the first-kind and contrast with the fact that eq. (3) is applicable to evaluations just ahead of the crack tip.

CONCLUSIONS

1. It has been shown, through a semi-quantitative approach, that residual stress fields affect the fracture resistance. The value of δ as well as 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.

2. A re-assessment of transverse residual stresses has been carried out on the basis of the difference between the real and the apparent toughness of the material. The calculated residual stresses are considered in fair agreement with those measured experimentally.

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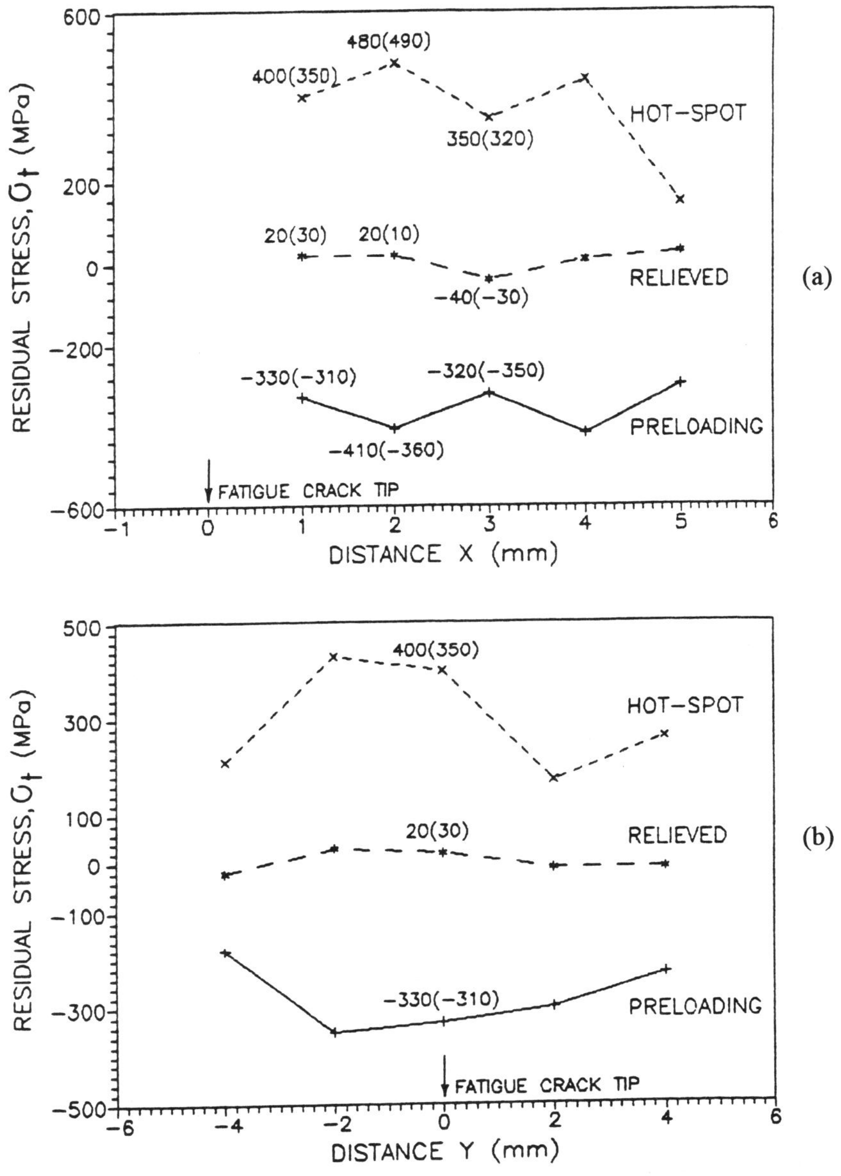

Figure 1 Transverse residual stress distribution: (a) along crack plane at y = 0mm and (b) across crack plane at x = 1mm.