INFLUENCE OF RESIDUAL STRESSES ON THE FRACTURE BEHAVIOR OF STEELS IN THE TRANSITION RANGE

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Experimental investigations are reported regarding the influence of residual stress fields on the fracture behavior in the toughness transition range of high strength constructional steels. The hot-spot technique and room temperature prestressing are applied to generate residual tensile and compressive stress states in the crack tip vicinity. The residual stress distribution is evaluated by means of X-ray measurements and by using the hole-drilling method. The results confirm a significant influence of the residual stresses on brittle fracture initiation in the transition temperature range.

INTRODUCTION

The introduction of compressive residual stresses at surface layers can improve the fatigue resistance while reducing the effective tensile stress component acting along the loading direction. But tensile residual stresses due to welding or thermal cycles etc. may have the opposite effect, such as drastically reducing the service life time or contributing to premature fracture of structural components with the enhancement of the multiaxiality of the stress state additionally triggering brittle fracture. The evaluation of the influence of residual stresses on low stress fracture events (low temperature brittle fracture, subcritical crack growth at low stress intensities) is adequately solved by simple linear superposition rules of the stress intensities induced by the primary and secondary stresses, but their effect on the transition from lower to upper shelf toughness in structural steels remains an open question. The R6 and reference stress approaches (1-5) represent engineering treatments to handle the problem in a simplified manner.

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EXPERIMENTAL PROCEDURE

TABLE 1: Investigated Materials

Steel	R_e(20°C) MPa	R_m(20°C) MPa	Tü °C	Microstructure
Weldox 700 [1]	860	890	-40	martensitic-bainitic
stress relieved [2]	840	880		
Weldox 900 [1]	990	1020	-30	martenstic-bainitic
stress relieved [2]	990	1030		

[1] Continuously rolled plate, quenched from 920°C/H_2O, tempered at 620°C/0.5h (Weldox 700) and 580°C/0.5h (Weldox 900), resp.

[2] The stress relief heat treatment of the specimens was performed at 550°C/ 2h.

Generation of Residual Stresses. Residual tensile stresses were introduced by means of the ***"hot spot"*** technique using a welding simulator with cooling the outer surfaces of the specimen. The center of the hot spot was located at the crack tip showing a peak temperature T ≅ 470°C (Fig.1). Compressive residual stresses were realized by *preloading* the precracked samples at 20°C till below general yield but well above the anticipated fracture load at the test temperature (Fig.2). A CMOD≈ 0.55mm proved to be appropriate.

Fracture Mechanics Testing was performed using 3-point bend specimens with a cross section of 10 x 20 mm^2. Fatigue precracking (a/W ≅ 0.5) was done applying a two step high R-ratio procedure (R=0.1→0.5). The fracture tests were performed at T = -40°C. This temperature was chosen with respect to the evaluated Charpy impact transition temperature (Fig.3). The toughness parameters were derived according to the ESIS procedure P2-91D.

Residual Stress Measurements were performed on the side surfaces of the specimens by X-ray diffraction ($\sin^2\psi$-method) after surface removal up to 0.5mm. The measurements were done ahead of the crack tip (y=0mm) at x = 1, 2, 3, 4, 5 mm as well as across the crack plane (x=1.0mm) at y = -4, -2, 0, +2, +4 mm. Additionally, the hole-drilling method (hole depth till 3mm) was applied in order to evaluate the through-thickness residual stress distribution ahead of the crack tip (at x=1mm, y=0mm).

EXPERIMENTAL RESULTS

Residual Stress Distribution. The distribution of the transversal component of the residual stresses created by the hot-spot and preloading techniques is depicted in Fig. 4-6 as compared to the stress relieved condition. Considering the limited local resolution the anticipated distribution is observed. Besides a minor excentricity of the hot-spot with respect to the crack plane, a qualitative difference between the hot-spot and preloading conditions is obvious in that the hot-spot stresses are maximized at the specimen surface. According to the higher strength level of Weldox 900 the created residual stresses in this steel are higher but more concentrated around the crack tip.

Fracture Toughness. The results of the fracture tests are summarized in Fig.7. Fracture occured without or after sufficiently small precritical crack growth, i.e. $\Delta a \leq 0.2$mm. Thus, the CTOD and J-Integral at instability, i.e. (δ_c) and (J_c), are given in dependence on the ratio σ_t/σ_y, with σ_t - transversal residual stress component 2mm ahead of the crack tip and σ_y - yield stress. In terms of an "effective toughness" both measures are markedly enhanced by residual compressive stresses, but reduced in the residual tensile stress field. In accordance with the higher strength level both toughness figures exhibit less scatter and a clearer residual stress influence for Weldox 900. By means of additional experiments strain hardening and crack tip blunting during preloading as well as the hot-spot thermal treatment were proven not to exert any significant influence. Data analysis based on the R6 strip yield approach with the residual stresses altering the applied side and a simple superposition of the stress intensity due to primary and secondary stresses gave only roughly consistent results (6).

CONCLUSIONS

1. An experimental procedure has been developed for the investigation of the influence of residual stresses on the fracture behavior of higher strength steels in the transition range of toughness.
2. The investigations revealed the enhancement of the fracture resistance due to compressive residual stresses produced by prestressing as well as its decrease in the presence of tensile residual stresses around the crack tip.
3. Further research should cover the whole transition range from the lower to the upper shelf as well as FEM calculations, which allow to incorporate the residual stresses in a straightforward manner.

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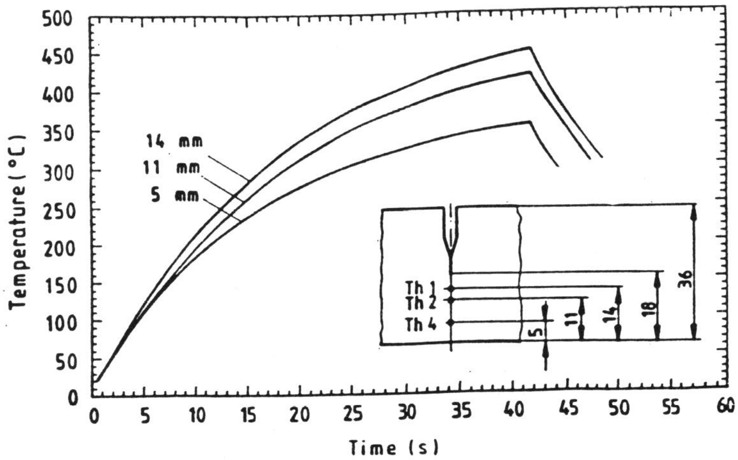

Fig.1: Hot-spot thermal cycles measured ahead of the crack tip using thermocouples (Th), StE 690, 18mm thick SENB specimen

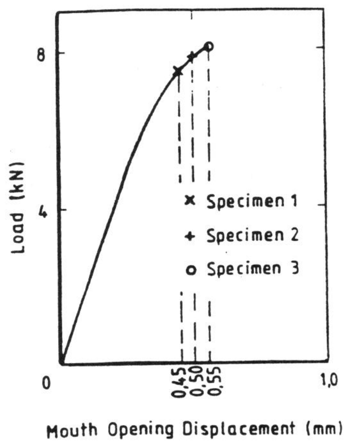

Fig.2: Screening tests for the preloading technique

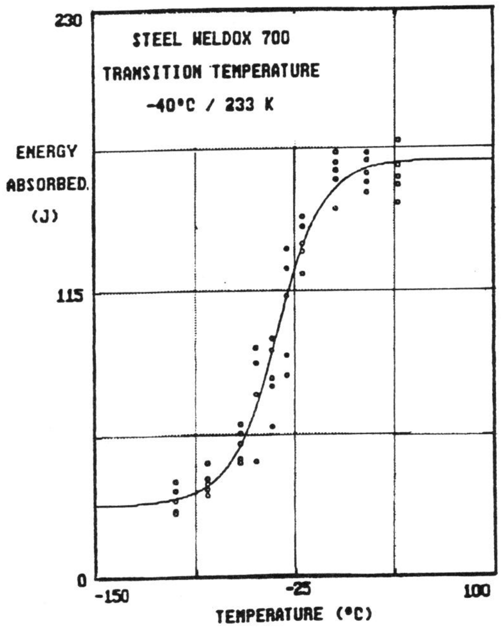

Fig.3: Charpy-V energy transition of Weldox 700

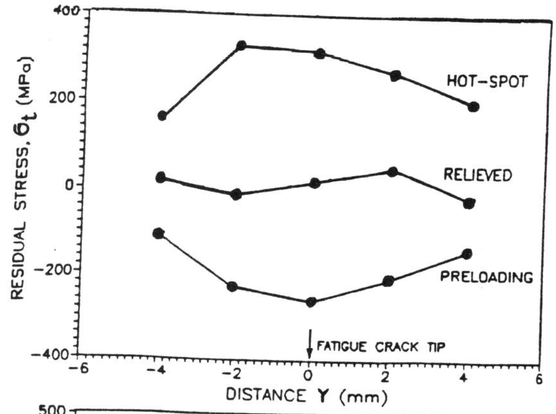

Fig.4:
Residual stresses, distribution across the crack plane at x=1.0mm, transversal component σ_t Weldox 700

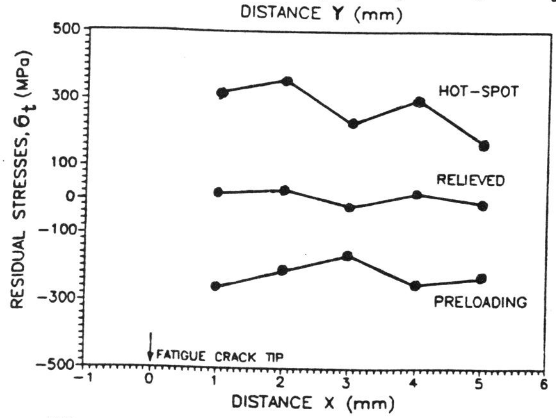

Fig.5:
Residual stresses, distribution along the unracked ligament (W-a) transversal component σ_t Weldox 700

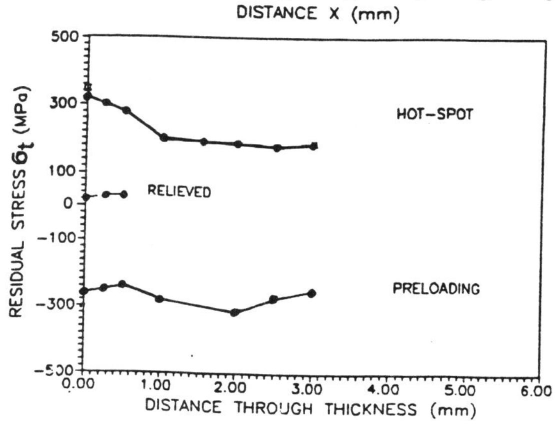

Fig.6:
Residual stresses, through-thickness distribution,
transversal component σ_t Weldox 700

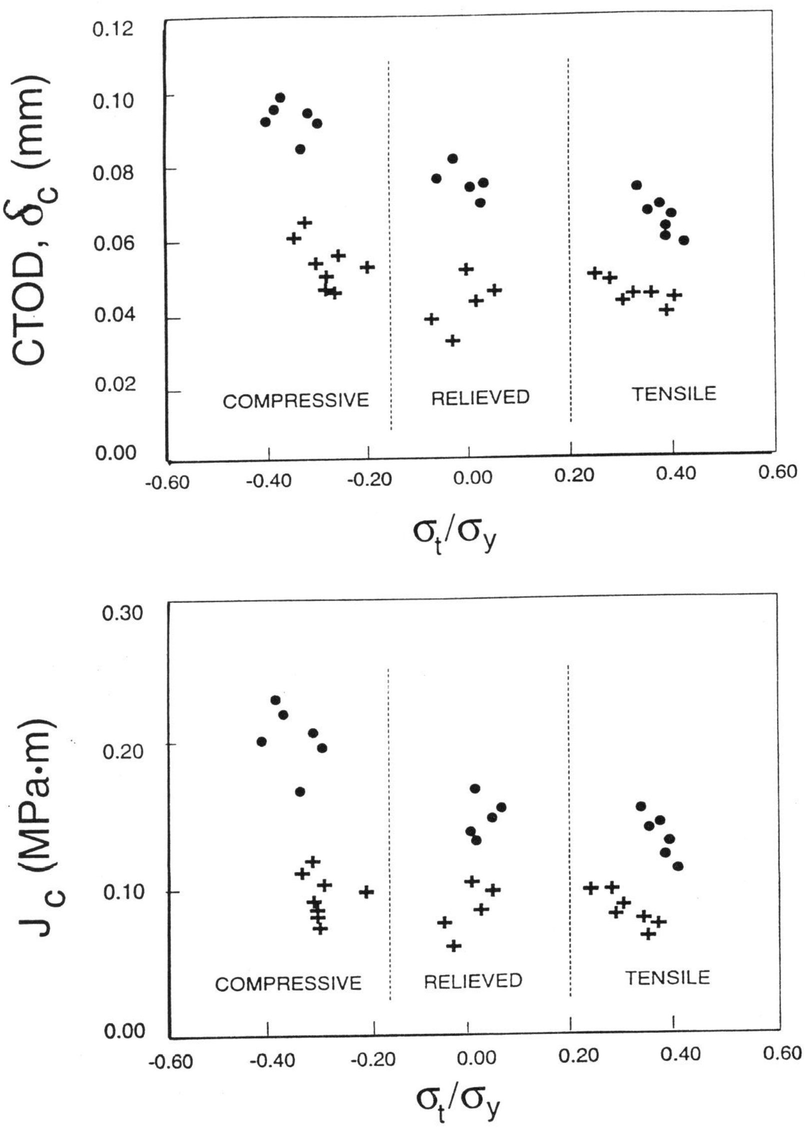

Fig.7: Influence of residual stresses on unstable (cleavage) fracture initiation (precritical crack growth $\Delta a \leq 0.2$mm)
+ - Weldox 700, • - Weldox 900