# FRACTURE BEHAVIOUR CLOSE TO CRACK INITIATION IN PRESENCE OF RESIDUAL STRESS FIELDS

**M. Pereira**

Catholic University of Rio de Janeiro (PUC-Rio) and CEFET "CSF" - RJ
Department of Materials Science and Metallurgy
P.O. Box 38008, Rio de Janeiro, RJ, CEP 22453-900, Brazil

**H. Wohlfahrt**

Technical University of Braunschweig (TU Braunschweig)
Institute of Welding Technology
Langer Kamp 8, 38106 Braunschweig, Germany

**M. Schaper**

Technical University of Dresden (TU Dresden)
Institute of Materials Science
Helmholtzstr. 7, 01062 Dresden, Germany

**Abstract**. The purpose of this work is to investigate fracture resistance close to crack initiation in a high strength structural steel in the presence of residual stresses. Residual stress fields were produced in the fatigue precrack region and measured on the surface of the specimens using X-ray diffraction as well as in the crack tip using the hole-drilling method. The specimens were tested at a temperature within the ductile-brittle transition region of the material. The fracture resistance was then evaluated on the basis of the Crack Tip Opening Displacement (CTOD) and J-integral. It was possible to determine qualitatively the influence of the residual stresses on the fracture resistance behaviour. Tensile residual stresses acting in the loading direction result in a decrease of the fracture resistance of the specimens.

**Resumo**. O objetivo desta pesquisa é investigar a iniciação de trincas em aço estrutural de alta resistência mecânica na presença de tensões residuais. Tensões residuais foram produzidas na região da pré-trinca de fadiga. Mediu-se a distribuição das tensões residuais nas superfícies dos corpos de prova através de difração de raios-X, enquanto que, na região diretamente à frente da ponta da pré-trinca de fadiga, adotou-se a técnica do "furo-cego". Os corpos de prova foram ensaiados em temperatura pertencente à região de transição dúctil-frágil do material. A resistência à fratura foi avaliada com base na abertura da ponta da trinca (Crack Tip Opening Displacement, CTOD) e da Integral J (J-Integral). As tensões residuais trativas, agindo na direção do carregamento dos corpos de prova, foram responsáveis pela diminuição da resistência à fratura.

## 1. INTRODUCTION

An important problem associated with the strenght and the fracture toughness of materials is the presence of residual stress fields which arise from the fabrication processes or from the elastic loading during the assemblage of structures or both. Their influence on the fracture toughness of materials is largely studied. High tensile residual stresses in regions near the crack tip may promote brittle fracture, fatigue and stress corrosion [1-4]. In such cases they can lead to a premature failure of the structural member and occurs at a stress level inferior to what would normally be expected. They increase the effective tensile stress component acting along the loading direction. Compressive residual stresses can improve the fatigue resistance of materials [5], reducing the effective tensile stress, increasing the closure at the fatigue crack tip and consequently, retarding the growth rate. The residual stress fields may also contribute to an enhancement of the multiaxiality of the total stress state [6]. Residual stress fields acting in the thickness direction may be high enough to restrict the straining in this direction, thus creating a plane strain condition.

## 2. EXPERIMENTAL PROCEDURE

A low alloy high-strength structural steel StE 690, namely N-A-XTRA 70, has been selected in this investigation. The mechanical properties and microstructures are reported in Table 1.

### 2.1 Specimen Preparation

SENB specimens of 18mm thickness were machined in the L-T orientation, according to the ESIS P2-91D procedure [7]. Fatigue precracking with an a/W equivalent to 0,5 was carried out applying a "step-wise high R-ratio" procedure ($R = 0.1 \rightarrow 0.5$) to ensure a uniform fatigue precrack front shape [8]. After fatigue precracking all the specimens were stress relieved at a temperature of 550°C during 2 hours.

### 2.2 Generation of Residual Stresses

It was possible to create surface and subsurface compressive residual stress fields by means of shot-peening [9]; both sides of the specimens were peened at the fatigue precrack region, making use of globular steel shots with a diameter of 1.397mm and an Almen intensity of 9C.

Tensile residual stresses were introduced by means of two different techniques [9]. Some specimens have been subjected to a grinding, for the purpose of creating surface and subsurface tensile stress states. The grinding direction coincided with the crack propagation direction and the specimens were dry ground with a corundum grinding wheel on both sides. Cutting speed and depth of cut were set at 28 m/min and 0.005mm, respectively.

Tensile residual stresses through the thickness of the specimens were created by means of a special heating technique called "hot-spot" which was carried out on a welding simulator [9]. Copper electrodes were pressed at each border of the specimens. A water cooling system was placed on surfaces of the specimens in order to allow a heat concentration in the fatigue precrack region only. The procedure has been controlled by the peak temperature measured on the specimen surface within 5mm of the fatigue precrack tip. When the peak temperature reached the range of 450-500°C the simulation was stopped.

### 2.3 Residual Stress Measurements

The surface residual stresses has been evaluated by means of X-ray diffraction and according to the multiple exposure $\sin^2\Psi$ method [10]. The measurements were done ahead of the precrack tip (y=0mm) at x = 1, 2, 3, 4, 5mm as well as across crack plane (x = 1.0mm) at y = -4, -2, 0, +2, +4mm. The subsurface residual stresses up to a depth of 0.5mm were also measured by X-ray diffraction after an electropolishment. Additionally, the hole-drilling method [11] was performed in order to evaluate the residual stress fields up to a depth of 3mm ahead of the crack tip.

### 2.4 Fracture Mechanics Testing

Fracture mechanics tests have been carried out in three-point bending at -20°C, according to the ESIS P2-91D procedure [7]. The temperature was chosen with respect to the evaluated Charpy impact transition temperature.

## 3. RESULTS

The distribution of the transversal component of the residual stresses is depicted in Figs. 1-3. Each distribution has been obtained by averaging both specimens sides while the average value of all specimens (both sides) in the same condition is given in brackets.

The specimens exhibited a non-linear force-displacement record and stable crack growth. The plotting of the fracture resistance $\delta$ and J against $\Delta a$ has been carried out according to the ESIS P2-91D procedure [7]. The ductile regime fracture parameters $\delta_{0.2/BL}$, $J_{0,2/BL}$, $\delta_{0.2}$ and $J_{0.2}$ were selected to characterize the fracture resistance of the specimens. These parameters are presented in Table 2.

## 4. DISCUSSION

The "hot-spot" induces tensile residual stresses in a region which has been subjected to a local compressive yielding [9]. Caused by a local heating, a volume of material expands whilst the cool material surrounding this "hot-zone" restricts its expansion and consequently, this restriction leads to yielding. The contraction of the "hot-zone" is constrained during cooling due to the irreversible plastic deformation. Thus, the surrounding elastic material has to make the system fit and exerts tensile residual stresses on the plastically deformed area in order to achieve a self-equilibrating condition.

According to Table 2 one remark must be made. It concerns the specimens which were subjected to shot-peening and grinding. If one takes into account that both techniques induce superficial and residual stress fields only [9], it could be expected that there is no significant influence on the fracture resistance data of the specimens with a thickness of 18mm. To evaluate the influence of surface finishing treatments on the fracture resistance of the materials, it is more convenient to use thin specimens [1].

The presence of tensile residual stresses due to "hot-spot" influenced the fracture parameter as is shown in Table 2. This influence could be expected if one observes Figs. 4 and 5. The stretched zone width of a specimen which has been subjected to "hot-spot" is smaller than that of a specimen subjected to shot-peening (provided that surface treatment did not influence the fracture resistance of the specimen as discussed early). Since the stretched zone width is correlated with the CTOD at crack initiation then the parameters close to this event should be also influenced [9].

The transversal residual stresses at the fatigue precrack tip induces it to an initial "crack-opening" displacement [9, 12, 13]. The external and residual loads reinforce each other when testing starts and they both lead to a premature fracture of the specimen. The "crack-opening" effect is the cause of lower values of CTOD close to crack initiation after "hot-spot" technique. The results obtained in the presence of tensile residual stresses are very similar to those obtained in the presence of thermal stresses [2-6]. Some premature crack initiation in pressure vessels have been observed and attributed to the "crack-opening" due to the thermal stresses.

## 5. CONCLUSIONS

A fundamental problem relative to the strength and the fracture resistance of materials has been the main topic of this research. Here are the conclusions:

- In the vicinity of the fatigue precrack tip tensile residual stress fields are induced successfully by the "hot-spot" technique.

- CTOD and J-Integral seem to be appropriate parameters to evaluate the influence of the residual stresses on the fracture behaviour of high-strength steels in the ductile-brittle transition region.

- It has been possible to determine qualitatively the influence of residual stresses on crack initiation. The tensile residual stresses acting in the load direction diminish the fracture resistance of the materials markedly.

- Surface treatments, if applied to thick specimens, do not affect their fracture behaviour in monotonic loads.

## REFERENCES

[1] Sinha, F., Prasad, T. and Mishra, A., "Influence of residual stresses on fracture behaviour: an experimental study", Eng. Fract. Mech. **21**, 1113-1118 (1985).

[2] Rybicki, E.F., Stonesifer, R.B. and Olson, R.J., "Stress intensity fractors due to residual stresses in thin-walled girth-welded pipes", J. Pressure Vessel Technol. (Trans. ASME) **103**, 66-P74 (1981).

[3] Rybicki, E.F. and Stonesifer, R.B., "An LEFM analysis for the effects of weld-repair-induced residual stresses on the fracture of the HSST ivt-8 vessel", J. Pressure Vessel Technol. (Trans. ASME) **102**, 318-323 (1980).

[4] Bryan, R.H. et al., "Test of thick vessel with a flaw in residual stress field", J. Pressure Vessel Technol. (Trans. ASME) **103**, 85-93 (1981).

[5] Wohfahrt, H., "Shot-peening and residual stresses", Proceedings of the Army Materials Conference Residual Stress and Stress Relaxation, London, United Kingdom (1982), pp. 71-84, Plenum Press, London (1982).

[6] Wohlfahrt, H., "Residual stresses due to welding: their origin, calculation and evaluation", Proceedings of the European Conference on Residual Stresses, Karlsruhe, Germany (1983), pp. 81-86, DGM Verlag, Oberursel (1983).

[7] European Structural Integrity Society (ESIS), "ESIS procedure for determining the frature behaviour of materials"/ESIS P2-91D, ESIS Publications, Delft (1991).

[8] Koçak, M. et al., "Effects of welding residual stresses on fatigue precracking of CTOD specimens" Proceedings of the International Conference: Residual Stresses 89, Los Angeles, U.S.A. (1989) pp. 249-254, IITT-International, Gournay-Sur-Marne (1990).

[9] M. Pereira, "Efffect of residual stresses on the fracture behaviour of steels of different yield limits", Ph.D. Dissertation, Kassel University, Kassel, Germany (1993), VDI Verlag, Düsseldorf (1994).

[10] Preckel, U., Eigenspannungen - Rechnergestutzte Bestimmung in Umformteilen, Verlag TUV Rheinland GmbH, Koln, Germany (1988).

[11] ASTM, "Standard method for determining residual stresses by the hole-drilling strain-gage method", ASTM E 837-81, American Society for Testing and Materials, Philadelphia (1982).

[12] Martinez, L.L., Pereira, M. and Wohlfahrt, W., "Effects of residual stress fields on the brittle fracture of high-strength structural steels", Proceedings of EUROMAT 92, Genua, Italy (1992), AIM, Milano (1992).

[13] Pereira, M., Wohlfahrt, H. and Schaper M. "Influence of residual stresses on the fracture behaviour of steels in the transition range", Proceedings of the 10th European Conference on Fracture: Structural Integrity, Berlin, Germany (1993), pp. 755-760, EMAS Publishers, Warley (1993).

**Table 1** - Mechanical properties and microstructures for StE 690 steel

| | Mechanical properties and microstructures | | | | | |
|---|---|---|---|---|---|---|
| | $\sigma_Y$ (MPa) | | $\sigma_t$ (MPa) | | $T_0$(°C) | microstructures |
| | room | -20°C | room | -20°C | | |
| AR | 730 | 750 | 865 | 870 | -60 | tempered martensite and lower bainite |
| SR | 715 | - | 835 | - | - | tempered martensite and bainite |

AR = as-received condition. Continuously rolled plate, water quenched from 920°C, tempered at 620-650°C/30 min.
SR = stress-relieved condition performed at 550°C during 2 hours.
$T_0$ = ductile-brittle transition temperature.

**Table 2** - Ductile regime fracture parameters close to the onset of crack initiation.

| CONDITION | $\delta_{0.2/BL}$(mm) | $\delta_{0.2}$(mm) | $J_{0.2/BL}$(MPa.m) | $J_{0.2}$(MPa.m) |
|---|---|---|---|---|
| SHOT-PEENING | 0.350 | 0.270 | 0.525 | 0.400 |
| GRINDING | 0.295 | 0.215 | 0.460 | 0.335 |
| "HOT-SPOT" | 0.238 | 0.200 | 0.400 | 0.315 |
| STRESS-RELIEVED | 0.350 | 0.280 | 0.556 | 0.450 |

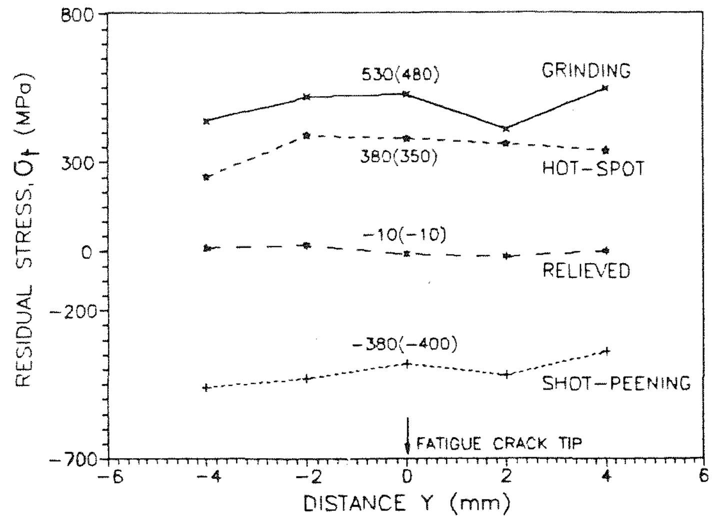


Fig. 1 - Transversal residual stresses, distribution across the crack plane at x=1.0mm.

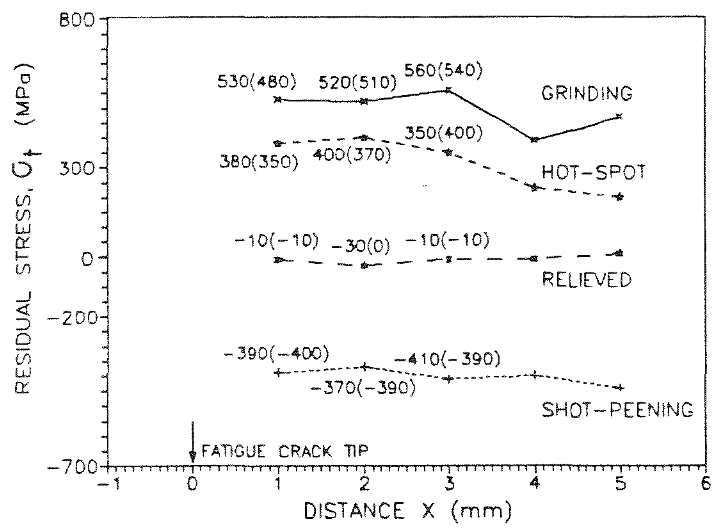


Fig. 2 - Transversal residual stresses, distribution along the uncracked ligament at y=0mm.

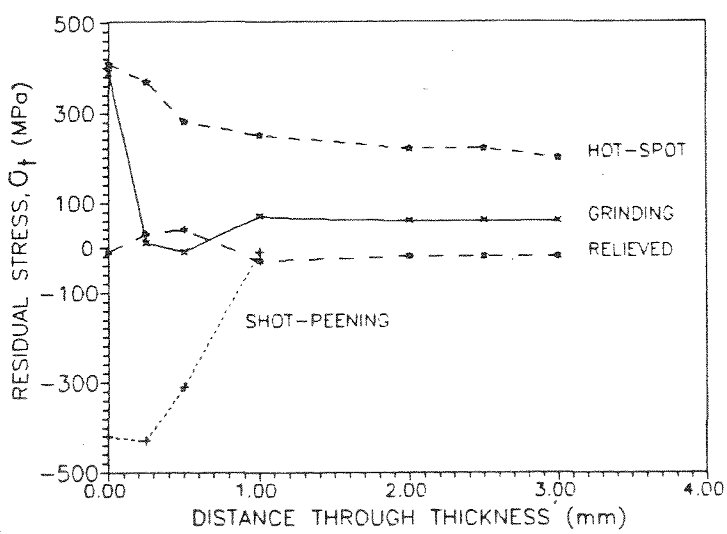


Fig. 3 - Transversal residual stresses, through-thickness distribution.

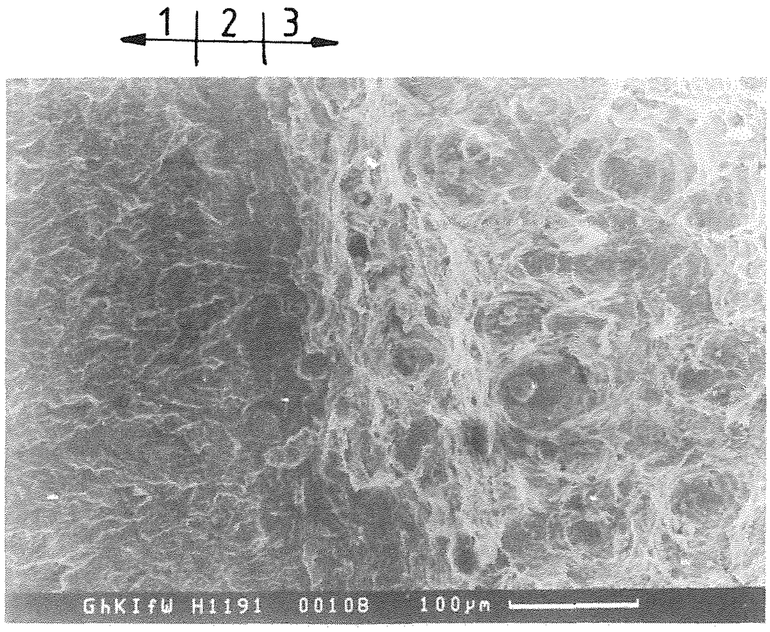


Fig. 4 - Fractographic feature close to crack initiation in a specimen subjected to shot-peening. Fatigue precrack extension (1), stretched zone (2) and stable crack growth (3).

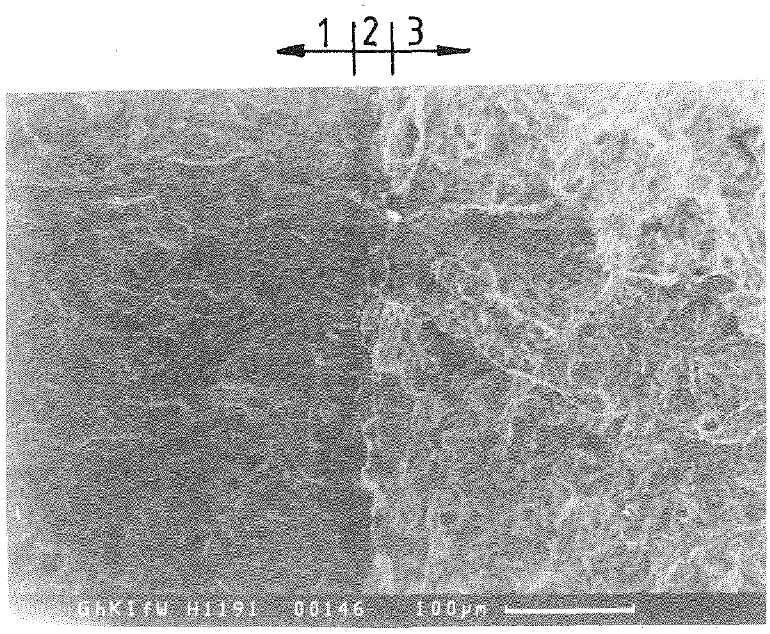


Fig. 5 - Fractographic feature close to crack initiation in a specimen subjected to "hot-spot". Fatigue precrack extension (1), stretched zone (2) and stable crack growth (3).