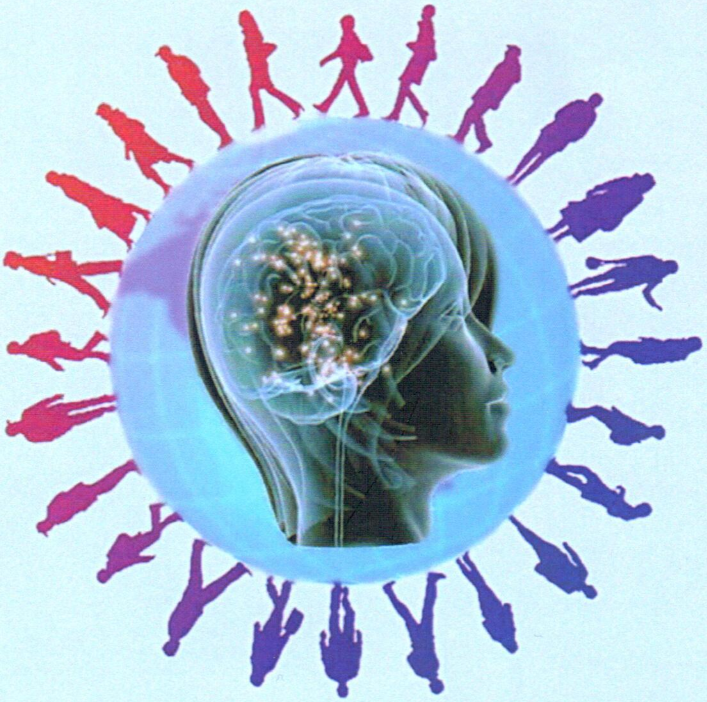
Multiscaling and Mesomechanics Aspects of Globalization in Science and Culture

Budapest, Hungary, Sept. 25-28, 2012

Edited by
George C. Sih
Tamás Fekete
Filippo Berto



Hungarian Academy of Sciences
Centre for Energy Research

Effect of strain localization at the crack tip and material hydrogenation on fracture toughness of heat resistant steel

P. Maruschak[a], I. Okipnyi[a], S. V. Panin[b], I. Konovalenko[a]

[a]*Ternopil National Ivan Pul'uj Technical University, Ruska 56, Ternopil, 46001, Ukraine*
[b]*Institute of Strength Physics and Materials Science SB RAS, Tomsk, 634021, Russia*
email: Maruschak.tu.edu@gmail.com.

Abstract

The fracture toughness of steel 15Kh2MFA(II) after the PTL was investigated. It was established that the crack start is a multilevel process, in which the defining role is played by the turning modes of deformation. Regardless of the PTL modes in air and in the aggressive medium (electrolytic hydrogen), the resistance to brittle failure of the steel investigated increases as compared to static fracture toughness of the material in the initial state.

Keywords: Fracture; Failure; Fatigue crack; Strain localisation; Hydrogenation; Thermomechanical loading.

1. Introduction

The main idea of applying the preliminary thermomechanical loading (PTL) to bodies with crack-like defects consists in the following: the material is subjected to force loading at the temperature that exceeds that of the brittle-to-ductile transition, which allows increasing its fracture toughness due to blunting and stress relaxation at the fatigue crack tip [1]. In this connection, it is topical to use the approaches of physical mesomechanics, which considers deformation and failure of materials as the multilevel hierarchically organized process, in which the internal borders of the material define the size and behavior of independent subsystems [2]. From this point of view, the PTL process creates a highly defective substructure, which blocks the development of strain at the microlevel leading to stress relaxation at the mesolevel. One of the parameters that link the structural properties of the material to its crack growth resistance is the zone of stretching (SWZ) [3]. Most often it is considered as a barrier, which characterises the material ductility at the crack start.

Its appearance is caused specifically by the crack tip blunting and activation of localized microplastic processes that precede its growth [4]. Thus, this parameter allows linking the structural and mechanical properties of the material to its crack growth resistance.

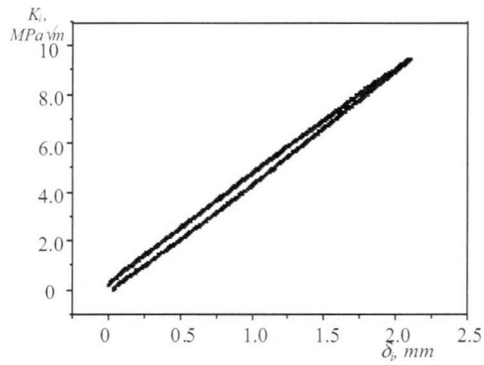
This work is dedicated to studying the scale levels of deformation and regularities in strain localization at the crack tip in steel 15Kh2MFA(II) before and after the PTL.

2. Research technique

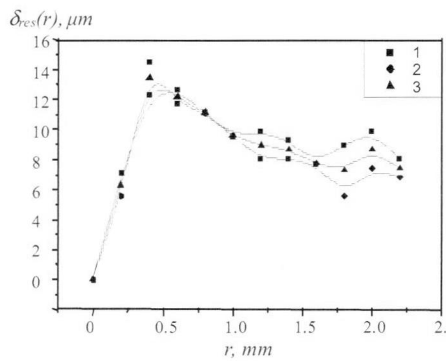
Crack growth resistance of the material in the initial state and after the PTL was investigated on compact specimens with the thickness of 19 mm. The static crack growth resistance of the reactor pressure vessel steel 15Kh2MFA(II) was determined after thermal treatment, which simulates the material embrittlement in the WWER-440 reactor in the middle of its service life: tempering at 1000 °C for 6 h in oil; annealing at 600 °C for 6 h (one-time) in air.

Fatigue cracks were grown preliminarily on all the specimens at the load cycle asymmetry coefficient $R = K_{min} / K_{max} = 0.1$ and loading frequency of 40 Hz [1] (here K_{min} and K_{max} are the highest and the lowest values of the stress intensity factor (SIF), respectively). The relative crack length of the specimens investigated was (0.45 … 0.55)b (b is the specimen width). Taking into account the fact that the value of unloading has practically no effect on the critical SIF K_f value of steel 15Kh2MFA(II), the PTL scheme with a complete unloading was used during experiments [1]. The technique of the material hydrogenation was considered in detail earlier in [5] and is not described here. The microrelief in the zone of stretching (crack start) was studied using the stereoscopic fractography method, according to which several photo images of the same section were compared before and after a turn at an angle of 5°, 10°, 15° around the axis perpendicular to the direction of photography.

This method was used to study the morphology of the quasistatic fracture and measure the stretching zone height (h) of specimens after the PTL at various distances from the fatigue crack tip. Figure 1.(a) shows the values of the residual crack tip opening after the PTL. It should be noted (see Fig. 1.(a)) that after treatment the residual opening $\delta_{res}(r)$ remains at the crack tip, which is the manifestation of the deformation transition from the micro- to the mesolevel. The residual $\delta_{res}(r)$ and averaged residual crack opening on the specimen surface measured by the MIM-10 microscope depend on the alienation from the crack tip (Fig. 1.(b)). The $\delta_{res}(r)$ parameter attains its highest value at a distance of 0.4…0.6 μm from the crack tip r.



a



b

Fig. 1. Material deformation graph – a; dependence of $\delta_{res}(r)$ - r in steel 15Kh2MFA (II) after the PTL at a temperature of 623 K on its alienation from the crack tip – b; Front surface of the specimen (1); back surface of the specimen (2); averaged values (3).

Later on, a decrease in the residual crack opening is observed as it moves away from the crack tip. It should be noted that Fig. 2.(b) shows the data related to only one specimen after the combined PTL at 623 K and $\overline{K}_1 = 0.85$; the dependence for other specimens has a similar nature. We investigated specimens subjected to several processing schemes (D – specimens deformed statically; DC – specimens deformed with the application of the low-amplitude component; DCH – as in the previous case plus hydrogenation; *DH* – specimens deformed statically with the subsequent hydrogenation), see Table 1. [5].

Table 1. Dependence of the critical SIF Kf value after the PTL on the critical crack tip opening

Treatment scheme	K_f, MPa$\sqrt{m}$	δ_f, mm	h, mm	K_f, MPa$\sqrt{m}$
D	138.4	0.133	0.120	138.4
DC	108.1	0.076	0.100	108.1
DCH	121.8	0.118	0.400	121.8
DH	101.5	0.071	0.200	101.5

As a result of investigation of the fracture toughness of steel 15Kh2MFA(II) after the PTL it was established that the crack start is a multilevel process of the turning type. Regardless of the PTL modes in air and in the aggressive medium (electrolytic hydrogen), the resistance to brittle failure of the steel investigated increased as compared to static fracture toughness of the material in the initial state. In case of the static PTL, the resistance to brittle failure increased by 40 %, and for the hydrogenated material – by 20 % [5].

3. Analysis of the stretched zone and discussion of results.

The topicality of investigating the zone of stretching is confirmed by the main provisions of the deformation approach of fracture mechanics, according to which the fracture mechanism of the material and its ultimate state are determined by the limit value of strain at the crack tip.

The formation of this zone in the deformed specimens (*D*) is preconditioned by the localized yielding of the material at the crack tip by the shear mechanism, or due to sliding of individual sections of the material, Fig. 2.(a). The parameters of this zone depend on stresses that act in the structural component of the material. It is established that the geometry of the stretching zone of specimens (*DC*) has significant morphological non-uniformities caused by the imposition of the low-amplitude cyclic component during deformation, Fig. 2.(b). It was established in previous papers that the presence of hydrogen leads to the intensification of damage and embrittlement of the material [6]. In addition, we can presume that the critical opening value is the triaxility function of the stress state. Loading of the material with a crack-like defect leads to the appearance of singular stress fields and strains at its tip. The imposition of the cyclic component increases the size of the zone of stretching as compared to the initial state, Fig. 2.(c). The start and propagation of the crack in the specimen processed by the *DH* scheme took place upon the attainment of a much lower critical value of the defect opening and, correspondingly, the zone of stretching, Fig. 2.(d). If we consider the process of the crack start with due account of the concept of structural levels, we should indicate the consistency of evolution of the loss of shear stability at the tip of the crack-like defect. In addition, the microlevel is represented by grains and subgrains of the material, the mesolevel – by grain conglomerates, and the macrolevel considers the specimen as the quasiuniform medium. In this case, the mesolevel is implemented by shear displacements of grain conglomerates, which cause the nucleation and coalescence of micropores, and transition of the failure process to the macrolevel. Thus, proceeding from the physical ideas about the consistency of the crack nucleation, the microgeometry of fracture may testify to the presence of a certain level of microstresses, and a change of the shape – to a local blunting of the crack and the effect of deformation processes at the crack tip.

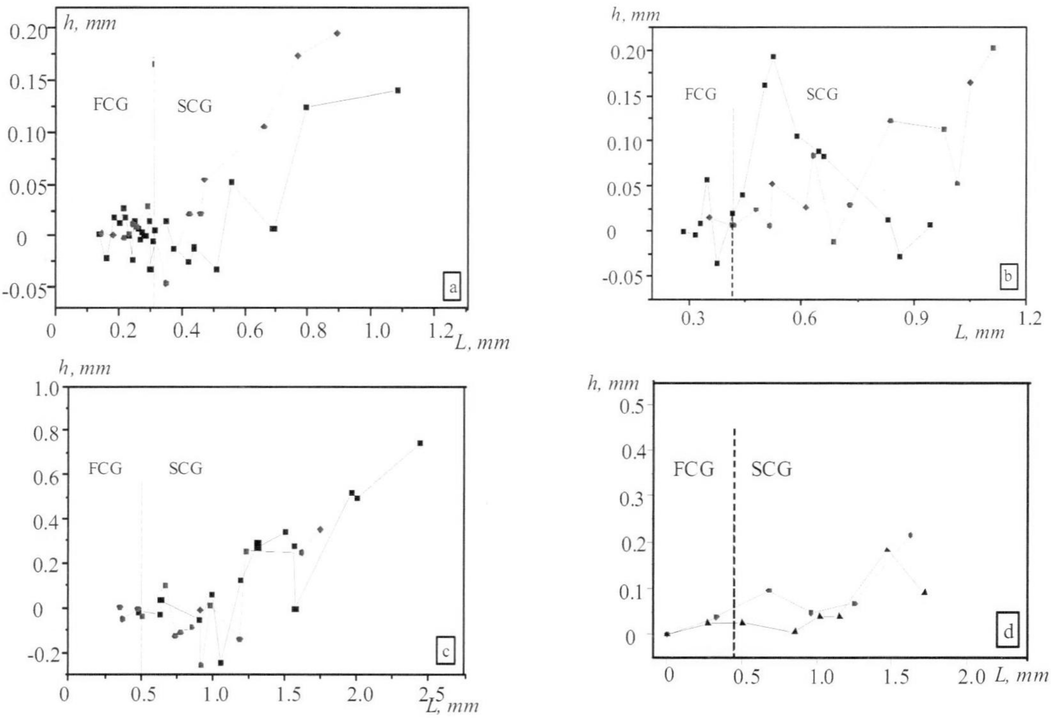


Fig. 2. Morphological peculiarities of the crack start section for specimens investigated under different deformation schemes, D – a; DC – b; DCH – c; DH – d, see Table 1; FCG – fatigue crack growth; SCG – static crack growth

4. Conclusions

The effect of the PTL modes on the structural and mechanical regularities in the material deformation at the crack tip is studied using the force and deformation parameters of fracture mechanics. The results obtained are the basis for a more precise definition of the guaranteed strength of structural elements with the crack-like defects. It is established that the main component of the crack start zone micromorphology is the dimples of microplastic deformation. They are present on fractographs of all the specimens investigated, which testifies to their active participation in the process of deformation of the microstructural components of the material, as well as disperse inclusions.

References

[1] Pokrovsky V.V., Troshchenko V.T., Kaplunenko V.G., Podkol'zin V.Yu., Fiodorov V.G., Dragunov Yu.G.: A promising method for enhancing resistance of pressure vessels to brittle fracture. Int J Pres Ves & Piping 1994; 58:9-24.

[2] Panin V.E., Grinyaev Yu.V., Egorushkin V.E.: Foundations of physical mesomechanics of structurally inhomogeneous media. Mech of Solids 2010; 45: 501-518.

[3] Margolin B.Z., Shvetsova, V.A., Gulenko A.G.: Radiation embrittlementmodelling for reactor pressure vessel steels: I. Brittle fracture toughness prediction. Int J Pres Ves & Piping 1999; 76, 715-729.

[4] Krasowsky A.J., Vainshtok V.A.: On a relationship between stretched zone parameters and fracture toughness of ductile structural steels. Int J of Fracture, 1981; 17: 579-592.

[5] Yasniy P.V., Okipnyi I.B., Maruschak P.O., Bishchak R.T., Sorochak A.P.: Toughness and failure of heat resistant steel before and after hydrogenation. Theor & Appl Fract Mech, 2011; 56: 63–67.

[6] Okipnyi I., Maruschak P., Sorochak A., Sergejev F.: Measurement of deformation hardening of heat-resistant steel of the WWER –type reactor. In: Proc. of the 8-th Int. conf of DAAAM Baltic Industrial Engineering (April 19-21), Tallin, Estonia, TUT; 2012, p. 694-699.