EXPONENT OF DEFORMATION HARDENING AND THE PROCESS ZONE IN HSLA STEELS

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Study represents the follow-up of previous analyses of influence of HSLA steel micro-structure on fracture toughness parameters, based on statistical-stereological studies of deformation fracture processes in front of the tip of fatigue crack, analysis of the shape and size of process or stretch zones and on individual failure micro mechanisms. Knowledge of influence of mechanical properties of HSLA steel on fracture toughness parameters is presented with particular attention to the exponent of deformation hardening n. Its physical importance from the viewpoint of influence of ferritic grains and precipitation hardening on the shape and size of plastic and process zones is discussed.

INTRODUCTION

The presented study is directly related with the results published in (1). In that paper we have presented basic methodic and fractographic procedures of determination of parameters of stretch and process zones in HSLA steels, see Fig. 1., as a starting point for the determination of the structural essence of parameters of fracture toughness. The basis is the knowledge of the structural essence of mechanical properties of HSLA steels (2). Special attention is paid to the importance of an exponent of deformation hardening "n" and its influence on parameters of the stretch zone and fracture toughness. The basic structural starting point is the knowledge of an effect of an embrittlement hardening component ΔR on values n, Fig. 2, which comprises first of all the precipitation hardening component. In this case it holds that: $\Delta R = R_e - R_{Mn} - R_G$, where $R_G = 19 . d^{-1/2}$ is the hardening contribution of a ferrite grain of size "d" and R_{Mn} is the substitution hardening on account of manganese (2).

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EXPERIMENT

Analyses were carried out on HSLA steels, hot rolled, with the following chemical composition: 0,73 - 0,10 % C; 0,5 - 1,4 % Mn; 0,03 - 0,11 % Si; 0,008 - 0,01 % P; 0,009 - 0,019 % S; microalloyed Nb, V, Ti with additions of Mo or Zr. Selection of structural states followed the aim to assure the variability of the size of a ferrite grain d (from 3,6 μm to 45 μm) and the state of precipitation which, expressed as the component ΔR, changes from 40 to 300 MPa. A complex of strength, plastic and brittle failure properties and parameters of fracture toughness were evaluated in all seven states in the temperature range from -196 °C to +20 °C. Fractographic analyses of individual failure micromechanisms were carried out together with the determinations of W_{SZ} and a_{SZ} parameters of the stretch zone.

ANALYSIS OF RESULTS

Fig. 3 shows the scheme of changes of stretch zone parameters and x_o parameter (Fig.1) with temperature as presented in the previous study (3). We can observe a lasting character of all stretch zone parameters with two temperatures defined for each structural state: Tx_o - transition temperature at which the first stable crack growth x_o can be observed and Tx_{oD} - transition temperature above which the stretch zone parameters remain unchanged and growth of ductile failure can be observed across the whole cross section.

Under the assumption of an elliptical shape the transitional behaviour of stretch zone parameters has been described (4) as follows:

$$x^2/W_{SZ}^2 + y^2/a_{SZ}^2 = \{ 1 + tgh \; [(T-T_o)/B] \}$$

where $T_o = (Tx_o + Tx_{oD}) /2$; $B = (Tx_{oD} - Tx_o) /2$;

Fig. 4 shows the dependence of W_{SZ} values on temperature and Fig. 5 the dependence of W_{SZmax} on the value of the of the deformation hardening exponent at $T > Tx_{oD}$. Despite the fact that surface ductile processes are involved in stretching we obtain a highly logical dependence. The growth of the exponent of deformation hardening results in a more intensive development of the stretch zone above the temperature Tx_{oD}. The figure shows individual states together with the ΔR values. It is obvious that the development of the stretch zone is primarily controlled by the embrittlement component of hardening ΔR. The increasing ΔR values suppress the development of the stretch zone. In the No.5 state the combined effect of considerable coarsening of grains and of the relevant ΔR value is involved.

Fractographic analyses of ductile growth x_o were used to determine the transition temperature Tx_o. Below this temperature an abrupt brittle failure of specimens occurs in the LEFM region after the previous blunting of the fatigue crack during the test of fracture toughness. Despite the limited set of data we succeeded in quantification of the effect of grain size d and the embrittlement component of hardening ΔR on the physically defined temperature Tx_o:

$$Tx_o = -85 - 30\ \ln d^{-1/2} + 0{,}4\ \Delta R\ ; \quad r = 0{,}94$$

From the viewpoint of fracture toughness parameter Tx_o is the highest temperature which allows to obtain valid K_{IC} values. By means of the Tx_o temperature we define the process of crack initiation and propagation with physical accuracy. Quantification of the influence of hardening contribution ΔR and R_Z on K_{IC} values, determined at the temperature Tx_o, acquired a form:

$$K_{IC} = 39{,}7 + 0{,}16\ R_Z - 0{,}11\ \Delta R ;(r = 0{,}9676)$$

This indicates a positive effect of the refining of grains and degradation effect of ΔR on K_{IC} values.

Fig. 6 shows a complex nomogram of the relations of K_{IC}, Tx_o, d, ΔR. Using the well known knowledge of the influence of ΔR on values of n, Fig. 2, we can quantify the influence of plasticity on these parameters, see Fig. 6. (With regard to the studied set for n from 0,12 to 0,20). It is obvious that the change of the value of n from 0,12 to 0,17 (at a given grain) improves the Tx_o values by as much as 65 °C and increases K_{IC} by 0,10 $MPa.m^{1/2}$.

Very interesting is the question of the relationship between the critical root of crack COD and stretch zone parameters. The effort to find an explicit relation between COD and $2a_{SZ}$ parameter for $T < Tx_o$ in the subtransition branch was unsuccessful, Fig. 7. The linear relationship has been confirmed, however, with a considerable dispersion: $COD = k \cdot (2a_{SZ})$, "k" ranges from 2,8 to 15, while $k \sim 1/n$, which is logical from the viewpoint of the intensity of crack face blunting and the way of scanning of COD. In addition to the blunting of the crack face the effect of the ductile crack growth x_o on continued thermal behaviour of COD must be taken into account. The stretch zone is stabilized above the temperature Tx_{oD} and opening of COD is controlled by the plastic crack opening. Presented knowledge is summarized in a scheme in Fig. 8, providing a confirmation of the influence of deformation hardening exponent on the relationship between COD and $2a_{SZ}$.

CONCLUSION

Our study presents the knowledge of the influence of deformation hardening exponent on the development of the stretch zone in front of the fatigue crack tip in fracture toughness tests. Quantitative expression of the influence of n or ΔR on K_{IC} and Tx_o values has been provided together with a qualitative description of the relation to COD values. Presented knowledge suggests a close relationship between the structural failure processes in front of the crack tip and fracture toughness parameters.

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(4) Parilák, Ľ. and Dojčák, J., In. Proceedings "Fractografia 1991", Herľany, PSHS ÚEM SAV, 1991, p. 7-11.

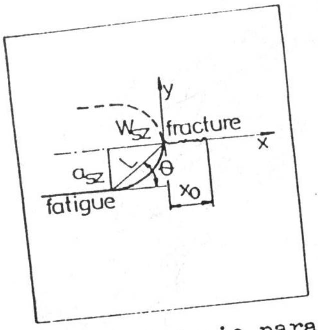

Figure 1 Basic parameters of stretch and process zones
W_{SZ}, a_{SZ} - stretch zone width, depth,
x_o - ductile crack growth, θ- vertex angle

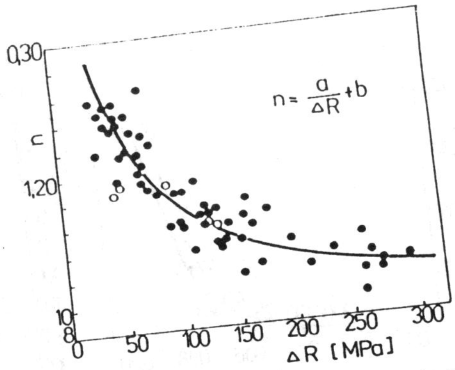

Figure 2 Dependence of deformation hardening exponent on ΔR

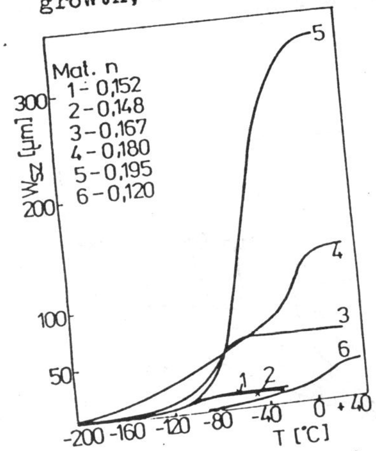

Figure 3 Temperature dependence of W_{SZ} for states with different values of "n"

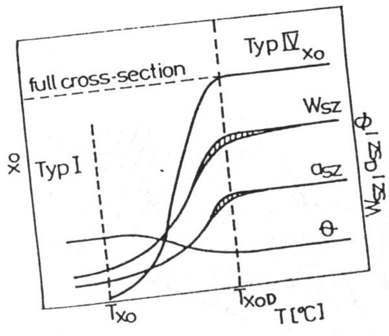

Figure 4 General scheme of temperature dependence of the stretch and process zone parameters

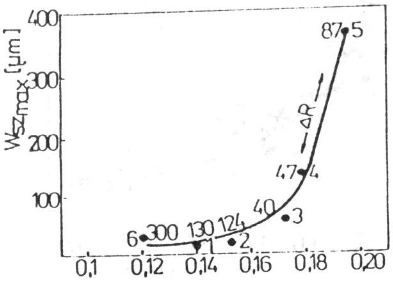

Figure 5 Dependence of W_{SZ} on the exponent of deformation hardening

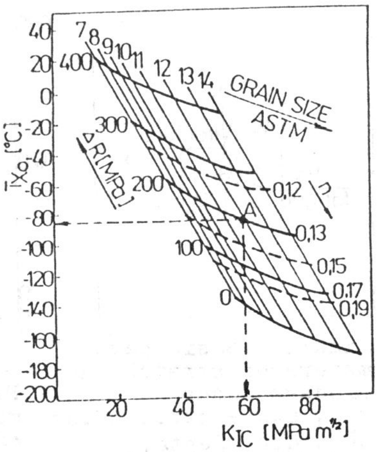

Figure 6 Effect of deformation hardening exponent on Tx_o and K_{IC}

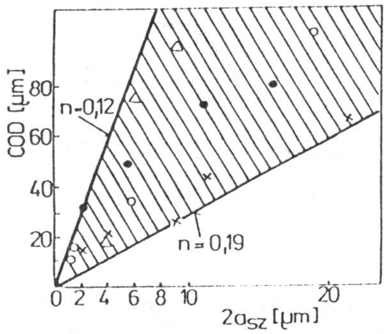

Figure 7 Relationship between COD and the stretch zone depth $2a_{SZ}$ at $T < Tx_o$

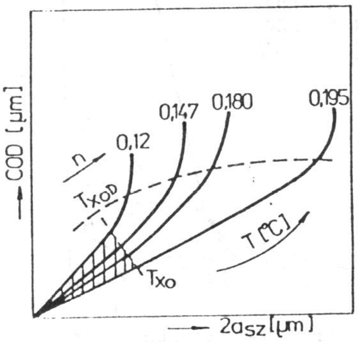

Figure 8 Scheme of the relationship between COD and $2a_{SZ}$ over the whole temperature interval for different values of "n"