EQUILIBRIUM FRACTURE STRESS (EFS) - NEW PARAMETER FOR TOUGHNESS OF MICROSTRUCTURES IN STEEL

P. Staněk and M. Lorenc+

The control of the effective strain in real time gives possibility to reach the equilibrium between external loading and deformation processes in the microstructures of steel. Experimental results obtained by means of the equipment for TV controled and computer aided tensile test are presented here. The maximum value of effective stress in given conditions has been named equilibrium fracture stress (EFS).

MOTIVATION

There is evidence to show that all kinds of fracture processes are initiated by the local plastic deformation. Thus, from this reason, it can be considered as primary mechanism resulting in fracture of metal components. In the process of plastic deformation the voids are nucleated in the material (1,2). These voids are primarily formed in the surroudings of inclusions or precipitated particles and they play very important role in ductile fracture and resulting toughness of steel.

Various models have been proposed to find the relationship between microstructural characteristics determining the initiation of ductile fracture and fracture toughness (3). The Krafft´s relation, for example, gives possibility to express correlation between K_{IC} and interparticle distances of inclusions. Another model describing the initiation of an unstable fracture have been presented by Hahn and Rosenfield.

+ Research Institute of Materials and Technology, Brno, Czechoslovakia

This model was modified by Rice and Johnson. Further modification of Hahn s model has been proposed by Ritchie et al. (4).

The ductile fracture is evoked by the nucleation of voids in the material, by their growth during loading and by the coalescence of these voids before the final failure. Some experimental results related to this problem are summarized in references (5,6) etc. The last stage of the ductile fracture is the macroscopical fail in bond of the stressed material. The experimental research proved, that by a tensile test, before unstable rupture, the growth of the central crack takes place. This crack is caused by coalescence of the single microvoids.

The disadvantage of above mentioned models used for explanation of fracture toughness phenomena lies in the fact, that they not exactly differentiate between the structure parameters and mechanical properties. In given equations both factors are used which of cause cannot be considered as a fully independent variables. The solution of this problem needs the quantitative analysis of the microstructure of the material, including size and distribution of second phase particles (microdiscontinuities). Further, it is necessary to have the physical formulation of the deformation process, especially the holding of its stationary character as a base for equilibrium of structural changes taking place in the material.

PRACTICE

The experiment with low carbon, low alloyed medium strength steel having tempered martensitic-bainitic structure was proposed (7). The specimens for experimental testing have been cut from a cast ingot of the height 2500 mm, width 1500 mm, thicness 200-300 mm (wedge-shaped ingot). With regard to the solidification and cooling conditions the material was chemically very homogeneous. The as cast structure and the heat treatment give possibility to obtain different parameters of the microstructure.

For the illustration of the difference between the specimens taken from different places of the ingot, Fig. 1 represents the marginal probability of Charpy V-notch toughness at different temperatures. The impact transition curves have been aproximated by the function tgh (T) and the distribution of measured values has been fitted by Weibull´s law.

The size and distribution of inclusions were evaluated with the Quantimet (QTM). Two hundred fields per sample have been used to determine the number of inclusions greater than 3, 6, 12, 24, 36 and 48 μm, the average volume percentage of particles, the local concentration of microdiscontinuities measured as quantile 70, 80, 90, 95% of statistics of their relativ area. This arrangement corresponded to a nominal area examined per sample in excess of 30 mm^2.

Besides the light microscopy, TEM and SEM (fractures) qualitative characteristics, the metalic matrix has been described by X ray diffraction analysis. The lattice parameters, grain size, density of dislocation, surface stress, including their dispersions and further derived variables, for example coefficients of distribution function of lattice distortion (Gauss, Cauchy) or models of stress distribution in grains (Reuss, Voight) were evaluated

TABLE 1 - Experimental results (7)

Quantity	Average value	Standard deviation	The most important correlations
R_m	739	22	grain size, lattice
$R_p0.2$	652	18	parameter
Z	53.1	13.5	inclusions greater
A_5	15.7	3.5	than 12 μm
KCV,20°C	67.6	32.2	inclusions smaller
K_{IC}	91.4	8.8	than 12 μm, lattice distortion (density of dislocation), A_5, Z

To meet the requirements of the physicaly defined conditions of the deformation process in the moment of failure initiation, it has been designed an equipment shown in Fig. 2 (8). Here, in the course of the tensile test process, the profile of specimens is evaluated by TV camera and a computer. During the tensile test there are observed the time dependences of loading force and further quantities, which can be derived from the strain - stress diagram of axisymetrical test bars. It deals with minimum diameter d, true strain $\varepsilon_i = 2 \ln (d_0/d)$ and effective stress $\sigma_i = 4F/\pi d^2$. With high degree of strain, where the microdiscontinuities are comming into the process of macrodeformation, the part of the strain - stress curve behind the conventional limit of strength (UTS) is important. Here, ductile materials are forming so called neck and the diameter d is related to the diameter d is related to the local deformation in the narrowest section, when the effective stress is given by the relations of Davidenkov and Spiridonova or Bridgeman (9). For these relations it is necessary to determine the neck radius of curvature R in the longitudinal direction from the TV signal during the test.

To eliminate the thermomechanical softening and to establish the condition of the uniform growth of the voids, the true strain should be controled by the TV system, so that the strain rate 10^{-4}/s remains constant. These conditions of loading are changing the traditional strain-stress diagram which without the strain control just before the fracture of the bar has expressive dynamic character. The tensile test with constant and a relatively small increase of strain can be considered as isothermic, which is characterised by a maximum σ_m. When this maximum is reached, the material is losing the ability for further strengthening (Fig. 3). We have named this point as the Equilibrium fracture stress (EFS). Fig. 4 represents a neck longitudinal section of the tested bar (10 mm diameter), when the testing has been interrupted in moment of decreasing of σ_i, i.e. immediately after obtaining the stage EFS.

EXPERIENCE

The results of the experiments are in accordance with the knowledge, plastic strain is an index of the relative effect of inclusions on the mechanical properties. It means, that at the same matrix the material having less impurities exhibits greater ability for the plastic deformation. The fact, if this plasticity results in increasing or decreasing of the resistence against failure, can be expressed by the parameter efs. The relatively soft structural state brings about decreasing of EFS value from the point of view of the lower strength of the matrix. The relatively hard matrix becomes failured by a brittle fracture and the EFS will be again smaller than in case of the ductile fracture. Between the marginal cases there exists an optimal microstructure as represented by Fig. 5 and 6. Here is established an accordance between the matrix hardening and the effect of inclusions (cleanliness) on the progress of plastic strain. For the compensation of the effect of greater amount of impurities very, soft state of matrix is necessary and on the other hand, high degree of hardening is only effective in the range of corresponding cleanliness. The schematic diagrams which are shown here correspond to the real tensile tests of the experimental set.

SYMBOLS USED

K_{IC} = plane strain fracture toughness (MPa $m^{-1/2}$)

T = test temperature (^{o}C)

KCV = Charpy V - notched toughness (J/cm^2)

R_m = tensile strenght (MPa)

$R_p0.2$ = 0.2% proof stress

A_5 = elongation to fracture - 5 d_o gauge length (%)

Z = reduction in area (%)

ε_i = true strain

σ_i = effective stress (MPa)

d_o = initial diameter of tensile test bar (mm)

d = minimum diameter of tensile test bar (mm)

F = loading force (kN)

R = radius of curvature of the neck (mm)

ε_p = plastic strain

σ_f = flow stress (MPa)

σ_m = maximum of effective stress (MPa)

REFERENCES

(1) Tai, W.H. and Yang, B.X., Eng. Fracture Mech., Vol. 27, 1987, pp. 371-378.

(2) Barnby,J.T., Shi,Y.W. and Nadkarni,A.S., Int. J. of Fracture, Vol. 25, 1984, pp. 273-283.

(3) Van Stone, R.H. et al., Ing. Metals Rev., Vol. 30, 1985, pp. 157-178.

(4) Ritchie, R.O. and Thompson, A.W., Metall. Trans.A, Vol. 16 A, 1985, pp. 233-248.

(5) Thompson, A.W., Acta Metall., Vol.31, 1983, pp. 1517-1523.

(6) Pickering,F.B., "Inclusions", The Institution of Metallurgist - Monograph No 3, London, 1979.

(7) Staněk, P. and Lorenc, M.: Slévárenství, No 7, 1988 (in press).

(8) Staněk, P., Lorenc, M., Doležal, L. and Weiss, F., "Apparatus for evaluating deformation characteristics of mechanicaly tested materials", Patent USA No 4186610, 1980, ČSSR No 193720, 1982, GB No 2027538, 1983, BRD, No 2834504, 1986.

(9) Mesmacque, G. and Foct, J., Materials Science and Engineering, Vol. 75, 1986, pp. 127-136.

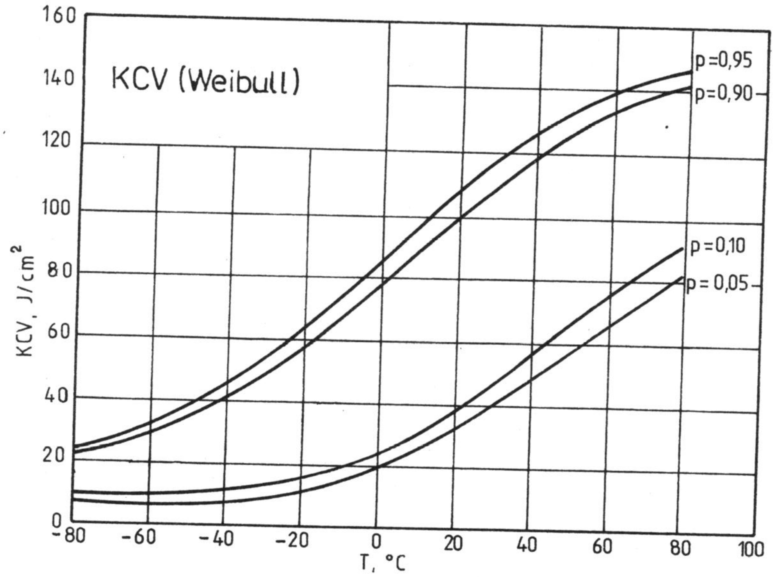

Figure 1 The marginal boundary for probability p in the Charpy V-notch impact test

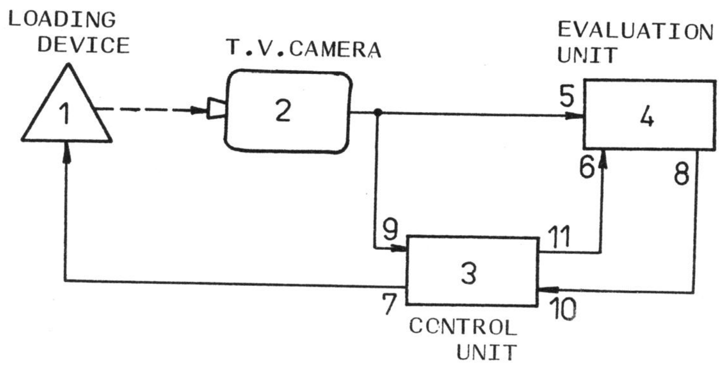

Figure 2 TV system for the computer aided tensile test

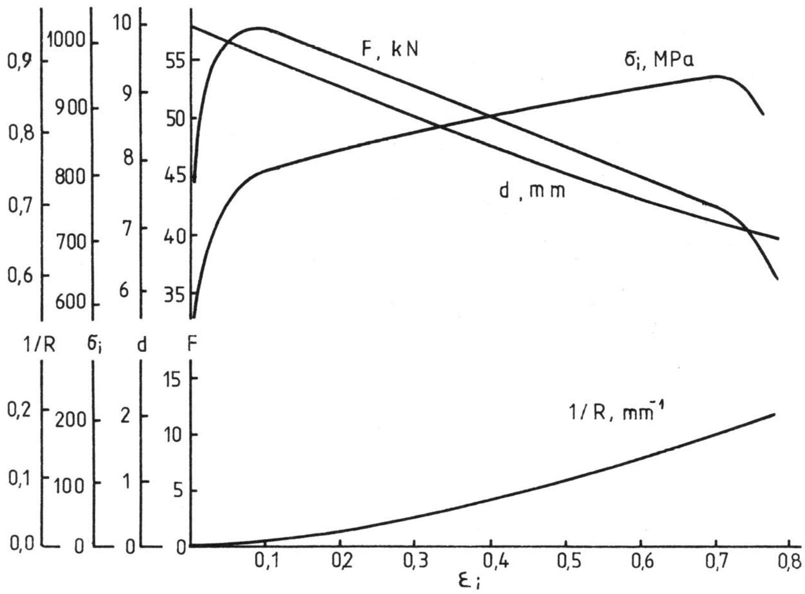

Figure 3 The record of parameters of the tensile test with the controled true strain

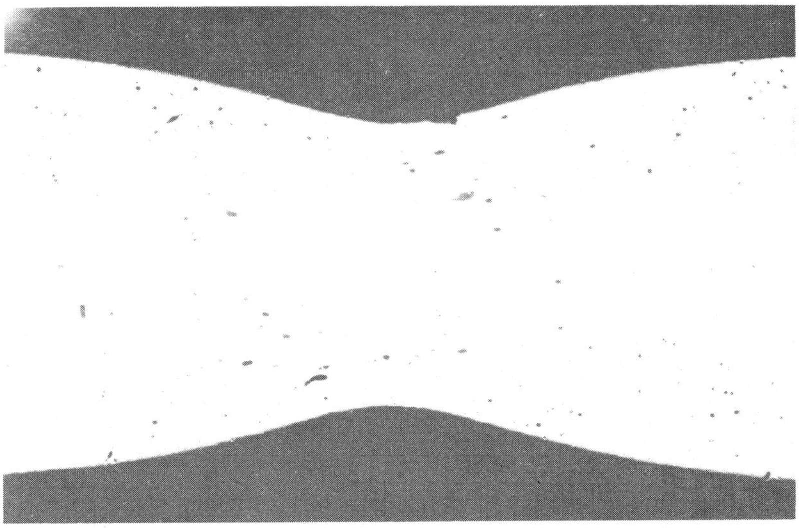

Figure 4 The cross-section of the tensile tested bar in the stage EFS

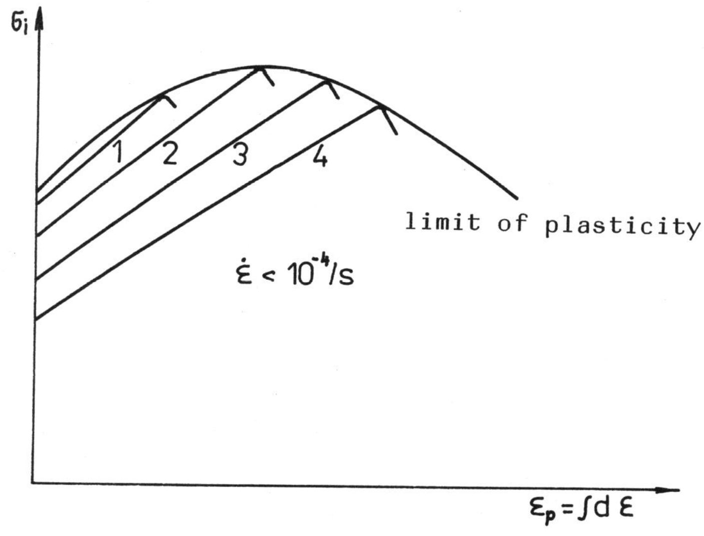

Figure 5 Idealized diagrams for different hardening levels of matrix and the imaginary cleanliness

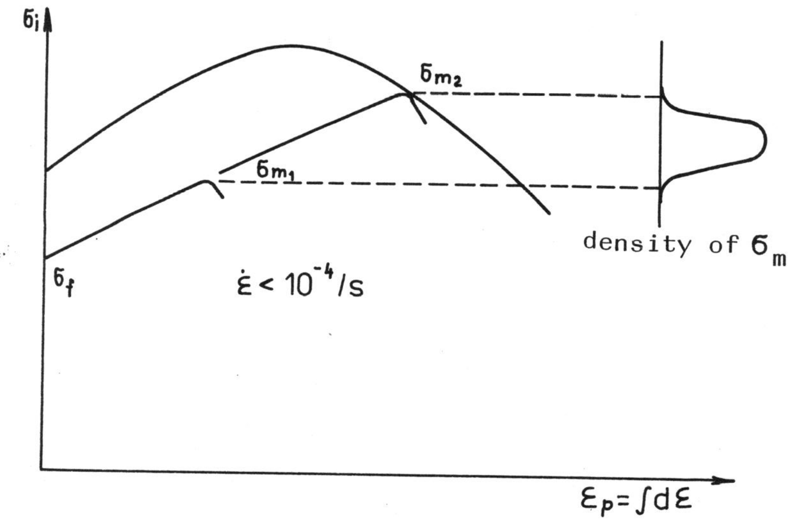

Figure 6 Idealized diagrams for a range of cleanliness and the imaginary constant microstructures