STRETCHED ZONE STEREOSCOPIC MEASUREMENTS AS AN INDEPENDENT CONTROL OF MATERIAL FRACTURE TOUGHNESS

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The paper presents the results of comprehensive investigations of the stretched zone performed by two methods. Experimental data are compared for three steels tested under static and dynamic loading in the temperature range from 77 to 293 K and the specimen thickness range from 3 to 300 mm.

A stretched zone on a fracture surface is generally related to the crack tip plastic blunting process and to the crack initiation when a specimen or a structural component is under monotonically increasing load. Since this process is accompanied by the plastic crack tip opening displacement (CTOD), the stretched zone geometric parameters are expected to correlate with the material fracture toughness (Spitzig (1), Krasowsky and Vainshtok (2), Krasowsky et al (3)). In contrast to other methods of metals fracture toughness measurement, the stretched zone as a subject for investigation has a number of unique properties, some of them are as follows:

- a possibility of the material fracture toughness evaluation at any time after the fracture process has been completed;
- a possibility of the direct measurement of the critical COD related to the actual moment of the crack initiation;
- accessibility of any stretched zone profile for

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measurement whatever its location along the crack front;
- a possibility of an additional evaluation of the material fracture toughness independent of other conventional methods used for its measurement.

Our investigations mainly involve two methods of stereoscopic measurements of the stretched zone geometric parameters:
(i) measuring the profile of the stretched zone on one fracture surface (Krasowsky et al (4), (2));
(ii) superimposing the mating profiles of the two opposite fracture surfaces (Krasowsky and Stepanenko (5), Krasowsky et al (6), Bilek et al (7)).

The investigations were carried out on fracture surfaces of standard specimens used for the static and dynamic fracture toughness tests. The materials studied were: the 15Kh2NMFA steel of different heat treatment (2), (3) made in the USSR, heat-resistant ČSN15313 steel made in Czechoslovakia (6), (7) and a low-carbon steel (0.05 % C) (Krasowsky et al (8)). Measurements were made on 3 to 300 mm thick specimens tested in the temperature range from 77 to 293 K with the loading rate $\dot{K}_I$ varying from 10^{-2} to 10^{6} $MPa\sqrt{m}\cdot s^{-1}$ (Figs 1,2).

The method involved stereo pairs photographed in a scanning electron microscope with their subsequent quantitative analysis in a precision stereocomparator in accordance with the recommendations of photogrammetry (Fig.3).

Measurements of the stretched zone profile with the first of the aforementioned methods revealed essential scatter of results associated primarily with the irregular height and width of the stretched zone along the crack front. In this case an average value of the stretched zone height, h , was estimated from the increased number of measurements on the same specimen. To obtain the COD value, basing on the assumption of the symmetric stretched zone on both sides of the crack plane which may be argued upon, the measured average value of the stretched zone height was doubled, $2h$. Then this value was compared with the material fracture toughness obtained by conventional methods.

When using the second method (superimposing the mating profiles of the two opposite fracture surfaces), it is of importance to find the mating points on the opposite fracture surfaces to measure the stretched zone profiles along one and the same line. In this case good results can be obtained with those points being cleaved particles of the brittle phase or nonmetallic inclusions. The scatter of the stretched zone measurement results obtained by this method is much smaller relative to the first method.

First we shall indicate the main results confirmed by both methods.
1. In the temperature range where no subcritical crack growth occurs prior to the specimen fracture, a correlation was found between the stretched zone height and the fracture toughness characteristics of steels under static and dynamic loading (Fig.2). The comparison was made using the formula

$$\delta_c = 2h = \alpha \frac{K_{Ic(d)}^2}{\sigma_{Y(d)} E} \qquad (1)$$

where the value of $K_{Ic(d)}$ was determined when the condition of plane strain both at static and dynamic (index "d") loading was satisfied. The magnitude of the proportionality factor α obtained for all the materials and loading conditions is within the range of 0.56 to 1.15 which is not beyond the limits of the theoretical, numerical and experimental estimates of this value (Krasowsky et al (9)). This result can be considered as the evidence of the validity of the materials fracture toughness evaluation by measuring the stretched zone height along with other methods.
2. In the temperature range where a subcritical crack growth is observed the correlation expressed by Eq.(1) is violated. All the stretched zone measurements reveal that actual crack initiation occurs much earlier than it is predicted by the conventional techniques involving J_{Ic} and R-curves measurements, but considerably later than it is predicted by the recommended practice for the P_Q evaluation by the 5 % secant rule in the K_{Ic}-determination standard. Therefore, in case of a ductile fracture K_Q characterizes the conditions of the plastic zone development at the crack tip rather than the fracture process itself. On the other hand, the material fracture toughness evaluation by the actual crack initiation, i.e. by the stretched zone height, gives conservative results as compared to those determined by the standards for J_{Ic} and R-curves.
3. In the specimen thickness range from 10 to 300 mm at ambient temperature the stretched zone width and height have been found invariant to the specimen thickness (steel 15Kh2NMFA). This fact confirms the acceptability of the use of $2h$ and, therefore, δ_c-

values as fracture criteria in the elastic and elasto-plastic regimes since both the typical ductile fracture with non-linear load - displacement diagrams (small specimens) and typical brittle fracture with linear diagrams (300 mm thick specimens) were observed under above conditions.

4. A linear correlation between the stretched zone height and width was found for all the materials studied over a wide temperature range. Only in the region of brittle fracture there is a tendency towards the violation of this correlation. For instance, at -196°C the stretched zone height can be determined but its width is not visible. This can be associated with the character of the initial stages of the plastic zone evolution at the crack tip: first the plastic zone fans are developing normally to the crack plane and consequently the crack faces displacement in this direction is prevailent.

At the same time the method of the stretched zone measurement by superimposing the mating profiles of the two opposite fracture surfaces has a number of specific features which determine its advantages over the other method:

(i) For all the steels studied the geometrical parameters of the stretched zone on one of the two fracture surfaces depend on the location of the measured profile along the crack front. Such measurements generally reveal essential scatter of results. Simultaneously the superimposing of the two corresponding opposite profiles always gives close results irrespective of the location of the measured profiles along the crack front.

(ii) The method made it possible to reveal the fact that the direction of the crack growth during its initiation always deviates from the main direction of the crack growth determined by the design of the specimen and its loading conditions (Fig.3). A conclusion was made that the crack initiation occurs into one of two plastic zone fans along the trajectory of the maximum damage accumulation in the material due to plastic deformation. That is why no mirror-symmetric profiles of the stretched zone are generally observed on the opposite fracture surfaces.

The investigation of the stretched zone geometric parameters confirmed the efficiency of this method in different branches of the materials and structural components fracture mechanics: when it is necessary to determine the actual moment of the crack initiation while measuring the material fracture toughness; in the structural component failure analysis; while measuring the material fracture toughness in those cases when other methods are difficult to implement, for instance, at very high loading rates. Figure 4 presents the results of the fracture toughness evaluation for the carbon steel (0.45 %C) in the range of high projectile and target impact velocities (10). In the range of loading rates where it was possible to estimate the material fracture toughness using conventional fracture mechanics methods, the stretched zone measurements agreed satisfactorily with those estimates. At the same time these measurements made it possible to evaluate the material fracture toughness at the impact velocity exceeding 300 m/s.

SYMBOLS USED

h, w = stretched zone height and width measured by the stereofractography method

δ_c = critical crack tip opening displacement

α = proportionality factor

K_{Ic}, K_{Id} = fracture toughness of the material under static and dynamic loading respectively

σ_Y, σ_{Yd} = yield stress under static and dynamic loading respectively

J_{Ic} = plane strain fracture toughness of an elastic-plastic material estimated by the J-integral

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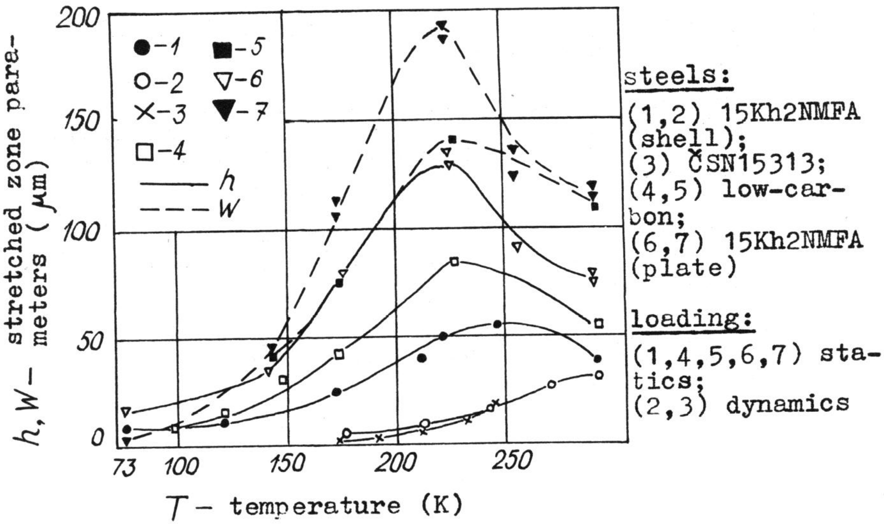


Figure 1 Temperature dependence of the stretched zone parameters

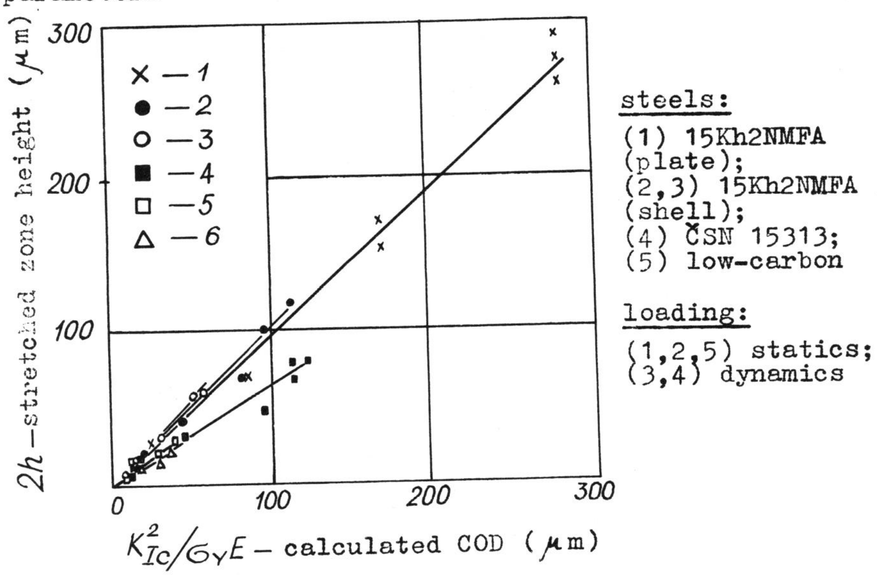
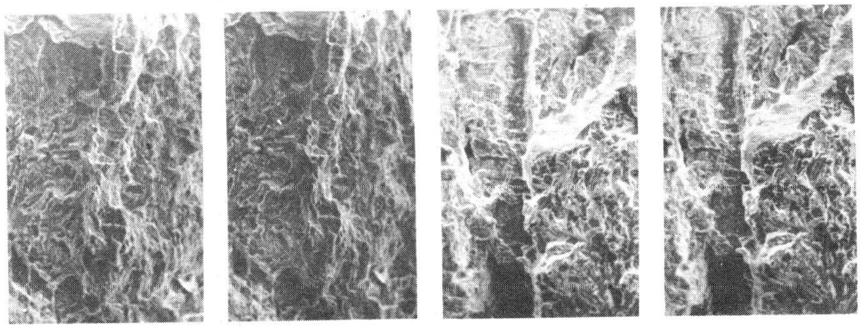


Figure 2 Relationships between the measured ($2h$) and calculated COD



steel 15Kh2NMFA
temperature 213 K
$\dot{K}_I = 10^2$ MPa$\sqrt{m}\cdot s^{-1}$

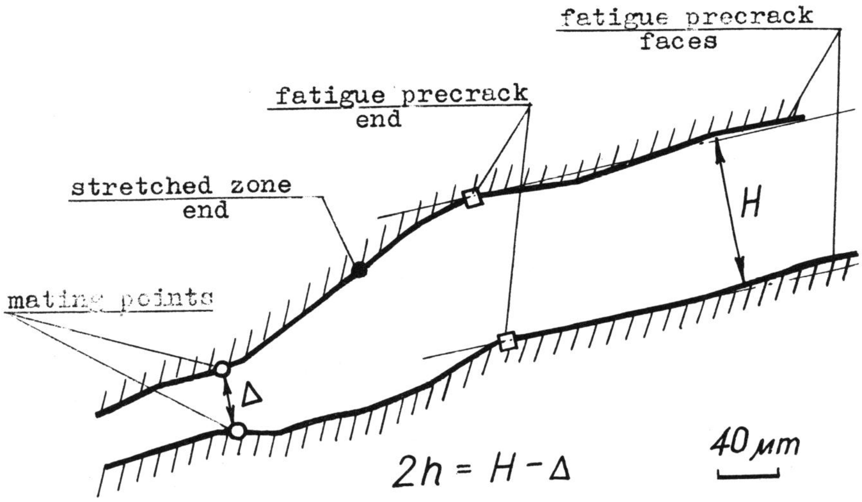
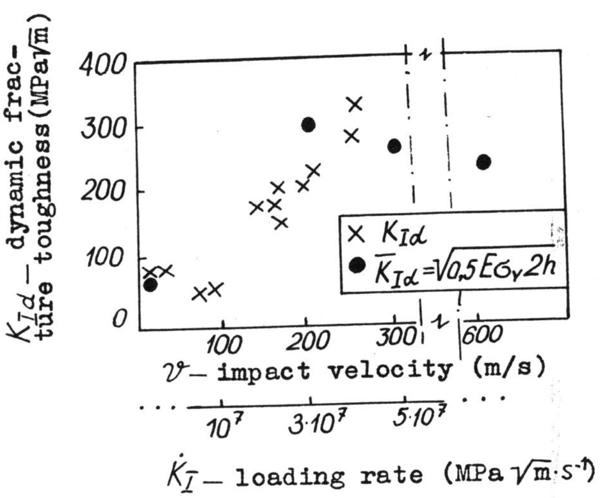


Figure 3 Stereopairs and stretched zone profiles on the mating fracture surfaces



carbon steel

Figure 4 Dependence of measured K_{Id} and estimated $\bar{K}_{Id}$ on v and $\dot{K}_I$