BREAKING STRENGTH AT LOW TEMPERATURES AND METHODS OF ITS EVALUATION

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ABSTRACT

The present paper deals with fracture resistance - grain size and fracture resistance - plastic zone relationships at various temperatures. The nature of these relationships changes with a decrease in temperature. For the purpose of the investigations specimens with crack were tested for crack resistance. The fractures were studied by X-ray analysis. The results obtained allow the crack resistance evaluation on the basis of fractures which appear in service.

KEYWORDS

Low temperature; crack resistance; methods of crack resistance evaluation; transition temperature; fracture energy; plastic zone radius.

INTRODUCTION

A decrease in temperature is known to produce marked effect on fracture in structural steels. It normally leads to an increase in yield stress which often causes fracture at stresses lower than the yield strength. As a result, the benefit of the steel ductility is unlikely to be used to the full extent and fracture comes about with lower energy comsumption.

In the present paper, the temperature effect on fracture toughness K_{IC} of normal and low strength structural steels is considered, having regard to the plastic deformation processes which occur in the crack tip. The investigations were carried out on the steels, the mechanical characteristics of which are given in Table 1. The eccentric tension steel specimens with a crack were tested by a static load using Instron testing machines. The specimens were 25, 50 and 60 mm thick.

TABLE 1 Mechanical Properties of Tested Steels

Steel quality	$\sigma_{0,2}$	σ_B	δ	ψ	T_{50}
	MPa	MPa	%	%	°C
30CrMo	693	826	8	44	+ 60
35CrMoV	754	900	14	61	+120
38CrMo	842	950	12	69	-120
38CrNiMo	1020	1117	11	59	-120
St. 35	382	670	25	37	- 40
St. 20	348	588	17	43	- 60

The fracture toughness was determined by standard methods within the temperature range of plus 120 to minus 140 °C (1980).

All the results obtained are summarized in the diagrams presented in Fig. 1, which shows K_{IC} as a function of grain size at different test temperatures. The mechanical characteristics of the tested steels differ markedly due to different structure of the steels: ferrite/pearlite mixture (cast steels St. 20, St. 35), tempered bainite (35CrMoV), ferrite/sorbite/ /bainite mixture (30CrMo), tempered martensite(38CrMo,38CrNiMo).

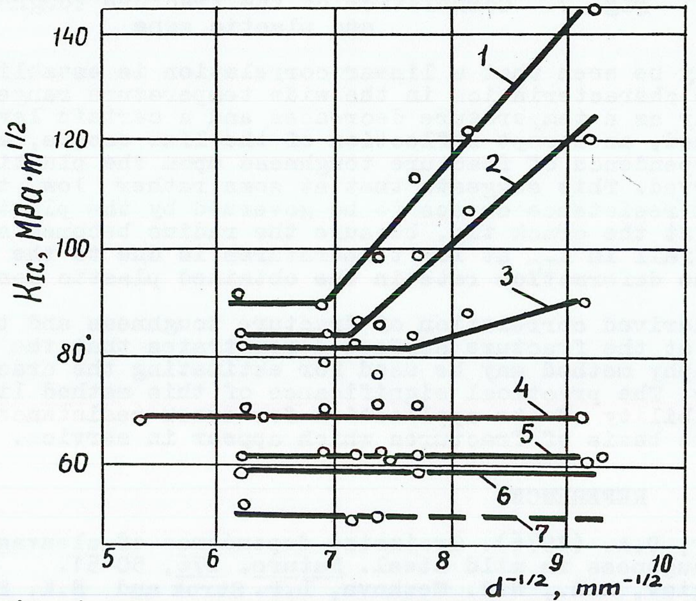

Fig. 1. K_{IC} - grain size relationship at various test temperatures: 1. T_{50}+ 60°C; 2. T_{50} + 20 °C; 3. T_{50}; 4. T_{50} - 20°C; 5. T_{50} - 60 °C; 6. T_{50}- 100 °C; 7. T_{50} - 140 °C.

To avoid the strong influence of different microstructures on cold brittleness of steel, the lines on the plot of Fig. 1 were drawn for different relative temperatures T_{50}, T_{50}- 20°C, etc. As a critical temperature T_{50}, the temperature was taken at which 50% ductile component in the fracture of 10 mm thick Charpy specimens was obtained during a static bending test. This made it possible to derive general relationships between grain size and crack resistance. Such presentation of the results allows comparison of steels, different in structure and strength under the conditions of similar macroscopic characteristics of fracture. It is well-known that the relationship between the temperature and the ductile component contribution to the fracture and that between the temperature and the radius of the plastic deformation zone under the fracture are of identical nature and give nearly the same transition temperatures (Georviev, 1981). Thus, it may be asserted that the above approach to the result analysis enables to compare steels under conditions of similarity of the local zone in the crack tip.

As it may be seen from Fig. 1, at fixed temperature intervals below T_{50} no relationship is observed between K_{IC} and grain size. At higher temperatures the linear dependence of crack resistance on grain size (of Hall-Petch type) appears and it is to be noted that the higher is the temperature the greater is the slope. The results obtained show that with a decrease in temperature dependence of fracture toughness on grain size becomes less pronounced and on reaching a certain critical temperature ceases to exist.

The relationship thus established may be used to explain the discrepancy in data on the effect of grain size on the fracture toughness. In some cases no dependence is observed, in other cases monotonic or non-monotonic relationship between K_{IC} and grain size is found to exist (Curry, 1978). Apparently, the tests were conducted at the temperatures below T_{50} in the first case, and above T_{50} in the other case.

Upon compiling experimental data, it seems possible to use such relationships for approximate evaluation of fracture toughness of steels. It is suggested that fracture toughness be evaluated on the basis of the relationships obtained between K_{IC}, test temperature and steel grain size after the determination of the transition temperature and measurement of mean grain size. If such evaluation is to be made for relatively low temperatures, grain size need not be measured. The K_{IC} - grain size relationship seems to be absent at low temperatures due to the small plastic zone at the fracture surface and, hence, minor contribution of plastic deformation to the total fracture energy.

To find the relationship between the crack resistance and the plastic zone at the fracture surface, X-ray analysis of fractures was made. X-ray line broadening (211) in Cr-K-α radiation was analized. In order to estimate the change in the plastic deformation nature through the fracture depth, layer-to-layer pickling was used. Then the radius of the plastic zone at the crack tip was determined which was assumed to be the depth penetration of the plastic deformation under the fracture surface.

The obtained relationships between the X-ray line broadening and the depth of the pickled layer from the fractures of 50 mm thick specimens, made of 38CrMo steel (Table 1) showed that with a decrease in test temperature from plus 20 to minus 120°C the plastic zone radius reduces from 3 to 0,24 mm.

Figure 2 provides an illustration of the temperature - plastic zone relationship obtained. Plotted on the diagram are also the results derived from a theoretical calculation using fracture toughness characteristics K_C (at 20 and 0 °C) and K_{IC} (at minus 20, 60, 80 and 120 °C).

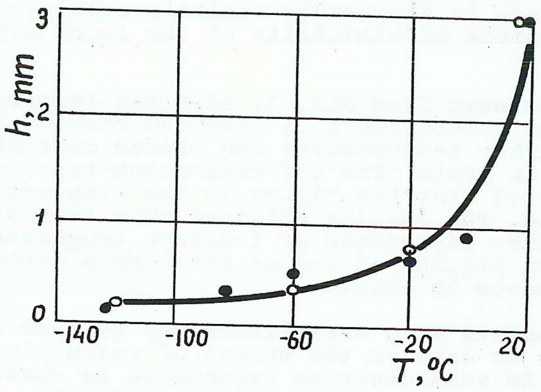

Fig. 2. Temperature - plastic zone relationship obtained experimentally ( ) and theoretically ( ).

The radius of the plastic zone was estimated on the basis of the correlations of the fracture mechanics

$$r_p = \frac{I}{6\pi}(K_{IC}/\sigma_{0,2})^2 \qquad (1)$$

$$r'_p = \frac{I}{2\pi}(K_C/\sigma_{0,2})^2$$

where r_p and r'_p are the radii of the plastic zone in case of plane-strain and plane-stress state;

$\sigma_{0,2}$ is 0,2 per cent proof stress.

As it may be seen from Fig. 2, the plastic zone radii determined experimentally and theoretically are nearly the same. These results show that fractographical characteristics obtained by X-ray analysis and criteria of fracture mechanics K_{IC} and K_C are closely connected.

Shown in Fig. 3 is the correlation of the fracture toughness characteristics and the plastic zone as determined by X-ray fractography.

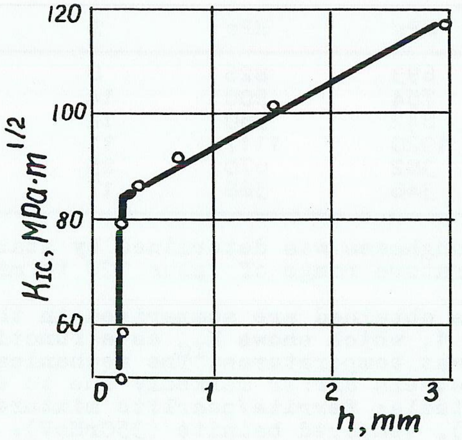

Fig. 3. Correlation of the fracture toughness and plastic zone

It may be seen that a linear correlation is established for these characteristics in the wide temperature range. However, as far as a temperature decreases and a certain level K_{IC} is reached, an abrupt inflection of the line occurs, after which no dependence of fracture toughness upon the plastic zone is observed. This suggests that at some rather low temperature crack resistance ceases to be governed by the plastic zone radius at the crack tip, because the radius becomes stable. Further fall in K_{IC} at low temperatures is due to the reduction in the deformation rate in the obtained plastic zone.

The derived correlation of fracture toughness and the plastic zone at the fracture surface demonstrates that the X-ray fractography method may be used for estimating the crack resistance. The practical significance of this method lies in the possibility of its application for crack resistance evaluation on the basis of fractures which appear in service.

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