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 consumption.

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**

<table>
<thead>
<tr>
<th>Steel quality</th>
<th>( \sigma_{0.2} ) MPA</th>
<th>( \sigma_B ) MPA</th>
<th>( \delta ) %</th>
<th>( \psi ) %</th>
<th>( T_50 ) °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>30CrMo</td>
<td>693</td>
<td>826</td>
<td>8</td>
<td>44</td>
<td>+60</td>
</tr>
<tr>
<td>35CrMoV</td>
<td>754</td>
<td>900</td>
<td>14</td>
<td>61</td>
<td>+120</td>
</tr>
<tr>
<td>38CrMo</td>
<td>842</td>
<td>950</td>
<td>12</td>
<td>69</td>
<td>-120</td>
</tr>
<tr>
<td>38CrNiMo</td>
<td>1020</td>
<td>1117</td>
<td>11</td>
<td>59</td>
<td>-120</td>
</tr>
<tr>
<td>St. 35</td>
<td>382</td>
<td>670</td>
<td>25</td>
<td>37</td>
<td>-40</td>
</tr>
<tr>
<td>St. 20</td>
<td>348</td>
<td>588</td>
<td>17</td>
<td>43</td>
<td>-60</td>
</tr>
</tbody>
</table>

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 \( K_I \) 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/orbite/bainite mixture (30CrMo), tempered martensite (38CrMo, 38CrNiMo).

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 radiation of the plastic deformation zone under the fracture zone are of identical nature and give nearly the same transition temperatures (Georgiev, 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 \( K_I \) 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 \( K_I \) 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 \( K_I \), 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 \( K_I \) - 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 utilized. 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.

![Fig. 1. \( K_I \) - grain size relationship at various test temperatures: 1. \( T_50 + 60 \) °C; 2. \( T_50 + 20 \) °C; 3. \( T_50 + 10 \) °C; 4. \( T_50 - 20 \) °C; 5. \( T_50 - 60 \) °C; 6. \( T_50 - 120 \) °C; 7. \( T_50 - 140 \) °C.](image-url)
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 36CrMo 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).

![Graph showing temperature-plastic zone relationship](image)

**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

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

$$r'_p = \frac{1}{2\pi} (K_C/\sigma_{0,2})^2$$

(1)

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.

![Graph showing correlation of fracture toughness and plastic zone](image)

**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 $K_C$ 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 $K_C$ at low temperatures is due to the reduction in 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.

**REFERENCES**

