Effects of Structural Changes on Fracture-Mechanic Characteristic Magnitudes

W. Dahl and W.-B. Kretzschmann, Aachen
Institute for Ferrous Metallurgy of the RWTH Aachen
Technical University Aix-la-Chapelle

For characterizing the stress and tension field at the crack tip, the fracture mechanics uses the stress intensity factor K, the energy release rate G, and the crack opening displacement δ, the critical values by means of which the fracture toughness can be measured. For a normal tension fracture, the equation

$$K_{Ic} = \sigma_c \cdot \sqrt{\pi . a_o} \cdot f(a_o/B) \quad (1)$$

as known, results. Initial presentations concerning the relation between stress and crack length were based on the linear-elastic behaviour. Improved models include plastic behaviour at crack tip. The magnitude of the plastic zone is then added to the crack length a_o. The equations

$$a = a_{tot} \left(1 - \cos(\pi . F/A_o . 2 . \sigma_{0.2})\right) \quad (2)$$

$$a = (1/2\pi) \, (K_I/\sigma_{0.2})^2 \, (1 - 2\nu)^2 \quad (3)$$

as given by Dugdale[1] (equation (2)) and Irwin-McClintock[2] (equation (3)) present themselves as correction relation. Here, it must be taken into consideration that both corrections are based on ideal elastic-plastic behaviour. It can thus be assumed that with solidifying materials, the actual fracture toughness values are somewhat lower than the results obtained with the above corrections[3].

The range of validity of the formulae (2) and (3) is limited as follows: A prerequisite for such a derivation is the elastic behaviour of the specimen itself. A correction is no longer significant if and when general yield occurs in the test cross section. Furthermore, a correction should no longer be carried out as soon as macroscopic stable crack growth arises - even if purely elastic formation occurs in the remaining cross section - since the crack length a_0 is then constantly changing. The crack middle moves faster than the edges, thus resulting in a severe bulging of the notch bottom. An exact definition of the critical crack length is therefore questionable.

In addition, a maximum is derived at when calculating with the help of formula (2) so that it is impossible to correct over and above a certain $\sigma_{0.2}$ ratio. Mathematically speaking, a wider application range up to a ratio of $\sigma/\sigma_{0.2}$ = 1 results with formula (3).

Test procedure

For testing purposes, single-edge notched tension specimens of the St 37-3 and St 52-3 steel grades were used, the dimensions of which meet the British Standard proposal[4] (Fig. 1). All specimens were provided with a fatigue starting crack, the ratio of crack length a_o to specimen width B being between 0.49 and 0.51. The St 37-3 steel was tested in the -196 °C to +22 °C temperature range, tests with St 52-3 being carried out at -196 °C. The maximum tension intensity factor K_{fmax}

$$K_{fmax} \leq 0.5\ (\sigma_{s1}/\sigma_{s2})K_{Ic} \qquad (4)$$

recommended by ASTM standard[5] for bringing home the approx. 3 mm long fatigue starting crack, could not be adhered to under tests with K_{Ic} values below approx. 1,500 Nmm$^{-3/2}$.

The bulging of the notch bottom was determined by means of two extensiometers. The K value has been calculated according to the formula given by Brown Jr. and Srawley[4] for single-edge notched tension specimens. The correction of the plastic zone was effected according to the Dugdale formula, viz. in such a way that instead of a_o in the given formula $a_{tot} = a_o + \Delta a$ was used.

Results

In Fig. 2 the fracture toughness K_c of St 37-3 is plotted against the temperature for grain sizes of 18 µm (A), 72 µm (B), and 108 µm (C). The dots, circles and asteriks indicate the course of the uncorrected measuring values, the triangles, crosses and squares the cor-

rected values when taking into account the plastic zone.

The non-corrected K_{Ic} values with specimens A rise from a level at low temperatures starting at approx. 1.200 Nmm$^{-3/2}$ to higher temperatures of up to 4.000 Nmm$^{-3/2}$. With specimens B and C and the same low temperature, a K_{Ic} value of approx. 700 Nmm$^{-3/2}$ is measured which rises to higher temperatures of 3.100 and 2.800 Nmm$^{-3/2}$ respectively. With low temperatures, correction for the plastic zone is minute, but rises steeply according to the increasing $\sigma/\sigma_{0.2}$ ratio.

Macroscopic stable crack growth having a streaky, dull structure between fatigue starting crack and crystalline residual crack surface can be noted at -15 °C with specimen A, at +22 °C with specimen B and at +40 °C with specimen C. Also plotted in the illustration are the limits set for applying fracture mechanics, estimated according to ASTM Standard ($D \geq 2.5 \cdot (K_{Ic}/\sigma_{0.2})^2$), and the limit according to recorder up to which - as far as accuracy measurement goes - a purely elastic behaviour prior to fracture is shown. At a fracture toughness reduction of 450 and 700 Nmm$^{-3/2}$ respectively, the transition temperatures indicated by the recorder of specimens B and C are 25 and 30 °C respectively higher as compared to specimens A.

When recording the load, the crack bulge was also noted and converted as regards crack tip. Fig. 3 shows the critical crack opening COS depending on the temperature. The dots indicate the course of measuring values for specimens A, the circles those for specimens B and the crosses those for specimens C. The critical bulge in the transition amounts to 0.075 mm with specimens A, to 0.05 mm with specimens B, and to 0.040 mm with specimens C.

Fig. 4 illustrates the fracture toughness K_{Ic} of St 52-3 at -196 °C depending on the top load F_o set when bringing home the fatigue starting crack. The fatigue starting crack was swung in at room temperature. The fracture toughness drops from 1.185 Nmm$^{-3/2}$ at 15 tons top load to 687 $Nmm^{-3/2}$ at 6 tons. The 15 ton load is the approximate limit of the linear course of the load-bulge curve at room temperature, as far as accuracy measurement goes. No fatigue crack progress has been noted below the 6 ton load. With the specimen being normalized subject to swinging-in of the fatigue starting crack, the K_{Ic} value at a top load of 15 tons is reduced by 375 $Nmm^{-3/2}$.

Discussion

Due to the grain coarsening, the transition temperature according to recorder is now 25 to 30 °C higher. The specimens A and C taken from the Charpy V specimens and notched at 5.4 m/sec., however, show a T_N temperature movement of 40 °C with increasing grain size.

The COS values to be determined with a high degree of accuracy coincide with all three grain sizes at low temperatures. When the transition temperature determined by means of the recorder is exceeded, the curves rise accordingly.

When test temperatures lie above the formation of stable crack growth, calculations with fracture mechanics formulae are no longer possible. These K_c values, however, indicate the maximum load of the single-edge notched test cross section. This load is thus noticeably reduced by means of the grain coarsening.

Fig. 4 shows that the regulation governing the swinging-in according to equation (4) is indeed justified. However, it is not always possible to adhere to this rule. The maximum permissible load in the case on hand would have been approx. 3 tons. With this load, no crack progress was made, however, although in this specimen a 0.2 mm long fatigue starting crack had already been swung in.

The solidification and stresses at the crack tip decreased by means of a normalizing heat treatment account for a reduced K_{Ic} value. It is very likely that the K_{Ic} value does not drop to the lowest possible value since the notch radius of the specimen swung in with a 15 ton top load is larger than that at a 6 ton top load.

Literaturverzeichnis

1. Dugdale, D.S.: in: J.Mech.Phys.Solids,(1960),Vol.8,S.100
2. Irwin,G.R. und F.A.McClintock: in: ASTM Special Technical Publication Nr. 381, S.84
3. Hahn,G.T. und A.Rosenfield: in:Acta Met.,Vol.13(1965)S.293
4. Brown,Jr.,W.F. und J.E.Srawley: in: ASTM Special Technical Publication Nr. 410, S. 1/65
5. BISRA Industrie Report MG/EB/350/68

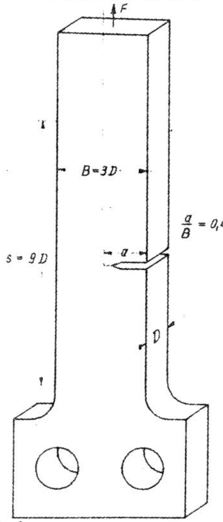
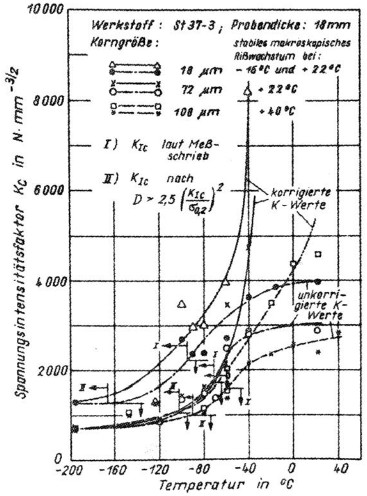
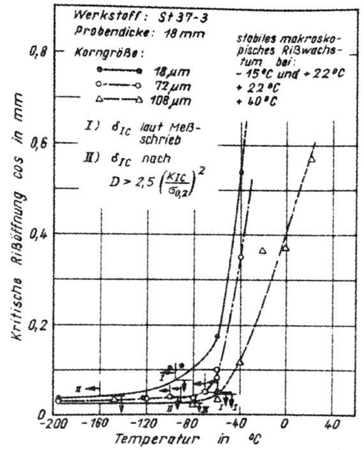


Bild 1



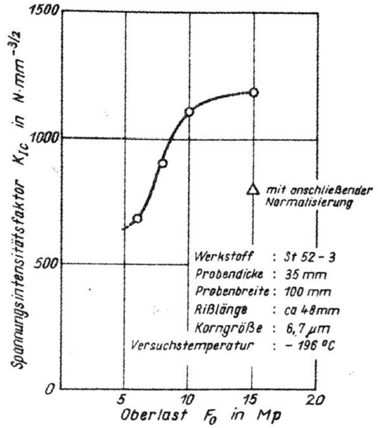
Spannungsintensitätsfaktor für einen St 37-3 für drei verschiedene Korngrößen in Abhängigkeit von der Temperatur

Bild 2



Kritische Rißöffnung für einen St 37-3 bei drei verschiedenen Korngrößen in Abhängigkeit von der Temperatur

Bild 3



Spannungsintensitätsfaktor K_{Ic} in Abhängigkeit der beim Einbringen des Ermüdungsanrisses aufgegebene Oberlast F_0

Bild 4