1o. Influence of Specimen Size on Fracture Toughness

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The purpose of this work is to give some additional information of the effect of specimen size on plane strain fracture mechanics [1...4]. The tests were carried out on a high-strength structural steel Fe E 460 with 0.17 % C; 0.31 % Si; 1.48 % Mn; 0.021 % P; 0.013 % S; 0.66 % Ni, and 0.20 % V in a temperature range from -196 °C (77 K) to room temperature (293 K). In this region the fracture mechanism changes from cleavage to dimple.

The dimensions of the tested compact tension specimens according to the ASTM-designation [5] are listed in fig. 1. Specimens are used with thickness from 3 to 38,5 mm and widths from 26 to 150 mm. In the linear elastic range the fracture toughness, the critical crack opening displacement calculated by the linear extrapolation, and the critical value of the J-integral [6] were calculated from the maximum values of the linear load displacement curves. With growing temperature and plasticity, these parameters are calculated for 3 particular points:

a) at the 5 % deviation from linearity,
b) at the maximum load, and
c) - at room temperature - at the beginning of stable crack growth.

The beginning of stable crack growth was detected by ultrasonics.

Fig. 2 shows the fracture toughness and the yield strength as a function of temperature for specimens 9 and 13 mm thick and a width of 50 mm.

In fig. 2 and the following pictures certain temperatures are indicated:

I.) The temperature up to which the ASTM-plane strain size criterion is valid:

$$B \geq 2,5 \left(\frac{K_c}{R_{eL}}\right)^2$$

II.) the temperature up to which the load displacement-curve is linear,

III.) the beginning of stable crack growth.

The 13 mm thick specimens have a plane strain fracture toughness up to -120 °C (153 K) and the load displacement-curves are linear up to -100 °C (173 K). Above -80 °C (193 K) the deviation from linearity is more than 5 % and K_Q can be calculated. At temperatures above -25 °C (248 K) and a fracture toughness of about 100 $MNm^{-3/2}$ stable crack growth is observed on the fractured surfaces. With increasing temperature K_Q and K_i remain constant.

Fig. 3 shows the fracture toughness from maximum load as a function of temperature for specimens with different thicknesses and a constant width of 50 mm. So the 25 mm thick specimens are equal to the 1 inch standard specimens. In the figure 3 different temperature ranges can be distinguished:

1. From the lowest temperatures up to -150 °C (123 K) no influence of thickness can be detected. The data for all specimen thicknesses are in a common scatterband. It can be seen that the required thickness by ASTM (numeral I) is too conservative and can be reduced.
2. The first deviation from the common scatterband is noticed at -150 °C (123 K). From this temperature up to -20 °C (253 K) the K_c-T-curves differ according to the theory in the range of transition. The relatively larger plastic zone due to the less constraint situation in the thinner specimens results in larger K_c-values. This effect is seen with the 3 and 6 mm thick specimens.
3. After the rise the individual K_c-T-curves reach their maximums at the same plateau, but at different temperatures. Numeral III indicates the beginning of stable crack growth. Remarkable is that stable crack growth can be observed independent of specimen thickness, if a certain value of fracture toughness is achieved.

Fig. 4 shows the different criterions fracture toughness, crack opening displacement and K from the J-integral in the same manner as the last picture. All tested criterions show the same thickness dependence. No one criterion is any better in this regard.

The influence of specimen width on the fracture toughness from maximum load is shown in fig. 5 for the 13 mm thick specimens. Above the transition temperature according to the ASTM requirements with regard to specimen width, smaller fracture toughness values result from decreasing width. Reason for this is the lack of elastic domain around the plastic zone and so the loss of linear elastic behaviour.

A three dimensional figure of the influence of specimen width and thickness on the fracture toughness from maximum load is shown in fig. 6. In the different temperature surfaces the validity of the ASTM size requirements are marked on:

1. with regard to thickness and width,
2. only to width, and
3. the specimen dimensions fulfil neither the requirements to thickness nor to width.

It can be seen that a value below the required thickness does not immediately effect an increase of the toughness, but a value below the required width results in a decrease of the toughness. Along the right side of the temperature surfaces there are the ASTM standard specimens with a width to thickness proportion of 2. In these specimens the influence of width dominates the influence of thickness. With decreasing specimen size there always results a decrease of the fracture mechanic values at maximum load.

For the observed high-strength structural steels the size requirements of ASTM recommendation to thickness are found to be too conservative. On the other hand, the result with regard to the width correlates very well with ASTM specifications.
As an effect of stress state and thus of geometry, in the transition temperature region both fracture mechanism - the ductile as well as the cleavage - occur at the same temperatures - f.i. at -80 °C (193 K) ductile fracture in the specimens 3 mm thick and cleavage in the thicker ones. All criterions show the same geometry dependence in this region.

References

1. Irwin, G.R.:
   Fracture Testing of High Strength Sheet Materials under Conditions Appropriate for Stress Analysis
   NRL Report 5486 US Naval Research Laboratory, Wshington D.C. (USA), 1960

2. Hahn, G.T., and A.R. Rosenfield:
   in: Applications Related Phenomena in Titanium Alloys
   ASTM STP 432, American Society for Testing and Materials, 1968
   pp. 5/32

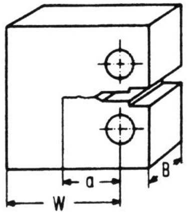
3. Kaufman, J.G., and F.G. Nelson:
   in: Fracture Toughness and Slow-Stable Cracking
   ASTM STP 559, American Society for Testing and Materials, 1974
   pp. 74/85

4. Dahl, W., W.-B. Kretzschmann, and H.-Ch. Zeislmair:
   Ermittlung der Bruchzähigkeit mit Hilfe von Rißaufweitungsmessungen
   ECSC Final Report No. 6210/KE-I-102, Institut für Eisenhüttenkunde, Aachen, 1977

5. E 399: Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials
   Annual Book of ASTM Standards, Designation: E 399-74, American Society for Testing and Materials

6. Rice, J.R., P.C. Paris, and J.G. Merkle:
   in: Progress in Flow Growth and Fracture Toughness Testing
   ASTM STP 536 (1973), pp. 231/45

Type of specimen



Dimensions

Specimen thickness B [mm]

Specimen width W [mm]	3	6	9	13	25	38,5
26	●	●	●	□		
50	●	●	●	●	□	
100	●	●	●	●	●	
150	●	●	●	●	●	●

□ ASTM - Standard specimen

Fig. 1: The tested specimen type and the variation of specimen thickness B and width W

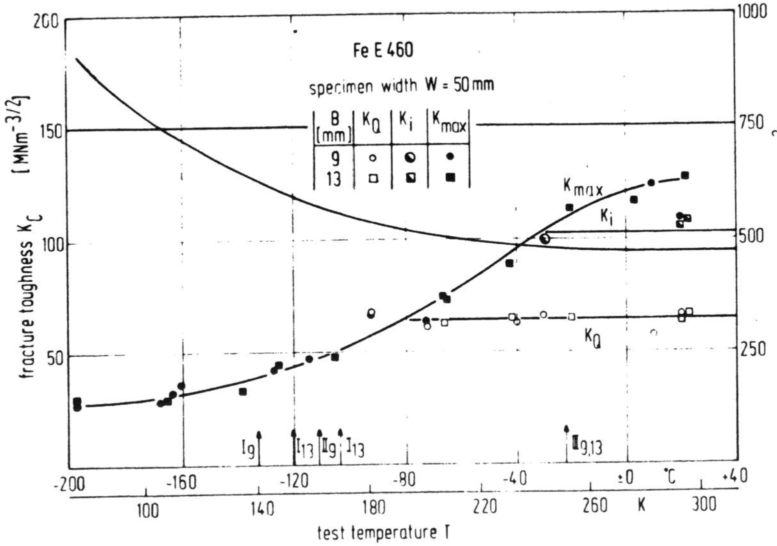


Fig. 2: Temperature dependence of fracture toughness and yield strength

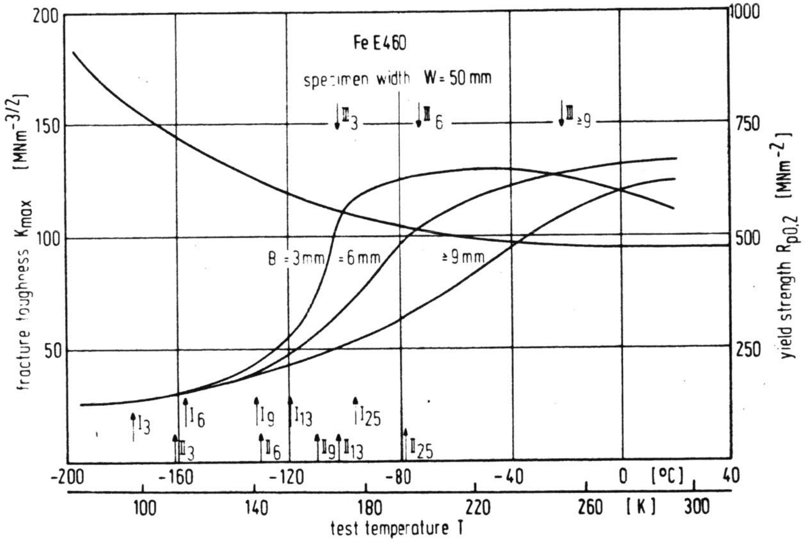


Fig. 3: Temperature dependence of fracture toughness from maximum load for different specimen thickness

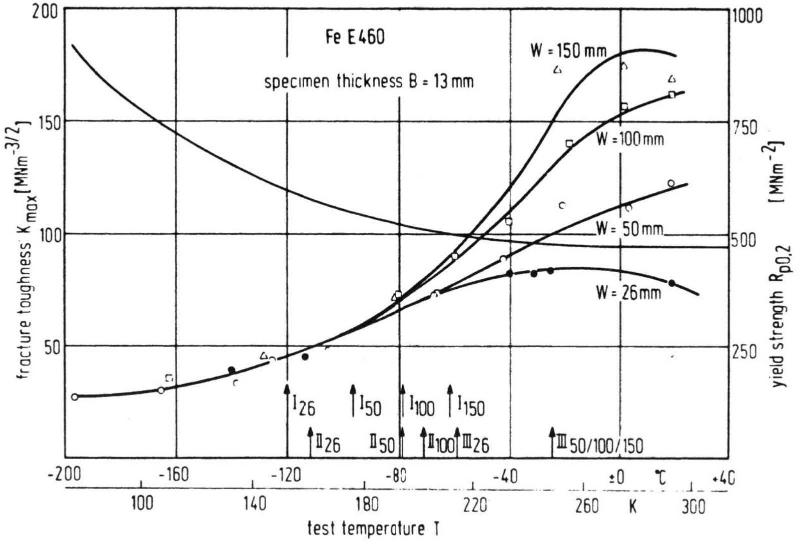


Fig. 5: Temperature dependence of fracture toughness from maximum load for different specimen widths

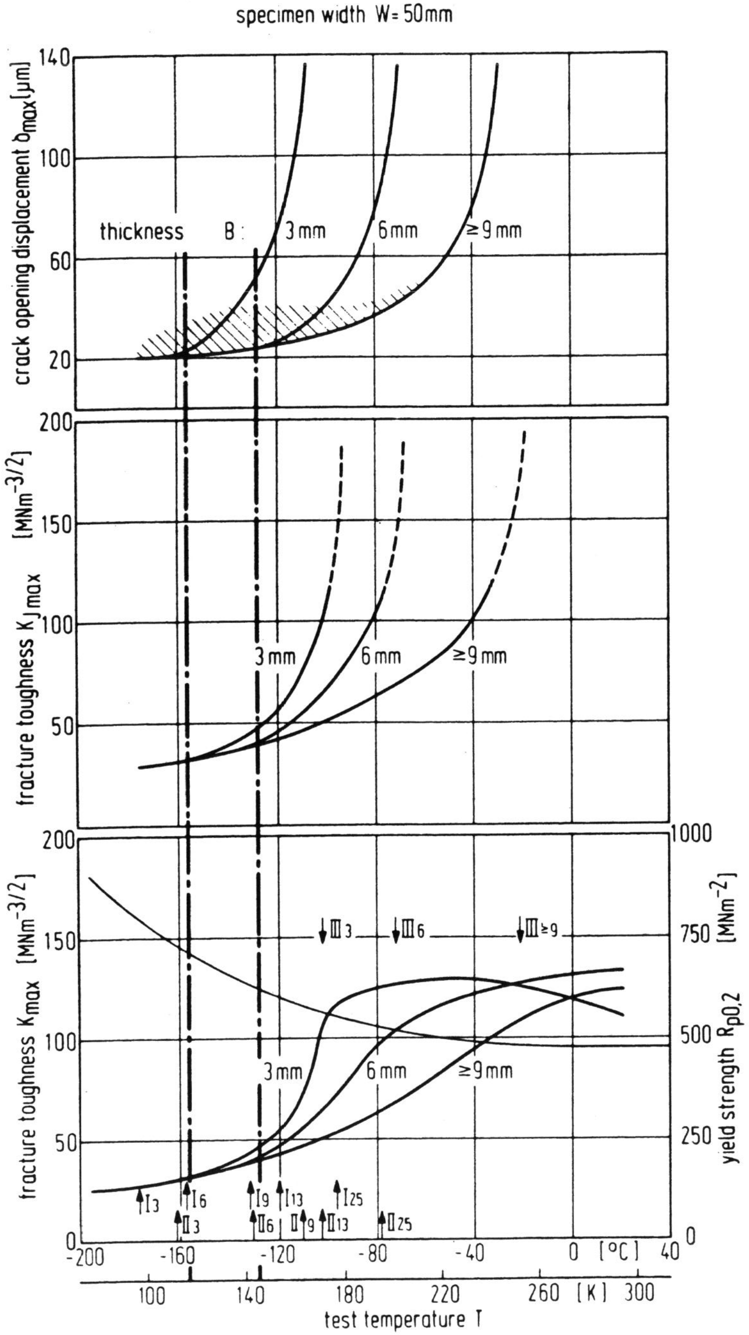


Fig. 4: Temperature dependence of the critical COD calculated by linear extrapolation, the K-value calculated from the critical J-Integral and the fracture toughness from maximum load for different specimen thicknesses

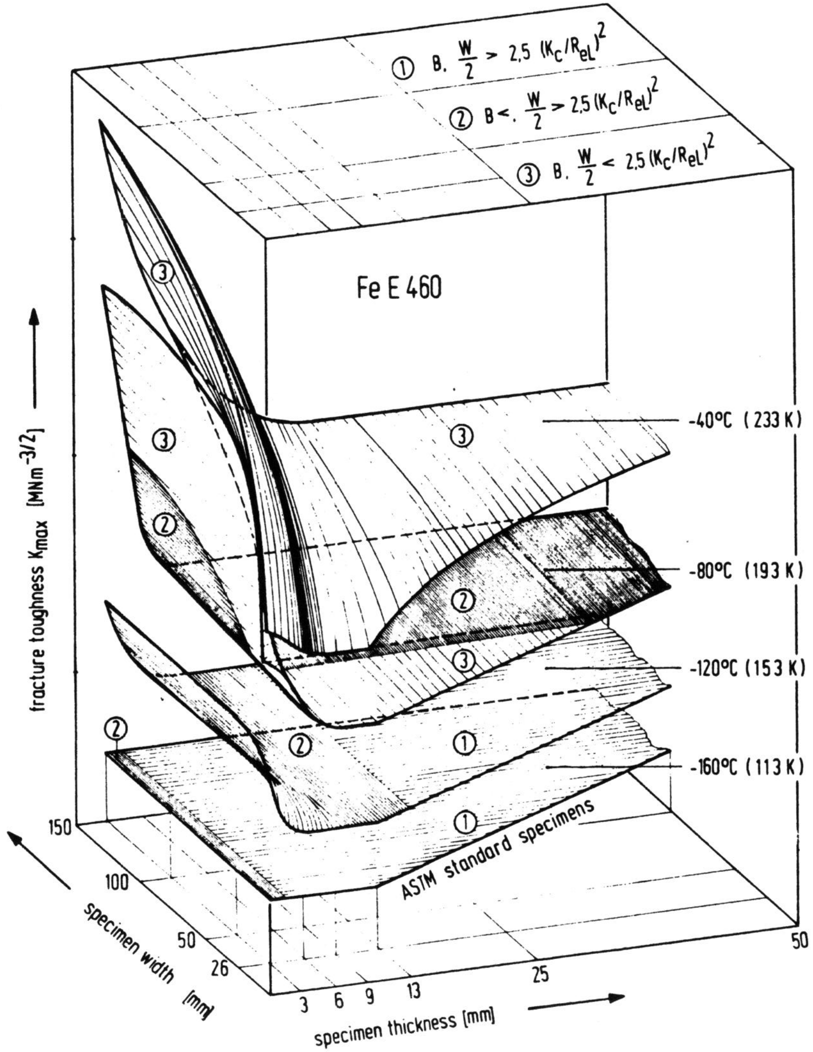


Fig. 6: Specimen size dependence of fracture toughness from maximum load at different temperatures