INFLUENCE OF MICROSTRUCTURE AND OTHER PARAMETER ON FRACTURE-MECHANICS VALUES OF A STRUCTURAL STEEL

H.Mildner*, T.Varga** and G.Schneeweis**

Parts of the same rolled plate had been tested to obtain $J_{IC}$ and $COD$ in three different heat treatment conditions (normalised; quenched and tempered; coarse grain treated and quenched and tempered). Specimen of different size were used to measure $J_{IC}$ and COD at initiation. All tests were conducted practically in the upper shelf region. An influence of specimen size on the above material characteristics has been observed, which was dependent on microstructure and testing temperature. As a consequence, $a$ values had to be increased from 25 to $\geq 50$.

INTRODUCTION

Fracture mechanics provides quantitative means to relate defect size with stress in function of a material property. In consequence, the design engineer is able to choose materials, defect tolerances and loading conditions for a failure safe structure. The necessary material characteristics have to be measured on laboratory test specimens. These values have to be independent of specimen size, if they are to be applied for different structures. Minimum size (thickness) requirements are sometimes controversial. Furthermore, a temperature and microstructural influence on the size requirement seems to be possible.

The present paper was aimed to produce different microstructures of a CT structural steel and to test the impact of specimen size and testing temperature on the elastic plastic fracture mechanics material characteristics.

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Requirements for the size of specimens

For linear elastic fracture toughness, $K_{IC}$, measurement the ASTM (1) size criterion is mostly used:

$$B, a \geq 2.5 \left( \frac{K_{IC}}{R_{p0.2}} \right)^2 \tag{1}$$

The above expression leads with increasing plasticity to very big specimen sizes, which are then regarded as impractical. Ritter (2) gave another criterion:

$$B, a \geq 400 \frac{K_{IC}^2}{E \cdot R_{p0.2}} \tag{2}$$

Smaller specimen sizes result as compared to equ. 1 in case, that $R_{p0.2} < E/160$ (for steels, if $R_{p0.2} < 1300$ N/mm$^2$). For elastic plastic material behaviour mostly COD (Crack Opening Displacement) (3, 4) and $J_{IC}$ (Path independent work integral) (5) are used.

For COD testing full section size specimens are recommended both by BS (3) resp. Varga at al. (4). The ASTM testing standard (5) however permits the use of smaller size specimen, if a similar condition like in equ. 1 is regarded:

$$B, (N-a) \geq a \frac{J_{IC}}{\sigma_y} \tag{3}$$

The relation to equ. 2 is given by

$$J_{IC} = K_{IC}^2 \frac{1-v^2}{E} \tag{4}$$

(Structural steel: $1-v^2 \approx 0.92$).

The minimum allowable specimen size is much smaller according to equ. 3 as compared to equ. 1 in the elastic range. ASTM (5) defines $a = 25$; several workers however indicate $a = 50$ to 100 (7, 8, 9, 10). It seems therefore, that is not a constant, but material dependent, varying mainly with microstructure and testing temperature. This dependence will be investigated in
the following.

Steels investigated:
Testing material was a Mn and Si-alloyed and Al-treated steel of 52 mm thickness, delivered in the water quenched and tempered condition. Parts of the actual plate were subjected additionally to a coarse grain overheating plus water QT or to a normalising heat treatment (6). Therefore three different steels of identical chemical composition but of varied microstructure and hence mechanical properties were at disposal. Their designation was
Steel A: normalised
Steel B: water quenched and tempered
Steel C: coarse grain treated plus water quenched and tempered.
Fig. 1 shows the heat treatments and the photographs of the microstructures. Steel A shows a ferritic-pearlitic, Steel B a fine grain bainitic, steel C a coarse grain bainitic structure, the latter similar to some weld HAZ regions.

Testing was completed by grain size definition according to (11), see also Fig. 1, tensile and impact testing (ISO-V) at different temperatures, drop weight testing (12) for measuring TNDT. Mechanical properties stemmed from the transversal direction in mid-thickness, see Tables 1 und 2.

Fracture mechanics tests:
Three-point bend specimens were machined (3) and precracked (5); standard geometry specimens of B x 2 B x (8 B + 40 mm) were taken transversal of plate mid-thickness. The following thicknesses were investigated: B = 50 mm (full plate thickness) 25 mm and 12.5 mm, additionally some intermediate size specimens between B = 18.5 to 37.5 mm (see Table 2).

Testing temperatures were related to the NDT-Temperature; they were at TNDT + 20 K, TNDT + 70 K and TNDT + 150 K. The actual testing temperature range was -30 to +150°C. For every specimen a load-deflection and a load -COD record was taken. There were for each dimension and testing temperature three to four specimens tested. The multiple specimen technique was used
to find by extrapolation of stable crack growth the initiation point. The values of $J_{IC}$ and $\delta_1$ are listed in Table 2; they support the elastic plastic behaviour of the specimens in the upper shelf fracture toughness region.

Results and discussion

$J_{IC}$-values show in Table 2 the influence of specimen size: full plate thickness specimen ($B = 50$ mm) show an increase of up to 25 % compared to the smallest ($B = 12.5$ mm). Apparently there exist two levels: intermediate size specimens shift with increasing testing temperature from the upper to the lower level. The difference between the two levels seems to be independent from testing temperature here.

$\delta_1$-values exhibit also size dependence, the two levels however seem to be less pronounced.

According to equ. 3 each $J_{IC}$-measurement point may be attributed to a specific value of $\alpha$, viz. Table 2. The $\alpha$-values lie between 20 and 160, i.e. in a wider range than found before (7, 8, 9, 10). A limit line may be drawn, above which the full plate thickness $J_{IC}$ was attained, see Fig. 3. In consequence, by neglecting some scatter, minimum $\alpha$ values may be defined for every testing temperature, which yield the full size $J_{IC}$.

Beside the testing temperature the influence of microstructure becomes apparent. The value of $\alpha = 25$ seems to be generally too low: the normalised steel A exhibits $\alpha = 50$ with very little variation over testing temperature. Steels B and C however need $\alpha$ between 50 and 130.

The differing values of $\alpha$ are only one of the factors influencing the necessary minimum specimen size. If the respective $R_p 0.2$ are also put into equ. 3, the following minimum specimen dimensions result for the three steels at $T_{NDT} + 70$ K.
A: $a \geq 50$  \hspace{1cm} B, \ (N-a) \geq 30 \text{ mm}
B: $a \geq 67$  \hspace{1cm} B, \ (N-a) \geq 26 \text{ mm}
C: $a \geq 102$  \hspace{1cm} B, \ (N-a) \geq 37 \text{ mm}

Minimum specimen dimensions would have been 9 to 15 mm for $a = 25$ according to (5). But even the higher necessary $a$ lead to specimens 4 to 10 times smaller than calculated using equ. 2. Applying equ. 1, the difference becomes even larger; a direct comparison however is not possible in this case.

**SYMBOLS USED**

- $a$ = total crack length (mm)
- $b$ = specimen thickness (mm)
- $E$ = Young's modulus (N/mm$^2$)
- $J_{IC}$ = J-integral at onset of stable crack growth (N/mm)
- $K_{IC}$ = fracture toughness (kN/mm$^{3/2}$)
- $R_{p0.2}$ = 0.2 % proof stress (N/mm$^2$)
- $R_m$ = ultimate tensile strength (N/mm$^2$)
- $W$ = specimen width (mm)
- $a$ = proportionality factor
- $\Delta a$ = amount of stable crack growth (mm)
- $\delta_i$ = crack tip opening displacement at onset of stable crack growth (mm)
- $v$ = Poisson's ratio
- $\sigma_y$ = "effective yield strength" $\sigma_y = 0.5 \ (R_{p0.2} + R_m) \ (N/mm^2)$

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### Analysis (weight percents)

<table>
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<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Cr</th>
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### Tensile test results

<table>
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<tr>
<th>Steel</th>
<th>Testing temperature °C</th>
<th>$R_{p0.2}$ N/mm²</th>
<th>$R_m$ N/mm²</th>
<th>$A_5$ %</th>
<th>$Z$ %</th>
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<tr>
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<td>640</td>
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**Table 1**

**Impact energy values as a function of temperature**

![Impact Energy Graph](image-url)
### Fracture mechanics results

<table>
<thead>
<tr>
<th>Steel A, normalised</th>
<th>Steel B, QT</th>
<th>Steel C, coarse grain treat., QT</th>
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<tbody>
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<td><strong>Temp. B</strong></td>
<td><strong>B</strong></td>
<td><strong>J_\text{lc}</strong></td>
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<td><strong>\degree C</strong></td>
<td><strong>\text{mm}</strong></td>
<td><strong>\text{KN} \text{mm}^{-1/2}</strong></td>
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</table>

Tab 2
Fig. 3

Minimum values of α

Steel C (coarse grain treated + QT)
Steel B (QT)
Steel A (normalised)
ASTM (S)

Testing temperature

α

-50  0  +50  +100  +150 °C

150

100

50