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

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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 an quenched andtempered). 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, α values had to be increased from 25 to ≥ 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 QT structural steel and to test the impact of specimen size and testing temperature on the elasitc 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:

$$B,\ a \geq 2{,}5 \left(\frac{K_{Ic}}{R_{p0,2}} \right)^2 \qquad (1)$$

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

$$B,\ a \geq 400 \ \frac{K_{Ic}^{\ 2}}{E.R_{p0,2}} \qquad (2)$$

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:

$$B,\ (W-a) \geq \alpha \frac{J_{Ic}}{\sigma_y} \qquad (3)$$

The relation to equ. 2 is given by

$$J_{Ic} = K_{Ic}^{\ 2} \ \frac{1-v^2}{E} \qquad (4)$$

(Structural steel: $1-v^2 \triangleq 0{,}92$).

The minimum allowable specimen size is much smaller according to equ. 3 as compared to equ. 1 in the elastic range. ASTM (5) defines $\alpha = 25$; several workers however indicate $\alpha = 50$ 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 T_{NDT}. 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 T_{NDT} + 20 K, T_{NDT} + 70 K and T_{NDT} + 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 δ_i 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.

δ_i -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 α , viz. Table 2. The α-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 α 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 $\alpha \triangleq 50$ with very little variation over testing temperature. Steels B and C however need α between 50 and 130.

The differing values of α 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: $\alpha \geq 50$ B, $(W-a) \geq 30$ mm
B: $\alpha \geq 67$ B, $(W-a) \geq 26$ mm
C: $\alpha \geq 102$ B, $(W-a) \geq 37$ mm

Minimum specimen dimensions would have been 9 to 15 mm for $\alpha = 25$ according to (5). But even the higher necessary α 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 moduls (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)
α = proportionality factor
Δa = amount of stable crack growth (mm)
δ_i = crack tip opening displacement at onset of stable crack growth (mm)
ν = Poisson's ratio
σ_y = "effective yield strength" $\sigma_y = 0{,}5\ (R_{p0,2} + R_m)$ (N/mm^2)

REFERENCES

1. ASTM E 399-81, Standard test method for plane-strain fracture toughness of metallic materials

2. J.C.Ritter, A modified thickness criterion for fracture toughness testing
Engng.Fract.Mech. 9, 1977, 529 - 540

3. BS 5762/1979: Methods for crack opening displacement (COD) testing

4. T.Varga, G.Prantl and D.H.Njo, Test procedure for C.O.D. (Crack Opening Displacement) determination
Aktennotiz ASK-AN 220, Rev. 1, Eidg. Amt für Energiewirtschaft, Abt. für die Sicherheit der Kernanlagen

5. ASTM-Standard method - The determination of the elastic plastic toughness parameter, J_{Ic} E 813-81

6. H.Mildner, Beitrag zur Ermittlung von J-Integral und Rißaufweitung als Werkstoffkennwerte und zu deren Anwendung bei der Sicherheitsabschätzung von Druckbehältern.
Dissertation TU-Wien 1981

7. J.A.Begley and J.D.Landes, A comparison of the J-Integral fracture criterion with the equivalent energy concept
ASTM STP 536, 1973, 246 - 263

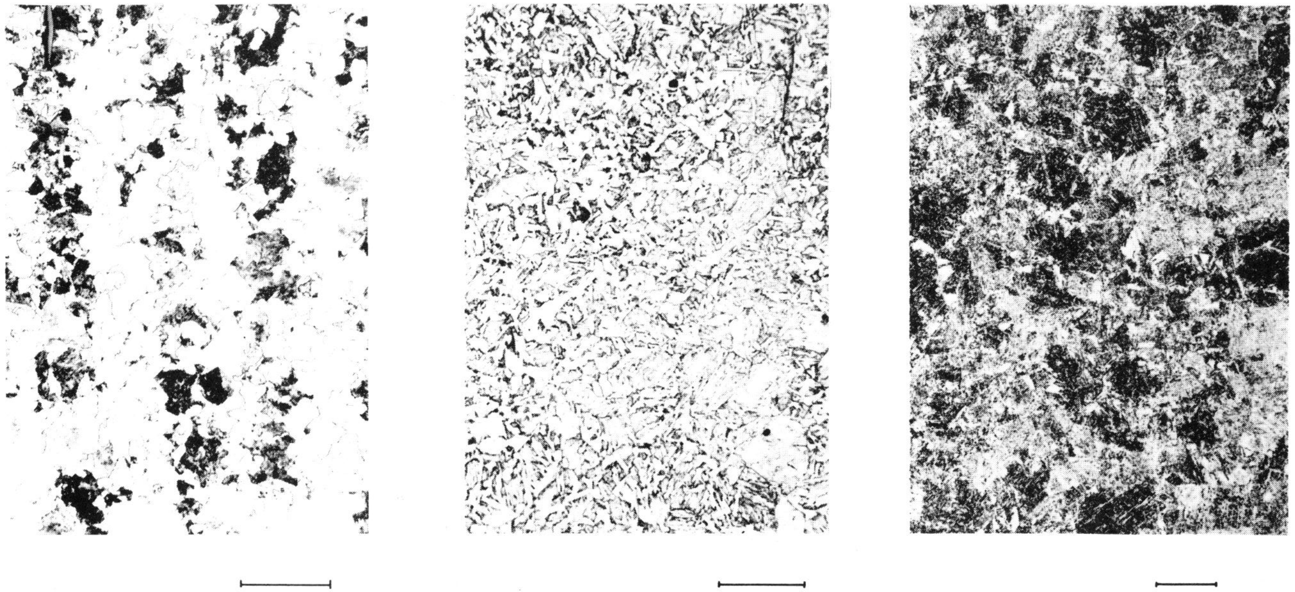
8. R.Stahlberg, Schritte zur Vereinheitlichung der Prüfverfahren zur Ermittlung bruchmechanischer Kennwerte mit dem J-Integral
Stahl u. Eisen 97, 1977, 1039 - 1043

9. D.Sunamoto, M.Sato, T.Funada and M.Tomimatsu, Study on fracture toughness test method using small specimens based on the J-Integral
Mitsubishi Heavy Industries Ltd. Technical Review
Oct. 1977, 449 - 457

10. H.P.Keller, Über das J-Integral und andere Auswerteverfahren der Fließbruchmechanik sowie über die Gültigkeitsgrenzen der linear-elastischen Bruchmechanik
Dissertation an der R.-W.T.H.Aachen, 1979

11. ASTM E 112-77, Standard methods for estimating the average grain size of metals, 1977

12. ASTM E 208-69



Steel A: 50 µm

ASTM grain size: env. 10

910°C, 1,5 h, cooling in still air

Steel B: 50 µm

ASTM grain size (austenite): env. 8

940°C, 1,5 h, water

550°C, 2 h, still air

Steel C: 500 µm

ASTM grain size (austenite): env. 0,5 - 1

1190°C, 3 h, water

550°C, 2 h, still air

Fig. 1

Analysis (weight percents)								
C	Si	Mn	P	S	Al	Cr	Ni	Mo
0,20	0,52	1,66	0,013	0,013	0,055	0,21	0,02	0,05

Steel	Testing temperature °C	Tensile test results			
		$R_{p0,2}$	R_m	A_5	Z
		N/mm²		%	
A	-10	407	640	27,0	62
	+20	374	603	28,4	64
	+120	331	552	29,6	63
B	-30	588	782	21,4	59
	+20	534	711	20,8	60
	+100	512	679	19,4	59
C	+20	610	774	16,8	51
	+70	546	697	17,6	52
	+150	525	678	16,2	52

Table 1

IMPACT ENERGY VALUES AS A FUNCTION OF TEMPERATURE

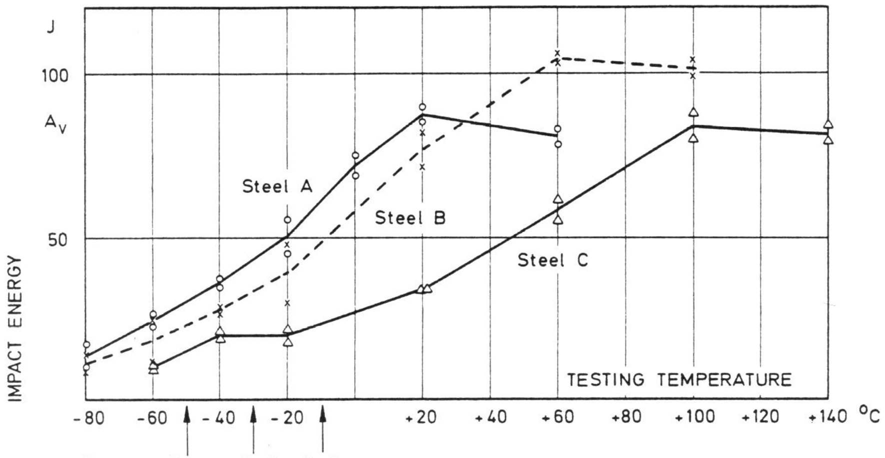


Fig. 2

Fracture mechanics results

Steel A, normalised						Steel B, QT						Steel C, coarse grain treatm.+QT					
Temp.	B	J_{Ic}	K_{Ic}	α	δ_i	Temp.	B	J_{Ic}	K_{Ic}	α	δ_i	Temp.	B	J_{Ic}	K_{Ic}	α	δ_i
°C	mm	$\frac{N}{mm}$	$\frac{kN}{mm^{3/2}}$	-	mm	°C	mm	$\frac{N}{mm}$	$\frac{kN}{mm^{3/2}}$	-	mm	°C	mm	$\frac{N}{mm}$	$\frac{kN}{mm^{3/2}}$	-	mm
-10	50	307	8,36	74	0,355	-30	50	270	7,84	112	0,211	+20	50	195	6,67	158	0,151
	32	314	8,46	51	0,364		25	262	7,73	63	0,212		25	187	6,53	92	0,154
	25	290	8,13	44	0,361		18,5	252	7,58	50	0,202		20,5	163	6,09	85	0,128
	12,5	250	7,55	23	0,301		12,5	214	6,98	36	0,179		12,5	146	5,77	53	0,119
+20	50	292	8,16	78	0,420	+20	50	241	7,41	108	0,196	+70	50	225	7,16	121	0,180
	37,5	290	8,13	60	0,380		32	250	7,55	79	0,194		33	203	6,80	100	0,168
	25	255	7,62	47	0,340		25	222	7,11	60	0,176		25	165	6,13	93	0,156
	12,5	250	7,55	22	0,301		12,5	177	6,35	40	0,160		12,5	154	5,92	46	0,134
+120	50	285	8,06	68	0,453	+100	50	195	6,81	139	0,194	+150	50	177	6,35	151	0,178
	37,5	284	8,04	58	0,410		32	178	6,36	109	0,175		33	153	5,90	129	0,155
	25	222	7,11	49	0,348		25	172	6,26	95	0,174		25	128	5,40	115	0,125
	12,5	215	7,00	23	0,310		12,5	141	5,68	49	0,155		12,5	130	5,44	51	0,128

Tab. 2

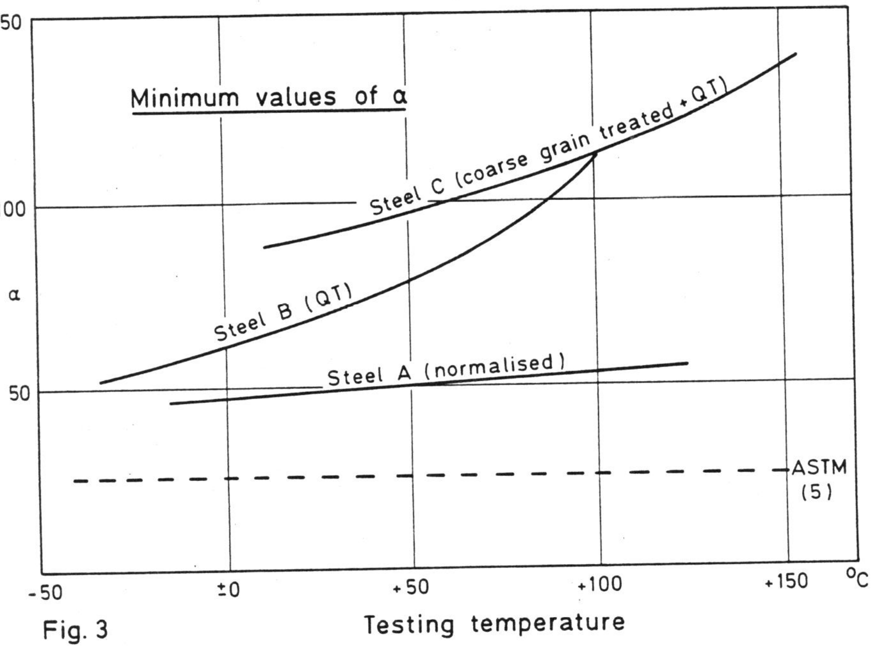

Minimum values of α
Steel C (coarse grain treated + QT)
Steel B (QT)
Steel A (normalised)
ASTM (5)
α
150
100
50
-50
±0
+50
+100
+150
°C
Testing temperature

Fig. 3