THE RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND MICROSCOPIC CLEAVAGE FRACTURE STRESS OF STEEL 20 MnMoNi 5 5

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ABSTRACT

Tensile tests with notched and unnotched specimens and finite element calculations were performed to determine the microscopic cleavage fracture stress σ_f^* for two differently heat treated plates of the pressure vessel steel 20 MnMoNi 5 5. By applying the Ritchie, Knott and Rice (RKR) criterion (Ritchie, Knott and Rice, 1973) which states that cleavage fracture is initiated when the maximum local tensile stress σ_{yy} exceeds σ_f^* across a critical distance x_c, σ_f^* was related to fracture toughness K_{Ic}. Knowledge of the temperature dependence of the yield stress, σ_f^* and a crack tip stress distribution analysis made it possible to predict K_{Ic}-values over a large temperature range with reasonable accuracy. An attempt was made to correlate the critical distance x_c with microstructural units.

KEYWORDS

Cleavage fracture criterion; microscopic cleavage fracture stress fracture toughness; finite element calculations; critical distance; microstructural parameters

INTRODUCTION

The initiation of plane strain cleavage fracture is commonly described by a critical stress criterion. According to Ritchie, Knott and Rice (1973) cleavage cracks propagate when the maximum local tensile stress σ_{yy} ahead of crack tip or notch root exceeds the microscopic cleavage fracture stress σ_f^* across a critical distance x_c. σ_f^* is considered as a material property nearly independent of temperature and strain rate and x_c as a microstructural parameter.

In combination with an elastic-plastic near crack tip stress distribution analysis it is possible to estimate the fracture toughness K_{Ic} over a certain temperature range if the temperature dependence of the yield stress is known.

The correlation between microscopic cleavage fracture stress σ_f^* and fracture toughness K_{Ic} has been applied successfully to mild steels. The aim of this investigation was to find out whether it is also applicable to materials with more complicated microstructures.

EXPERIMENTAL PROCEDURE

Two differently heat treated plates (24 and 25) of the pressure vessel steel 20 MnMoNi 5 5 were investigated. Chemical compositions and heat treatments are listed in Table I.

Table I - Composition and Heat Treatments of the Steel 20 MnMoNi 5 5

	C	Si	Mn	P	S	Cr	Mo	Cu	Ni	Sn	As	Al	V
24	.20	.24	1.41	.011	.004	.16	.49	.10	.80	.006	.013	.030	.015
25	.23	.24	1.41	.010	.005	.16	.50	.09	.80	.006	.012	.027	.0155

Heat Treatment

24:	900 °C/40'/ forced air cooled	/650 °C/80'/	air cooled
25:	900 °C/45'/ furnace cooling to	650 °C/	air cooled

The microstructure found in plate 24 (Fig. 1a) is characterized by a tempered bainitic grain structure. Plate 25 (Fig. 1b) shows a banded microstructure with bands of proeutectic ferrite and bands of bainite and martensite with a high carbon content.

Tensile tests were performed with cylindrical unnotched and rectangular double-notched specimens between 77 K and 293 K in order to determine the microscopic cleavage fracture stress σ_f^* (Kühne, 1982). Fracture toughness values were obtained with CT-specimens (W = 100 mm, B = 28 mm, a/W = 0,5) between 77 K and 223 K according to ASTM E399 and with wide plate CCP-type specimens (W = 450 mm, B = a = 30 mm) at 173, 203 and 283 K.

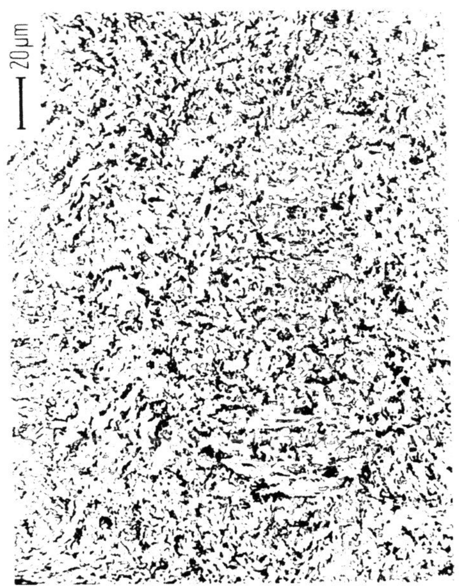

Fig. 1a. Microstructure of the forced air cooled condition (plate 24)

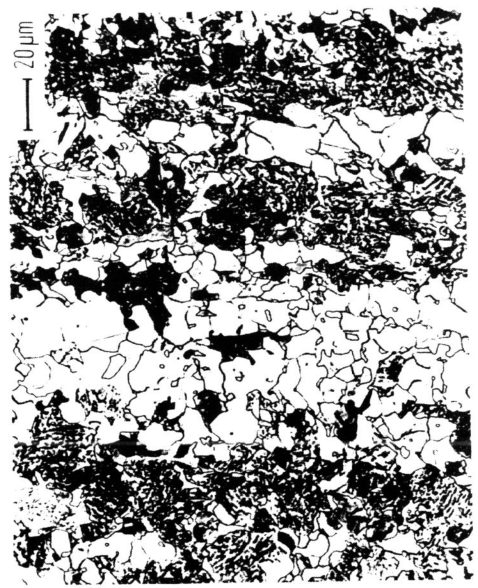

Fig. 1b. Microstructure of the furnace cooled condition (plate 25)

RESULTS AND DISCUSSION

The results from uniaxial tensile testing were of main importance for the finite element calculations discussed below.

Fig. 2 shows the temperature dependence of the yield stress for both heat treatments, the yield stress increasing with decreasing temperature.

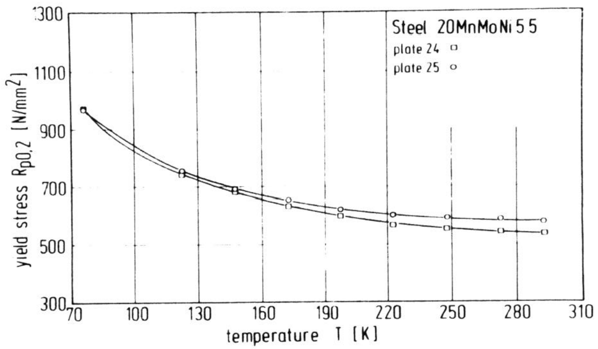

Fig. 2. Temperature dependence of the yield stress of unnotched tensile specimens ($\dot{\varepsilon} = 10^{-4}\ s^{-1}$)

Fracture and yield stresses received from double-notched tensile specimens vs temperature are shown in Fig. 3a and 3b. Stress σ_1 corresponds to first deviation from elastic behaviour, σ_3 and σ_5 to a notch displacement of 0,6 µm and 1,2 µm respectively, and σ_{10} stands for general yield. For the furnace cooled condition (plate 25) stress values are somewhat lower than those of the forced air cooled condition (plate 24) with a relatively large temperature region in which fracture occurs at general yield.

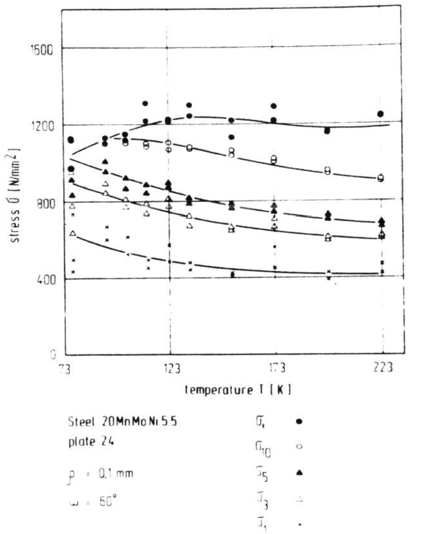

Fig. 3a. Temperature dependence of fracture and yield stress of double-notched tensile specimens (plate 24 air cooled)

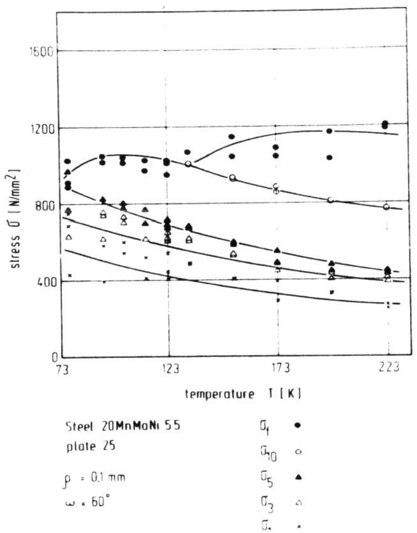

Fig. 3b. Temperature dependence of fracture and yield stress of double-notched tensile specimens (plate 25 furnace cooled)

The microscopic cleavage fracture stress $\sigma_f{}^*$ was determined according to the fracture criterion by Ritchie, Knott and Rice (1973)

$$\sigma_f{}^* = \sigma_{yy}(x_c).$$

The σ_{yy}-stress distribution below the notch root was calculated by a 2-dimensional finite element program (Redmer, 1981) using isoparametric 8-nodal elements and assuming plane strain behaviour. True stress-strain-curves obtained with unnotched tensile specimens were taken into account. Strain hardening was considered by the Ludwik-equation ($\sigma = K \cdot \phi^n$). Fig. 4 shows the σ_{yy}-stress distribution in a notched tensile specimen tested at 77 K. The maximum value increases with increasing load gradually moving towards the centre of the specimen until general yield. $\sigma_f{}^*$ is found in the load step which corresponds to the measured fracture load, being $\sigma_f{}^* = 2155$ MPa for plate 24 and

$\sigma_f{}^* = 2032$ MPa for plate 25.

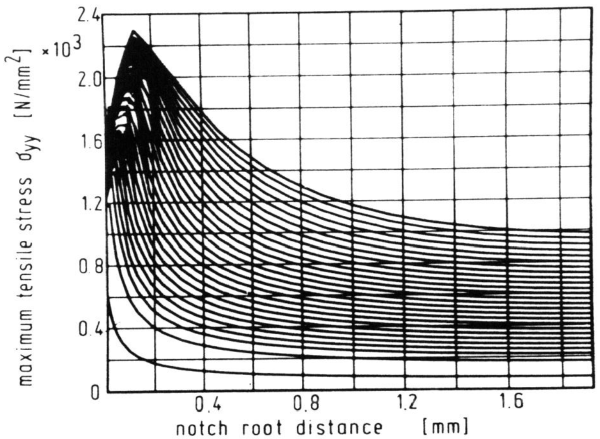

Fig. 4. σ_{yy}-stress distribution of a double-notched tensile specimen

Referring to Tracey's finite element solution (1976) for crack tip behaviour in small scale yielding, where the ratio of maximum tensile stress σ_{yy} to flow stress $\sigma_y (= \sigma_o)$ is plotted against $x/(K/\sigma_y)^2$ (Fig. 5), the critical distance was fitted at a certain temperature from a knowledge of $\sigma_f{}^*$, σ_y and one measured K_{Ic}-value.

Assuming that $\sigma_f{}^*$ and x_c are temperature independent, it was possible to predict fracture toughness over a large temperature range. Predicted K_{Ic}-values are compared to values measured with CT- and wide plate specimens in Fig. 6. The agreement between predicted and measured values is quite good in range of LEFM. Above the temperature at which the ASTM-geometry criterion is no longer valid, predicted values turn out to be too low. In this case the increasing plastic deformation leads to crack tip blunting, which was not taken into consideration in Tracey's stress distribution analysis.

Since the critical distance x_c cannot be measured directly, this size must be fitted and subsequently correlated to some microstructural unit. x_c was determined to 30 µm for the forced air cooled condition (plate 24) and to 40 µm for the furnace cooled (plate 25). The microstructure found in plate 24 exhibits no definite microstructural unit except the former austenite grain size. The fact that its diameter has the same length as the critical distance is probably a mere coincidence, because the former austenite grain size has no significant influence on the initiation of cleavage fracture (Kotilainen, 1980).

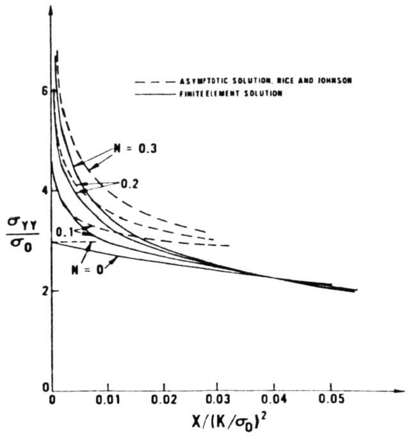

Fig. 5. Variation of $\frac{\sigma_{yy}}{\sigma_y}$ $(\sigma_y = \sigma_o)$ ahead of a crack

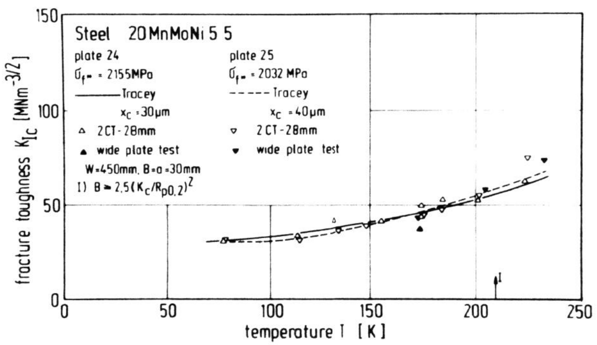

Fig. 6. Temperature dependence of fracture toughness

The banded microstructure of plate 25 has a ferrite grain size of 10 - 12 µm, whereas the bands of bainite and martensite are difficult to characterize. Assuming that the ferrite bands determine fracture behaviour, x_c has the size of 3 - 4 grains which is comparable to values found in literature.

CONCLUSIONS

The RKR-Model can be used to predict fracture toughness as a function of temperature for the more complex structures from a knowledge of the microscopic cleavage fracture stress, temperature dependence of the yield stress and a stress distribution analysis. The good agreement between predicted and measured K_{Ic}-values confirms the validity of the critical stress criterion for cleavage fracture $\sigma_f^* = \sigma_{yy}(x_c)$. A difficulty lies in the determination of the critical distance x_c, especially in absence of definite microstructural units.

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