THE APPLICATION OF SLOW-STRAIN-RATE TENSION TEST FOR QUANTITATIVE EVALUATION OF HYDROGEN-INDUCED CRACKING SUSCEPTIBILITY OF HIGH STRENGTH STEELS

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The decreasing of fracture ductility caused by lowered strain rate at tension has been used to determinate hydrogen-induced cracking susceptibility of high strength steel with 5 wt.%-Cr.
The relevance of the slow-strain-rate tension test to establish the threshold stress intensity factor K_{TH} of high strength steel has been checked by the validity of the Gerberich's equation (1), which seems to be a sufficient rationalization.

INTRODUCTION

The most critical aspect of the effect of hydrogen in high strength steels is usually considered to be hydrogen induced cracking, the best known type being classical delayed failure. Is such a process, a crack is first nucleated and then grows until failure occurs, as it is shown in Fig. 1 (1). The lowest stress intensity which causes failure is called the threshold stress intensity K_{TH}.

Initiation of microcracks arises as a consequence of elastic interaction between the mobile hydrogen atoms in steel and the triaxial stress fields at different discontinuities in the metal. The first crack can initiate when the critical hydrogen concentration is attained. On the basis of this concept Gerberich (2) developed the following equation for K_{TH}:

$$K_{TH} = (RT/\alpha\bar{V}_H)\ln(\beta/\sigma_{ys}) - \sigma_{ys}/2\alpha \;.......(1)$$

in which β has to be a constant, specific for definite types of steel.

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The question of whether or not initiation of microcraks is stress controlled has not been resolved in general. There is some evidence that ductile fracture initiation in hydrogen charged steel has been observed to occur along characteristic logarithmic-spiral slip-line traces (Fig. 2), (3,4) and that it is not restricted only to the locations of maximum hydrogen concentration i.e. to the locations of maximum stress.

This problem could be overcome by the approach of McClintock (5) who has alternatively utilized a stress-modified critical strain criterion. For a situation in which strain exerts partial or full control of the fracture initiation process, a critical strain of the type shown in Fig. 3 should be relevant.

Considering the above mentioned critical strain criterion, Hahn and Rosenfield (6) developed one of the most reliable and yet simple model for fracture toughness calculation, which does not incorporate the observed behaviour of microvoid nucleation and coalescence. According to this model, the following semiempirical equation for K_{IC} was derived:

$$K_{IC} = (0{,}05\,\varepsilon_f\, n^2\, E\, \sigma_{ys}/3)^{1/2} \quad ....(2)$$

Although the critical stress intensity factor K_{IC} of hydrogen-charged high-strength steel is not essentially worse and the appearance of the fracture aurface of such steel is not necessarily brittle because it contains a small amount of hydrogen (less than 1 ppm), however nucleation of microcracks, as a strain controlled process, is easier due to decreasing fracture ductility by slow-strain-rate tension test. This fact gave the idea that the decreased fracture ductility due to lowered strain rate at tension could be used to establish the threshold stress intensity K_{TH} with the Eq. (2), though this equation was developed only to calculate fracture toughness K_{IC}.

The K_{TH}-values, calculated with the Eq. (2) could be then substituted into Gerberich's equation (1), so that β value could be deduced. The relevance of slow-strain-rate tension test for establishing the delayed fracture susceptibility of high strength steel is therefore reduced to the determination of the constancy of β value in Eq. (1).

EXPERIMENTAL

Cylindrical tensile specimens of diameter 10 mm were machined from secondary hardening steel with 5 wt.% of chromium. Specimens were austenitized at 980°C, quenched and tempered 2 hours at temperatures 620°C, 640°C and 670°C respectively so that three distinct classes of yield strength of 1220 MPa, 1020 MPa and 900 MPa respectively were achieved.

The cathodic charging with hydrogen was carried out 1 hour in a 1 N sulphuric acid at current density of 0,3 mA/cm^2.

Tensile tests were made 20 hours after charging was finished so that the concentration of hydrogen in steel could drop to the nearness of time-independent residual values (aprox. 0,6 to 0,8 ppm).

Tensile tests were performed at conventional strain rate i.e. at crosshead speed of 1 mm/min as well as at lower-strain-rate i.e. at crosshead speed of 0,1 mm/min. Uniform elongation and reduction of area were measured on each specimen, whereas a few Charpy V-noch impact tests were also made on uncharged steel.

RESULTS

The fracture toughness K_{IC} was calculated according to Hahn-Rosenfield correlation (2) on the basis of conventional tension tests made at crosshead speed of 1 mm/min. For comparison, some of fracture toughness data on uncharged steel were obtained also with Rolfe-Novak correlation (7) on the basis of the results of Charpy measurements.

Threshold stress intensity factor K_{TH} of cathodic charged steel was calculated also with Eq. (2) but on the basis of the results obtained at crosshead speed of 0,1 mm/min.

The results attained at Charpy V-notch measurements on uncharged steel and the results of different strain rate tests for both uncharged and hydrogen charged steel are pointed out in Table 1 and 2.

TABLE 1 - Mechanical properties of uncharged steel

Yield strength (MPa)	Charpy V-notch toughness (J)	Crosshead speed 1 mm/min Uniform elongation (%)	Crosshead speed 1 mm/min Reduction of area (%)	Crosshead speed 0,1 mm/min Uniform elongation (%)	Crosshead speed 0,1 mm/min Reduction of area (%)	Fracture toughness (MPa.m$^{1/2}$) Rolfe-Novak	Fracture toughness (MPa.m$^{1/2}$) Hahn-Rosenfield
900	44	8,5	52	8,7	52	143	122
1020	36	7,5	51	6,8	51	130	113
1220	28	6,1	49	6,2	50	112	100

The microfractographic examinations of fracture surfaces of hydrogen charged specimens confirm that hydrogen induced fracture at slow-strain-rate tension is not predominantly cleavage but is locally ductile, tearing type of fracture of the kind which can be described as quasicleavage (Fig. 5, 6 and 7).

TABLE 2 - Mechanical properties of cathodic charged steel

	Crosshead speed 1 mm/min		0,1 mm/min				
Yield strength (MPa)	Uniform elongation (%)	Reduction of area (%)	Uniform elongation (%)	Reduction of area (%)	Fracture toughness ($MPa.m^{1/2}$)	Threshold stress intensity ($MPa.m^{1/2}$)	β value (MPa)
900	8,4	50,1	8,1	47,6	118	110	4000
1020	7,3	49	6,7	42,7	108	90	3908
1220	6,1	47,3	6,0	27	97	67	3984

The results of our investigations are also summarized in a diagram in Fig. 4.

DISCUSSION

Our investigations confirm that the real value of the threshold stress intensity factor K_{TH} can be calculated by measuring the fracture ductility at slow-strain-rate tension tests as a first approximation for tension test at constant static load (delayed fracture test).

It was also confirmed that the correlation of Hahn-Rosenfield (2) can be used for calculation of K_{TH} assuming that the local equivalent plastic strain must exceed a critical fracture strain or ductility over a characteristic distance comparable with the mean spacing of the void initiating particles (Fig. 3). This is in accordance with the results of microfractographic examinations which show that hydrogen-induced fracture at slow-strain-rate tension is not predominantly cleavage, but remains locally ductile, tearing type of fracture, so that the term hydrogen embrittlement may be even too restrictive.

Threshold values, which have been substituted together with the corresponding yield strengths into Gerberich's equation (1), enable the expression of β value. A constant i.e. a value independant of the yield strength of steel, with a worth of 4000 was obtained. The constant value of β as calculated out of the Eq. (1) confirms also the validity of Gerberich's approach which assumed that the critical location for microcracks initiation is that of maximum triaxial stress. Therefore, the relevance of appropriate criteria concerning crack initiation remains controversable.

On the other hand, the constancy of β value suggests that the crosshead speed of 0,1 mm/min is low enough to registrate correctly the influence of the small amount of hydrogen on the ductile properties of high strength steel.

CONCLUSIONS

The relevance of the slow-strain-rate tension test to establish the threshold stress intensity factor K_{TH} of high strength steel, charged with small amounts of hydrogen, has been proved by measuring the constancy of the β value in the Gerberich's equation (1). It has also been confirmed that initiation of cracks in high strength steel with low concentration of hydrogen is a mainly strain controlled process.

SIMBOLS USED

K_{TH} = threshold stress intensity factor ($MPa.m^{1/2}$)

K_{IC} = critical stress intensity factor ($MPa.m^{1/2}$)

R = gas constant (8,314 J mol^{-1} K^{-1})

T = absolute temperature (K)

α, β = constants in Gerberich's equation

ε_f, $\bar{\varepsilon}_f^*$ = fracture ductility and critical local fracture ductility respectively

l_o^* = characteristic dimension for fracture

d_p = mean spacing of the void initiating particles

δ = crack-tip opening displacement

n = strain hardening exponent

E = Young's modulus (MPa)

σ_{ys} = yield strength (MPa)

RA = reduction of area (%)

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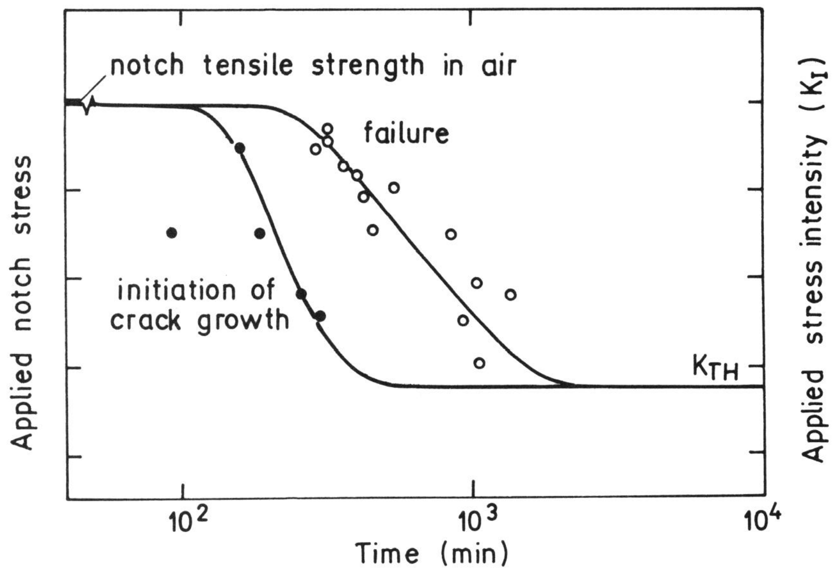


Figure 1 Typical delayed-failure phenomena for notched tensile specimens (adapted from Ref. 1)

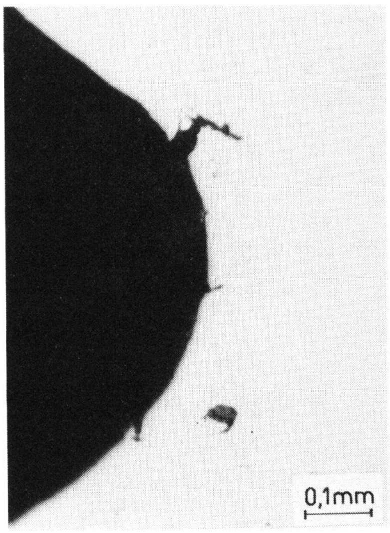


Figure 2 Initiated microcracks at the notch tip (from Ref. 3)

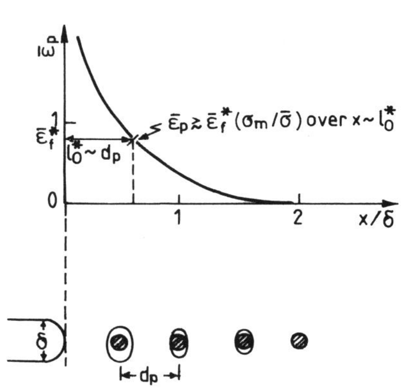


Figure 3 Critical strain fracture criteria (from Ref. 5)

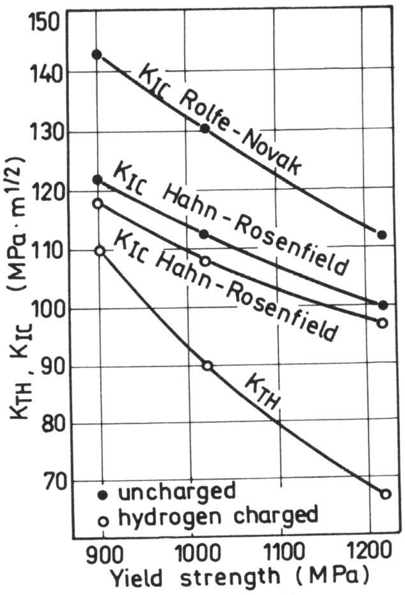
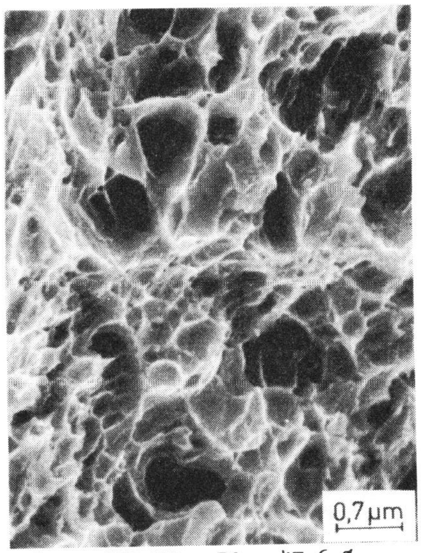
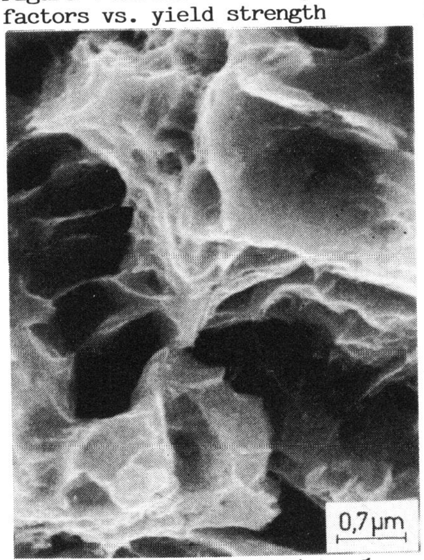


Figure 4 Stress intensity factors vs. yield strength



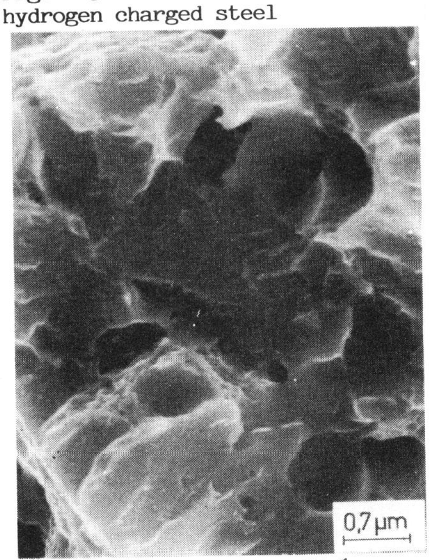
σ_{ys} = 900 MPa, RA = 47,6 %

Figure 5 Ductile fracture of hydrogen charged steel



σ_{ys} = 1020 MPa, RA = 42,7 %

Figure 6 Quasi-cleavage fracture of hydrogen charged steel



σ_{ys} = 1220 MPa, RA = 27 %

Figure 7 Quasi-cleavage fracture of hydrogen charged steel