APPLICATION OF LOCAL APPROACH OF FRACTURE *IN A PEARLITIC STEEL CATHODICALLY HYDROGENATED*

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During railway steel elaboration at high temperature, hydrogen may diffuse inside the metal. After cooling and during stockage, delayed failures were observed. On the other hand, hydrogen embrittlement level is governed not only by hydrogen concentration, but also by the nature (chemical and/or physical) and the distribution of traps, such as carbides (cementite) or MnS inclusions.

The aim of this work is to apply the local approach of cleavage fracture in pearlitic steels having different sulphur contents in the range of 0.009 to 0.029% (wt%) and cathodically hydrogenated in molten salts bath. The results are compared with those of the steels tested in air.

The results show that in presence of hydrogen the mean cleavage stress level at failure σ_u is higher and independent of the sulphur content whereas the scatter is increased. The K_{Ic} level estimated from the local criteria is lowered by about 5 MPa $\sqrt{m}$ when the virgin steel is cathodically hydrogen charged. However, the characteristic distance observed is larger when the steel is hydrogenated than that in the virgin steel.

INTRODUCTION

The models of the local criteria to predict the brittle crack extension in steels had been studied by many authors (1-6). These models involve a critical stress σ_c which is responsible for a cleavage crack propagation. When σ_c level exceeds that the principal stress ahead of the crack tip, a characteristic distance X_0 is promoted. The parameters σ_c and X_0 were proved by finite element calculations to predict an unstable crack propagation (3,6) and then to predict the K_{Ic} level as a function of the test temperature or/and the strain rate. The physical meaning of X_0 is

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not yet clear and authors relate it to the metallurgical parameters such as grain size (7) or the carbide size distribution (4). Moreover these models give no estimation on the scatter of the experimental results. One of the solutions to overcome this difficulty is to apply the BEREMIN approach [8] derived from WEIBULL work [9] for brittle fracture which was applied in experimental studies such as on A 508 steel (8) and railway steels (10).

The cumulative distribution function P_R, over a small volume V_0 ahead of a crack tip, can be expressed as :

$$P_R = 1 - \exp\left[- (\sigma_W / \sigma_u)^m \right] \qquad (1)$$

where σ_W WEIBULL stress, σ_u mean cleavage stress and m is an empirically determined parameter presenting the degree of scatter in measured strength values and its value was found to be about 21 for two low alloy steels (8, 11).

Therefore the application of the BEREMIN model for a given probability P_R leads to a variation of K_{Ic} level as :

$$K_{I_c}(T, \dot{\varepsilon}) \left[\sigma_{ys}(T, \dot{\varepsilon})\right]^{\frac{m}{4}-1} \qquad (2)$$

T and $\dot{\varepsilon}$ are test temperature and strain rate respectively.

On the other hand, the fracture toughness of steels is strongly influenced by their hydrogen content. The various microstructures of steels in conjunction with the hydrogen activity on the surface and with its distribution in the various traps complicate the modelling of threshold or fracture toughness levels. Single parameters measurement like the stress intensity factor K or J integral often characterize the stress field near the crack tip in a macroscopic scale and do not take into account the statistical microstructure change such as the pearlite structure.

In this work, we applied the BEREMIN model in conjunction with finite element calculations to estimate σ_u and K_{Ic} levels on a brittle pearlite steel having different sulphur contents with and without cathodic hydrogen before tensile test.

EXPERIMENTAL PROCEDURE

The three steels studied have all a pearlite structure and differ only by the sulphur content. Table I gives the chemical composition of these steels.

Table I : Chemical composition of the steels studied

Element (wt%) / Designation	C	Mn	P	S	Si	Cr
1	0.787	1.116	0.012	0.009	0.430	0.176
3	0.793	1.102	0.014	0.019	0.416	0.172
5	0.782	1.135	0.018	0.029	0.443	0.174

Two specimens axisymmetrically notched geometries have been used ; AE 1.25 and AE 6.4 beside a smooth one AE∞, figure 1. Half of these specimens have been cathodically charged, before the tensile test, in a molten salts bath at 200°C during one hour with a polarization potential of - 3V/Ag. The average hydrogen content outgassed in vacuum (10^{-3}Pa) at 600°C is about 2 ppm independently of the notch geometry and of the sulphur content. Tensile tests have been achieved with a crosshead speed of 0.5 mm/min., at room temperature and the tensile axis was parallel to the rolling direction. All the failure surfaces are of cleavage brittle type. The results have been analysed using the finite element method and have been also computed with the stress-strain curves obtained by recording continuously the load P and the actual diameter of the minimum section of the axisymmetric specimens.

RESULTS AND DISCUSSION

- Local criteria calculations

Table II gives the plastic deformation at failure ε_f levels as a function of : the sulphur content, the notch sharpness, and the presence of hydrogen. Hydrogen embrittlement factor F% [F% = (ε_{fAIR} - $\varepsilon_{fHyd.}$/ ε_{fAIR}) x 100] is also given.

Table II : ε_f and F% as a function of S%, notch sharpness and hydrogen charging.

S%	ε_{fAIR}			$\varepsilon_{fHyd.}$		
	AE1.25	AE6.4	AE∞	AE1.25	AE6.4	AE∞
0.009	0.067	0.116	0.167	0.023 (65.7)*	0.056 (51.7)	0.141 (15.6)
0.019	0.044	0.118	0.163	0.015 (65.9)	0.057 (51.7)	0.100 (38.6)
0.029	0.055	0.114	0.166	0.024 (57.3)	0.056 (50.9)	0.119 (28.3)

* ( ) presents F% level

The results show that the aggressivity of hydrogen presented by F% increases when the stress triaxiality increases but no evidence that this aggressivity changes with the sulphur content. The mechanical behaviour law of the smooth specimens is slightly affected either by the sulphur content or by the presence of hydrogen, figure 2. We have chosen then to introduce in the numerical calculations an average law and then to correct the results with respect to the yield stress levels. A good agreement is especially obtained in the case of the notched axisymmetric specimens, Figures 3a and b. Following BEREMIN's model, the WEIBULL stress σ_W as a function of the average diametrical deformation $\bar{\varepsilon}$ is plotted in figures 4a and b, taking V_0 equal to 10^6 μm^3 and m equal to 32 and 18 for the results obtained in air and with hydrogen respectively. The results show, for the two notch radii 1.25 and 6.4 mm, that the WEIBULL stress is systematically higher in presence of hydrogen than that in its absence. It is worth noting that the average yield strength levels calculated with and without hydrogen are equivalent and equal to 592 MPa. The difference between σ_W calculated for hydrogenated specimens is higher by about 100 MPa than σ_W calculated for virgin specimens due to the difference in m values. We have observed (figure 5) that the cracks are numerous for the hydrogenated steels and that their density is very high close to the fracture plane (in a 500 μm for H_2 and 50 μm for virgin material).

The intrinsic cleavage stress σ_u is calculated on figure 6: without H_2 the best fit is obtained for m = 32 and σ_u = 2208 MPa and m = 18, σ_u = 2309 MPa with H_2.

- K_{Ic} levels estimation

The details of the method of K_{Ic} levels estimation on SENT specimens using the local criteria are described elsewhere (10,12). The variation of the critical load P with σ_u levels is given on figure 7. Table III gives the critical load values corresponding to different K_{Ic} levels for the hydrogenated steels and not for three fracture probability values : 10, 50 and 90%.

Table III : Estimated critical values of P_c and levels of K_I for different P_R values in presence and in absence of internal hydrogen.

P_R (%)	AIR		Hydrogen	
	P_c (KN)	K_{Ic} MPa$\sqrt{m}$	P_c (KN)	K_{Ic} MPa$\sqrt{m}$
10	25.3	40.1	21.1	33.6
50	29.1	46.2	26.1	41.4
90	31.7	50.3	30.0	47.6

The last results show that K_{Ic} level is independent of the sulphur content, slightely decreased by hydrogen charging whereas the scatter is enlarged. For $P_R\%$ = 50, the decrease is about 5 MPa $\sqrt{m}$. Compiling the results mentioned in PINEAU's paper (13) relative to the relationship between K_{Ic} and σ_{ys}, equation 2, we find that the right hand side of this equation depends on the empirically determined parameter m as shown in figure 8. Our data for the virgin and hydrogenated steels agrees well with linear relation $\ln\left[K_{Ic}\,(\sigma_{ys})^{\frac{m}{4}-1}\right] = f\left(\frac{m}{4}-1\right)$

CONCLUSION

The local approach of cleavage fracture is applied in pearlite steels having different sulphur contents in the range of 0.009 to 0.029% (wt%) and cathodically hydrogenated at 200°C in molten salts bath. The results are compared to the steel tested in air. The results suggest the following conclusions :

1) The hydrogen quantity outgassed at 600°C in vacuum from simulated notched samples is equal to about 2 ppm. This hydrogen content promotes embrittlement which increases when the notch sharpness increases. Hydrogen embrittlement is independent of the sulphur contents when tests are carried out in the long direction.

2) The calculated parameter m is equal to 32 and 18 for the virgin and hydrogenated steels respectively. Mean cleavage stress at failure for steels hydrogen charged is higher by about 100 MPa than that of the steels tested in air. SEM examinations indicate that the characteristic distance and the density of stable micorcracks in presence of internal hydrogen are larger than that observed in virgin steels.

3) For $P_R\%$ = 50, K_{Ic} level of steels without hydrogen is greater by 5 MPa$\sqrt{m}$ than that in hydrogenated steels. For these steels K_{Ic} is an independent parameter of the sulphur content in the long direction.

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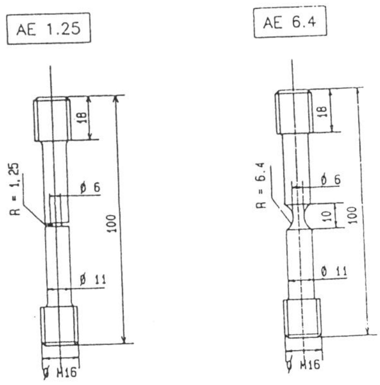

Fig.1 : Geometries and dimensions of the notched tensile specimens.

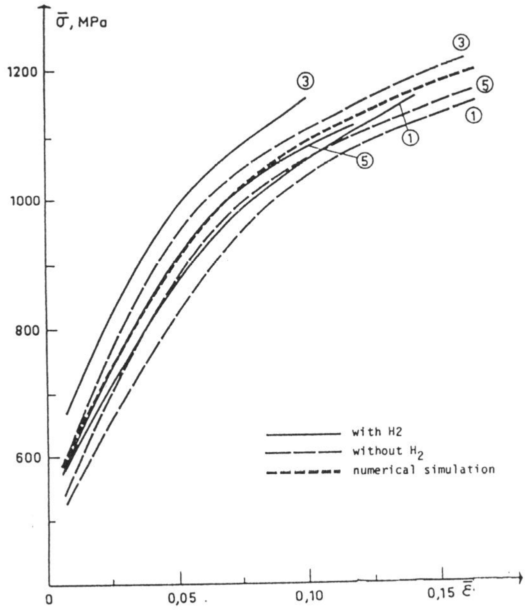

Fig.2 : Experimental mechanical behaviour laws and the one used for numerical simulations in railway steels.

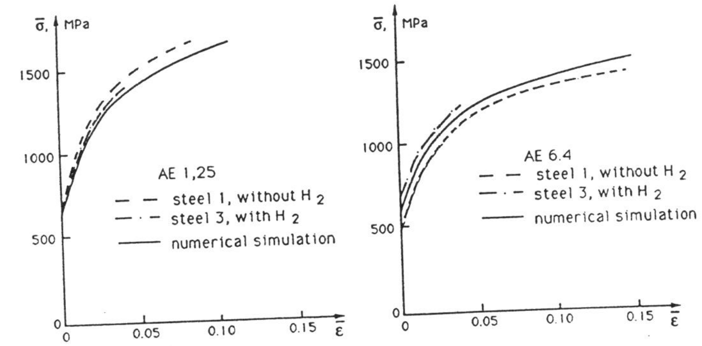

Fig. 3 : Comparaison between experimental and numerical simulation for :
a) AE 1.25 specimens
b) AE 6.4 specimens

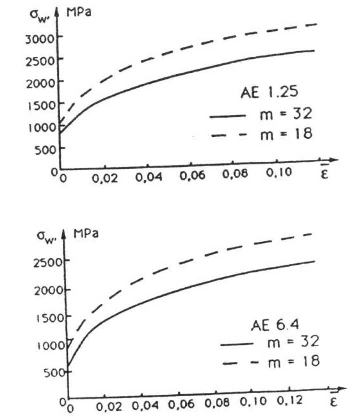

Fig 4 WEIBULL stress σ_w versus the average diametrical deformation $\bar{\varepsilon}$ for
a) AE 1.25 specimens with and without hydrogenation
b) AE 6.4 specimens with and without hydrogenation

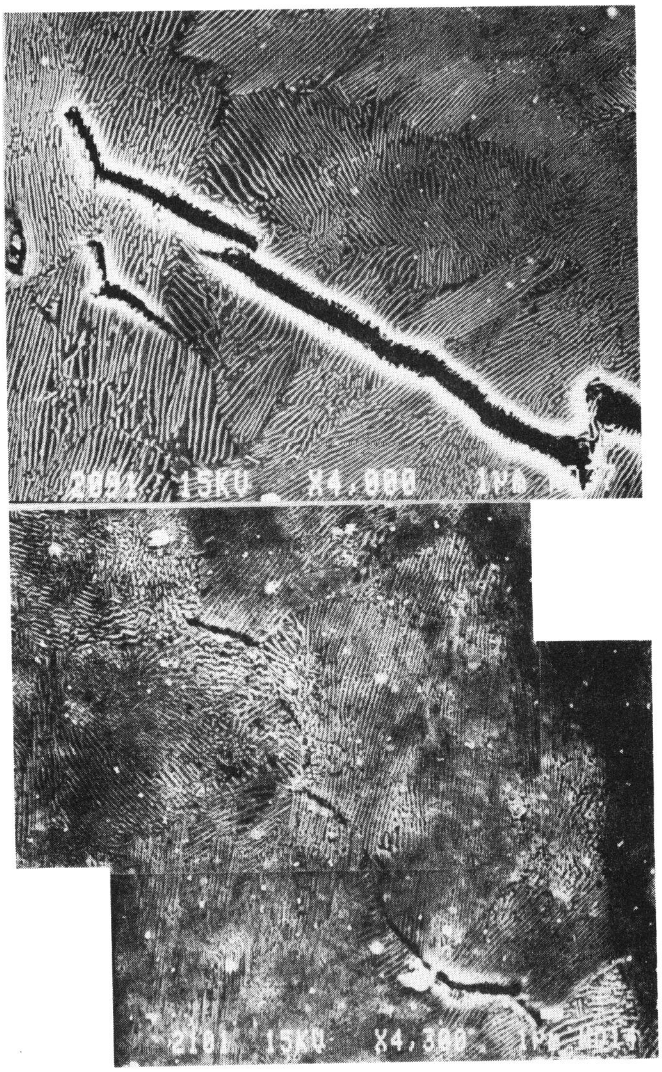

Fig.5 : Observed cracks at notch root in :
a) virgin steels
b) hydrogenated steels

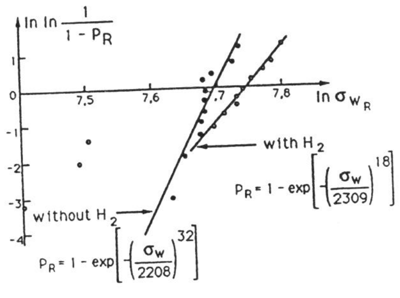

Fig. 6 : Variation of WEIBULL stress at failure σ_{w_R} as a function of P_R% in presence and in absence of cathodic hydrogen

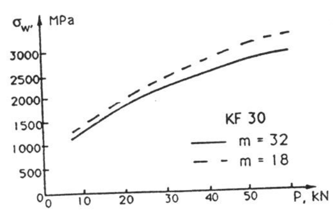

Fig. 7 : Variation of the critical load P values as a function of σ_w levels.

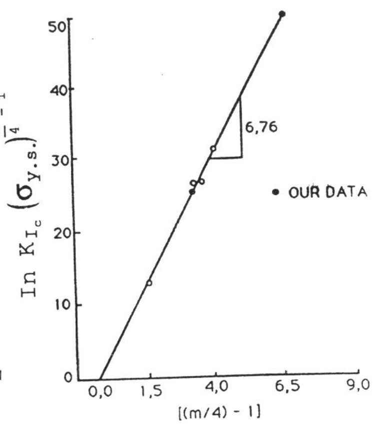

Fig. 8 : $\ln\left[K_{I_c}(\sigma_{y.s})^{\frac{m}{4} - 1}\right]$ versus $\left(\frac{m}{4} - 1\right)$