COMBINED EFFECT OF HYDROGEN AND STRESS CONCENTRATIONS IN AUSTENITIC STAINLESS STEEL

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The physical damage produced by hydrogen embrittlement on tensile notched specimens of 316 L steel is examined in this work. Tensile tests with simultaneous hydrogen charging by cathodic polarization were performed at different loading rates and interrupted just after maximum load to section the specimens for direct observation of damage. The experimental evidence so gained reveals hydrogen assisted cracking processes in accordance with the losses of maximum load as explained from simple mechanical damage models.

INTRODUCTION

316 L steel is an extraordinarily ductile austenitic stainless steel very suitable as structural material for applications where hydrogen embrittlement could occur, given its low sensitivity to hydrogen embrittlement, even when compared with other austenitic stainless steels. However, the effect of hydrogen on this steel is not well understood yet despite extensive research into the hydrogen embritlement of metals.

Losses of strength and ductility, as measured in smooth tensile specimens, serve to assess the hydrogen effect on 316L steel. Often the specimens are of very small thickness in order to enhance the hydrogen action, which is concentrated on the surface of the specimens. The results obtained in this kind of testing (1, 2, 3) have shown that no significant strength losses are found when 316L steel is tensile tested after hydrogen embrittlement in the commercial condition, regardless of the specimen thickness (sheets 0.2 mm thick or round bars 6.25 mm diameter), of the hydrogenation method (exposure to pressurized hydrogen gas or cathodic polarization), and of the mechanical testing subsequent to or simultaneous with hydrogen charging. The ductility parameters, however, provided by the tensile test (maximum uniform elon-

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gation and fracture elongation) undergo significant losses in thin specimens, but show no change in massive specimens. Stressing after or during hydrogen charging does not produce slow crack growth (SLG), and microvoid coalescence holds as the rupture mechanism. However, in almost all the cases surface damage in the form of shallow cracking has been reported. The resulting size effect would be operative in the thin specimens and would explain the differences of ductility between these specimens and the massive ones.

In a previous work (4), the authors examined the hydrogen effect on 316L steel when subjected to stress concentrations. Blunt and sharp round notched specimens were tensile tested during hydrogen charging by cathodic polarization. It was found that a process of extended shallow cracking developed at the notch profile and the specimens showed substantial losses of bearing capacity. These losses were shown not to be attributable to a slow crack growth process in mechanical terms, but no attempt was made to ascertain the actual hydrogen damage inside the specimens. In a more recent work (5), precracked tensile compact specimens were also tested during hydrogen charging by cathodic polarization, and branched slow crack growth was detected at very low loading rates.

The present work is an extension of the research work (4) aimed at direct observation of the hydrogen damage in notched specimens of 316 L steel and a subsequent contrast with that detected in precracked specimens as well as with that predicted by the damage model proposed in (4) in purely mechanical terms.

MATERIALS AND EXPERIMENTAL PROCEDURE

The hydrogen embrittlement experiments were carried out on a type 316L steel of commercial grade in the as-received condition. The steel was supplied as a 30 mm thick plate with a final grain size of roughly 60 μm and an entirely austenitic microstructure. The heat treatments after hot rolling were performed by the manufacturer according to current industrial practice (bright annealing at 1100°C and water quenching). The chemical composition is given in Table 1 and the tensile mechanical properties in Table 2.

Table 1.- Chemical composition of the tested 316L steel.

% C	% Mn	% Si	% P	% S	% Cr	%Ni	% Mo
0.018	1.75	0.35	0.02	0.001	17.30	12.09	2.31

Table 2.- Tensile mechanical properties of the tested 316L steel.

Young´s modulus	0.2 % Yield stress	Ultim. tensile strength	Max. uniform elongation	Reduction in area
190 GPa	290 MPa	575 MPa	60 %	85 %

The same geometrical configurations as in reference (4) were adopted for the notched specimens, namely axisymmetrically notched round bars of a gross diameter of 6.0 mm, a minimum diameter of 4.8 mm ,and a circular notch profile of two different radii: 2.2 mm for the blunt notched specimen (BNS) and 0.2 mm for the sharp notched specimen (SNS).

Hydrogen charging by cathodic polarization was conducted simultaneously with tensile loading at room temperature by keeping the specimen immersed during the tension test in an 1N H_2SO_4 aqueous solution. A small content of Na As O_2 was added to the solution as a hydrogen recombination poison and a potentiostat with a three electrode arrangement was used to control the cathodic potential. A potential of −1000 mV versus saturated calomel electrode (SCE) was applied, the cathodic current density measured for that potential and for the solution previously deaerated being 0.1 A/cm^2. This potential differs from the -1200 mV of reference (4) and was chosen as producing the most intense hydrogen action according to preliminary tests.

Since the branched slow crack growth of (5) occurred only at an extremely low loading rate, the range covered in (4) was widely extended (from 0.1 to 1000 μm/min rather than from 0.6 to 150 μm/min) by exploring a twofold number of extension rates. The tensile load was continuously registered throughout each test up to the final interruption when the first decreasing values of the load were attained. For each notch configuration and extension rate one specimen was sectioned through an axial plane and polished after testing in order to examine the notch profile in the scanning electron microscope.

RESULTS AND DISCUSSION

As in (4), hydrogen does not produce a brittle failure by fast crack extension but causes a significant reduction in the maximum load sustained by the specimens as compared with that sustained by a hydrogen free specimen notched in the same way. The losses in maximum load decrease with the extension rate for the two notch configurations. A picture of the overall results is shown in Fig.1, where the lost percentage of maximum load in the hydrogen free condition of the specimen is plotted versus the time required to attain the maximum load, i. e., the time that the specimen has been subjected to the hydrogen action.

Together with the experimental results, two theoretical curves corresponding to the NEM and NCM mechanical models proposed in (4) are plotted in Fig 1. In the NEM (notch enlargement model) the combination of the hydrogen damage with the notch is assumed to behave as an enlarged notch whose minimum diameter and profile radius have decreased proportionally, so the lost fractions of maximum load and minimum cross section are the same. Otherwise, in the NCM (notch cracking model) the hydrogen action is assumed to be predominant at the notch root and to produce a macroscopic crack extending ahead of the notch inside the specimen. In this case, no simple reason is found for the relationship between the losses of maximum load and the minimum cross section, and it was numerically determined by finite element modelling of the blunt and the sharp notched specimens of 316L steel, computing the maximum load sustained by the two specimens with cracks of several depths emanating from the notch root. These numerical results fitted into a single curve for the two specimens, which has been used in this work.

To draw the curves of Fig.1, an additional relationship is required giving the damage depth c (the decrease of radius in the minimum cross section of the NEM and the crack length in the NCM) as a function of the embrittlement time t_m. In (4), the function suggested by the elementary diffusion theory ($(c=A\sqrt{t_m})$ was checked with the constant A as an adjustable parameter and it was found that only the NEM predictions coincided with the experimental data. In this work a minor refinement is introduced by using the function $c=At_m^{0.6}$ which agrees better with the diffusion solution for cylindrical symmetry (6) and seems more appropriate for axisymmetry. The curves of Fig.1 are obtained for $A = 0.02$ mm/h$^{0.6}$, the same value as in (4) for the new time exponent used. For the range of embrittlement times recorded in (4) (roughly below 100 hours), the experimental points cluster round the curve of the NEM, regardless of the notch configuration. For longer times, the NCM curve seems to be approached, the points from the blunt notched specimens approaching it faster than that of the sharp notched ones. This change of mechanical behaviour might be explained if the hydrogen action ahead of the notch root increases until becoming dominant, and the hydrogen damage would then change from extended multicracking along the notch profile to localized cracking of this zone. The SEM macrographs of the blunt and sharp notched specimens sectioned longitudinally just after maximum load provide experimental evidence of this. As seen in the notch profiles of Fig. 2, damage increases with the embrittlement time and produces slow crack growth at the notch root in competition with the extended multicracking process that affects the overall notch profile. However, the conflict seems to be decided in favour of the slow crack growth when the embrittlement time is sufficiently long.

CONCLUDING REMARKS

Localized slow crack growth and extended multicracking compete as hydrogen damage mechanisms in notched specimens of 316L steel when tensile tested and hydrogen charged by cathodic polarization simultaneously. Extended multicracking is dominant at an early stage of the embrittlement process and failure occurs at this stage if the loading rate is high enough. On the contrary, for extremely low loading rates the dominance is transferred to localized crack growth prior to failure. This description of the hydrogen action is supported by the physical evidence gained by direct observation of sectioned failed specimens and by the agreement between the loss of mechanical resistance measured in the tests and the theoretical estimations made from the models proposed in (4).

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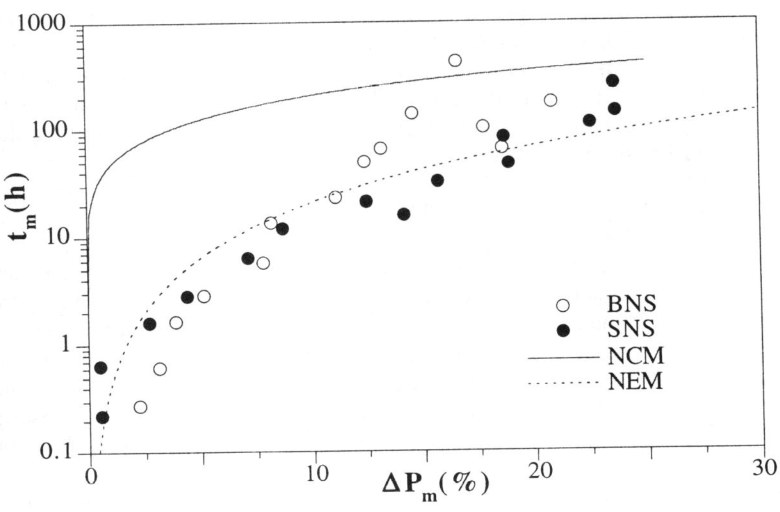

Figure 1 Loss of mechanical resistance versus embrittlement time for notched specimens of 316L steel stressed while hydrogen charged by cathodic polarization

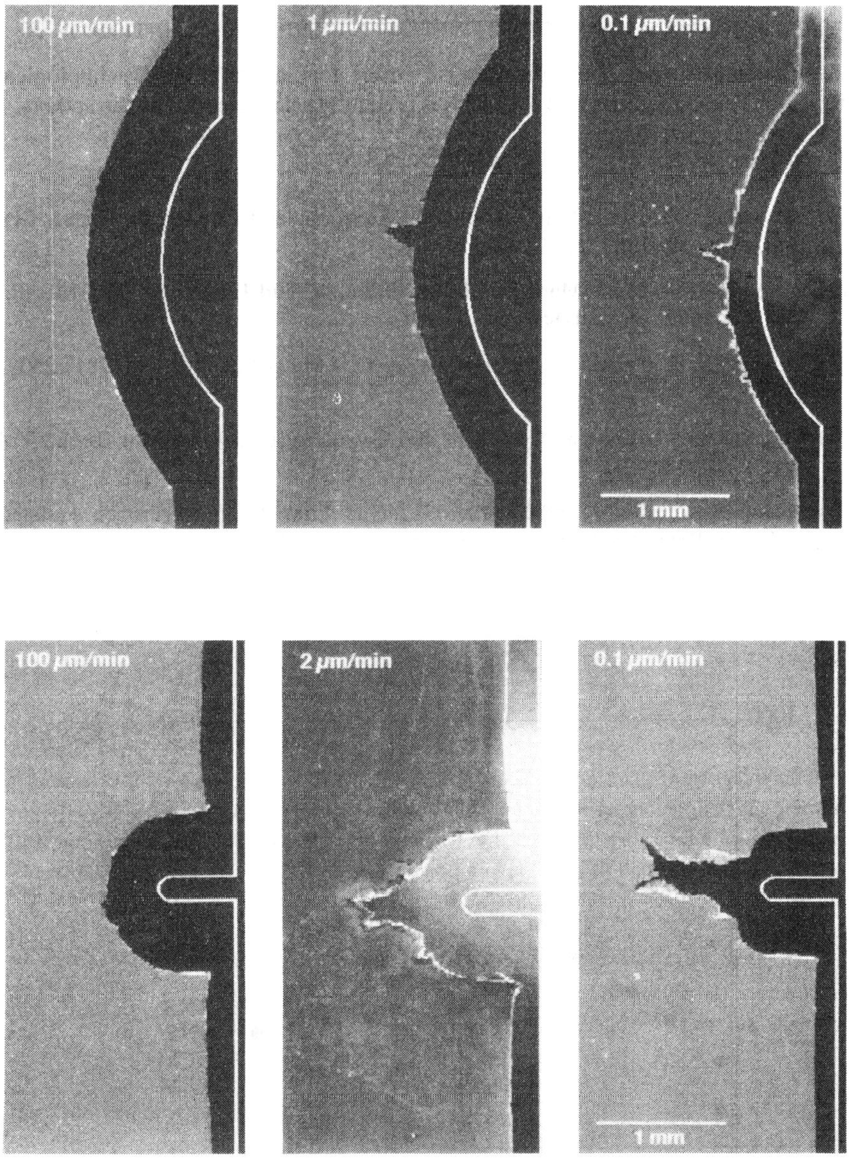

Figure 2 Notch profiles at maximum load of blunt (top) and sharp (bottom) notched specimens tensile tested at the indicated extension rate with simultaneous hydrogen charging (white lines show the shape and position of the original profiles).