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Letter to the Editors

Interaction between blue brittleness and stress corrosion cracking

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Abstract

Steels of composition $30Cr_2Ni_4MoV$ and $25Cr_2MoV$ used in a nuclear power plant showed blue brittleness near 230°C and 180°C, respectively. Susceptibility to stress corrosion cracking (SCC) for the steels in aqueous solutions at the test temperatures was very low except at the blue brittleness temperature. At the blue brittleness temperature, there was a strong interaction between blue brittleness and SCC, resulting in a steep increase in the susceptibility to SCC.

1. Introduction

The phenomenon of increase in yield strength and decrease in elongation when soft steels are strained at 150°C to 300°C, which makes them brittle, is called blue brittleness [1]. When the diffusion velocity of the cloud of impurities like C and N, which surround the dislocations, matches the velocity of dislocation motion, the yield and aging will happen alternately or simultaneously, termed dynamic strain aging, resulting in blue brittleness [1]. For low alloy steels with medium carbon, however, the occurrence of the blue brittleness is still unclear. Stress corrosion cracking (SCC) could occur in aqueous solutions for these steels at various temperatures and the process of SCC was controlled by hydrogen that entered into specimen during SCC [2–5].

An extensive inspection program was conducted after the catastrophic rupture of a turbine disc in the Hinkley point 'A' nuclear power plant, and cracks were found in 124 discs in other 50 British rotors [6]. Cracking in turbine discs of power plants in many countries was reported latter [7]. It is generally agreed that the mechanism responsible for the cracking is SCC [6,7].

For the rotor steel used in nuclear power plant, SCC can occur at temperature of the steam outlet, e.g., 280°C. On the other hand, blue brittleness may be present around this temperature. The paper aims to investigate whether blue brittleness exists for the steels used in nuclear power plants and whether there exists interaction between blue brittleness and SCC.

2. Experimental

The steels of $20Cr_{12}NiMoWV$, $25Cr_2MoV$ for bolts and the steel of $30Cr_2Ni_4MoV$ for rotors were studied. They were noted as no. 1, no. 2 and no. 3, respectively. The compositions of the steels are listed in Table 1. Cylindrical specimens with a diameter of 3 mm and a gage length of 25 mm were used. The specimens of the steels no. 1, no. 2 and no. 3 were heated at 980°C, 930°C and 840°C and then oil quenched. The former two were tempered at 670°C for 1 h, and the latter was tempered at 670°C, 650°C and 590°C for 1 h, respectively. The yield strengths σ_{ys} for no. 1 and no. 2 were 760 and 740 MPa. They were 640, 730 and 780 MPa for the steel no. 3 tempered at different temperatures and were noted as no. 3–3, no. 3–4 and no. 3–5.

The slow strain tests were conducted with $d\varepsilon/dt = 8 \times 10^{-6}\ s^{-1}$ using an MTS machine with a high-pressure vessel at temperatures from 25°C to 280°C in air and in 3.5% NaCl or 8% NaOH + 0.25 g/l NaCl solutions, respectively. The precision in temperature during tests was less than 0.5°C. The reductions of

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Table 1
The compositions of the samples (wt%)

Steel	C	Cr	Ni	Mo	V	W	Mn	Si
$20Cr_{12}NiMoWV$	0.19	12.2	1.32	0.22	0.15	0.42	0.43	0.22
$25Cr_2MoV$	0.24	1.72	–	0.31	0.19	–	0.49	0.26
$30Cr_2Ni4MoV$	0.29	1.61	3.45	0.41	0.09	–	0.32	0.25

fracture area in air and in aqueous solution, Ψ_{air} and Ψ_{sol} were measured and the susceptibility to SCC, I_Ψ, was calculated by $I_\Psi = [(\Psi_{air} - \Psi_{sol})/\Psi_{air}] \times 100\%$.

3. Results and discussion

The effect of temperature on the yield strength and the area reduction, tested in air for $30Cr_2Ni_4MoV$ (no. 3) steel with different strengths, are shown in Figs. 1(a) and (b), respectively. Each plotted point in the figures is the average of three tests. It is evident that the yield strength has the maximum and the area reduction has the minimum at 230°C for all the samples with different strengths. It means that $30Cr_2Ni_4MoV$ steel exhibits blue brittleness at 230°C.

The susceptibility to SCC for the steel no. 3 with three strength levels in the 3.5% NaCl solution is plotted versus temperature in Fig. 2. Fig. 2 indicates that the susceptibility to SCC for the steel is little except near the blue brittleness temperature, i.e., 230°C. Near this temperature the susceptibility to SCC suddenly increases. That is to say that there is an interaction between blue brittleness and SCC for the steel.

For the samples strained in air at all test temperatures and in the solution at all test temperatures except at 230°C, the fracture surfaces consists of dimples. There was no microcrack on the surface near the necking, as shown in Figs. 3(a) and (b). For the samples strained in the solution at blue brittleness temperature, however, the fracture surfaces were mainly quasi-cleavage, and there were many microcracks on the profile of the fracture, as shown in Fig. 3(c).

The effect of test temperature on the yield strength and area reduction in air for the steels no. 1 and no. 2 is shown in Fig. 4. No blue brittleness was exhibited for the steel no. 1 ($20Cr_{12}NiMoWV$). The following two reasons probably caused the disappearance of the blue brittleness: (1) C content is lower in the high Cr steel; (2) the higher Cr content could react with C to form carbide

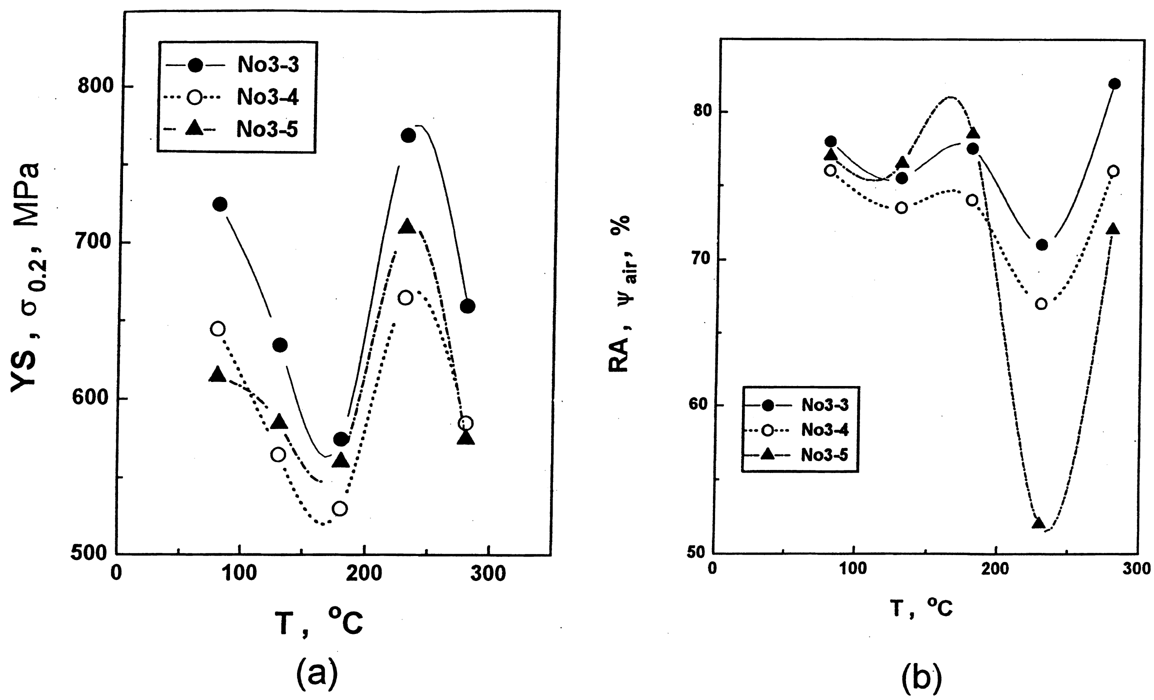

Fig. 1. (a) The yield strength $\sigma_{0.2}$ and (b) the reduction Ψ versus test temperature for $30Cr_2Ni_4MoV$ steel strained in air.

$Cr_{23}C_6$ which results in decrease in solid-solution carbon. The two reasons retard the formation of carbon cloud around dislocations. For the steel $25Cr_2MoV$, blue brittleness appeared at 180°C. The susceptibility to SCC, I_ψ, of the two steels in 8% NaOH + 250 mg/l NaCl solution is plotted versus temperature in Fig. 5. Fig. 5 indicates that I_ψ for the steel no. 1 is less than 10% and is independent of test temperature. For the steel $25Cr_2MoV$ (no. 2), however, I_ψ has the maximum value at the blue brittleness temperature of 180°C. It also shows that there is an interaction between blue brittleness and SCC. More passivation in the higher Cr steel prevents the steel from corrosion in the solution. As a result, the generated hydrogen in the solution is less than the steels with lower Cr. Thus, for the steels with higher Cr the susceptibility to SCC controlled by hydrogen is lower than that for the steels with lower Cr.

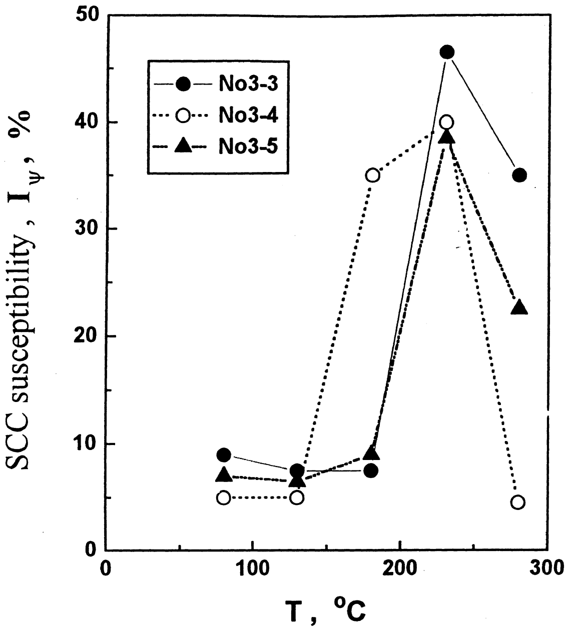

Fig. 2. The susceptibility to SCC in 3.5% NaCl solution I_ψ vs test temperature for $30Cr_2Ni_4MoV$ steel with three kinds of strength.

The SCC for high or medium strength steels is one kind of hydrogen-induced cracking (HIC), which is controlled by locally accumulated hydrogen in the specimen [2–5]. HIC occurs when the accumulated hydrogen reaches a critical concentration C_{th}. Stress induced diffusion can cause hydrogen enrichment and the hydrogen concentration will increase from C_0 to C_σ [8]. On the other hand, the cloud of hydrogen will move along with the dislocations during deformation and enter into the specimen during SCC. Thus, the plastic strain can also induce hydrogen enrichment, C_ε, which is related to the localized plastic strain. The total accumulated concentration of hydrogen is $C = C_\varepsilon + C_\sigma$ [9]. Both C_σ and C_ε increase during slow strain test in the solution and the total hydrogen concentration

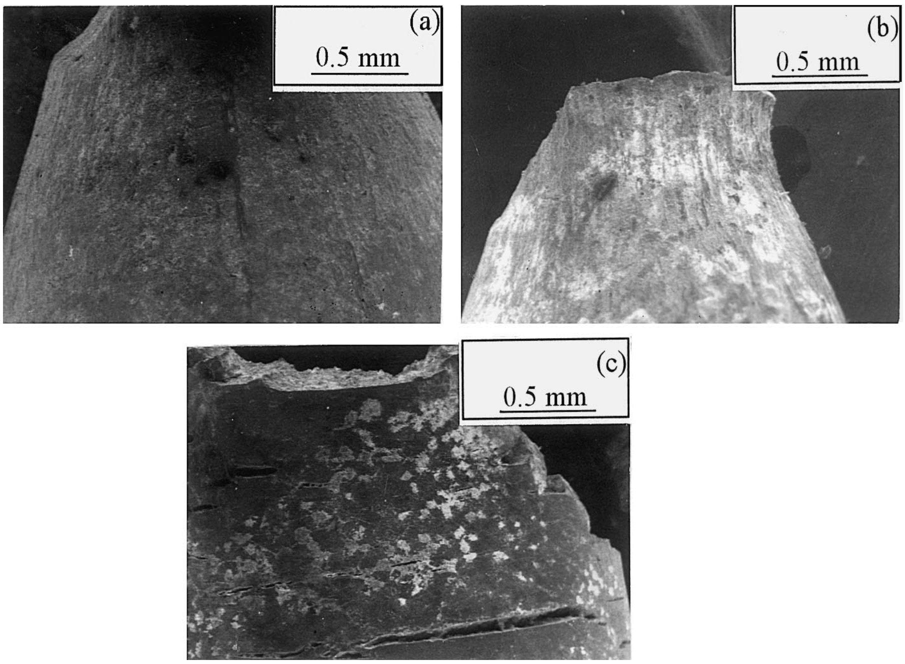

Fig. 3. The profiles of the fracture strained in 3.5% NaCl solution for $30Cr_2Ni_4MoV$ steel with yield strength of 780 MPa: (a) 180°C; (b) 280°C; (c) 230°C.

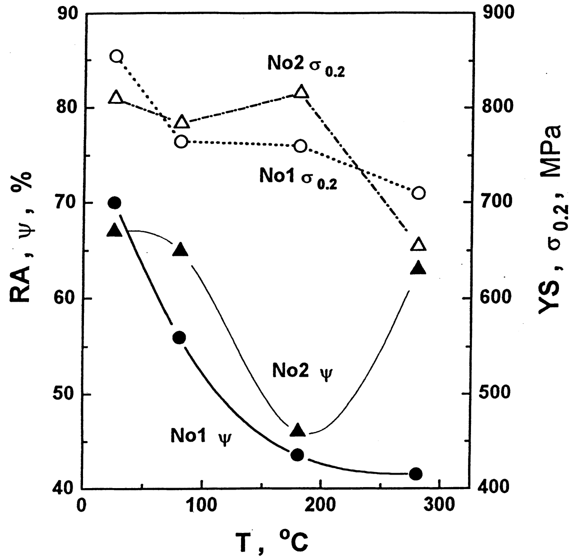

Fig. 4. The yield strength $\sigma_{0.2}$ and the area reduction Ψ vs temperature for steels 20CrNiMoV (no. 1) and $25Cr_2MoV$(no. 2).

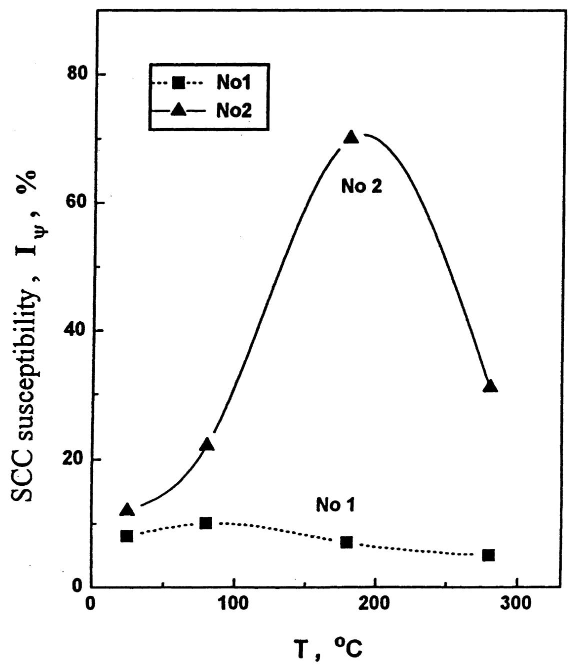

Fig. 5. The susceptibility to SCC in NaOH solution vs test temperature for 20CrNiMoV (no. 1) and $25Cr_2MoV$(no. 2).

$C = C_\varepsilon + C_\sigma$ can reach to the critical value C_{th} required for HIC to occur.

Experiments indicated that hydrogen could enhance dislocation emission and motion [10–12]. On the other hand, hydrogen can enhance the localization of plastic deformation [13–15]. HIC occurs when the localized plastic deformation enhanced by hydrogen develops to a critical condition [5,10] although the strain of the whole sample is still very low. On the other hand, dynamic strain aging, i.e., blue brittleness, can also induce the localization of plastic strain, like Lüders bands. During SCC at blue brittleness temperature, there is an interaction between dynamic strain aging and hydrogen. At the beginning of plastic deformation the strain will be localized within Lüders bands and the dislocation in the bands are surrounded by hydrogen cloud. Thus, the concentration of hydrogen in the Lüders bands is very high. Since the enrichment of hydrogen in the Lüders bands can promote dislocation multiplication and motion, the plastic strain becomes more and more concentrated at the original strain localization sites, i.e., in the Lüders bands. The interaction between dynamic strain aging and hydrogen which entered into the specimen during SCC results in a synergistic action to induce more stain localization. Therefore, the localized strain can reach the critical condition when the average strain of the specimen is still very little, and the hydrogen concentration in the Lüders band will equal to the critical value, C_{th}. This resulted in the initiation and propagation of HIC within the Lüders bands until delayed failure. This is to say that the strain to fracture or area reduction during SCC is very little at blue brittleness temperature is because of the interaction between dynamic strain aging and hydrogen entered into the specimen during SCC.

4. Conclusions

1. The medium-carbon low alloy steels ($30Cr_2Ni_4MoV$ and $25Cr_2MoV$) strained at a slow strain rate exhibited blue brittleness at 230°C and 180°C, respectively; the high alloy steel ($20Cr_{12}NiMoWV$) did not exhibit blue brittleness.
2. Susceptibility to SCC of the three steels in aqueous solution was very low except near blue brittleness temperature.
3. There was a synergistic action between blue brittleness and SCC, resulting in a steep increase in the susceptibility to SCC tested at the blue brittleness temperature.

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