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A new aspect on intergranular hydrogen embrittlement mechanism of solution annealed types 304, 316 and 310 austenitic stainless steels

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ABSTRACT

The objective of this paper is to propose a new intergranular hydrogen embrittlement mechanism of solution annealed austenitic stainless steels (types 304, 316 and 310) on the basis of the results already reported. An intergranular hydrogen embrittlement (IG-HE) took place for type 316 at potentials less noble than the open-circuit potential in a HCl solution, and for types 304 and 316 at a lower test temperature under an open-circuit condition in saturated boiling magnesium chloride solutions by using a constant load method, while type 310 suffered only a transgranular stress corrosion cracking (TG-SCC) in both solutions under the same experimental conditions, but not IG-HE. In addition, TG-SCC occurred for types 304 and 316 under an open-circuit condition in the HCl solution irrespective of test temperature and in saturated boiling magnesium chloride solutions at higher test temperatures. Thus, the occurrence of IG-HE depended upon the material and test temperature. The new IG-HE mechanism was developed that explains the results obtained in terms of martensite transformation, hydrogen-enhanced local plasticity (HELP), grain boundary sliding (GBS) and so on.

1. Introduction

In a series of the papers [1,2], we have reported the potential dependence of the three parameters (time to failure, t_f, steady state elongation rate, l_{ss} and transition time when the elongation curve deviates from linearity, t_{ss}) in elongation time curves under the constant applied stress conditions for solution annealed types 316 and 310 austenitic stainless steels in 0.82 kmol/m^3 HCl solution at 353 K [1] and the test temperature dependence of the parameters for solution annealed types 304, 316 and 310 steels at their rest potentials (open-circuit condition) in boiling saturated magnesium chloride ($MgCl_2$) solutions [2]. It was found that the solution annealed types 316 and 310 suffered a transgranular stress corrosion cracking (TG-SCC) subjected to anodic reaction (film formation and dissolution) at a potential from a slightly lower potential than the rest potential to a higher potential. An intergranular hydrogen embrittlement (IG-HE) took place for type 316 in the negative potential range, while type 310 showed little IG-HE. On the other hand, the solution annealed types 304 and 316 in the boiling saturated magnesium chloride solutions suffered TG-SCC at a higher test temperature and IG-HE for a lower test temperature, whereas type 310 showed only the TG-SCC susceptibility.

Up to the present, although various HE mechanisms have been proposed, we have no unified HE mechanism to explain HE of the materials. According to Birnbaum [3], there are the three representative HE mechanisms: (1) hydrogen-related phase-change mechanism, (2) hydrogen-enhanced local plasticity (HELP)-related fracture and (3) decohesion mechanism. The hydrogen-related phase-change mechanism is considered to be applied to HE of austenitic stainless steels (martensite formation). However, it seems that there is little explanation of how martensite is fractured. As we have already reported the TG-SCC and IG-SCC mechanisms of the solution annealed and sensitized types 304, 316 and 310 [4], we will focus on IG-HE of types 304 and 316 in this work. Therefore, the objective of the present work is to propose a new HE mechanism for explaining IG-HE of the austenitic stainless steels.

2. Intergranular hydrogen embrittlement of solution annealed austenitic stainless steels

We have investigated the potential dependence of three parameters (t_f, t_{ss} and l_{ss}) for the solution annealed types 316 and 310 austenitic stainless steels in 0.82 kmol/m^3 HCl solution under a constant applied stress condition [1], where the three parameters were obtained from the corrosion elongation curves (elongation–time curves) under constant applied stress: t_f, time to failure; t_{ss}, transition time and l_{ss}, steady state elongation rate. Fig. 1 shows

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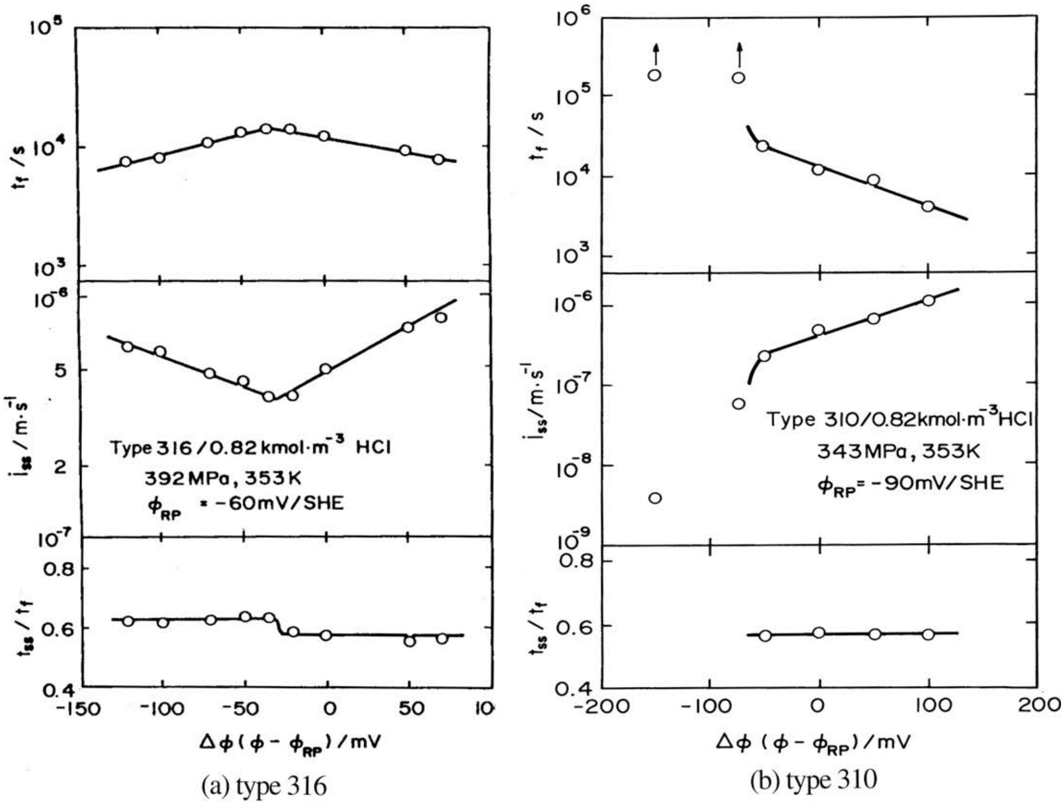

Fig. 1. The potential dependence of the three parameters (t_f, time to failure, I_{ss}, steady state elongation rate and t_{ss}, transition time) for solution annealed austenitic stainless steels (types 316 and 310) in 0.82 kmol/m^3 HCl solution at 353 K under the constant applied stress conditions, where φ_{RP} is the rest potential.

the three parameters for solution annealed types 316 and 310 as a function of overpotential ($\Delta\varphi = \varphi - \varphi_{RP}$; φ, applied potential, φ_{RP}, rest potential) at a constant applied stress of 392 MPa for type 316 and 343 MPa for type 310 in 0.82 kmol/m^3 HCl solution. From Fig. 1 and the fracture appearances [1], the following things were summarized.

(1) TG-SCC for types 316 and 310 took place at a slightly less noble potential than rest potential (the open-circuit condition: $\Delta\varphi = 0$), at which cathodic reaction (hydrogen evolution reaction) proceeded, and the TG-SCC susceptibility increased with increasing potential.
(2) The meta-stable austenitic stainless steel of type 316 showed the IG-HE susceptibility at the negative potential range, while the stable austenitic stainless steel of type 310 did not.
(3) In addition, types 304 and 316 have been reported to show only TG-SCC in the HCl solutions irrespective of applied stress and environmental factors such as test temperature, pH and so on under an open-circuit condition [5,6].

Fig. 2 shows the relationship between time to failure and a reciprocal of test temperature for solution annealed types 304, 316 and 310 at a constant applied stress of 300 MPa in boiling saturated magnesium chloride solutions under an open-circuit condition [2]. In this figure, types 304 and 316 had two regions (Region I and Region II) and type 310 only one region (Region I). Correspondingly, Fig. 3 shows the test temperature dependence of t_{ss}/t_f for those steels. The value of t_{ss}/t_f in Region I showed 0.57 ± 0.02 independent of the steels, while that in Region II had a much larger value than that of Region I. Furthermore, the fracture appearance in Region I was transgranular and that in Region II intergranular. Therefore, the following things from these results were summarized.

(1) Types 304 and 316 suffered TG-SCC at a higher test temperature region (Region I) and IG-HE at a lower test temperature region (Region II). In addition, IG-HE of type 304 took place at a lower test temperature than that of type 316.
(2) Type 310 suffered only TG-SCC independent of test temperature.

Thus, under the different experimental conditions types 304 and 316 suffered IG-HE or TG-SCC, while type 310 suffered only TG-SCC.

With respect to TG-SCC, we have already proposed the TG-SCC mechanism [4], which was on the basis of the film rupture-formation event. In this mechanism the interaction between dislocation movement by dissolution and its inhibition by film played an important role in TG-SCC, by which an additional local stress was generated. On the other hand, we have not yet proposed an IG-HE mechanism explaining the results obtained. In the following sections we will discuss in more details to propose a new IG-HE mechanism.

3. The roles of stress (or strain) and hydrogen

3.1. Martensite formation

3.1.1. Stress (or strain)-induced martensite

It is well known that a stress-induced martensite transformation takes place, when a load is applied to meta-stable austenitic stainless steels such as types 304 and 316. On the other hand, a stable austenitic stainless steel, type 310 is recognized to show little