Stress Corrosion Cracking of SUS 631 Stainless Steel Deformed at High Strain Rate*

By Hitoshi UCHIDA,** Keiji KOTERAZAWA** and Iwao YAMADA**

Synopsis

The effect of cold working on stress corrosion cracking (SCC) susceptibility of semiaustenitic precipitation-hardening stainless steel has been investigated in the present study. The specimens, prepared from A-treated SUS 631 stainless steel sheets containing delta ferrite, were prestrained at low or high strain rate and successively subjected to TH-treatment. The SCC susceptibility of these specimens was estimated in boiling $MgCl_2$ solution under the constant applied stress.

The cold working gives a remarkable effect not only for the mechanical properties but for the SCC susceptibility of A- and TH-treated specimens. Namely, the strength of TH-treated specimens decreased with increasing prestrain, and the strength level of these specimens prestrained at high strain rate was larger than those at low strain rate. But, the above-mentioned behavior of TH-treated specimens was the very reverse to that of A-treated specimens. While, the SCC susceptibility of A- and TH-treated specimens decreased with increasing prestrain, and its susceptibility of these specimens prestrained at high strain rate was larger than those at low strain rate.

On the basis of the results obtained above, the effects of prestrain and strain rate on the SCC susceptibility of SUS 631 stainless steel were discussed.

I. Introduction

Precipitation-hardening stainless steel, high-strength steel in itself, is representative of the alloy that preserves its corrosion resistance as so-called “stainless steel” and that increases its strength and hardness through a combination of martensitic transformation and precipitation-hardening, and a few types have developed.¹⁾ Generally, it is known that semiaustenitic SUS 631 stainless steel is superior in the cold working property and practically hardened by double heat treatment after cold working.

While, a few papers²⁻⁶⁾ on stress corrosion cracking (SCC) of precipitation-hardening stainless steels have mainly discussed the effect of heat treatment conditions on SCC susceptibility in various corrosive environments. For the sake of clarifying that these steels can be more widely used or not as SCC-resistant steel, it is important to investigate the effect of cold working conditions on SCC susceptibility. It is seemed, however, that such a paper has not been published to date.

On SUS 631 stainless steel prestrained at low or high strain rate and successively performed double

heat treatment, the effects of prestrain and strain rate on SCC susceptibility have been investigated in the present study.

II. Experimental Procedure

1. Material and Specimen Preparation

The commercial SUS 631 stainless steel (solution annealed, hereinafter referred to as “A”) was used in the present study. The chemical compositions and the mechanical properties are shown in Tables 1 and 2, respectively. In the case of as-received material, the two-phase structure containing austenite of matrix and delta ferrite, laminated, parallel to rolling direction is observed as shown in Photo. 1. The specimens (Fig. 1(a)) used for cold working (hereinafter referred to as “W”) were machined from as-received material with their tensile axis parallel to rolling direction. At room temperature ($20^{\circ}\sim 22^{\circ}C$), the prestrain of these specimens was given at the strain rate of 1.7×10^{-3} and $6\times 10\text{ sec}^{-1}$ (hereinafter referred to as suffix “S” and “D”) by Instron type and explosive type tensile testing machine,⁷⁾ respectively. After being subjected to the double heat treatment mentioned below, these specimens were machined for SCC specimens as shown in Fig. 1(b). The surface finishing process of SCC specimens was similar to the previous paper,⁸⁾ such as emery polishing, electrolytic polishing, degreasing and mixed acids immersing.

2. Heat Treatment

As-received material is semiaustenitic precipitation-hardening stainless steel. In this case, the double

Table 2. Mechanical properties of as-received material.

Heat treatment	Yield strength* (kg/mm ²)	Tensile strength (kg/mm ²)	Elongation (%)	Hardness** (D.P.N.)
A	36.7	79.7	44.8	180.3

* 0.2% off-set

** load of 500 g

Table 1. Chemical compositions of as-received material. (wt%)

Material	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	Al
SUS 631	0.07	0.48	0.72	0.029	0.004	7.06	17.13	0.17	0.12	1.06

* Originally published in *Corrosion Engineering (Boshoku Gijutsu)*, **28** (1979), 386, in Japanese. English version received February 12, 1980.

** Himeji Institute of Technology, Shosha, Himeji 671-22.

← Rolling direction →

Photo. 1. Microstructure of as-received material.

Fig. 1. Dimension of specimens. (mm)

heat treatment of TH 1050 (JIS G 4305 (1972), hereinafter referred to as "TH") is in general use for precipitation-hardening treatment.¹⁾ Namely, the transformation of austenite to martensite was induced by T-treatment ($760^{\circ}\text{C} \times 1.5$ hr, ice water cooled), and its martensite was precipitation-hardened by H-treatment ($565^{\circ}\text{C} \times 1.5$ hr, air cooled), successively.

3. SCC Test

The SCC tests in boiling 35% (adjusted to pH 3 at room temperature by hydrochloric acid) and 42% MgCl_2 solution were carried out by the constant tensile loading apparatus.⁹⁾ The specimens used in SCC (or tensile) tests were of A series (A, A- W_s and A- W_D) and TH series (A-TH, A- W_s -TH and A- W_D -TH), and these symbols were classified according to the process of specimen preparations in the present paper.

III. Experimental Results

1. Tensile Test

The results obtained through tensile test ($1.7 \times$

Fig. 2. Effects of prestrain and strain rate on yield strength, tensile strength, elongation and hardness of A series specimens.

Fig. 3. Effects of prestrain and strain rate on yield strength, tensile strength, elongation and hardness of TH series specimens.

10^{-3} sec^{-1} , room temperature) are shown in Fig. 2. At any prestrain value in Fig. 2, the yield strength, tensile strength and hardness of A- W_D specimens are smaller than those of A- W_s specimens. While, the elongation of A- W_D specimens is conversely larger than that of A- W_s specimens.

In the same way as Fig. 2, the results of TH series specimens are shown in Fig. 3. The strength of TH series specimens decreases with increasing prestrain. Furthermore, at any prestrain value in Fig. 3, the yield strength, tensile strength and hardness of A- W_D -TH specimens are larger than those of A- W_s -TH specimens; however, both elongations are a negligible difference. As mentioned above, the behavior of TH series specimens is the very reverse to that of A series specimens.

2. SCC Test

The results obtained through SCC test of A and A-TH specimens are shown in Fig. 4. The SCC

threshold stress of A-TH specimens is larger than that of A specimens. At any applied stress level over the SCC threshold stress of A-TH specimens, however, A-TH specimens fracture at shorter time than in the case of A specimens. While, on estimating the SCC susceptibility of both specimens from the relation between time to fracture and ratio of applied stress/yield strength, it is found that the SCC susceptibility of A-TH specimens is larger than that of A specimens at any ratio of applied stress/yield strength.

The results obtained through SCC test of A and TH series specimens are shown in Fig. 5. On the whole, the time to fracture of any specimen depends on the concentration of MgCl_2 solution, and increases with increasing prestrain except that 40% prestrained A- W_s specimens fracture at extremely short time. Furthermore, at any prestrain value in Fig. 5, the

SCC susceptibility of both A- W_D and A- W_D -TH specimens is larger than that of both A- W_s and A- W_s -TH specimens.

3. Observation of SCC Fracture Surface

Since SCC fracture surface morphology mainly depends on heat treatment conditions, its morphology of A and A-TH specimens is shown in Photo. 2 as an example. The SCC of A specimen is initiated and propagated by mixing of intergranular and transgranular fracture (Photos. 2(a) and (b)), and its mechanical fracture surface shows the ductile pattern with dimple (Photo. 2(c)). While, the SCC of A-TH specimen is initiated at transgranular and changed to mixing fracture mode (Photos. 2(d) and (e)), and its mechanical fracture surface shows the brittle pattern with quasi-cleavage (Photo. 2(f)).

IV. Discussion

As mentioned above, it was found that the cold working gave a remarkable effect not only for the mechanical properties but for the SCC susceptibility.

Hereinafter, the effects of prestrain and strain rate on the mechanical properties and SCC susceptibility of TH series specimens are discussed in comparison with A series specimens.

1. Mechanical Properties

As shown in Fig. 2, the mechanical properties of A series specimens are similar to those of SUS 301 stainless steel reported in the previous paper.⁸⁾ In the case of such steels with metastable austenite, it is expected that the strain rate in prestraining has a great influence not only on the strain-induced α' martensitic transformation^{8,9)} but on the age-hardening.

The stress-strain curves of A specimens obtained through tensile test (room temperature) are shown in Fig. 6 as a function of strain rate. In this case, the yield strength increases with increasing strain rate, and this fact is mainly caused by "dynamic effect".* While, the work hardening rate and consequently the flow stress level conversely decrease with increasing strain rate. This fact is caused by the following: The longer loading time of tensile stress is, the more age-hardening progresses. Consequently, it is seemed that the age-hardening in prestraining, as mentioned above, affects the mechanical properties of A series specimens.

Generally, as-received SUS 631 stainless steel used in the present study is semiaustenitic structure. By T-treatment, Cr-carbides are precipitated at grain boundaries and then M_d point is raised above room temperature. Consequently, the transformation of austenite to martensite is induced during cooling. Successively, by H-treatment, Ni-Al compounds are precipitated into its martensite, and consequently the precipitation-hardening progresses more remarkably.¹⁰⁾ As shown in Fig. 3, however, the precipitation-hardening of TH series specimens shows a com-

Fig. 4. Effect of applied stress on time to fracture of A and A-TH specimens in boiling 35% MgCl_2 solution.

Fig. 5. Effects of prestrain and strain rate on time to fracture of A and TH series specimens in boiling 35% and 42% MgCl_2 solution.

* Generally, the effect of strain rate on stress-strain curve includes both "dynamic effect" based on the change of only strain rate and "structural effect" based on the change of structure caused by strain rate.⁹⁾

(a), (b), (c): A specimen, 40 kg/mm² applied (d), (e), (f): A-TH specimen, 60 kg/mm² applied
 Photo. 2. Effect of heat treatment conditions on SCC fracture surface morphology of A and A-TH specimens in boiling 35% MgCl₂ solution.

Fig. 6. Effect of strain rate on stress-strain curves of A specimens.

plicated behavior. Particularly, the strength of TH series specimens is different from that of A series specimens in point of the following:

(1) The strength of TH series specimens decreases with increasing prestrain.

(2) At any prestrain value, the strength level of A-W_d-TH specimens is larger than that of A-W_s-TH specimens.

As for the cause of (1) and (2) mentioned above, reverse transformation of martensite to austenite, grain coarsening, and so on during double heat treatment are considered.¹¹⁻¹³⁾ In the present paper, the authors have paid attention to the reverse transforma-

Fig. 7. Effects of prestrain, prestraining temperature and heat treatment conditions on delta ferrite, martensite and austenite content of A-W_s, A-W_s-T and A-W_s-TH specimens (strain-induced α' martensite: included in "martensite content").

tion of strain-induced α' martensite to austenite.¹⁴⁾ Then, the delta ferrite, martensite and austenite content obtained through X-ray diffraction method are shown in Fig. 7 as a function of heat treatment condition. In the case of A-W_s specimens prestrained at 100°C considered as the vicinity of M_d point, austenite hardly transforms to strain-induced α' martensite during prestraining, and each of these specimens always

contains about 22% delta ferrite.* Then, on the successive T-treated specimens, *i.e.*, A-W_s-T specimens, all retaining austenite of A-W_s specimens transforms to martensite during T-treatment. Furthermore, on the successive H-treated specimens, *i.e.*, A-W_s-TH specimens, a part of martensite reversely transforms to austenite during H-treatment, and its austenite content shows the constant value independent of pre-strain. While, in the case of A-W_s specimens pre-strained at room temperature, the strain-induced α' martensite content increases with increasing prestrain. The more strain-induced α' martensite content (or prestrain) of these specimens increases, the more reverse transformed austenite content of successive T-treated specimens, *i.e.*, A-W_s-T specimens, increases. Furthermore, on the successive H-treated specimens, *i.e.*, A-W_s-TH specimens, the degree of its reverse transformation enlarges still more.

As shown in Fig. 7, with increasing the prestrain given at room temperature, the reverse transformation of strain-induced α' martensite to austenite occurs easily, and consequently the strength decreases. It is seemed that this fact has an effect on the behavior of (1) mentioned above. Furthermore, in the case of specimens prestrained at room temperature, since the strain-induced α' martensite content depends on not only prestrain but strain rate,^{8,9)} it is expected that the reverse transformed austenite content of successive double heat treated specimens changes as follows: In the case of high strain rate prestraining, the temperature rise of specimen itself is larger, and consequently the strain-induced α' martensite content is smaller, than in the case of low strain rate prestraining. Consequently, the reverse transformed austenite content of A-W_s-TH specimens is larger than that of A-W_D-TH specimens. It is seemed that this fact has an effect on the behavior of (2) mentioned above.

2. SCC Susceptibility

As shown in Fig. 4, the SCC threshold stress of A specimens is similar to that of SUS 301 stainless steel,⁸⁾ while its stress of A-TH specimens increases more remarkably in comparison with A specimens. Since SUS 631 stainless steel used in the present study is generally used under a state of martensitic structure, the SCC susceptibility of this case is considered to be similar to that of martensitic stainless steel.

On estimating the SCC susceptibility with the ratio of applied stress/yield strength, however, it was shown that its susceptibility of A-TH specimens was larger than that of A specimens. The tensile surface morphology of A specimen is shown in Photo. 3 as an example. In the case of A specimens, the remarkable dissolution of delta ferrite during SCC testing is observed as compared with A-TH specimens. It is expected that the SCC behavior of A specimens with two-phase structure containing austenite of matrix and delta ferrite is similar to that of so-called “two-

phase stainless steel”. Generally, it is noted that the effective factors on the SCC susceptibility of two-phase stainless steel scattered ferritic phase in austenitic phase of matrix are given as follows: (1) Since ferritic phase has more difficulty in deforming than austenitic phase, mechanically, the propagation of crack is prevented by ferritic phase, *i.e.*, “keying effect”. While, (2) since the corrosion potential of ferritic phase is less noble than that of austenitic phase, electrochemically, the propagation of crack is prevented by cathodic protection.¹⁵⁾ On conjecturing the dissolution of delta ferrite as shown in Photo. 3, it is seemed that the difference of SCC susceptibility between A and A-TH specimens is under the influence of not only the change of structure based on double heat treatment but the factor of (2) mentioned above.

The effects of prestrain and strain rate on the SCC susceptibility of A and TH series specimens were shown in Fig. 5. In the case of A series specimens, not only the mechanical properties but the SCC susceptibility show a behavior similar to those of SUS 301 stainless steel reported in the previous paper.⁸⁾ It demonstrates that the SCC susceptibility of metastable austenitic stainless steel decreases with increasing prestrain and consequently with increasing strain-induced α' martensite content. In too much strain-induced α' martensite by prestraining, however,

Photo. 3. Tensile surface morphology of A specimen exposed to boiling 35% MgCl₂ solution during SCC testing.

* The effect of heat treatment conditions on each content of delta ferrite, martensite and austenite in 17Cr-7Ni-1Al alloy has been investigated by G. Krauss *et al.*¹¹⁾ It is reported that the delta ferrite content, independent of heat treatment conditions, shows the constant value.

its susceptibility increases reversely, *i.e.*, as 40% prestrained A-W_s specimens fractured at extremely short time in the present study. On the basis of these results, it is noted that strain-induced α' martensite has different effect on SCC susceptibility between in a large and small amount of its martensite.* Consequently, it is implied that the difference in SCC susceptibility of A series specimens as a function of prestrain and strain rate is mainly caused by the degree of strain-induced α' martensitic transformation, and partially of age-hardening besides. While, in the case of TH series specimens, it is seemed that the electrochemical effect of two-phase structure, as discussed on A specimens, due to the reverse transformation slightly relates to the SCC susceptibility. In the present paper, however, the authors have paid attention to the following: The strength of TH series specimens decreases with increasing prestrain, and the strength level of A-W_D-TH specimens is larger than that of A-W_s-TH specimens. On the contrary, the SCC susceptibility of A-W_D-TH specimens is larger than that of A-W_s-TH specimens, and either of its susceptibility decreases with increasing prestrain. This fact indicates that it is difficult to estimate the SCC susceptibility of prestrained and successive double heat treated specimens, TH series specimens, with the dimension of strength level.

Generally, it is said that, since the solubility of hydrogen in ferritic and martensitic structure is small and then the diffusivity of that is large, the hydrogen embrittlement depends on mechanical properties, *i.e.*, larger the tensile strength and hardness, it occurs easily.¹⁶⁾ D. C. Vreeland⁴⁾ has investigated the successful cathodic protection of precipitation-hardening stainless steels exposed to seawater, consequently the required cathodic potential range insusceptible to pitting, crevice corrosion and hydrogen embrittlement was clarified. While, C. T. Fujii⁶⁾ has indicated that the SCC susceptibility of 17-7PH steel increases with increasing cathodic potential, and furthermore put emphasis on the role of hydrogen in SCC mechanism. As clarified in the present study, the SCC susceptibility of TH series specimens with martensitic structure decreases with increasing prestrain and consequently decreasing strength. On the basis of this fact, it is likely seemed that the SCC of TH series specimens is mainly caused by hydrogen embrittlement, now under investigation in details.

V. Conclusion

The effects of prestrain and strain rate on the SCC susceptibility of TH series specimens prepared from SUS 631 stainless steel were investigated in boiling MgCl₂ solution, and the results were compared with those of A series specimens. The main results obtained are summarized as follows:

(1) The cold working gives a remarkable effect not only for the mechanical properties but for the SCC susceptibility of A and TH series specimens.

(2) The strength of TH series specimens decreases with increasing prestrain. The strength level of A-W_D-TH specimens is larger than that of A-W_s-TH specimens. The above-mentioned behavior is the very reverse to that of A series specimens.

(3) The SCC susceptibility of A and TH series specimens decreases with increasing prestrain. The SCC susceptibility of A-W_D-TH specimens is larger than that of A-W_s-TH specimens.

(4) The SCC fracture surface morphology mainly depends on heat treatment conditions. The SCC of A series specimens is initiated and propagated in the mode of mixture of intergranular and transgranular fracture. The SCC of TH series specimens is initiated at transgranular and changed to mixing fracture mode.

Acknowledgements

The authors are pleased to acknowledge the support of Himeji Works, Nippon Kayaku Corp. and Hanshin Works, Kawasaki Steel Corp. Sincere appreciation is also due to Mr. M. Irie for his assistance to carry out the experiments.

REFERENCES

- 1) K. Ebato: *Stainless Steels Handbook* (Sutenresu-ko Binran), ed. by M. Hasegawa, Nikkan Kogyo Shinbunsha, Tokyo, (1976), 483.
- 2) R. A. Davis, G. A. Dreyer and W. C. Gallagher: *Corrosion*, **20** (1964), 93.
- 3) M. Mizuno, S. Shimodaira, G. Ito, H. Atsumo, K. Yokota and S. Onodera: *Bull. Japan Inst. Metals*, **3** (1964), 622.
- 4) D. C. Vreeland: *Mat. Protect. Perform.*, **9** (1970), 32.
- 5) C. S. Carter, D. G. Farwick, A. M. Ross and J. M. Uchida: *Corrosion*, **27** (1971), 190.
- 6) C. T. Fujii: *Stress Corrosion—New Approaches*, ed. by H. L. Craig, Jr., *ASTM Special Tech. Publ.*, (1976), 213.
- 7) I. Yamada, T. Sugita and K. Koterazawa: *J. Soc. Mat. Sci., Japan*, **14** (1965), 192.
- 8) H. Uchida, K. Koterazawa and I. Yamada: *Corrosion Engineering (Boshoku Gijutsu)*, **27** (1978), 63.
- 9) H. Uchida, K. Koterazawa and I. Yamada: *Corrosion Engineering (Boshoku Gijutsu)*, **25** (1976), 543.
- 10) K. Yokota and K. Ebato: *Bull. Japan Inst. Metals*, **10** (1971), 226.
- 11) G. Krauss, Jr. and B. L. Averbach: *Trans. ASM*, **52** (1960), 434.
- 12) N. Yukawa, M. Mizutani and H. Saka: *J. Japan Inst. Metals*, **31** (1967), 846, 850 & 855.
- 13) T. Furukawa: *J. Japan Inst. Metals*, **32** (1968), 105.
- 14) H. Kamide and H. Sugawara: *J. Japan Inst. Metals*, **40** (1976), 1243.
- 15) M. Kowaka: *Bull. Japan Inst. Metals*, **17** (1978), 657.
- 16) T. Okada *et al.*: *Corrosion and Protection Engineering of Materials (Zairyo no Fushoku to Boshoku no Kogaku)*, ed. by The Soc. Mat. Sci., Japan, Kyoto, (1969), 65.

* Published in *Journal of The Society of Materials Science, Japan*, **29** (1980), 499, in Japanese, after contributing to this journal.