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Short Range Ordering in 316L Stainless Steel and Its Effect on Dislocation Channeling in Irradiated Austenitic Stainless Steels

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1. Introduction

As the lifetime of water-cooled reactors extends to 60 years and above, irradiation assisted stress corrosion cracking (IASCC) of austenitic stainless steels used for PWR core internal is one of the hot issues to be tackled by the nuclear industry. Much attention was paid to an understanding of the IASCC mechanism in view of corrosion, the approach of which failed to account for intergranular cracking in 304L stainless steel without Cr depletion [1]. Thus, intergranular (IG) cracking of IASCC should be taken into account from mechanistic view points.

With increasing neutron irradiation, 304 stainless steels are known to show dislocation channeling or radiation-induced localization of plastic deformation, which is suggested to cause IG cracking of the irradiated 304 sensitized stainless steel [2]. Thus, understanding dislocation channeling is a key to elucidating IG cracking in irradiated austenitic stainless steels used as the reactor internals in water-cooled reactors. Unfortunately, it remains unclear about the cause of dislocation channeling and the effect of neutron irradiation. Given our first observation [3] that planar type dislocations in 316L stainless steels occur by short range ordering (SRO), it is suggested that dislocation channeling occurs by short range ordering. The aim of this study is to describe SRO in unirradiated and irradiated austenitic stainless steels and its effect on dislocation structures in both of them.

2. Experimental Procedures

Tensile tests were conducted on solution-annealed and water quenched 316L stainless steels in a temperature range of RT to 700°C with the strain rate changing from $1x10^{-4}$/s to $1x10^{-2}$/s. To provide evidence for SRO, the lattice spacing of a 40% cold-worked 316L stainless steel were determined as a function of aging time using a neutron diffractometer in Hanaro upon aging at a constant temperature of 400°C. Furthermore, TEM observations were made on the 316L stainless steel after tensile tests at various temperatures to show the evolution of dislocation structures with SRO.

3. Results and Discussion

Fig. 1 shows the degree of stain hardening in the 316L stainless steel with 0.01wt% N at $1x10^{-3}$/s which is termed (TS-YS)/YS. The degree of strain hardening

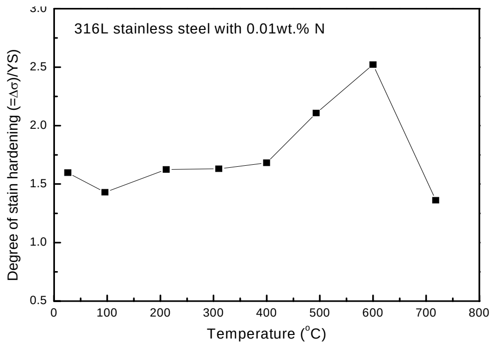

Fig. 1. The degree of strain hardening of a solution-annealed and water-quenched 316L stainless steel with tensile testing temperature, which is defined as (TS-YS)/YS.

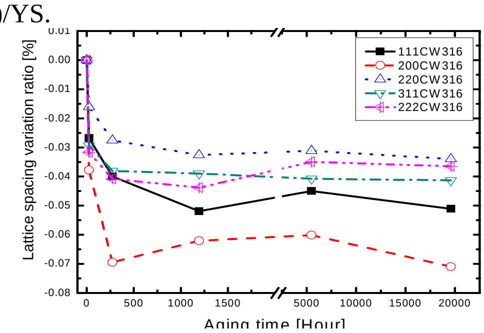

Fig. 2. A change in the lattice spacing of the 40% cold-worked 316L stainless steel with aging time at 400°C.

was constant independent of temperature over a temperature range of RT to 400°C and then increased rapidly from 400°C to 600°C. This rapid increase of strain hardening is suggested to occur by short range ordering (SRO). Evidence is provided by the lattice contraction of the 316L stainless steel upon aging at 400°C, as shown in Fig. 2. Upon aging at 400°C, the lattice contraction occurred rapidly and then leveled off to a constant with aging time. Considering that short range ordering promotes a high probability for unlike atoms to meet together, resulting in the lattice contraction, the lattice contraction that was seen to occur at 400°C, as shown in Fig. 2 demonstrates the operation of SRO at high temperatures like 400°C. To show the effect of SRO on the dislocation structures, we investigated the dislocation structures of the 316L stainless steel after the tensile tests at 200°C and 400°C. The cellular type dislocations were seen at 200°C where no SRO was operating. However, at 400°C where SRO was operative, many planar type dislocations were observed. Consequently, it is demonstrated first that SRO causes the dislocation structure to change from cellular to planar. Supportive evidence for the effect of SRO on planar type dislocations or slip bands is found from the deformation behavior of bulk metallic glasses (BMG) whose structure is composed of SRO. As expected, all the BMG of Cu-Zr composition showed serrations and straight slip bands during compression. Hence, it is evident that SRO is the cause of slip bands or planar type dislocations.

Note that the BMGs show softening right after yielding, revealing that SRO is the cause of this softening or a yield drop. Furthermore, given that SRO causes the serrated flow consisting of many yield drops, the softening just after a yielding in irradiated 304L stainless steel after 2 dpa and above as shown in Fig. 3 [4] seems to be caused by SRO. Using the thermally sensitized 304L that were solution annealed followed by the thermal treatment at 750^{o}C for 100 min and then at 500^{o}C for 24h, Onchi showed that IG cracking occurred in oxygenated water above a critical neutron fluence of around $1x10^{20}$ n/cm^2 corresponding to the appearance of dislocation channeling. During irradiation, lots of vacancies and dislocations are formed. The concentration of vacancies produced during neutron irradiation will depend on irradiation temperature and the fluencies. These vacancies will facilitate diffusion of Ni or Fe atoms in austenitic stainless steels, promoting short range ordering during a slow strain rate tensile test (SSRT) at 290^{o}C, which could not occur at the tensile test temperatures below 400^{o}C for the unirradiated 316L stainless steel as shown in Fig.1. Given that SRO yields planar type dislocations in plastic deformation of austenitic stainless steels, it is clear that dislocation channeling observed in irradiated austenitic stainless steels above a critical neutron fluence occurs by SRO that is promoted by enhanced diffusion due to high concentrations of vacancies produced in irradiated austenitic stainless steels.

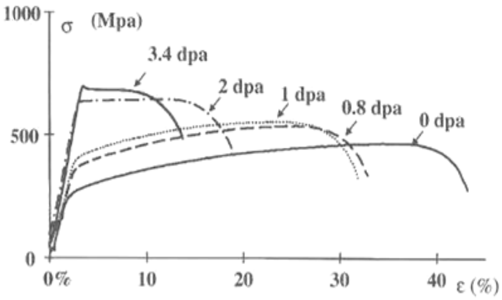

Fig. 3. Stress-strain curves at 330^{o}C for the solution annealed 304L after irradiation at the same temperature [4].

4. Conclusions

The 316L stainless steel showed a rapid strain hardening over a temperature range of 400 to 600^{o}C, This strain hardening occurred due to SRO which is evidenced by the lattice contraction of the 316L stainless steel upon aging at 400^{o}C. Furthermore, SRO changed the dislocation structure in the 316L stainless steel from non-planar to planar. Supportive evidence is provided by the bulk metallic glasses with SRO that showed serrated flow, strong slip bands and softening after yielding. Given this fact, it is demonstrated that dislocation channeling in the irradiated austenitic stainless steels occurs due to SRO accompanied during irradiation tests or slow strain rate tests.

ACKNOWLEDGMENTS

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