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Misunderstanding and Understanding of Primary Water Stress Corrosion Cracking of Structural Components in the Primary System of PWRs

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1. Introduction

All the structural components in the primary system of pressurized water reactors that are in contact with primary water are made of austenitic Ni-Cr-Fe alloys which are known to be corrosion resistant. Nevertheless, these Ni-Cr-Fe alloys such as Alloy 600, weld 182/82, austenitic stainless steels suffer from intergranular stress corrosion cracking (IGSCC) after their 10 year operation in reactors although the environment to which they have been exposed is almost pure water of pH 6.9 to 7.2, which is called primary water stress corrosion cracking (PWSCC). Given that the underlying mechanism of PWSCC remains unidentified so far, there are many misunderstandings related to PWSCC of the structural components, which may lead to unreasonable mitigation measures. The aim of this work is to highlight understanding and misunderstanding of PWSCC related to austenitic Ni-Cr-Fe alloys.

2. Misunderstanding of PWSCC

2.1. Tensile stress

The general consensus is that when the three components of tensile stress, susceptible material and the environment are sufficiently severe, stress corrosion cracking occurs. Especially IGSCC of the welds is known to occur by the weld residual stress remaining after welding. Considering this misunderstanding, some engineering measures to reduce the residual stress have been developed and implemented by the nuclear industry. However, if the residual stress were the cause of PWSCC of the welds and austenitic Ni-Cr-Fe alloys, the structural components would fail by PWSCC more frequently at beginning of life. Considering that PWSCC is observed to occur after a long incubation time of 100,000h in reactors and the residual stress is relieved by 80 to 100% 24 hours after exposure to high temperature of 300 to 350^{o}C, it is clear that PWSCC of the welds is not related to the residual stress. Thus, it is expected that shot peening to induce a layer of compressive stress near the surface of the structural components would be ineffective in mitigating PWSCC initiation and growth, which has already been observed in a Korean plant by Hur [1]. This rationale shows that stresses are developed internally besides the residual stress in the structural components including the welds, which has been disregarded so far. This misunderstanding of the stress is one of obstacles to a full understanding of PWSCC.

2.2. Grain boundary carbides

Thermally treated (TT) Alloys 600 and 690 is known to be highly resistant to PWSCC when compared to the untreated ones or those with intragranular carbides. Observing that TT-Alloy 600 show the carbides primarily distributed along the grain boundary, it is stated that grain boundary carbides are beneficial to PWSCC resistance. Based on Bruemmer's observation [2] that planar dislocations emitted from the grain boundary, it is proposed that grain boundary carbides would promote crack blunting, suppressing IG cracking at the grain boundary, which is also recently referred to by Hwang [3]. However, this proposal is strongly speculative because there is no direct evidence that grain boundary cracking is related to dislocation emission from the grain boundary and that carbides play a role in emitting dislocations from the grain boundary. In fact, more noticeable thing is the presence of planar dislocations and not cellular ones, which remains unnoticed so far. Another thing to note is that Alloy 690 with no grain boundary carbides showed 2 times lower crack growth rates than that with continuous grain boundary carbides. Given these observations, the role of grain boundary carbides in IG cracking is controversial. In fact, the water quenched (WQ) Alloy 600 after solution annealing above 1000^{o}C has shown higher PWSCC susceptibility than the furnace-cooled one after the same solution annealing treatment. Observing that the former with higher PWSCC susceptibility has no carbides at grain boundaries and the latter with lower PWSCC susceptibility has carbides to some extents at grain boundaries, they claim that PWSCC susceptibility of Alloy 600 is related to the presence or absence of grain boundary carbides. However, this claim has a logical problem in that no reasonable explanations can be given to the effect of grain boundary carbides on grain boundary cracking. Another thing is that the presence of grain boundary carbides cannot explain the build-up of internal stress in austenitic Ni-Cr-Fe alloys as discussed above. Thus, it seems that the observed grain carbide effect on IG cracking is not the cause but the result.

2.3. Corrosion or oxidation of grain boundaries

Corrosion approach was applied for several decades to explain IGSCC of Alloy 600 considering that Cr depletion at the grain boundary enhances cracking of austenitic stainless steels. However, this corrosion approach has been disregarded in the environment of pure water given the fact that Cr depletion does not increase PWSCC susceptibility of Alloy 600. Instead, another hypothesis that grain boundary cracking occurs by enhanced oxidation of grain boundaries has been suggested by Scott [4] based on the TEM observation of oxide layers at the leading edge of an intergranular crack. The problem with this grain boundary oxidation hypothesis is that they have no idea about if the oxide layer observed by TEM is formed before or after the onset of grain boundary cracking. Considering Guerre's observation [5] that oxygen and hydrogen transport in the oxidized grain boundary is much faster relative to the SCC crack growth rate, it is evident that grain oxidation occurs after the onset of grain boundary cracking. Another thing is that this GB oxidation model cannot account for build-up of the internal stress with exposure time in reactors.

3 Understanding of IG Cracking

Marucco and her workers have observed lattice contractions in various nickel alloys which increased with aging time upon isothermal aging. However, they haven't given much attention to the effect of lattice contraction on IG cracking. The real example showing the effect of lattice contraction is mud cracking that occurs when muds shrink when water evaporates in a condition like a drought. Another example showing grain boundary cracking is Kohara and Kuzynski's observation [6] that a tri-crystal CuAu has splitted into 3 pieces by grain boundary cracking 35 seconds after aging treatment at 350°C for ordering reaction. Thus, it is evident that the lattice contraction by the ordering transformation is the cause of IG cracking or IGSCC or PWSCC, which is our unique idea.

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