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Residual Stress and Intergranular(IG) Crack of Feeder Pipe in CANDU Reactor

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1. Introduction

The primary system of the CANDU reactor consists of pressure pipes and feeder pipes. Structural materials in the primary system contact with heavy water, which is a coolant, causing corrosion. The pressure tube is made of Zr-2.5%Nb alloy and absorbs deuterium formed by corrosion to have sensitivity to delayed hydride cracking(DHC). On the other hand, a case has been reported in the outlet feeder pipe that supplies high-temperature coolant to the steam generator, resulting in thickness thinning due to the erosion of the coolant and intergranular (IG) fracture [1. 2].

Thirteen cases of bend cracking found at the Point Lepreau Power Plant in Canada have been reported [1], and one case of weld cracking has been reported. Since intergranular fractures in feeder pipes are found in deformation areas or welds where bending operations have been performed, the causes have been assumed to be due to low-temperature creep and residual stress, respectively. Feeder pipe damage patterns are shown in Figure 1-3.

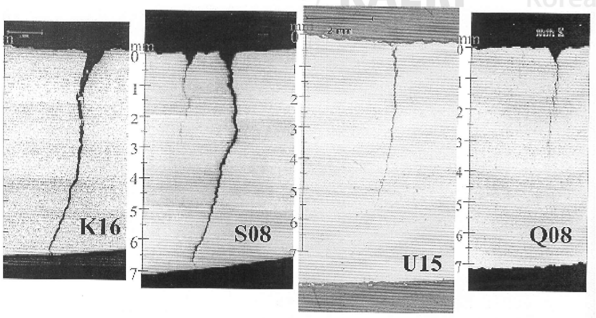

Fig. 1. Metallographic images of IG cracks of feeder pipes in Point Lepreau Nuclear Power Plant [1].

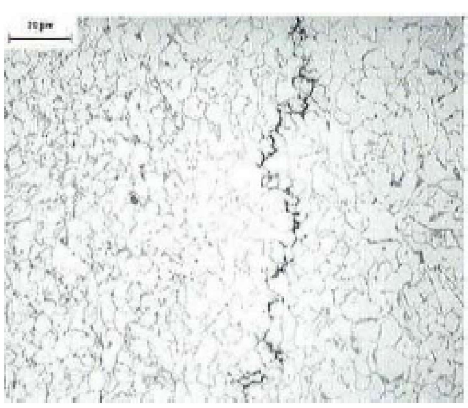

Fig. 2. Metallographic images of feeder pipes in Point Lepreau Nuclear Power Plant [1].

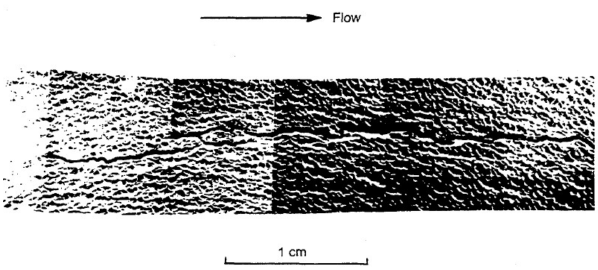

Fig. 3. Metallographic images of feeder pipes in Point Lepreau Nuclear Power Plant [2].

Recently, it has been reported that thermo-mechanical treatment of structural materials disrupts the atomic alignment, changing the atomic arrangement to an unstable state and increasing the configuration (arrangement) entropy. Therefore, this study is based on the concept that the entropy remaining in the thermally and mechanically treated structural material is reduced by the atomic diffusion process, causing the change in the length of the structural material and the contraction of the length of the crystal to generate internal stress by itself. It was shown that the essence that was misunderstood as is residual entropy.

2. Entropy increase by thermo-mechanical treatment

In discussing the entropy of materials, two essential points must be considered: (a) atoms are not spherical, and (b) entropy is formed even in pure metals.

(a) So far, we have assumed that the atoms constituting materials are spheres, but atoms are not spheres, actually. If the shape of an atom is not spherical, it should be considered that entropy is formed according to the arrangement of atoms. (b) Until recently, entropy only considered the mixing entropy that occurs when atoms A and B are mixed, but since atoms are not spheres, entropy is formed as the arrangement of atoms is disturbed. The second law of thermodynamics is defined as entropy ($S=Q/T$). Assuming that atoms are elliptical, this study shows in principle that entropy increases and length increases when the atomic arrangement is disturbed.

The entropy formed in a pure metal or alloy has a mixture component and an arrangement component. However, until now, the field dealing with the regular arrangement of atoms in high-concentration alloys has only considered entropy due to the regularity of mixed atoms. For example, the short-range ordering dealing with alloys such as Cu3Au, CuAu, and CuAu3 consider only the entropy of the mixture. Even in the case of high entropy alloys that have been studied recently, only mixed entropy is dealt with. However, configuration entropy is an important and broad concept of entropy that is formed not only in pure metals but also in alloys. Figure 4 (a) compares the case where the atoms are elliptical and well-ordered, and (b) shows that the area increases when the entropy increases because the atomic arrangement is disordered. When the elliptical atoms are arranged, the area occupied by the same atoms increases, which is an effect of increasing entropy due to the disordered atomic arrangement.

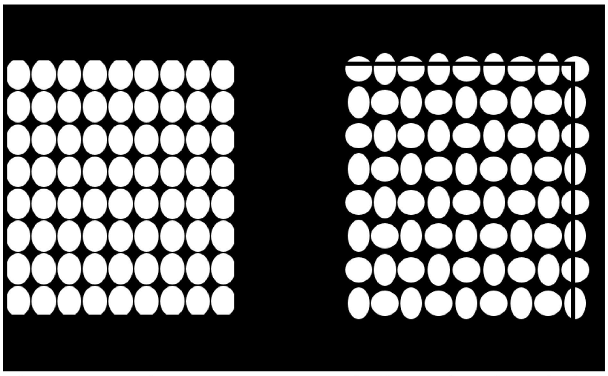

Fig. 4. Atomic arrangement and dimensional variation with entropy in material with ellipsoidal atoms[3-5].

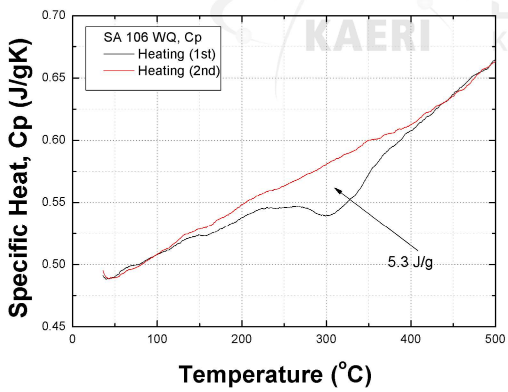

Fig. 5. The specific heat (Cp) variation analyzed by DSC in WQ and Mild steel.

The entropy remaining inside the material thermos-mechanical treatment in the material is ultimately heat and can therefore be measured by differential scanning calorimeter (DSC). The feeder pipe material is SA106 grade B, which is finally water quenched (WQ) treated in the manufacturing process, and the feeder pipe is bent and welded. As shown in Figure 5, this material in the WQ state causes an exothermic reaction in DSC, which is observed because the entropy remaining during the WQ treatment at high temperature is released. The black line denotes a WQ and the red line denotes furnace cooled (FC). The amount of exothermic energy of WQ SA106 grade B is measured by 5.3 J/g.

3. Reason of IG cracking in feeder pipe

The bend crack and weld crack reported in the feeder pipe of Point Lepreau Power Plant in Canada are cold worked and welded parts, respectively. It has been assumed that IG cracks appearing in these are usually residual stresses formed by thermal mechanical treatment such as cold working or welding. However, as shown in Figure 5, strain or heat applied by thermos-mechanical treatment increases entropy, so the cause of grain boundary fracture is not low-temperature creep or residual stress, but self-generated stress inside the material due to a decrease in residual entropy. Until now, this has been evaluated as residual stress in the sense that stress remains in the material.

Let's look at how residual entropy works in materials. Commercial materials are made of polycrystals, and each crystal grain has an anisotropic arrangement. As described above, the length increases as the atomic arrangement changes due to thermal mechanical treatment, and when it is exposed to a high-temperature operating environment, the entropy decreases due to the diffusion of atoms, and the length of the material shrinks. At the same time, each crystal grain shrinks and the grain boundary is subjected to tensile stress, resulting in grain boundary fracture. This process is shown in Figure 6.

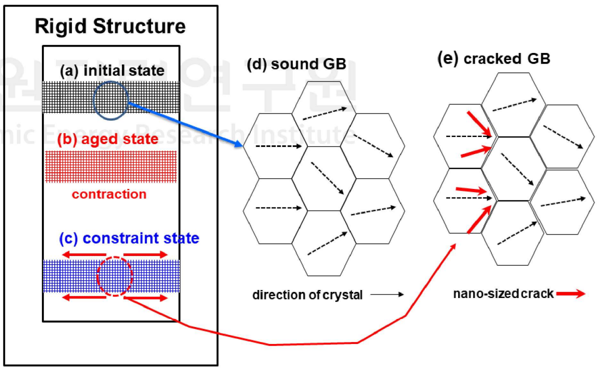

Fig. 6. The macroscopic consequence in structure and the microscopic variation due to anisotropic lattice contraction originated by decrease in entropy.

Because CANDU structural materials contact with heavy water, which is a coolant, the surface cannot avoid corrosion. Since the corrosion process occurring in this process has the effect of slightly accelerating the IG fracture, the IG fracture of the feeder pipe material has been considered as IG stress corrosion cracking. However, a more accurate interpretation is that the cause of the grain boundary widening is the grain boundary tensile stress created by itself as the entropy inherent in the material decreases.

4. Conclusion

Thermo-mechanical treatment of SA106 grade B increases and retains the entropy of the material. This residual entropy causes the lattice expansion. When exposed to operating reactor environment, the entropy decreases while the lattice contracts. Thermo-mechanical treatment of Fe alloy increases entropy to cause lattice expansion, and in the operating environment, atoms are aligned by atomic diffusion and the lattice is contracted. This behavior is a sufficient condition for generating tensile stress at the grain boundaries of the material and causing grain boundary failure. Therefore, the essence of increasing the sensitivity of IGSCC is the increase in entropy.

Acknowledgments

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