

Effect of Carbon Mass Transfer Behavior on the Mechanical Property of Fuel Cladding Materials of Sodium-cooled Fast Reactor

Sang Hun Shin ^{a*}, Jun Hwan Kim ^a, Sung Ho Kim ^a

^aSFR Fuel Development Division, Korea Atomic Energy Research Institute (KAERI), P.O. Box 105, Yuseong, Daejeon 34057, Republic of Korea

*Corresponding author: shshin@kaeri.re.kr

1. Introduction

A sodium-cooled fast reactor (SFR), a reactor that uses fast neutrons as a fission process, is considered one of the most probable candidates in 4th generation reactors because it can maximize the uranium utilization when compared to conventional water reactor. Liquid sodium is used as a coolant in a SFR, because it has superior efficiency of fast neutron economy and high thermal conductivity, which enables a high power core design. However, previous research reported that fuel cladding materials like austenite and ferritic/martensitic steel (FMS) react sodium coolant so that it results in the loss of the thickness, intergranular attack, and carburization or decarburization process to induce the change of the mechanical property [1,2].

Especially, the structural materials are subject to carbon mass transfer phenomena in liquid sodium. The effect of a sodium environment in mechanical properties depends largely on the degree of carburization/decarburization that occurs in austenite and FMS during long term exposure to sodium, and this can significantly affect microstructural stability and mechanical properties of the steels [3].

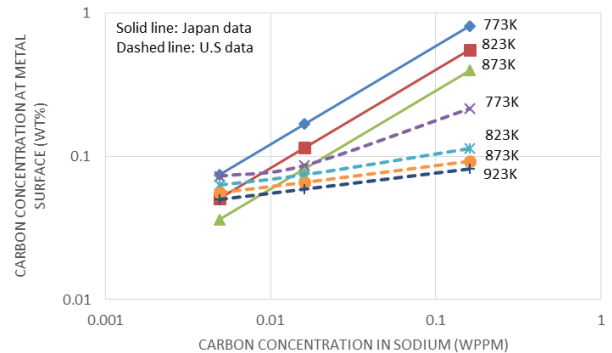
In this study, the carbon mass transfer and its effect on the mechanical property of the fuel cladding is discussed.

2. Literature review

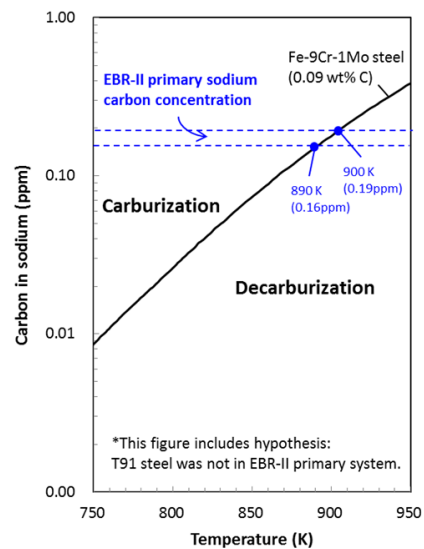
In a mono-metallic sodium system, austenitic stainless steels tend to decarburize in the reactor core region and carburize in the internal heat exchanger one [4]; low-Cr ferrite steels, such as 2.25Cr-1Mo, are susceptible to decarburization in sodium due to their inherently high C activity [5-7]; high-Cr materials such as 9Cr and 316 steels have relatively lower C activity, and are more resistant to carbon loss in sodium environment [8-10]. Decarburization of 2.25Cr-1Mo steel exposed in a sodium environment to temperatures up to 550 °C leads to a progressively reduction in the tensile and yield strengths of the steel [11, 12].

When austenite and FMS are exposed to sodium, the concentration of carbon at the interface is going to be equilibrated between the metal surface and the liquid sodium. In the U.S [10] and Japan [13], the correlation between carbon content in liquid sodium and carbon content at the metal surface of 9Cr FMS is expressed as Fig. 1 (a). As shown in the figure, when the carbon

content in liquid sodium is between 0.0049 and 0.016 wppm, the U.S and Japan data show similar value. As results of the carbon mass transfer, the carburization-decarburization at the metal occur as shown in fig. 1 (b). The carburization-decarburization regimes for 9Cr-1Mo steel containing 0.09 wt% of carbon under EBR-II primary sodium system (0.15~0.2 wppm of carbon) has been shown in Fig. 1 (b) [10, 15].



(a)



(b)

Fig. 1. (a) The relation of carbon concentration in Na and carbon concentration at metal surface [10, 13] and (b) carburization-decarburization regimes for Fe-9Cr-Mo steel in EBR-II primary sodium system in terms of the carbon concentration in sodium and temperature [10, 15].

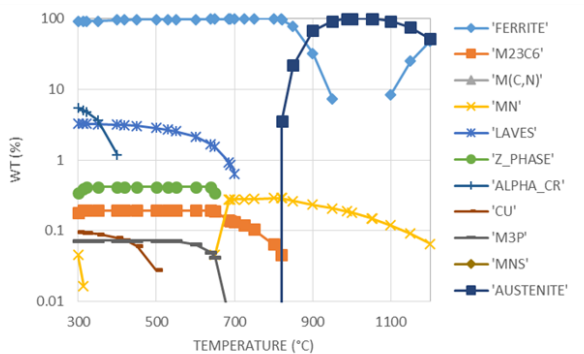
When a carbon concentration in liquid sodium is under 0.26 ppm at 650 °C, the 9Cr-1Mo steel is going to be decarburized in the sodium environment. The carbon concentration in liquid sodium is mostly depends on the carbon concentration of the structural materials in a SFR core system, so that the carbon content in liquid sodium in a SFR system can be variable. In EBR-II primary system, the carbon concentration is maintained at 0.15~0.2 wppm for 6 years (1973 to 1978) [15,16].

Based on the literature data, especially the EBR-II case, it can be estimated that the 9Cr FMS is going to be decarburized at 650 °C in SFR primary system.

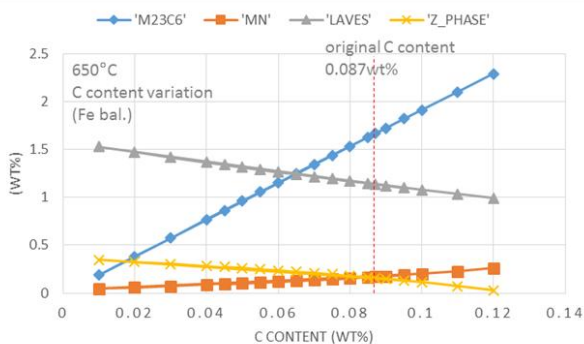
2. Results and discussion

In this study, the effect of the carbon mass transfer on the microstructure and the mechanical property is estimated by reviewing the literature data, modifying corrosion and decarburization model, and computational calculation by JMatPro 8.0.

As the first, thermodynamic equilibrated phases in Gr. 92 steel are shown in Fig. 2 (a) as a function of temperature. At 650 °C (as peak temperature of the SFR cladding), the amount of the precipitate such as $M_{23}C_6$, Laves, $M(C,N)$ is affected by the carbon mass transfer which occurs at the interface between liquid sodium and the surface of the metal as shown in Fig. 2 (b).



(a)



(b)

Fig. 2. (a) Thermodynamic equilibrated phases in Gr. 92 steel as function of a temperature and (b) sensitivity of the precipitates ($M_{23}C_6$, Laves, $M(C,N)$, Z phase) as function of C content at 650 °C as calculated by JMatPro 8.0.

The carbon mass transfer between the 9Cr ferritic steel with 0.087 wt% of carbon and a liquid sodium containing 0.15~0.2 wppm of carbon (based on the EBR-II primary sodium environment) will result in decarburization of the cladding over 617 °C. In the same environment, the Gr. 92 steel bears a metal loss and intergranular oxidation in case of high dissolved oxygen in liquid sodium. Using a modified empirical model, the thickness of decarburization and metal loss of the Gr. 92 steel is estimated as shown in Fig. 3. The condition of liquid sodium is that sodium contains 0.15~0.2 wppm of carbon and 3 wppm of oxygen. Then, the total thickness loss for 5 years at 650 °C is 85 μm . The typical thickness of cladding tube in the SFR reactor is 500 μm . For a conservative estimation, the total thickness loss is used to estimate the rupture time of Gr. 92 with a certain applied hoop stress as shown in Fig. 4.

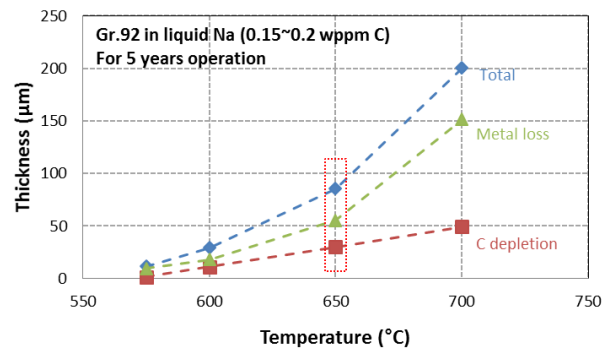


Fig. 3. The estimated thickness of the decarburization and the metal loss after exposure to 550 to 700 °C liquid sodium containing 0.15~0.2 wppm carbon.

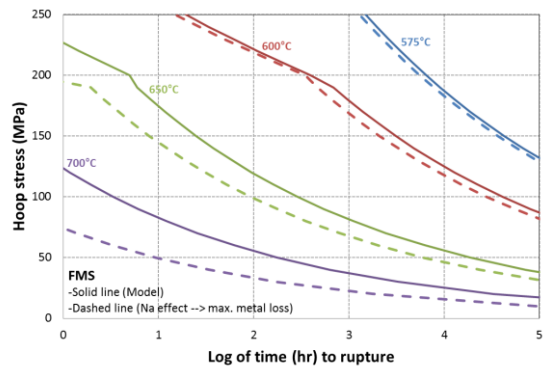


Fig. 4. Effect of liquid sodium on the rupture time of FMS.

4. Conclusions

At sodium environment, the carbon mass transfer occurs at the interface between the liquid sodium and the metal surface until the carbon activity is equilibrated at a certain temperature. In this study, the Gr. 92 cladding tube is exposed to liquid sodium which

contains 0.15~0.2 wppm of carbon and 3 wppm of oxygen, and the metal will lose its thickness by the decarburization and the metal loss. For the conservative analysis, the thickness loss effect on the rupture time is estimated. At 650 °C, 68% of reduction of the rupture time occurs when the hoop stress is 100 and 150 MPa.

ACKNOWLEDGEMENT

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