Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

Inter-diffusion of HT9 and Cr at 650 °C

Ju-Seong Kim*, Seongsoo Yoo, Jeong Mok Oh, Heung Soo Lee, Cheol Min Lee, June-Hyung Kim
Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon 34057, Republic of Korea
**Corresponding author: juskim@kaeri.re.kr*

1. Introduction

The nuclear fuel of the sodium-cooled fast reactor (SFR) is U-Zr metallic fuel, and the cladding material is HT9, a type of ferritic-martensitic stainless steel cladding tube. Fuel cladding chemical interaction (FCCI) between the fuel and the cladding is a crucial factor that determines the integrity and lifetime of the metallic fuel. Therefore, various coating layers have been studied to prevent FCCI, and the Cr coating layer is a promising candidate material known for its excellent prevention of FCCI. The main role of the Cr coating layer is to prevent interactions between the cladding and rare earth elements produced by fission. Currently, the Korea Atomic Energy Research Institute is developing Cr-coated cladding tubes, and this paper studies the inter-diffusion between Cr and HT9 for understanding the stability of the coating layer.

2. Experimental

The chemical composition of HT9 is shown in the Table 1. The disk type HT9 specimen of 12 mm diameter and 2 mm thick was used. Cr was electroplated onto a surface of HT9 around 15-20 µm. Fig. 1 shows back scattering electron image of the interface between HT9 and Cr coating. To evaluate the effect of inter-diffusion on the coating layer, isothermal annealing was conducted at 650 °C in a vacuum environment for 1000 hours. After the annealing, the elemental distribution of Cr and Fe was examined using EPMA.

Table 1. Chemical composition of HT9 (wt%)

Fe	Cr	Ni	Mo	W	Mn	V	C
Bal.	12	0.48	1.00	0.49	0.49	0.3	0.2

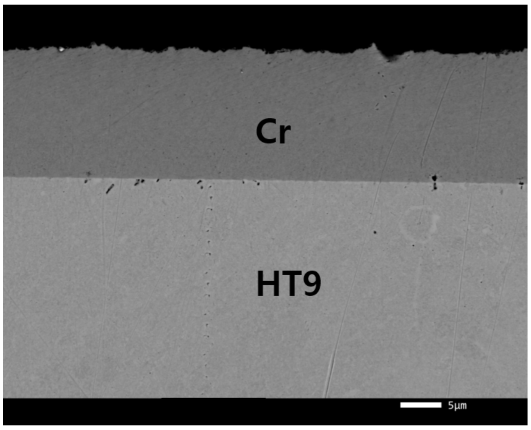

Fig. 1. Surface morphology of Cr coated HT9.

3. Results and discussion

3.1 Element distribution of inter-diffused layer.

There is no significant difference between the morphology of Cr coated HT9 before and after the annealing. Fig. 2 shows the chemical composition of Fe, Cr at the reaction interface between HT9 and Cr coating layer. As shown in the figure, Cr migrated to the HT9 and Fe in HT was diffused to Cr coating layer. As shown in the figure, inter-diffused region is around 10-15 µm, and thus the inter-diffusion at this temperature seems not to be active. Precisely, the inter-diffusion reaction between HT9 and Cr is not a binary diffusion system, however, since the total weight % of minor elements of HT9 excluding Fe and Cr is less than 3 wt%, the major inter-diffusion elements are Fe and Cr. Therefore, the minor element of Ni, Mo, W, Mn, V, C was excluded in the analysis and only major elements, Cr and Fe was used in the analysis and the inter-diffusion between Cr and HT9 was assumed to be a binary diffusion reaction.

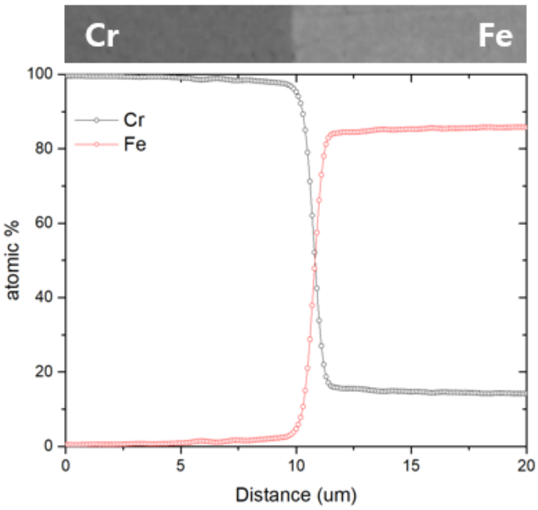

Fig. 2 Line profile of Cr and Fe at the interface between HT9 and Cr coating layer

3.2 Determination of inter-diffusion coefficient of Cr and HT9

When two alloys A and B are diffusion coupled, the inter-diffusion coefficient in Cartesian coordinates can be determined as follows [1]:

$$\widetilde{D}(C_B^*) = -\frac{1}{2t}\left(\frac{dx}{dC_B}\right)_{C_B^*}\int_{C_B^-}^{C_B^*} x\,dC_B$$

This method is called Bolzmann-Matano method [2, 3] which is used for determining the inter-diffusion coefficient in binary alloy systems. However, due to the unclear initial position of contact boundary, it is difficult to locate the Matano plane. Therefore, the graphical approach method by den Broeder[4] was applied to determine the diffusion coefficient. The inter-diffusion coefficient proposed by den Broeder is as follows

$$\widetilde{D}(Y_C^*) = \frac{1}{2t}\left(\frac{dx}{dY_C}\right)_{Y_C^*}[(1 - Y_c^*)A + Y_c^* B]$$

Where, Y_C is concentration normalizing variable of Fe, A and B are the areas in Fig.3

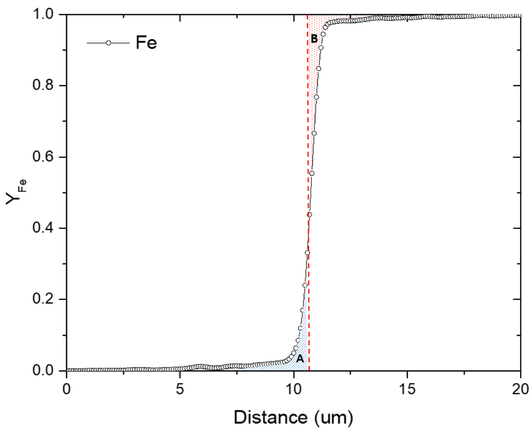

Fig. 3 Distribution Fe at the coating interface as a function of Y_C

The calculated inter-diffusion coefficient of Cr-Fe at 650 ℃ is given in Fig.4. The inter-diffusion is faster at lower composition of Fe and Cr and is rather slow in the intermediate composition.

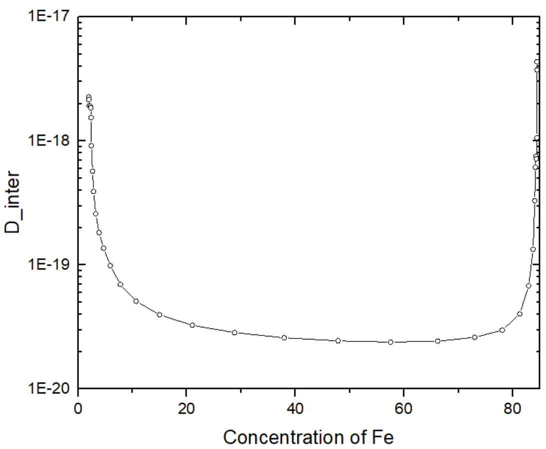

Fig. 4 Inter-diffusion coefficient $\widetilde{D}[m^2/s]$ as a function of Fe concentration in Cr(Fe) solid solution

The inter-diffusion coefficient at a high Fe concentration is higher than that at a high Cr concentration, which may due to a smaller atomic radius of Fe (156 pm) than that of Cr (0.166 pm).

4. Summary

Cr was electroplated on the surface of HT9 and annealed 1000 hour to evaluate the structural integrity and inter-diffusion between Cr and HT9. The minor element of HT9 was excluded in the inter-diffusion analysis and thus, the inter diffusion of Cr and HT9 was assumed as binary diffusion of Cr and Fe. The inter-diffusion is faster at lower composition of Fe and Cr and is rather slower in the intermediate composition.

Acknowledgement

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2021M2E2A2081066).

References

[1] V.A. Baheti, A. Paul, Development of different methods and their efficiencies for the estimation of diffusion coefficients following the diffusion couple technique, Acta Materialia 156 (2018) 420-431.
[2] C. Matano, On the Relation between the Diffusion-Coefficients and Concentrations of Solid Metals, Japan. J. Phys. 8 (1933) 109.
[3] L. Boltzmann, Zur Integration der Diffusionsgleichung bei variabeln Diffusionscoefficienten, Annalen der Physik 289(13) (1894) 959-964.
[4] F.J.A. den Broeder, A general simplification and improvement of the matano-boltzmann method in the determination of the interdiffusion coefficients in binary systems, Scripta Metallurgica 3(5) (1969) 321-325.