Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2015

Finite element analysis of plate rolling of duplex-layer steels for long-period fast reactor application

Jungki Lee[a], and Ji Hyun Kim[a]*
[a] *School of Mechanical and Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulju-gun, Ulsan 44919, Republic of Korea*
[*]*Corresponding author: kimjh@unist.ac.kr*

1. Introduction

With dramatic increase in demand for energy in the 21st century, the need for consistent energy production without environmental contaminant became significant. The concept of liquid metal cooled reactor (LMFR) with long-cycle/long-period options is discussed profoundly in Generation IV International Forum (GIF) and Global Nuclear Energy Partnership (GNEP).

For long-cycle/long period LMFR, the integrity of reactor materials including fuel cladding and structural materials is important, and especially in the case of structural materials, it should be compatible in high temperature, high dpa, and also special chemical environment according to its liquid metal coolant type up to end of reactor life time. For 30 or even 60 years of reactor operation service, degradation of materials can be snowballing problem so compatibility of materials with liquid metal in reactor environment including corrosion and creep strength must be cautiously studied.

In high temperature liquid metal environment, there are usually two types of corrosion; one is corrosion by dissolution of alloy elements into liquid metal, and another is corrosion by chemical reaction among impurities in liquid metal and structural alloy. To protect the structural materials from corrosion, alloy elements can form protective oxide layers on its surface which act as diffusion barrier. But in the case of high temperature or impurities in some range make the protective film to be unsustainable [1]. So there have been some researches to develop new alloys that can form more dense scale on the surface even in wider impurity range and higher temperature range [2, 3].

M.P Short et al. devised functionally graded composite which is composed of two layers – one is a thin corrosion resistant layer and another is thick structural layer which guarantees mechanical strength, creep rupture strength and shows less irradiation swelling. In his study, he select Fe-12Cr-2Si as corrosion-resistant layer and T91 or HT9 as structural layer. By weld-overlay technique, Fe-12Cr-2Si onto F91 billets, co-extruding them and followed by pilgering process, coolant piping and cladding can be produced [4].

The weld overlay technics are widely used approach in nuclear industries; light water reactors typically use this hybrid layer technic in pressure vessel and the fuel cladding. Pressure vessels are usually made of carbon steels which will endure the pressure. With weld overlaying of stainless steel inside of the vessel, which acts as corrosion-resistant layer of the pressure vessel [5]. In fuel cladding tubes, which hold the fissile fuel in a core, pure zirconium are clad inside the zirconium alloy such as Zircaloy-4 (Zr-1.4Sn-0.2Fe [6])[7]. The pure zirconium serves as the corrosion-resistant layer, while the zircaloy serves as the structural layer. The zirconium liner on the inside of this type of fuel cladding, known as barrier fuel, helps prevent fuel-clad interactions [8]. These concepts are not suitable for fast reactor applications,

The cold mill pilgering process uses ring dies and a tapered mandrel to reduce tube cross sections by up to 90 percent. Because the process relies on large number of small forming steps, the result is tube or pipe that has nearly homogenous material characteristics. In this study, however, plate rolling of weld overlaid alloys is preferentially studied to see characteristics of two alloys in one composite during cold working which can be directly applied to production of FGC plate or used in the next research for pilgering process.

For the cold plate rolling of FGC, the 3-dimensional finite element analysis is used.

2. Finite element analysis

2.1 selection of composite materials

J.Y. Lim et al. proposed Fe-Cr-Si system alloy for high temperature corrosion resistance material. From corrosion test with a series of alloys based on Fe-Cr-Si system, it verified that Fe alloys with suitable levels of Cr (>12 wt.%) and Si (>2.5 wt.%) will be protected by either a tenacious oxide film (over a wide range of

Table 1. Chemical composition of Fe-12Cr-2Si weld wire and F91 in wt.%

	Fe	Cr	Mn	Mo	Ni	Si	V	W	N	C
F91	bal	9.4	0.51	1.0	0.28	0.35	0.19	0.07	-	-
Fe-12Cr-2Si	bal	13.11	0.02	-	0.006	2.0	-	0.17	-	0.01

oxygen potentials above the formation potential for Cr and Si oxides) or by a low solubility surface region at low oxygen potentials. Experimental result obtained from model alloys after LBE exposure at 600℃ demonstrated the film formation process. The hypothesis that Si addition would promote the formation of a diffusion barrier was confirmed by the actual reduction of oxide thickness over time. The Si effect was magnified by the addition of Cr to the system [2].

From the above J.Y. Lim's result, M.P. Short et al. devised a Functionally Grade Composite (FGC) which consists of two layers, a thin Fe-Cr-Si layer as corrosion-resistance layer, and F91 was chosen as structural layer of the composite for its strength and radiation resistance [4]. Also other Ferritic/martensitic steels like HT9 or Gr.92 can be selected for structural layer materials for each reactor application. HT9 and Gr.92 already showed great mechanical properties in high temperature sodium environment [9]. Table 1 shows chemical composition of Fe-12Cr-2Si and F91 steels. For plate for FEA, Fe-12Cr-2Si and F91 are selected as corrosion-resistant layer and structural layer.

2.2 3D FEM setting

For finite element method of plate rolling, 15% reduction rate is selected. Figure 1 shows schematic of half-symmetric plate rolling model. Dimension of the plate is 1000 x 500 x 1000 mm and the thick ness ratio of upper/lower layer is set as 1/9. Roll diameter is set to 200 mm. To simulate weld overlay characteristics, bonded option is applied in the interface between upper and lower plate.

Flow stress-strain curve and mechanical properties are calculated by JMatPro-v8 using chemical composition of each alloys. With piece-wised linear option, non-linear properties of materials can be applied in FEM. Figure 2 shows the piece-wised linear flow stress-strain curves for F91 and Fe-12Cr-2Si alloys and Table 2 shows mechanical properties of those alloys calculated from JMatPro v8.

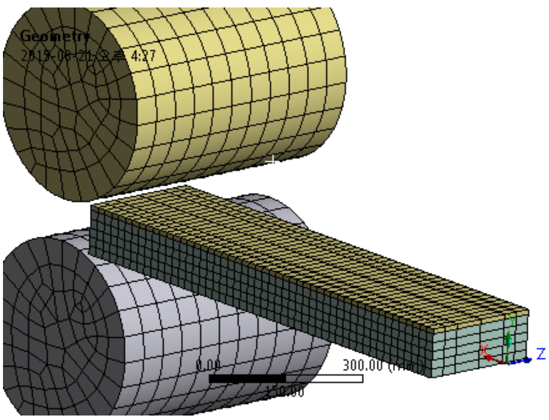

Fig 1. Schematic of 3D plate rolling.

Table 2. Mechanical properties of F91 and Fe-12Cr-2Si alloys calculated by JMatPro-v8

	F91	**Fe-12Cr-2Si**
Young's modulus (GPa)	192	178
0.2% proof stress	312	417
Tensile stress	468	567

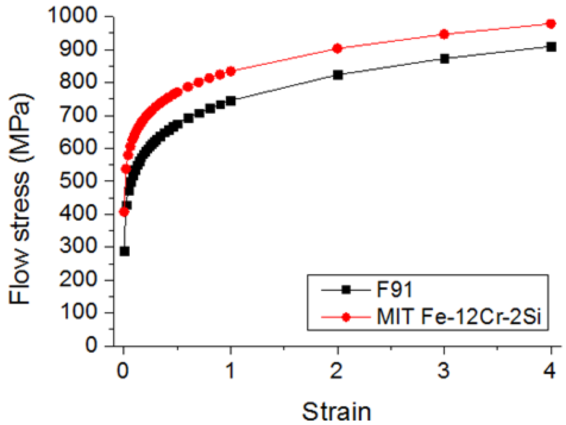

Fig 3. Piece-wised linear flow stress-strain curves of F91 and Fe-12Cr-2Si alloys at 25 ° C calculated by JMatPro-v8.

Rotation velocities of upper roll is set to 15 ° /sec and lower roll is controlled by 11 and 15 ° /sec. Also friction coefficient of upper roll-plate contact area is controlled by 0.2, and 0.3 while lower roll-plate friction coefficient is fixed at 0.2.

3. Result and discussion

3.1 FEA result when roll speed is controlled

When upper and lower roll rotation speed and friction coefficient at contacts are set to 15 °/sec and 0.2, the rolled product shows that curvature is formed toward upward after passing the rolls. Figure 4 shows equivalent stress and plastic strain distribution of plate after the rolling. Because of the flow stress differences between F91 and Fe-12Cr-2Si alloys, which can be observed in figure 3, it showed that deformation of the thicker F91 layers is larger than that of a thin Fe-12Cr-2Si layer. Less stress is needed to for F91 steel to have the same amount of deformation with Fe-12Cr-2Si because F91 show softer characteristics in the flow stress-strain curve. Distribution of the von-Mises equivalent stress shows that it is mostly concentrated on Fe-12Cr-2Si layer and distribution of the equivalent plastic strain shows it is concentrated on lower part of F91 layer.

To get flat rolled product, lower roll rotation speed is adjusted as 11 °/sec, which means the roll rpm ratio of upper and lower roll speed is 1.36. The rolled product shows the curvature is eased as roll speed of lower roll is slowed.

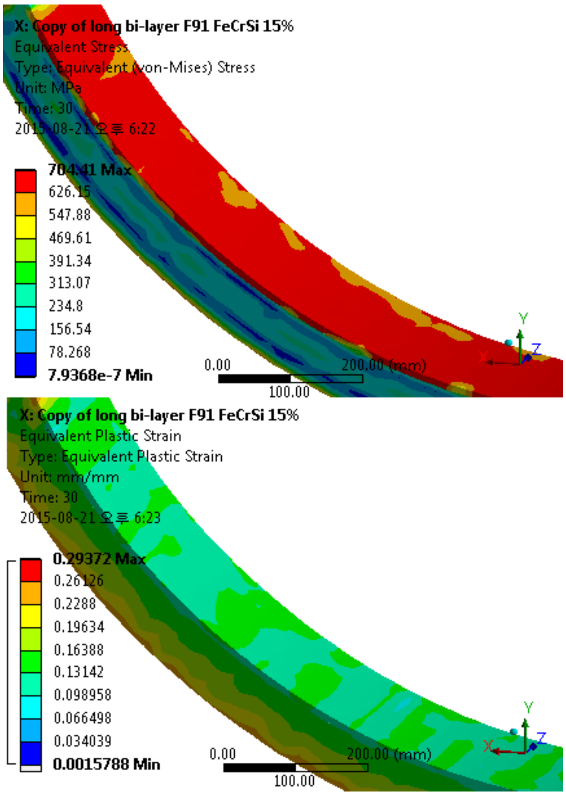

Fig. 4. Equivalent stress and plastic strain distribution of rolled product when rotation speeds of upper and lower rolls is the same and friction coefficient is 0.2.

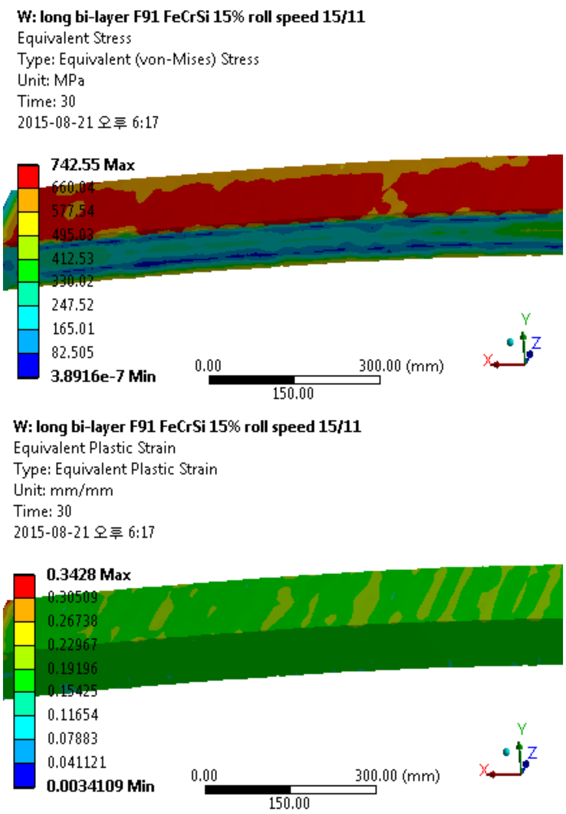

Fig. 5. Equivalent stress and plastic strain distribution of rolled product when rotation speed of upper roll is 15 °/sec and lower roll is 11 °/sec. the friction coefficients are set to 0.2.

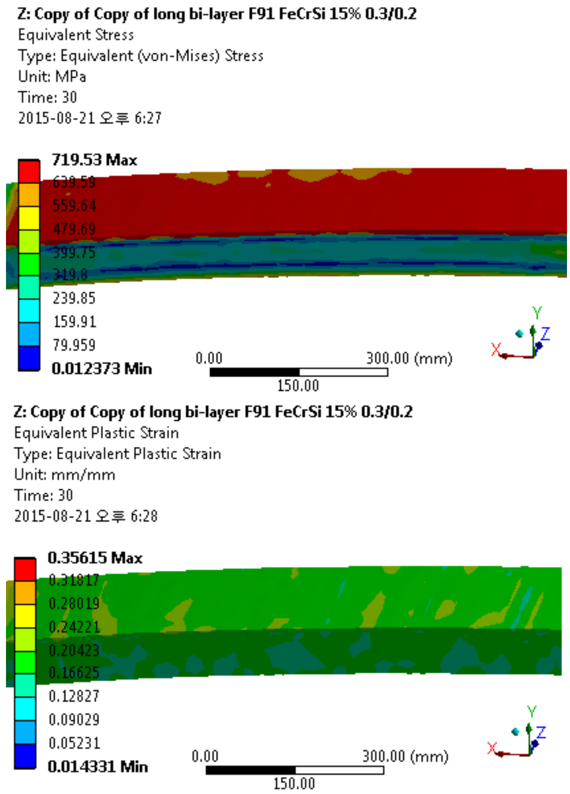

Fig. 6. Equivalent stress and plastic strain distribution of rolled product when rotation speed of upper and lower roll are the same and the friction coefficients are set to 0.3 in upper roll-plate contact and 0.2 in lower roll-plate contact.

The FEA results of equivalent stress and plastic deformation distribution are showed in figure 5. The von-Mises equivalent stress distribution showed that the stress is still concentrated on upper Fe-12Cr-2Si layer, however, it also shows that equivalent plastic strain is distributed uniformly comparing with upper and lower roll speed ratio is 1.0.

3.2 FEA result when friction coefficients are adjusted

To ease the curvature of the rolled product, other than controlling upper/lower roll rpm ratio, another way is adjusting the friction coefficients at upper and lower contacts. By adjusting friction coefficient, stress that transferred to plate can be differed. The friction coefficient of upper roll-plate is set to 0.3 and lower one is set to 0.2 while roll speed is fixed at 15 °/sec on both side. FEA result shows that curvature also can be eased as shown in figure 6. It showed similar result with controlling upper/lower roll rpm ratio.

4. Conclusion

Functionally graded materials is composed of functional (corrosion resistant) layer and structural layer. Weld overlay technique is used to make metallurgical bonding between those two alloys. FEM is used to simulate cold plate rolling in this study. With same roll speed and same friction coefficient, curvature is formed on rolled product from FEA result. To reduce this curvature and plastic strain which cause reduction in fabricability, two ways are selected; (i) controlling upper/lower roll speed, and (ii) adjusting upper/lower friction coefficient and contacts. Both results shows it can reduce the curvature and equivalent plastic strain of the plate after the rolling. It can be applied in real plate rolling processing and also the next research for pilgering process for tube and pipe production.

AKNOWLEDGEMENT

This work was supported by the National Nuclear R&D program (SFR Cladding Development Project) through the Sodium-cooled Fast Reactor Development Agency funded by Ministry of Science, ICT and Future Planning, and by the National Nuclear R&D program (No. 2010-0018678) organized by the National Research Foundation (NRF) of South Korea in support of the Ministry of Science, ICT and Future Planning.

REFERENCES

[1] N. Li, Active control of oxygen in molten lead-bismuth eutectic systems to prevent steel corrosion and coolant contamination, Journal of Nuclear Materials, Vol. 300, pp.73, 2002.

[2] J. Y. Lim, R. G. Ballinger, and P. W. Stahle, Corrosion resistant alloy development for Pb-Bi eutectic service, Transactions of the American Nuclear Society, Vol. 92, pp.133-136, 2005.

[3] J. Lim, I. S. Hwang, and J. H. Kim, Design of alumina forming FeCrAl steels for lead or lead-bismuth cooled fast reactors, Journal of Nuclear Materials, Vol. 441, pp.650-660, 2013.

[4] M. P. Short, and R. G. Ballinger, A functionally graded composite for service in high-temperature lead- and lead-bismuth-cooled nuclear reactors - I: Design, Nuclear Technology, Vol. 177, pp.366-381, 2012.

[5] F.M. Haggag, W.R. Corwin and R.K. Nanstad, Effect of irradiation on the fracture properties of stainless steel weld overlay cladding, Nuclear Engineering and Design, Vol. 124, pp.129-141, 1990.

[6] J.J. Kearns, Terminal solubility and partitioning of hydrogen in the alpha phase of zirconium, Zircaloy-2 and Zircaloy-4. Journal of Nuclear Materials, Vol. 22, pp.292-303, 1967.

[7] W. J. Reich, R. S. Moore, and K. J. Notz, Distribution of characteristics of LWR spent fuel (ORNL/TM-11670), Technical report, Oak Ridge National Laboratory, 1991.

[8] D. F. Wilson, E. C. Beahm, T. M. Besmann, J. H. DeVan, J. R. DiStefano, U. Gat, S. R. Greene, P. L. Rittenhouse, and B. A. Worley, Potential effects of gallium on cladding materials (ORNL/TM-13504), Technical report, Oak Ridge National Laboratory, 1997.

[9] J. H. Kim, and S. H. Kim, Microstructure and mechanical property of ferritic-martensitic steel under a 650 ˚C liquid sodium environment, Journal of Nuclear Materials, Vol. 443, pp. 112-119, 2013.