Development of Pilgering Process of Hybrid-layer Cladding for Advanced Small Modular Fast Reactor Application

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Abstract. Lead-cooled Small Modular Reactors (SMRs) have been rapidly developed for inherent safety and for minimizing high level wastes, Structural materials for lead cooled SMRs have been developed to increase corrosion resistance at temperature up to 600 C in order to open its application to replace supercritical coal power plants. A Si-containing corrosion-reswas made instant material has been produced into surface layer of a functionally graded composite pipe with Alloy T91 as structural substrate responsible for mechanical strength, by means of weld-overlay followed by hot extrusion. . The functionally graded composite (FGC) pipe is to be cold-pilgered into small tubing for fuel cladding and steam generator tubing. In order to optimize pilgering process, 3D computational analyses for elastic-plastic pilgering process on FGC tube were conducted by using elastic-plastic finite element analysis (FEA) technique. In order to benchmark FEA model, an overlay welding of Si-containing steel has been made on T91 plate that was then rolled it into simulated FGC plate. Evolution of microstructures and textures as well as strain distribution after the cold rolling of FGC have been investigated by electron back scattered diffraction (EBSD) and scanning electron microscopy (SEM) as well as grain size determination. Deformed microstructure can be classified into five types according to the grain subdivision pattern and the characteristics of dislocation boundaries. On this ground, a correlation has been established between each type of deformed microstructure and grain orientations. Differences between simulation and complex pilgering in strain distribution examined.process. These observations confirmed that FEA simulations can form the basis of a rapid methodology for optimizing pilgering processes for complex FGC materials.

Key Words: Small modular reactor, functionally graded composite, rolling, finite element analysis

1. Introduction

Small Modular Reactors (SMRs) based on extensive naval experience has been rapidly developed in order to provide much higher safety and flexibility in tailoring capacity. Structural materials of liquid-metal cooled fast-neutron SMRs need to be improved to improve their corrosion resistance.

The deformation mechanism and the evolution of deformed microstructure in metals are extensively studied by a large variety of features. The formation of different deformation microstructure features is usually related with many metallurgical factors and deformation process factors [1], [2].

Hot rolling and cold rolling are some of the most important industrial processes to manufacture finished or semi-finished bulk products. The finishing stands of a strip mill are generally operated by the number of work rolls. The surface layer of these work rolls are subject to rapid changes of mechanical and thermal loads due to the cyclic contact with the hot/cold strip and the cooling water or oil with every revolution [3].

The extrusion process to produce components by pushing or drawing the material through a die of the desired cross-section. Various materials such as aluminum, polymers and steels can be used to manufacture extruded pieces. Hot extrusion is prior heating of billet to above its recrystallization temperature. Reducing strength and increasing ductility of the metal permits reduction of size and shape complexity more than before.

The hot rolling and hot extrusion processes have similar characteristics and procedures. Those processes can be classified as hot working. It refers to the process where metals are deformed above their recrystallization temperature and strain hardening does not occur.

In this paper, 3D computational analyses for elastic-plastic pilgering process on functionally graded composite (FGC) tube were conducted by using finite element modeling technique to describe the hybrid-layer plate. Furthermore, overlay welding on T91 plate specimen and rolling it into simulated FGC tube were done. Evolution of microstructures and textures during the cold rolling of FGC was investigated by electron back scattered diffraction (EBSD) and scanning electron microscopy (SEM). The results showed that deformed microstructure can be classified into five types according to the grain subdivision pattern and the characteristics of dislocation boundaries. Simultaneously, a correlation has been established between each type of deformed microstructure and grain orientations.

2. Modeling and Simulation

2.1 Selection of Composite Materials

Lim et al. proposed the Fe-Cr-Si alloy system as a high-temperature, corrosion-resistant material. From corrosion tests with a series of alloys based on the Fe-Cr-Si system, it has been 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 oxygen potentials above the formation potential for Cr and Si oxides) or by a low solubility surface region at low oxygen potentials. Experimental results obtained from model alloys after LBE exposure at 600°C 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 enhanced by the addition of Cr to the system.

Based on their extensive characterization study, they proposed the concept of an FGC consisting of two layers, a thin Fe-Cr-Si layer as a corrosion-resistant layer and F91—chosen for its strength and radiation resistance—as a structural layer. In addition, other ferritic/martensitic steels, like HT9 or Gr.92, can be selected for structural layer materials for various reactor applications. HT9 and Gr.92 have already showed good mechanical properties in a high-temperature sodium environment. Table 1 shows the chemical compositions of Fe-12Cr-2Si and F91 steels. For finite element analysis (FEA) of the plate, Fe-12Cr-2Si and F91 were selected as the corrosion-resistant layer and structural layers, respectively.

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

2.2 3D FEM Setting

For pilger process of plate, finite element method is conducted by ANSYS. Pilger process accompanies metal plasticity which requires large deformation and nonlinear material behavior analysis. When there are larger material reduction and faster operational speeds, ANSYS rigid dynamic models can be used with a fully or partially flexible model. Therefore, material nonlinearities by pilger process of plate can be analyzed with deformation, stress, strain by ANSYS finite element method.

Before pilger process simulation, it has to be configured material nonlinearities about Fe-12Cr-2si and T91 layers involved in plate. Pilger process needs physical, mechanical and thermal properties information [4]. Physical properties information means basically material density. Elastic information of the layers is applied by isotropic elasticity. There are Yong’s modulus and Poisson’s ratio. Through them it can be get modulus and shear modulus information. Tensile yield strength and tensile ultimate strength are used as plastic information. These values of Fe-12Cr-2si and T91 are shown on Table 1. However, structure steel data from ANSYS was used as the density and isotropic thermal properties. Since structure steel and T91 have similarity with structure materials. Also, chemical composition of T91 is similar with Fe-12Cr-2Si. But mechanical values of Fe-12Cr-2Si were measured through tensile test and values of T91 were taken by JMatPro 8.0, computational thermodynamic software. In pilger process, multilinear isotropic hardening rule is used. Fe-12Cr-2Si and T91 show plastic behavior of Fig. 3 and 4, respectively.

Table 2. Thermal and mechanical properties of Fe-12Cr-2Si and T91

Property	Fe-12Cr-2Si	T91
Density (g/cm^3)	7.75	7.75
Isotropic thermal expansion coefficient at 22 ℃ (1/℃)	$1.7*10^{-5}$	$1.7*10^{-5}$
Young’s modulus (GPa)	178	192
Poisson’s ratio	0.31	0.33
Bulk modulus (GPa)	157	188
Shear modulus (GPa)	68.1	72
Tensile yield strength (MPa)	698	312
Tensile ultimate strength (MPa)	799	468

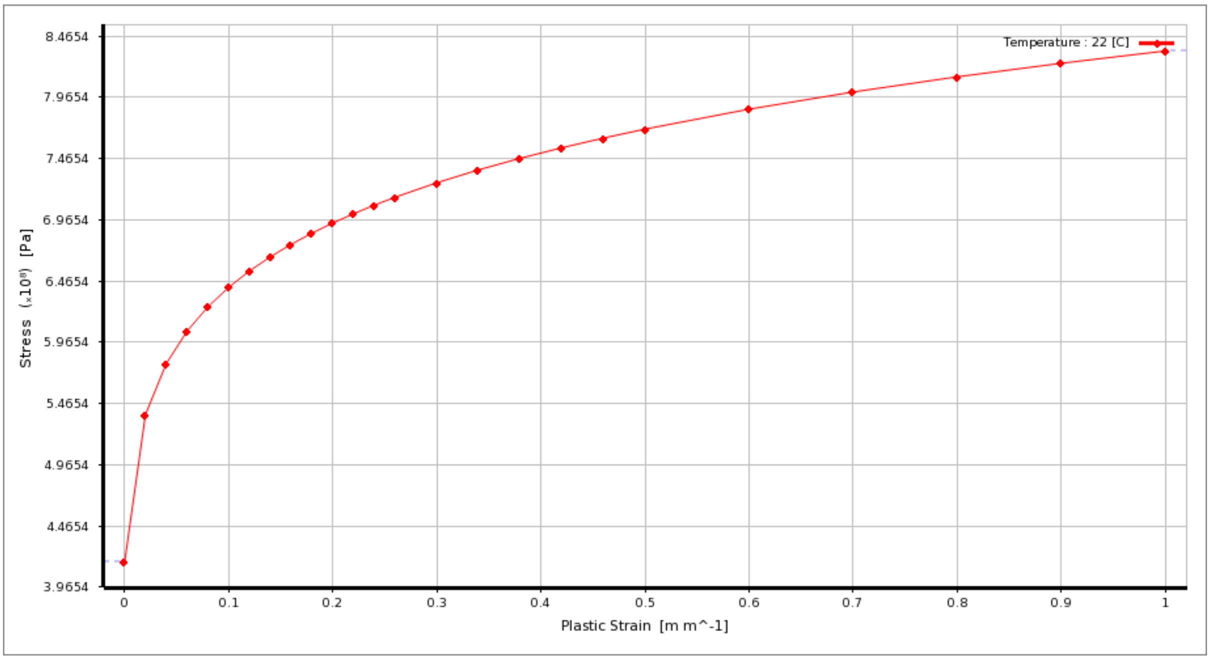

Fig 1. Hardening behavior of Fe-12Cr-2Si

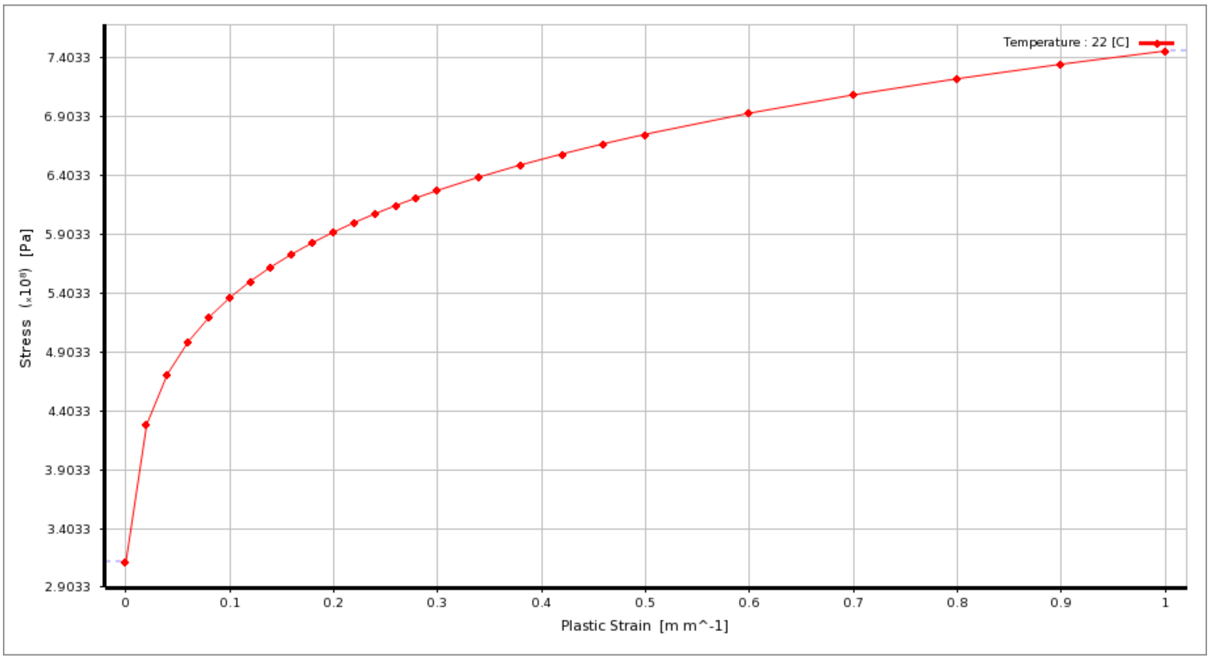

Fig 2. Hardening behavior of T91

2.3 Plate rolling

The composite design consists of an T91 base structural layer with a thin Fe-12Cr-2Si corrosion resistant barrier. The material is ASTM A213 T91 steel. The investigated T91 steel with the composition of Fe-8.38Cr-0.10C-0.35Si-0.50Mn-0.18V-0.09Nb-0.05N (wt.%) was prepared by plate specimen. The initial size of T91 plate specimen was 570 mm * 320 mm * 95.3 mm. Weld wire from the Fe-12Cr-2Si was weld overlaid on 15 mm the top/bottom of plate specimen. After the weld overlay procedure, plate specimen was separated the two of 570 mm * 160 mm * 125 mm specimen. Welding method is tig welding process. (A welding current of 50 ADC and a negative electrode were used with pure argon cover gas at a flow rate of 20 cubic feet per minute (CFM) with 20 seconds of post weld flow to avoid oxidation.)

These plates were then hot rolling into Test-bed at ~1200 ℃ which is located in Korea Institute of Materials Science (KIMS). Then the specimen was machined into the test bed for cold rolling after change the die for cold rolling. As the plate is rolled over by the dies, the cross sectional area of the tube is reduced and its length is increased. The ratio of the starting tube cross-sectional area to the final tube cross-sectional area is called the Elongation factor of the tube. This factor is used in the die design to determine the die groove profile decided by pass schedule. The reduction rate and Q factor are developed for rolling process. The reduction rate was widely varied from 51 % to 91 % and the Q-factor was varied from 1.0 to 3.8. In this case, it is set under the 60 % and near 1.5 value for the safety rolling process, respectively.

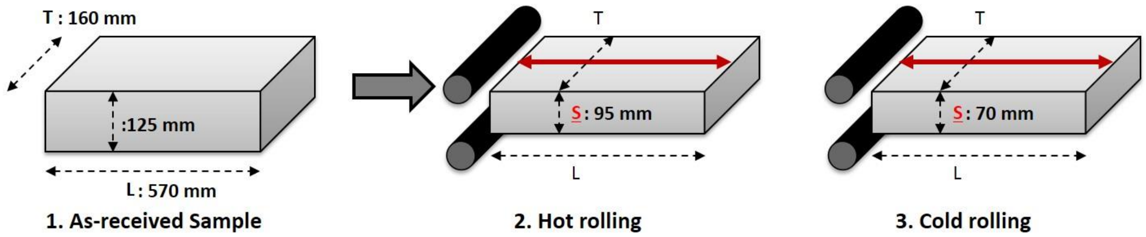

Fig. 3. Rolling process for hot/cold rolling

3. Results and discussion

3.1 Microstructure

Optical images for microstructures of plate specimen after the hot rolling and the cold rolling are shown in fig. 4. The results clearly show that the specimen after the hot rolling and cold rolling consists of fine equiaxed grains and a portion of elongated grains along with the rolling direction. From the fig.4, it is considered that fine equiaxed grains are martensite and the elongated grains parallel to the rolling direction are delta-ferrite phase and austenite phase in steel.

During rolling deformation, the evolution of microstructure is a comprehensive process of deformation, dynamic recrystallization and grain growth. Fine and coarse grains can be formed by dynamic recrystallization after sufficient accumulation of dislocations. Furthermore, the microstructure consists of lath martensite and delta ferrite are nucleated during the rolling process.

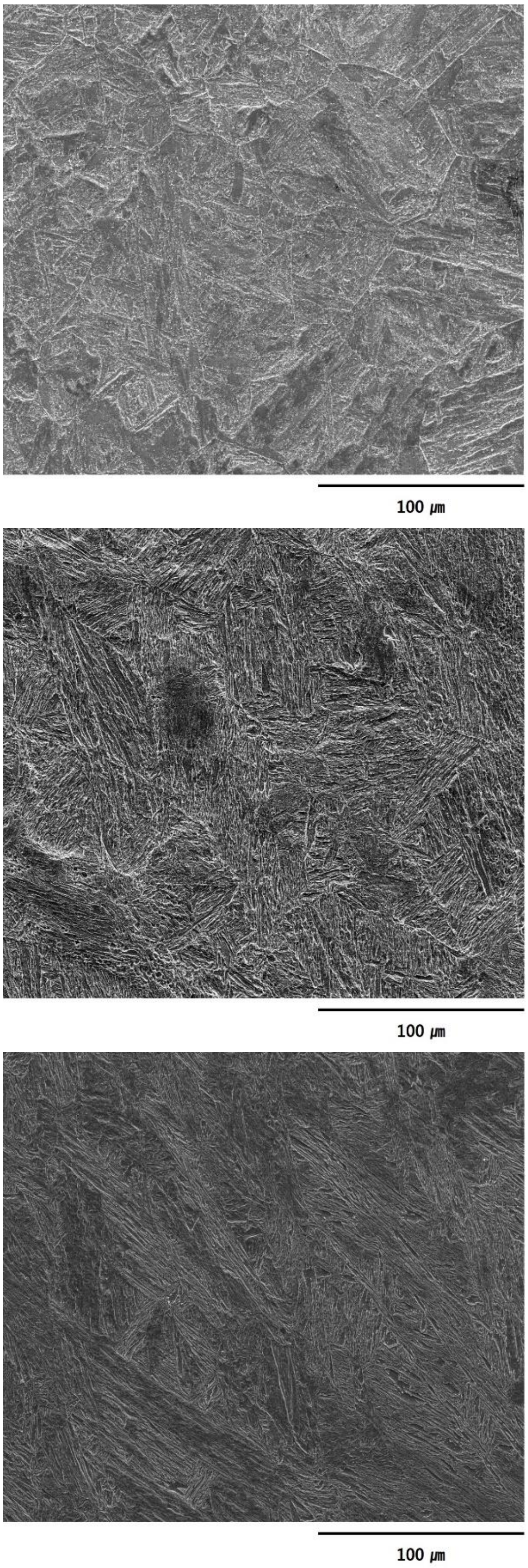

Fig 4. SEM micrographs of (a) as-received (b) hot-rolled and (c) cold rolled T91 with Fe-12Cr-2Si.

These differences of microstructure are effect of cross rolling. Cross rolling can affect the material properties in many ways [5]; possible effects on the material due to change in rolling directions are

i. Microstructural changes and changes in crystallographic texture

ii. Changes in plastic anisotropy

iii. Changes in residual stress distribution

In generally, shape of the grain depends on type of the solidification and the subsequent thermomechanical processes, which are lath martensite, delta ferrite, and austenite phase in steel.

Stresses remained in the solid material are called as residual stress. Residual stress caused by thermal load is normally called as thermal stress. During hot rolling, the material is subjected to both the types of loading; and due to the non-uniformity in deformation and presence of temperature gradients; the residual stress distribution in the material after rolling is not uniform. Residual stress may distort the shape of the rolled material and it also has significant effect on further processes of the product.

As a result of rolling, searches for crack and split of specimen have not resulted in any significant finds on the surface and microstructure.

3.2 Simulation result

Optical microstructures of plate specimen after the hot rolling and the cold rolling are shown in fig. 4. The results clearly show that the specimen after the hot rolling and cold rolling consists of fine equiaxed grains and a portion of elongated grains along with the rolling

Fig. 5 shows hot rolling process. Maximum stress appears at contact regions of Fe-1 2Cr-2Si. From fig. 6, stress distribution of Fe-12Cr-2Si shows uniform deformation and generation of stress is starting from contact region and maximum stress is applied at end point of contact region. After end point, any more force does not act on plate from dies . However, reduced plates have residual stress. In fig. 7EEE, stress distribution at T91 is similar with Fe-12Cr-2Si and residual stress of reduced T91 plate is lower than that of reduced Fe-12Cr-2Si plates. This hot rolling process results do not consider thermal treat ment. It can be expected that there are relieved stress results.

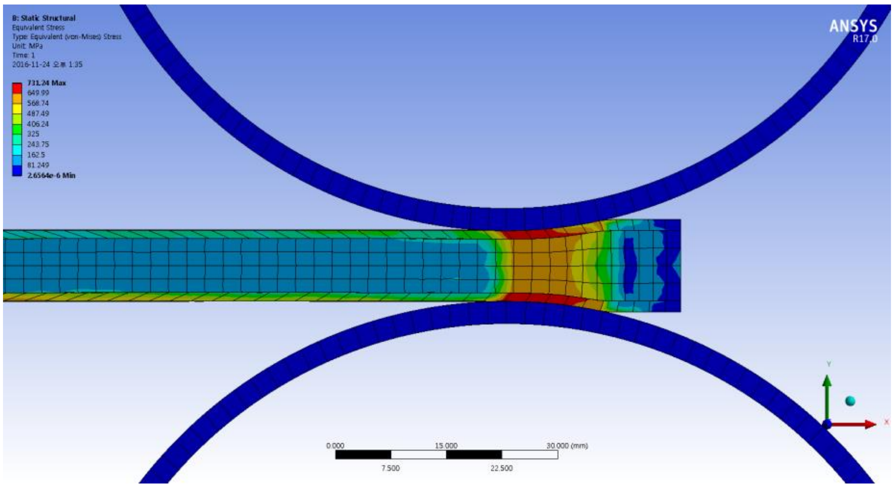

Fig 5. von-Mises stress analysis of hot rolling process

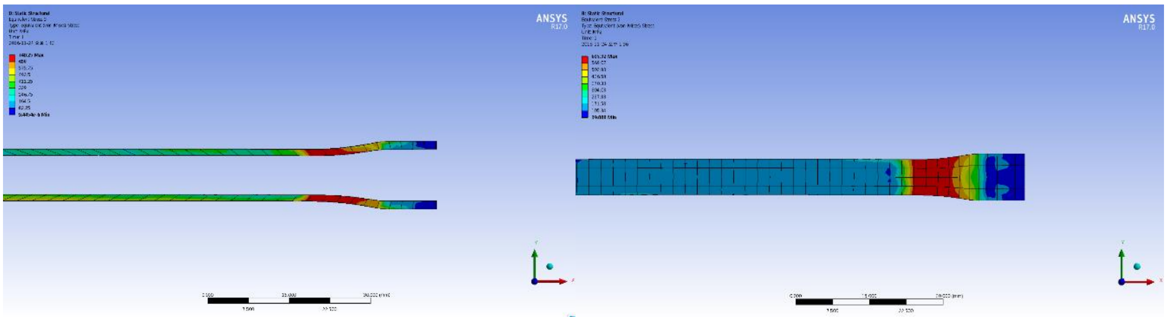

Fig. 6. von-Mises stress analysis of Fe-12Cr-2Si and T91 after hot rolling process

Fig. 6 shows maximum von Mises stress by time. After 0.2 s, uniform deformation is started. At the same time, the stress maintain almost constant values. The simulation analysis shows well conversed results.

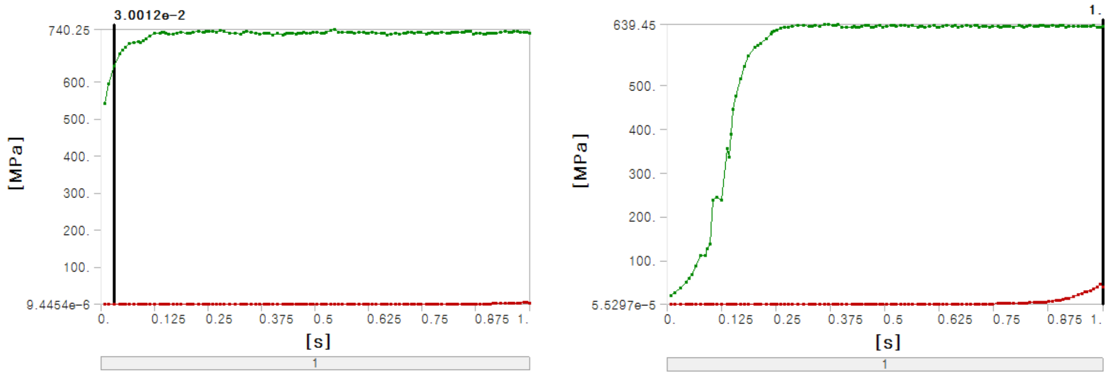

Fig. 7. maximum stress plots of Fe-12Cr-2Si and T91 at hot rolling process

Cold rolling process results show similar with tendency of hot rolling process results. From the stress distribution of Fe-12Cr-2Si shows uniform deformation and generation of stress is starting from contact region and maximum stress is applied at end point of contact region. After end point, any more force does not act on plate from dies. However, reduced plates have residual stress. But residual stress of cold rolling process do not consider thermal effect. Therefore, residual stress may be remained.

Fig. 7 shows maximum von Mises stress by time. The uniform deformation is started. At the same time, the stress maintain almost constant values. The maximum stress of Fe-12Cr-2Si and T91 at contact region are MPa and MPa. The simulation analysis shows well conversed results.

From comparison stress between Fe-12Cr-2Si and T91 at fig. 7, Fe-12Cr-2Si is exposed to more high stress. Outside layer experiences large deformation and strain of change. Moreover, Fe-12Cr-2Si has more hardness resulting in high stress. So, pilger process o f double layer should consider sensitivity of Fe-12Cr-2Si layer. And the stress distributio n of Fe-12Cr-2Si layer turns to un-pilger region on T91. This phenomenon is occurred when there is large frictional constant or large radius of die [3].

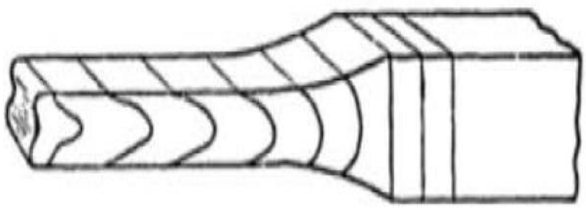

Fig. 8. The flow of metal during rolling [3]

Therefore, it can be controled friction and size of die. There is relationship between frictional coefficient and size of die. If it neglect forward and backward tension on plate, equation 1 is established to avoid metal flow.

$$\mu_m = \sqrt{\frac{t*r}{2D}} \quad (1)$$

μ_m is frictional coefficient between plate and die. t is initial thickness of plate and r is reduction ratio. D is diameter of die. From this equation, if right hand side is bigger than left side hand, flow of metal forms convex line. Therefore, it should be reduced fri ctional coefficient or enlarge diameter of die of this model. Frictional coefficient can be controlled by lubricant, and then size of die for model is followed.

At T91, stress flow is relatively uniform and slightly convex. Convex region ranges i n start point of contact. This means that pilger process of T91 work nicely. Convex regi on is just resulted from overlay-welding with Fe-12Cr-2Si.

At cold pilger process, it can be observed similar stress distribution. But, this calcula tion does not consider residual stress by generating previous pilger process. Residual stre ss expects to make more severe metal flow. Therefor it should be tried to control neutral metal flow.

4. Conclusion

In this study, as-received Gr.92 and irradiated Gr.92 specimen in the oxygen-saturate d liquid sodium were

In this study, order to understand the behavior of work rolls during of hot rolling,col d rolling for microstructure and simulation under service conditions have been examined in detail. The following conclusions can be made:

i. Ausforming or austenitizing of T91 steels at hot rolling condition and greater produces primarily martensite. These transformed martensites coupled with auto-tempering leads to materials with good ductility.

ii. It was confirmed that a microstructure change occurred by generating PAGB while performing rolling.

iii. As a result of simulation, it was confirmed that the cracking did not occur in the rolling process, and the cracking did not occur in the actual process.

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