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Analysis of Zircaloy-4 tube deformation during the cold tube pilgering process

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1. Introduction

In light water reactor(LWR), zirconium alloys which have low thermal neutron absorption cross section have been used broadly. However, when Loss Of Coolant Accident(LOCA) at nuclear power plant is occurred such as the Fukushima Daiichi melt down in 2011, the zirconium cladding reacts with high temperature steam and produces vast amounts of hydrogen, which can lead to explosions and the release of radioactive materials into the environment. To solve this problem, a cladding material which has high oxidation resistivity and low hydrogen generation is required although fuel cladding temperature are rising at LOCA.

In order to avoid these problems in LWRs going forward, we aim to develop a multi-metallic layered composite (MMLC) which compromises between the neutronic advantages of zirconium alloys and the accident-tolerance. A schematic diagram of our MMLC cladding concept is shown in Fig. 1.

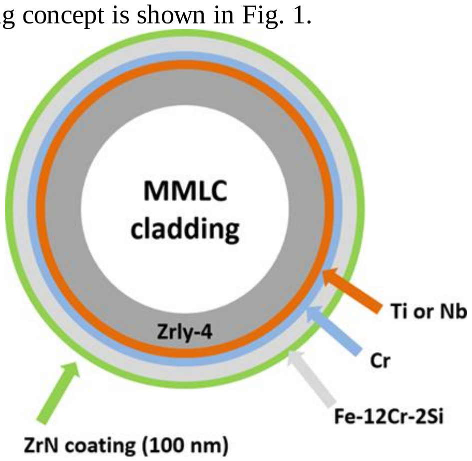

Fig. 1. Description of MMLC cladding cross-section

The layers of the proposed MMLC are designed to perform specific functions unattainable by single alloys. Fuel cladding composed of a iron-based alloy, overlaid onto a Zircaloy base, could reduce the amount of Zr in the reactor, resulting in less hydrogen evolution during a severe accident. In addition, a MMLC cladding will be less susceptible to sudden, brittle failure of fuel cladding due to directional hydride formation in Zircaloys. Finally, the water-facing layer of Fe-12Cr-2Si layer will resist severe accident corrosion better than Zircaloys. Diffusion barrier layers of Cr(or Cr+Mo) and Ti(or Nb) must be used in between Zr and an iron-based alloy, to avoid detrimental eutectic phase or intermetallic formation [1].

For cladding size, outer diameter and thickness of the MMLC tube need to be reduced by hot extrusion process and cold pilgering process. The cold pilgering process involves repeated rolling through grooved conical shaped rolls and over a moving mandrel which maintains the desired size. A pair of grooved rolls and a mandrel are used to reduce both the wall thickness and the diameter of the mother tubes. The cold pilgering processed tube has advantages that close-dimensional tolerances and very high reductions in both wall thickness and tube diameter are possible. Moreover, superior surface finish and better metal surgical control with high quality are possible. High reduction can reduce the step for manufacturing and eventually lead to reduction in manufacturing coasts.

However, multi-layers of the MMLC tube expect to occur different deformation processes because they have different mechanical properties. Distortion of the joint will make crack at interface and then reduce the utilization of products. To improve utilization of cold pilgering process, we should evaluate the process in terms of stress distribution and morphology of each layer [1], [2].

Before analysis of MMLC tube deformation, comparison analysis of pilgering process of Zircaloy-4 tube is conducted. In this paper, using materials data for Zircaloy-4 alloys, 3-dimensional computational analyses tube have been made using a finite element modeling technique to describe that. And, this analysis will consider behavior of rolls like stroke rate and feed rate because pilgering process has a lot of manufacturing factors.

2. Modeling and Simulation

Pilger process accompanies metal plasticity which requires large deformation and nonlinear material behavior analysis. Therefore, finite element method by using ABAQUS is conducted for calculation of stress distribution. Material nonlinearities by pilger process of tube can be analyzed with deformation, stress, strain by finite element method.

Before pilger process simulation, it should be configured material nonlinearities about Zircaloy-4 alloy. Pilger process needs physical, mechanical and thermal properties information [3]. Physical properties information means basically material density. Elastic information of the layers is applied by isotropic elasticity. There are Young's modulus and Poisson's ratio. And tensile yield strength and tensile ultimate strength are used plastic information [4]. This values of Zircaloy-4 shown at Table 1. Also, flow stress plot is described in Fig.2.

Table I: Thermal and mechanical properties of Zircaloy-4

	Value
Density (g/cm3)	6.56
Young's modulus (GPa)	99.3
Poisson's ratio	0.37
Yield strength (MPa)	661
Compressive strength (MPa)	1990

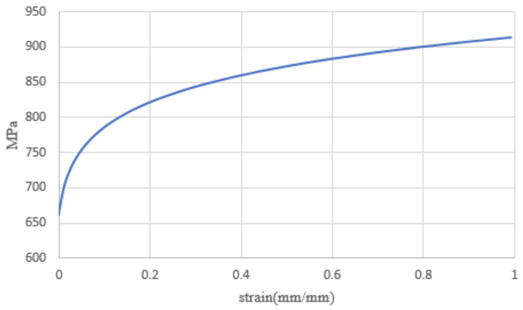

Fig. 2. Flow stress of Zircaloy-4

Fig. 3. Pilgering simulation model

After setting the properties, the pilgering process tube model is made [5]. Outside diameter of tube is 50 mm. Thickness is 3.7 mm. And pilgering tool is used with VMR 50. The grooves of VMR pilger mill tooling have a cross-section. With each cycle, the die does a half rotation. Mandrel has concave shape according to die grooves. There are reduction session and sizing section in mandrel. At reduction section, diameter and thickness of tube is reduced. Sizing section normalizes the dimensions from oval shape of tube. Therefore, reduction and sizing section are located inlet and outlet position, respectively.

The simulation will reduce the outside diameter and thickness to 38 mm and 2 mm. After completion of geometry model, explicit analysis is used for large deformation solution. From the analysis results, we can recognize possibility of pilger process and develop optimized safe process through sensitivity of process parameter.

For running simulation, contact conditions of tube surfaces and pilgering tool is set with frictional type. Conventional frictional coefficient is 0.1-0.4 and this value is changed by lubricant and pilger process cycle rate. To form conservative condition, the frictional is chosen with 0.1. Next, motion of die is controlled by boundary condition. Therefore, die can rotate and translate over the tube.

3. Results and Discussion

Table II. shows case type by stroke rate and feed rate. The stroke rate and feed rate is maximum and minimum rate used for conventional pilgering process at VMR 50. By this case study, optimization rate can be deducted.

Table II: Case type by stroke and feed rate for simulation

Stroke rate (stroke #/min)	Feed rate (mm/ stroke)	Type
190	9	Case1
75	9	Case2
190	3	Case3
75	3	Case4

From the results of case studies, we can estimate dimension quality of deformed Zircaloy-4 tube. Most of case reach target dimension. Also, eccentricity shows low value. This means the simulation is conducted correctly. Although there are a few of difference, the difference is small when comparing with total dimension change. To increase reliability of this simulations, the dimension value will be compared with actual value of pilgering processed Zircaloy-4 tube.

Table III: OD, WT and Eccentricity by case studies

Type	OD (mm)	WT (mm)	Eccentricity
Case1	38.1	2.53	0.15
Case2	39.0	2.06	0.24
Case3	38.1	2.10	0.22
Case4	38.5	2.04	0.16

At stress analysis, maximum stress appears at contact regions of die. Fig. 4 shows absolute value of maximum compressive principal stress and the stress distribution figure by ABAQUS GUA. The severe region by compressive stress is 100-300 mm region of mandrel with axis direction. The region shows over 2000 MPa at case 1, 2 and 4. This means that the Zircaloy-4 tube can have crack at contact region.

Specially, high feed rate case shows more severe compressive stress condition. High feed rate can causes more reduction every stroke of die, so more compressive stress may be applied. Although compressive stress is equal or small than 2000 MPa at low feed rate case, Case3 shows 2100-2200 MPa at 100 and 300 mm position. It is considered that low stroke rate die can deform the tube during enough time. So, the high deformation is reflected at the high stress. Similarly, at high feed rate case, case1 shows low compressive stress at 100 mm position. Synthetically, low feed rate is useful to get high quality tube by pilgering process. Nevertheless, because productivity of cladding can decrease, we have find stable high feed rate. And stroke rate should be fast plenarily. However, considering the impact by fast die movement, high stroke rate is unconditionally correct. Next analysis will consider the impact.

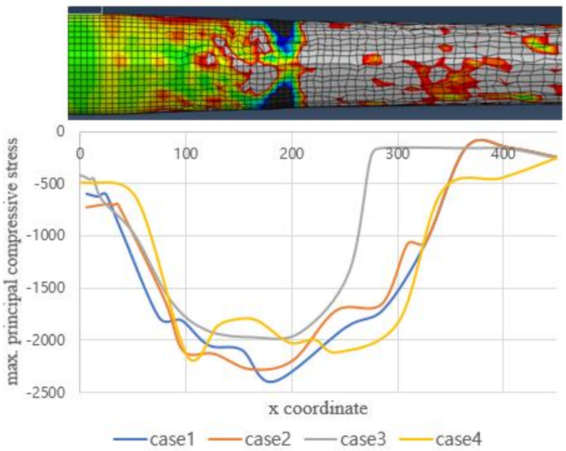

Fig. 4. Maximum principal compressive stress of Zircaloy-4 tube at case1-4

4. Conclusion

In this paper, pilgering process simulation of Zircaloy-4 tube is analyzed before starting simulation of MMLC cladding tube. As the result of case study by using conventional stroke and feed rate at VMR 125 pilgering machine, the dimension change reach target dimension. The difference is small to assure simulation results. And the stress analysis, maximum principal compressive stress is observed at high curvature region of mandrel. Even so, low feed rate case shows low maximum principal compressive stress at same region because low deformation. Moreover, high stroke rate case has lowest stress value. Therefore, high feed and low stroke rate is useful to get high quality tube by pilgering process.

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