Study on Q-value in Finite Element Analysis of Pilgering Process of Accident Tolerance Fuel Cladding

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1. Introduction

In a reactor filled with high temperature steam when the loss of coolant, zirconium alloys generate hydrogen from the oxidation reaction and expose the reactor to explosion hazards. Accident resistant fuel cladding is a cladding which suppresses the generation of hydrogen by reducing the oxidation reaction with high temperature steam. One of them is a cladding having a multi-metal composite layer structure in which accident-resistant metal is placed on a zirconium alloy [1]. However, during the pilgering process, which reduces the tube diameter to produce the cladding, the multiple layer structure can cause delamination problems. The above problem should be solved by the Q factor related to the crack generation in the pilgering process. In this paper, optimized process parameters are derived to improve productivity of cladding by analyzing various Q values through finite element analysis.

2. Factors for pilgering process

In this section some of the parameters used to model a dimension of tube during pilgering process are described. The main parameters include Q value and reduction rate.

2.1 Q value

In order to increase the production rate or decrease the failure rate, the pilgering process must consider various process parameters such as the dimensions of the equipment and the schedule of the process. Those include the behavior of the equipment, the method of inserting the tube, the material characteristics and the heat treatment method as well as the equipment type. The Q value is one of the most important parameters in the pilgering process, which is the ratio of the reduction of the outer diameter of the tube to the reduction of the thickness [2-4]. Q value can be expressed by equation (1). This serves as a factor for the deformation of the tube outer diameter and inner diameter.

$$Q\ value = \frac{ln\left(\frac{OD_{final}}{OD_{initial}}\right)}{ln\left(\frac{t_{final}}{t_{initial}}\right)} \qquad (1)$$

It is known that cracks at inner or outer surface of the cladding can grow according to the value of Q value. Empirically, cracks are generated in the inner surface when it is smaller than 1, and cracks occur in the outer surface when it is too large. The inner surface of the cladding tube was wrinkled vertically in the circumferential direction just before the inner crack occurred. However, tubes have a cracked surface such as bamboo when the outer crack occurred like figure 1. H. Abe describes that the cross section of the tube was divided into groove parts directly contacted with the die and the flange part not contacted with die as shown in Fig. 2 [5]. And the parts were evaluated by Furugen's plastic deformation model. For a tube with a low Q-value, the tube undergoes constant compression in the circumferential direction during the pilgering process, causing wrinkles and crack growth, whereas at high Q-values crack growth was mitigated by tensile stress at groove parts despite of compressive stress on flange parts.

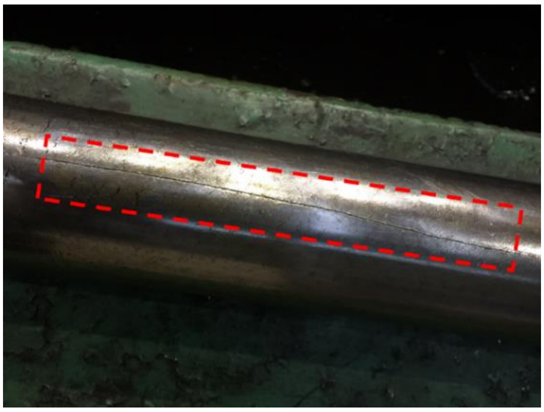

Fig. 1. Micro-crack on outer surface after pilgering process.

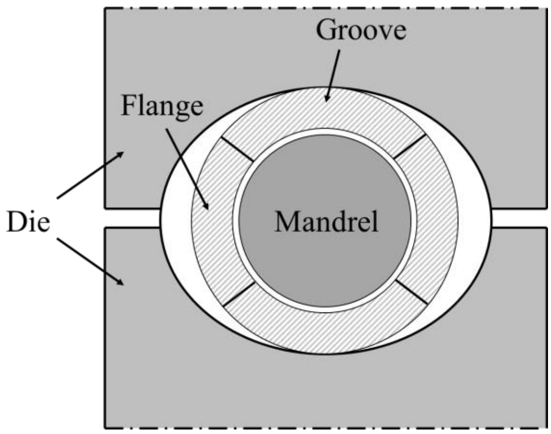

Fig. 2. Cross-section of pilgering tool.

The MMLC cladding is based on zirconium alloys, but the different behavior of various metal layers cause problems at interface of each layer if conventional Q values are applied. In this paper, various Q-values are applied to the analysis of the pilgering process to evaluate crack growth by calculating the strain of the MMLC tube.

2.2 Reduction rate

The thickness reduction rate is measured as the change in the cross-sectional area of the tube as shown in equation (2) [4]. When the reduction rate is high, the pilgering process is carried out in small steps to reach the target cladding dimensions. Moreover, the uniformity, microstructure, structural properties, mechanical properties, and surface condition of the tube are improved. However, if it is too high, the tubes may be broken during the process.

$$Reduction\ rate(\%) = \frac{Area_{in} - Area_{out}}{Area_{in}} \quad (2)$$

$Area_{in}$ and $Area_{out}$ are cross section area of entering and leaving tube at pilgering machine, respectively.

3. Simulation model

3.1 Model design

The ABAQUS 6.19 analysis program is suitable for analyzing very large deformation and nonlinear material behaviors such as the pilgering process. In order to improve the accuracy of the analysis, it is necessary to apply the information of the material properties and components of the pilgering process. In this analysis, the MMLC tube was composed of three layers of FeCrSi alloy, pure Cr, and Zircaloy-4. Table 1 shows the physical properties of each material in the MMLC cladding. For the analysis, the material density should be considered as a factor affecting the collision and large deformation analysis, and other elastic modulus, Poisson's ratio, and true stress of each material are applied. Zircaloy-4 was calculated considering the anisotropy. And isotropic hardening model is applied. The yield strength and the maximum tensile strength are not directly addressed in the analytical calculation. However, those values are applied to the evaluation of whether the stable plastic behavior has progressed through the obtained analysis results.

Table I: Material properties of MMLC components

Material	FeCrSi	Cr	Zrly-4
Density (g/cm^3)	7.76	7.19	6.56
Elastic modulus (GPa)	179	250	99.3
Poisson ratio	0.33	0.21	0.37
Tensile yielding strength (MPa)	698	247	645
Ultimate tensile strength (MPa)	799	419	786

The pilgering model consists of mandrel and die for rigid part and MMLC tube for plastic deformation. The mandrel and die were created with regional mesh part only in direct contact with MMLC tube like Fig. 3 so that the efficiency of analysis is increased. Change of tube diameter and thickness of MMLC tube is shown in Table 2 according to the Q-value. The tube cross-sectional area reduction is fixed at 58% which is based on commercialized pilgering tool for Zirconium cladding. Thickness of Fe-Cr-Si, Cr, Zircaloy-4 are 0.649, 0.649 and 2.402, respectively.

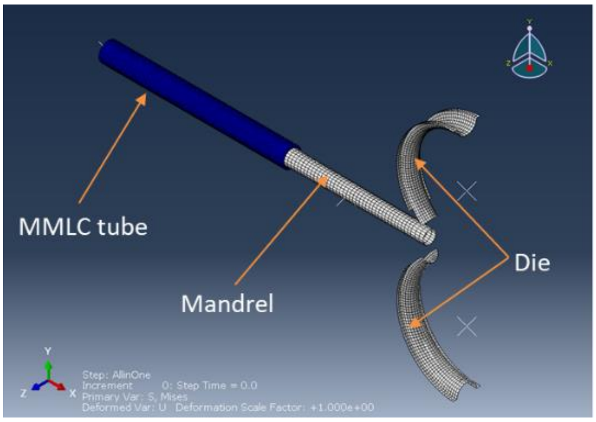

Fig.3. Finite element analysis model for pilgering process.

Table II: Schedule of pilgering process

	Before pilgering	After pilgering	Q-value
A	50Ø × 3.7t	38Ø × 2.00t	2.2
B		42Ø × 1.79t	4.2

In the case of mandrel and die, the 'discrete rigid body' condition was applied assuming that there is no deformation in the part characteristic. The size of the element was 3.7 mm in consideration of efficiency and the curvature of the die grooves. The frictional force acting between the die / mandrel and the tube was 0.1. During the pilgering simulation, dies have translation and rotation movement on the mandrel as contacting with inserting tube. Stroke rate of dies is 190 # stroke/min. And feed rate of tube is 9 mm/stroke. As being fed, the tube will rotate with 90° along z-axis in Fig. 3.

4. Simulation analysis

4.1 Strain analysis

As mentioned earlier, the main cause of the cracks in the pilgering process is the strong compression in the circumferential direction. In order to evaluate the safety of the process, it is necessary to carry out the analysis in the place where the compression is greatest. Fig. 5 shows the circumferential stress applied according to the position of the mandrel. The flange part showed the greatest compressive force around 320 mm, and the groove part showed the greatest compressive force around 194 mm. Both parts have almost the same stress value. In this analysis, strain analysis was carried out at 194 mm, in which the stress value was high in the vulnerable groove part by directly touching the die.

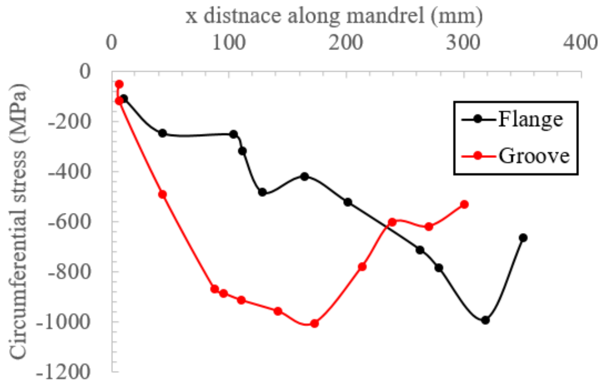

Fig. 4. Distribution of circumferential stress along mandrel at Q=2.2.

The results of the strain calculation in the circumferential and radial directions are shown in Fig. 4. In the flange part, the strain was decreased radially and circumferentially as a whole. On the other hand, in the groove part, the strain in the radial direction increases at the beginning and decreases. This tendency of strain was confirmed by the fact that the die was increased while pushing the tube and decreased after passing. The strain in the circumferential direction tends to change from compression to tensile as Q-value increases. Although the strain is small, when the Q-value is less than 2.2, there is a risk of crack growth if sustained pressure is applied. However, in 4.2, compression and tensile are repeatedly applied to strain, which may reduce crack growth.

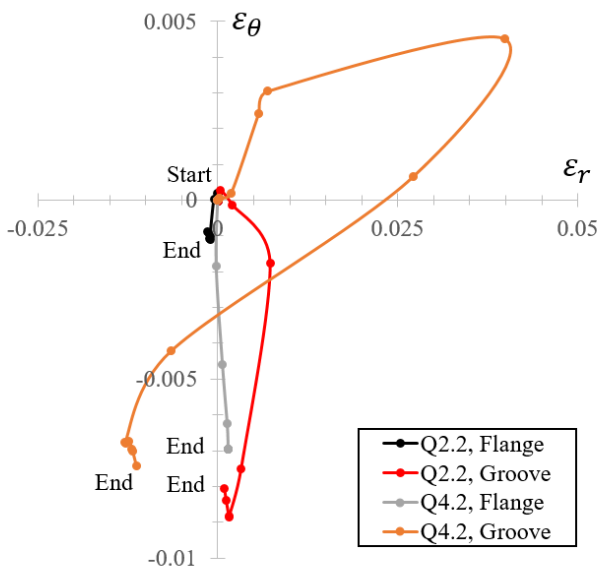

Fig. 5. Distribution of circumferential and radial strain on 194 mm of mandrel at Q=2.2 and 4.2.

The present interpretation reflects the strain of the whole tube and the influence of the thickness of the layer on the generation of cracks by reflecting the strain on each layer in the future will be analyzed not only for the optimum schedule in the pilgering process of the MMLC cladding, we will derive the appropriate thickness in future work.

5. Conclusions

In this paper, the finite element analysis of the multi-metal composite cladding was discussed. The strain was calculated in the circumferential and radial directions with different Q-factor values. For the strain, the strain was calculated at the region where the groove of the tube sensitive to the crack was subjected to the greatest compressive force. In the flange part, both circumferential and radial directions were small but compressed. On the other hand, the groove part showed a tendency to increase and decrease in the radial direction, but the circumferential direction was changed from compression to tensile as the Q-value increased from 2.2 to 4.2. Therefore, it would be advantageous to reduce the crack growth by increasing the Q-value so that the strain is not continuously compressed.

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