TENSILE BEHAVIOR MODELING OF THE 15-15Ti CLAD USING FINITE ELEMENT METHOD

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The paper presents a finite element analysis performed in order to determine the tensile behavior of 15-15Ti alloy, material proposed for use in lead fast reactors for fuel pin claddings. The finite element model was developed using experimental test data and Ramberg-Osgood type stress-strain curve. The main test materials were 24% and 46% cold worked fuel cladding tubes. The study involves modelling of ring tensile tests for 15-15Ti clad, in order to predict stress-strain distribution at different temperatures. The approach proposed could be applied to preliminary estimate the mechanical properties of different materials used in lead fast reactor structures.

Keywords: 15-15Ti clad, ring tensile test, finite element modeling, stress-strain distribution

1. Introduction

Fuel cladding integrity is one of the most important aspects to be evaluated in terms of safety performance of the present and future nuclear fuel concepts.

There are several testing techniques and evaluation methodologies to be carried out for the assessment of material performance and mechanical properties of fuel cladding tubes [1].

Tensile testing still remains the most widely method used for understanding the mechanical behavior of materials and is routinely conducted to obtain stress-strain data. Stress-strain data in tensile tests are typically recorded up to the maximum force point, corresponding to the ultimate tensile strenght (UTS). The constitutive behavior beyond the UTS is assumed in the models typically

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used in finite element (FE) programs. The finite element method is a numerical technique used to perform finite element analysis of any given physical phenomen. The Finite Element Analyses (FEA) is useful for problems with complicated geometries, loadings and material properties where analytical solution can not be obtained [2].

Tensile testing gives information about the mechanical properties of materials, including the modulus of elasticity, yield strength, tensile strength, elongation, and the stress–strain curve. Therefore, it is important to understand the mechanical and metallurgical phenomena occurring during the tensile testing of materials [3].

RATEN ICN Pitesti (Technologies for Nuclear Energy State Owned Company, Institute for Nuclear Research) performed ring tension tests on the 15-15Ti specimens, with the purpose to determine material properties in the hoop direction of a tube. The hoop direction properties are needed for tubular structural components which are known to have anisotropic mechanical properties due to the fabrication process [1].

The aim of the present study was to investigated the 15-15Ti mechanical behavior using ANSYS finite element software [4]. The developed model includes true data obtained from tensile tests results and Ramberg-Osgood equation to describe the stress-strain curve of the studied material. Ramberg-Osgood law provides an empirical, nonlinear strain-stress relationship and it is usually used in computer programs to describe the behavior of different materials, such as: stainless steel, cold-formed steel, aluminum alloys [5].

Thus, in this paper, ANSYS simulations were carried out for 15-15Ti clad specimens with different cold working rates, at various temperatures. Also, a study regarding the influence of the friction coefficient on mechanical properties has been performed.

The results are obtained based on the Ramberg-Osgood model and the asymptotic law (fitted on the true values obtained from experimental data).

2. Material and methodology description

The material analysed in this study was 15-15Ti austenitic steel and the specimens were obtained from 15-15Ti fuel cladding tubes, with 24% and 46% cold work rates and an outer diameter of 6.55 mm with a nominal wall thickness of 0.45 mm [1]. The tested specimens were processed with two symetrically distributed narrowing sections, as it can be seen in Fig. 1.

The tensile test was performed by applying a tensile force to the inside of the ring. The main shortcomings of the test are the bending deformation due to specimen curvilinear shape and the impact of friction between inserts and test material. The radial displacement is induced by a moving a plug into halfcylinders and friction is therefore an issue. The tensile tests were performed at 500ºC and 600ºC with a slow deformation rate about 0.017 mm/s [1].

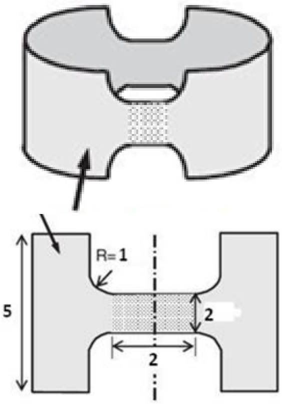

Fig. 1. Ring specimen used for tensile tests [1]

The most relevant mechanical characteristics obtained from the material curve are [6]:

Tensile strength (R_m), defined as the maximum load, F_m divided by the initial area of the cross section, S_0.

$$R_m = \frac{F_m}{S_0} \tag{1}$$

Strain, ε, defined as the elongation at breaking point expressed as a percentage of its original length:

$$\varepsilon = \frac{\Delta L}{L_0} \cdot 100 \tag{2}$$

Yield strenght $\sigma_{0.2\%}$ is defined as the stress associated with a plastic strain of 0.2%.

In general, the data obtained from the tensile tests represent engineering data. While the engineering stress-strain curve is ideal for performance application, the true stress-strain curve is ideal for material properties analysis. Therefore, in our simulation we use the true strain–stress curve, obtained as follows [7]:

$$\sigma_{true}(Total) = \sigma_{engineering} \cdot (1 + \varepsilon_{engineering}) \tag{3}$$

$$\varepsilon_{true}(Total) = \ln(1 + \varepsilon_{engineering}) \tag{4}$$

The difference between the engineering and true values increases with plastic deformation. Also, the above equations are only valid before necking occurs.

After obtaining the true stress-strain curve, an asymptotic function was used and the fitting parameters can be observed in Table 1:

$$y = a - b \cdot c^{x} \tag{5}$$

Table 1

Fitting parameters used in equation (5)

Specimen	Parameters		
	a	b	c
24%CW 500ºC	620.6739	168.63644	0.0365
24%CW600 ºC	606.53333	139.95132	0.1701
46%CW500 ºC	702.24804	194.8567	0.1100
46%CW600 ºC	686.42584	242.35746	0.2047

Ramberg-Osgood law is usually used in computer programs to describe the behavior of different materials [5]:

$$\tilde{\varepsilon} = \frac{\tilde{\sigma}}{E} + \left(\frac{\tilde{\sigma}}{H}\right)^{\frac{1}{n}} \tag{6}$$

where: $\tilde{\varepsilon}$ is the total true strain, E is the young modulus, H is the strength coefficient and n represent the strain hardening exponent, $\tilde{\sigma}$ represents the true stress.

$$H = \frac{S_y}{\tilde{\varepsilon}_{yp}^{\,n}} \text{ and } n = 3.93 \cdot \left\{ \ln\left(\frac{S_u}{S_y}\right) \right\}^{-0.754}, \ \varepsilon_{yp=0.002}$$

The R-O type stress-strain curve can be estimated using only the yield (S_y) and ultimate strenghts (S_u).

Stress-strain curves are depicted in Fig. 2, where a comparison between tensile test data and the values obtained with the R-O model and the asymptotic law is provided.

When applying FEA, the domain of the analysed physical system, is meshed in finite subdomains, the real system is replaced with a network of so-called finite elements. The differential equations that describe the system behavior will be verified for each element. The mathematical construction of the finite elements ensures a certain degree of approximation continuity at crossing of the boundary between the elements. Continuity is realised using remarkable points associated with the elements (known as nodes). In fact, the approximation of the exact solution problem results as a function of the unknown values in the respective nodes [7].

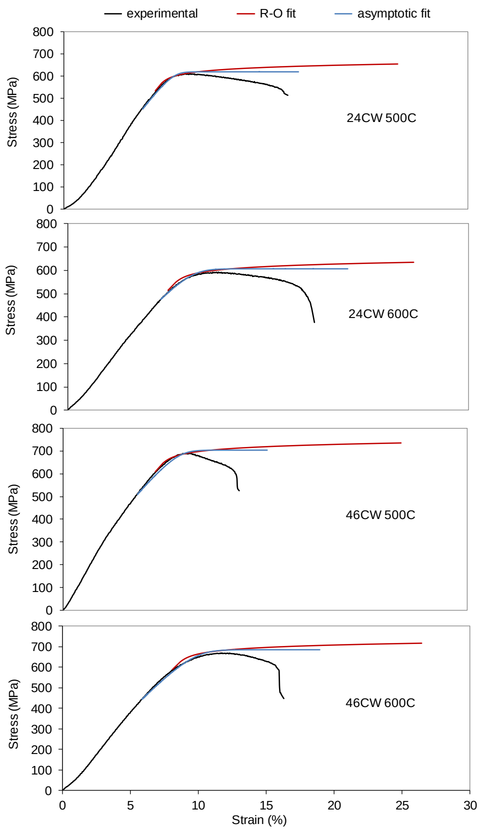

Fig. 2. Stress-strain curves at different temperatures and various cold work rates

Due to the symmetry reasons and to avoid long calculation time, we modelled only an eighth of the specimen, as it can be seen in Fig. 3, resulting thus 3792 elements and 19704 nodes, Fig. 4 . The model designed to simulate only an eighth of the specimen should produce similar results with the situation when the entire specimen is considered (called a full analysis model).

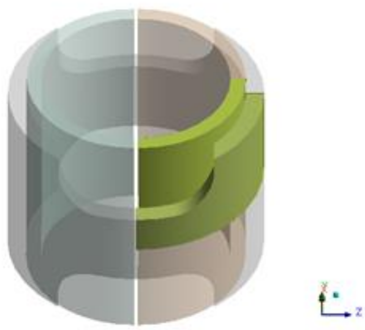

Fig. 3. Geometric modeling

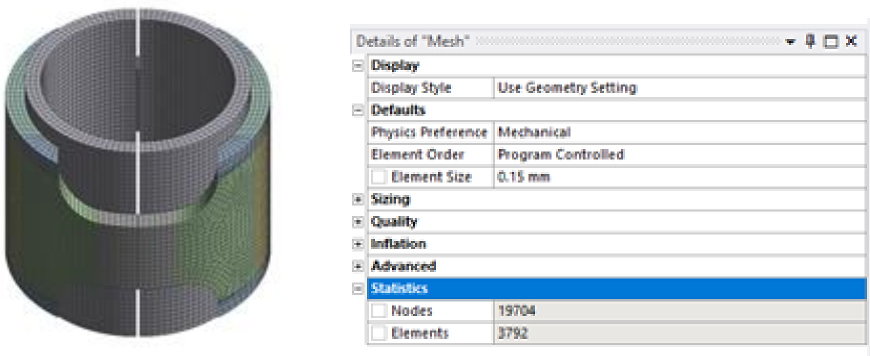

Fig. 4. Ring specimen discretization

The next step in creating our model was to apply the boundary conditions and set the contacts between specimen and the cylinders of the ring tension device. Initially, no friction between cylinders and the specimen was considered, therefore the contact between the ring and the testing device is assumed to be perfect.

3. Results and discussions

In this section, the ANSYS simulation results are discussed, for various temperatures and different cold work rates.

The results are extracted at the last time step, associated with a directional displacement of the cylinder equal to 0.2 mm. The main outcomes of the present study refer to equivalent stresses (Von Misses) and equivalent plastic strains. The predicted stresses and strains are obtained based on the Ramberg-Osgood model and the asymptotic law, for various specimens with different cold work rates, as follow: 24%CW respectively 46%CW.

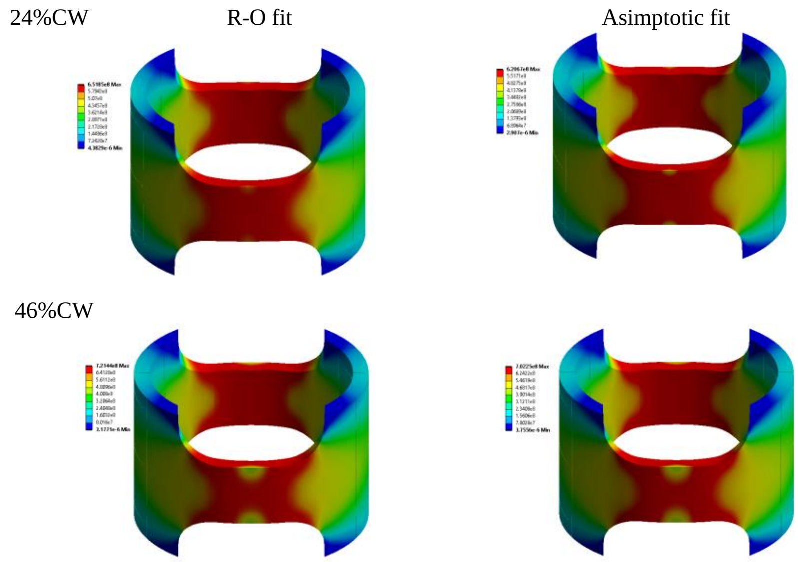

Fig. 5. Von Misses stresses [Pa] obtained at 500ºC for 15-15Ti specimens

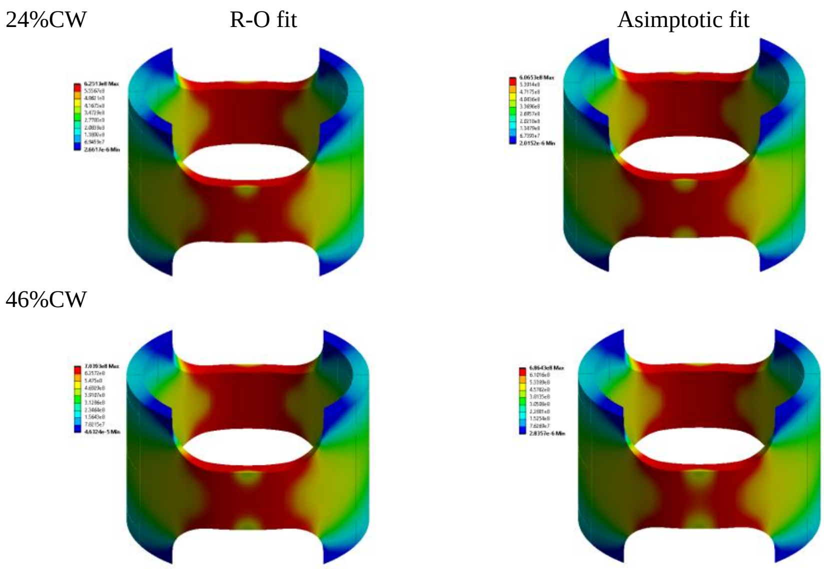

Fig. 6. Von Misses stresses [Pa] obtained at 600ºC for 15-15Ti specimens

It can be seen from Fig. 5 and Fig. 6 that, at the same testing condition, the specimen with 46%CW exhibits higher equivalent stresses, compared to 24%CW specimen. The finite element analysis results also showed that, there is a difference of about 20 MPa between the maximum stress values obtained at 500ºC compared to 600ºC, for both specimens. The predicted stresses of the Ramberg-Osgood model are larger than those obtained with the asymptotic law (fitted on experimental data).

The distribution of the equivalent plastic strain is reported on Fig. 7 and Fig. 8. The first illustration refers to the cladding specimen tested at 500ºC, and the second describes the plastic strain of the specimen at 600ºC. As expected, the higher deformation is mainly concentrated on the specimen gauge section, through inner surface of the cladding tube.

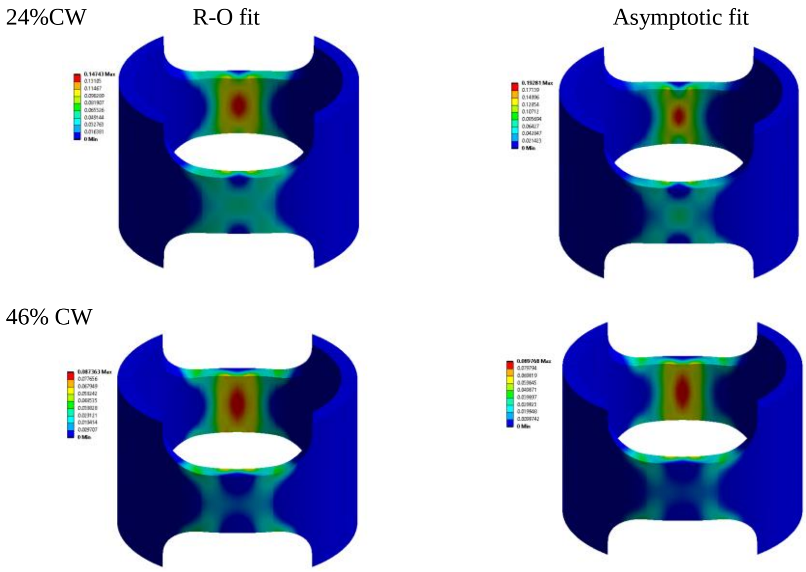

Fig. 7. Equivalent plastic deformation [mm/mm] obtained at 500ºC for 15-15Ti specimens

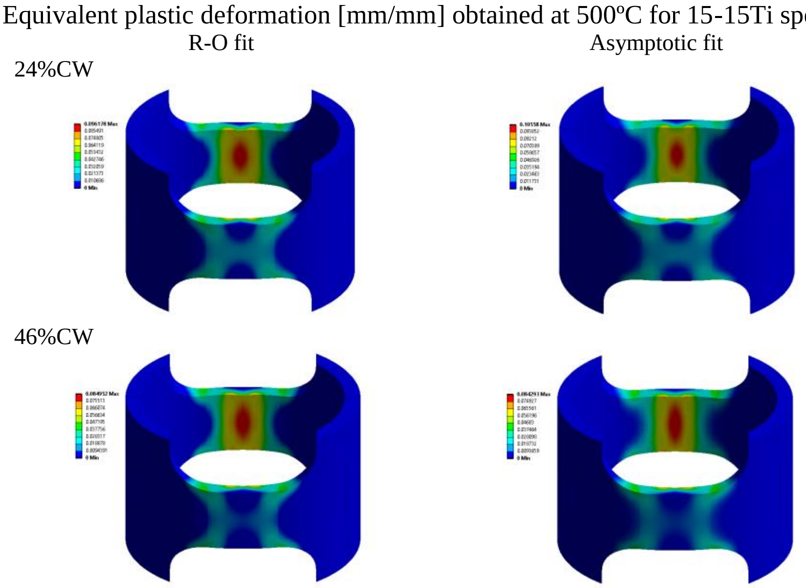

Fig. 8. Equivalent plastic deformation [mm/mm] obtained at 600ºC for 15-15Ti specimens

At the same time, it can be seen that as the cold working rate increases the values of the equivalent plastic strain decreases. Also, when applying a similar displacement of the cylinder, the peak values reported for the testing temperature of 500ºC are slightly higher compared to 600ºC, for both specimens.

In addition, the comparison between Ramberg-Osgood model (only based on yield strength and tensile strength) and the asymptotic law predictions (obtained by fitting the experimental data) shows only a slight disagreement of the results. Based on this comparison one can conclude that, in absence of valid experimental data, the Ramberg-Osgood model can be applied with confidence to describe the mechanical properties of different materials.

The next stage of the present study consists in assessment of the friction coefficient influence on the mechanical properties of the 15-15Ti clad. During the experimental procedure, to minimize the friction coefficient between the outer surface of the cylinders and the inner surface of the specimen, a Teflon tape has been used. Initially, in our analyses a perfect contact between the specimen and the test cylinders was considered. Thus, additional analyses were performed with ANSYS for different values of the friction coefficient, as follows: 0.01, 0.1, 0.2. The mechanical properties of the 15-15Ti austenitic steel material obtained with different friction coefficient are shown in Table 2. For the sake of brevity, only the results for the 24%CW specimen tested at 500ºC were reported.

Table 2

15-15Ti material properties obtained with ANSYS for different frictions coefficients

Coeff	24%CW 500ºC					
	R-O fit			Asymptotic fit		
	Eqv stress [MPa]	Eqv plastic deformation [%]	Total deformation [%]	Eqv. stress [MPa]	Eqv plastic deformation [%]	Total deformation [%]
0.0	651.8	14.74	18.43	620	19.3	22.8
0.01	651.8	14.77	18.45	620	20.5	24.0
0.1	652.3	15.08	18.77	620	20.8	24.3
0.2	652.7	15.44	19.13	620	21.1	24.6

From Table 2 it can be seen that the plastic strain increase continuously with the friction coefficient. A difference of about 4% for the R-O model predictions and ~9% for the asymptotic law results was observed between the ideal case (friction coefficient = 0.0) and the situation when the friction coefficient is 0.2.

4. Conclusions

Based on the finite element simulations, carried out with ANSYS software, the following conclusions are drawn:

- At the same testing conditions, the specimen with 46%CW exhibits

higher strength, compared to 24%CW specimen;
- The simulations results obtained at 600ºC showed a lower tensile strength, compared with 500ºC, with a difference of about 20 MPa between the maximum stress values;
- The predicted stresses of the Ramberg-Osgood model are slightly higher than those obtained with the asymptotic law (derived from the experimental data);
- As the cold working rate increases the equivalent plastic strain of the cladding tube decreases;
- It was emphasized that the higher deformation of the simulated specimens was mainly concentrated on the gauge section, through the inner surface of the cladding tube;
- Regarding the friction coefficient influence on the mechanical properties of the 15-15Ti clad, it was observed that the plastic strain increases continuously with friction coefficient;
- The Ramberg-Osgood model can be used with confidence in numerical simulations to describe the mechanical properties of different materials, on absence of valid experimental data.

The 15-15Ti steel is proposed for use in lead fast reactor structures, which means great challenges for the material, imposed by the extremely corrosive environment and high temperatures. The results presented in this study showed good mechanical properties of the investigated material to be used as cladding for nuclear fuel elements.

R E F E R E N C E S

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