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**CNEA Developments in U-Mo-Zry-4 Miniplates, Dog Bone
Studies and Plates Co-rolling Control**

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ABSTRACT

The Uranium Molybdenum alloy was the material chosen to develop the fabrication of high density nuclear fuel. At present, the study is focused on the application of this alloy to monolithic fuel plate development. The Zry-4 alloy used as cladding material is extensively known in the nuclear industry due to its low neutron capture section efficiency and excellent mechanical and corrosion resistance properties. Since first experiments in 2003, CNEA is employing this material as cladding. Miniplates fabrication process involves a welded compact made of two Zry-4 covers and a frame surrounding a monolithic U-Mo core, which is co-rolled under temperature. Mo contains of 7% to 10% (mass) in U-Mo alloys guarantees the presence of meta-stable bcc gamma phase without penalizing in excess the neutron economy due to the capture cross section of the isotope Mo⁹⁸.

The calculation from initial dimensions (length, width, thickness) final ones for cladding, frame and core to fulfil after co-rolling the prescribed specifications is a key issue regarding miniplates and plate fabrication. Important facts are that U-Mo and Zry-4 have different strength shield values and different deformation rates under hot co-rolling.

Based on theoretical calculation and empirical data corroboration, this work presents the development of a control loop to properly fabricate in specifications U-Mo/Zry-4 miniplates and plates.

1. Introduction

During fuel compact hot co-rolling, composed with different materials, available information are initial dimensions of compact (length, width and thickness of frame, covers and core), compact thickness after each co-rolling step and co-rolling temperature,. The purpose for this process is to arrive to specified dimensions after all co-rolling steps. In the fuel plate fabrication case, final core thickness is a critical parameter due to the neutronic and thermal consequences that would have its departs from specifications.

After co-rolling and by means of X-ray radiography it is possible to obtain other final dimensions of core, frame and covers. But, from the point of view of fabrication it is desirable to have a relationship linking the deformation rate and strength shield of each material at co-rolling temperature to assess final dimensions of plate and core without stopping each co-rolling step for X-ray checking.

1.1 Fluency condition

Hot rolling of metallic sheaths is a plastic deformation process by plane compression at constant volume. Assumption that width of the piece remains constant during rolling process is consistent with experimental variation of 1.5 – 2%. The piece is free to flow along the length direction. The plastic deformation depends on deviator tensor components which, along the principal axes, areⁱ:

$$s_{xy} = \sigma_{xy} - \sigma_m \cdot \delta_{xy}; \sigma_m = \sum \sigma_i / 3$$
$$s = \begin{bmatrix} \sigma_1 - \sigma_m & 0 & 0 \\ 0 & \sigma_2 - \sigma_m & 0 \\ 0 & 0 & \sigma_3 - \sigma_m \end{bmatrix}$$

Its 2° order invariant is:

$$I_2(s) = -\frac{1}{6} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \quad (\text{Ec.2.1.1})$$

From it is formulated the equivalent tensor and Von Mises fluency condition: the equivalent tensor is greater to the strength shield

$$\bar{\sigma} = \sqrt{\frac{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}{2}} > \sigma_F = Y \quad (\text{Ec.2.1.2})$$

1.2 Dependence of the strength shield on temperature

As an example the U-Mo strength shield vs. T(°C) graph is presentedⁱⁱ. A similar one is possible to obtain for Zry-4:

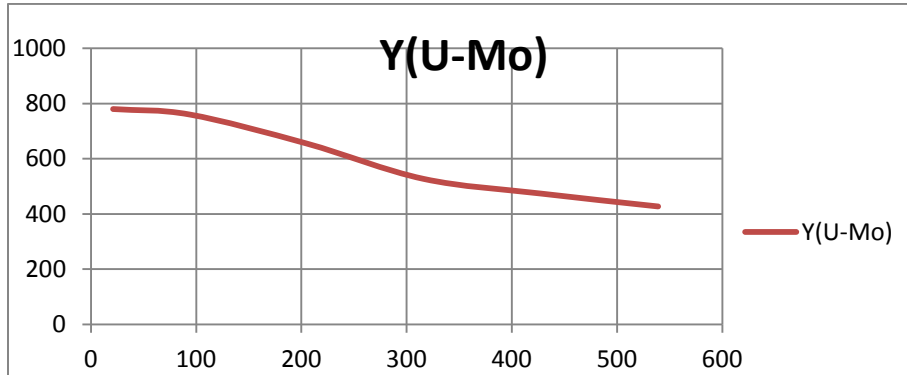


Figure 2.2.1: Strength shield as a function of temperature (°C)

It is worthy to say that no data is available for U-x%Mo neither for Zry-4 at co-rolling temperature (650 °C)

1.3 Rolling scheme

Main geometrical parameters are shown below. If a_p and L_p stand for plate width and length and e_0 , e_f for initial and final thickness during a rolling step, the rolling surface over which acts the rolling force isⁱⁱⁱ:

$$a_p * L_p = a_p * \sqrt{R^2 - \left(R - \frac{e_0 - e_f}{2}\right)^2} \approx a_p * \sqrt{R(e_0 - e_f)} \quad (\text{Ec.2.3.1})$$

$$F = \bar{\sigma} \cdot a \cdot \sqrt{R \cdot \Delta e_n} \cdot \left[1 + \frac{\mu \cdot \sqrt{R \cdot \Delta e_n}}{e_{n-1} + e_n} \right] = \bar{\sigma} \cdot a \cdot \sqrt{R \cdot \Delta e_n} \cdot \left[1 + \frac{\lambda \cdot \Delta e_n}{e_{n-1} + e_n} \right]$$

(Ec.2.4.1)

, where 2.3.2 was recalled. P equals the product of the rolling force times the tangential velocity. This equals the rolling length times the roller angular velocity

$$P = F \cdot v_t; v_t = L_p \cdot \omega$$

(Ec.2.4.2)

Angular velocity equals 2π times the rolling machine frequency ν (1/s) so we have:

$$P = 2\pi\nu \bar{\sigma} \cdot a \cdot R \cdot \Delta e_n \cdot \left[1 + \frac{\lambda \cdot \Delta e_n}{e_{n-1} + e_n} \right] = 2\pi\nu \bar{\sigma} \cdot a \cdot R \cdot \Delta e_n \cdot \left[1 + \lambda \frac{1 - \varepsilon_n}{1 + \varepsilon_n} \right]$$

(Ec.2.4.3)

, where $\varepsilon_n = e_n / e_{n-1}$. For most cases during a smooth co-rolling process $0.95 > e_n / e_{n-1} > 0.8$, so bracket in 2.3.4 ranges from 1 to 2.25 no matter which phase is it.

The applied power during co-rolling process means deformation energy per unit time which plastically deforms both materials U-Mo and Zry-4. In this case involved materials have different deformation rates and strength shields, so cancelling common factors and taking into account ε_n possible values it stands:

$$\left[\sigma \Delta e_n \right]^{U-Mo} \cong \left[\sigma \Delta e_n \right]^{Zry-4}$$

(Ec.2.4.4)

I.e.

$$\frac{\left[\sigma \right]^{U-Mo}}{\left[\sigma \right]^{Zry-4}} \cong \frac{\left[\Delta e_n \right]^{Zry-4}}{\left[\Delta e_n \right]^{U-Mo}} \Rightarrow \frac{\left[\sigma \right]^{U-Mo}}{\left[\sigma \right]^{Zry-4}} \cong \frac{\sum \left[\Delta e_n \right]^{Zry-4}}{\sum \left[\Delta e_n \right]^{U-Mo}} = \frac{\left[e_0 - e_f \right]^{Zry-4}}{\left[e_0 - e_f \right]^{U-Mo}}$$

(Ec.2.4.5)

1.5 Experimental findings and thickness calculations

After co-rolling several miniplates and measuring through X-ray radiography final dimensions of each phase it was possible to prepare the following table:

TABLE 2.5.1

ESSAY	(1) MINIPLATE THICKNESS DIFFERENCE (e0-ef) (mm)	(2) CORE THICKNESS DIFFERENCE (e0-ef) (mm)	(3)=1/2*(1-2) COVER THICKNESS DIFFERENCE (e0-ef) (mm)	(3)/(2) DIFFERENCE RATIO
1	4,48	0,636	1,922	3,024
2	4,55	0,592	1,979	3,343
3	4,826	0,72	2,053	2,853
4	4,83	0,713	2,059	2,889
5	4,6	0,65	1,975	3,037
6	5,13	0,661	2,234	3,379
7	4,96	0,731	2,114	2,892
	STANDARD DEVIATION:	0,218	AVERAGE VALUE:	3,060

So results of table 2.5.1 and equation 2.4.6 give us an accurate value of thickness difference quotient which allows a control loop during co-rolling:

$$\frac{[e_{n-1} - e_n]^{Zry-4}}{[e_{n-1} - e_n]^{U-Mo}} = \frac{[e_0 - e_f]^{Zry-4}}{[e_0 - e_f]^{U-Mo}} \cong 3.06 \pm 0.22$$

(Ec.2.5.1)

Consider now a co-rolling strategy built by consecutive miniplate thickness reductions so that $0.95 > e_n / e_{n-1} = \rho_n > 0.8$. After some operations we have:

$$e_F^{MP} = \rho_F e_{F-1}^{MP} = \dots = \prod_{i=1}^F \rho_i e_0^{MP} \Rightarrow e_0^{MP} - e_F^{MP} = e_F^{MP} \left[\left(\prod_{i=1}^F \rho_i \right)^{-1} - 1 \right]$$

$$\frac{[e_0 - e_F]^{Zry-4}}{[e_0 - e_f]^{U-Mo}} = \frac{\left[(e_0^{MP} - e_F^{MP}) - [e_0 - e_f]^{U-Mo} \right]}{2[e_0 - e_f]^{U-Mo}} =$$

$$\frac{e_F^{MP} \left[\left(\prod_{i=1}^F \rho_i \right)^{-1} - 1 \right] - [e_0 - e_f]^{U-Mo}}{2[e_0 - e_f]^{U-Mo}} \cong 3.06 \pm 0.22$$

$$e_F^{U-Mo} + \frac{e_F^{MP} \left[\left(\prod_{i=1}^F \rho_i \right)^{-1} - 1 \right]}{7.56} < e_0^{U-Mo} < e_F^{U-Mo} + \frac{e_F^{MP} \left[\left(\prod_{i=1}^F \rho_i \right)^{-1} - 1 \right]}{6.68}$$

Ec 2.5.2

So, given the final product specification for both phases (and so for the miniplate), it is possible to reconstruct initial (and at any stage) length and thickness if co-rolling strategy ρ_n is provided. Having calculated initial thickness for U-Mo phase it follows that:

$$2.84 * e_F^{Zry-4} \left[e_0^{U-Mo} - e_F^{U-Mo} \right] < e_0^{Zry-4} < 3.28 * e_F^{Zry-4} \left[e_0^{U-Mo} - e_F^{U-Mo} \right]$$

Ec 2.5.3

Both last inequalities provide the control co-rolling process that we were looking for.

4. Discussion

Results obtained shows that when reductions are under 5%, the core thickness stays homogeneous during the co-rolling process. A disadvantage of this process is that the process requires more steps to reach the desire thickness. In this case, this final thickness depends on the miniplates irradiation conditions

Considering the results obtained in the experiences and de calculations analyses, a new co-rolling protocol was developed, in order to minimize both the Dog Bone and the number of steps. A commitment between these characteristics is obtained with decreasing percent reductions. The irradiations specifications for a miniplate fuel [13] demand the Dog Bone to be under 30%. The better co-rolling process consists on maintaining the percent reduction under 5%. The new objective is to extrapolate these results to a full-size plate.

5. Conclusions

Based on the experiences and de calculations detailed in this work, it can be concluded that the co-rolling process can be done with constant percent reductions: up to a 5% reduction or less are suggested. This way, the thickness difference between the edges and the center is less than 30%.

6. References

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- ⁱ “Elementos de la Teoría de Plasticidad”. Principios Fundamentales, .Alfredo Sáenz López-A.O. Lucaioli CNEA-AC 11/83 PMTM/A-47
 - ⁱⁱ Douglas Burkes, BWXT R&D manager. Personal communication
 - ⁱⁱⁱ “Fundamental concept in metal rolling” Tapany Undophol, Suranaree University of Technology, 2007