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PHYSICAL MODELLING OF THE PLASTIC WORKING PROCESSES OF MODIFIED Zr-Nb ZIRCONIUM ALLOY BARS AND TUBES

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The article presents the results of physical modelling of the processes of plastic working of the modified Zr - 1%Nb (Zr – 1,0 % Nb – 0,7 % Fe – 0,9 % O) zirconium alloy, obtained using different methods of plastometric testing. The «Gleeble 3800» metallurgical process simulator, a DIL805 A/D dilatometer with a plastometric attachment, and a «Setaram» plastometer were used for the tests. Based on the obtained testing results, the values of the yield stress and limiting plasticity of the alloy were determined for wide ranges of temperature variation (T = 20 - 950 °C) and strain rate variation ($\dot{\varepsilon}$ = 0,1 – 15,0 s^{-1}) under continuous loading conditions. It was found that by using different testing methods, different alloy properties, characteristic of a given plastic working process, could be obtained.

Keywords: Zr - 1%Nb, rods, tube, physical modeling, hot, warm, cold deformation

INTRODUCTION

From the zirconium alloy plastometric testing results reported in references [1 - 4] it can be found that the selection of the testing method (tension, compression or torsion) when modelling plastic working processes will significantly influence both the yield stress magnitude and the shape (behaviour) of the determined plastic flow curves for the zirconium alloys under consideration. Each of the above-mentioned methods not only enables the determination of the rheological properties of materials being deformed in a wide range of thermomechanical parameters, but also allows the mode of increasing the presetting strain in time to be allowed for.

The correct selection of the testing method in physical modelling of plastic working processes assures the accurate shape of plastic the flow curves depending on the process parameters to be obtained. The results of such tests can be used both during the design of a new technology and in improving the existing technological operations of manufacturing rods, tubes and other fuel rod elements of modified zirconium alloys [5].

TEST MATERIAL AND TESTING METHODOLOGY

The tests were carried out for conditions prevailing during the plastic working of the modified zirconium alloy Zr - 1%Nb (Zr – 1,0 % Nb – 0,7 % Fe – 0,9 % O). Three testing methods relying on the tension, compression and torsion tests, respectively, were employed. The «Gleeble 3800» metallurgical process simulator and a «Setaram» torsional plastometer were used for the tests. Each of the methods reflected a different technological operation, hence different alloy properties were obtained, which were characteristic of a specific type of testing.

For plastometric tests by the compression method using the «Gleeble 3800» plastometer, specimens of a working part diameter of 10 mm and a height of 12 were used. The tension tests specimens had a working part diameter of 10 mm and a length of 85 mm. Specimens of a working part diameter of 6 mm and a length of 15 mm intended for torsion tests were made from 14 mm-diameter bars.

Prior to the physical modelling of the plastic working processes of semi-finished products of the alloy under investigation, the analysis of the basic parameters of each process making up the technological sequence was performed to determine the possible ranges of variations of these parameters. On this basis it was determined that the experiments would be conducted with a wide range of temperature variations (T = 20 - 950 °C) and strain variations ($\dot{\varepsilon}$ = 0,1 - 15,0 s^{-1}).

During testing in the «Gleeble 3800» simulator the specimens were resistance heated with direct current, while controlling the rate of their heating (at 5 °C/s). For the control and monitoring of specimen temperature, a chromel-copel thermocouple welded to the central specimen part was used.

During the compression tests, thin pads of a graphite-based material were used as a lubricant.

The torsion test specimens were heated in an electric furnace at an average heating rate of 0,5 °C/s.

The tests were conducted in a vacuum in order to prevent the test specimen surface from oxidation and saturation with gas during specimen heating.

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Based on the tension tests, after employing the methodology developed by Kolmogorov [6], the diagrams of limiting plasticity Λ_p were plotted. In the case of uniform deformation (up to the point of neck formation), the limiting plasticity value can be determined using the unit elongation A:

$$\Lambda_p = 1{,}73 \ln[100/(100 - A)], \tag{1}$$

while for non-uniform deformation (after the formation of the reduction of area), using the percentage reduction of area, Z:

$$\Lambda_p = 1{,}73 \ln[100/(100 - Z)], \tag{2}$$

The limiting plasticity (limiting strain at shearing), Λ_p, can be determined from the compression test, using the following relationship:

$$\Lambda_p = \sqrt{3}\ln(h_0/h_p),\ \text{with}\ (\sigma_m/\tau_i)_m = -\,0{,}5; \tag{3}$$

where: h_0 – initial specimen height, h_p – specimen height at the point of failure occurrence, σ_m – mean stress, τ_i – shearing stress intensity.

The limiting plasticity value for specimens subjected to torsion is determined on their surface from the following formula:

$$\Lambda_p = \gamma,\ \text{where}\ \gamma = \pi dN/L \tag{4}$$

where: γ – redundant strain (torsional angle up to specimen failure); L , d – specimen working part length and diameter; N – number of specimen rotation up to specimen failure.

TESTING RESULTS

The results of the tests carried out are shown in Figures 1 - 6. It can be seen from the data in Figure 1 that with the increase in specimen temperature, the strain hardening ratio of the examined alloy decreases, and more and more clear dynamic recovery processes appear in the plastic flow curves. The kinetics of the dynamic recovery and recrystallization process occurring in the metal is largely reflected by the position of the maximum in the $\sigma_p - \varepsilon$ curves

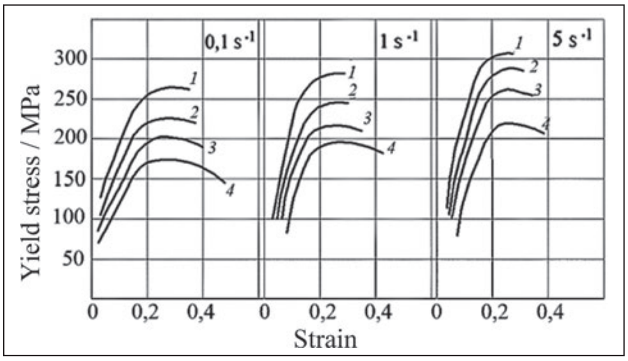

Figure 1 Strain hardening curves for Zr alloy, obtained from tension tests on the «Gleeble 3800» plastometer; at a temperature of, respectively: 1 - 580; 2 - 650; 3 - 700; and 4 - 770, in °C

The limiting plasticity Λ_p for the tension specimens was determined by the Kolmogorov method from formulas (1) and (2) based on the determined values of elongation, A, and the reduction of area, Z.

The data shown in Figure 2 shows that with the increase in specimen temperature T from 650 °C to 950 °C, the limiting plasticity Λ_p of the Zr – 1,0 % Nb – 0,7 % Fe – 0,9 % O alloy varies not uniquely.

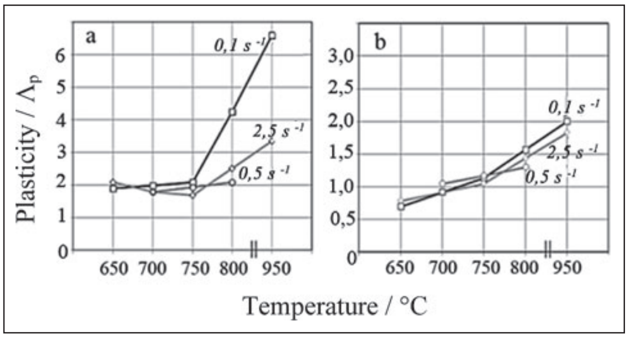

Figure 2 The effect of temperature and strain rate on the limiting plasticity of the Zr alloy; as calculated based on: a) elongation, A; b) reduction in area, Z

At a strain rate of $\dot{\varepsilon} = 0{,}1\ \mathrm{s^{-1}}$, the limiting plasticity of the alloy increases monotonically, in calculations using both the elongation A and the reduction of area Z. For $\dot{\varepsilon} = 2{,}5\ \mathrm{s^{-1}}$ and with the use of elongation A in calculation, the limiting plasticity decreases in a temperature range of up to T = 750 °C. In the temperature range of T = 650 - 680 °C and at a strain rate of $\dot{\varepsilon} = 2{,}5\ \mathrm{s^{-1}}$, the limiting plasticity value of the alloy under examination is greater than that determined for the strain rate of $\dot{\varepsilon} = 0{,}1\ \mathrm{s^{-1}}$. This phenomenon is caused by the occurrence of a thermal effect that inhibits the formation of the test specimen plastic flow location and has the effect of increasing the alloy plasticity.

The occurrence of the considerable difference between the limiting plasticity values determined using the indices A and Z can be explained by the inequality of specimen deformation in the transverse and the longitudinal directions.

Figure 3 shows $\sigma_p - \varepsilon$ plastic flow curves for the Zr – 1,0 % Nb – 0,7 % Fe – 0,9 % O alloy, obtained with continuous loading of the specimens. The strain hardening ratio of the examined alloy at a temperature of T =

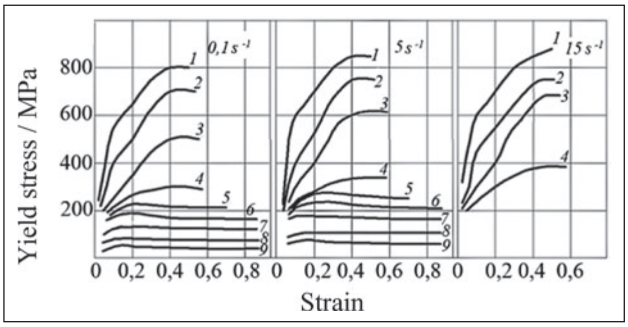

Figure 3 Strain hardening curves for the Zr alloy, (compression test - Gleeble 3800); at a temperature of, respectively: 1 - 20; 2 - 200; 3 - 350; 4 - 500; 5 - 580; 6 - 650; 7 - 770; 8 - 850; and 9 - 950, in °C

20 °C clearly decreases with the increase in the preset strain, as the yield stress curve section corresponding to the single stage, and them multiple slip, passes into a parabolic section, and the Drucker postulate [7, 8] becomes violated.

In the region of $\varepsilon = 0,3 \div 0,4$, the ratio $d\sigma_p / d\varepsilon$ is equal to zero. This phenomenon is characteristic of metals and alloys having the A3 lattice. These materials are distinguished not only by a considerable thermal effect occurring in both cold and hot deformation at large rates, but also by an anisotropy of their properties, associated with their textural inhomogeneity.

In the range of test specimen temperature T from 500 °C to 580 °C, the dome-like shape of the Zr – 1,0 % Nb – 0,7 % Fe – 0,9 % O alloy flow curves becomes prominent, with a heavily extended steady flow section, which clearly indicates the initiation of dynamic recovery processes in the specimen being deformed. In the high strain region, during steady flow, the metal structure is characterized by greater homogeneity, with a relatively small dislocation density [9, 10].

In the temperature range corresponding to hot deformation (T = 650 - 950 °C) and in the strain rate range of $\dot{\varepsilon}$ = 0,1 - 15,0 s^{-1}, the maximum value of σ_p decreases when using small strains of $\varepsilon \approx$ 0,1 - 0,2. A steady flow section, $\sigma_p = \sigma_{pu}$, comes up in the plastic flow curves. With the increase in temperature, this section becomes even more extended.

The influence of strain rate on the limiting plasticity is definite (Figure 4). In the temperature range from 20 °C to 650 °C and at considerable strain rates ($\dot{\varepsilon}$ = 5 - 15 s^{-1}), the limiting plasticity is significantly influenced by the thermal effect of plastic deformation. For these reasons, the plasticity curves determined for the given strain rate range lie above the curves determined for the strain rate of $\dot{\varepsilon}$ = 0,1 s^{-1}.

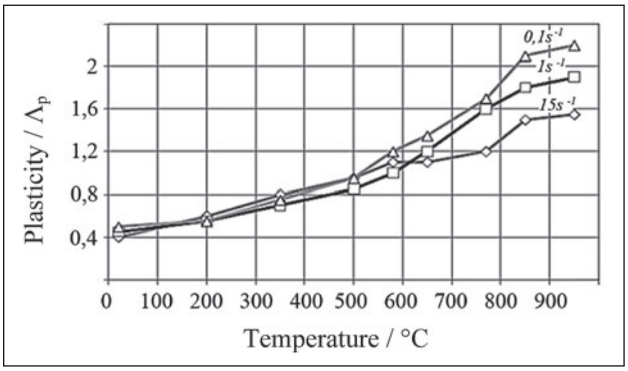

Figure 4 The influence of temperature and strain rate on the limiting plasticity of the Zr alloy for the temperature range of T = 20 - 950 °C (compression test -Gleeble 3800)

In the temperature range of T = 650 - 950 °C, the impact of the thermal effect is smaller, and with the increase of the strain rate, the plasticity of the examined alloy decreased.

Figure 5 shows that the difference in the flow curve distributions in the temperature range from 20 °C to 200 °C is caused by the influence of strain hardening due to the increase in strain rate.

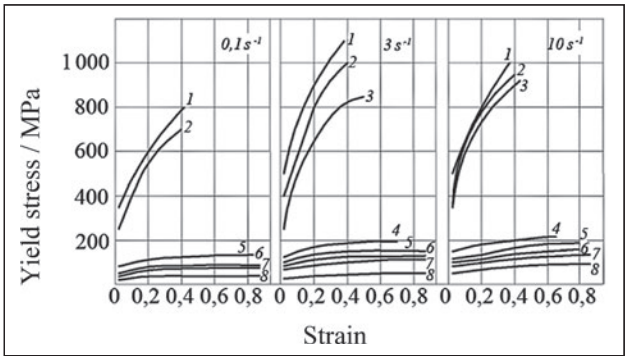

Figure 5 Strain hardening curves for the Zr alloy, (torsion tests - Setaram); at a temperature of, respectively,: 1 - 20; 2 - 100; 3 - 200; 4 - 580; 5 - 650; 6 - 700; 7 - 750; and 8 - 950, in °C

In the range from 3 s^{-1} to 10 s^{-1} the σ_p value attains values from the range of 980 - 1 000 MPa. The $\sigma_p - \varepsilon$ curves essentially have the same behaviour in terms of both shape and value, which is associated with the occurrence of a thermal effect at higher rates of conducting the loading process.

In the hot deformation range (at T = 200 - 580 °C), the plastic flow curves of the examined alloy change their behaviour, which is due to the dynamic recovery process coming up.

At a temperature of 700 °C and the lowest strain rate of $\dot{\varepsilon}$ = 0,1 s^{-1}, a section of steady flow $\sigma_p - \sigma_{pu}$ can be observed to appear in the flow curves. The occurrence of this section in the $\sigma_p - \varepsilon$ curves is indicative of the process of dynamic recovery and dynamic polygonization occurring in the metal.

In the temperature range of 750 °C - 950 °C, a maximum σ_p value can be found to occur at $\varepsilon \approx$ 0,6 - 0,8 in the plastic flow curves of the alloy. This evidences the occurrence of the dynamic recovery process in the large strain region in the metal after the ε_{ch} (characteristic strain) has been attained, when $d\sigma_p / d\varepsilon < 0$.

From the diagrams of limiting plasticity variation of the examined Zr – 1,0 % Nb – 0,7 % Fe – 0,9 % O alloy (Figure 6) it can be found that it is characterized by the occurrence of some peculiarities when examined at varying temperatures and strain rates.

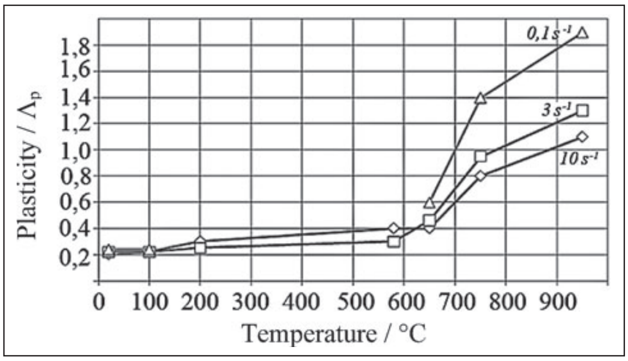

Figure 6 The influence of temperature and strain rate on the limiting plasticity of the Zr alloy for the temperature range of T = 20 - 950 °C in torsion tests

In the temperature range of 20 - 950 °C, the influence of strain rate on the value of Λ_p cannot be uniquely determined. The examined Zr – 1,0 % Nb – 0,7 % Fe 0, 9 % O alloy at 580 °C and for $\dot{\varepsilon} = 10$ s^{-1} exhibits higher plasticity than for lower strain rates.

At a temperature of 650 °C and the same strain rate it can be observed a reduced plasticity of the examined alloy which is associated with the allotropic change $\alpha \rightarrow \alpha+\beta$ in the alloy [11].

With the continued increase in specimen temperature, the value of the limiting plasticity Λ_p for $\dot{\varepsilon} = 10$ s^{-1} is smaller than for other strain rates. Starting from $T = 700$ °C, a considerable increase in the limiting plasticity occurs at all strain rates, and by reducing the strain rate $\dot{\varepsilon}$, it is possible to positively influence the deformability of the examined alloy.

SUMMARY

Based on the investigations carried out, the following findings and conclusions have been formulated:

The presented data shows that:

- The σ_p yield stress curves plotted in the $\sigma_p - \varepsilon$ system, determined from the tension tests, lie above the curves determined from the compression and torsion tests, which is due to the fact that the plastic flow curves developed based on the tension tests reproduce conditions that fundamentally differ from the uniaxial stress and strain state scheme.
- In order to determine the actual values of the yield stress σ_p of the alloys examined by the specimen tension method, a correction to the experimental $\sigma_p - \varepsilon$ curves should be made according to the methodology of Siebel, Davidenkov – Spiridonov and Bridgman.
- The shape of the plastic flow curves of the investigated alloy in the temperature range from 20 °C to 580 °C (during cold and hot deformation) is most influenced by the thermal effect of plastic deformation.
- With increasing plastic strain rate, the value of the yield stress of the Zr – 1,0 % Nb – 0,7 % Fe – 0,9 % O alloy changes only slightly.
- In the temperature range from 580 °C to 650 °C in torsion tests at a strain rate of 10 s^{-1}, an inhibition of the limiting plasticity increase can be observed, which is associated with allotropic changes taking place.
- With the increase in the temperature of test specimens from 700 °C to 950 °C, the plasticity of the investigated alloy increases.

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