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THE THERMOMECHANICAL CONDITIONS OF OPEN DIE FORGING OF ZIRCONIUM ALLOY INGOTS DETERMINED BY RHEOLOGICAL TESTS

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The article reports the results of investigation into variations in the rheological properties of the Zr-1 % Nb alloy when deformed under the conditions of physical modelling of the process of multi-stage hot open die forging of ingots. The programme for rheological testing of the alloy was developed based on the simplex planning method. Tests were carried out on a „Gleeble 3800" plastometer. Based on the rheological test results, a new scheme of ingot deformation in forging process was developed and the experimental verification of the model study results was made in industrial conditions. From the obtained results, high effectiveness of the method of determining the thermomechanical conditions as applied to the process of forging zirconium alloy ingots has been found.

Keywords: zirconium alloy, forging, physical modelling, rheological test, flow stress

INTRODUCTION

Zirconium-based alloys are currently widely used as materials for the manufacture of finished products to be used mainly in the nuclear, chemical and petrochemical industries. Zirconium products are also used in medicine in surgeries, as they do not cause any undesirable allergic reactions in the human body [1,2].

To provide finished products with the required properties, ingots of zirconium alloys are subjected to many technological operations and thermomechanical treatments, the first of which being multi-stage hot open die forging [3,4].

For the existing stress state pattern and the active diffusion of gases from the environment to the outer layers of the metal being plastically deformed, of key importance to the open die forging is the correct selection of thermomechanical parameters specific to the hot deformation process, including: forging start and end temperature, the deformation speed range, single and total reduction values and inter-load break durations. On the one hand, to refine the structure occurring in a cast ingot and to equalize the physicochemical properties within the deformed metal, larger single deformations, as well the appropriate total reduction should be used in forging ingots. On he other had, however, increasing the loads will result in the formation of gas-bearing and oxidized outer metal layers that move into the material being forged. This has a very adverse effect on the quality of zirconium alloy semi-finished products to be obtained in subsequent technological operations, such as the processes of extrusion, rolling, etc. [5-6].

The currently known method of determining the parameters of open die ingot forging consists primarily in determining the value of the absolute reduction $\Delta h = h_0 - h_1$, (where: h_0, h_1 – feedstock height and semi-finished product height, respectively) in a single pass, and the relative feed $k = l/H$ (where l – absolute value of stock feed, mm; H – height of the deformed forging length cross-section, mm) [7]. A drawback of this method, however, is the fact that it does not allow for the effect of thermomechanical forging parameters on the margin of plasticity (rheological characteristics – flow stress, σ_p; and the value of the limiting strain to cracking, Λ_p) of zirconium alloys.

TEST MATERIAL AND TESTING METHODOLOGY

The influence and interaction of the thermomechanical parameters of plastic working processes can be most completely determined by physical modelling of the intermittent deformation process [8,9]. Material for the investigation of the variations in the rheological properties under the conditions of open die ingot forging was the alloy Zr - 1 % Nb (0,7 % Fe, 0,9 % O; and the balance Zn).

During physical modelling of the ingot forging process, it is justifiable to use the simplex planning method for two variables: test specimen temperature, T_n; and the value of the true strain, $\varepsilon = ln\,(h_1 / h_0)$. For that case, the simplex is a triangle in plane $T_n - \varepsilon$.

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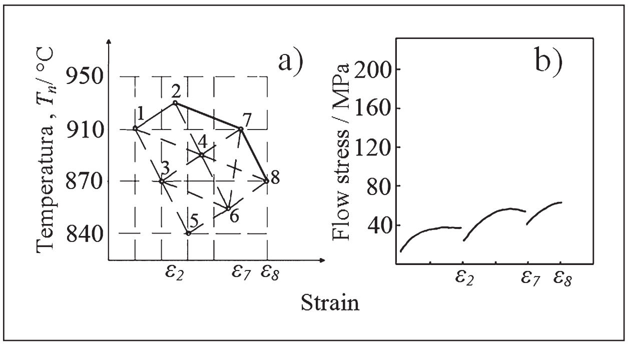

Figure 1 Simplex planning of physical modelling: a) simplex planning for two variables, T_n and ε; b) examples of plastic flow curves

At the points of the starting simplex (points 1, 2, 4 in Figure 1a), a randomized test is performed to determine the worst value of the function under examination. A criterion for the evaluation of the function is the smallest or comparable value of flow stress σ_P in the flow curves $\sigma_P - \varepsilon$, obtained at the maximum values of T_n and ε in individual passes of the forging operation.

Then, an experiment should be carried out for conditions corresponding to point 7 which is a mirror image of point 1 with respect to its opposite edge 2 - 4, and points 2, 4, 7 are considered as a new simplex, and so on, until the selected testing scheme yields a total deformation value that ensures a uniform flow stress value to be obtained in individual hot forging passes (Figure 1b) with a reduced range of deformed ingot temperature. Should considerable fluctuations in σ_P value (over 50 %) occur from pass to pass in the forging process, the thermomechanical conditions for the conducted experimental tests will have to be changed.

In order to determine the variations in flow stress magnitude for the Zr - 1 % Nb alloy in the multi-stage hot forging process, a scheme of conducting experimental tests has been developed (Table 1), which covers variations in thermomechanical parameters in individual hot forging passes, where: ε - average true deformation value, T – deformed specimen temperature, $\Delta\tau$ – duration of breaks between preset loads. According to the scheme shown in Table 1, the deformation value varied from 0,10 to 0,16, and the temperature, from 830 °C to 918 °C. Physical modelling was carried out for the conditions of forging ingots on a hydraulic press, occurring industrially.

During testing, the specimens were heated up to a temperature of 950 °C, then were held at that temperature for a duration of 5 minutes and then cooled down to a temperature of 918 °C (which corresponded to the operation of transporting the ingots from the heating furnace to the hydraulic press stand).

The metal cooling rate, T^{ε}_{ch}, between successive passes was set at 0,2 °C/s, while the average strain rate, at $\dot{\varepsilon}$ = 0,5 s^{-1}. Specimens of the Zr - 1 % Nb alloy in a crystallized state, each of a working portion diameter of 10 mm and a height of 12 mm, were used for the tests. The tests were conducted with the „Gleeble 3800" plastometer by the compression method using the „Pocket Jaw" module.

Table 1 **Scheme of physical modelling of the process of multi-stage hot forging Zr - 1 % Nb alloy ingots using a „Gleeble 3800" plastometer**

Pass No	ε	T / °C	$\Delta\tau$	Pass No	ε	T / °C	$\Delta\tau$
1	0,16	918	-	10	0,14	886	30
2	0,16	916	10	11	0,13	878	40
3	0,15	914	10	12	0,13	870	40
4	0,15	912	10	13	0,12	862	40
5	0,14	909	15	14	0,12	854	40
6	0,14	905	20	15	0,11	846	40
7	0,13	901	20	16	0,11	838	40
8	0,12	897	20	17	0,1	830	40
9	0,14	892	25	-	-	-	-

TESTING RESULTS

The results of the plastometric tests are shown in Figure 2. The data in Figure 2 shows that the value of stress σ_P in physical modelling of successive forging passes in the range from 1 to 8 varies in the interval 35 - 45 MPa. In passes from 9 to 12, the flow stress magnitude increases from 45 to 55 MPa and then increases further in pass 17 (Fig. 3). From the analysis of the testing results illustrated in Figures 2 and 3 it can be noticed that, in spite of the decrease in single deformation magnitudes, a more intensive increase in flow stress values is observed when deforming specimens at forging temperatures T < 870 °C (passes from 13 to 17). The behaviour of the plastic flow curves obtained for the experimental scheme (Table 1) shows that it is possible to obtain an even more uniform distribution of σ_P values during the entire forging cycle. To achieve this, it is necessary to reduce the temperature interval of forging under industrial conditions by reducing the number of passes to 14 and by slightly increasing the magnitudes of single deformations in passes 3 - 8 and simultaneously decreasing the magnitudes of single deformations in passes 11 and 12. Equalizing the magnitudes of flow stress σ_P in individual passes will contribute to obtaining a lesser non-uniformity of strain within the volume of the forged alloy and a lower consumption of energy necessary for carrying out the ingot forging process [10].

EXPERIMENTAL VERIFICATION OF THE DEVELOPED INGOT FORGING SCHEME

Taking into consideration the physical modelling results (Figures 2 and 3) and formulas (1) and (2) referred to below, a new scheme of open die forging of 420 mm-diameter round ingots of Zr - 1 % Nb alloy into 200 mm × 200 mm square cross-section forging (billet) in 14 passes has been developed (Figure 4). This forging scheme satisfies the condition of obtaining an approximately constant value of pressure force in successive passes and considers the increase in the magnitude of

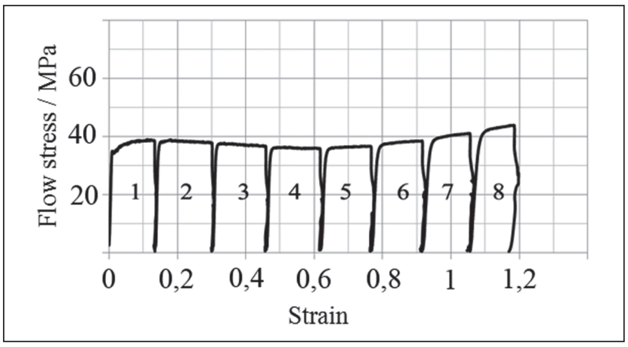

Figure 2 Effect of thermomechanical forging parameters on the variations in the magnitudes of the flow stress σ_p of alloy Zr - 1 % Nb in passes 1 - 8

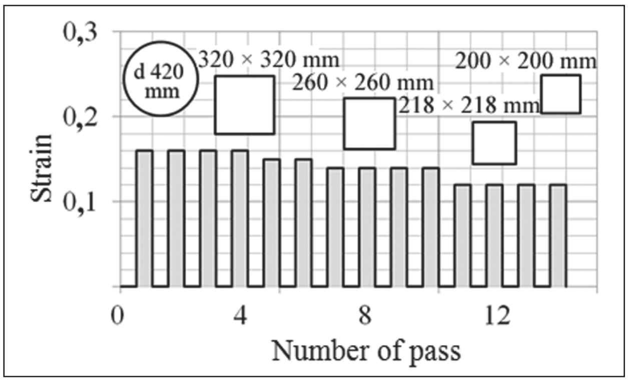

Figure 4 The scheme of forging ingots (420 mm) of alloy Zr - 1 % Nb into 200 × 200 / mm square cross-section billet in 14 passes on the hydraulic press

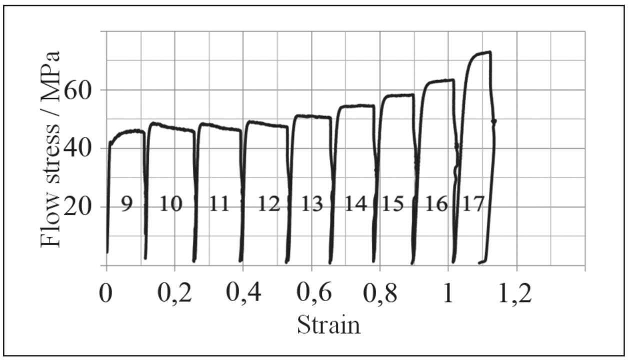

Figure 3 Effect of thermomechanical forging parameters on the variations in the magnitudes of the flow stress σ_p of alloy Zr - 1 % Nb in passes 9 - 17

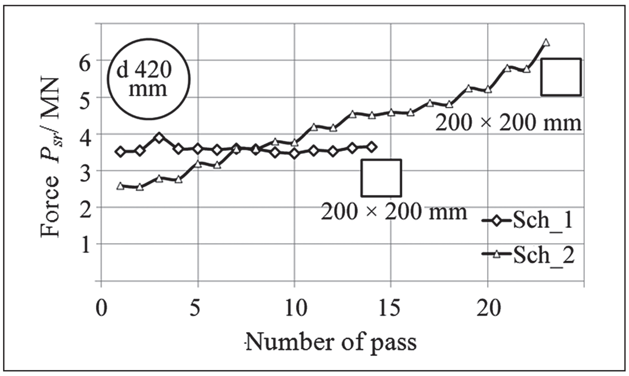

Figure 5 Distribution of force P_{sr} in passes of forging ingot according to the newly developed deformation scheme, Sch_1, and the current industrial scheme, Sch_2

the plastic deformation thermal effect in forging, and also incorporates the narrowed temperature interval of the forging process.

In defining the new ingot forging scheme (Figure 4), formulas provided in study [7] were used:

- the determination of the dimensions of the forging square cross-section required for obtaining a rectangular cross-sections of dimensions h × b (where h – height / mm; b – width / mm) was made using the formula below:

$$a = \frac{h + 3b}{4}; \quad (1)$$

- the determination of the rectangular cross-section width was made from the formula:

$$b = \frac{4a - h}{3}. \quad (2)$$

The value of relative feed *k* was taken in the range from 0,5 to 0,8 [7].

The experimental verification of the developed ingot forging scheme, shown in Figure 4, was made under industrial conditions during open die forging of forgings on a hydraulic press using two flat anvils. Initially, a 420 mm - diameter round ingot was heated in a furnace up to a temperature of T = 950 °C. The heated ingot was transported to the hydraulic press station. The following parameters were recorded during the forging process: the time of transporting ingots from the heating furnace to the hydraulic press (t_t = 100 s), the total ingot forging time ($t_c \approx$ 550 s), the distribution of *load* force inindividual forging passes (Figure 5 sch_1). For recording metal temperature in the forging process, a thermovision camera was used.

From the results of distribution of *pressure* force P_{sr} in successive passes it can be noticed that the process of forging the ingot until a 200 mm × 200 mm square cross-section forging is obtained, following the newly developed deformation scheme (Figure 5 sch_1), takes place with a relatively uniform distribution of the magnitudes of *pressure* force in all passes, compared to the industrial scheme (Figure 5 sch_2). For the new forging scheme (Figure 4), variations in pressure force magnitude were contained in the range from 3,5 to 3,9 MN, whereas the drop in temperature T (on the forging surface) was around 100 °C, as against 250 °C in forging conducted according to the current industrial forging scheme.

Figure 6 shows the microstructures of samples taken in transverse forging direction from locations corresponding to the upper and the middle ingot part, respectively. In the peripheral layers, as well as in the axial zone of the forging, its structure after deformation is visible, whose grains are elongated primarily in the direction tangential to the metal–anvils contact surface, while they being more deformed in the outer layers of the forging. From structural examination and hardness test results, the occurrence of a relatively uniform structure and a uniform hardness distribution over the length on the cross-section of a 200 mm × 200 mm cross-section forging was found (Figure 6). The variation in hardness between the surface layers and the axial zone of the forging lay in the range from 164 HV to 193 HV.

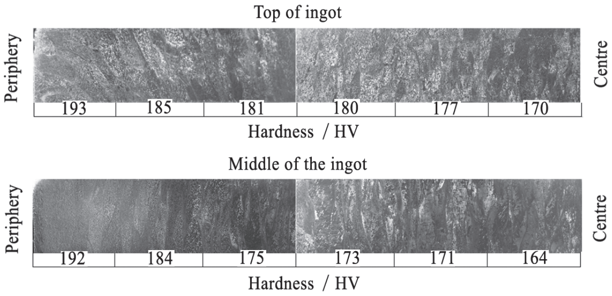

Figure 6 Macrostructure and the results of hardness testing along the cross-section forging after plastic working done according to the Sch_1

The quality control of the obtained forgings did not find the occurrence of any surface defects or material discontinuities. The forgings met the requirements of the acceptance standards.

SUMMARY

1 Based on the results of physical modelling, a new scheme of forging 420 mm-diameter round ingots of alloy Zr - 1 % Nb into a 200 mm × 200 mm cross-section forging (billet) in 14 passes has been developed. The developed forging scheme ensured the required quality and geometry of forgings to be obtained.

2 The shortening of the ingot forging cycle by reducing the number of passes from 23 to 14 resulted in a narrowing of the forging temperature interval to ΔT = 100 °C (as against ΔT = 250 °C in forging according to the industrial scheme), and in the equalization of the distribution of forging forming forces in all passes and an enhancement of structure homogeneity along the forging's length and cross-section.

3 The obtained data for the rheological properties of alloy Zr - 1 % Nb for the conditions of multi-stage open die hot ingot forging enabled a better use of the margin of plasticity of the alloy being worked, which favourably contributed to an increase in productivity and a reduction of energy consumption.

4 The results obtained from the examination of the physical modelling results and their verification in industrial conditions will enable the development of a technology for the manufacture of a wide range of forgings of all zirconium alloys.

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