DOI: 10.24425/amm.2019.127616

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THE STUDY OF THE EFFECT OF ALTERNATE INTERMITTENT DEFORMATION ON THE BAUSCHINGER EFFECT IN A ZIRCONIUM-BASED ALLOY

The article reports the results of research on the influence of the alternate intermittent deformation of specimens by a torsion method on the Bauschinger effect in the Zr-1%Nb zirconium-based alloy. Tests were carried out using an STD 812 torsion plastometer. Based on the tests carried out, diagrams have been plotted, which represent the influence of the pre-deformation magnitude, the temperature of heat treatment prior to deformation, and deformation rate on the variation in the values of the flow stress and yield strength of the alloy under study. Conditions have been defined, in which larger magnitudes of plastic deformation of Zr-1Nb% alloy material can be used during its cold plastic working.

Keywords: zirconium-based alloy, cold metal plastic working, alternate deformation, flow stress, yield strength, Bauschinger effect

1. Introduction

Zirconium-based alloys are widely used for the manufacture of constructional elements to be used in nuclear power engineering and in the chemical industry, where high mechanical properties and corrosion resistance are demanded of materials [1-2]. The technology of manufacturing finished products of these alloys includes hot and cold plastic working. The hot plastic working of stock in the form of large-mass ingots is carried out by forging, rolling and extrusion methods [2]. W To obtain finished product, the obtained semi-finished product is subjected to subsequent cold plastic working by pilger rolling, drawing and straightening, while employing interstage and final heat treatment.

The magnitude of the flow stress σ_p of zirconium alloys under intermittent plastic working is influenced by numerous factors, including the temperature of deformed metal, preset deformation value, deformation rate and the history of metal loading [3]. In the case of hot plastic working, the appropriate distribution of reductions in a technological cycle (for example, in forging) causes the ingot temperature not to drop too quickly, whereby the plastic working of material of the investigated alloys can be increased in a narrower temperature interval. In cold deformation conditions (for instance, in pilger rolling), the magnitude of flow stress is influenced primarily by the rate and magnitude of deformation and by the history of deformation [4]. Based on their studies, the authors of numerous publications have pointed out that when determining the optimal cold plastic working process parameters, the Bauschinger effect occurring in the intermittent processes of pilger rolling, drawing and straightening of products should be taken into account [5-7]. This is caused by the possibility of a greater throughput of plastic working of the investigated alloy owing to a lower value of its yield strength, $R_{0.2\%}$. However, during the last operation of the cold plastic working process, that is straightening, the occurrence of the Bauschinger effect may adversely affect the mechanical properties, including yield strength $R_{0.2\%}$, of the finished product.

For the statistical range of loads, at deformation rates of $\dot{\varepsilon} = 10^{-4} - 10^{-2}\ s^{-1}$, methods for defining and determining the magnitude of the Bauschinger effect have been developed for many constructional materials. For the cases of dynamic alternate loading, the information on the Bauschinger effect is very limited [8]. Therefore, it is essential to investigate the Bauschinger effect with respect to dynamic metal working processes, including cold pilger rolling of zirconium-based alloys.

The results of the investigation of the effect of alternate dynamic loading on the magnitude of the flow stress σ_p of zirconium alloys will enable recommendations for the new unit strain distribution to be drawn up for intermittent cold metal plastic working processes used in the manufacture of round and flat products. In order to practically utilize the experimental data for technological processes, such as pilger rolling, drawing and product straightening, as well as other cold plastic working processes, the complex influence of the material structure, and the rate and magnitude of deformation at alternate loading on the variation of flow stress σ_p and yield strength $R_{0.2\%}$ needs to be assessed. The effect and interaction of these parameters can

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be determined using modern plastometric testing equipment, in conditions similar to those of technological processes used for manufacturing finished products of zirconium alloys [9-10].

The importance of the Bauschinger effect in respect of alternate intermittent deformations

During deformation within the elastic deformation region, deviations from the purely elastic deformation behaviour occur in the majority of metals and alloys, to a lesser or greater extent. One of the causes of this situation is the occurrence of the Bauschinger effect, whereby the value of the yield strength $R_{0.2\%}$ of deformed metal decreases as it is alternately loaded. With multiple or repeated deformation in the region of small plastic deformations running in opposite directions, also the flow stress σ_p magnitude of the deformed metal decreases.

The occurrence of this phenomenon is due to a different mode of formation of the dislocation structure at continuous deformation and intermittent alternate deformation. During multiple alternate loading, the dislocation structure of deformation changes. The dislocations are forced to move back to their sources, which causes an additional „Bauschinger" deformation to form. At the same time, after a considerable plastic pre-deformation with alternate loading, the redistribution of dislocations is difficult and the „Bauschinger" deformation magnitude approaches zero. The cause of the occurrence of the Bauschinger effect are, above all, ascending dislocations that move when the sign of the load changes, even at small deformations [11].

When examining the results of research on the Bauschinger effect, the following can be found:

- the Bauschinger effect is different for different metals; it is observed both in polycrystalline metals and in monocrystals, whereas, it occurs to a lesser extent in pure metals than in alloys;
- this effect depend on the magnitude of pre-deformation,
- the Bauschinger effect is not eliminated by a long break between loadings,
- the effect can be eliminated by employing heat treatment between loadings; whereas, for each material, there is a minimum heat treatment temperature and duration, at which the effect disappears.

In the conditions of cyclic (multiple) loading at small single deformations, the Bauschinger effect may be considerable. Therefore, the "single curve" hypothesis, which is widely used in plastic working mechanics, may only be used for continuous load processes. Whereas, the Lode index, μ_σ, is considered to be close to zero, which corresponds to pure shearing or the plane state of strain. The thermal effect of plastic deformation substantially increases the stress relaxation rate. Phenomena, such as the dislocation motion, punctual defects and the displacements of atoms within the grain boundary region become increasingly visible. An intensification of localized plastic strains and a decrease of stresses and forces needed for deformation follow. This is obviously of great practical importance, especially for the processes of pilger rolling, product straightening, etc. These processes are an example of distinct alternate intermittent loading of material under cold deformation conditions.

The size of the Bauschinger effect is most easily determined based on the curves of strain hardening (flow) of a given metal or alloy, obtained from alternate loading of specimens in a combination of different tests, such as upsetting-tension, alternate bidirectional torsion, tension-torsion, compression-torsion, etc.

Figure 1 shows a schematic diagram of alternate loading tests for the determination of the Bauschinger effect factor. At the first stage of loading, the specimen was deformed to a deformation value of ε_1 and went into a plastic state at a flow stress of σ_{p1}. After removing the load and taking a short break, the specimen was deformed in the direction opposite to the ε_2 strain magnitude. At the second stage, the specimen went into a plastic stage already at a flow stress of σ_{p2}, which is smaller than σ_{p1}. For the sake of analysis simplification, the flow curve $\sigma_p - \varepsilon$, obtained during deformation in the opposite direction, was rotated by 180° relative to the x axis.

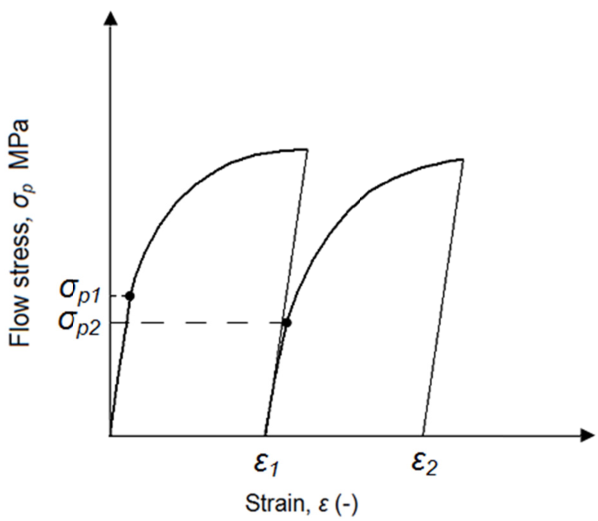


Fig. 1. Schematic diagram of the determination of the Bauschinger effect factor in alternate loading [7]

There are several parameters that are used for determining the magnitude of the Bauschinger effect [12]. In this study, the ratio of $R^1_{0,2\%}$ to $R^2_{0,2\%}$ was used for Bauschinger effect analysis:

$$k = \frac{R^2_{0,2\%}}{R^1_{0,2\%}} \tag{1}$$

where: k – Bauschinger effect factor, $R^2_{0,2\%}$ – yield strength at loading in the opposite direction, $R^1_{0,2\%}$ – yield strength during pre-loading.

Cold metal plastic working technologies, such as pilger rolling, product straightening and other intermittent processes are characterized by small partial deformations that usually do not exceed ε = 5-10%. For example, for the majority of pilger rolling grooved rolls used in tube rolling mills, partial deformations do not exceed 5% [5]. For this reason, the article reports testing results mainly for a small deformation range. The tests

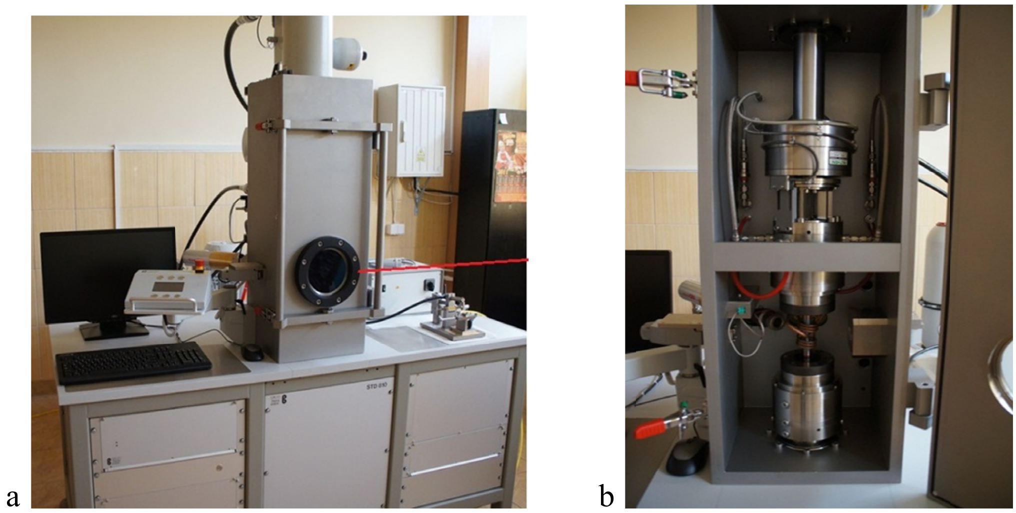


Fig. 2. The STD 812 plastometer: a) overall view; b) positioning of the holders in the working chamber

of alternate loading of zirconium alloy specimens were carried out on an STD-812 torsional plastometer (Fig. 2).

The characteristic of this instrument shows that it enables tests to be conducted at loads close to the conditions of intermittent alternate deformation in industrial cold plastic working processes.

2. The aim, scope and methodology of investigation force

The purpose of the study was to investigate the Bauschinger effect in alternate loading of the Zr-1% Nb zirconium alloy, for the conditions of cold plastic working of round cross-section products that had been previously heat treated at varying temperatures.

Zirconium-based alloys, including alloy Zr-1% Nb, are distinguished by the anisotropy of properties in the longitudinal direction and the transverse direction (the direction tangential to the axis of round cross-section product), which is associated with the texture that forms in the material due to the specificity of plastic working and heat treatment processes [13]. The value of the yield strength $R_{0,2\%}$ ($R_{0,2\%} = P_{0,2}/F_0$, where: $P_{0,2}$ – the force determined on the force-elongation diagram at a strain of 0.2%, F_0 – cross-sectional area of the working part of the specimen before testing) at room temperature and, above all, at temperatures occurring during the operation of the finished product, is especially important in the transverse material deformation direction, because during the operation of finished product (a fuel element can in nuclear power engineering) tensile stresses occur in the transverse direction due to an increase in internal pressure caused by an increase in the volume of products forming as a result of nuclear reaction.

Therefore, a torsion method was used in the study for the investigation of the Bauschinger effect, whereby specimens are deformed in the direction transverse to the product axis. The method of determining the flow stress σ_p ($\sigma_p = \sqrt{\sigma_{a.f}^2 + 3\tau_{\max}^2}$, where: $\sigma_{a.f.} = P_{a.f}/\pi r^2$, $P_{a.f}$ – axial force; $\tau_{\max} = 3M_t/2\pi r^3$, M_t – torque) in the torsion test is described in references [14]. The redundant strain in torsion is determined in the formula below:

$$\varepsilon = \pi dN/L \tag{2}$$

where: N – number of specimen rotations; d, L – specimen diameter and length.

Specimens of a working portion diameter of 6 mm and a length of 30 mm (Fig. 3) were made of cold rolled material. Before testing, the specimens were annealed at temperatures of $T = 540°C$, $T = 580°C$ and $T = 610°C$ for a duration of 180 minutes. The above temperatures correspond to the conditions used for interstage and final heat treatments, between cold plastic working operations, and assure an either partially ($T = 540°C$) or partially ($T = 580\text{-}610°C$) recrystallized structure of semi-finished products or finished products [15-16]. After increasing the annealing temperature from $T = 580°C$ to $T = 610°C$ during heating, the phase transition $\alpha \rightarrow \alpha + \beta$ starts in the Zr-1% Nb alloy.

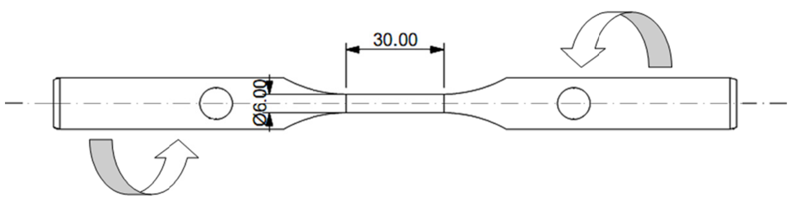


Fig. 3. Schematic diagram of loading a Zr-1% Nb alloy specimen in the STD-812 torsional plastometer

Figure 4-6 show programmes used for the examination of the Bauschinger effect of the Zr-1% Nb alloy at alternate loading by the specimen torsion method. These programmes differed in the magnitude of load employed in each alternate deformation cycle.

Programme 1, illustrated in Fig. 4, describes cyclic alternate loading of a specimen. After two identical cycles of deformation, its value in two subsequent cycles increased. The deformation ratio, $\varepsilon_2/\varepsilon_1$, was 1.00 in all cycles. This program covered the ε deformation range from 0.015 to 0.360.

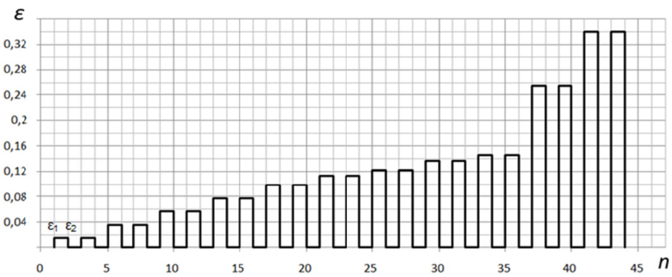


Fig. 4. Programme 1 of alternate ε deformation distribution in testing cycles n

Programme 2, shown in Fig. 5, is characterized by a different deformation amplitude in each alternate loading cycle and encompasses two testing schemes. For scheme 1, the ε deformation range was from 0.015 to 0.080, while the $\varepsilon_2/\varepsilon_1$ deformation ratio was contained in the range from 0.21 to 1.00. For scheme 2, the ε deformation range spanned from 0.09 to 0.14, while the $\varepsilon_2/\varepsilon_1$ deformation ratio was contained in the range from 0.74 to 1.00. The adopted ranges of deformation ratio values corresponded to conditions prevailing during the commercial manufacture of Zr-1% Nb alloy products by cold forming methods.

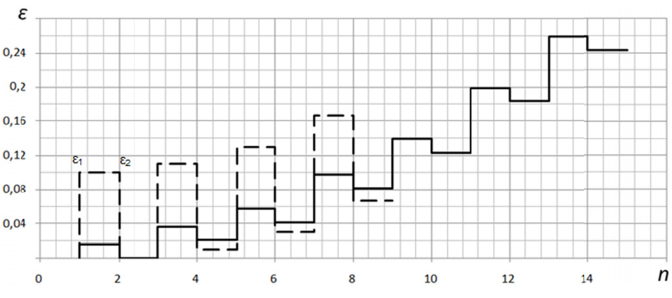


Fig. 5. Programme 2 of alternate ε deformation distributions in testing cycles n. Scheme 1 – solid line, Scheme 2 – dotted line

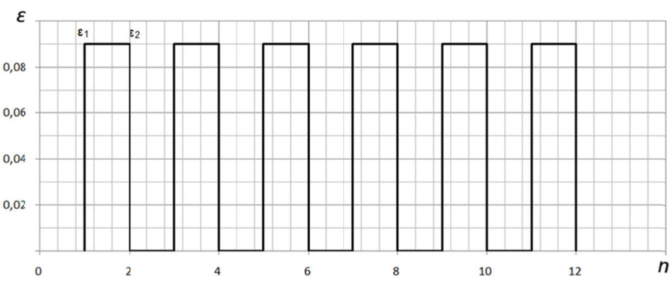


Fig. 6. Programme 3 of alternate ε deformation distribution in testing cycles n

Programme 3, shown in Fig. 6, contains 6 cycles of continuous alternate loading with a deformation of $\varepsilon = 0.09$. The $\varepsilon_2/\varepsilon_1$ deformation ratio was 1.00 for all deformation cases.

For the testing programmes shown (Figs. 4-6), breaks between loadings were 5 s, while the deformation rate did not exceed 0,5 s^{-1}.

3. Analysis of the investigation results

Figure 7 shows the Zr-1% Nb alloy flow curve for 4 deformation cycles, obtained using Programme 1 of intermittent loading (Fig. 4). When analyzing the first deformation cycle it can be noticed that the yield strength $R^1_{0,2\%}$ at pre-loading (1) amounts to 380 MPa, which corresponds to the results reported in previous studies [3]. With subsequent loading in the opposite direction, the yield strength decreased to 230 MPa, and the flow stress σ_p value decreased by approx. 10%. In the second loading cycle, with the same deformation range, the behaviour of flow stress σ_p value variation was retained. The yield strength, $R^1_{0,2\%}$, during pre-deformation is above the $R^2_{0,2\%}$ yield strength of the specimen rotated in the opposite direction. With the increase in deformation ε from 0.015 to 0.035, the value of flow stress σ_p increases with pre-loading and with loading in the opposite direction. Whereas, the difference between the values of $R^1_{0,2\%}$ and $R^2_{0,2\%}$ decreases.

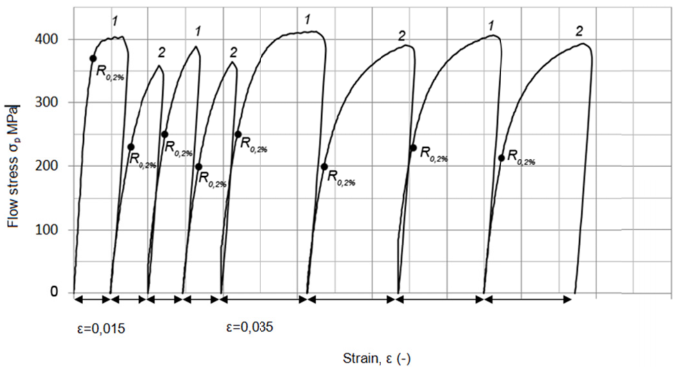
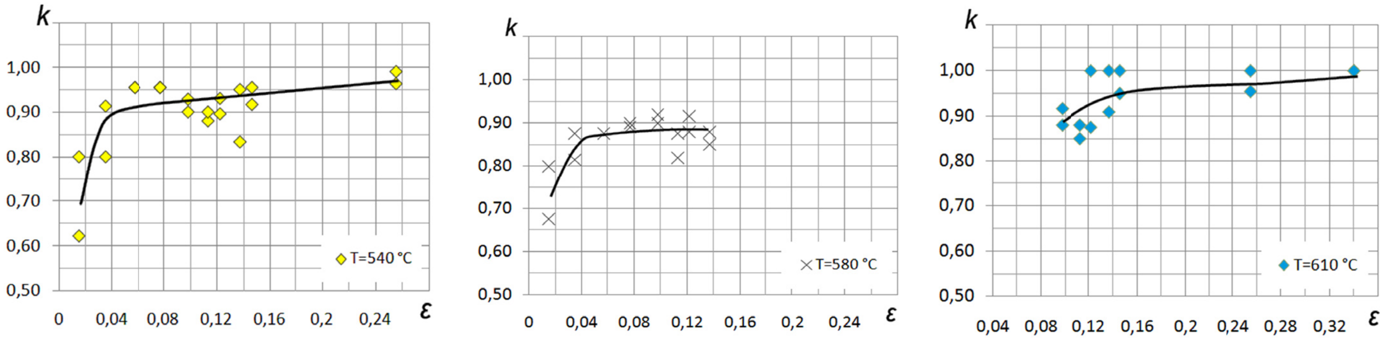


Fig. 7. The flow curve $\sigma_p - \varepsilon$ for the Zr-1% Nb alloy, obtained from alternate loading of specimens annealed at $T = 540°C$ on the STD-812 torsional plastometer; 1 – pre-deformation; 2 – deformation in the opposite direction

Figure 8 shows the values of Bauschinger effect coefficient k, determined for specimens annealed at different temperatures. It can be noticed that with the increase in pre-deformation magnitude, the value of k increases non-uniformly. In the deformation range of $\varepsilon = 0,01 \div 0,04$, the k value is in the interval from 0.60 to 0.90.

In the case of specimens subjected to heat treatment at a temperature of $T = 540°C$ (Fig. 8a), the k coefficient assumes slightly greater values for ε deformations from the range from 0.01 to 0.04, compared to specimens heat treated at a temperature of $T = 580°C$ (Fig. 8b). For specimens deformed according to Programme 1, the maximum increment in Bauschinger effect



a b c

Fig. 8. The dependence of Bauschinger effect coefficient k on the magnitude of pre-deformation ε in intermittent loading of Zr-1% Nb alloy specimens in the STD-812 torsional plastometer according to Programme 1, after heat treatment at: a) 540°C, b) 580°C, c) 610°C

coefficient value for all specimens occurs for an ε deformation range of up to 0.04. The smaller the value from the 0.6-1.0 range is attained by coefficient k for the investigated alloy, the greater the Bauschinger effect is.

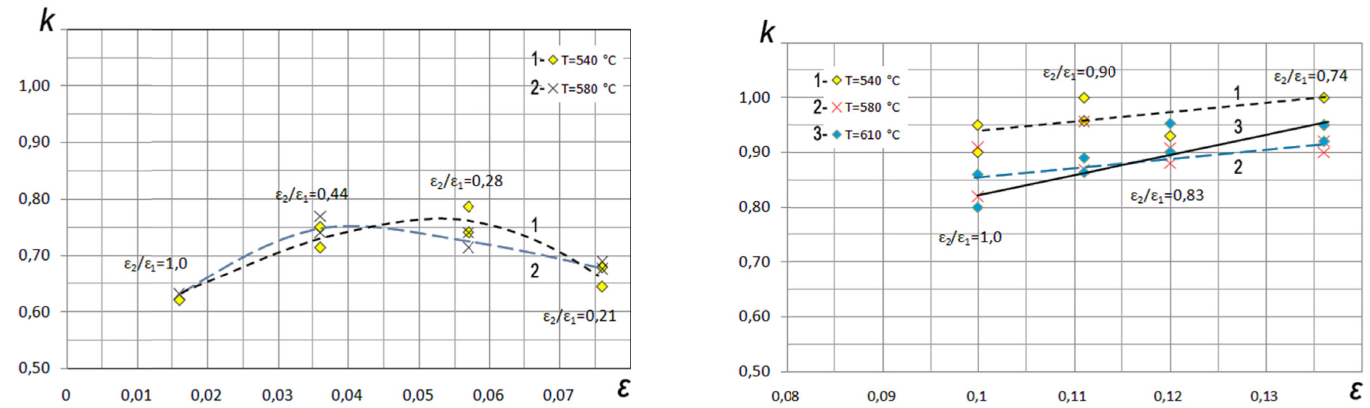
With the increase in heat treatment temperature, the range of deformations, for which the $R_{0.2\%}$ value decreases more, increases when the specimens are loaded in the opposite direction. During testing specimens prepared from stock after heat treatment carried out at temperatures of $T = 540°C$ (Fig. 8a) and $T = 580°C$ (Fig. 8b), for deformations $\varepsilon \leq 0.14$, the Bauschinger effect does occur, with the greatest magnitude of this effect being observed for specimens annealed at T = 580°C.

After increasing the stock heat treatment temperature from 580°C (Fig. 8b) to 610°C (Fig. 8c), an increase in the value of Bauschinger effect coefficient k was observed in the deformation range of $\varepsilon > 0.12$. A probable cause of this is the initiation of the phase transition $\alpha \rightarrow \alpha + \beta$ in these conditions, which leads to a hardening of the examined alloy.

After exceeding the deformation value of $\varepsilon > 0{,}16$ (Figs. 8a and 8c), coefficient k approaches 1.0, which means that no Bauschinger effect occurs for these conditions.

Figure 9 shows the results of Bauschinger effect testing for the Zr-1% Nb alloy, carried out according to Programme 2 for two loading schemes. It can be noticed from the data illustrated therein that, in the ε deformation range from 0.01 to 0.08, the Bauschinger effect is influenced by the magnitude of the $\varepsilon_2/\varepsilon_1$ deformation ratio (Fig. 9a). With the decrease in the value of this ratio from 1.00 do 0.21, the Bauschinger effect coefficient slightly increases with the increase in pre-deformation value up to $\varepsilon \approx 0.04$, and then decreases to $k \approx 0.65$-0.75 at $\varepsilon \approx 0.08$. With the increase in specimen heat treatment temperature from $T = 540°C$ do $T = 580°C$, the maximum in k-ε curve (2) slightly shifted towards smaller deformations. For the entire presented deformation region, there are no significant differences between k-ε curves (1) and (2) represented in Fig. 9a. According to the results shown in Fig. 9b, with the increase in ε deformation value from 0.10 to 0.14 and with the decrease in $\varepsilon_2/\varepsilon_1$ ratio value from 1.00 to 0.74, the behaviour of k-ε curves (1-3) is similar to that of the curves shown in Fig. 8. The influence of the $\varepsilon_2/\varepsilon_1$ deformation ratio on the Bauschinger effect for this range is not visible.

For a deformation of $\varepsilon = 0.09$, when the Bauschinger effect is negligible (Fig. 8), tests were carried out to determine the effect of the number of alternate loading cycles n, with their increase from 1 to 6, on the value of coefficient k. Looking at the results shown in Fig. 10 it can be noticed that with the increase in the number of cycles n at a constant deformation value, the Bauschinger effect decreases (the value of coefficient



a b

Fig. 9. Dependence of Bauschinger effect coefficient k on the value of pre-deformation ε in alternate loading of heat treated Zr-1% Nb alloy specimens in the STD-812 torsional plastometer according to Programme 2

k approaches 1.0). Moreover, in the case of specimens that had previously been heat treated at a higher temperature, the decrease in the Bauschinger effect was less noticeable. This phenomenon can be explained by the difficulty in dislocation redistribution with the increase in the number of loading cycles *n* in the range of applied deformations, at which a small Bauschinger effect occurs. Based on the presented test results it can be assumed that for the deformations, at which Bauschinger effect coefficient $k > 0.85$, with the increase in the number of loading cycles *n*, the Bauschinger effect coefficient value will approach zero for all examined heat pre-treatment variants. Therefore, the selection of deformations larger than $\varepsilon > 0.09$, from the point of view of the utilization of the Bauschinger effect, is not recommended for multi-cyclic plastic working processes, for example for pilger rolling.

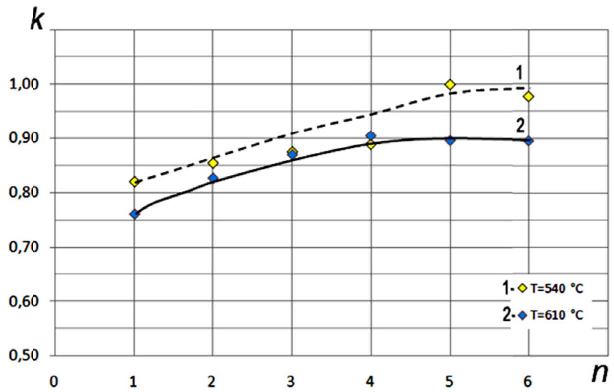


Fig. 10. Dependence of Bauschinger effect coefficient *k* on the number of cycles *n*, at a pre-deformation magnitude of $\varepsilon = 0.09$ in alternate loading of heat treated Zr-1% Nb alloy specimens in the STD-812 torsion plastometer according to Programme 3

To determine the influence of deformation rate on the Bauschinger effect for the Zr-1% Nb alloy, tests were carried out at $\dot{\varepsilon} = 0.1$ s^{-1} and 0.5 s^{-1} i deformations ε in the range from 0.03 to 0.09 ($\varepsilon_2/\varepsilon_1$ =1.0).This deformation range is more advantageous from the point of view of the intensification of cold plastic working processes. The increase in deformation rate above 0.5 s^{-1} was impossible due to small values of deformations applied. According to the results of the tests carried out, a slight decrease in the Bauschinger effect (not more than 6%) is observed with the increase in deformation rate to 0.5 s^{-1} (Fig. 11). Considering the fact that in intermittent cold plastic working processes the deformation rate in partial loadings rarely goes beyond the range examined in the study, its influence on the Bauschinger effect can be omitted.

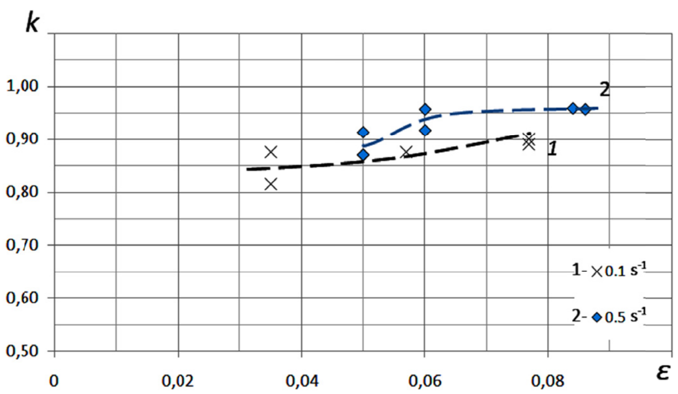


Fig. 11. Dependence of Bauschinger effect coefficient *k* on the magnitude of pre-deformation *ε* of Zr-1% Nb alloy specimens annealed at *T* = 580 °C, in alternate loading in the STD-812 torsional plastometer at a deformation rate of $\dot{\varepsilon}_1 = 0.1$ s^{-1} and $\dot{\varepsilon}_2 = 0.5$ s^{-1}

4. Conclusions

Based on the obtained results of the investigation of the occurrence of the Bauschinger effect during alternate loading of the Zr-1%Nb alloy by the torsion method, the following conclusions can be drawn:

1. There is a relatively small deformation value ($\varepsilon < 0.04$), at which the largest Bauschinger effect occurs (a small *k* coefficient value), and therefore it is advisable to determine the influence of the magnitude of pre-deformation on the change in flow stress σ_p and yield strength $R_{0,2\%}$.
2. For the improvement of the effectiveness of the processes of cold plastic working of Zr-1%Nb alloy products, it is advantageous to pre-anneal the stock at *T* = 580°C, because it is in these conditions that the Bauschinger effect in the deformed metal is the greatest and occurs for the largest *ε* deformation range.
3. To improve the effectiveness of cold plastic working processes through the utilization of the Bauschinger effect, when determining the partial deformations, one must strive for increasing the value of the $\varepsilon_2/\varepsilon_1$ ratio, with a range of ε_1 deformations not greater than 0.08.
4. In the alloy under investigation, with partial deformations in the ε range from 0.09 to 0.16, a small Bauschinger effect occurs; however, with the increase in the number of alternate loading cycles *n* for this deformation range, the difference between the values of the yields strengths $R^1_{0,2\%}$ and $R^2_{0,2\%}$ decreases. For this reason, this range of partial deformations, from the point of view of the utilization of the Bauschinger effect in multi-cyclic plastic working processes, is not recommended.
5. With the increase in deformation rate from 0.1 s^{-1} to 0.5 s^{-1}, a very negligible decrease in the Bauschinger effect occurred. Because, in intermittent cold plastic working processes, deformation rate at partial loadings seldom goes beyond the investigate range, the authors propose that the influence of deformation rate on the Bauschinger effect should be omitted for those processes.

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