PECULIARITIES OF THE DEFORMATION OF TITANIUM ALLOYS UNDER PLANE STRESS

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When establishing the connection between the stresses and strains for non-linearly elastic bodies, with the aim of simplification we use a number of hypotheses. Fundamental out of them are the hypotheses about proportionality of the spherical stress tensor to the spherical strain tensor, similarity of the stress and strain deviators, and uniqueness of the deformation curve. The validity of these hypotheses have been repeatedly verified experimentally on a series of material: steel [1, 6, 13], copper [4, 8], brass [1], nickel [4, 10], bronze [3], aluminum an magnesium alloys [5, 7, 14]. For certain materials these hypotheses were confirmed, for other systematical deviations are observed. For titanium and its alloys such data is practically inexistent.

Side by side with this the mechanism of plastic strain of titanium alloys, in view of the peculiarity of their structural state, substantially differs from other metals. Thus, for example, during the development of simultaneous slip along different planes a large number of packing defects is formed. As a result of this the densely packed hexagonal lattice is transformed into a body-centered lattice directly or with formation of an intermediate face-centered lattice. At the same time phase transformations are accompanied by a volume variation of the material.

In the given paper, on an example of the titanium alloys VT-6S and VT-14, we have verified the hypotheses about a unique deformation curve, similarity of the stress and strain deviators, as well as about applicability of the well-known plasticity conditions for the assessment of the limiting states. Both alloys were first subjected to a heat treatment according to the following regime: VT-6S, hardening from 900° C, aging at 480° C for 2 h; VT-14, hardening from 870° C, aging at 480° C for 8 h. In the undeformed state the difference of the yield points under uniaxial tension along and across the rolling direction was 2% for VT-6S, while for VT-14 it was 3%.

A plane stress state was produced by loading thin-walled tubular testpieces (the ratio of the diameter to the wall thickness D/δ = 29.5/0.75 ∼40) by an axial force and an internal pressure.

The straight lines passing through the origin of the coordinates

\[ \sigma_1 = n \sigma_t \quad (n = 0; 0.2; \pm 0.5; 0.8; \pm 1; \pm 2; \pm \infty) \]

served as the loading trajectories. Here \( \sigma_1 \) is the stress coinciding with the direction of the axis of the testpiece; \( \sigma_t \) is the transverse (tangential) stress.

We note that the coefficient \( n = \infty \) corresponds to longitudinal tension, \( n = -\infty \) corresponds to longitudinal compression, \( n = 0 \) corresponds to transverse tension, and \( n = -1 \) corresponds to pure shear.

The tests were carried out on a machine of the TsDMU-30t type, the deformations were measured by mechanical extensometers with IGM microindicators [12]. A deformation curve in the generalized coordinates (stress intensity \( \sigma_1 \) – strain intensity \( \varepsilon_1 \)) was plotted for each value of \( n \).

§ 1. The influence of the character of the stress state on the deformation curve is usually connected with the value of the average normal stress and the form of the stress deviator, which, respectively, can be determined by the coefficient \( K = \sigma_{av}/\sigma_1 \) and the Lode parameter

where \( \sigma_{av} \) is the average normal stress; \( \sigma_1, \sigma_2, \sigma_3 \) are the principal stresses, with \( \sigma_1 > \sigma_2 > \sigma_3 \).

For a plane stress state we have

\[
\sigma_{av} = \frac{\sigma_1 + \sigma_2}{3}; \quad \sigma_i = \sqrt{\sigma_i^2 - \sigma_i \sigma_i + \sigma_i^2}.
\]

Introducing the notation \( \sigma_1/\sigma_i = n \), the expression \( K \) can be represented in the form

\[
K = \frac{n + 1}{3\sqrt{n^2 - n + 1}}.
\]

Graphically in the region being investigated this relationship is depicted by the curve 1 in Fig. 1. Here along the abscissa axis, for the sake of convenience, we have marked off the quantity \( \alpha = \arctan n \). As we see, the maximum value of \( K \) occurs for \( n = 1 \) (\( K = 0.663 \)), while the minimum value (for the region \( \sigma_1 > \sigma_i > \sigma_2 \)) occurs for \( n = -\infty \) (\( K = -0.333 \)). We note that these stress states are characterized by the identical Lode parameters \( \mu_\sigma = 1 \).

In Fig. 2a (VT-6S) and 2b (VT-14) we have shown the average deformation curve with the experimental points corresponding to \( n = 1 \) (hollow circles), \( n = -\infty \) (filled-in circles) and \( n = 0 \) (crosses). For the last stress state the quantity \( K \) assumes an intermediate position between the first two, while \( \mu_\sigma = -1 \).

From Fig. 2 we see that the effect of the average normal stress for both materials is practically inexistent. The effect of the sign of \( \mu_\sigma \) also does not manifest itself. The largest deviation of the stress from the average value, for the same deformation, amounts to 3% for the alloy VT-6S; for the alloy VT-14 it amounts to 2%.

The influence of the average normal stress on the deformation curve has most extensively been investigated by Bridgman [2] on pure metals and steels. In this work it is shown that an appreciable change in the resistance to deformation is observed only when \( \sigma_{av} \) is increased by several orders. On the other hand, tests [3] on iron, beryllium and aluminum bronze are known from which we see that a small variation of \( K \) (from 0.333 to 1.5) can lead to a substantial deviation of the generalized curves (up to 15%). This circumstance is connected with a metastable structure of the material [11] or with an anisotropy [5, 7].

The absence of the influence of the average normal stress noted above allows us to investigate the role of the form of the stress deviator. In connection with this we shall analyze the character of dependence of the Lode parameter \( \mu_\sigma \) on the ratio of principal stresses \( n \).

For \( \sigma_1 > \sigma_i > 0 \) we have \( \sigma_1 = \sigma_i; \quad \sigma_2 = \sigma_i; \quad \sigma_3 = 0 \). Consequently,

\[
\mu_\sigma = \frac{2}{n} - 1 \quad (n = 1 - \infty).
\]

If \( \sigma_1 > \sigma_i > 0 \), then \( \sigma_1 = \sigma_i; \quad \sigma_2 = \sigma_i; \quad \sigma_3 = 0 \). Then

\[
\mu_\sigma = 2n - 1 \quad (n = 0 - 1).
\]

For \( \sigma_i > 0 > \sigma_i \) we obtain \( \sigma_1 = \sigma_i; \quad \sigma_2 = 0; \quad \sigma_3 = \sigma_i \). With this notation taken into account, we find that

\[
\mu_\sigma = \frac{1 + n}{1 - n}.
\]