International Applied Mechanics, Vol. 41, No. 3, 2005

PLASTIC INCOMPRESSIBILITY OF ANISOTROPIC MATERIAL*

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Some characteristics of an initially anisotropic aluminum alloy are investigated. The coefficients of transverse elastoplastic and plastic strain are calculated. It is established that the coefficients of transverse plastic strain are much different from 0.5 in directions that are not in the plane of isotropy. It is also shown that the material is plastically incompressible. The possibility of using Hill's theory of flow with isotropic hardening to describe the inelastic behavior of the material is examined

Keywords: orthotropic solid, plastic incompressibility, isotropic hardening

Introduction. The hypotheses that the yield point is independent of the mean normal stress and that the material is plastically incompressible are among the most important initial assumptions made in many theories of anisotropic plasticity. The former hypothesis underlies Hill's and Mises' theories of anisotropic plasticity [14, 19]. Because of this assumption, the plastic strains following from the associate flow rule satisfy the plastic-incompressibility condition. The nonquadratic Hill criterion later formulated in [15] is also based on this assumption. Developing methods for description of anisotropic plasticity, many authors assumed that the yield point is independent of the mean normal stress, referring mainly to Bridgeman's experiments. The authors of [23] pointed to the importance of the assumptions that yield is independent of hydrostatic pressure and plastic incompressibility in the theory of plasticity. The relationship between the effect of hydrostatic pressure on the yield point and plastic compressibility was analyzed in [21, 24], where it was revealed for various steels and polymers that the yield point strongly depends on pressure, without the corresponding plastic change in volume. Using experimental data for aluminum alloys and carbon steels, the authors of [16] confirmed the hypothesis that during inelastic deformation the volume of a material does not change while the strains are less than 4%. The authors of [12] experimentally detected the plastic compressibility of flat aluminum-alloy samples and attributed that to plastic anisotropy.

Many publications describe anisotropic plasticity using various assumptions, including the hypothesis that the material is plastically compressible. A theory of anisotropic plasticity for plastically compressible materials was addressed in [10, 26–29]. The paper [10] proposed a generalized potential for anisotropic materials that accounts for the Bauschinger effect and plastic compressibility (a special case of this potential is the Hill potential) and showed, based on experimental data for a titanium alloy, that the behavior of yield locus is essentially dependent on the compressibility parameter introduced by the author.

Deformation-type equations describing the inelastic behavior of an anisotropic material under proportional loading were derived in [22]. There are many publications that propose deformation-type equations to describe anisotropic plasticity (see, e.g., [1, 3, 5, 6]). The equations in [22] have been derived without assumptions (as to plastic potential, hardening, plastic incompressibility, etc.) usually used by other authors. These equations have the form of stress–strain relations as a generalization

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* The study was partially sponsored by the State Fund for Basic Research of the Ministry of Education and Science of Ukraine (Grant No. 01.07/00010).

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TABLE 1

Element	Cu	Mg	Mn	Al
Percentage	4.1	1.6	0.6	93.7

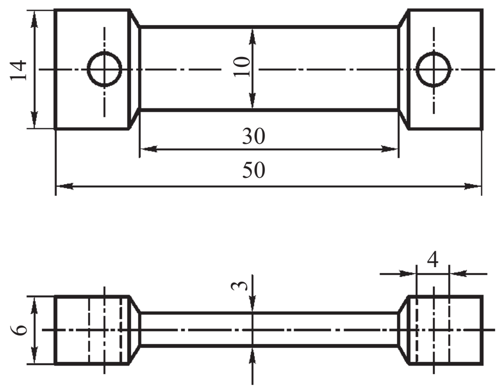

Fig. 1

of Hooke's law for an orthotropic body where elastic constants are replaced by shear strain intensity functions determined from uniaxial tension tests on flat samples. The matrix of coefficients of the resulting constitutive equations turned out to be asymmetric beyond the elastic limit, as the analogous matrix in [2]. In the elastic domain, these coefficients turn to the elastic constants and the matrix becomes symmetric. After determining these coefficients from uniaxial tension tests on flat samples, the authors of [22] applied the equations to describe the deformation of thin-walled tubular samples under proportional loading by tension, internal pressure, and torsion. The theoretical and experimental results turned out to be in good agreement.

We will use the experimental data obtained in [22] to analyze the plastic incompressibility of an aluminum alloy over a range of strains up to 4%. These data were partially used in [7–9, 13] to solve boundary-value problems of the theory of shells. We will also calculate the coefficients of transverse plastic strain, since many authors (such as those of [11, 18, 20, 25, 30]) use them to determine anisotropic yield criteria. The possibility of describing inelastic deformation by Hill's theory of flow with isotropic hardening will be discussed too. The results to be cited below might be useful for deriving constitutive equations that describe anisotropic plasticity.

1. Material, Samples, and Experimental Data. Experimental data have been obtained for D16T aluminum alloy samples in the form of a bar 5 mm in diameter. The chemical composition of the material is given in Table 1. The bar has been hot die pressed, but has not been annealed. Owing to the manufacturing technique, we may assume that the material of the bar is transversely isotropic and its axes of anisotropy coincide with the axes of a cylindrical coordinate system r, φ, z (the z-axis running along the bar). The principal axes of anisotropy were checked by compressing solid cylindrical samples, as indicated in [22]. Also, the homogeneity and anisotropy of the material were tested. To this end, flat samples had been cut out of the bar along its axis and radius. The samples with dimensions are shown in Fig. 1. The samples were subjected to tension at a constant temperature of 20 °C on a TsDM-5 testing machine. A pneumatic stain-gauge [4] was used to measure the longitudinal and transverse strains in the direction of the major lateral dimension.

To check whether the material is homogeneous, four groups of flat samples (a, b, c, and d) were cut out of the bar, in parallel to and at different distances from its axis (Fig. 2). The test data for the samples of groups a, b, and c were averaged, since their range of variability did not exceed 5%. The test data for the group d samples differed from those for the samples of groups a, b, and c by more than 5%. Thus, it was established that the material is homogeneous within the limits of ∅40 mm and that samples should be cut out so that their test portion is within these limits. The results of testing the samples of groups a, b, and c were plotted (σ_{zz} vs. ε_{zz} curves) and are summarized in Table 2.

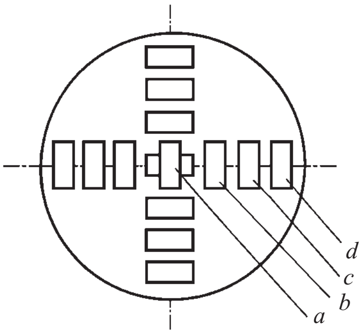

Fig. 2

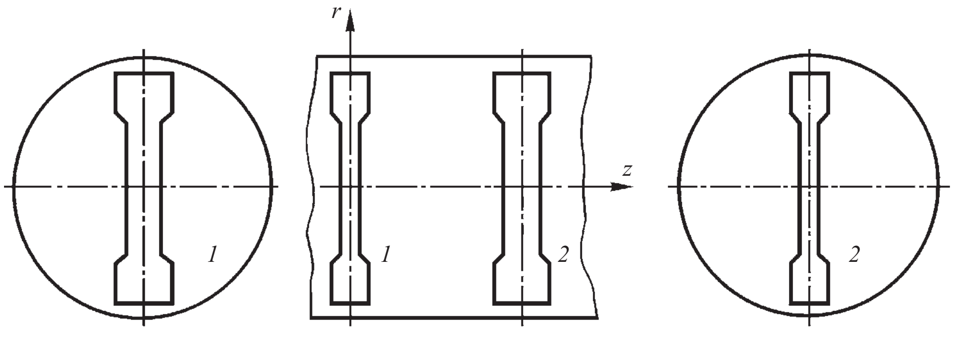

Fig. 3

TABLE 2

σ_{zz}, MPa	$\varepsilon_{zz} \cdot 10^2$	$\varepsilon_{rr} \cdot 10^2$
172.1	0.195	–0.065
378.0	0.429	–0.143
420.1	1.07	–0.456
429.2	1.30	–0.569
439.5	1.62	–0.725
444.8	1.80	–0.816
452.6	2.11	–0.969
455.8	2.25	–1.04
462.5	2.57	–1.20
470.4	2.97	–1.40
485.7	3.86	–1.84
488.0	4.00	–1.91

TABLE 3

σ_{rr}, MPa	$\varepsilon_{rr} \cdot 10^2$	$\varepsilon_{\varphi\varphi} \cdot 10^2$	$\varepsilon_{zz} \cdot 10^2$
166.1	0.199	–0.063	–0.063
276.1	0.420	–0.190	–0.106
312.1	1.02	–0.682	–0.200
320.0	1.24	–0.855	–0.244
328.9	1.54	–1.09	–0.304
332.5	1.68	–1.20	–0.331
340.5	2.01	–1.46	–0.398
344.3	2.20	–1.61	–0.436
349.1	2.45	–1.81	–0.487
355.7	2.83	–2.11	–0.563
367.5	3.65	–2.76	–0.729
369.3	3.79	–2.87	–0.758

To check whether the material is anisotropic, flat samples of two types were cut out of the bar along its radius (Fig. 3). The major lateral dimension of the type 1 samples lies in the plane $r\varphi$ and of the type 2 samples is aligned along the z-axis. These samples were subjected to tension, and the longitudinal and transverse strains were measured. The transverse strains were measured in the direction of the major lateral dimension at the same stress σ_{rr}, i.e., the strain $\varepsilon_{\varphi\varphi}$ was measured on the type 1 sample and the strain ε_{zz} on the type 2 sample at the same tensile stress σ_{rr}. The test data were averaged over 12 samples of each type. After that, the σ_{rr} vs. ε_{rr} curves were plotted and the results obtained collected in Table 3.

To check whether the cross section of the bar is isotropic, thin-walled tubular samples 21 mm in diameter were made from the bar so that their axes coincide with the bar axis. The tubular samples were subjected to internal pressure and measured. The measurement results were used to plot the $\sigma_{\varphi\varphi}$ vs. $\varepsilon_{\varphi\varphi}$ curves, which turned out to coincide with the σ_{rr} vs. ε_{rr} curves. This confirms the assumption of isotropy of the bar's cross section. Figure 4 shows σ_{zz} versus ε_{zz} (curve *1*) and σ_{rr} versus ε_{rr} (curve

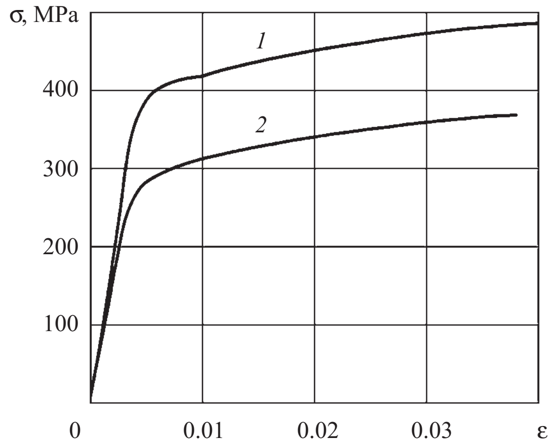

Fig. 4

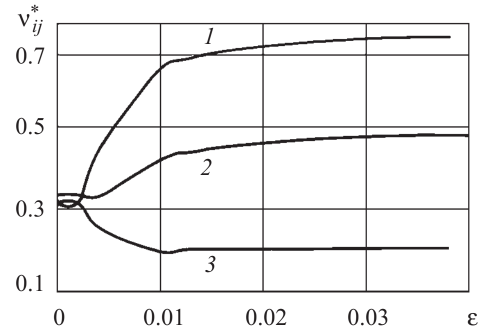

Fig. 5

2). As is seen, the properties of the material in the r- and z-directions differ insignificantly in the elastic domain and significantly in the plastic domain.

2. Basic Assumptions. Consider a homogeneous orthotropic body described in an orthogonal coordinate system r, φ, z with axes coinciding with the principal axes of anisotropy. Let the inelastic strain tensor ε_{ij} be defined by

$$\varepsilon_{ij} = \varepsilon_{ij}^{(e)} + \varepsilon_{ij}^{(p)}, \tag{1}$$

where $\varepsilon_{ij}^{(e)}$ and $\varepsilon_{ij}^{(p)}$ are the elastic and plastic components. Assume that the elastic strains $\varepsilon_{ij}^{(e)}$ are related to the stresses by the generalized Hooke's law for an orthotropic body:

$$\varepsilon_{rr}^{(e)} = \frac{\sigma_{rr}}{E_r} - \nu_{r\varphi}\frac{\sigma_{\varphi\varphi}}{E_\varphi} - \nu_{rz}\frac{\sigma_{zz}}{E_z}, \quad \varepsilon_{r\varphi}^{(e)} = \frac{\sigma_{r\varphi}}{2G_{r\varphi}} \quad (r, \varphi, z), \tag{2}$$

where E_i are the elastic moduli along the principal axes of orthotropy, $G_{ij} = G_{ji}$ are the shear moduli between these axes, ν_{ij} are Poisson's ratios characterizing the strains along the i-axis due to tension along the principal axis j, and σ_{ij} are the components of the stress tensor in the principal axes of orthotropy. The symbol (r, φ, z) denotes cyclic permutation of indices (the other expressions can be obtained by replacing r by φ, φ by z, and z by r). For the transversely isotropic material under consideration, the r- and φ-directions are equivalent: $E_r = E_\varphi, G_{rz} = G_{\varphi z}, \nu_{rz} = \nu_{\varphi z}, \nu_{r\varphi} = \nu_{\varphi r}$, and $\nu_{z\varphi} = \nu_{zr}$.

3. Coefficients of Transverse Strain. Plastic Incompressibility Condition. Consider flat samples under uniaxial tension. Their planes coincide with the plane of orthotropy. When a sample is stretched in the direction of orthotropy r, the strains in the φ- and z-directions can be expressed in terms of its strain ε_{rr} in the r-direction:

$$\varepsilon_{\varphi\varphi} = -\nu^*_{\varphi r}\varepsilon_{rr}, \quad \varepsilon_{zz} = -\nu^*_{zr}\varepsilon_{rr} \quad (r, \varphi, z), \tag{3}$$

where ν^*_{ij} are the coefficients of transverse strain. When the tensile strains of a sample are elastic, these coefficients are ordinary Poisson's ratios for an orthotropic body, i.e., $\nu^*_{ij} = \nu_{ij}$.

By analogy with (3), the plastic strains are

$$\varepsilon_{\varphi\varphi}^{(p)} = -\nu^{**}_{\varphi r}\varepsilon_{rr}^{(p)}, \quad \varepsilon_{zz}^{(p)} = -\nu^{**}_{zr}\varepsilon_{rr}^{(p)} \quad (r, \varphi, z), \tag{4}$$

where ν^{**}_{ij} are the coefficients of transverse plastic strain. If the material is plastically incompressible, then

TABLE 4

$\nu_{\varphi r}^{**}$	ν_{zr}^{**}	ν_{rz}^{**}
0.956	0.014	0.292
0.872	0.126	0.500
0.856	0.143	0.499
0.843	0.156	0.500
0.839	0.160	0.500
0.831	0.168	0.500
0.828	0.171	0.500
0.825	0.175	0.500
0.821	0.178	0.500
0.816	0.184	0.500
0.815	0.184	0.500

TABLE 5

Δ_1	Δ_2	Δ_3
–1.16	–6.93	–2.00
–1.24	–5.14	–2.01
–1.24	–5.11	–1.99
–1.25	–5.10	–2.01
–1.25	–5.09	–2.00
–1.25	–5.07	–2.00
–1.25	–4.97	–2.00
–1.25	–5.06	–2.01
–1.25	–4.99	–2.00
–1.25	–4.97	–1.95

$$\varepsilon_{rr}^{(p)} + \varepsilon_{\varphi\varphi}^{(p)} + \varepsilon_{zz}^{(p)} = 0. \tag{5}$$

And if (4), then

$$1 - \nu_{\varphi r}^{**} - \nu_{zr}^{**} = 0 \quad (r, \varphi, z). \tag{6}$$

Let us calculate the coefficients of transverse strain and transverse plastic strain and test conditions (6) using Tables 2 and 3. The first rows of Tables 2 and 3 correspond to the elastic state of the material. From these values, we can determine the elastic moduli and Poisson's ratios: $E_r = 834673$ MPa, $E_z = 882564$ MPa, $\nu_{r\varphi} = 0.317$, $\nu_{rz} = 0.335$, and $\nu_{zr} = 0.317$; and from Tables 2 and 3, the coefficients of transverse plastic strain. Figure 5 shows how these coefficients depend on the longitudinal strains (curves *1*, *2*, and *3* correspond to $\nu_{\varphi r}^{*}$, ν_{rz}^{*}, and ν_{zr}^{*}, respectively). It is seen that the larger the longitudinal strain, the less intensively the functions $\nu_{\varphi r}^{*}$, ν_{rz}^{*}, and ν_{zr}^{*} vary.

Let us determine the plastic strains induced by uniaxial tension. Using formulas (2) and Table 2 (tension in the *z*-direction), we get

$$\varepsilon_{rr}^{(e)} = \frac{\sigma_{rr}}{E_r}, \quad \varepsilon_{\varphi\varphi}^{(e)} = -\nu_{\varphi r}\varepsilon_{rr}^{(e)}, \quad \varepsilon_{zz}^{(e)} = -\nu_{zr}\varepsilon_{rr}^{(e)}, \tag{7}$$

and then from (1) and (7), we obtain

$$\varepsilon_{rr}^{(p)} = \varepsilon_{rr} - \varepsilon_{rr}^{(e)}, \quad \varepsilon_{\varphi\varphi}^{(p)} = \varepsilon_{\varphi\varphi} - \varepsilon_{\varphi\varphi}^{(e)}, \quad \varepsilon_{zz}^{(p)} = \varepsilon_{zz} - \varepsilon_{zz}^{(e)}. \tag{8}$$

Using (8), we determine the coefficients of transverse plastic strain $\nu_{\varphi r}^{**} = \left|\frac{\varepsilon_{\varphi\varphi}^{(p)}}{\varepsilon_{rr}^{(p)}}\right|$ and $\nu_{zr}^{**} = \left|\frac{\varepsilon_{zz}^{(p)}}{\varepsilon_{rr}^{(p)}}\right|$. Following a similar procedure and using Table 3 (tension in the *r*-direction), we can determine the coefficient of transverse plastic strain ν_{rz}^{**}. The values of the coefficients are summarized in Table 4.

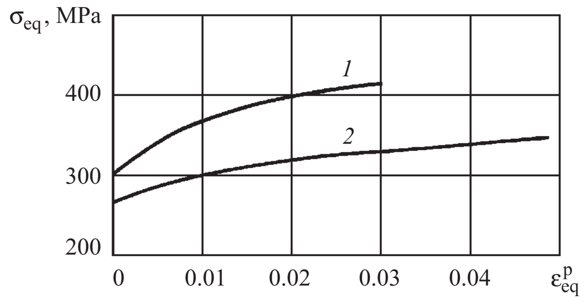

Fig. 6

Based on the data of Table 4, we test the three conditions (6), considering that $\nu^{**}_{r\varphi}=\nu^{**}_{\varphi r}$, $\nu^{**}_{z\varphi}=\nu^{**}_{zr}$, and $\nu^{**}_{\varphi z}=\nu^{**}_{rz}$ for the material under consideration because (r,φ) is the plane of isotropy. As is seen, the conditions (6) are satisfied for all rows of Table 3, except for the first one. The reason is that the first row contains the minimum plastic strains commensurable with the gauge error.

4. Isotropic (Proportional) Hardening Condition. We will use the above results to test the isotropic (proportional) hardening condition of Hill's theory of flow [14]. For an orthotropic material under uniaxial tension, these conditions are

$$d\varepsilon^{(p)}_{rr}:d\varepsilon^{(p)}_{\varphi\varphi}:d\varepsilon^{(p)}_{zz}=H_0+G_0:-H_0:-G_0 \tag{9}$$

in the r-direction,

$$d\varepsilon^{(p)}_{\varphi\varphi}:d\varepsilon^{(p)}_{rr}:d\varepsilon^{(p)}_{zz}=F_0+H_0:-H_0:-F_0 \tag{10}$$

in the φ-direction, and

$$d\varepsilon^{(p)}_{zz}:d\varepsilon^{(p)}_{rr}:d\varepsilon^{(p)}_{\varphi\varphi}=G_0+F_0:-G_0:-F_0 \tag{11}$$

in the z-direction, where F_0, G_0, and H_0 are constants related to the anisotropy parameters F, G, and H as $F=F_0/h^2$, $G=G_0/h^2$, and $H=H_0/h^2$, and $h\geq 1$ is the constant of proportionality. If the material is transversely isotropic and (r,φ) is its plane of isotropy, which is the case here, then $F_0=G_0$. Using the values of plastic strains calculated above, we determine their increments and incremental ratios according to (9)–(11). The incremental ratios of $(\Delta\varepsilon^{(p)}_{rr})/(\Delta\varepsilon^{(p)}_{\varphi\varphi})=(H_0+G_0)/(-H_0)=\Delta_1$, $(\Delta\varepsilon^{(p)}_{rr})/(\Delta\varepsilon^{(p)}_{zz})=(H_0+G_0)/(-G_0)=\Delta_2$, and $(\Delta\varepsilon^{(p)}_{zz})/(\Delta\varepsilon^{(p)}_{rr})=(G_0+F_0)/(-G_0)=\Delta_3$ are collected in Table 5. The table demonstrates that beginning with the second row ($\varepsilon_{rr}>1\%$, $\varepsilon_{zz}>1\%$), the incremental ratios of plastic strains may approximately be considered constant, since they differ from the mean value by no greater than 2%. For Hill's theory of flow with isotropic hardening to describe plastic behavior adequately, it is not sufficient, according to [17], that the parameters $F_0=G_0$ and H_0 be constant, as the theory requires. It is necessary to establish the relationship between the equivalent stress σ_{eq} and the equivalent plastic strain ε^{p}_{eq}. Toward this end, we use Table 5 and the uniaxial tension curve (σ_{rr} versus $\varepsilon^{(p)}_{rr}$) to calculate σ_{eq} and ε^{p}_{eq} by the formulas

$$\sigma_{eq}=\alpha\sigma_{rr},\qquad \varepsilon^{p}_{eq}=\frac{\varepsilon^{(p)}_{rr}}{\alpha},\qquad \alpha=\sqrt{\frac{3\left(G_0+H_0\right)}{2\left(F_0+G_0+H_0\right)}}.$$

After that, using the uniaxial tension curve (σ_{zz} versus $\varepsilon^{(p)}_{zz}$), we again plot the σ_{eq} vs. ε^{p}_{eq} curve, where $\sigma_{eq}=\beta\sigma_{zz}$ and $\varepsilon^{p}_{eq}=\dfrac{\varepsilon^{(p)}_{zz}}{\beta}$, $\beta=\sqrt{\dfrac{3\left(F_0+H_0\right)}{2\left(F_0+G_0+H_0\right)}}$.

If the material is described by Hill's theory, then these two curves (σ_{eq} versus ε^{p}_{eq}) must coincide. Figure 6 shows both curves: σ_{rr} versus $\varepsilon^{(p)}_{rr}$ (curve *1*) and σ_{zz} versus $\varepsilon^{(p)}_{zz}$ (curve *2*). As is seen, these curves do not coincide. What this means is that Hill's theory of flow with isotropic hardening can describe the elastoplastic behavior of the material only approximately. It should be noted that the equations from [22] describe well the inelastic behavior of the material.

5. Conclusions.

1. The transversely isotropic material examined is plastically incompressible.

2. The coefficients of transverse plastic strain vary with increase in longitudinal strain and tend to constant levels.

3. The coefficients of transverse plastic strain in directions that are not in the plane of isotropy are much different from 0.5.

4. Despite the fact that Hill's proportionality condition is satisfied for the material, the σ_{eq} vs. ε^{p}_{eq} curves derived from the curves of uniaxial tension in two principal directions of anisotropy differ significantly. To describe the plastic behavior of the material approximately based on Hill's theory of flow with isotropic hardening, the averaged σ_{eq} vs. ε^{p}_{eq} curve can be used.

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