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Abstract

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EXPERIMENTAL STUDY OF THE LIMIT LOAD-BEARING CAPACITY OF THIN-WALLED NICKEL TUBES UNDER VARIOUS LOADING PATHS BY TENSILE FORCE, TORQUE, AND INTERNAL PRESSURE

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Numerous works have been devoted to the study of the ultimate resistance of plastic materials using thin-walled tubular specimens. Nevertheless, this question cannot be considered clarified with sufficient completeness. The present work* was undertaken with the aim of achieving a possibly more thorough study of the phenomenon on a sufficiently homogeneous and isotropic material over a wide range of variation in the form of the stress deviator. The quantities of the true stresses and strains corresponding to the limiting values of the loads were studied.

The tests were carried out on thin-walled tubular specimens made of technically pure nickel, which after annealing possessed a sufficiently good degree of homogeneity and isotropy (the material and specimens are described in ([1])). The specimens were tested on a special installation in which the tensile force and torque were produced by direct loading, and the internal pressure by a hydraulic press. The installation was equipped with a device ensuring shockless application of the load. During the tests, the longitudinal and transverse strains and the angle of twist were measured; the radial strain was determined from the condition of constancy of volume.

The stage of limiting load-bearing capacity was reached both by proportional loading (carried out in true stresses) and by complex paths. Complex loading in most cases was carried out in two stages: the specimen was first subjected to the action of one force factor, which thereafter remained constant, and was brought to failure as a result of the increase of one or two other force factors. In loading the specimens by torque and internal pressure, several multistage paths were also used. Testing along each path was repeated on 2–3 specimens.

The experiments showed that exhaustion of the load-bearing capacity (i.e., attainment of such a state in which further deformation is accompanied by a decrease of at least one force factor) occurs either because of local loss of stability due to necking or bulging (formation of a bubble), or because of general loss of stability (occurring in all cases at the stage of plastic deformation with violation of the cylindrical form of the tube). The latter was observed when testing specimens in tension with torsion.

The characteristics of the limiting states for cases in which the load-bearing capacity proved to be exhausted as a result of local loss of stability are given in Table 1 (proportional loadings) and in Table 2

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* Reported at the First All-Union Congress on Theoretical and Applied Mechanics.

Table 1

Loading path	Stress-deviator parameter, μ	$2\tau_{max}$, kg/mm^2	σ_i, kg/mm^2	$\varepsilon_i \cdot 10^2$
$\sigma_t = 0;\ \tau = 0$	−1	46,8	46,8	25,3
$\sigma_x = 2,75\,\sigma_t;\ \tau = 1,3\,\sigma_t$	−1	46,9	46,9	24,2
$\sigma_x = 1,37\,\sigma_t;\ \tau = 1,12\,\sigma_t$	−0,957	47,6	47,3	25,6
$\sigma_x = 3\,\sigma_t;\ \tau = 0,5\,\sigma_t$	−0,717	47,2	44,0	23,8
$\sigma_x = 0,5\,\sigma_t;\ \tau = 0,5\,\sigma_t$	−0,708	45,1	42,2	22,7
$\sigma_x = 3,96\,\sigma_t;\ \tau = 0$	−0,5	46,6	42,2	21,7
$\sigma_x = 0,5\,\sigma_t;\ \tau = 0,375\,\sigma_t$	−0,5	46,3	41,7	21,9
$\sigma_x = \sigma_t;\ \tau = 0,5\,\sigma_t$	−0,5	45,9	40,6	19,5
$\sigma_x = 1,37\,\sigma_t;\ \tau = 0,5\,\sigma_t$	−0,374	49,1	42,9	23,8

Loading path	Stress-deviator parameter, μ	$2\tau_{max}$, kg/mm^2	σ_i, kg/mm^2	$\varepsilon_i \cdot 10^2$
$\sigma_x = 0,5\,\sigma_t;\ \tau = 0,166\,\sigma_t$	−0,143	45,7	39,8	20,9
$\sigma_x = 0,5\,\sigma_t;\ \tau = 0$	0	44,9	38,9	20,2
$\sigma_x = 2\,\sigma_t;\ \tau = 0$	0	45,7	39,6	20,8
$\sigma_x = 1,37\,\sigma_t;\ \tau = 0,245\,\sigma_t$	0	45,3	39,8	20,6
$\sigma_x = 1,11\,\sigma_t;\ \tau = 0,35\,\sigma_t$	0	46,7	41,2	21,2
$\sigma_x = 0,812\,\sigma_t;\ \tau = 0,18\,\sigma_t$	0,268	44,6	39,8	19,8
$\sigma_x = 0,137\,\sigma_t;\ \tau = 0$	0,465	46,7	41,8	20,4
$\sigma_x = 0,75\,\sigma_t;\ \tau = 0$	0,5	44,2	39,8	20,2
$\sigma_x = \sigma_t;\ \tau = 0$	1	44,1	44,1	22,1

(complex loadings). From these data, curves were constructed representing the limiting states in the three-dimensional subspace of the five-dimensional space of stress deviators [2]. The use of such curves permits—

Table 2

Method of carrying out the first stage	Stresses at the end of the first stage, kg/mm^2	Types of loading added at the second stage	Stress-deviator parameter at the end of loading, μ	$2\tau_{max}$, kg/mm^2	σ_i, kg/mm^2	$\varepsilon_i \cdot 10^2$
Tension	$\sigma_x = 31,1$	Internal pressure	0,088	47,8	41,6	20
Tension	$\sigma_x = 28,4$	Internal pressure	0,298	48,4	42,6	22,8
Tension	$\sigma_x = 25,5$	Internal pressure	0,585	47,2	43,1	18,9
Tension	$\sigma_x = 19,9$	Internal pressure	0,98	46	45,6	22,9
Internal pressure	$\sigma_t = 28,7$	Tension	0,358	47,7	42,5	18,3
Internal pressure	$\sigma_t = 35,8$	Tension	0,861	47,4	45,8	23,4
Torsion	$\tau = 8,9$	Internal pressure	−0,173	45	39	19,2
Torsion	$\tau = 7,2$	Internal pressure	−0,113	44,9	39	20,6
Torsion	$\tau = 5,7$	Internal pressure	−0,075	44,3	38,3	20,5
Torsion	$\tau = 4,5$	Internal pressure	−0,128	46,8	40,2	20,1

Method of carrying out the first stage	Stresses at the end of the first stage, kg/mm^2	Types of loading added at the second stage	Stress-deviator parameter at the end of loading, μ	$2\tau_{\max}$, kg/mm^2	σ_i, kg/mm^2	$\varepsilon_i \cdot 10^2$
Alternating stages of loading by torque and internal pressure			−0,627	45	41,4	23,5
Alternating stages of loading by torque and internal pressure			−0,441	46,2	41,1	22
Alternating stages of loading by torque and internal pressure			−0,232	45,3	39,8	21,3
Internal pressure	$\sigma_t = 17,7$	Tension and torsion	−0,45	48,2	43,1	23,2
Internal pressure	$\sigma_t = 26,7$	Tension and torsion	−0,063	47,8	41,7	22,2

Fig. 1. *a*—proportional loading, *b*—complex loading

Figure 1: Fig. 1. *a*—proportional loading, *b*—complex loading

Fig. 2

Figure 2: Fig. 2

Method of carrying out the first stage	Stresses at the end of the first stage, kg/mm^2	Types of loading added at the second stage	Stress-deviator parameter at the end of loading, μ	$2\tau_{\max}$, kg/mm^2	σ_i, kg/mm^2	$\varepsilon_i \cdot 10^2$
Internal pressure	$\sigma_t = 34$	Tension and torsion	−0,26	45,9	40,4	20,2
Tension	$\sigma_x = 12,1$	Torsion and internal pressure	−0,53	46,6	41,4	22,9
Tension	$\sigma_x = 20,6$	Torsion and internal pressure	−0,38	48,9	42,9	23,1

and, under complex loading, to reveal the influence of deformation anisotropy on the limiting resistance of the material. However, comparison of the results showed that, in the indicated cases, the nature of the loading (proportional or complex), ending at close values of μ, did not noticeably affect the magnitudes of the limiting stresses. This makes it possible, in presenting the results of such experiments, to use a simpler procedure instead of the curves mentioned above, depicting the limiting stressed states as points on the deviatoric stress plane (Fig. 1). From Fig. 1 and the table it is seen that the limiting states agree better with the criterion of the III theory of strength, the largest deviations from which are only $\pm 6.5\%$, whereas the deviations from the criterion of the IV theory of strength reach -21%.

Fig. 1. *a*—proportional loading, *b*—complex loading

Fig. 2

In addition to comparing the results with the criteria of the III and IV theories of strength, a check was made of the criterion proposed by Lankford and Saibel ([3]) for the case of the combined action on a tubular specimen of a tensile force and internal pressure, namely the criterion of stability of the process of uniform plastic deformation. In the cited work the following expressions were obtained for the critical values of the true principal stresses:

a) if instability is caused by internal pressure, then

$$\sigma_t = \frac{d\sigma_t}{d\varepsilon_t}\frac{2\alpha - 1}{3\alpha} \quad \text{for } \sigma_t > \sigma_x, \qquad \sigma_x = \frac{d\sigma_x}{d\varepsilon_x}\frac{2\beta - 1}{3} \quad \text{for } \sigma_t < \sigma_x,$$

where $\alpha = \sigma_t/\sigma_x$; $\beta = \sigma_x/\sigma_t$;

b) if instability is caused by the external axial tensile force, then

$$\sigma_x = \frac{d\sigma_x}{d\varepsilon_x}.$$

The application of the Lankford and Saibel criterion in analyzing the results of the experiments carried out seemed quite justified, since in the cases investigated, after the limiting resistance was reached, a decrease in load occurred, accompanied by localization of plastic deformation in the form of necking or local bulging; precisely these conditions formed the basis for deriving the indicated criterion. However, the values of limiting resistance (σ_x, σ_t) calculated by this criterion proved to be higher than the experimental ones, exceeding them in some cases by 130–140%.

The results of experiments in which the load-carrying capacity proved to be exhausted as a consequence of a general loss of stability are presented in Fig. 2.

in the coordinates $\sigma_x - \sqrt{3}\tau$, corresponding in the space of stress deviators to the plane $\sigma_t = 0$*. Curve 2 is constructed from points obtained under proportional loading; curve 1 pertains to cases of two-stage loading in which a tensile force was first applied to the specimen, and curve 3 to such two-stage loadings in which a torque was first applied to the specimen. As can be seen from Fig. 2, the curves differ substantially from one another. Thus, in those cases where the load-carrying capacity is exhausted as a result of general loss of stability, a dependence of the limiting resistance on the nature of the loading path and on the sequence of application of the force factors is revealed—a dependence that has not been noted in the literature.

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* The coordinates are chosen with a modified scale, for which the modulus of the vector represents the stress intensity.

Note: Figure translations are in progress. See original paper for figures.