Deformability criteria of metal at uniaxial tension

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Abstract. This paper is devoted to study of the laws of metals deformation behavior determined by carrying out standardized uniaxial tensile tests. The analysis of deformability of materials was carried out. The metals vary in yield limit from 40 to 1050 MPa and in ultimate strength from 460 to 1240 MPa. The ratio of the deformation work of uniform plastic deformation (from the yield point to the ultimate strength of materials) to the volume of the material was determined to assess the mechanical deformability. An inverse relationship between uniform deformation work and ratio of yield limit to ultimate strength was established. It was also found that the normalized specific work of deformation linearly increases with strength. The deformability criterion can be considered as the universal criterion for ferrous and non-ferrous metals and its magnitude can be estimated from known quantity of the ultimate strength. In practice, the numerical values of compliance criterion can be used to predict the behavior of materials with different strength under mechanical perturbations in the course of operation and machining (metal forming and cutting).

1. Introduction

One of the burning issues is development of reliable methods for assessing the carrying capacity of constructions and for defining the remaining life of technical systems, which have been in service for long. However, problem solution for precluding accidents is never ‘cut and dried matter’; it calls for a fresh approach to this urgent problem which would combine coordination and systematization of studies in this sphere.

Material fracture problem is a complex of scientific and technical issues. The beginning of active research in this sphere dates back to A. Griffiths whose followers were E. Orowan, J. Irwin and others [1-3]. Due to a joint effort of the workers G.I. Barenblatt [4], three basic sets of fracture criteria were developed in strength physics and fracture mechanics: these are energy, force and deformation criteria. Traditionally, the threshold force or energy characteristics of material response to the external action are used as probable criteria of strength and fracture of solids. Among these are the following characteristics, which can be determined experimentally: yield limit, ultimate strength, impact ductility, etc., as well as critical values of crack tip stress intensity factor for normal cleavage and in-plane and out-of plane shear. There are also other criteria of crack propagation, which take into account the structural characteristics of a solid in combined stressed state [5, 6].

The application of new materials in machine building, modernization of technologies of material treatment and enhancement of the performance of mechanical equipment – all this is directly related to the advancement of science in the sphere of material strength and endurance of constructions. The structure and substructure of metallic materials and the kinetics of structural changes are investigated employing a wide range of methods, i.e. X-ray diffraction methods developed by Berg-Barret, Shultz,
Fujivar and Lang; method of moving X-ray detector, diffractometry of residual stresses, etc. Thus X-ray methods were used to examine test samples under special loading conditions. The data obtained on the dislocation and block-type structure of metallic materials is of basic importance; it enables gaining an insight into the nature of plastic deformation in metallic materials. Moreover, X-ray methods are found to be an effective tool for assessing the state and endurance of construction parts. Of the many challenges facing researchers is the development of an innovative approach to the problem of strength and fracture on the base of dependable criteria and trustworthy coefficients.

The basic assumption that crack occurrence in the loaded solid is implicit has to be reexamined, since it puts limitations on this approach by precluding the issue of crack nucleation, which was studied in sufficient detail over the last few decades by fracture physics [7]. In accordance with the conventional concepts of physics and mechanics of fracture, it is implicitly assumed that the stress-strain state of material would remain homogeneous on the macro-scale up to the point of main crack development or the onset of necking in plastic materials. However, the experimental evidence obtained by a number of workers strongly suggests that the plastic flow in metals would exhibit an inhomogeneous behavior at different stages of loading [8].

A comprehensive research of plastic deformation macrolocalization was performed for a range of metals and alloys in [9-12]. It is found that after the attainment of yield limit, the plastic flow would exhibit an inhomogeneous behavior; the inhomogeneities have characteristic size comparable to the deforming solid dimensions. The macroscopic inhomogeneity is a specific feature of plastic deformation development, which has been observed for all the studied metals and alloys by all types of loading. Of particular note is the space-time periodicity of localization patterns observed for most deforming solids. All the types of macrolocalization patterns have been examined in sufficient detail. It is found that within the localized plasticity nuclei defect fracture development would occur at a higher rate relative to the rest of material volumes, so that the likelihood of crack nucleation in the same regions is high. This finding suggests that plastic flow inhomogeneities are directly related to the processes involved in crack nucleation and development at the pre-fracture stage.

Computational evaluation methods of the stress-strain state of materials and products are often complex in dealing with problems of stress and strain distribution in samples or real products of complex shape especially when the material has an internal structure. This structure can change during the deformation due to successive processes of formation and relaxation of stress concentrators [13]. As a result of mechanical tests, stress-strain curves are obtained, which qualitatively and quantitatively characterize the material’s response to loading, and determine the strength and ductility of materials. This work is devoted to the study of the laws of the deformation behavior of metals, determined in standard uniaxial tension tests. The basis for evaluation of the deformability criteria will be deformation work, determined by the area of the tension diagram.

2. Experimental part

The uniaxial tension tests were performed on universal test machine (Instron-1185) at a constant speed of gripping \( V_m = 0.2 \text{ mm} / \text{min} \). A wide range of metals and alloys (Cu; \( \gamma-\text{Fe} \); Ni; Sn; Nb; Zn; Mg; V; \( \alpha-\text{Fe} \); Zr; Al; Ti; Mo) with various characteristics of durability and plasticity were studied and tested. The load curves of the studied materials are presented in Figure 1. In the thermodynamic terms the macroscopic result of deformation (changes in shape and size) is a dissipative process, that is the transition of a part of the kinetic energy to the internal energy of the deformable metal. It is realized in the formation of a certain internal structure [14 - 17]. Furthermore, the amount of energy absorbed during deformation is determined by the work of deformation, and absorption rate is defined as the deformation resistance [18]. In the case of tension test, the deformation work is numerically equal to the surface area under stress-strain curve, and is the sum of the work of elastic and plastic deformation.
3. Results and discussions
The stress-strain curves (Figure 1) obtained as a result of mechanical tests were fitted in the form of fourth-order polynomials by using software package Table Curve:

$$\sigma_i = a_0 + a_1 \cdot \Delta \varepsilon_i + a_2 \cdot (\Delta \varepsilon_i)^2 + a_3 \cdot (\Delta \varepsilon_i)^3 + a_4 \cdot (\Delta \varepsilon_i)^4$$ (1)

At least 15 points were used. The polynomial was used as an integrand to calculate the surface area under stress-strain curve, i.e. the deformation work. An inverse proportion between the deformation work on a field of uniform plastic deformation and the ratio of the yield limit to the ultimate strength of test materials was established and the correlation coefficient is 0.83 (Figure 2a).

To estimate the mechanical deformability, the ratio of deformation work (from yield limit to ultimate strength of materials) to the deformable volume calculated as the product of the initial area and working length of tested sample was determined. Thus, the specific work of uniform plastic deformation was determined as:
The specific work reflects the material deformability in terms of the limiting work that is irreversible for shaping of the given metal in the individual stages [17], as such it quantitatively reflects the energy dissipation. Another reflection of the material deformability may be the “compliance” proposed in [18] as a resistance to deformation under the condition the deformation increases due to external factors. This quality of metal is defined as the ratio of the specific work to the deformation corresponding to the ultimate strength:

$$k_{\text{unif}} = \frac{\alpha_{\text{unif}}}{\varepsilon_B}$$

It is actually characterized by the rate of energy dissipation under uniaxial tension.

A linear relationship between the normalized specific work $k_{\text{unif}}$ and the ultimate strength of the studied metals $\sigma_B$ was established with correlation coefficient of 0.9 (Figure 2 b). The quantity of specific energy, in units mJ/mm$^3$, required to increase the true strain $\varepsilon$ by 1% is taken as the conventional units of the coefficient $k_{\text{unif}}$.

4. Conclusions

The analysis of deformability of materials was carried out. Noted that the yield limit is 40–1050 MPa, and the ultimate strength is 460–1240 MPa for all studied materials used for construction products. It was established that the specific work of concentrated deformation normalized to the corresponding deformation $k_{\text{unif}}$ increases linearly with increasing strength. In the applied aspect, the numerical values of $k_{\text{unif}}$ can be used to predict the behavior of materials with different strength under mechanical perturbations in the course of operation and machining (metal forming and cutting). Taking into account the wide range of material’s strength, the deformability criterion (Figure 2b) can be considered as the universal criterion for ferrous and non-ferrous metals and the magnitude of $k_{\text{unif}}$ can be estimated from known quantity of the ultimate strength.

Acknowledgements

The work was carried out within the framework of the Program of Fundamental Scientific Research of the State Academies of Sciences for 2013-2020.

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