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CONTROL AND EXPERIMENTAL DATA PROCESSING IN TORSION TESTING WITH VARIABLE ACCELERATION

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ABSTRACT

The paper is devoted to the new method of torsion testing with variable acceleration, which is conducted in order to determine the shear strain resistance of materials. In order to study the rheological properties of materials, which are sensitive to strain rate, with the use of proposed method, test control and experimental data processing algorithms have been developed. It is shown that two control parameters *c* and *k* determine the ranges of the strain and strain rate values in which the rheological properties of materials are studied. They also determine the duration of testing. For the case of testing samples with a cylindrical working part of a solid circular cross section, formulas are given for calculating the values of the sample twist angle at each time point. Changing the twist angle of the sample in accordance with these values provides a reliable determination of the rheological properties of materials, which are sensitive to strain rate. In order to verify the new testing method, mathematical modeling of the torsion test was performed using the Wolfram Mathematica software. The simulation results indicate the consistency of the proposed method for testing materials, which are sensitive to strain rate.

1. Introduction

The torsion test is one of the basic methods for determining of the rheological properties of materials [1–25]. The advantage of this method, in comparison with the tension and upsetting, is the possibility of obtaining of large values of the strain and strain rate, which take place in many real processes of metal forming [13–15]. However, the existing methods of testing samples in torsion, for example [18–23], do not allow us to study the rheological properties of the strain rate-sensitive steels and alloys, especially in hot state [24].

In the application for the invention No. 2018132149 dated 07.09.2018, the method for testing samples in torsion is proposed. The distinctive feature of this method is the loading regime with a variable acceleration. The essence of the proposed method for determining of the shear strain resistance of materials is that the torsion tests are carried out at a constant level of temperature of the sample's working part θ. During the test, the values of the sample's twist angle φ, as well as the values of the torque *M* (under the influence of which the plastic deformation of the sample's working part is carried out) are measured. At the same time, during the tests, the following condition is ensured:

$$\frac{\xi_u}{\varepsilon_u} = \text{const}\ , \tag{1}$$

where ξ_u is the true rate of deformation, ε_u is the true degree of deformation.

In the case of an application of samples with a cylindrical working part with the radius *r* and length *l,* to fulfill the condition (1), the values of the twist angle are exponentially changed:

$$\varphi = \sqrt{3}\frac{l}{r}ce^{kt}\ ,$$

where *c* and *k* are the arbitrary coefficients.

The shear strain resistance of the material is determined by the formula

$$\tau_s\left(\varepsilon_u, \xi_u, \theta\right) = \frac{1}{2\pi r^3}\left(3M + \frac{dM}{d\varepsilon_u}\varepsilon_u\right), \tag{2}$$

where

$$\varepsilon_u = \frac{1}{\sqrt{3}}r\frac{\varphi}{l}\ , \xi_u = k\varepsilon_u\ .$$

The proposed test method allows us to take into account the effects of the high-speed hardening and softening of materials in hot state. At the same time, the existing methods are suitable for studying the rheological properties of materials only at cold deformation.

The subject of this work is the development of control algorithms for the testing samples in torsion with the variable acceleration and processing of experimental data, as well as the efficiency evaluation of the proposed method of testing using a mathematical modeling.

2. Test control algorithms and experimental data processing

Testing of samples in torsion by new method involves the changing of the angular rotation rate of the test-unit's grips in accordance with the value of the strain on the sample surface. Taking the right part of the condition ξ_u/ε_u = const equal to *k*, we can write:

$$\frac{d\varepsilon_u}{dt} = k\varepsilon_u\ . \tag{3}$$

The differential equation (3) has a solution

$$\varepsilon_u = ce^{kt}\ , \tag{4}$$

where *c* is a constant of integration.

We note that condition (4) is impracticable throughout the test, because the strain on the sample surface at the initial time is zero (we are not talking about the accumulated degree of deformation).

The solution of this problem can be implemented as follows. We choose an arbitrary time moment t^*, up to which $\varepsilon_u \neq c\,e^{kt}$. However, at the moment of time t^* and after it, we ensure a strict fulfillment of the condition $\varepsilon_u = c\,e^{kt}$. Next, we will consider one of the variants for an implementation of the proposed test method in torsion.

One of the easiest ways to accumulate a deformation at the initial time $t < t^*$ is the linear law of changing of the strain rate (**Fig. 1**), that is

$$\xi_u = \frac{\xi_u^*}{t^*} \cdot t\,,$$

where ξ_u^* is the strain rate on the sample surface at the time t^*.

To ensure that the condition $\varepsilon_u = c\,e^{kt}$ is met at the time $t \geq t^*$, and with the aim of eliminating the need for an instantaneous change of the rotation speed of the grips of the test unit, you need the following:

$$\int_0^{t^*} \frac{\xi_u^*}{t^*} t dt = \varepsilon_u^*; \quad \xi_u^* = k\varepsilon_u^*. \tag{5}$$

Solving the system of equations (5), we find the value of t^* for a specific variant of an embodiment of the test method in torsion:

$$t^* = \frac{2}{k}\,.$$

The choice of the values of the parameter k is carried out at the stage of an experiment planning in such a way as to investigate the range of interest of variation of the strain and strain rate (**Fig. 2**). Thus, the choice of the values of k determines the time value t^*, after which the formula (2) makes it possible to determine the reliable values of the shear strain resistance of material depending on the strain, strain rate and temperature of deformation. Up to this point in time, the data about the resistance to a deformation will be unreliable. In turn, the time t^* determines the critical values of the strain and strain rate of material. At the test beginning, in the case of an application of the linear law of the change of the strain rate, they are determined by the expression

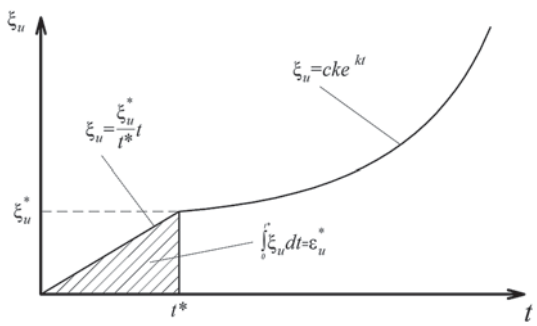

Fig. 1. Variant for the maintenance of condition $\varepsilon_u = c\,e^{kt}$

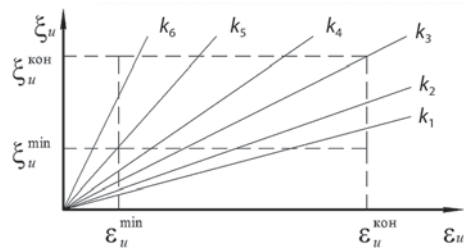

Fig. 2. The choice of coefficient k on the basis of the region of interest of changes in the degree and rate of deformation

$$\varepsilon_u^* = ce^{kt^*} = ce^{k \cdot \frac{2}{k}} = ce^2; \quad \xi_u^* = cke^{kt^*} = cke^{k \cdot \frac{2}{k}} = cke^2.$$

It is not possible to obtain the reliable data about the resistance to a deformation for values of the strain and strain rate less than the critical values. However, there remains the possibility of changes in the values ε_u^* and ξ_u^* by choosing the constant of integration c:

$$c = \frac{\varepsilon_u^{min}}{e^2} \;\; or \;\; = \frac{\xi_u^{min}}{ke^2}\,.$$

If the value c decreases, the critical values of the strain and strain rate decrease, and the test duration increases (**Fig. 3**). This also makes it possible to stabilize the temperature regime of deformation, because with a longer duration of the test, the maintaining of the sample temperature at a constant level is facilitated.

Knowing the desired final value of the strain $\varepsilon_u^{кон}$ or the strain rate $\xi_u^{кон}$, the calculation time of the test can be carried out according to the formulas

$$t^{кон} = \frac{1}{k}\ln\left(\frac{\varepsilon_u^{кон}}{c}\right) \text{ or } t^{кон} = \frac{1}{k}\ln\left(\frac{\xi_u^{кон}}{ck}\right).$$

In the case of testing of the samples with a cylindrical working part length l and a continuous circular cross-section radius r, as well as in the case of a linear law of change in the strain rate at the initial time, the values of the twist angle of the sample φ vary in accordance with the expression

$$\varphi = \frac{\sqrt{3}}{4}\frac{l}{r}ck^2e^2t^2 \text{ if } t < \frac{2}{k}; \quad \varphi = \sqrt{3}\frac{l}{r}ce^{kt} \text{ if } t \geq \frac{2}{k}. \tag{6}$$

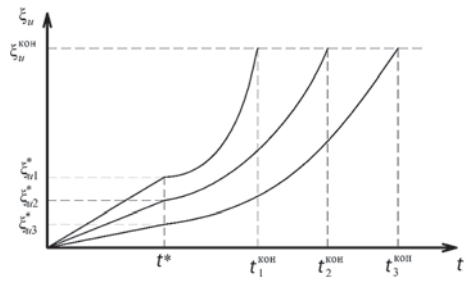

Fig. 3. Influence of coefficient k on the definitional area of the rheological properties of material ($t_1^{кон}$, $t_2^{кон}$, $t_3^{кон}$ — the end time of deformations at values $c_1 > c_2 > c_3$)

The values of the angular rate of the rotation of the test unit grips can be determined as follows:

$$\omega = \frac{\sqrt{3}}{2}\frac{l}{r}ck^2e^2t \text{ if } t < \frac{2}{k}; \quad \omega = \sqrt{3}\frac{l}{r}cke^{kt} \text{ if } t \geq \frac{2}{k}. \quad (7)$$

The expressions (6) and (7) are the control algorithm of the test unit in the case of use of cylindrical samples, taking into account the selected values of the coefficients c and k, determined at the stage of experiment planning. In this case, the test temperature is fixed and maintained at the constant level, for example, with the help of an automatic control system.

The experimental data are processed in the following way. During testing of samples in torsion, starting from time t^* to the final time of the test $t^{кон}$, the values of the torque and twist angle of the sample are fixed. The torque and twist angle can be determined by means of the specialized measuring devices. The strain on the sample surface is determined by the formula

$$\varepsilon_u = \frac{1}{\sqrt{3}}r\frac{\varphi}{l}.$$

The strain rate on the sample surface is calculated as follows:

$$\xi_u = k\varepsilon_u,$$

but the values of the strain resistance are determined by the expression (2).

By performing a series of torsion tests on the samples at different values of the coefficient k and temperatures, it is possible to determine the shear strain resistance of the material as a function of the temperature-velocity conditions of deformation according to the formula (2).

3. Evaluation of effectiveness of the test with help of mathematical modeling

The idea of an evaluating of the effectiveness of the new method of a specimens' testing in torsion is as follows. Using the program Wolfram Mathematica, a mathematical model of the test process is created that allows us to calculate the torque of the sample as a function of time. The length and radius of the working part of the cylindrical sample, the rheological properties of the tested material in the form of an arbitrary function of the shear strain resistance from the strain and strain rate, as well as the change law of the strain rate on the sample surface are fed to the input of the model. The temperature of the material is assumed constant and is not taken into account during the simulation. The model of the test process includes the calculation of the distribution fields of strain and strain rate in the volume of the working part of the sample, taking into account that they are proportional to the radius, as well as the calculation of a value of the torque by the following formula:

$$M = 2\pi\int_0^r \tau(\varepsilon_u, \xi_u, \theta)\rho^2 d\rho,$$

where M is the value of the developed torque, r is the radius of the working part of the sample, ε_u and ξ_u are the true value of the degree and rate of deformation, θ is temperature of the material.

Found on the basis of a mathematical model, the functions of changing the strain and strain rate, as well as the torque from time, are the initial data for the solution of the inverse problem. On the basis of these data, the shear strain resistance $\tau_s^{факт}$ is calculated according to the formula (2). Then it is compared with the original model of the rheological properties of the tested material.

In the course of mathematical modeling, the sample of length $l = 10$ mm and radius of working part $r = 3$ mm was chosen for testing. The rheological properties of the sample material were set arbitrarily at two levels:

$$\tau_{s1} = \frac{1}{\sqrt{3}}\left(100 + 2\varepsilon_u^{0,2} + 100\xi_u^{0,5}\right),$$

$$\tau_{s2} = \frac{1}{\sqrt{3}}\left(100 + 500\frac{2\varepsilon_u + 1}{\varepsilon_u^2 + 10}\cdot\frac{2\xi_u + 1}{\xi_u^2 + 1}\right).$$

The material *1* is a viscoplastic monotonically strengthened material throughout all range of the strain and strain rate, while the material *2* has the effects of the power and speed weakening.

The function, describing the strain rate of the metal particles in the sample volume, was accepted at two levels:

$$\xi_{u1} = \frac{\rho}{r}, \quad \xi_{u2} = 0{,}001\cdot\frac{\rho}{r}\cdot e^{0,1t}.$$

In the first variant, the strain rate is constant over the entire period of time. The second high-speed test regime is a uniform acceleration of the active grip under the sample loading. The last regime of loading is carried out in accordance with the proposed method of the samples testing in hot torsion. For each of the two simulated materials, the torque calculations were performed for the torsion test samples in the case of different loading conditions. Then by the formula (2), the actual values of the shear strain resistance were calculated. The results of calculations (in the form of graphs of shear strain resistance from time) are shown in **Fig. 4** and **Fig. 5**.

Data, presented in fig. 4, indicate that the loading conditions of samples with a constant strain rate do not provide reliable data on the rheological properties of materials, which are sensitive to the strain rate. This is true for both materials with an arbitrary selected hardening curve. In this case of the material *1*, which has monotonically hardening over the entire period of time, the actually determined values of the shear strain resistance are understated, and for the material *2*, which has the effects of the power and speed weakening, the values are overstated.

Data, presented in fig. 5, indicate that the loading regime with a variable acceleration, corresponding to the proposed test method of sample in torsion, provides the reliable data about the rheological properties of materials sensitive to the strain rate, because the actually determined values of shear strain resistance coincide with the known laws of hardening for two arbitrarily specified materials.

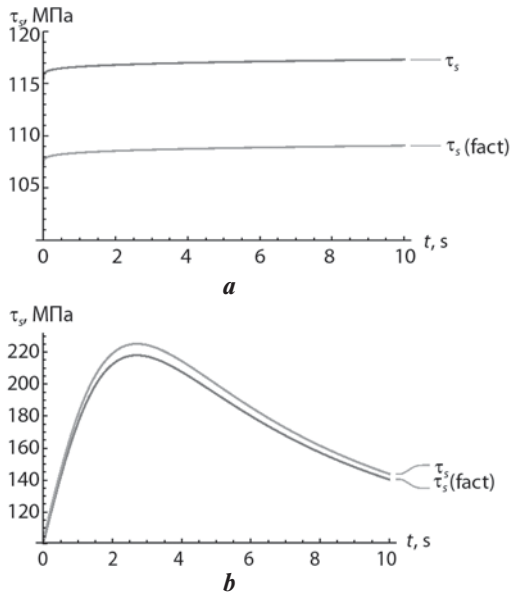

Fig. 4. Stresses on the sample surface for materials *1* (*a*) and *2* (*b*), the loading regime *1*

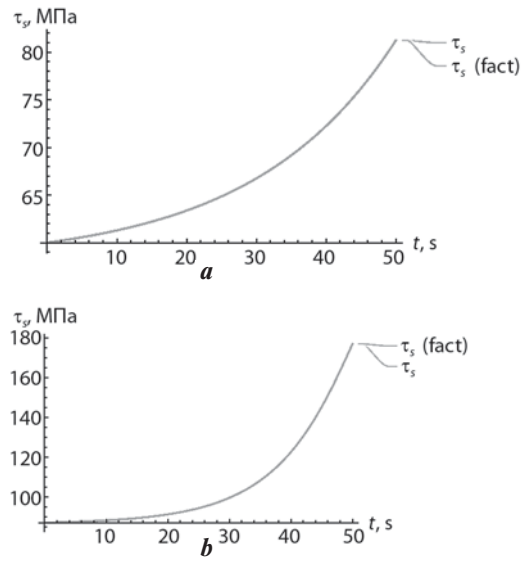

Fig. 5. Stresses on the sample surface for materials *1* (*a*) and *2* (*b*), the loading regime *2*

4. Conclusion

The paper describes the new method for determining the shear strain resistance of materials in torsion, as well as the algorithms for controlling the test unit and processing the experimental data. An evaluation of the effectiveness of the proposed method of the samples testing in torsion with the use of mathematical modeling showed that the application of the loading regime of samples with a variable acceleration by the proposed method allows us absolutely exact to take into account the speed hardening of materials and to obtain the reliable data about the rheological properties of materials.

The application for the invention № 2018132149 dated 07.09.2018 was submitted on this method of testing samples.

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