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Abstract. The article is devoted to the study of rheological properties of metals and alloys in a hot state. A method for torsion testing of materials is considered. It is known that the strain heterogeneity is observed along the gauge length of cylindrical specimens during torsion. Its value can reach several tens of percent, depending on a material and the quality of specimen preparation. Therefore, torsion tests are often carried out on specimens having a notch of a certain shape. In this work, the method of finite element modeling is used to study the effect of the hardening curve of a material on the strain distribution along the gauge length of specimens with a circular notch, as well as on the strain evolution in the minimum section of the notch. Using 12Kh18N9T steel and VT–16 and VT–33 titanium alloys as an example, three different variants of a hardening curve are considered, namely, monotonic hardening, monotonic softening, and also the curve with a local maximum of stress. The results of the study have shown that the stress-strain behaviour of a material has a significant effect on the strain distribution along the notch length of the specimen. In addition, the dependence of the strain value in the minimum cross-section of the specimen on the twist angle cannot be predicted. It makes difficult to control a test setup when it is necessary to provide accurate strain rate values during the test. The use of notched specimens for torsion testing requires the development of new automatic-control systems for changing the strain rate values in the minimum cross-section of the notch according to a specified time law.

1. Introduction
The stress acting during plastic deformation is the most important characteristic of materials that determine not only the energy and force parameters of the forming process, but also the metal flow inside the deformation zone. The dependence of the flow stress on the strain, strain rate and temperature of the material together with the force action scheme and the geometry of the workpiece determine the strain distribution over the volume of finished products and the level of their mechanical and operational characteristics.

One of the most advanced methods for determining the hardening curve of materials is torsion testing [1–7]. This kind of test allows you to achieve the strain and strain rate values in a wide range close to industrial one [8]. This provides a more accurate analysis of existing and emerging metal-forming technological processes. In addition, there is no metal displacement relative to the tool during testing specimens for torsion and, therefore, there is no influence of a contact friction on a test results. However, the test of cylindrical specimens has a limitation associated with the heterogeneity of the strain along the gauge length. Its value can reach several tens of percent, depending on the material

and the quality of specimen preparation [9]. In this case, the torque developed by a test setup cannot be associated with the calculated strain value, which is determined by the twist angle of grips and the dimensions of the specimen. Moreover, the position of the strain localization region is random and is determined by the homogeneity of the material properties, the accuracy of specimen preparation, and the temperature distribution along the gauge length [9–19].

More promising is the use of specimens with a curved gauge length, and not with a cylindrical one. One of the first scientists who pointed out this were Bogatov and Krynytcyn [9]. They used specimens with a circular notch of radius R when studied the plasticity of aluminum and a lead-antimony alloy. In this case, the deformation was localized in the notch section with the smallest diameter d, i.e. the position of the cross-section of the specimen with a maximum strain value was fixed.

However, the use of notched specimens for determining material hardening curves is not well studied. First of all, it concerns the issues of controlling the test setup, when it is necessary to provide accurate values of the strain rate on the surface of the specimen at each instant of the test.

This work is aimed at solving this problem by studying the dependence of the strain in the minimum cross-section of the notch on the twist angle of the grips of a test setup for different materials.

2. Control algorithms for a torsion test setup

Usually, the hardening curves of metals and alloys are defined in a form of the dependence of flow stress on the strain at various fixed values of the strain rate and temperature [1–5, 20–22]. The current technological level of testing equipment makes it possible to maintain these parameters at a constant level, and in some cases, to change according to a specified time law with high accuracy [23–24]. However, the control of the strain rate during torsion testing of specimens is carried out indirectly, by setting the rotation velocity of the grips of the test setup depending on the required values of the strain rate.

When testing cylindrical specimens, the calculated values of the strain and strain rate on the working surface of the specimen are determined by the expressions:

$$\varepsilon = \frac{1}{\sqrt{3}} r \frac{\varphi}{l} , \qquad (1)$$

$$\xi = \frac{1}{\sqrt{3}} r \frac{\omega}{l} , \qquad (2)$$

where φ and ω are the twist angle and the angular velocity of the grips of the test setup, r and l are the radius and gauge length of the specimen.

In the case of testing specimens with a constant strain rate, the angular velocity of the grips is also constant and is determined by the necessary value of the strain rate:

$$\omega = \sqrt{3} \frac{l}{r} \xi = \text{const} . \qquad (3)$$

Equation (3) defines one of the most common control algorithms for the test setup. However, it can be used only in the case of cold tests, when the material does not experience strain-rate hardening. It was shown in [25–26] that the determination of reliable values of equivalent stress during hot torsion testing of cylindrical specimens is possible only if the following condition is true:

$$k = \frac{\xi}{\varepsilon} = \text{const} . \qquad (4)$$

Equation (4) allows you to take into account the heterogeneity of the tangential stress distribution in any cross-section of the specimen. However, you need to change the strain rate value in accordance

with the current value of the strain at each instant of the test. According to [26], equation (4) is satisfied if you control the grips angular velocity of the test setup in accordance with the expression:

$$\omega = \begin{cases} \dfrac{\sqrt{3}}{2}\dfrac{l}{r}ck^2\,\mathrm{e}^2\,t, & t \le \dfrac{2}{k}; \\[3mm] \sqrt{3}\,\dfrac{l}{r}ck\,\mathrm{e}^{kt}, & t \ge \dfrac{2}{k}, \end{cases} \tag{5}$$

where c is the parameter determining the total duration of the test.
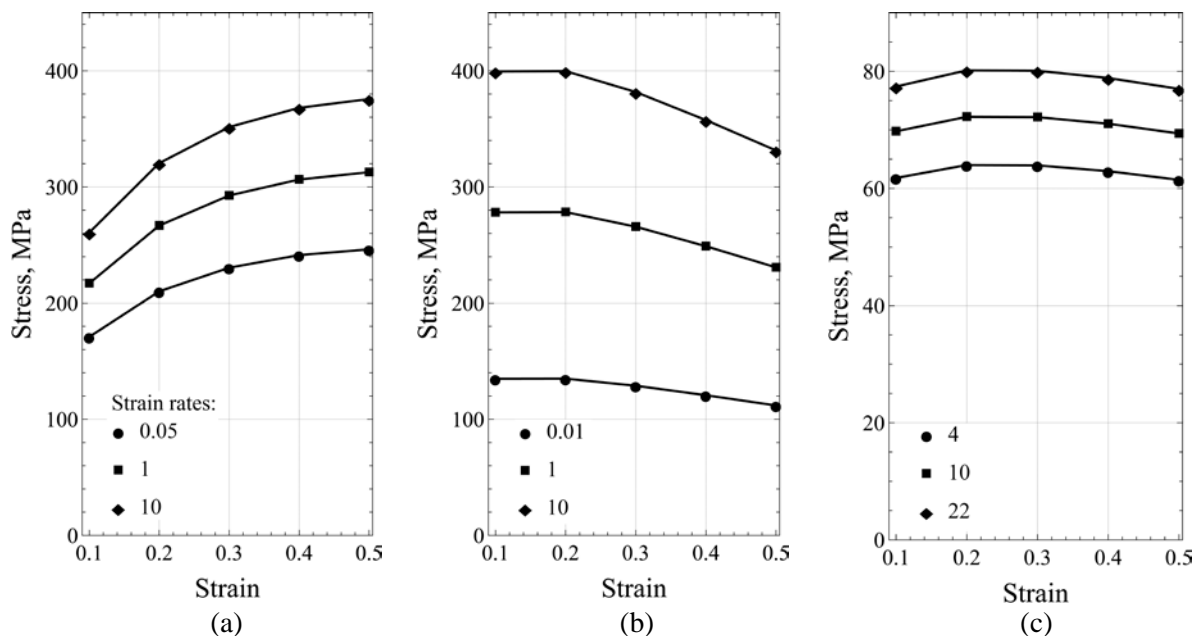
Equations (3) and (5) show that the grips angular velocity of the test setup is determined by dimensions of the gauge length of cylindrical specimens. In the case of using notched specimens, the grips angular velocity can be set only after determining the dependence of the strain value corresponding to the surface of the specimen on the twist angle [9]:

$$\varepsilon = f_1(\varphi) \Rightarrow \omega = f_2(\xi). \tag{6}$$

3. Finite-element simulation

To solve the formulated problem, the finite element method implemented in the Deform-2D software was used. Unlike physical modeling, this method allows us to exclude from consideration such factors as heterogeneity of the material structure, the irregularity in the distribution of temperature over the cross-section and length of the working part of the specimen, and, finally, allows to ensure the identical size of specimens made from different materials.

For the study, steel 12Kh18N9T as well as titanium alloys VT–16 and VT–33 were used [1]. The choice of these materials is due to their hardening curves at a temperature of 900°C (figure 1). Steel 12X18H9T is hardened throughout the test, while the VT–16 alloy is only softened. VT–33 alloy has a more complex character of the hardening curve, at which a maximum of flow stress is observed with a strain value of about 0.25.
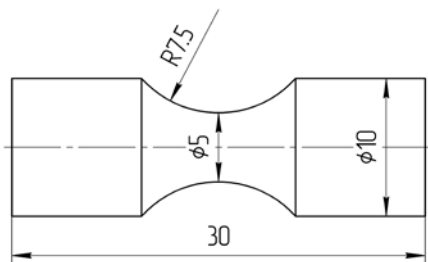

Figure 1. Hardening curves of materials at a temperature of 900°C: (a) 12Kh18N9T steel, (b) VT–16 titanium alloy, (c) VT–33 titanium alloy.
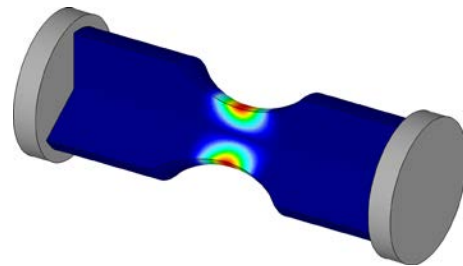
In [9], it was found that the ratio of the notch radius of curvature R to the minimum cross-sectional diameter of the specimen d should be in the range from 0.5 to 3.0. Such geometry of the notches facilitates the preparation of the specimens, and also allows to achieve the maximum plasticity of

materials. In this work we have used notch having ratio *R/d* equal to 1.5. Figure 2 shows the dimensions of the specimens used in this paper.

The effects of deformation heating and heat transfer have not been considered when formulating the problems of computer simulation. The angular velocity of specimen twisting has been set constant and equal to 2π rad/s. The sticking condition has been set on the contact surface between the specimen and grips. Figure 3 shows the computer model for the torsion test of specimens having round notch.
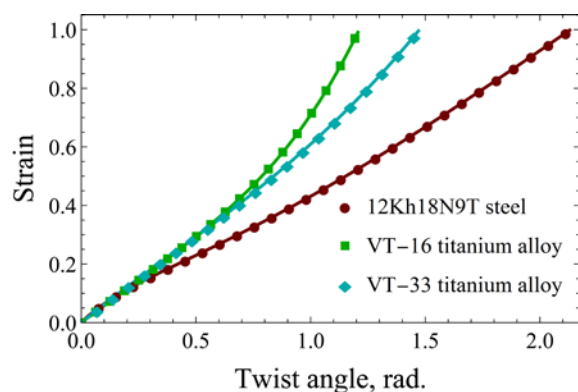

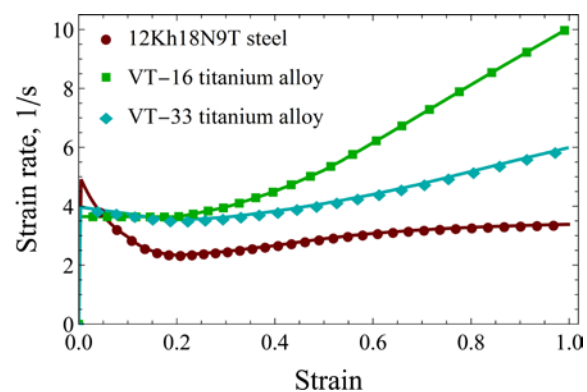**Figure 2.** Round notched specimen geometry.

Figure 3. Computer model for the torsion test of specimen (specimen shown in section).

4. Research results and discussion

As a result of the computer simulation, the strain and strain rate values at various points on the surface of the specimens working part were determined for each material and at each instant of the test. Figures 4 and 5 show the dependences of the strain and strain rate in the minimum notch section on the twist angle respectively. According to figure 4, all three materials behave similarly at the beginning of the test, when the twist angle does not exceed 0.2-0.25 rad. However, figure 5 shows that the strain rate of the steel specimen is less than the strain rate of titanium specimens for almost the entire duration of the test. This is due to a more intense hardening of steel (see figure 1, a). The strain rate of two titanium specimens is the same up to the strain of 0.2. When the strain value is greater than 0.2, the VT–16 alloy experiences a more intense softening than VT–33 alloy, and it leads to an increase in the strain rate (figure 5). In general, computer simulation of testing specimens with round notch for hot torsion shows that the strain and strain rate in the minimum cross-section of the notch are determined by the hardening curve of the material. At the same time, it is not possible to establish a single relationship between the strain and the twist angle the test setup grips.
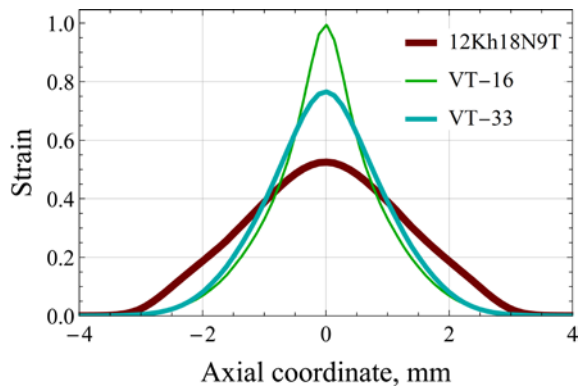

Figure 4. Dependences of the strain corresponding to the surface of specimens on grips twist angle.

Figure 5. Dependences of the strain rate corresponding to the surface of specimens on grips twist angle.

Figure 6 shows the curves characterizing the distribution of the strain along the notch of different specimens with the same twist angle of 0.603 rad. You can see that the strain distribution diagrams are dome-shaped for all three materials. This is due to the fact that the load-carrying ability of specimen, determined by its cross-sectional area, decreases towards the minimum section of the notch. However,

the strain distributions along the notch differ for various materials. According to figure 6, the most uniform strain distribution is characteristic of a steel specimen. The more uniformity of the strain distribution is caused by the involvement of greater sections of the notch in the deformation process while they have a lower level of stresses corresponding to the hardening curve. For titanium alloys having the effect of softening, the stress level in the minimum notch section increases slightly or even decreases, so the deformation is carried out mainly in this cross-section with the lowest load-carrying ability. The computer simulation results show that the material hardening curve determines the strain distribution along the working part of the specimens with the round notch.

Figure 6. Strain distributions corresponding to the surface of specimens along the notch length.

The results of the study indicate that the use of round notched specimens in hot torsion testing as well as the control of the test are problem difficult to solve. To satisfy equation (4), you need to change the angular velocity of the test setup grips, taking into account the relationship between the strain in the minimum cross-section of the specimen and the twist angle. However, this relationship depends on the character of a material hardening curve. In other words, the rheological properties of the material, which must be determined from the test results, affect the conduct of the test itself.

The law of change in the grips angular velocity of the test setup can be found by the results of preliminary tests carried out with a constant rate of grips rotation. During the main tests, it is necessary to apply the found law of change in the grips angular velocity according to equation (6). However, during main tests carried out in a hot state with a variable rate of grips rotation, the change in the strain rate will lead to the change in the stress level in the minimum cross-section of the specimen. This leads further to a redistribution of the strain along the notch in a manner different from preliminary tests. In other words, the control algorithm of the test setup found on a basis of preliminary tests will fail during the main tests due to the strain-rate hardening of a material. Note that the influence of deformation heating has not been taken into account in this work. But it is obvious that in practice the redistribution of deformations along the specimens working part will be more complex.

In essence, the above conclusions make preliminary tests useless. However, the use of notched specimens in order to study the rheological properties of materials is possible without conducting preliminary tests. To do this, you need to control the strain values on the surface of the specimen directly during the test in a real time. This approach requires the development of appropriate control systems and sensors capable of measuring the strain value at large angles of rotation.

5. Conclusions

It is shown that the use of notched specimens for hot torsion testing is only possible with the use of an automatic-control system that allows to read the strain values from the surface of the specimen during the test and use these values to generate control signals that provide the change in the strain rate in the minimum cross-section of the notch according to the specified time law.

Acknowledgments

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