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Evaluation of storage energy of the constructional steel during plastic deformation

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Abstract

The results concerned with the evaluation of storage energy in the process of plastic deformation of the constructional steel are presented. Temperature measurements during the static tensile tests were conducted using an FPA-based infrared camera. The heat evolved in the process of plastic deformation was determined by solving the heat conduction equation simultaneously with the use of infrared radiation measurement data. The obtained data of energy storage within the range of rates from 9×10^{-4} s^{-1} to 9×10^{-3} s^{-1} do not depend appreciably on deformation rate.

1. Introduction

Generally, plastic deformation of the constructional steel is accompanied with the generation and motion of dislocations. Change of the density and configuration of the defects always leads to energy dissipation, which causes the specimen temperature increase. The phenomenon of temperature increase in the process of plastic deformation of solids is known as thermoplastic effect.

The part of work of plastic deformation A_P is absorbed by a material while the another part is transformed into released heat Q. Thus the storage energy E_S is determined as a difference between the work of plastic deformation and the heat released into surroundings [1]:

$$dE_S = dA_P - dQ \tag{1}$$

Work of plastic deformation is usually determined from the stress-strain curve. The heat Q can be evaluated with the use of calorimeter [2, 3]. However, the calorimetric method is limited by its low speed of response [3].

Besides, the investigations of deformation in metals and steels are sometimes carried out with the use of infrared imaging cameras [4 - 6]. In this case, the change in sample temperature during deformation is measured. However, the correct determination of the released heat during deformation remains the difficult problem and needs to be studied. In the latter case, the heat Q can be determined by simulation of the process of sample heating during deformation by applying electrical power $P(t)$ in such a way that the temperature increase with time t during the simulation is identical with that measured during tensile testing [5].

2. The materials and instruments tested

The goal of the present work is to evaluate the energy storage in the process of plastic deformation of the constructional steel. The standard sheet specimens from the steel 18G2S were subjected to static tensile test at various rates

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of deformation: 9×10^{-4} s^{-1}, 2×10^{-3} s^{-1}, 4×10^{-3} s^{-1}, and 9×10^{-3} s^{-1}. The chemical composition of the steel was ***0.15 wt % C***, ***0.85 wt % Si***, ***1.4 wt % Mn***, ***0.25 wt % Cr***, ***0.15 wt % Ni***, and ***0.31 wt % Cu***. Dimensions of the tested specimens were 0.075 m - length, 0.02 m - width, and 0.002 m - thickness. Tensile tests were performed on the "Instron-1195" testing machine with a constant strain rate. The yield strength and the ultimate strength of steel 18G2S were 410 MPa and 560 MPa, respectively.

Temperature measurements during the specimen deformation were performed using the infrared thermography system TKVr-IFP/"SVIT" equipped with a computer. The temperature sensitivity of the infrared camera (NETD at 30 °C) was 0.028 °C. The field of view was about 0.09 m × 0.09 m at the distance between the camera and specimen of 0.3 m. IR images were stored in the computer memory at frequency 20 frames per second. The sensitivity spectral range of the device was 2.45 ÷ 3.05 μm. The analysis of both surface temperature map and stress diagram was carried out to evaluate the energy storage during plastic deformation.

3. Work of plastic deformation

When material is deformed, a certain fraction of total work A is expended on the work of elastic deformation A_e and another one - on the work of plastic deformation A_P. From this it follows that

$$A_P = A - A_e \tag{2}$$

Principle of determining the work of plastic deformation A_P during the tensile test is presented in Figure 1, where σ - stress, ε - strain. Total work A is determined as the shaded area between the stress-strain curve *1* and the straight line *2*. Work of elastic deformation A_e is shown as a twice shaded area between the straight lines *2* and *3*.

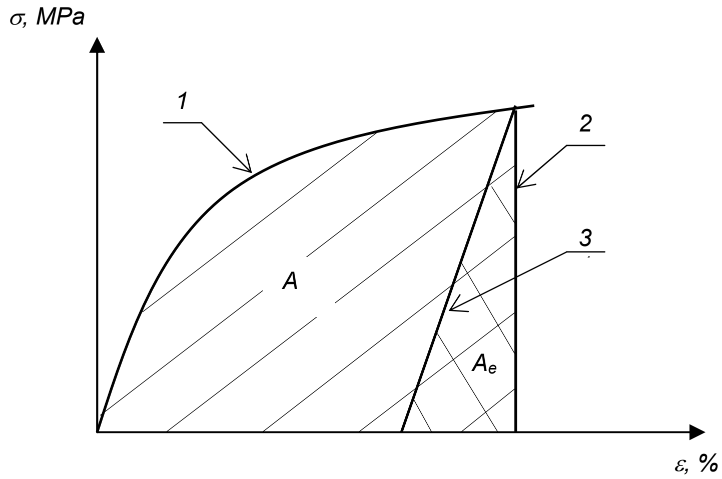

Fig. 1. *Principle of determination of the work of plastic deformation during tensile test*

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The dependence of specific work of plastic deformation $a_p = A_P / V$ (V – the volume of a specimen) on relative elongation ε % at different strain rates is presented in Figure 2. As it follows from Figure 2, the difference between works of plastic deformation made at different strain rates does not exceed 4 %.

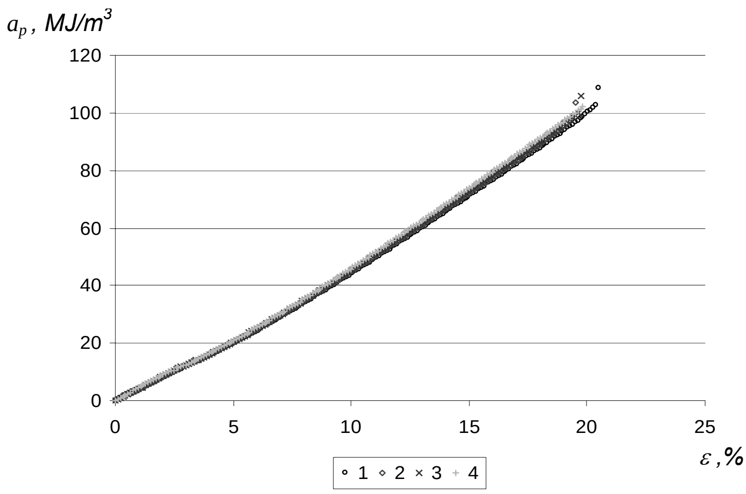

Fig. 2. *The curves of plastic deformation specific work of steel 18Г2С at different strain rates* $\dot{\varepsilon}$ *vs.* relative elongation *: 1 – at* $\dot{\varepsilon} = 8{,}98\times10^{-4}\ s^{-1}$; *2 –* $\dot{\varepsilon} = 1{,}78\times10^{-3}\ s^{-1}$; *3 –* $\dot{\varepsilon} = 3{,}57\times10^{-3}\ s^{-1}$; *4 –* $\dot{\varepsilon} = 8{,}93\times10^{-3}\ s^{-1}$

4. Evaluation of the evolved heat

In this paper, the heat evolved in the process of plastic deformation is determined by solving the heat conduction equation simultaneously with the use of infrared radiation measurement data.

The evolved heat Q during deformation is evaluated from the solution of one-dimensional heat conduction equation with a heat source $q(t)$:

$$\frac{\partial T(x,t)}{\partial t} = a\frac{\partial^2 T(x,t)}{\partial x^2} - \nu(T(x,t) - T_c) + \frac{q(t)}{c\rho} \tag{3}$$

Here, a is the temperature conductivity, ν - thermal diffusivity, c - heat capacity, ρ - density, $T(x, t)$ and T_c are the distribution of temperature on surface of the specimen and the temperature of surroundings, respectively. Within this problem, the specimen was simulated as an axisymmetric finite-size bar with known boundary conditions:

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$$T(x,0) = T_c, \qquad T(0,t) = T_c, \qquad T(l,t) = T_c \quad . \tag{4}$$

Solutions of the heat conduction equation (3) for the heat source are:

$$q\ (t) = \frac{\Delta \overline{T}(x,t)}{a_1 - a_2 \cdot \exp[-b_1 \cdot t] - a_3 \cdot \exp[-b_2 \cdot t]} \tag{5}$$

where a_1, a_2, a_3, b_1, and b_2 are the constants dependent on the length of bar, thermal conductivity, density, and heat capacity. The temperature distribution $\Delta \overline{T}(x,t)$ is obtained empirically with the use of infrared system. Dependence of the heat source power on time is presented in Figure 3. The evolved heat q (Eq. (6)) can be obtained from the integration of solutions (5) of heat conduction:

$$q = \int_0^t q(t) \cdot dt \quad . \tag{6}$$

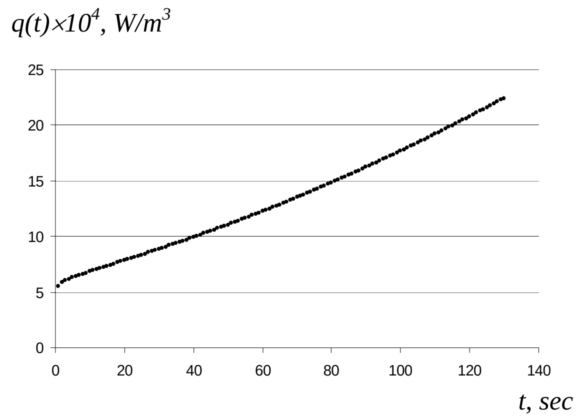

Fig. 3. *Dependence of the heat source power of steel 18G2S on time*

5. Results

The dependences of the specific work of plastic deformation a_P, specific storage energy e_S and evolved heat q in the tensile tests on strain of the steel 18G2S are presented in Figure 4. It is seen that the amount of evolved heat makes up to 30 % of work of plastic deformation, and the rest of this work is stored by material. The obtained results differ from the data presented in [5] where the amount of evolved heat for the stainless steel makes 60-70 % of the work of plastic deformation. At the same time, the absolute value of the storage energy for 18G2S steel exceeds that for stainless steel and amounts to 37.5 MJ/m^3 and 30 MJ/m^3, respectively.

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Dependence of the storage energy at different deformation rates on strain is shown in Figure 5. The difference between storage energies amounts to not more than 12 %. One can conclude that the storage energy within the range of rates considered above does not depend appreciably on deformation rate.

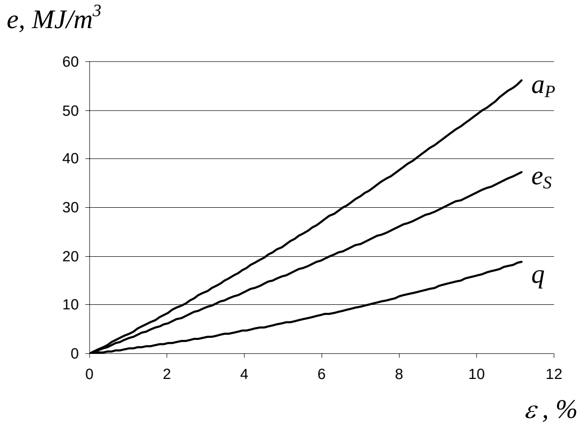

Fig. 4. *Dependence of the specific plastic work a_P, specific storage energy e_S and evolved heat q in the tensile on strain of the steel 18G2S.*

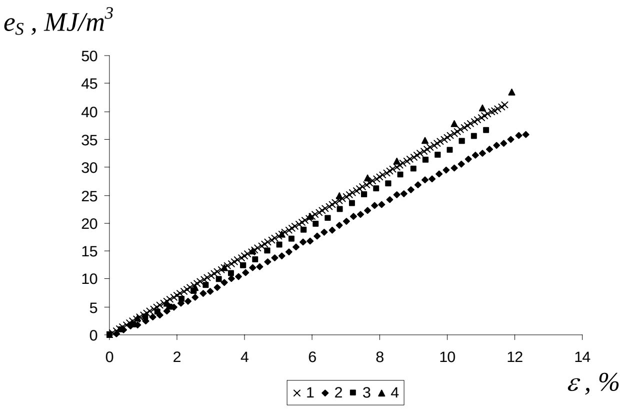

Fig. 5. *Dependence of the specific storage energy received by the different deformation rates on strain, where 1 – by $\dot{\varepsilon}$ = $8{,}98\times10^{-4}$ s^{-1}; 2 – $\dot{\varepsilon}$ = $1{,}78\times10^{-3}$ s^{-1}; 3 – $\dot{\varepsilon}$ = $3{,}57\times10^{-3}$ s^{-1}; 4 – $\dot{\varepsilon}$ = $8{,}93\times10^{-3}$ s^{-1}.*

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Thus, solution of the inverse problem of conductivity allows to evaluate the amount of heat evolved under the influence of thermoplastic effect with taking into account the heat dissipated into surroundings. The described above calculation-experiential technique exploiting infrared imaging camera enables to determine the energy stored by the material at static tensile test of specimens.

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