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DEFORMATION AND DESTRUCTION OF THE STRUCTURAL STEEL SUBJECTED TO SEVERE PLASTIC DEFORMATION AND THERMAL PROCESSING

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Abstract. The article represents the results of investigation of combined thermomechanical processing effects on the steel strength properties. Methods of thermomechanical processing include forging, torsion, and equal channel angular pressing (ECAP) with various types of thermal processing. The results of investigation of the strength and plasticity of low-carbon steel subjected to ECAP, forging, and torsion are given, as well as results of fracture toughness tests in conditions of normal and low temperatures.

The study of the steel plasticity properties was carried out with the use of the developed experiment-calculated technique based on thermovision method of the specimen surface temperature measurement and solution of inverse problem of thermal conductivity with constant coefficients.

1. INTRODUCTION

A prior trend of the material science is development of new materials. The nomenclature of structural materials of industrial use is currently fairly wide. However, development of modern techniques and pioneer approaches to project engineering stimulates progress in novel methods and techniques aimed at improving properties of existent materials. As an example, the method of severe plastic deformation (SPD) through ECAP set forth by R.Z.Valiev *et al.* [1] makes it possible to substantially increase strength of processed metals and alloys.

Strengthening of manufactured articles by ECAP is carried out in the special accessory with two channels of equal diameter intersecting inside the compression mold at a certain angle (90°, 120° *etc.*). The cylindrical blank is pressed under high pressure through the compression mold described above. In the zone of channels intersection the metal blank is subjected to severe plastic deformations. Reduction of grain structure is achieved by shear strains in metal along glide planes [2]. The average grain size in metals subjected to ECAP can reduce to tens and hundreds nanometers. Manufactured articles subjected to mechanical processing by ECAP

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technique have a unique structure and high strength properties.

Application of SPD for strengthening low-carbon steels through ECAP provides for 2-3 times higher yield point, from 300·350 MPa to 800·1000 MPa [3]. However, such an approach does not always ensure optimal performance parameters of processed steel. Strengthening the low-carbon steel by ECAP leads to embrittlement of the material. The higher transition temperature of the steel strengthened by ECAP is especially negative in low climatic temperature conditions. Thus, investigation of cold-resistance of structural steels strengthened by ECAP is an actual theoretical and practical task.

2. OBJECT OF RESEARCH

As an object of research, the 09G2S structural low-carbon low-alloy steel was used. Chemical analysis of the steel under study was made with “Foundry-Master” atomic emission spectrometer of “World-wide Analytical Systems AG (WAS AG)” company and showed the following content: 0.12 wt.% C, 0.8 wt.% Si, 1.7 wt.% Mn, 0.3 wt.% Cr, 0.3 wt.% Ni, 0.3 wt.% Cu, Fe — the rest. On evidence of metallographic analysis by scanning electron microscope, 09G2S steel has a ferrite-pearlitic structure with 18.5 mm average grain size. Mechanical testing of standard plain specimens of 09G2S steel in the initial state carried out at UTS-20k tensile-testing machine at 5 mm per minute load rate showed that the yield strength and yield value were 330 MPa and 460 MPa, respectively.

3. STRENGTHENING OF STEEL UNDER INVESTIGATION

Strengthening of 09G2S steel was carried out with the help of a special accessory made for exercising SPD technique by ECAP. Channels intersection angle 120°. To implement ECAP, PSU-125 press with the maximum load to 125 t was used. Linear dimensions of cylindrical specimens used for calculation of the accessory for ECAP realization: 100 mm in length, 20 mm in diameter.

Cylindrical specimens of the corresponding dimensions were made of 09G2S steel. Steel blanks were subjected to ECAP by route B_c with 4 passages at 723K pressing temperature. Compression mold must be heated to increase plasticity of the deformed material.

Also, the influence of preliminary forging and torsion of the material on the steel strength was studied. The types of thermomechanical processing of steel are listed in Table 1. The first type is 09G2S steel in the initial state. The second type — preliminary steel quenching in water with the temperature of 1203K with subsequent equal channel angular pressing by route B_c in 4 passages. Preliminary steel quenching makes it possible to get more fine-grained structure in the course of ECAP realization. The third type of thermomechanical processing includes hot forging at the temperature of 1173÷1023K in three cycles with subsequent steel quenching in water with the temperature from 1203K and ECAP. The fourth type — steel torsion at the temperature of 1173÷1023K with two axial rotations, quenching, and ECAP at the same temperature regime.

That is, the initial temperature of torsion deformation and forging of cylindrical blanks is 1173K, the final one — 1023K. The all-around forging of heated ∅20x60 mm blanks in three cycles was made with the help of a pneumatic hammer. The torsion was carried out in a special device. For this, the preliminary heated cylindrical blank with the dimensions of ∅25x170 mm was put in a clutch and subjected to the torsion deformation in two revolutions by a turning gear.

Table 1. Types of thermomechanical processing 09G2S steel is subjected to.

Types	Thermo-mechanical processing of steel 09G2S
Type 1	Steel 09G2S in initial condition.
Type 2	1. Quenching at temperature T=930 °C in water; 2. ECAP by route B_c with n=4 times.
Type 3	1. Forging at T=900÷750 °C to 3 times; 2. Quenching at temperature T=930 °C in water; 3. ECAP by route B_c with n=4 times.
Type 4	1. Torsion at T=900÷750 °C to 2 rotation; 2. Quenching at temperature T=930 °C in water; 3. ECAP by route B_c with n=4 times.

4. RESEARCH RESULTS

Flat plain specimens with dimensions of 30×4.0×1.15 mm for static tension tests were made of steel blanks after their thermomechanical processing and ECAP. Static tension tests were carried out at UTS-20k tensile-testing machine at the constant load rate $\varepsilon = 8.33 \cdot 10^{-2}$ mm/sec at room temperature. Figure 1 gives a conventional strain diagram of 09G2S steel subjected to thermomechanical processing of the 3rd type (forging + quenching + ECAP). The strain diagram for the 4th type of steel thermomechanical processing (torsion + quenching + ECAP) is analogous. Table 2 gives mechanical properties of the investigated steel for each type of its thermomechanical processing.

As shown in Fig. 1, yield strength of 09G2S steel after its thermomechanical processing with ECAP is substantially higher in comparison with its initial state equaling 1045 MPa. Also, the elastic range is more than 3÷4 times larger (3.5%). At the same time, proportion of the plastic deformation is significantly lower (only 3÷5% of the total specimen elongation). By comparison, 09G2S steel plastic strain after failure in the initial state is 20÷22%. The fact gives an indication of high strength properties but, at the same time, low plasticity of the low-carbon steel subjected to thermomechanical processing and ECAP.

To evaluate brittle fracture strength, impact strength tests were made. Standard impact strength test specimens with V-form notches were made of steel blanks subject to thermomechanical processing. Impact fracture strength tests were carried out at MK-30 impact pendulum-type testing machine both at normal and at lowered to 213K temperatures, according to GOST (State Standard) 9454-78.

Fracture toughness tests showed that the values of impact strength for the low-carbon steel at room temperature are significantly lower. For example, even at 293K test temperature impact strength for the low-carbon steel in the initial state was 121×10^4 J·m^{-2}, while after ECAP – only 25×10^4 J·m^{-2}. Such a considerable decrease of brittle fracture strength is probably connected with lower plastic properties of the steel strengthened by ECAP.

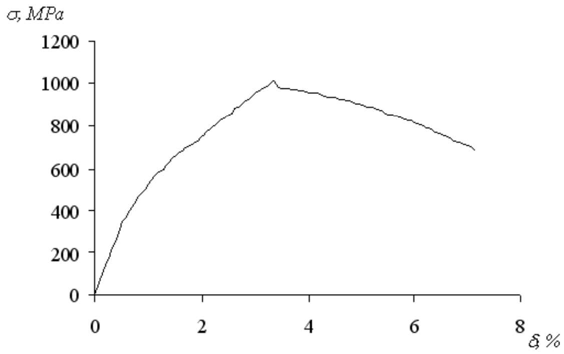

Fig. 1. Stress-strain diagram of 09G2S steel after forging + quenching + ECAP.

However, as further investigation showed, the use of additional post-deformation thermal processing makes it possible to improve brittle fracture strength properties. Table 3 gives values of impact fracture strength of the low-carbon Fe360 steel subjected to ECAP and various types of thermal processing. The values in Table 3 were taken at the test temperature of 213K. As seen in Table 3, the best results for impact fracture strength were obtained at combined type of thermomechanical processing, namely, at preliminary quenching in water with the temperature from 1203K with subsequent ECAP and post-deformation annealing. The use of post-deformation annealing (after ECAP) makes it possible to get more uniform structure with lower residual stress. In turn, it leads to higher plasticity of steel and better material resistance to brittle fracture.

Table 2. Mechanical properties of 09G2S steel subjected to different types of thermomechanical processing.

Type	*Material condition*	*Yield strength,* MPa	*Ultimate strength,* MPa	*Relative elongation,* %
Type 1	Steel 09G2S in initial condition	337	462	24.4
Type 2	Quenching +ECAP	1160	1230	7.2
Type 3	Forging +Quenching +ECAP	1045	1045	7.5
Type 4	Torsion + Quenching + ECAP	1003	1003	7.4

Table 3. Impact strength of steel 09G2S at test temperature -60 °C after ECAP and ECAP + thermal processing.

ECAP and thermal processing	*Impact strength*, $KC \times 10^4$ J·m^{-2}
Steel 09G2S in initial state	24
ECAP by route «B_c» at T=450 °C, n=4	10,1
Quenching at T=930 °C + ECAP «B_c», T=450 °C, n=4	25
Quenching at T=930 °C + ECAP «B_c», T=450 °C, n=4 + annealing	183

5. STEEL PLASTICITY RESEARCH TECHNIQUE

As shown above, the low-carbon steel subjected to ECAP has high strength properties but, at the same time, low plasticity. Lower steel plasticity, in its turn, leads to the material embrittlement.

To study plasticity of the strengthened steel, the technique was elaborated permitting evaluation of the energy stored in the process of the plastic flow of the material. Plasticity of the structural steels is generally connected with generation, movement, locking, and annihilation of dislocations. Changes of dislocation structure have an irreversible character, partially recoverable only in the process of recovery or recrystallization of metals. It is assumed that dislocation mobility as well as their density provide for the material's capacity to absorb external energy. On the other hand, changes in density and configuration of linear defects are always accompanied by energy dissipation exhibited as local increase of the material temperature in the zone of development of plastic deformations (thermoplastic effect). It is thought that the local temperature increase is connected to appearance of additional oscillating motion of atoms of crystal structure at dislocation movement across Peierls relief.

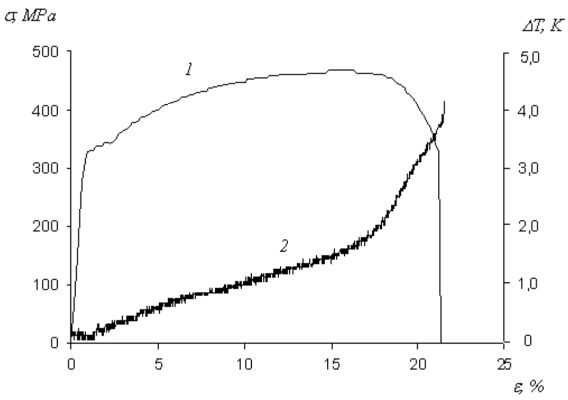

Fig. 2. Stress-strain diagram of 09G2S steel in initial state *1* and temperature change curve *2* of the specimen.

From the aforesaid, it may be concluded that external work dA_p consumed at the specimen plastic deformation at its elongation is partially dissipated in the form of heat dQ (thermoplastic effect), while its other portion is stored by the material dE_S and is largely associated with the changes of dislocation structure. Thus, in accordance with the first law of thermodynamics, the energy stored by the material dE_S in the process of plastic deformation can de expressed by the following correlation [4]:

$$dE_S = dA_p - dQ \,. \qquad (1)$$

The energy stored by the material dE_S reflects all irreversible structural changes taking place in the material and its capacity to resist brittle fracture.

Mechanical work consumed for plastic deformation can be determined through conventional strain diagram. Heat emitted in the process of plastic deformation can be evaluated with the help of a calorimeter [5,6]. However, calorimetric method is featured by certain response rate that increases calculation error [6].

On the other hand, heat emitted at plastic deformation can be evaluated with the help of IR-camera [7-9]. In this case it is possible to make real-time temperature measurement at the specimen surface. However, it is quite difficult to evaluate heat diffusion to the environment. In this case the desired heat value can be determined by introduction of electrical heat analog, where *P(t)* – function of electric power heating the specimen – is chosen so that the specimen temperature increase for the time *t* is identical to the temperature achieved at the static elongation of the analogous specimen [8].

In the present study the evaluation of heat emitted in the process of plastic strain was carried out with the help of "TKVr-ISP" thermovision camera with the heat sensitivity of 0.028K. Spectral sensitivity

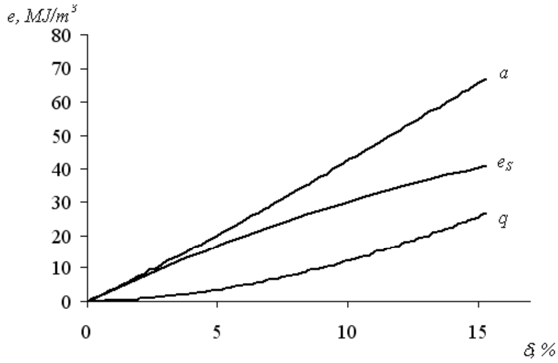

Fig. 3. Dependence of the specific plastic work a_P, stored energy e_S and evolved heat q of the steel 09G2S in initial condition versus elongation.

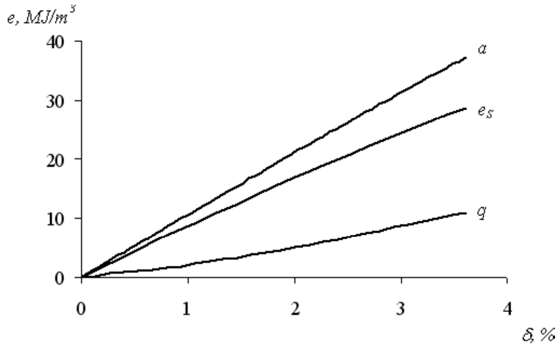

Fig. 4. Dependence of the specific plastic work a_P, stored energy e_S and evolved heat q of the steel 09G2S after forging + quenching + ECAP verses elongation.

of infrared radiation detector was 2.65 ÷ 3.05 mm. Temperature distribution across specimens' surfaces was measured at 0.3 m distance, wherein the camera's field of view is 0.09 × 0.09 m. Thermograms are recorded on PC in the video film regime at 20 frames per second rate. Thus, the thermal imaging system makes it possible to get the function of temperature distribution across the specimen surface in relation to time.

Evaluation of stored energy was carried out on flat plain specimens with the working part of 0.05 m long, 0.0055 m high, and 0.0025 m wide made of 09G2S steel preliminary subjected to ECAP with various types of thermomechanical processing. Static elongation of specimens was made at UTS-20k tensile-testing machine at constant deformation rate of 2.4×10^{-3} s^{-1}. Measurements of changes in surface temperature by thermal imaging system were made in parallel with recording the computer diagram of the specimen deformation. Conventional diagram of deformation of the specimen of 09G2S steel in the initial state in combination with temperature change curve are shown in Fig. 2, where *1* – stress, 2 – temperature change measured with the help of thermal imaging system.

The technique of evaluating heat emitted in the process of plastic deformation of steel is detailed in Material Science and Engineering Journal [10].

6. RESULTS OF EVALUATION OF PLASTIC DEFORMATION ENERGY

Fig. 3 gives values of specific plastic deformation work, stored energy and evolved heat for 09G2S steel in the initial state. As shown in Fig. 3, up to 40% of plastic deformation work is dissipated in the environment in the form of heat. The rest of plastic deformation work is stored by the material.

Charts for 09G2S steel subjected to thermomechanical processing look somewhat differently. Specific plastic deformation work, stored energy and heat for 09G2S steel after forging, quenching, and ECAP are shown in Fig. 4. Charts for the steel subjected to torsion, quenching, and ECAP are not shown as they are identical to curves in Fig. 4. As seen in Fig. 4, heat dissipated in the plastic flow process of the steel strengthened by ECAP is only 15-20% of plastic deformation work. This indicates that the major part of the work is stored by the material. Most likely, ability of the steel strengthened by ECAP to absorb energy more effectively allows to achieve high strength properties. Figures show that energy stored per unit deformation (elongation) of 09G2S steel strengthened by ECAP is ≈7.8 MJ/m^3, while in the initial state it is only ≈2.5 MJ/m^3.

7. CONCLUSION

ECAP usage allows to increase strength properties of steel due to reduction of grain structure. For example, steel yield strength is 2÷3 times higher after ECAP than in the initial state. Mechanical processing, as forging and torsion, also leads to higher strength properties of the material. On the other hand, on the basis of impact strength data it is shown that low-carbon steel subjected to ECAP has low brittle fracture strength. That is probably connected with decrease of strengthened steel plasticity. However, brittle fracture strength properties can be significantly improved by the use of post-deformation annealing of steel.

Solution of inverse problem of thermal conductivity with constant coefficients makes it possible to evaluate the quantity of heat emitted as a result of thermoplastic effect.

Developed experiment-calculated technique with the use of thermovision camera makes it possible to determine energy stored by the material. This developed experiment-calculated technique is more preferable in comparison with the calorimetric method, as the latter has certain response rate, as well as the method of metal heating by electric current put forward by E.A.Pieczyska, S.P.Gadaj, and W.K.Nowacki [8].

It is shown that steel subjected to ECAP is capable of more effective absorption of plastic deformation energy. On the other hand, quantity of heat emitted as a result of thermoplastic effect is most probably defined by the material plasticity.

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