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PORTEVIN – LE CHATELIER EFFECT AND STRAIN BEHAVIOR OF AUSTENITIC STEEL 02Kh18N8G2FV2AB AT HIGH TEMPERATURES

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The strain behavior of austenitic steel 02Kh18N8G2FV2AB in static tensile tests is studied in a wide range of temperatures (23 – 740°C) and deformation rates ($1.3 \times 10^{-5} - 1.3 \times 10^{-2}$ sec^{-1}). The influence of the Portevin – Le Chatelier effect on the strength and ductility of steel 02Kh18N8G2FV2AB at elevated temperatures is determined. The relation between the characteristics of static strength and the creep resistance of the steel is considered.

Keywords: austenitic steels, Portevin – Le Chatelier effect, mechanical properties at elevated temperatures, creep.

INTRODUCTION

Newly erected coal-fired steam power plants in Japan, the USA, and other countries operate at a working steam temperature of 600 – 620°C [1, 2]. The maximum temperature of the pipes of such power plants exceeds 650°C. This requires the use of austenitic steels for the final heating loop and intermediate superheating loops. Today Russia does not produce austenitic steels possessing weld strength satisfactory for different-kind materials and suitable for operation at such temperatures. Such steels have been created in Japan by Nippon Steel and Sumimoto Metals Ind. on the base of steel 304 (18% Cr – 8% Ni) due to additional alloying with tungsten and copper, respectively. These steels are widely used in components of new-generation coal-fired power plants. Public data on the structure and mechanical properties of these steel are virtually absent despite their wide application. The physical nature of the unusually high creep resistance of these materials remains unclear.

The aim of the present work consisted in studying the mechanical properties of austenitic steel 02Kh18N8G2FV2AB, which is the Russian counterpart of grade XA704.

METHODS OF STUDY

Stainless steel 02Kh18N8G2FV2AB of austenitic class was obtained by chill casting. The chemical composition of the metal was as follows (in wt.%): 0.018 C, 18.2 Cr, 8.2 Ni, 2.1 W, 1.75 Mn, 0.43 Nb, 0.17 N, 0.29 V, 0.14 Si, remainder Fe. The ingots were forged at 1180°C with a reduction ratio of 18.5. Hot-rolled bars with cross section of 20×20 mm were subjected to standard heat treatment [3], which included heating to 1150°C, 1-h hold, and water cooling for fixing the solid solution.

Flat specimens with functional part 25 mm long and cross section of 7×3 mm were subjected to mechanical tests. The specimens were deformed in a mode of equiaxed tension in an "INSTRON-5882" universal testing machine at a temperature of 23 – 740°C and deformation rate of $1.3 \times 10^{-5} - 1.3 \times 10^{-2}$ sec^{-1}. The tests at elevated temperatures were performed in a three-section furnace with individual regulation of zones. The temperature difference over the height of the furnace was ± 3°C. Before testing, the specimens were held in the furnace at the test temperature for 30 min.

The microstructure was studied with the help of an Olympus GX70 light microscope. The specimens for metallographic analysis were etched in a solution of 30% H_2O + 30% HCl + 10% HNO_3. The electron microscope study was performed under a Jeol JEM-2100 transmission microscope at an accelerating voltage of 200 kV. The foils were prepared by jet electropolishing in a solution of 10% $HClO_4$ + 90% CH_3COOH using a TenuPol-5 device.

RESULTS AND DISCUSSION

Microstructure. A typical structure of steel 02Kh18N8G2FV2AB after standard heat treatment is presented in Fig. 1. It is represented by austenite grains with a

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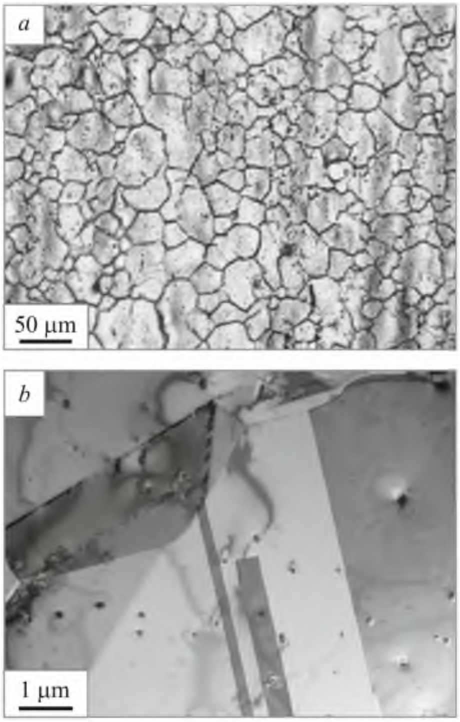

Fig. 1. Microstructure of steel 02Kh18N8G2FV2AB after standard heat treatment: *a*) light metallography, × 200; *b*) transmission electron microscopy, × 8000.

mean size of 16 μm (Fig. 1*a*), which contain numerous annealing twins. The austenite matrix bears particles of second phases (Fig. 1*b*) about 50 nm in size identified as (Nb, Cr)N nitrides. The dislocation density after the heat treatment was 1.2×10^{13} m^{-2}. Thus, the microstructure of the steel before the mechanical tests corresponded to a fully annealed state. This allowed us to compare the mechanical properties of the steel with those of steel 304 in annealed condition.

Mechanical Properties. Mechanical tests at 23 – 740°C at deformation rates of 1.3×10^{-5} – 1.3×10^{-2} sec^{-1} showed that the straining of the metal was accompanied by discontinuous yielding (DY), which manifested itself as cyclic hardening and softening, resulting in a serrated form of the $\sigma - \varepsilon$ curves (Fig. 2*a*). Discontinuous yielding of the material is a feature of the effect of Portevin – Le Chatelier (PLC) [4]. It can be seen from the $\sigma - \varepsilon$ curves of the steel deformed in the range of 410 – 740°C at a rate of 1.3×10^{-3} sec^{-1} that the type of the serration changes upon growth in the test temperature. In accordance with the classification used in the literature [4], three types of DY can be distinguished (Fig. 2*b*). At 530°C the deformation of the metal is accompanied by serration of type *E*; the curves exhibit weakly manifested stress jumps. In the range of 590 – 620°C the serration is of a mixed type, i.e., the stresses grow and then decline abruptly (type *A*); type-*E* serration is observed between such jumps. At 650 – 680°C the serration is also of a mixed type; high-frequency stress jumps are present between serrations of type *A* (type *C*).

The nature of the detected types of DY is as follows. Type *A*, which is commonly observed at low temperatures and high deformation rates, is connected with the continuous formation of strain bands in one part of the deformed specimen and their propagation over the functional part of the specimen in one direction. This type is characterized by continuous growth in the yielding stresses above the average stress level and subsequent abrupt drop below this level. This pattern is explained by cyclic locking-unlocking of the sources of dislocations as a result of the emission of atmospheres of dissolved elements on the leading dislocations of a plane cluster. Serration of type *C* appears at high temperatures and is characterized by cyclic decline of the yielding stresses below the average level. It is explained by unlocking of dislocations when they cut coherent particles, which causes dissolution of the latter. Type *E* is close in nature to type *A* (the collective motion of dislocations in a strain band is locked – unlocked) and differs from it in the virtually complete absence of hardening during the motion of the strain bands [4].

The temperature-and-rate range in which the studied steel manifests DY is presented in Fig. 3. It can be seen that the region of DY depends on the temperature and rate of the

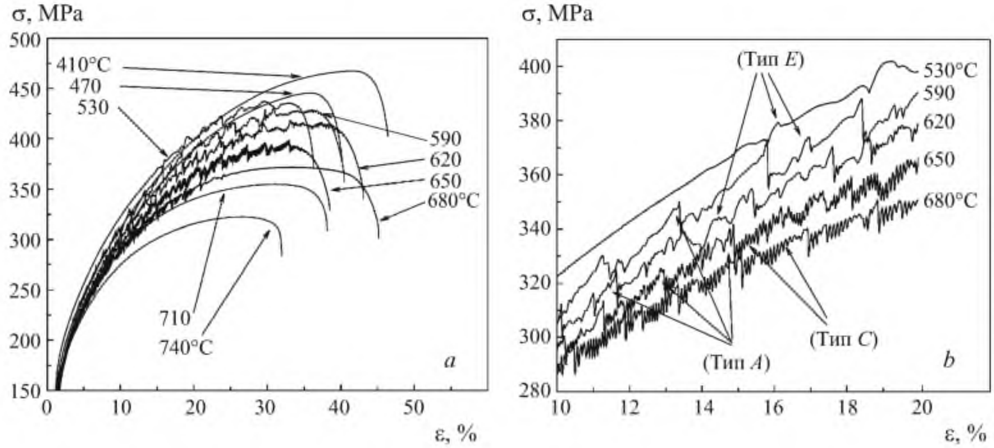

Fig. 2. Dependence of the yielding stresses on the degree of strain in the range of 410 – 740°C (the figures at the curves) at a deformation rate of 1.3×10^{-3} sec^{-1}: *a*) typical form; *b*) magnified region of the $\sigma - \varepsilon$ dependence, which represents different types of discontinuous yielding.

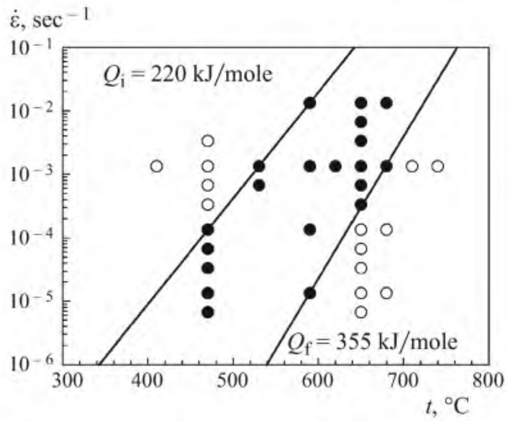

Fig. 3. Temperature and rate range of discontinuous yielding in steel 02Kh18N8G2FV2AB: filled circles) occurrence of discontinuous yielding; empty circles) its absence.

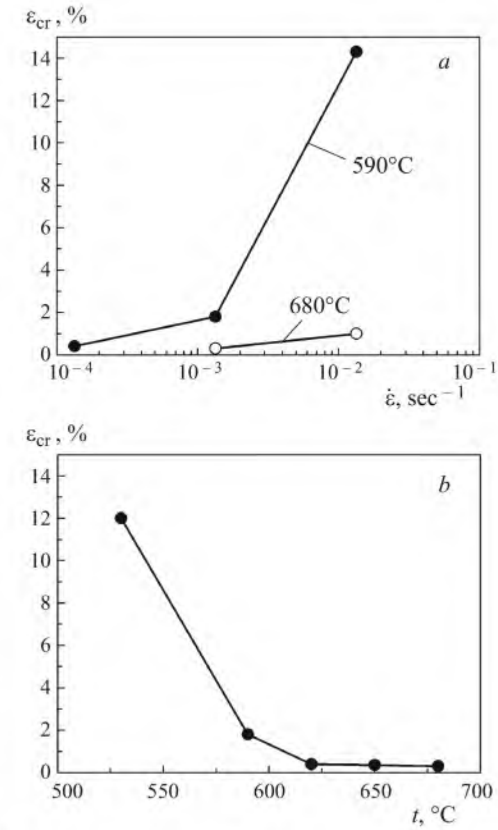

Fig. 4. Dependence of the critical degree of strain ε_{cr} on the rate (*a*) and temperature (*b*) of the deformation. The deformation temperatures are given at the curves.

deformation and shifts to higher rates upon growth in the temperature; this region is describable by the following equation [5]:

$$\dot{\varepsilon} = \frac{4b\rho C_v D_0}{l} \exp\left(-\frac{Q}{kT}\right), \tag{1}$$

where b is the Burgers vector, ρ is the dislocation density, C_v is the concentration of vacancies, D_0 is the diffusivity, l is the effective radius of the Cottrell atmospheres, Q is the activation energy of migration of dissolved elements, and k is Boltzmann's constant.

The slopes of the lines bounding the range of occurrence of DY were used to compute the activation energy of its start ($Q_i = 220$ kJ/mole) and end ($Q_f = 355$ kJ/mole). The differences in the values of the activation energy show that the experimentally observed types of DY develop by different mechanisms. As a rule, the mechanism responsible for DY in austenitic steels at low temperatures (the boundary of the initiation of DY) is connected with diffusion of interstitial atoms such as carbon and nitrogen; at high temperatures (the boundary of the end of DY) it is connected with diffusion of substitutional atoms, i.e., chromium [6]. It is obvious that in steel 02Kh18N8G2FV2AB the lower temperature-and-rate boundary of manifestation of the PLC effect in connected with formation of Cottrell atmospheres of interstitial atoms (carbon and nitrogen) and the upper boundary is connected with formation of Cottrell atmospheres of substitutional atoms.

In the range of the deformation temperatures and rates presented in Fig. 3 DY appears at a specific degree of strain ε_{cr}, the values of which depend on the test temperature and on the deformation rate. For example, the critical strain increases at high deformation rates (Fig. 4*a*). At the same time, growth in the deformation temperature causes lowering of the values of ε_{cr} (Fig. 4*b*). Such dependence of the critical strain is a "normal" manifestation of the PLC effect [7].

The temperature dependences of the mechanical properties of steel 02Kh18N8G2FV2AB are presented in Fig. 5. The conventional yield strength $\sigma_{0.2}$ varies little in the temperature range of 350 – 740°C remaining at a level of about 168 MPa (Fig. 5). We may say that in this temperature range the yield strength is independent of the deformation temperature. Comparing this feature with the dependence of $\sigma_{0.2}$ on the temperature for the base steel 304L in the annealed condition, which exhibits such a plateau at 320 – 500°C [8, 9], we may infer that alloying of this steel with 2.1% W widens the plateau toward higher temperatures by 180°C. Note that in steel 304L the yielding stresses on this plateau constitute 60% of the level of stresses at room temperature [8, 9], whereas in steel 02Kh18N8G2FV2AB the figure is 48%. At the same time, the absolute level of stresses on this plateau for steel 02Kh18N8G2FV2AB is 60 MPa higher than for 304L.

The data presented in [8, 9] allow us to say that steel 304L manifests features of the PLC effect in a temperature range much narrower than steel 02Kh18N8G2FV2AB. Consequently, we may infer that the introduction of tungsten into steel 304L has led to widening of the range of the PLC effect toward high temperatures. It has been shown in recent works [10, 11] that the PLC effect can raise the creep resistance at

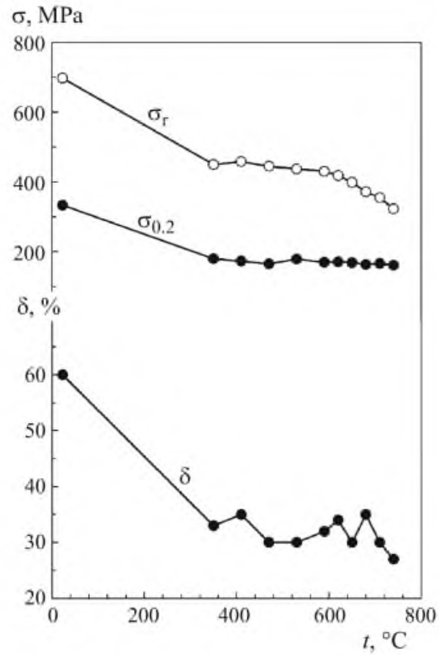

Fig. 5. Temperature dependences of mechanical properties of steel 02Kh18N8G2FV2AB.

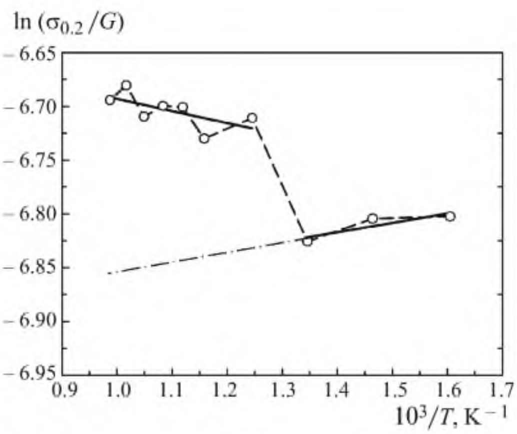

Fig. 6. Yield strength normalized to the temperature dependence of the shear modulus as a function of reciprocal temperature.

high temperatures and that increase in the ultimate long-term strength is observed at a temperature 50 – 100°C higher than the upper temperature boundary of the PLC effect, i.e., we are dealing with what is known as an aftereffect [10]. Steel 02Kh18N8G2FV2AB also exhibits the latter. Growth in the temperature from 680 to 740°C does not cause a significant decrease in the yielding stresses (Fig. 5) despite the fact that the PLC effect in this range does not occur.

To perform a detailed analysis of the deformation behavior of steel 02Kh18N8G2FV2AB, we plotted the variation of the yield strength normalized to the temperature dependence of the shear modulus G(t) on reciprocal temperatures (Fig. 6). The plot reflects an obvious tendency of the normalized stresses $\sigma_{0.2}/G$ to grow with the temperature at 530 – 740°C, i.e., the temperature dependence of the yielding stresses due to the PLC effect is positive [10, 11]. This very dependence is responsible for the high strength of steel 02Kh18N8G2FV2AB at high temperatures.

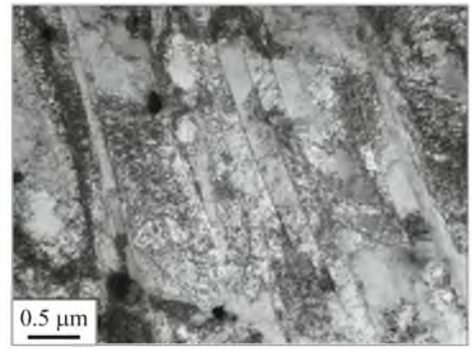

Fig. 7. Dislocation structure of the steel deformed under the conditions of occurrence of the Portevin – Le Chatelier effect at 650°C and deformation rate of 1.3×10^{-3} sec^{-1}, × 20,000.

The test temperature also affects considerably the rupture strength σ_r. It can be seen from Fig. 5 that below 350°C the values of σ_r decrease continuously. In the range of 530 – 680°C, where DY is observed, σ_r remains virtually invariable, forming a plateau (Fig. 5). At high temperatures, where DY does not exist, the value of σ_r decreases again. Thus, the temperature dependences of σ_r and $\sigma_{0.2}$ differ; a plateau appears on the $\sigma_r(t)$ dependence only at the temperatures of manifestation of the PLC effect. This is connected with the fact that the occurrence of the PLC effect is accompanied by accelerated accumulation of lattice dislocations in the process of plastic straining and this is responsible for the high values of σ_r [5, 10 – 13].

Figure 7 presents the dislocation structure of steel 02Kh18N8G2FV2AB deformed in the range of temperatures and rates corresponding to the existence of the PLC effect. It can be seen that in simple tension with relatively low strain (about 30%) the dislocation density attains very high values that ensure formation of components of a low-energy dislocation structure. In other words, a relatively low plastic strain has increased the dislocation density by three orders of magnitude. Figure 7 reflects the formation of strain-induced microbands.

Another consequence of intense accumulation of dislocations as a result of the PLC effect is the low rate of creep in steel 02Kh18N8G2FV2AB when the applied stresses exceed the yield strength (Fig. 8). This phenomenon is not typical for conventional thermotechnical steels that do not exhibit the PLC effect near the operating temperatures.

One more consequence of the PLC effect is the temperature dependence of the elongation unusual for stainless steels; its form is not typical for a steel manifesting the PLC effect [4, 12, 13]. The elongation of steel 02Kh18N8G2FV2AB decreases with decrease in the test temperature to 350°C and

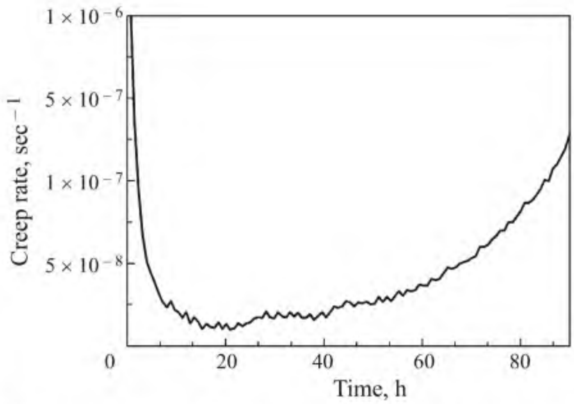

Fig. 8. Dependence of the creep rate of steel 02Kh18N8G2FV2AB on the duration of loading at a stress $\sigma = 230$ MPa and a temperature of 680°C.

remains virtually invariable upon growth in the temperature above this value (Fig. 5*b*). This circumstance is explainable by the fact that the PLC effect makes it possible to preserve the strain hardening $\theta = d\sigma/d\varepsilon$ at an invariable level, which is about 0.3 in the temperature range of the occurrence of the PLC effect.

Thus, alloying of steel 304L with tungsten promotes widening of the temperature range of manifestation of the PLC effect toward high temperatures. The effect ensures invariability of the yield strength and of the elongation to up to 740°C, which is responsible for the high creep resistance of this steel at temperatures unusually high for steels with 18% Cr and 8% Ni.

CONCLUSIONS

1. Tensile tests of steel 02Kh18N8G2FV2AB in the range of deformation rates of $1.3 \times 10^{-5} - 1.3 \times 10^{-2}$ sec^{-1} and temperatures of 23 – 740°C have shown that the high-temperature deformation gives rise to the following features of the Portevin – Le Chatelier effect:

(a) discontinuous yielding reflected in the serrated form of the stress – strain curves;

(b) "normal" dependence of the critical degree of strain on the temperature and rate of the deformation;

(c) presence of a plateau on the temperature dependences of the rupture strength and of the yield strength;

(d) positive temperature dependence of the yield strength normalized to the shear modulus $\sigma_{0.2}/G$.

2. The deformation temperature-and-rate range of manifestation of the Portevin – Le Chatelier effect has been determined. The calculated activation energies of the beginning and end of this range show that different mechanisms act on the lower and upper boundaries of the occurrence of the PLC effect.

3. Introduction of 2.1% W into a steel of type 18% Cr – 8% Ni promotes widening of the temperature range of the PLC effect toward high temperatures. This gives rise to the following consequences:

(a) the plateau on the temperature dependence of the yield strength and of the rupture strength widens to 740 and 680°C respectively;

(b) the elongation remains invariable at 350 – 740°C;

(c) the characteristics of creep resistance under deformation in the temperature range of occurrence of the PLC effect at stresses exceeding the yield limit are high.

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