Short-Range Order and Mechanical Properties of Nichrome

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INTRODUCTION

The appearance of short-range atomic order in nichrome and superalloys based on Ni–Cr solid solutions (Ni–20% Cr, in particular) results in an anomalous temperature dependence of their physical and mechanical properties in the temperature range of 400–600°C [1–3]. In most detail, the influence of short-range ordering has been studied in the case of electrical resistance of nichrome [3]. This phenomenon, known as the K state, is manifested as an anomalous increase in the electrical resistance upon heating of quenched nichrome in the temperature range of 400–550°C [3]. At the same time, the influence of short-range ordering on the mechanical properties of nichrome has been given insufficient attention [1, 2], in spite of its great practical importance. In this work, we attempt to fill this gap. To this end, we will analyze in detail the influence of short-range ordering on the strength properties of nichrome.

EXPERIMENTAL

In this work, we studied a nichrome alloy of the following chemical composition: Ni (base), 21% Cr, 1.1% Si, 0.6% Mn, 0.75% Fe, 0.31% Al, 0.08% Ti, 0.35% Cu, and 0.05% C. A homogenous structure with an average grain size of 100 μm was obtained by annealing a hot-rolled rod 40 mm in diameter at a temperature of 1025°C for 2 h with subsequent cooling in air. The mechanical tests by upsetting cylindrical samples with a diameter of 10 mm and a height of 12 mm were conducted on a Schenck universal dynamometer in the temperature range of 150–1000°C at an initial strain rate of 7×10^{-4} s^{-1}. In the range of temperatures of 500–950°C, the samples were subjected to deformation with initial strain rates in the interval of 1.5×10^{-6} to 5×10^{-2} s^{-1}. In detail, the methods of mechanical tests and microstructural studies are described in [4]; the calculation of the "threshold" stresses is considered in [5].

The differential scanning calorimetry (DSC) was performed using an SDT Q600 (TA Instruments) device. The sample was prepared in the form of a disk with a weight of 53.6 mg. The measurements were conducted using a preliminarily quenched sample upon heating at a rate of 20 K/min.

RESULTS AND DISCUSSION

The calorimetric studies revealed the temperature range of short-range ordering in nichrome (Fig. 1). The exothermic peaks, which testify to the formation of short-range order in nichrome [3], were observed at 388 and 546°C. At 388°C, the short-range order is formed, apparently, as a result of displacements of Cr atoms due

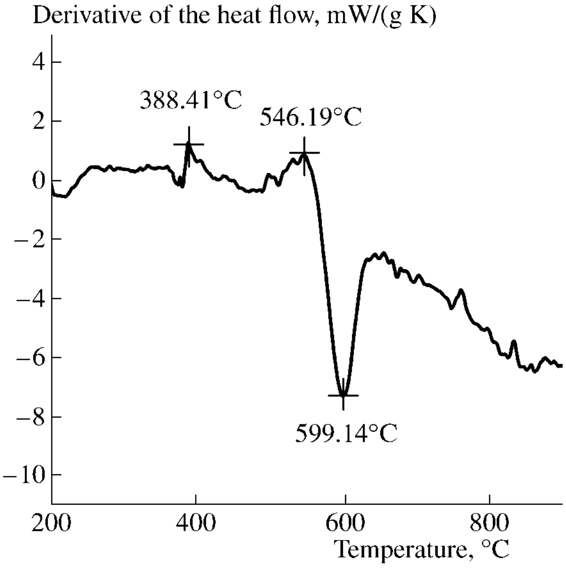

Fig. 1. Calorimetric curve recorded upon heating of nichrome at a rate of 20 K/min.

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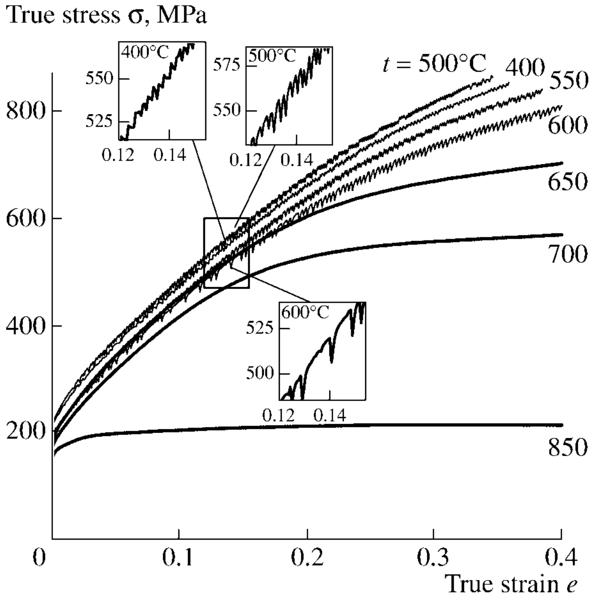

Fig. 2. True-flow-stress–true-strain curves.

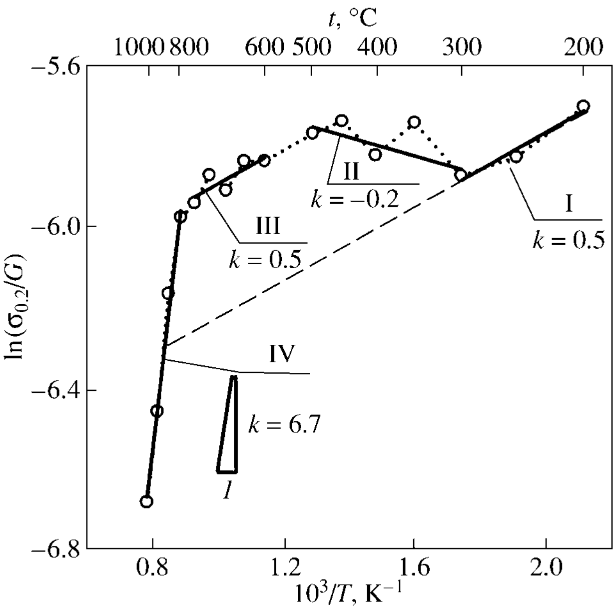

Fig. 3. Semilogarithmic plot of the yield stress $\sigma_{0.2}$ normalized to the temperature dependence of the shear modulus $G(T)$ as a function of the reciprocal temperature of deformation.

to the interaction with quench vacancies present in high concentrations, while at 546°C there occurs an additional ordering due to the self-diffusion of Cr atoms [3]. A further increase in temperature increases the diffusion rate to such an extent that the process of disordering begins [3], which is manifested as an endothermic peak at a temperature of 599°C.

The short-range atomic ordering in nichrome in the temperature interval of 400–600°C is the source of at least three anomalies of mechanical properties.

First, there is observed the Portevin–le Chatelier (PLC) effect [4], which consists in the appearance of serration in the σ–e curves (Fig. 2). The pronounced serration in the σ–e curves reflects the alternation of stages of strengthening and softening upon plastic flow of nichrome. In the presence of short-range ordering, the moving dislocations are forced to cut the regions of short-range order, which requires an increase in the applied stresses. As a result, there occurs a certain strengthening of the material; only those dislocations that are located in flat pileups prove to be capable of moving, where they move under the action of the superposition of the applied stresses and stresses that arise at the leading dislocation of the flat pileup. The generation of flat dislocation pileups of high density by Frank–Reed sources [4] gives the possibility of pushing leading dislocations of the pileups through the regions of short-range order. In the course of their cooperated movement, the dislocations of flat pileups destroy the short-range order, which leads to a decrease in stresses of the lattice resistance to dislocation motion and to the localization of slip in the disordered regions. In the σ–e curves, there is observed a reduction in the stresses [4]. During the subsequent deformation, the short-range order is restored, and the process is repeated. Thus, serrations appear in the σ–e curves.

The height of serrations and their extent in the σ–e curves increase with increasing deformation temperature because of an increase in the size of short-range-order domains. Accordingly, for these domains could be cut by dislocations, there are required higher flow stresses, which leads to an increase in the amplitude of serrations from 10 MPa at 400°C to 25 MPa at 600°C. For destroying short-range order in these regions, it is required that a larger number of dislocations pass through them, which increases the extent of the range of serrations; i.e., it leads to an increase in the degree of deformation between the stress peaks.

Second, nichrome exhibits a positive temperature dependence of the yield stress $\sigma_{0.2}$ in the temperature range of 300–500°C (Fig. 3). In the presence of short-range order, the moving dislocations are forced to cut clusters of regularly arranged Cr atoms, which requires an increase in the yield stress for the beginning of deformation. In the graph of the variation of the yield stress $\sigma_{0.2}$ normalized to the temperature dependence of the modulus of shear $G(T)$ as a function of the inverse temperature plotted in semilogarithmic coordinates, four regions can be distinguished, which are characterized by different temperature dependences of the yield stress. The temperature intervals I (200–300°C) and III (600–800°C) are characterized by identical values of the coefficient k, which is equal to the slope of the straight line $\ln\sigma_{0.2}/G$ – $1/T$ and reflects the rate of the decrease in the flow stress with increasing temperature [5]. In the temperature range II (300–500°C), there is

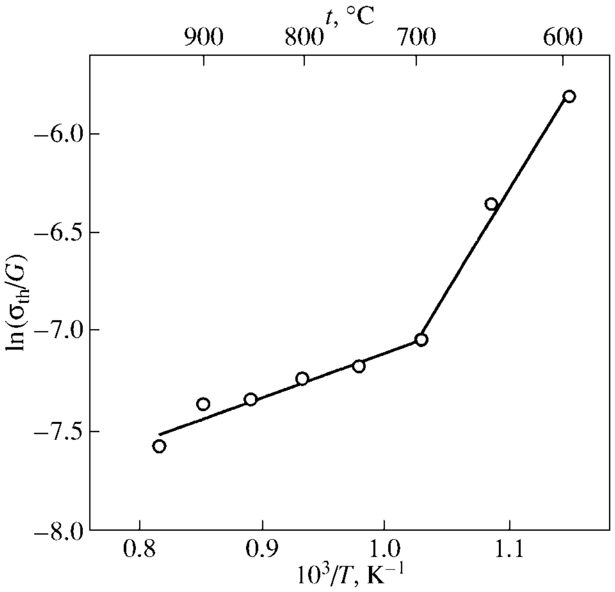

Fig. 4. Semilogarithmic plot of the "threshold" stress σ_{th} normalized to the temperature dependence of the shear modulus $G(T)$.

observed an increase in the normalized flow stress with increasing temperature from 300 to 350°C and from 400 to 450°C. In spite of the large spread of the experimental points because of the PLC effect, it can be said that in the temperature range of 300–500°C there is observed a tendency to growth of $\sigma_{0.2}/G$ with increasing temperature. In this case, the coefficient k takes on a negative value. It should be noted that in metals the positive temperature dependence of the flow stress is observed extremely rarely [6]. In the temperature range IV, at $t \geq 800$°C there is observed a rapid reduction in the flow stress ($k = 6.7$). Short-range ordering not only increases the yield stress of nichrome at $t \leq 500$.C, but also results in high strength properties in the interval of 600–800°C, in which nichrome is in the disordered state. It can be seen from Fig. 3 that the straight line III is located considerably higher than the straight line I extrapolated into the temperature range of 600–800°C. The distance between these two straight lines is a quantitative characteristic of the strengthening "aftereffect" caused by the short-range ordering, which is approximately 80–100 MPa.

Third, the short-range ordering can result in high values of the "threshold" stresses below which no deformation occurs in the material [5] (Fig. 4). The absolute values of the "threshold" stresses at $t \leq 650$°C are greater than 114 MPa, which ensures high creep characteristics of nichrome. This value is comparable with the value of the "aftereffect" from the short-range ordering. It can be asserted that the high creep strength of nichrome at temperatures lower than 650°C is caused by the appearance of short-range order at $t \leq 600$°C. In contrast to the high-temperature region, at $t < 700$°C there is observed a significant temperature dependence of the "threshold" stresses. The creep strength of nichrome grows sharply with decreasing temperature.

CONCLUSIONS

Thus, short-range ordering can be considered as an important mechanism of strengthening materials. Alloying that leads to the appearance of short-range ordering is a promising method of designing high-strength steels and alloys (superalloys) of a new generation for service at intermediate temperatures [7].

ACKNOWLEDGMENTS

We are grateful to the Center of Collective Use of Scientific Equipment of Belgorod State University and personally to I.D. Tarasova for assistance in conducting thermal analysis.

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Translated by S. Gorin

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