Short-range ordering and mechanical properties of a Ni-20%Cr alloy

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Abstract. The mechanical behavior of a coarse-grained (100 μm) nickel-base alloy nichrome (Ni-20%Cr) was studied in compression at temperatures ranging from 150 to 1000°C. It was shown that in the temperature interval of 300-600°C this alloy demonstrates the following features of mechanical behavior: i) positive temperature dependence of yield stress; ii) jerky flow associated with the Portevin–Le Chatelier (PLC) effect; 3) very high value (115 MPa) of "threshold" stress at 650°C. These features of mechanical behavior can be related to short-range ordering (SRO). It was shown by differential scanning calorimetry that SRO takes place in this temperature range, causing PLC effect and positive temperature dependence of yield stress. In addition, SRO has persistency effect on yield stress and creep resistance.

1. Introduction

The short-range ordering (SRO) occurs in Ni-Cr-based alloys due to attractive forces operating between unlike atoms and results in abnormal temperature dependencies of physical and mechanical properties [1-3]. It is well known that SRO leads to a significant increase in electrical resistivity of Ni-Cr based alloys upon heating in the temperature range of 400-550°C, also known as the K state [3]. At the same time, poor attention was given to examination of effect of SRO on mechanical properties [1,2], in spite of its great practical importance for high temperature strength and creep resistance. The purpose of the present work is to report detailed information on deformation behaviour of dilute Ni-20%Cr alloy. Specific attention was paid to establish relationship between SRO and mechanical properties of the Ni-20%Cr alloy at high temperatures.

2. Experimental

The Ni-20%Cr alloy had the following chemical composition in weight pct.: Ni (base), 21%Cr, 1.1%Si, 0.6% Mn, 0.75% Fe, 0.31% Al, 0.08% Ti, 0.35% Cu, 0.05% C. A uniform structure with an average grain size of 100 μm was obtained by annealing of hot-rolled rod with 40 mm diameter for 2 h at a temperature of 1025°C with subsequent cooling in air. Mechanical compression tests were carried out using cylindrical samples with dimensions of $\varnothing 10\times 12$ mm^2 in the temperature range of 150-1000°C with initial strain rates ranging from 1.5×10^{-5} to 5×10^{-2} s^{-1}. Other details of mechanical and microstructural characterizations were described in previous work [4]. Values of "threshold" stresses were taken from previous study [5]. Differential scanning calorimetry was performed using an SDT Q600 (TA Instruments) device. Pure gold was used as inert reference material, the sample weight was less than 0.1 g and the experiments were carried out under an argon atmosphere.

3. Results and discussion

The calorimetric studies were undertaken in order to determine the temperature interval of SRO which depends on the exact chemical alloy composition [3]. Figure 1 shows differential scanning calorimetry (DSC) curves of the samples. Two exothermic peaks at about 200 and 550°C are distinguished in figure 1 (a) indicating the SRO in the quenched alloy. Four exothermic peaks are revealed in figure 1 (b) by the heating of the alloy subjected to severe plastic deformation. Two peaks are located at nearly the same temperatures as for quenched material. Moreover, at 370 and 625°C two additional exothermic peaks were found. Thus, DSC analysis shows that some SRO of the deformed alloy occurs at about 200 and 370°C and the more pronounced ordering transformation occurs in the temperature interval 450-610°C that complies with [3].

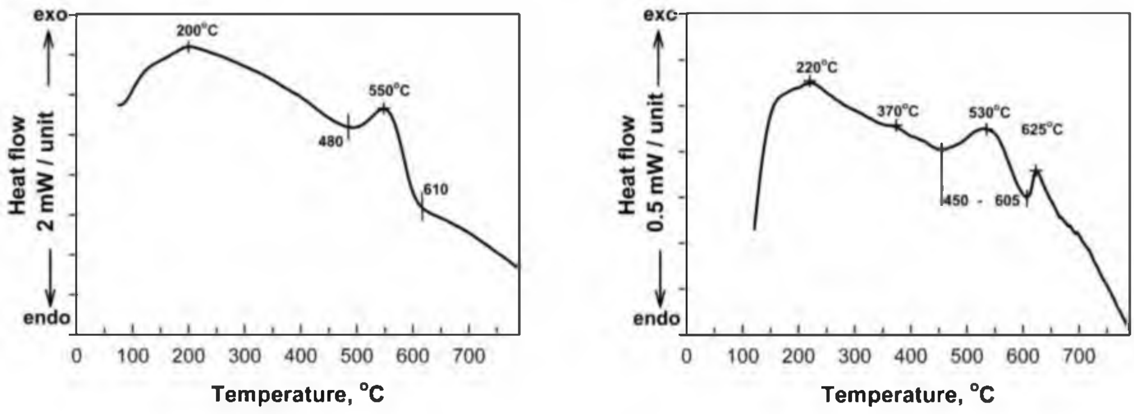

Figure 1. DSC thermogram of Ni-20%Cr alloy heated at 20°C/min (a) in the water quenched condition after solution treatment at 1100°C, (b) and after severe cold deformation by a Bridgman anvil to a strain of ~6.

Figure 2 shows true stress (σ) – true strain (ε) curves and values of the coefficient of strain rate sensitivity dlogσ/dlog$\dot{\varepsilon}$ in dependence of temperature. Three important features can be emphasized.

First, jerky plastic flow occurs at temperatures ranging from 300 to 600°C (figure 2 (a)). Such discontinuous flow is usually attributed to the Portevin–Le Chatelier (PLC) effect [6]. The PLC effect is known to be caused by the dynamic strain ageing, leading to periodic blocking and unblocking of dislocations by atmospheres of impurity atoms. The obtained negative strain-rate sensitivity of the flow stress (figure 2 (b)) is typical for the PLC effect [7]. It should be noted that the serrated σ-ε curves demonstrate extensive work hardening up to high strains while at T≥650°C the plastic flow attained the steady state.

In addition, non-typical behaviour for the PLC effect was revealed. The critical strain ε_c for the onset of jerky flow normally increases with increasing the strain rate and/or decreasing the temperature of deformation [7]. However, both the "normal" strain rate dependence (figure 3 (a)) and the "inverse" temperature dependence (figure 3 (b)) of critical strains were obtained for the present material. Such combination is a feature of materials strengthened by coherent precipitates [6,7]. Plastic flow becomes unstable in these alloys due to the softening induced by the shearing of the precipitates [6]. Surface observations of planar slip in the present alloy [4,5] support this conclusion. Furthermore, softening by planar slip was found [8] in SRO alloys as a result of cutting and disordering the SRO zones. In Ni-20 at.% Cr single crystal [9] SRO was reported to be correlated with planar slip which can initiate strain bursts in fatigue experiments. Thus, the SRO can result in jerky flow in the Ni-20%Cr alloy.

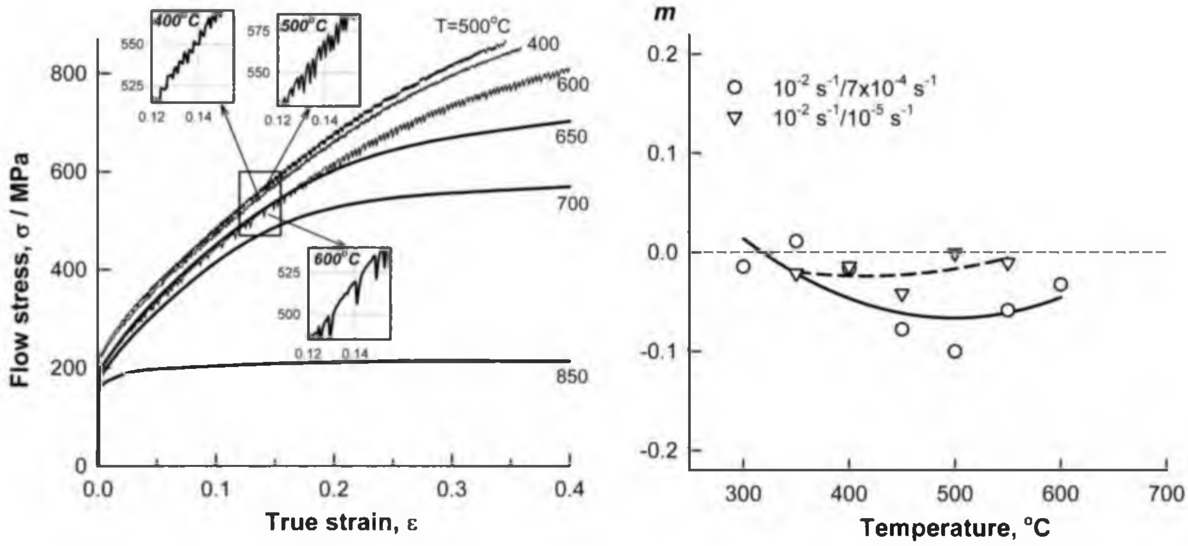

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Figure 2. (a) True stress – true strain curves at temperatures of 400-850°C and strain rate of 7×10^{-1} s^{-1} and (b) temperature dependence of the coefficient, *m*, of strain-rate sensitivity of the flow stress.

The height of serrations and their extent in the σ-ε curves increase with increasing the deformation temperature. This is probably caused by an increase in the size of the areas in which SRO took place. Accordingly, the applied stress being necessary to shear these regions by mobile dislocations increases which leads to an increase in the amplitude of serrations from 10 MPa at 400°C to 25 MPa at 600°C. For destroying SRO areas with increased dimension it is required that a larger number of dislocations pass through them; this is reflected in an increase in strain between the stress peaks.

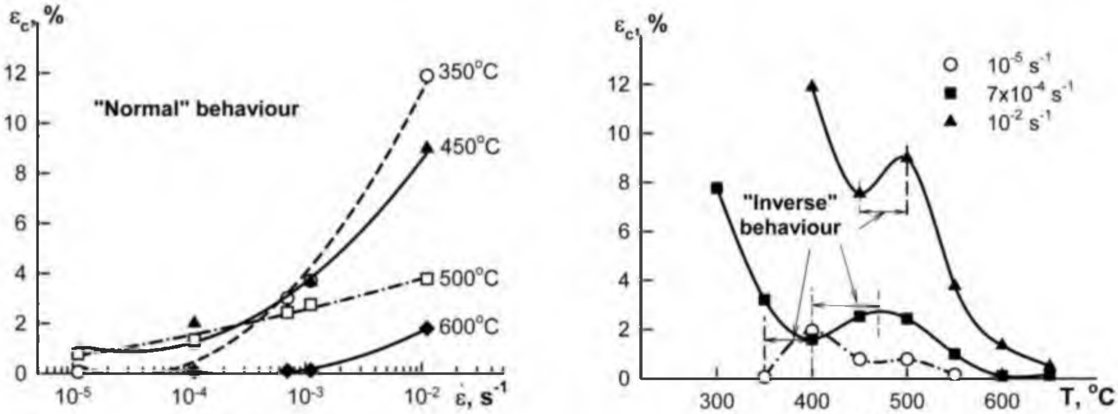

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Figure 3. Variation of the critical strains with strain rate (a) and temperature (b) of deformation.

Second, the alloy exhibits a positive temperature dependence of the yield stress $\sigma_{0.2}$ in the temperature range **II** of 300-500°C (figure 4 (a)). Four regions can be distinguished. The temperature intervals **I** (150-300°C) and **III** (600-800°C) are characterized by a similar slope of the straight line (0.3 and 0.5, correspondingly) reflecting the decrease in stress with increasing temperature. In range **II** the temperature dependence is affected by large scatter of the experimental points. However, the slope of the average straight line takes on a negative value (about -0.15). It should be noted that such a (positive) temperature dependence of the flow stress is rarely observed in metals [10]. The temperature

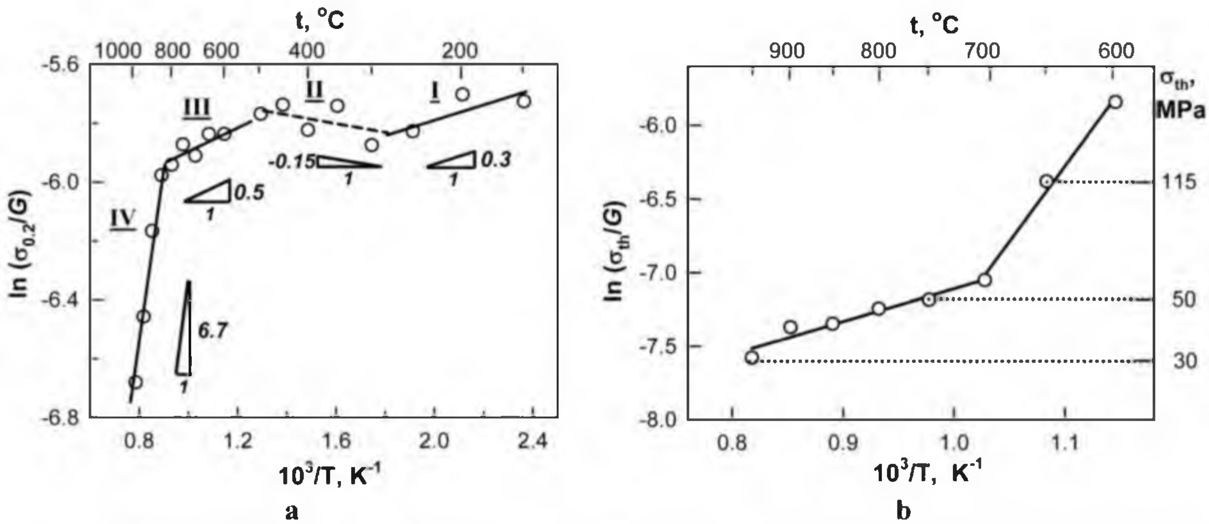

Figure 4. (a) Yield stress $\sigma_{0.2}$ and (b) "threshold" stress σ_{th} normalized by the shear modulus G(T) as functions of the reciprocal deformation temperature.

range **IV** (800-1000°C) is characterized by a significant decrease in the normalized yield stress. Therefore, there is evidence for the fact that SRO does not only increase the yield stress at T≤ 500°C but also results in high strength in the interval of 600-800°C where the alloy is in disordered state. Perhaps, this is caused by the stress necessary to drag solute atoms along with the dislocations. As it can be seen from figure 4 (a) the straight line **III** is located considerably above the straight line **I** extrapolated into the temperature range of 600-800°C.

Third, the SRO can result in high values of the "threshold" stresses σ_{th} below which the creep rate is extremely low [5]. The Ni-20%Cr alloy was shown to exhibit the "threshold" behaviour like a dispersion-strengthened material [5]. The absolute values of σ_{th} at T≤650°C higher than 115 MPa ensure excellent creep resistance of the Ni-20%Cr alloy.

4. Summary

Strengthening of the Ni-20%Cr alloy by short-range ordering is reflected in appearance of the Portevin–Le Chatelier effect in the temperature range of 300-600°C, a positive temperature dependence of the normalized yield stress $\sigma_{0.2}/G$ at 300-500°C and high values of "threshold" stress (>115 MPa) at T≤650°C.

Acknowledgments

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