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Enhanced plasticity observed in cold-worked alloys during heating

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Abstract Enhanced plasticity observed in preliminary cold-worked single-phase alloys has been experimentally studied. This type of enhanced plasticity has been compared with the fine-grain superplasticity and enhanced plasticity, caused by high-temperature phase transformations. The nature of these types of enhanced plasticity is discussed.

Introduction

Numerous investigations of high-temperature (non-martensitic) phase transformations revealed [1–6] that external stresses, applied to the material during polymorphous phase transformation, causes enhanced plasticity of the material. Detailed studies of this phenomena showed [7, 8], that the enhanced plasticity is caused, most probably, by the oriented motion of structural defects, produced during the phase transformation, and the oriented motion is determined by the direction and the strength of the applied external stress. It is important that the role of external stresses during phase transformations is not connected with provoking of plastic deformation itself—the stress provides orientational ordering of those spontaneous processes (for instance, migration of structural defects), which take place in the material without any external stress.

In the accordance with the empiric model, presented in [8], the effect of anomalous plasticity during the phase transformation can be realized, when structural defects are produced, when these defects are able to exhibit intensive thermally activated spontaneous migration, and when there is unidirectional external stress, providing oriented motion of these structural defects.

It can be assumed, that the effect of enhanced plasticity should be realized each time, when the material possessing structural defects is heated up to the specific temperature under external stress. Cold plastic deformation leads to the formation of multiple structural defects and to the increase of the Gibbs energy. The increase in the temperature allows the development of those kinetic processes, which leads to the decrease in the defects density and to the decrease of the accumulated energy (recovery, polygonization, recrystallization [9, 10]). As usual, the migration of structural defects during heating of cold-worked metals and the removal of these defects takes place statistically equiprobable in different directions, so the distortion of the shape of the material is not observed. It can be assumed that the application of an external stress during heating of preliminary cold-worked material will be able to cause oriented motion of structural defects and allows experimental registration of enhanced plasticity at a specific temperature. Experimental studies of deformation effects during heating of alloys, subjected to preliminary cold working, has been the aim of the present research.

Materials and experimental methods

For the experiments, high-purity single-phase alloys have been used: ferritic alloys Fe–3%Si (mass% everywhere) and Fe–5.5%Al or austenitic alloy, containing ~81%Ni, 5%Mo, and 11%Fe. Chemical compositions of the investigated alloys are presented in the Table 1. All investigated alloys were produced by the Pilot plant of the I.P. Bardin

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Table 1 Chemical composition of the alloys (mass.%)

Alloy	Fe	Ni	Al	Si	Mn	Ti	Mo	Cr	C	S	P
Fe–3Si	Base	0.01	0.01	3.1	0.1	0.01	<0.01	<0.01	0.01	0.003	0.005
Fe–5.5Al	Base	0.01	5.5	0.03	0.03	0.02	<0.01	<0.01	0.008	0.003	0.005
81Ni–5Mo–11Fe	11.1	Base	0.01	0.05	0.22	2.6	4.9	<0.01	0.008	0.005	0.005

Institute. The alloys Fe–5.5%Al and Fe-3%Si were melted in 10-kg vacuum induction furnaces and the alloy 81%Ni–5%Mo–11%Fe has been made using 20-kg vacuum induction furnace. To obtain high-quality test materials possessing uniform structure, all ingots have been subjected to standard metallurgical processing, including ingots grinding, forging, grinding of billets, hot rolling, pickling, and finally, cold rolling to get cold-rolled sheets (or strips), possessing different degrees of cold work.

Initially, all materials were in the shape of cold-rolled strips (or sheets), however, the samples were specially shaped for the studies under condition of external compressive stress.

For the tests, the samples made from the Fe–3%Si alloy were roll-shaped. The rolls (possessing the external diameter of 5 mm and the length of 20 mm) were coiled from the cold-rolled strip after preliminary deformation $\varepsilon = 80\%$ (thickness $t = 0.04$ mm). To avoid recoiling during experiments, the rolls have been fixed using special wire-clamps. Wire-clamps were fixed transversely to the longitudinal direction of the roll nearby the sample corners. Cross section of the rolled samples was equal to 2.2 mm^2. Maximum compressive load applied along the longitudinal direction of the roll-shaped samples did not exceed 6.4 kgf, which is equal to the applied stress of 29 MPa. The application of external stress along the longitudinal direction of the rolls means that the compressive stress has been applied transversely to the rolling direction of the material.

The samples made from the Fe–5.5%Al alloy were shaped as L-bars (the angle between basic planes $\alpha = 82$–$90°$), possessing the lengths of 10 or 20 mm, made from cold-rolled sheets after preliminary deformations $\varepsilon = 35$, 60, and 85% (cold rolling of the hot-rolled sheets possessing thickness $t = 3.0$ mm). The samples in the shape of elongated L-bars were made by means of bending of cold-rolled sheets followed by machine grinding of the corners of L-bars in order to obtain parallel planes of the sample corners. During experiments, compressive load has been applied along the longitudinal direction of the samples, so the compressive stress has been applied along the rolling direction of the material.

The samples made from the 81%Ni–5%Mo–11%Fe alloy were roll-shaped also. The rolls were coiled from thin ribbons possessing thickness $t = 30$ µm and total length of ribbon $l = 100$ mm (the degree of deformation during cold rolling was equal to $\varepsilon = 98\%$). During tests, compressive load has been applied to the corners of the rolls, possessing external diameter of 5 mm (length $l = 20$ mm). External compressive stresses were applied transversely to the rolling direction of the material.

The measurement of the sample deformation during heating under external loading has been made using the dilatometer with the induction sensor, which has been modified in accordance with the aims of the present research. The calibration of the dilatometer has been made by controlled displacement of the inductive core using special micrometer. The temperature of the samples has been measured with the help of T-type thermocouple, contacting with the sample. Experimental results (sample elongation—temperature) have been registered by automatic x–y potentiometer, supplied by Linseis. Sample loading during heating has been made with the help of elongated thin-walled quartz tube, transmitting external compressive loading from the cold zone of the furnace. The value of the compressive load has been maintained using the calibrated spring, compressed by additional micrometric screw.

Two cycles of heating have been made for each sample: the first—heating of the initial cold-worked sample (maximum heating temperature $T = 1{,}000$ °C) and the second—heating of the samples, subjected to the first cycle of heating (i.e., heating of annealed samples). In all cases, the heating rate was equal to 5 °C/min.

Experimental results

Experiments show, that heating of the sample without external loading is accompanied by linear growth of the sample length, which is caused by thermal expansion (Fig. 1, Curve 1).

When annealed sample is heated under external compressive load, at specific temperature irreversible decrease in the sample length (i.e., plastic deformation or creep) can be observed, and the change in length is increasing with the growth of temperature (Fig. 1, Curve 2).

For all alloys investigated, the deformation during heating under external load was found to start at substantially lower temperature in preliminary cold-worked alloys, as compared with the annealed alloys (Fig. 1, Curve 3). It

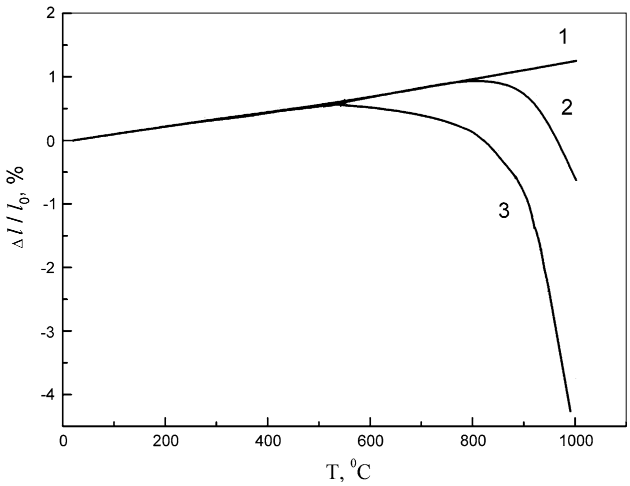

Fig. 1 Modification of the sample length during heating of Fe–3%Si alloy: 1—heating without loading ($\sigma = 0$); 2—heating of annealed sample under applied stress $\sigma = 16$ MPa.; 3—heating of cold-worked sample under applied stress $\sigma = 16$ MPa

can be seen from Fig. 1, that for the Fe–3%Si alloy the difference between the temperature of deformation start in the cold-worked material and in the annealed material (corresponding to the classic creep) attains 250–300 °C. In the present research, major attention is paid to the studies of preliminary cold-worked single-phase alloys during heating.

In the case of small external loading (Fig. 1) the deformation of cold-worked samples is larger than the deformation of annealed samples (up to the maximum temperature of heating, i.e., up to 1,000 °C). In the case of high external stresses, the deformation of annealed samples also starts at more high temperature than that for cold-worked samples. However, this deformation rises faster with the increase of temperature than the deformation of cold-worked samples, so at high temperatures, total deformation of annealed samples is almost the same as the deformation of cold-worked samples.

The temperature of the start of deformation (or creep) for the annealed samples decreases with the growth of external stress (Fig. 2, Curve 2).

The temperature of the start of deformation for the cold-deformed samples was found to be unchanged when the external stress is increasing (Fig. 2, Curve 1).

With the increase of applied stress, the temperatures of the deformation start during heating are tending to get equal both for deformed and annealed samples (Fig. 2).

The deformation, observed during heating of cold-worked samples under loading, is exponentially dependent on the temperature (Fig. 3) and applied stress (Fig. 4).

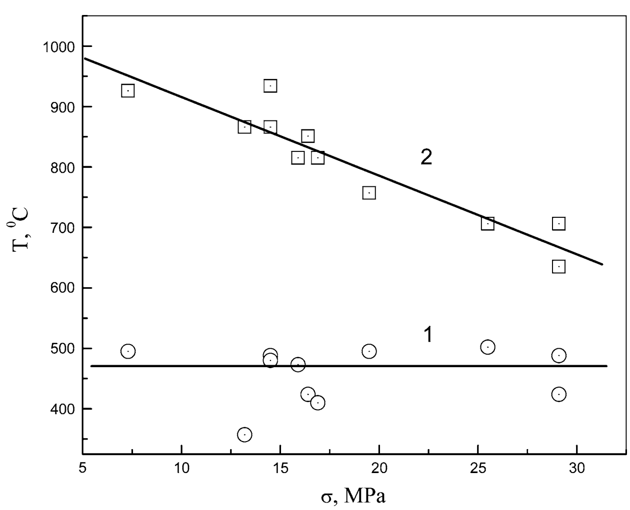

Fig. 2 Dependence of the deformation start temperature during heating T on the applied stress σ for the Fe–3%Si alloy: 1—first heating (cold-worked samples); 2—second heating (annealed samples)

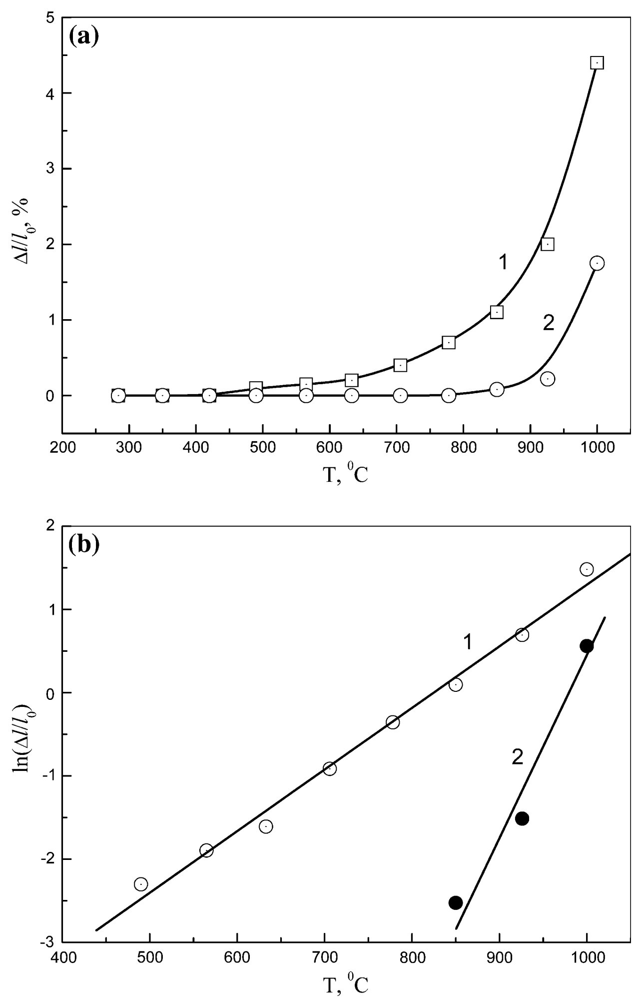

Fig. 3 Temperature dependence of deformation $\Delta l/l_0$ observed during heating of Fe–3%Si alloy under permanent external stress $\sigma = 14.5$ MPa: 1—cold-worked sample; 2—annealed sample; (**a**)—linear scale; (**b**)—logarithmic scale

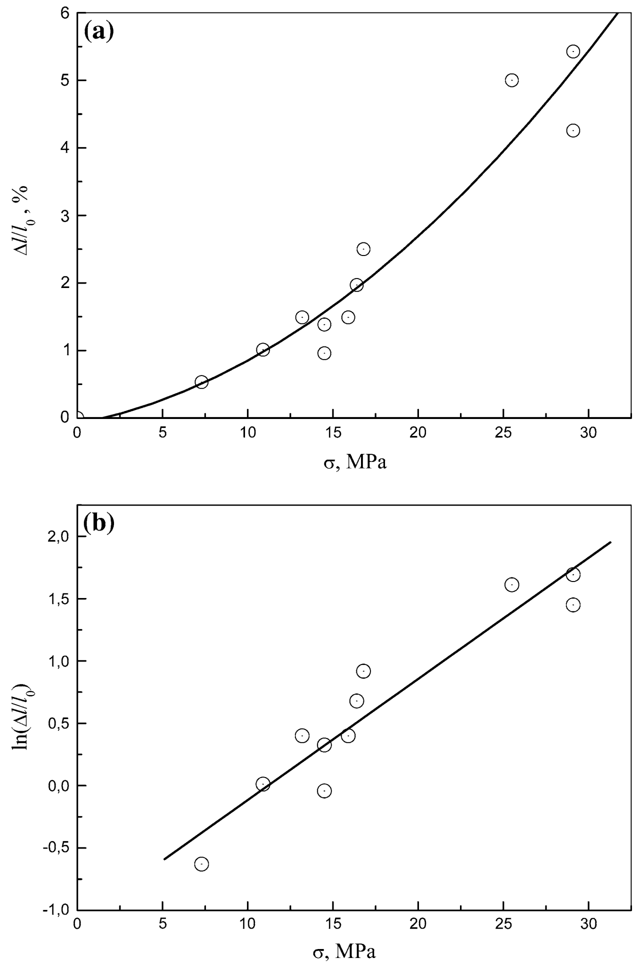

Fig. 4 Dependence of deformation during heating of cold-worked samples $\Delta l/l_0$ on applied stress σ for the Fe–3%Si alloy: (**a**)—linear scale; (**b**)—logarithmic scale

Qualitatively, analogous results were obtained for the austenitic alloy 81%Ni–11%Fe–5%Mo (on comparing with the above described results for Fe–3%Si).

The effect of the degree of preliminary cold working on the sample deformation has been investigated for the alloy Fe–5.5%Al (preliminary deformation $\varepsilon = 33$, 65, and 85%). It has been found that the deformation start temperature T is strongly dependent on the degree of preliminary cold working ε and it decreases with the increase in ε (from $T = 805$ °C at $\varepsilon = 0\%$ to $T = 525$ °C at $\varepsilon = 85\%$, Fig. 5).

The deformation $\Delta l/l_0$, observed during heating up to $T = 800$ °C under loading, was found to increase as the degree of preliminary cold working ε was raised (from $\Delta l/l_0 = 0$ at $\varepsilon = 0$ to $\Delta l/l_0 \sim 0.6\%$ at $\varepsilon = 85\%$, Fig. 5).

Analogous results have been observed for external loadings $\sigma = 6$, 8, and 12 MPa.

Preliminary heating (both under external loading and without it) leads to the increase in temperature of the

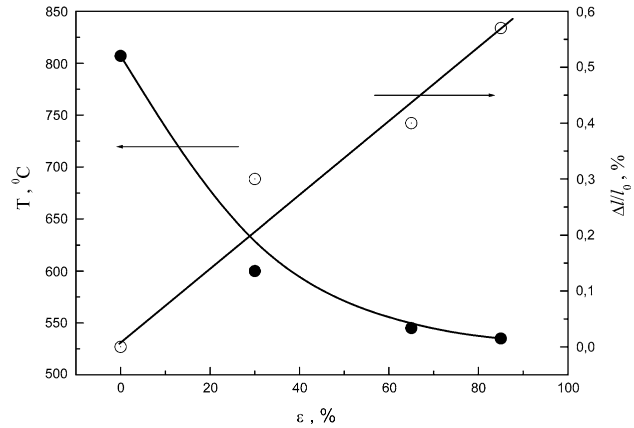

Fig. 5 Dependencies of the deformation start temperature (T) and total deformation during heating up to $T = 800$ °C ($\Delta l/l_0$) on the degree of preliminary cold work (ε) for the Fe–5.5%Al alloy. Applied stress during heating $\sigma = 10$ MPa

deformation start during the reheating cycle. Preliminary heating under small external loading leads to the decrease in deformation during the reheating under the same loading.

Discussion

Experimental results, obtained in the present research, clearly demonstrate the existence of enhanced plasticity during heating of cold-worked materials. This type of plasticity can be observed under small external loading (substantially lower, than the yield stress) and within the temperature range, which is substantially lower (in the order of hundreds °C), than the temperature range, corresponding to the regular creep in the non-deformed material. The temperature, corresponding to the start of deformation of cold-worked sample, is almost the same, as the temperature, corresponding to the start of primary recrystallization [11]—i.e., when active, thermally activated motion of structural defects takes place.

The enhanced plasticity can be explained taking into account the effect of oriented motion of structural defects (first of all—dislocations), resulting from the influence of unidirectional external stress on spontaneous processes, taking place during heating of cold-worked materials.

The reduction of defects density during heating of cold-worked materials can be considered as spontaneous process, taking place independently on the applied external stress. During heating of cold-worked polycrystalline materials, the motion of crystalline defects (dislocations and point defects) is statistically equiprobable with respect to different directions, so the dimensions of the sample are not distorted and the deformation is not observed. The role of external stresses can be interpreted as follows: the application of unidirectional elastic stress causes modifications in the local motion of crystalline defects. Oriented motion of crystalline defects leads to the geometrically oriented modification of dimensions of the material—i.e., to the deformation. The magnitude of anomalous deformation during heating of cold-worked polycrystalline materials is restricted by total amount of crystalline defects, produced during preliminary cold work (see Fig. 5).

Enhanced plasticity observed during heating of cold-worked polycrystalline materials is characterized by special features, which are similar to those features, characterizing fine-grain superplasticity or enhanced plasticity, caused by phase transformations. This is characteristic feature of all these types of enhanced plasticity that the deformation can be observed under small external stresses. Also, noticeable strengthening of the material is not realized (that allows the development of marked deformations). Both in the case of high plasticity, caused by phase transformations and in the case of high plasticity, observed in cold-worked polycrystalline materials during heating, anomalous deformation takes place only within specific temperature range (in the range of realization of phase transformation or in the range of recrystallization, correspondingly).

The interconnection between the mechanisms of enhanced plasticity observed during heating of cold-worked polycrystalline materials and fine-grain superplasticity should be specially discussed. The enhanced plasticity in cold-worked polycrystalline materials can be observed when three conditions are realized simultaneously: the existence of multiple structural defects, produced during preliminary cold working; the attainment of the temperature range, where thermally activated motion of structural defects is realized; the application of unidirectional external stress, providing oriented motion of the structural defects. All above-mentioned conditions are also realized during active high-temperature deformation of metals. Consequently, fine-grain superplasticity can be considered as high plasticity, accompanying the dynamic recrystallization, where structural defects are continuously produced during active deformation, and these defects are subjected to the oriented motion under external stress. The realization of fine-grain superplasticity is determined by the relationship between the intensities of two main processes: the intensity of structural defects production (i.e., the rate of active deformation) and the intensity of the removal of defects, which is dependent on the temperature. The consideration of these two factors allows effective analysis of the fine-grain superplasticity.

Summary

The enhanced plasticity in preliminary cold-rolled alloys has been experimentally studied. The enhanced plasticity of cold-rolled alloys can be observed at very small applied external stresses, which is analogous to the behavior of materials, exhibiting fine-grain superplasticity or plasticity, caused by high-temperature phase transformations. The enhanced plasticity of cold-rolled alloys has been observed at a temperature, which is substantially lower (in the order of hundreds °C) than the temperature range, corresponding to regular creep in the same material. The magnitude of deformation, caused by enhanced plasticity of cold-rolled alloys, increases with the rise of temperature and the degree of preliminary cold work.

The analysis of three types of anomalous plasticity (fine-grain superplasticity; enhanced plasticity, caused by high-temperature phase transformations; enhanced plasticity observed in cold-rolled alloys during heating) shows, that the role of external stresses for the last two types of high plasticity can be interpreted as follows: the application of external stresses leads to the appearance of selected direction, so spontaneous processes, taking place independently on the applied stress, are developed preferably along the selected direction. This leads to the deformation along this direction. Fine-grain superplasticity can be considered as a result of superposition of two processes—active deformation leading to the appearance of multiple structural defects and high plasticity of the material caused by the oriented motion of these defects under external stresses, applied during deformation.

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