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Mechanisms of Deformation of Austenitic Stainless Steel at Cold Rolling

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Abstract. The structure, mechanical characteristics and mechanisms of plastic deformation of stainless austenitic steel 12Cr15Mn9NiCu after high-temperature cross and screw and cold longitudinal rolling are examined with the help of mechanical testing, X-ray diffraction and electron transmission microscopy. It is shown that deformation martensitic transformations are the main mechanisms of deformation at temperatures less than 20 °C. The modes of thermomechanical treatment, which allow to obtain a good combination of strength and plastic properties in steel have been found out.

INTRODUCTION

Austenitic stainless steels are widely used in equipment, medicine, petrochemical and food industries, mechanical engineering. Metastable [1,2] 12Cr15Mn9NiCu (AISI 201) steel selected for research not properly studied. It is an inexpensive substitute for corrosion-resistant chromium nickel steels of grades 12Cr18Ni10Ti, 10Cr18Ni8Cu3NbB, 08Cr18Ni10, etc. It is optimally doped with chromium, nickel, manganese, copper and nitrogen. It does not have a ductile-brittle transition, which allows it to be used at low temperatures. The purpose of this study is to find optimal modes of steel hardening by intensive plastic deformation by rolling and annealing, which would expand its applications, including in the field of negative climatic temperatures.

MATERIALS AND METHODS

Cold longitudinal rolling of steel 12Cr15Mn9NiCu in the initial state and after cross and screw rolling was carried out on rolling mill 01002 "VEM-3 rollers with the automatic lubrication system" to total extent of deformation 1.8 - 2. High-temperature multistage cross and screw rolling of steel with the fall of temperature of rolling on each following pass was carried out on a three-roll minicamp of screw rolling in the range of temperatures from 950 to 750 °C. The procedure of reducing of temperature of rolling was applied to reduce the rate of growth of grains in the processes of dynamic recrystallization. Maximum extent of true logarithmic deformation of steel of $\varepsilon_{tr} = \ln(D/d)$ after 5 passes of cross and screw rolling was ≈ 0.80. The transmission electron microscope (TEM) JEM-2100 at the accelerating voltage of 200 kV and Hitachi HT7700 at the accelerating voltage of 100 kV in Nanotech Testing Center of Institute of Strength Physics and Materials science and in federal research Center of Institute of Physics of Siberian Branch of the Russian Academy of Science as soon as well as X-Ray DRON-7

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device were used for structural researches. Experiments on uniaxial tension with the help of Instron-5582 testing machine were carried out, with the strain rate being 5×10^{-4} s^{-1}.

RESULTS AND DISCUSSION

As was shown by tests in a condition of delivery steel 12Cr15Mn9NiCu at the room temperature on the uniaxial tension has high plasticity of δ ~ 90%, a yield of flow $\sigma_{0.1}$ ~ 400 MPa, tensile strength σ_{st} ~ 800 MPa (Fig. 1a, curve 1), with Vickers hardness being HV=2470 MPa. According to ESBD analysis [3], these properties are caused by an austenitic phase with an average size of grain of 20 microns of and a high share (96.9 %) of high-angle boundaries of grains. Half of high-angle boundaries of grains (46.8 %) have a twinning 600-missorientation with $\Sigma = 3$, and textural components are absent. The electron microscopy examination of the fine foils has found out that initial γ-phase grains practically don't contain dislocations. This fact and the lack of texture, demonstrate that high-temperature recrystallization has taken place in the material. The high plasticity of metastable steels is connected with forming deformation martensitic transformations under loading and large share of special twinning boundaries of grains which are more penetrating for deformation shifts, than boundaries of the general type [1-3].

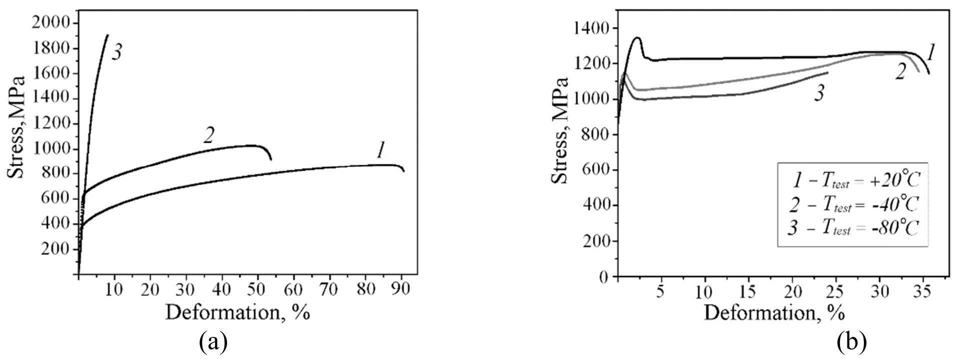


FIGURE 1. (a) Deformation curves of steel at various temperatures: 1 – a condition of delivery; 2 – after multistage high-temperature cross and screw rolling, 3 – after multistage high-temperature cross and screw rolling and cold rolling; (b) temperature dependence of deformation curves of steel after multistage high-temperature cross and screw rolling, cold rolling and annealing at 650 °C, 3 hours.

The submicrocrystalline structure of austenite with an average size of grain of 0.6 μm, non-uniform on bar section is formed (Fig. 1a, curve 2) after intensive cross and screw rolling in steel 12Cr15Mn9NiCu, which is characterized by higher hardness and durability, plasticity of δ ~ 50%. The main mechanisms of hardening of austenite at high-temperature cross and screw rolling are:

1. Grain boundaries hardening caused by reduction of the size of grain and increase in the volume fraction of boundaries of grains (according to Hall-Petch's ratio);
2. The hardening connected with the change of the type of grain boundaries after rolling – mainly from twin boundaries to those of the general type;
3. The hardening caused by the formation in grains of a low-angle substructure, dislocation congestions and defects of packing;
4. The hardening caused by crushing of a carbide subsystem [3].

The high-strength state is formed after cross and screw and subsequent cold rolling to ε_{true} ~ 1.8 in material, which is characterized by tensile strength (Fig. 1a, curve 3) close to σ_{st} ~ 1900 E/100 (E is Jung's module), and the plasticity is up to δ ~ 10%. The electron microscopy examination showed that the main mechanisms of plastic deformation and fragmentation of steel 12Cr15Mn9NiCu at cold rolling, also as in other metastable the steels [1,2,4,5] are deformation martensitic $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ transformations. Figure 2a,b shows the formation of germs of the ε-martensitic phase having HCP lattice on thin defects of packing in an austenitic matrix at initial stages of cold rolling. Further growth of plates takes place due to accession to them new defects of packing along the habitus plane $\{111\}_{\gamma} \| (001)_{\varepsilon}$. Only separate α'-martensite lamels are observed in other grains of material at the same time (Fig. 2c,d). It is shown [4] that orientation of grains concerning the enclosed loading in a polycrystal of metastable steel is the main factor of influence on the sequence and a volume fraction martensitic ε- and α'-phases.

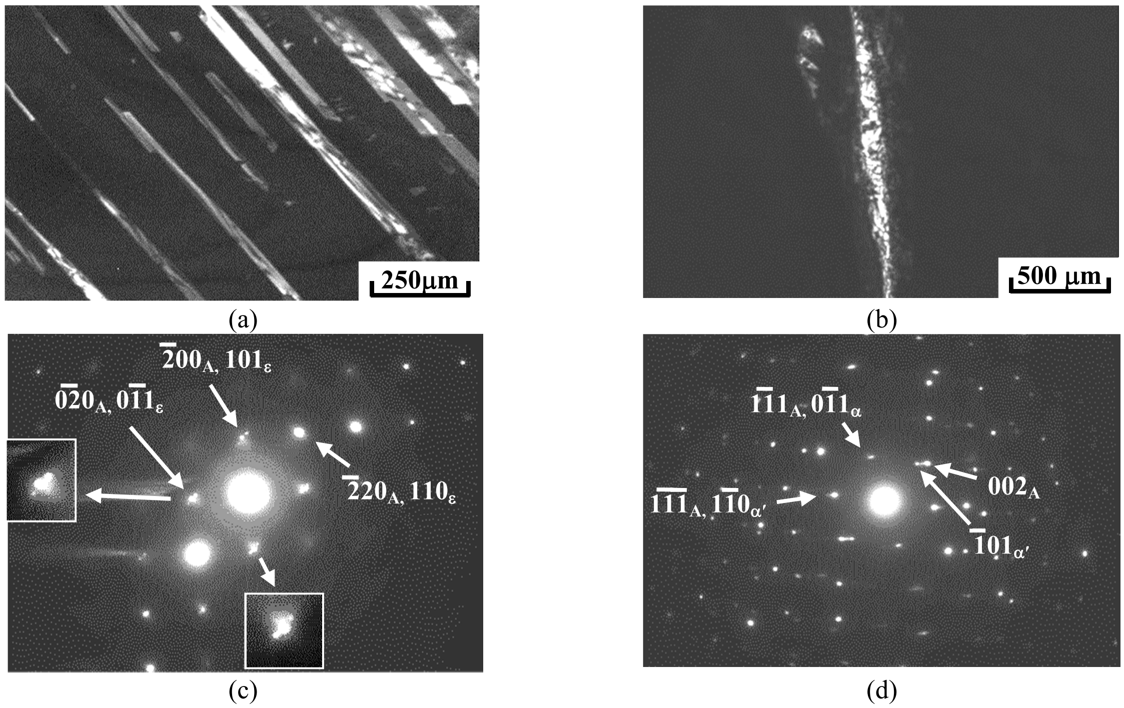


FIGURE 2. (a) dark field TEM the image of germs of ε-martensite lamels in reflection 0 1ε, value of cold deformation $\varepsilon_{tr} \approx 0.07$; (b) electron diffraction pattern to (a), a [001]-zone of austenite and [11]-zone ε-martensite; (c) dark field TEM the image of a lamel of α′-martensite in a reflection 10 α′; (d) electron diffraction pattern to (c), a [110]-zone of austenite and [111]-zone of α′-martensite

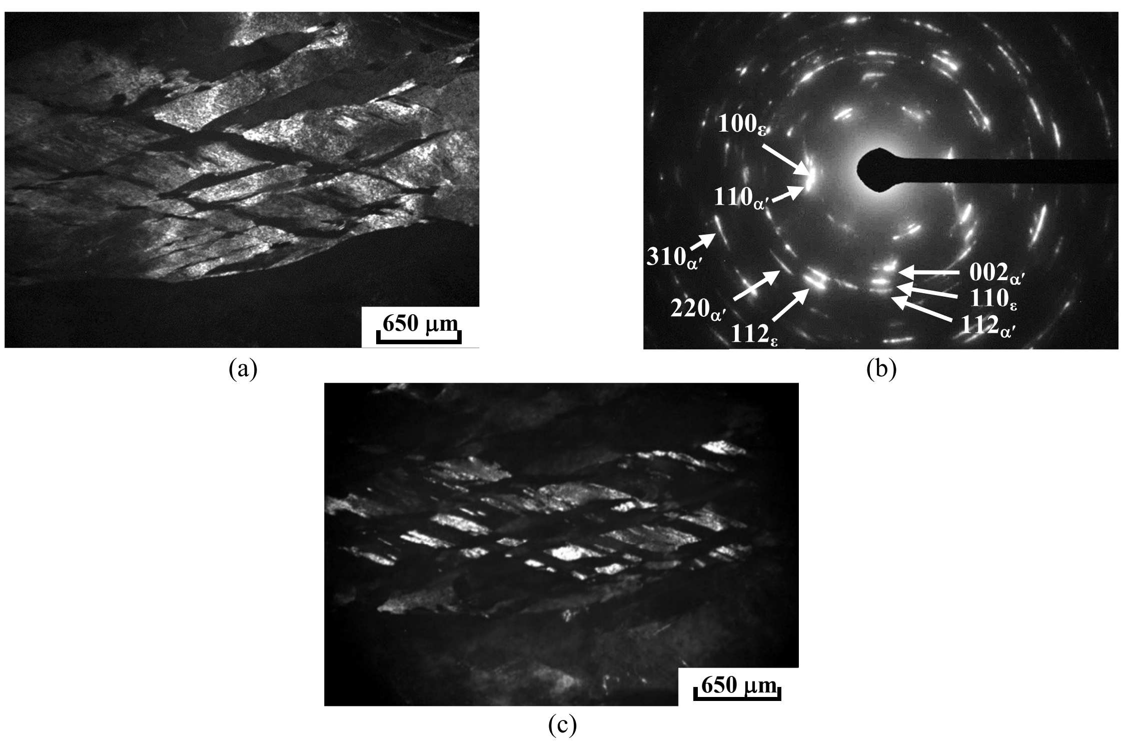
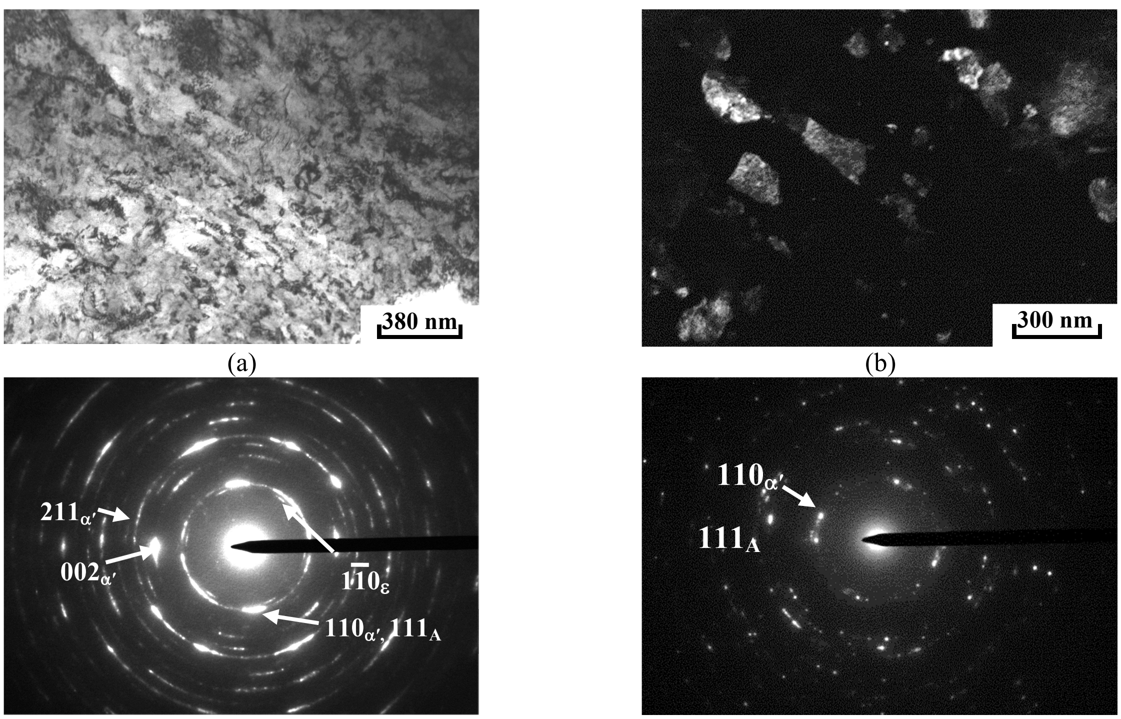


FIGURE 3. Formation of lamels α′-martensite in plates of a ε-martensitic phase, value of cold deformation $\varepsilon_{tr} \approx 0.4$. (a) dark field TEM the image in a reflection 011ε; (b) dark field TEM the image in a reflection $002_{\alpha'}$; (c) electron diffraction pattern to (a) and (b)

The nature of the formation of deformation martensitic transformations in steel 12Cr15Mn9NiCu is connected with the low energy of the defect of the packing caused by nitrogen impurity presence in its structure [6,7]. The volume fraction of martensitic phase estimated with help of X-ray diffraction increases and that of austenite one decreases with the increase in the extent of cold deformation. The size of plates of ε-martensite reaches 1 micron, and lamels α′-phase are formed in them (Fig. 3).

Two-phase nanocrystalline state is formed (Fig. 4a,b) with presence of α′-martensite and austenite grains after intensive cold rolling to $\varepsilon_{tr} \sim 1.8$ in material. By X-ray diffraction estimates of the volume fraction of α′-martensite is ≈ 86%, the size of areas of coherent dispersion is ~ 40 nanometers. The ε-phase is not fixed its share is probably less than 5%. Only separate reflections of ε-martensite are sometimes observed on electron diffraction pattern (Fig. 4c). It demonstrates that at intensive plastic deformation of $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ martensitic transformations take place. Cross and screw and cold rolling forms non-uniform structure, in material zones which were subjected to greater degree of plastic deformation, the size of grains is 40-100 nanometers. Austenitic grains with the size of 100-300 nanometers, and α′-grains with the one of 40-400 nanometers are observed in zones with smaller extent of deformation. In the structure of a hire are present carbide and a nitrides of chrome of 15-200 nanometers in size. The main carbide phase is $Cr_{23}C_6$.

To increase the plasticity of material with nanocrystal structure it was annealed at 600 °C within 3 hours. The deformation curves of samples after annealing are given in Fig. 1b. It is visible that at a temperature interval from + 20 to – 80 °C a yield of flow and tensile strength of steel decrease, but remains rather high – 1050 MPa and 1200 MPa, respectively (their value is, approximately, twice higher, than in an initial state), and the plasticity before the failure of steel increases up to 25%. After annealing material remains in a two-phase state with the prevalence of an austenitic phase. The share of α′-martensitic (ferrite) phase equals ~ 6% by X-ray diffraction estimates. The size of large grains of austenite increase, grains 200-400 nanometers are often met. Figure 4c,d shows submicrocrystalline structure of steel after cross and screw rolling, cold rolling and annealing at 650 °C, within 3 hours.



(c) (d)

FIGURE 4. Nanocrystal structure of steel after cross and screw rolling and subsequent cold rolling, value of cold deformation $\varepsilon_{tr} \approx 1.8$. (a) the bright field TEM the image; (b) electron diffraction pattern to (a); (c) submicrocrystalline structure of steel after cross and screw rolling, cold rolling and annealing at 650 °C, 3 hours, dark field TEM the image in a reflection austenite 111A; (d) electron diffraction pattern to (c).

The defective substructure inherited from martensite at the return $\alpha' \rightarrow \gamma$ martensitic transformation is observed at big magnification in grains, these are defects of packing, low-angle boundaries and dislocation congestions. A small share of residual α'-martensite (ferrite), existence of a defective subsystem and particles of disperse phases caused by annealing result in higher strength properties of steel, than in an initial state.

CONCLUSIONS

- It is shown that the combination of methods of intensive high-temperature cross and screw and cold rolling allows to create in steel high-strength two-phase nanocrystalline state with minimum size of crystallites 40 μm and σ_{str} equaling E/100 ≈ 2000 MPa. The plasticity is about 6%. By using annealing at the increased temperatures, it is possible to reduce the share of a martensitic phase and to increase plasticity of the material. By varying time of annealing it is possible to receive a series of stable materials with a good combination of strength and plastic characteristics in the range of negative climatic temperatures.
- Methods of the transmission electron microscopy and the X-ray diffraction analysis allow to make a conclusion that $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ deformation martensitic transformations are the main mechanisms of plastic deformation of steel at cold rolling at T ≤ 20 °C.

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