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Citation: AIP Conference Proceedings **1683**, 020123 (2015); doi: 10.1063/1.4932813
View online: http://dx.doi.org/10.1063/1.4932813
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1683?ver=pdfcov
Published by the AIP Publishing

The Features of Microstructure and Mechanical Properties of Austenitic Steel after Direct and Reverse Martensitic Transformations

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Abstract. The features of structural states of metastable austenitic steel after thermomechanical treatments, including low-temperature deformation, warm deformation and subsequent annealing are investigated. It is shown that under these conditions the direct ($\gamma \rightarrow \alpha'$) and reverse ($\alpha' \rightarrow \gamma$) martensitic transformations occur and submicrocrystalline structural states are formed. The proposed thermomechanical treatment allows varying the strength and plastic properties of austenitic steel in a wide range. The strength of steel in submicrocrystalline state is 4–6 times higher than its original value.

INTRODUCTION

Submicrocrystalline and nanocrystalline materials produced by severe plastic deformation exhibit enhanced or even unique strength and plastic properties, unachievable for coarse-grained materials [1–3]. Application of these techniques to austenitic steels allows the strength properties to be multiply increased, while maintaining a sufficient level of ductility [2, 3]. In metastable austenitic steels, submicrocrystalline structural states can be formed using a direct ($\gamma \rightarrow \alpha'$) martensitic transformation during cooling and (or) plastic deformation and a subsequent reverse ($\alpha' \rightarrow \gamma$) transformation during heating [3–7]. The deformation near the temperature of liquid nitrogen (T = 77 K) promotes the direct martensitic transformation [3, 7], while the deformation at elevated temperatures promotes the reverse martensite to austenite transformation [8–10].

This paper presents the results of investigations of the features of submicrocrystalline structural states of metastable austenitic steel Fe–18Cr–8Ni–Ti (AISI 321 grade) produced by thermomechanical treatments, including low-temperature deformation, warm deformation and subsequent annealing.

EXPERIMENTAL PROCEDURE

For the investigation, we used a chromium–nickel metastable austenitic steel Fe–18%Cr–8%Ni–Ti, AISI 321 (Fe–18.02%Cr–9.77%Ni–1.4%Mn–0.59%Ti). Prior to deformation the samples were annealed at 1100°C for 1 hour and then quenched in water. In the initial state, the volume content of austenite was about 100%, the average grain size was ≈40 μm. The initial sample size was ≈30×20×12 mm. Unlike severe plastic deformation, we used relatively low degrees of rolling deformation. Low temperature deformation was performed by multipass rolling with a total

Advanced Materials with Hierarchical Structure for New Technologies and Reliable Structures
AIP Conf. Proc. 1683, 020123-1–020123-4; doi: 10.1063/1.4932813

degree of strain, ε ≈ 10–20%. Before being placed into the rolling mill and between passes, the samples were kept at the liquid nitrogen temperature (T = 77 K). A subsequent warm deformation at ε ≈ 30–40% was carried out in the temperature range T = 673–873 K. After removal from the mill, the samples were quenched in water. Annealing was carried out in the temperature range of T = 873–1073 K; its duration from 200 s up to 1 hour.

The electron-microscopic investigations were conducted using a Philips CM-12 electron microscope at an accelerating voltage of 120 kV. Thin foils for examination were prepared from sections perpendicular to the rolling plane by electropolishing in an electrolyte containing 450 ml of orthophosphoric acid and 50 g of chromic anhydride.

The changes in the phase content were studied by X-ray diffractometry in a Shimadzu XRD-6000 device using CuK_α emission in the Bragg-Brentano geometry, focusing the monochromator on the secondary beam. The POWDER CELL 2.4 calculations of the phase composition included computations of the real texture of both phases. To determine the volume content of the magnetic phase, we employed the method of measuring specific magnetization depending on the magnetic-field strength in an N-04 Magnetometer. The resulting curves of specific magnetization versus the magnetic-field strength were converted into the volume content of the α′-phase.

Mechanical tests were carried out at ambient temperature by the method of active tensile deformation at a strain rate of $\approx 2\times10^{-3}$ s^{-1} using samples in the form of double blades with the gage section 13×2×1 mm.

RESULTS AND DISCUSSION

An X-Ray diffraction analysis, magnetic measurements and electron microscopy studies have shown that deformation with cooling in liquid nitrogen (LND) leads to intensive γ → α′ phase transformation. According to XRD and magnetic measurements, the volume content of α'-martensite is ≈55%. The resulting martensite is deformation-induced martensite, since the exposure of the work pieces at T = 77 K does not yield any martensitic transformation. For the formation of the same content of martensite at ambient temperature, a significantly higher degree of deformation (e ≈ 2–4, where e is true logarithmic strain) is required [4, 6]. According to the electron microscopic studies, the deformed structure of steel is represented by thin lamellae of submicron scale, composed of α′-martensite packets, austenite microtwins and individual plates of ε-martensite [10]. The resulting structural state provides high strength properties of steel—the yield strength of 920–930 MPa, elongation of 14–15% (Table 1).

The subsequent warm deformation (WD) at $T \leq 773$ K does not lead to an increase in the volume content of the austenite. The volume content of α′-martensite is as high as ~60%. In this case, the material reaches its maximum strength properties at minimum ductility (Table 1). In comparison with the low-temperature deformation (LND) the yield strength is about 200–300 MPa higher and reaches 1260–1350 MPa. Thus the ductility is reduced to 3–4% (Table 1). We attribute the high strength of steel to lamella structure with high volume fraction of packet α′-martensite, and high dislocation density.

Warm rolling deformation (WD) at $T \geq 873$ K after the low-temperature deformation (LND) leads to the reverse (α′ → γ) martensitic transformation. According to X-ray and magnetic investigations, the volume content of the austenite phase increases. As compared with the annealing at the same temperature, plastic deformation at T = 873 K improves the yield strength up to 50–70 MPa. A combination of warm deformation and annealing at T = 873 K and T = 1073 K allowed us to reach the yield strengths 950–980 MPa and 795–810 MPa, respectively, which is about 4–5 times higher than the initial values (Table 1).

TABLE 1. Phase content, yield point, ultimate strength and total elongation of steel after different treatments

Material processing	Phase content α′/γ, %	Yield point, MPa	Ultimate strength, MPa	Total elongation, %
Quenching	0/100	205	520	40
LND	55/45	920–930	1100–1100	14–15
LND + WD (773 K)	60/40	1260–1350	1390–1420	3–4
LND + WD (873 K) + T = 873 K, 1 h	17/83	950–980	1115–1130	12–15
LND + WD (873 K) + T = 1073 K, 200 s	5/95	795–870	960–1020	14–24

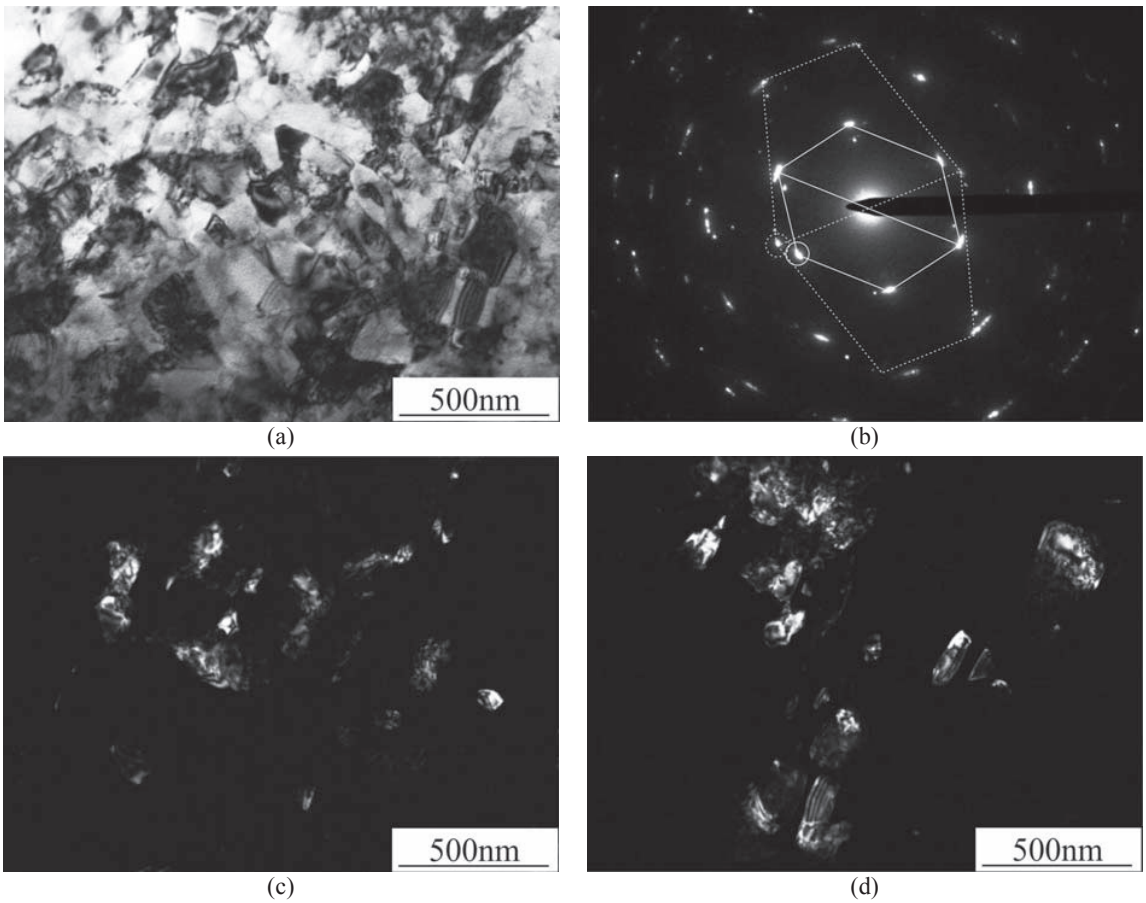

FIGURE 1. Microstructure of steel after termomechanical treatment consisting of LND, WD at T = 873 K and annealing at T = 1073 K, 200 s: (a) bright field image, (b) selected area diffraction pattern, two zone axes [110] and [130] are marked by solid and dash lines, respectively, (c) dark field image in g = [–111]γ, of [110] zone axis, (d) dark field image in [002]γ, of [130] zone axis

In the process of thermomechanical treatment combined with warm deformation and annealing at T = 1073 K, the maximum content of austenite (~95%) and the highest ductility values (14–24%) are obtained.

Electron microscopy studies of steel microstructure after thermomechanical treatments consisting in low-temperature deformation, warm deformation and annealing have shown primarily austenitic structure with lamellas and equiaxed submicrocrystalline scale fragments with an average size of ~200 nm (Figs. 1a, 1c, and 1d). Between the grains and fragments, both low angle and high angle, including twin misorientations are observed. The shape, size and misorientations of austenitic fragments are similar to packet martensite and may be characterized as "packet austenite". The grains with high dislocation density and nearly defect-free fragments are observed. The latter are indicative of recovery and recrystallization processes in the formation of the above-mentioned microstructure. The features of "packet austenite" evidence of participation of direct ($\gamma \rightarrow \alpha'$) and reverse ($\alpha' \rightarrow \gamma$) martensitic transformations in the formation of submicrocrystalline states.

A distinctive feature of the proposed treatment method is the use of warm deformation to form submicrocrystalline austenite during reverse martensitic transformation. At the same time, in contrast to severe plastic deformation [1–4] we used a relatively small degree of deformation (e < 1). The combination of warm deformation and annealing allows varying the content of austenite, strength and plastic properties of steel in a wide range.

CONCLUSION

Using a thermomechanical treatment consisting of low-temperature deformation, warm deformation and annealing of the metastable austenitic steel, submicrocrystalline structural states with high volume content of austenite have been formed. These structural states are observed to form during the direct ($\gamma \rightarrow \alpha'$) and reverse ($\alpha' \rightarrow \gamma$) martensitic transformations and are achieved without resorting to the methods of severe plastic deformation. In this case the total deformation is $e < 1$.

A feature of the submicrocrystalline states thus formed is lamella and fragmented structure of "packet austenite", similar to the packet α'-martensite. Grains and fragments may have low- and high-angle, including twin, misorientations. A fragments can have high dislocation density and could be nearly free of dislocations. The latter is caused by recovery and recrystallization processes by thermomechanical treatment.

The proposed thermomechanical treatment modes allow reaching the yield strengths values up to 1350 MPa, with minimum ductility and high (60%) content of martensite. The combination of warm deformation and annealing can increase austenite content (up to 95%), raise the value of ductility to 12–24% and high yield strengths maintained within 795–980 MPa. These mechanical properties are due to submicrocrystalline structure of metastable austenitic steel.

ACKNOWLEDGMENTS

This work performed under the Program of Basic Scientific Research of the State Academies of Sciences of Russian Federation for 2013–2020 (structural investigations), Russian Foundation for Basic Research, Grant No. 15-08-07416-a (thermomechanical treatments) and Tomsk State University Competitiveness Improvement Program (mechanical tests).

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