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Microstructure and Mechanical Properties of Medium Manganese Steel after Different Deformation and Thermal Treatments

V. I. Torganchuk[a], * and A. N. Belyakov[a]

[a] *Belgorod National Research University, Belgorod, 308015 Russia*

**e-mail: torganchuk@bsu.edu.ru*

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Abstract—An analysis is performed of the effect deformation and thermal treatment have on the structural phase state and mechanical properties of promising sparingly alloyed Fe–10Mn–0.2C medium manganese steel. The range of temperatures of the two-phase region with a high volume content of the austenite phase is determined.

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INTRODUCTION

The growth of the automobile industry depends largely on the properties of the available structural materials. The development of new grades of steel and the modification of engineering processes for their production are oriented toward solving several problems, the most important of which are improving the safety of passengers and reducing harmful emissions, including those caused by the reduced weight of the vehicles. Russia's automobile industry is trying to participate in solving these problems by using high strength steels. For example, the fraction of high strength steel at AUTOVAZ has been growing continuously, from 9% in the LADA Priora to 36% in the LADA Vesta. To accomplish this, state-of-the-art equipment has been purchased from Japan, Korea, and the European countries. However, existing Russian high strength steels are not of a technological level sufficient to take full advantage of the available equipment's potential. This makes the development of new sparingly alloyed steels highly relevant [1, 2].

Government actions have been taken over the last decade to reduce the negative environmental impact of vehicles by more than half [2]. This was also accomplished by developing innovative light metals and alloys of them. At the same time, this development of events brought with it numerous unsolved issues associated with combining new light metals and widely known steels. Conventional fusion welding is accompanied by the deposition of intermetallic compounds upon solidification, leading to the embrittlement of weld joints [3]. The industry of today is still not ready to produce competitive new materials based on nonferrous alloys with all of the targeted properties at moderate cost. The use of non-ferrous metals and alloys of then additionally imposes certain constraints, one of which is the possibility of repair outside of specialized semi-commercial workshops with expensive heavy equipment.

The World Auto Steel Association, made up of the world's largest steel manufacturers, was established to strengthen the position of structural steels against the backdrop of increasingly stringent requirements on the properties of materials. Russia is represented in the association by PAO Severstal [4]. The main efforts to accomplish its tasks are aimed at developing high strength steels (HSSes) and advanced high strength steels (AHSSes). The requirement to improve the equilibrium between strength and plasticity has resulted in the development of steels with increased manganese contents. A new class of steels with plasticity induced by twinning has thus appeared, generally with manganese contents in the range of 17–24 wt % [5]. The automobile industry is especially interested in improving the above steels in order to reduce the contents of manganese and other alloying elements. Alloys with plasticity induced by phase transformations (TRIP steels) are a new type of high strength steels [6]. A high balance of strength and plasticity in such steels is achieved via the martensite transformation of retained austenite during plastic deformation. Martensite transformation raises the rate of deformation strengthening at higher rates of deformation, thus restricting the localization of plastic flow and promoting uniform deformation to improve plasticity. The logic of using steel instead of, e.g., aluminum lies in its much environmentally friendlier production and means of processing, which can indirectly lower the amount of harmful atmospheric emissions [2].

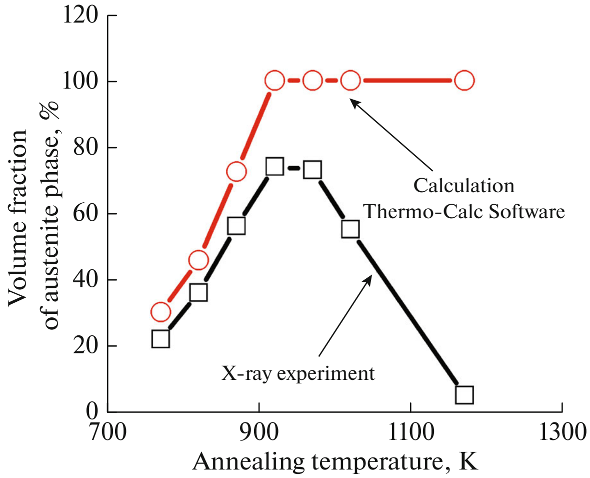

Fig. 1. Volume fraction of the austenite phase, as a function of the temperature of annealing.

Special attention must be given to alloying this class of steels. The contents of the steel should provide the required phase composition, i.e., stabilize the austenite phase at ambient temperatures. Special demands are thus made on deformation and thermal processing that allow us to create the required structural and phase compositions. In addition to mechanical properties, these steels must be characterized by good maintainability, and by good weldability in particular [7]. To accomplish this, the concentration of alloying elements is limited. The main contribution to strengthening comes from carbon, but there is a limit to weldability at concentrations of more than 0.2 wt %. It was shown in earlier works that medium manganese steels with a high carbon content of 0.6 wt % are subject to friction stir welding. The area of the weld joint is then stronger than the base material, which should improve the reliability of welded parts [8]. Unfortunately, friction stir welding is not widely used in manufacturing automobiles. In this work, we analyze sparingly alloyed medium manganese steel with a carbon content of 0.2 wt % in order to expand the list of steels that can be used in the development of vehicle designs.

EXPERIMENTAL

Our object of study was Fe–10Mn–0.2C steel with a moderate content of manganese (the actual chemical composition in wt % was Fe–0.2C–10.7Mn–0.02Al–0.05Si). This steel was produced via electroslag remelting into a water-cooled crystallizer. Our study was performed with hot and warm rolled steels. The ingots were preliminarily homogenized for 4 h at 1423 K. Hot longitudinal rolling was done at 1423 K with a cumulative drafting of 60% and subsequent cooling in water. Warm rolling with a cumulative drafting of 60% and subsequent cooling in water was done at 823 K. The ratio of austenite to ferrite in the steel was 1 : 1, according to the Thermo-Calc software. Annealing was done in furnaces, with the temperature being monitored in the central area near each sample.

Structural analysis was performed using a Nova NanoSem scanning electron microscope (SEM) equipped with an electron back scatter diffraction (EBSD) analyzer and TSL OIM Analysis 7 software, along with a JEOL JEM-2100 transmitting electron microscope. X-ray phase analysis was done using an X-ray diffractometer (Rigaku, Ultima IV) with CuK_α radiation. The operating voltage for the X-ray diffractometer was 40 kV; the current was 30 mA; and the range and increment of scanning were 35°–120° and 0.02°, respectively. Samples were prepared for electron microscopy and X-ray structural analysis via electrolytic polishing at the ambient temperature and 18 V, using A2 Struers electrolyte.

A series of tensile stress experiments were performed at a 10^{-3} s^{-1} rate of deformation using an Instron 5882 unit. Microhardness was measured according to Vickers using a Wolpert 402MVD hardness meter at loads of 0.5 N and holding times of 10 s.

RESULTS AND DISCUSSION

The structural and phase states of samples were analyzed after deformation treatment and subsequent annealing in wide range of temperatures. The effect of annealing temperature on the phase state of steel is shown in Fig. 1. The volume fraction of the austenite phase grew along with temperature, reaching a maximum at 923 K. It then fell upon a further increase in the temperature of annealing. Thermodynamic modeling of the phase composition (Fig. 1) revealed similar growth of the volume fraction of austenite phase when the temperature was raised to 923 K, where the austenite fraction reached 100% and did not vary upon a further increase in temperature.

Our microstructure studies indicated the formation of a two-phase state after isothermal rolling at 823 K with an average austenite grain size of 300 nm. Subsequent thermal treatment at 773 K produced no notable variation of the austenite grain (Fig. 2a). Raising the temperature of annealing to 873 K increased the volume fraction of the austenite phase and the mean grain size (Fig. 2b). The initial austenite grain size grew to 20 μm at 1173 K (Fig. 2c). The volume fraction of austenite was 4% after annealing at 1173 K and cooling to the ambient temperature (Fig. 2d). Our data are in good agreement with those of X-ray phase analysis.

The variation in microhardness as a function of the temperature of steel annealing after rolling at 823 K is illustrated in Fig. 3. A monotonous increase in microhardness is observed as the temperature of annealing rises. Its indicators correspond to 450 HV in the range of 1023–1173 K.

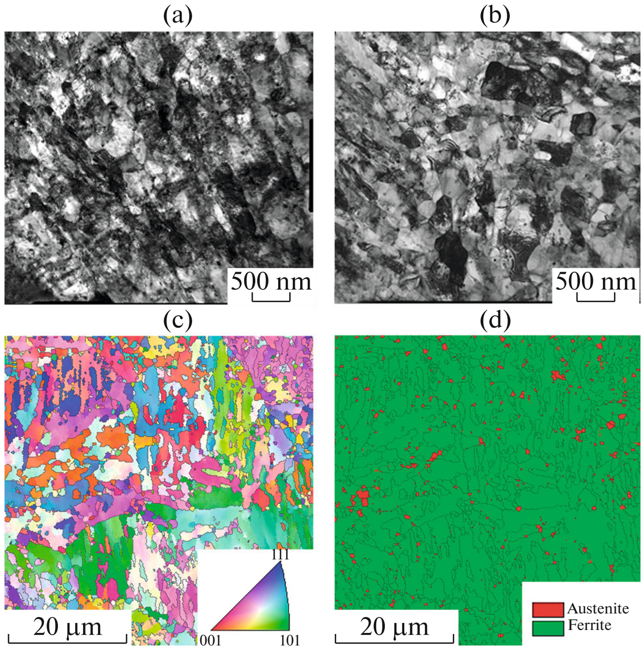

Fig. 2. Microstructure of Fe–10Mn–0.2C steel after annealing at different temperatures: (a) 773, (b) 873, and (c) 1173 K; (d) the steel's phase composition.

During mechanical uniaxial tension tests of samples cut along the direction of rolling, it was established that in the initial state (after hot deformation), the considered steel was characterized by moderate plasticity, and its relative uniform elongation was around 5%. The yield point and ultimate strength were thus 465 and 1340 MPa, respectively. Subsequent rolling at 823 K raised the yield point and ultimate strength to 700 and 1630 MPa, respectively. This deformation treatment allowed us to more than quadruple the steel's plasticity (relative stretching until failure).

Thermodynamic modeling of the phase composition of Fe–10Mn–0.2C steel using the Thermo-Calc software showed that this steel was characterized by the formation of a two-phase region in the temperature range of 573–923 K. Raising the temperature in this range increased the volume fraction of the austenite phase from 10% to its maximum (100%) at 923 K. Note that our studies of the structural and phase states via X-ray phase analysis revealed a similar trend of variation in the volume fraction of the austenite phase in the temperature range of 773–923 K, except that its values vary from the modeled ones of phase composition. This difference could be due to the determination of phase composition using the Thermo-Calc software corresponding directly to the modeled temperature, while our X-ray phase analysis was performed with a sample after annealing at a preset temperature and subsequent cooling to ambient temperature.

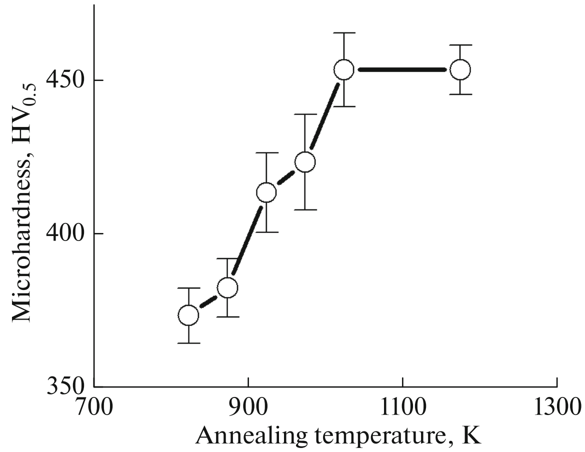

Fig. 3. Microhardness of steel after rolling at 823 K, as a function of the temperature of annealing.

The effect the holding time had on the phase composition of the considered steel was studied as well. Raising the holding time to 2 h at a preset temperature did not result in appreciable variation of the phase composition. We observed only impairment of surface quality of the considered steel, due to the formation of a thick scale layer.

It should be noted that a sharp drop in the volume fraction of the austenite phase was observed at 923 K. This behavior can be explained on the basis of thermodynamic calculations. A full austenite structure should be observed at this temperature of annealing. An increase in its volume fraction is accompanied by a redistribution of the alloying elements that determine the stability of the FCC phase at ambient temperature (their concentration in the austenite matrix falls). A phase transformation thus occurs upon cooling, as was demonstrated by X-ray phase analysis. Microstructure studies with electron transmitting and scanning

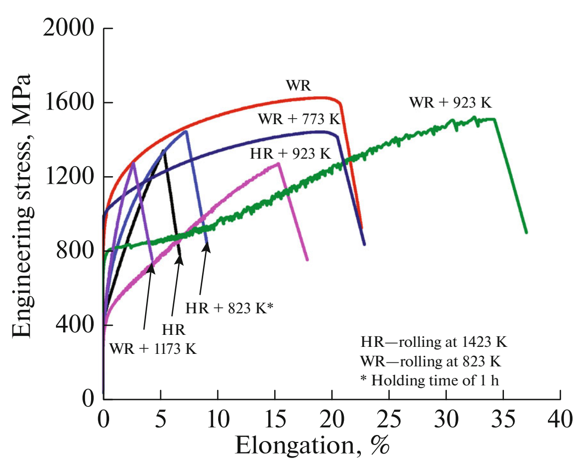

Fig. 4. Diagrams of deformation during a uniaxial tension test.

microscopy confirmed the proposed mechanism of structural formation after cooling from higher temperatures (Fig. 2).

At 873 K, a two-phase structure formed with a reduced volume fraction of retained austenite, relative to the predicted phase composition (Fig. 1). We can see that the austenite grain continued to grow to 20 μm at an annealing temperature of 1173 K. A phase transformation occurred upon cooling, however, resulting in a sharp drop in the volume fraction of austenite (Fig. 2d). It should be noted that this reduction had a weak effect on the variation in the microhardness of the considered steel in the 1073–1173 K range of annealing temperatures.

This class of steels is structural. They must be susceptible to both welding and shaping, but their technological plasticity after, e.g., hot deformation at 1423 K, is not enough to obtain the required configuration of items at lower temperatures. Their insufficient plasticity could in turn lower the level of safety of the final product. Hot rolling was done at 823 K to eliminate this flaw of the developed steel. The results from thermodynamic modeling showed this was the best way to achieve the required set of mechanical properties with the given ratio of ferrite to austenite phases. The proposed deformation treatment allowed us almost to double the creep limit and raise the ultimate strength to 1630 MPa. It also allowed us to more than quadruple the plasticity (relative stretching until failure), which would expand the advanced steel's field of application. The higher content of manganese (10 wt %) allows us to obtain an alloy characterized by high strength with greater plasticity of the material. Such high strengths and plasticities cannot be achieved in steels with lower manganese contents [9].

Changes in the structural and phase states are reflected in mechanical properties obtained upon uniaxial tension. Using the deformation curves, we can easily trace the chronology of changes in the structural and phase states from the material's susceptibility to deformation strengthening. A high level of plasticity is observed at the maximum volume fraction of the austenite phase (relative stretching until failure is more than 30%). Raising the temperature of annealing to 1173 K and reducing the volume fraction of austenite phase lowers the material's plasticity. At the same time, the strength remains high, testifying to the key role of austenite phase in the deformation strengthening of the considered Fe–10Mn–0.2C steel. An important role is also played by the initial structural and phase state, since annealing the considered steel at similar temperatures and holding times after deformation at 1423 K does not allow us to achieve the same strength and plasticity as after warm rolling. It has also been shown that annealing a sample at 823 K after it was deformed at 1423 K does not alter the mechanical properties of the initial hot rolled steel appreciably, while rolling at 823 K does increase the material's ultimate strength and creep limit, along with its plasticity. The efficiency of preliminary deformation treatment was therefore demonstrated in this work as well.

CONCLUSIONS

The optimum structural and phase state of Fe–10Mn–0.2C steel was determined, allowing us to obtain superior strength and plasticity. Warm rolling provided a high yield strength of 900 MPa and an ultimate strength of 1627 MPa in the considered steel. At the same time, the relative stretching until to failure was 21%. Preliminary deformation had a considerable effect on the strength of the considered steel after thermal treatment at 823–923 K. Raising the temperature of annealing past 923 K reduced its plasticity to the indicators of the initial hot rolled state. The effect the austenite phase had on the deformation strengthening of the considered steel was described. Plasticity grew along with the volume fraction of the retained austenite.

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