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Effect of the Rolling Temperature on the Structure and the Mechanical Properties of High-Nitrogen Austenitic Steels 05Kh21G9N7AMF and 04Kh22G12N4AMF

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Abstract—The structure and the mechanical properties of high-nitrogen austenitic 05Kh21G9N7AMF (0.56% N) and 04Kh22G12N4AMF (0.49% N) steels have been studied after hot rolling. It is found that the temperatures of the onset and end of hot deformation influence the structure and the mechanical properties of these steels. The higher set of mechanical properties of steel 05Kh21G9N7AMF after rolling in the temperature range 1100–900°C is due to the formation of a lamellar and equiaxed fragmented structure.

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1. INTRODUCTION

The mechanical properties of high-nitrogen austenitic Fe–Cr–Mn–Mo steels containing about 8% Ni are substantially dependent on the temperature of plastic deformation [1–5]. The studies [4] showed that Kh20AG14N8M (0.8% N) steel had a good combination of the mechanical properties (σ_u = 1080 MPa, δ = 36%, ψ = 56%, *KCV* = 1.5 MJ/m^2) after forging with a finishing temperature of 1000°C, and a decrease in the temperature to 850°C led to deterioration of the ductility and the impact toughness. Rolling of this steel at 700–800°C at reductions of more than 40% causes the formation of hot cracks.

Rolling at 950–1000°C at a 70% reduction made it possible to obtain high strength properties ($\sigma_{0.2}$ > 1000 MPa) of 05Kh22AG15N8M2F-Sh (0.55% N) steel, which was due to the formation of a fragmented structure with a high dislocation density during hot deformation [1].

The forging of 50-kg ingots of 05Kh23AG11N8MF (0.69% N) steel into rods 30 mm in diameter at forging temperatures lower than 1000°C was accompanied by the formation of cracks on the ingot surface along with a significant increase in the strain resistance [5]. Crack initiation was related to the formation of a colony of fine-lamellar precipitates of nitrogen pseudopearlite along grain boundaries. In this case, 04Kh20N6G11M2AFB (0.3% N) steel had a good combination of strength and ductility after quenching from rolling heating at a rolling finishing temperature not higher than 950°C [6]. It was related by the formation of a mixed (recrystallized, fragmented, lamellar) structure and a uniform distribution of nanophase precipitates in the defect sites of the crystal lattice.

The aim of this work is to study the influence of the rolling and forging temperatures on the structure and the mechanical properties of high-nitrogen austenitic Fe–Cr–Mn–Mo steels containing at most 8% Ni [7].

2. EXPERIMENTAL

We studied high-nitrogen austenitic steels with various nickel and manganese contents (Table 1), which were melted in VIAM. Workpieces of these steels were subjected to rolling in the temperature ranges 1100–900, 1050–900, 950–900°C at a 70% total reduction; subsequent rolling from the rolling finishing temperatures was performed in water. Using these conditions, an experimental batch of 5-mm-thick sheets was produced.

The standard mechanical tensile properties were determined using an INSTRON-1185 testing machine at a loading rate of 1 mm/min and a load of 10 t according to GOST 1497–84. The impact toughness tests were performed according to GOST 9454–78 at room temperature using an Amsler pendulum impact testing machine and V-notched specimens.

The structure was studied by optical microscopy (an Olympus microscope with an attachment for recording and analyzing images) and transmission electron microscopy (a JEM-200CX microscope, accelerating voltage 160 kV). The X-ray diffraction (XRD) study was carried out using a DRON-4-07dif-

Table 1. Chemical compositions of the steels (wt %)

Steel	C	N	Cr	Mn	Ni	Mo	V	Si	La	Y	Fe
05Kh21G9N7AMF	0.05	0.56	20.81	9.34	7.42	1.02	0.16	1.08	0.001	0.0002	Base
04Kh22G12N4AMF	0.04	0.49	22.12	11.82	4.13	0.99	0.16	0.75	0.005	0.0003	Base

Table 2. Mechanical properties of the steels after hot rolling and XRD results

Steel	Temperature range of rolling, °C	σ_u, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %	*KCV*, MJ/m^2	Content of phase, vol %		Lattice parameter of phase, Å	
							γ	α	γ	α
05Kh21G9N7AMF	1000–900	1202	1139	33	54	0.75	100	–	3.608	–
	1100–900	1157	1067	28	53	1.08	100	–	3.612	–
04Kh22G12N4AMF	950–900	1166	1142	21	18	0.23	98	2	3.607	2.876
	1000–900	1055	906	35	54	1.17	97	3	3.612	2.878

fractometer and filtered Co*K*α radiation at room temperature.

The ferromagnetic phase content was found using an MVP-2M multifunctional eddy-current device. The ferromagnetic phase content was calculated using the Gross formula $\Phi = (\mu - 1)/0.068$ (μ is the magnetic permeability).

3. RESULTS AND DISCUSSION

Rolling under the chosen conditions with subsequent cooling in water from the deformation final temperature provides high mechanical properties of the steels under study (Table 2). The best combination of strength, ductility, and impact toughness were obtained for the 05Kh21G9N7AMF steel after rolling in the temperature range 1100–900°C. The low rolling initial temperature (950°C) of the 04Kh22G12N4AMF steel caused a significant decrease in its ductility and impact toughness (*KCV* = 0.23 MJ/m^2) at high strength properties of the steel.

The difference in the mechanical properties is related to the structure-phase states of the steels. For example, the 05Kh21G9N7AMF steel with higher nickel and nitrogen contents than those in the 04Kh22G12N4AMF steel contains 100% austenite, the lattice period of which after rolling at 1100–900°C is larger than that after rolling at 1000–900°C (Table 2). The results of determination of the ferromagnetic phase content showed that the hot-rolled 05Kh21G9N7AMF steel did not contain ferromagnetic phases ($\mu < 1.01$ G/Oe), and their content in the 04Kh22G12N4AMF steel is 2–3% (μ = 1.2–1.4 G/Oe).

The microstructure of the 05Kh21G9N7AMF steel after rolling at 900–1000°C contained deformed austenite grains 5–30 μm long extended in the rolling direction. There were not of carbonitride phase precipitates along grain boundaries (Fig. 1a). The microstructure of the 04Kh22G12N4AMF steel contained 20–40-μm austenite grains and a small amount of δ ferrite (Fig. 1b). Its grains were slightly deformed and arranged as groups elongated in the rolling direction along austenite grain boundaries.

The electron-microscopy studies showed that the structure of the 05Kh21G9N7AMF steel after rolling at 1100–900°C contained two types of defect structures. The first type consisted of an equiaxed fragmented structure with 0.5–3.0-μm fragments and the misorientation angle between neighboring fragments smaller than 10° (Fig. 2a). The cell boundaries are diffuse; there are dislocation clusters and gradient dislocation structures. We can see characteristic lamellar strongly elongated dislocation fragments (Fig. 2b). In this case, the maximum fragment-boundary angle is 15°–20°, and the resulting misorientation across an entire lamella is 45°–50°. The lamellar fragments have a thickness of 0.1–0.5 μm, and the total thickness of the region with the lamellar structure of fragments is 3–5 μm. The boundaries of the lamellar fragments are strongly localized and are high-angle boundaries.

After rolling at 1000–900°C, the defect structure of the 05Kh21G9N7AMF steel is similar to that obtained after rolling at 1100–900°C but it contains a lower fraction of a lamellar structure (Fig. 2c). In this case, the lamellar fragments are substantially thinner (0.05–0.25 μm). The total thickness of the regions with lamellar structure is less than 1–2 μm.

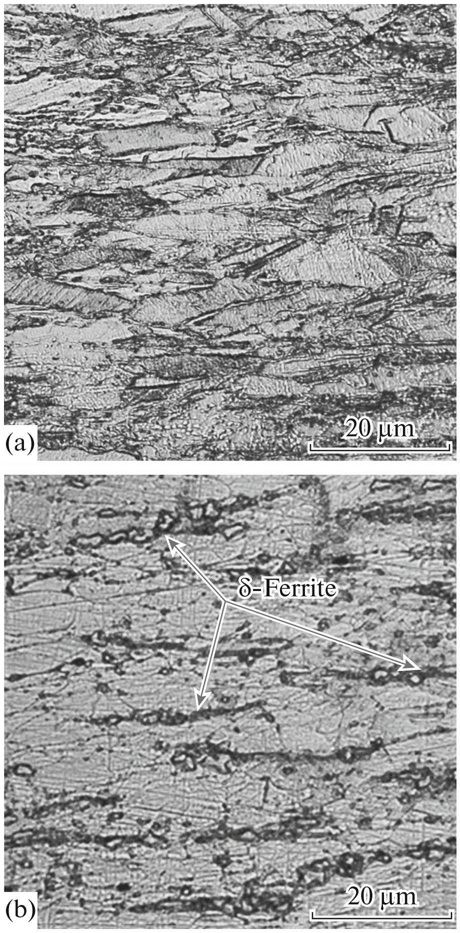

Fig. 1. (a) Structure of steel 05Kh21G9N7AMF after rolling at 1000–900°C. (b) Structure of steel 04Kh22G12N4AMF after rolling at 950–900°C.

The 05Kh21G9N7AMF steel demonstrates a certain tendency to the formation of a crystallographic texture after both regimes of rolling. In most cases, the rolling plane corresponds to orientation {110}.

In the 04Kh22G12N4AMF steel rolled at 1000–900°C, the lamellar structure of fragments can hardly be observed and an equiaxed fragmented structure is less clearly pronounced (Fig. 3a). The equiaxed fragment size is 0.5–3.0 μm. In addition, we observed colonies of fairly fine (0.25–2.0 μm) recrystallized grains accumulated into elongated strips, evidently, in the regions where lamellar fragments formed earlier (Fig. 3b). The width of bands with a recrystallized structure is 1–3 μm. The volume fraction of the recrystallized austenite matrix is ~20%. The recrystallized grains are almost free of dislocations; this demonstrates that dynamic recrystallization occurs at the final stage of hot rolling.

The structure of the 04Kh22G12N4AMF steel after rolling at 950–900°C is similar to the structure obtained after rolling at 1000–900°C. However, no lamellar structure is visible in fragments. The colonies of recrystallized grains have a lamellar structure as before (Figs. 3c, 3d). An equiaxed fragmented structure is observed more clearly and the misorientation angle between 0.25- to 1.0-μm fragments is 25°–30°.

Dynamic recrystallization was not observed in the 05Kh21G9N7AMF steel. The observed regions of lamellar structures are deformation bands, namely, the boundaries between the regions of the stable orientation upon hot rolling in which orientation is sharply changed from one texture component to another. Dynamic recrystallization takes place in the 04Kh22G12N4AMF steel to some degree. Recrystallization occurs in deformation bands, where nuclei

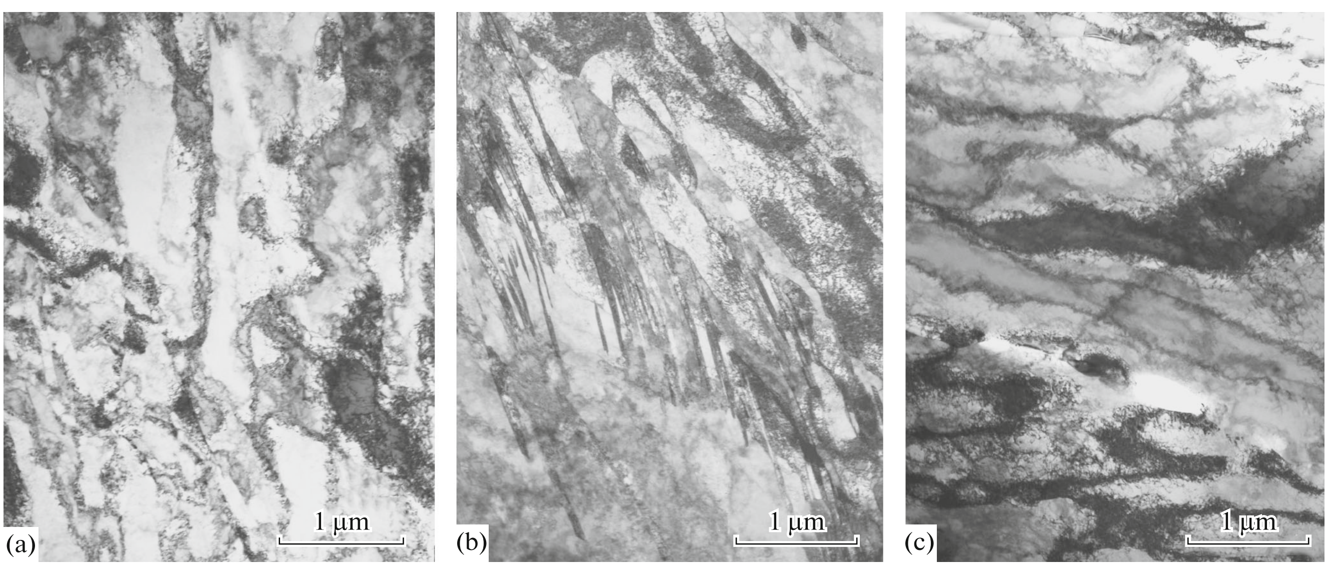

Fig. 2. Fragmented structure of steel 05Kh21G9N7AMF: (a) equiaxed structure after rolling at 1100–900°C, (b) lamellar structure after rolling at 1100–900°C, and (c) lamellar structure after rolling at 1000–900°C.

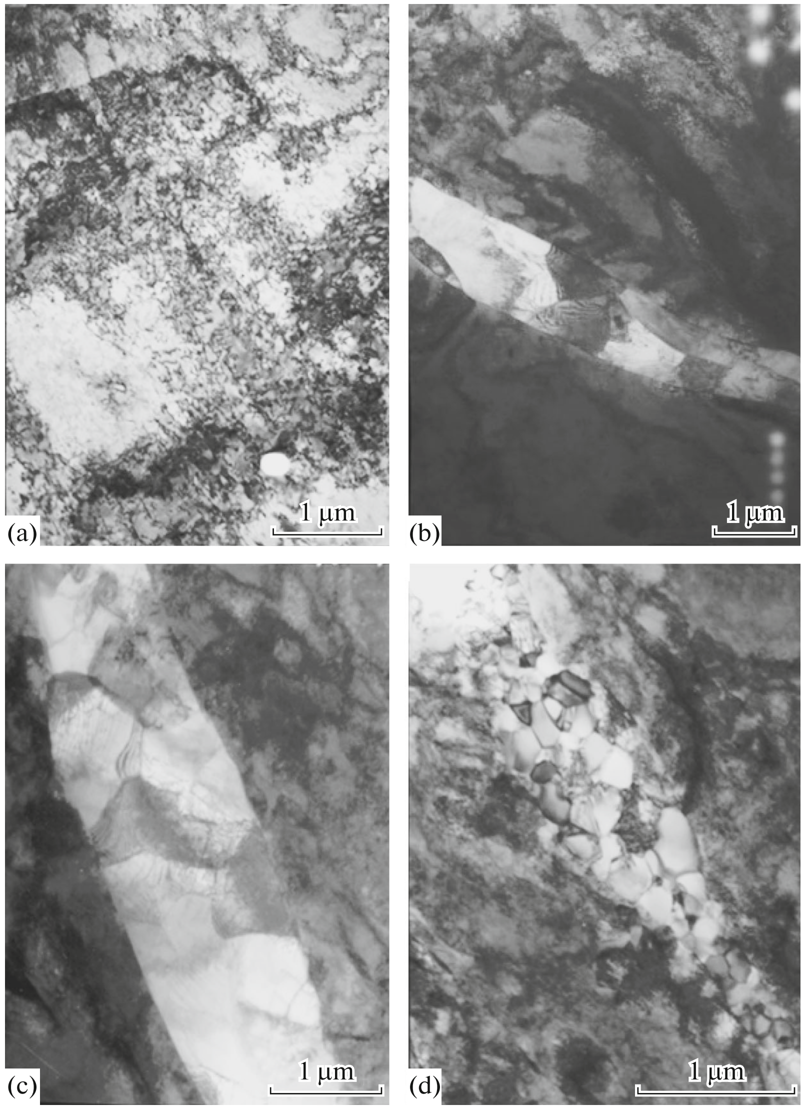

Fig. 3. Structure of steel 04Kh22G12N4AMF: (a) fragmented structure after rolling at 1000–900°C, (b) colonies of fragmented structure after rolling at 1000–900°C, and (c, d) early and late stages of recrystallization at 900–950°C, respectively.

form easier, since the misorientation angle between fragments in them is substantially higher and clearly formed boundaries of fragments exist.

4. CONCLUSIONS

(1) Steel 05Kh21G9N7AMF (0.56% N) has a higher set of the mechanical properties and a better magnetic permeability after rolling at 1100–900°C (σ_u = 1157 MPa, $\sigma_{0.2}$ = 1067 MPa, δ = 28%, ψ = 53%, *KCV* = 1.08 MJ/m^2, μ < 1.01 Gs/Oe). Steel 04Kh22G12N4AMF (0.49% N) subjected to rolling at temperatures 950–900°C has a high strength (σ_u = 1166 MPa, $\sigma_{0.2}$ = 1142 MPa) but a low impact toughness (*KCV* = 0.23 MJ/m^2).

(2) The high mechanical properties of steel 05Kh21G9N7AMF sheet workpieces are related to the formation of a fragmented lamellar structure due to thermal deformation treatment under the chosen conditions.

(3) In steel 04Kh22G12N4AMF, dynamic recrystallization takes place to some degree upon rolling in the temperature ranges 1000–900°C and 950–900°C.

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