Mechanical and Physical Properties of Cast Fe−Mn−Al−C−N Alloys

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Abstract—Cast Fe + 12.7−25.6% Mn + 0−14.4% Al + 0.02−2.18% C alloys are produced and studied, including high-strength materials microalloyed with nitrogen (0.001−0.135% N). Cast high-carbon, high-alloy Fe−Mn−Al−C alloys undergo hot deformation with 40−50% reduction, without hot-crack formation. In moderate-temperature deformation, a high-strength state (with σ_u up to 1810 MPa) appears in such alloys, with sufficient margin of plasticity (up to 50%). The yield point of high-carbon (up to 2.18% C) austenitic Fe−Mn−Al−C alloys at room temperatures reaches 1200 MPa. The specific heat and thermal conductivity of these alloys decline with increase in the total Al + C + N content. Strong iron alloys with high Mn and Al content may be used in the cast and deformed state to obtain a combination of hot strength, large margin of plasticity, thermal stability, and wear resistance.

Keywords: Fe−Mn−Al alloys, triplex alloys, microalloying with nitrogen, high-strength alloys, multiphase structure

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In developing a new generation of high-strength steel, one goal is to obtain a multiphase structure containing a considerable quantity of high-strength phases (such as martensite, bainite, or ultrafine-grain ferrite) and also plastic austenite with controllable resistance to martensitic transformation on deformation [1]. In addition, to meet the high technical requirements and quality and safety requirements in manufacturing today, the latest high strength structural steels must be characterized by a high level of plasticity and high unit strength.

These requirements are satisfied by high-manganese austenite triplex alloys with a high aluminum content, in which the conversion of the residual austenite to martensite on deformation is accompanied by strain hardening.

Triplex alloys are characterized by a combination of high strength and plasticity. The presence of 5−15% Al reduces the density by 15−20% relative to traditional high-strength complex-alloy steel [2, 3].

Besides excellent mechanical properties, modern materials must also have specific physical properties [4, 5]. The specific heat plays a significant role in the operation of cryogenic equipment, while the cooling rate depends directly on the thermal conductivity [6]. In addition, the thermal conductivity has a significant influence on heat treatment.

However, hot pressure treatment of high-alloy iron−manganese−aluminum alloys is often complicated by problems associated with reduced plasticity. That limits their applicability.

Accordingly, in the present work, we investigate the influence of the chemical and phase state on the physical and mechanical properties of iron alloys with high content of manganese (12.7−25.6%), aluminum (0−14.4%), and carbon (0.02−2.18%), including those microalloyed with nitrogen (0.001−0.135%) in the cast state at the temperatures of hot, moderate-temperature, and cold deformation.

In the experiments, we consider ferromanganese alloys with a high aluminum content produced in laboratory conditions [7, 8]. Table 1 summarizes their chemical composition.

The solid solution is modified by heating to 1070−1090°C, with subsequent cooling in water.

The resistance to hot and moderate-temperature deformation is studied in compressive systems by means of the Gleeble 3800 system. Hot deformation corresponds to 950−1000°C, and moderate-temperature deformation to 550°C. The strain rate $\dot\varepsilon = 0.1\ \text{s}^{-1}$; the strain is 25−50%. After deformation, the samples are sharply cooled by an air blast [7].

The susceptibility of the alloys to cold deformation is assessed by means of three-point transverse flexure tests on an Instron machine.

After treatment, the hardness *HV* of the alloys is measured; their phase composition is determined by

Table 1. Chemical composition of Fe−Mn−Al−C alloys with microadditions of nitrogen

Alloy	Group	Content of elements,* wt %					
		Mn	Al	Si	Mo	C	N
1	I (γ alloys with high carbon content)	16.8	0.01	0.86	2.0	1.62	0.020
2		21.2	6.2	0.50	0.20	1.10	0.006
3		19.1	7.5	0.60	1.20	1.47	0.002
4		19.1	9.0	0.50	0.03	2.18	0.001
5		23.9	4.0	0.54	0.01	1.80	0.032
6	II (γ alloys with low carbon content)	25.3	0.01	0.20	<0.001	0.02	0.014
7		23.8	4.6	0.20	<0.001	0.05	0.020
8		25.6	0.01	0.20	<0.001	0.03	0.135
9		24.1	5.3	0.32	<0.001	0.04	0.024
10	III α alloys	23.7	7.5	0.20	<0.001	0.05	0.008
11		22.6	14.4	0.20	<0.001	0.05	0.007
12		23.7	8.1	0.20	<0.001	0.05	0.008
13		24.3	11.5	0.20	<0.001	0.03	0.045

* The balance is Fe (wt %).

X-ray structural analysis; and the magnetization is estimated. The alloy density is determined by hydrostatic weighing; the thermal conductivity is determined by means of a differential thermocouple; and the specific heat is determined in the range 25−100°C [8].

Table 2 presents the phase composition and the physical and mechanical properties of the alloys. The resistance to hot deformation σ_{max} at 950−1000°C increases with increase in the aluminum, carbon, and nitrogen content and is less for ferritic alloys (σ_{max} = 50−150 MPa) than for austenitic alloys (σ_{max} = 120−180 MPa). An important result of the hot-compression tests is the discovery that the cast alloys are able to undergo 40−50% hot deformation without cracking.

The resistance to moderate-temperature deformation is greatest for high-carbon austenitic alloys of group I: 1450−1810 MPa at 550°C. The resistance to moderate-temperature deformation of group-III α alloys is 920−1290 MPa. Low-carbon austenitic alloys of group II are characterized by the least strength at T = 550°C: 660−1000 MPa. With similar chemical composition of the alloys in each group, the strength is greater after microalloying with nitrogen [9−12].

The high strength of high-carbon austenitic alloys of group I is accompanied by sufficient margin of plasticity. In moderate-temperature deformation, all the alloys withstand 25−50% strain without failure.

The strength is markedly greater in moderate-temperature deformation than in hot deformation. With increase in the carbon and aluminum content and decrease in the manganese content, the strength rises.

Microalloying with nitrogen also increases the strength.

In assessing the mechanical properties of the alloys at room temperature, we must note that group-III α alloys fail in the elastic region, like brittle materials (such as cast iron or ceramics). Low-carbon austenitic alloys of group II, conversely, combine high plasticity with fairly high flexural strength: σ_B reaches 1070−1770 MPa. Group-I alloys, despite their high carbon content, exhibit the greatest flexural strength, with satisfactory plasticity: σ_u may be as high as 1880 MPa.

The minimum density of the alloys is 6.5 g/cm³, with about 14% Al (Table 2). That is equivalent to 17−18% decrease in the density relative to pure iron. The reduced density of alloys with aluminum is mainly associated with the greater unit volume of the solid solution, which is due both to the lower mass of the elementary cell in the crystal lattice, where relatively heavy iron atoms (55.85 g/mol) are replaced by light aluminum atoms (26.99 g/mol), and to the increased volume of the elementary cell (swelling of the lattice). For example, the lattice period of a γ solid solution with approximately the same content of the other alloying elements (primarily carbon) increases from 3.6027 Å in the absence of aluminum to 3.6317 Å with 5.3% Al [8]. For an alloy with 12% Al, the total decrease in density is around 17% (to 6.6 g/cm³); the decrease in density due solely to swelling of the γ lattice is about 10%.

To assess the use of the alloys in different states, it is expedient to use the unit strength, which is the ratio of the alloy strength at specified temperature to its
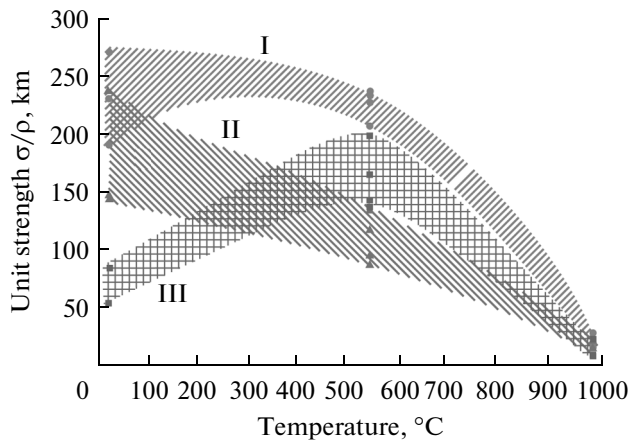
Fig. 1. Unit strength of Fe−Mn−Al−C alloys with microadditions of nitrogen at different test temperatures: (I−III) groups in Table 1.
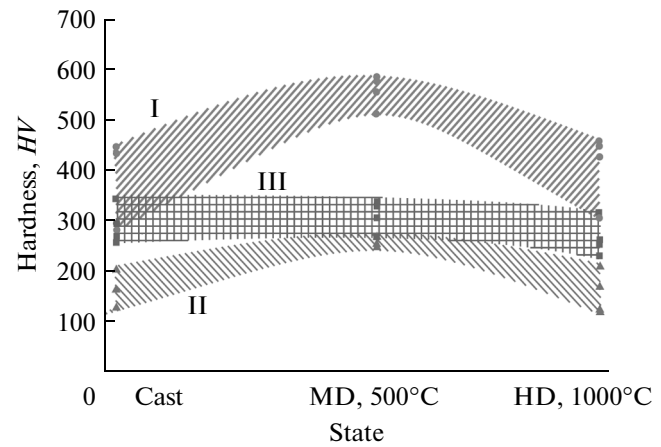

Fig. 2. Hardness of Fe−Mn−Al−C alloys with microadditions of nitrogen in the cast state, after moderate-temperature deformation (MD) and hot deformation (HD): (I−III) groups in Table 1.

density. Comparison of the unit strength of the alloys at different test temperatures leads to the following conclusions. In cold deformation, group-I alloys are characterized by the greatest unit strength, with good plasticity and hardness (Fig. 1). The strength and hardness may be increased by moderate-temperature deformation and aging (Fig. 2).

For group-II alloys, good properties are observed at low temperatures, but the wear resistance is low, since

the hardness after each treatment is no greater than that of traditional chromonickel stainless steel in the quenched state. However, they may be used in the cast and undeformed state as high-strength nonmagnetic structural materials that are relatively light.

In α alloys, aging occurs even in ingot solidification and aging and is more significant in moderate-temperature deformation. As a result of strain aging, their strength resembles that of group-I γ alloys. However,

Table 2. Phase composition and properties of Fe−Mn−Al−C alloys with microadditions of nitrogen

Alloy	Group	Phase composition	Density ρ, g/cm^3	Specific heat (25–100°C), J/(kg K)	Thermal conductivity (25–100°C), W/(m K)	Magnetic properties**	Hardness HV	Unit strength***		
								σ^{1000}/ρ, km	σ^{550}/ρ, km	σ_{fl}/ρ, km
1		$\gamma + [\varepsilon]^* + [Me_xC_y]^*$	7.7074	364	8.6	−	293	1.7	24	23.4
2		$\gamma + \kappa^*$	7.3282	399	8.4	−	279	1.7	23.2	23.6
3	I	γ	6.9552	405	8	−	434	1.7	24.2	27.5
4		$\gamma + \kappa$	7.0181	376	7.2	−	447	2.9	23.8	−
5		γ	6.9994	369	7.3	−	376	2.5	21.1	19.4
6		$\gamma + \varepsilon + (\beta\text{-Mn})$	7.4643	454	15.3	−	204	1.8	9	24.3
7	II	$\gamma + [\varepsilon]^*$	7.4774	427	9.5	−	130	2.2	13.7	14.6
8		$\gamma + \varepsilon + (\beta\text{-Mn})$	7.6462	465	15.2	−	164	2	9.7	15.2
9		γ	7.4041	417	9.3	−	127	2.5	12	15.1
10		α	6.7191	441	11.9	++	285	1.0	14	8.6
11	III	$\alpha + \varepsilon$	6.5151	426	9.9	+	345	0.8	20.2	−
12		$\alpha + \varepsilon$	7.1033	445	12.8	++	272	1.0	16.9	−
13		$\alpha + [\gamma]^*$	6.6027	450	9.6	++	259	2.4	14.6	5.5

* Traces (<1%).

** Notation: ++, very magnetic; +, magnetic; −, nonmagnetic.

*** σ_{1000} is σ_{max} at $T = 1000°C$ (or at $T = 950°C$ for alloys 10–12); σ_{550} is σ_{max} at $T = 550°C$; and σ_{fl} is σ_u in flexure tests at $T = 20°C$.

their use in the cast state is limited by their low plasticity. Therefore, they may be recommended for use in the deformed state, after distortion of the cast structure.

Experiments show that, within each group, the thermal conductivity declines with increase in the aluminum content (Table 2). In addition, in high-carbon alloys (group I) and alloys with microadditions of nitrogen, the thermal conductivity is reduced on account of impurity scattering at carbon (and/or nitrogen) atoms. The thermal conductivity of ferromanganese alloys with high aluminum content is close to that for classical austenitic chromonickel steels. Variation in the manganese content has practically no effect on the molar specific heat and thermal conductivity of the alloys considered. The molar specific heat of all the alloys declines with increase in the overall alloying. For γ alloys of groups I and II, this effect is more pronounced than for group-III α alloys. The thermal conductivity of all the alloys declines with increase in the total Al + C + N content—that is, the content of the alloying elements that most distort the crystal lattice. The specific heat and thermal conductivity are higher for α alloys than for γ alloys.

CONCLUSIONS

By adjusting the alloy composition and the thermomechanical treatment, triplex structure (γ + α + carbides; γ + ε + carbides; γ + ε + α) may be formed with different proportions, dimensions, and distributions of the phases, so as to obtained the specified set of mechanical and physical properties.

High-carbon, high-alloy Fe−Mn−Al−C cast alloys undergo hot deformation with 40−50% reduction, without hot-crack formation. The resistance to hot deformation increases with increase in the content of aluminum, carbon, and nitrogen.

On moderate-temperature deformation, a high-strength state (with σ_u up to 1810 MPa) appears in such alloys, with sufficient margin of plasticity. In moderate-temperature deformation, 25−50% strain is possible. The resistance to moderate-temperature deformation increases with increase in the content of carbon, nitrogen, and aluminum.

Alloying with up to 15% Al and up to 25% Mn reduces the density of Fe−Mn−Al−C−N alloys by 17−18% in comparison with traditional high-strength alloys. The specific heat and thermal conductivity of all the alloys decline with increase in the total Al + C + N content.

Strong iron alloys with high Mn and Al content may be used in the cast and deformed state to obtain a combination of hot strength, large margin of plasticity, thermal stability, and wear resistance.

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