INVESTIGATION OF IRON-ALUMINUM ALLOYS IN THE REGION OF THE COMPOUND Fe$_{3}$Al

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Figure 1

Figure 1: Figure 1

Abstract

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R. S. Mints and N. N. Samsonova

INVESTIGATION OF IRON-ALUMINUM ALLOYS IN THE REGION OF THE COMPOUND Fe_3Al

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The broad region of solid solutions of aluminum in iron has long attracted the attention of researchers, since complex ordering processes take place in it. At the same time, this region of alloys, owing to certain valuable physical and mechanical properties, is of great practical importance for the creation of specific structural materials (heat-resistant, paramagnetic, corrosion-resistant, etc.). X-ray structural investigations (^{1}) between pure iron and the FeAl compound have established the existence of a whole series of compositions with such atomic ratios as are prone to the formation of compounds with an ordered structure: $Fe_{15}Al$, $Fe_{11}Al$, $Fe_{14}Al_2$, $Fe_{13}Al_3$, Fe_3Al.

Fig. 1. Isotherms of the coefficient of linear expansion of alloys of the Fe—Al system

The existence of the compound Fe_3Al was confirmed by methods of thermal analysis (^{2}), electrical resistance (^{3}-^{5}), hardness (^{4}, ^{5}), and investigations of magnetic properties (^{1}, ^{4}, ^{5}). In addition, the following were studied: the heat effect of formation (^{6}), the kinetics of ordering (^{7}-^{11}), the Hall effect (^{7}), thermoelectric emf (^{12}), and high-temperature X-ray analysis (^{13}, ^{14}). In composition—property diagrams the compound Fe_3Al is revealed when measuring electrical resistance, hardness, and the crystal-lattice parameter. According to various investigations, the formation of the compound Fe_3Al from the solid solution occurs at 500-560°. It is accompanied by a decrease in electrical resistance, hardness, lattice parameter, magnetic susceptibility, and also by an increase in the temperature coefficient of electrical resistance and coercive force. In (^{15}) the presence of magnetic superstructure in an alloy of composition Fe_3Al was noted. There are indications (^{9}, ^{16}, ^{17}) of the cold brittleness of iron-aluminum alloys containing 5-16 wt.% Al.

In the present work, results are presented of an investigation of the properties of alloys of the Fe—Al system in the region of the compound Fe_3Al by methods of dilatometry, hot hardness, and high-temperature strength. In order to correlate our own data with the literature, in addition to the indicated methods, investigation of the microstructure, electrical resistance, and hardness was employed. The alloys were prepared from technical iron (0.02% C) and an iron–aluminum master alloy (49.61% Al). The master alloy, in turn, was melted from aluminum (99.99%) and technical iron. The alloys were melted in vacuum in an induction furnace, in corundum crucibles. The finished alloys were remelted under a basic flux for the fabrication, by Stepanov' s method, of rods

Table 1

Composition and properties of the investigated alloys of the Fe—Al system

Specimen No.	Fe, wt. %	Al, wt. %	Fe, at. %	Al, at. %	Hardness, quenched from 1200°	Hardness, slow cooling	Hardness, step anneal	Electrical resistivity, quenched from 1200°	Electrical resistivity, slow cooling	Electrical resistivity, step anneal
1	94,0	6,0	88,37	11,67	–	–	–	0,758	0,693	–
2	92,0	8,0	84,73	15,27	–	–	200	–	–	–
3	91,0	9,0	82,97	17,03	245	223	–	0,820	0,852	–
4	90,5	9,5	82,17	17,83	268	250	–	0,913	0,872	–
5	90,0	10,0	81,17	18,83	–	–	–	1,053	0,998	–
6	89,5	10,5	89,46	19,54	315	310	–	1,000	1,021	–
7	89,0	11,0	80,33	19,67	–	–	215	1,089	1,076	–
8	88,5	11,5	78,77	21,23	321	309	–	1,154	1,098	–
9	88,0	12,0	77,97	22,03	330	296	232	1,331	1,120	–
10	87,5	12,5	77,17	22,83	329	305	–	1,147	1,105	–
11	87,0	13,0	76,33	23,67	328	319	249	1,267	1,103	–
12	86,5	13,5	75,45	24,55	322	288	240	1,265	1,060	0,920
13	86,0	14,0	74,77	25,23	320	268	219	1,229	0,839	0,662
14	85,7	14,3	74,21	25,79	309	245	–	1,229	0,689	0,306
15	85,2	14,8	73,54	26,46	326	262	–	1,286	1,133	1,062
16	85,0	15,0	73,26	26,74	330	272	225	1,358	0,996	1,178
17	84,7	15,3	72,77	27,23	–	–	–	1,462	1,176	1,266
18	84,2	15,8	72,09	27,91	342	306	–	1,518	1,395	1,453
19	84,0	16,0	71,72	28,28	346	321	356	–	1,407	1,411
20	83,5	16,5	70,87	29,13	–	–	–	–	1,557	1,518
21	83,0	17,0	70,12	29,88	–	–	–	–	1,581	1,566
22	82,5	17,5	69,47	30,53	–	–	–	–	1,557	1,516
23	82,0	18,0	68,75	31,25	357	334	365	–	1,565	1,516

Specimen No.	Fe, wt. %	Al, wt. %	Fe, at. %	Al, at. %	Hardness, quenched from 1200°	Hardness, slow cooling	Hardness, step anneal	Electrical resistivity, quenched from 1200°	Electrical resistivity, slow cooling	Electrical resistivity, step anneal
24	81,5	18,5	68,03	31,97	–	–	–	–	1,498	1,518
25	81,0	19,0	67,35	32,65	–	–	–	–	1,570	1,468
26	80,0	20,0	65,66	34,34	–	–	350	–	–	–

with a diameter of 4 mm, a length of approximately 100 mm, and castings 15 mm in diameter. On specimens in the form of rods, the electrical resistivity was measured; subsequently, on the same specimens, the thermal expansion was measured and the heat resistance was tested. On the castings the microstructure was studied, and the hardness and hot hardness were measured.

Hardness was determined on a hardness tester with a diamond pyramid under a load of 10 kg. Electrical resistivity was measured by a compensation circuit using a PPTN-1 potentiometer. Thermal expansion was determined on a visual dilatometer ([18]). The specimens were rods 4 mm in diameter and 50 mm long; the increase in length during heating was measured with a dial indicator of clock type with a scale division of one micron. The specimens were heated to 1100° at a rate of 10°/min.; elongation measurements were made every 20°. The hot-hardness testing of the alloys was carried out on a Lozinskii apparatus ([19]) of the VIM-1M type in the temperature range from room temperature to 800°, at intervals of 100°. Testing at a higher temperature proved impossible because of adhesion of the diamond indenter to the specimens. The heat resistance of the alloys was tested by the centrifugal bending method on a KP-3 type machine ([20]) at various temperatures and loads. To study the microstructure of the alloys, specimens were quenched from 1200° in oil and were subjected to prolonged annealing according to the schedule: 1100° for 2 hours, 900° for 24 hours, 600° for $5 \cdot 24$ hours, 400° for $10 \cdot 24$ hours, then slowly cooled with the furnace to room temperature. Heat treatment of the specimens was carried out in evacuated quartz ampoules. The polished sections were etched electrolytically in 10% oxalic acid. Study of the microstructure of the quenched and annealed alloys confirmed the absence of structural changes associated with the ordering transformation Fe_3Al, as reported in works ([4,5]).

The results of measurements of hardness and electrical resistivity of the specimens after various types of heat treatment—quenching from 1200°, slow cooling, and after prolonged step annealing—are given in Table 1. On the composition—hardness and composition—electrical-resistivity curves for the annealed alloys, in full agreement with works ([3,5]), were found

Figure 2 graph

Figure 2: Figure 2 graph

Figure 3 graph

Figure 3: Figure 3 graph

singular minima in the alloy containing 14.3 wt.% Al (25.79 at.% Al), i.e., one lying close to the composition of the compound Fe_3Al. On the composition-electrical-resistivity curves for alloys quenched from 1200°, in the Fe_3Al region, slight breaks are observed, which indicate that it is impossible to fix the high-temperature state at the cooling rate used in quenching. These breaks testify to the high rate of transformation of Fe_3Al.

Fig. 2. Isotherms of hot hardness of alloys of the Fe—Al system

The dilatometric study was carried out on specimens after quenching in oil from 1200° and after prolonged step annealing. On the curves of linear expansion versus temperature for annealed alloys containing 13.5–14.8 wt.% Al, breaks are present in the temperature interval 500–600°. The linear-expansion curves for all the remaining alloys have no breaks; they differ from one another only in their inclination with respect to the temperature axis. When isotherms of linear expansion were plotted as a function of composition for alloys in the annealed state at the beginning of the experiment, curves with a sharp singular minimum at 14.3 wt.% Al were obtained. On analogous curves plotted for alloys in the quenched state, the singular minimum is absent.

In Fig. 1 are presented isotherms of the derivative of linear expansion, i.e., isotherms of the coefficient of linear expansion as a function of composition for alloys in the annealed state; at all temperatures from 100 to 1100° these show singular minima at a composition almost exactly corresponding to the compound Fe_3Al.

The hot-hardness test was carried out on specimens slowly cooled from a temperature of 1100°. The hot-hardness isotherms (Fig. 2), like the isotherms of the coefficient of linear expansion, reveal a singular minimum (at the same composition—14.3 wt.% Al), almost corresponding to the compound Fe_3Al. However, in contrast to the isotherms of the coefficient of linear expansion, on the hot-hardness isotherms still another minimum is clearly revealed at ~12.0 wt.% Al, which probably may be attributed to some other compound of iron with aluminum ($F_{13}Al_3$, as the authors of (1) indicate). In contrast to the singular minimu-

Fig. 3. Curves of hardness of alloys of the Fe—Al system as a function of temperature. 1—15% Al; 2—12.5% Al; 3—Fe_3Al

···on the composition Fe_3Al, which persists at all temperatures both on the isotherms of the coefficient of linear expansion and on the hot-hardness isotherms; at 12.0 wt.% Al it exists only up to 600°. In considering the hot-hardness test data, attention is drawn to the fact that the rate of softening upon heating of the alloy of composition Fe_3Al is less than the rate of softening of alloys having an excess or a deficiency of aluminum, as shown in Fig. 3. A smaller temperature coefficient of softening is a characteristic feature of intermetallic compounds. This feature persists up to temperatures of 500–550°, i.e., up to the dissociation temperatures of the compound Fe_3Al. Above this temperature the rate of softening on heating becomes of the same order as in alloys corresponding to solid solutions.

The heat resistance of the alloys was tested at increasing temperatures: 500° (100 h) ÷ 550° (100 h) ÷ 600° (30 h) and at a constant stress of 20 kg/mm^2. Before testing, the specimens were heat-treated at 1100° for 10 h with cooling in air. After 75 h of testing at 500°, a deflection of more than 5 mm was obtained in specimens containing 11.0–12.5 wt.% Al. At 550°, in less than 20 h of testing, a deflection of more than 60 mm was observed in specimens with 11.0–12.5 and 13.5–14.3 wt.% Al. The smallest deflection during 100 h of testing at 550° was shown by alloys containing 16.5 and 20.0 wt.% Al. The alloy with 20.0 wt.% Al proved to be the most stable at 600°. According to the phase diagram, this alloy should represent a disordered solid solution of Al in α-Fe. Under the given testing conditions, all alloys belonging to the Fe_3Al region did not show high heat resistance, as in a number of other similar cases (21). This question requires further study.

To determine the effect of compound formation and disordering of the structure on the heat resistance of the alloys, specimens were tested by the centrifugal method at 650 and 450°, i.e., at temperatures 100° above and below the transformation temperature of the alloy of composition Fe_3Al, equal to approximately 550°. At 650° the test was carried out at stresses of 10 and 15 kg/mm^2 for 50 h; at 450° the stress was increased to 40 kg/mm^2 so that the duration of the test would not exceed 100 h.

At 450° the alloys close to the composition Fe_3Al proved to have the lowest heat resistance. At 650° there is no drop in heat resistance in the Fe_3Al region; the heat resistance of Fe—Al alloys increases with increasing aluminum content; the maximum heat resistance is possessed by alloys in the region of the maximum aluminum concentration (16–18 wt.%) in the solid solution based on α-Fe.

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