Development of Fabrication Modes of Deformed Semifinished Products from the Experimental Scandium-Containing Aluminum Alloy and Investigation into Their Mechanical Properties

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Abstract—The urgency of works directed at the fabrication of new alloys of the Al–Mg system alloyed with scandium, which are characterized by a profitable combination of operational and mechanical properties such as weldability, corrosion resistance, and sufficient strength, is shown. Flat ingots of the experimental scandium-containing alloy 560 × 1360 × 4520 mm in size are fabricated in industrial conditions. Modes of thermal treatment and sheet rolling are developed and approved for billets with a maximal thickness of 40 mm cut from them. A DUO 330 mill with flat rolls with an initial diameter of 330 mm and barrel width of 540 mm is used as the rolling equipment. Experimental investigations, which include the preparation of billets to rolling (homogenizing annealing and face milling), hot rolling at 450°C, cold rolling to a thickness of 3 mm, and annealing of cold-deformed semifinished products, result in the fabrication of deformed semifinished products fabricated according to various schemes of reduction during rolling and passed heat treatment. The maximal degree of summary deformation while rolling the billets to a thickness of 3 mm is 92.5%, while drawing for the passage varies from 1.04 to 1.2. Mechanical properties of deformed and annealed semifinished products of various thicknesses made of the experimental alloy are determined using an LFM400 universal test machine with an effort of 400 kN according to *GOST* (State Standard) *1497–84* and regularities of their variation, depending on the summary degree of deformation during rolling, are revealed. It is established that, when rolling strips made of the experimental scandium-containing aluminum alloy, the temporary tensile strength and yield strength of the material increase, while the relative elongation decreases, which corresponds to general ideas of the theory of metal forming. An analysis of the mechanical properties of the semifinished products shows that the level of strength and plastic properties is rather high, wherein the temporary tensile strength for cold-deformed samples reaches 453–481 MPa, the yield strength of metal reaches 429–457 MPa, and the relative elongation reaches 3.8 5.0%. The application of annealing made it possible to increase the relative elongation to 14 16% at sufficiently high values of the yield strength (up to 277 MPa). The results of our investigations allow us to develop the modes of casting, rolling, and annealing for the preparation of semifinished products made of the alloy of the Al–Mg system economically alloyed with scandium in limits of 0.10–0.14%, which will be used when approving the machining technologies in industrial conditions.

Keywords: aluminum alloys, magnalia, scandium, alloying, flat ingots, hot and cold rolling, single drawing, deformed semifinished products, mechanical properties, rolling mill, rolling force and moment

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INTRODUCTION

Aluminum alloys of the Al–Mg system, the so-called magnalia, are widely used in industry; however, the reserve of increasing the strength of traditional materials is almost exhausted. Therefore, their alloying with small additives of rare-earth (REM) and transition metals is promising to increase their strength characteristics [1, 2]. The combination of weldability, corrosion resistance, and sufficient strength make it possible to use sheets made of an alloy of the Al–Mg system for plating the hulls of ships, in automobile and aviation industries, in rocket production, and in other branches of industry. Largely due to this fact, the sheets are the main type of deformed semifinished products made of magnalia. Taking into account that the rolling technology, in particular, for AMg5 and

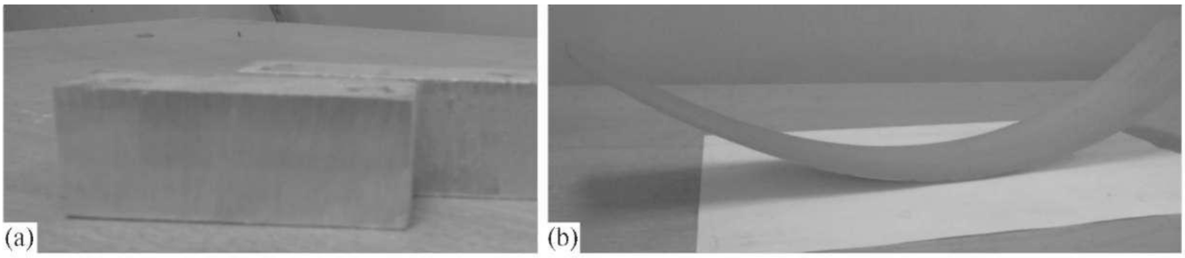

Fig. 1. (a) Billets for rolling and (b) a rolled strip made of the experimental alloy.

AMg6 alloys, is investigated rather well, it was selected as the basis for the experimental investigations on the fabrication of sheet deformed semifinished products made of a new alloy of the Al–Mg system economically alloyed with scandium with zirconium, chromium, and manganese additives.

Numerous scientific publications, including foreign ones, are devoted to investigations in the field of fabricating such materials and investigating the properties of wares produced of them [3–21]. In order to investigate the regularities of formation of mechanical and operational properties of wares made of aluminum alloys of the Al–Mg system alloyed with scandium in more detail, collaborators at the RUSAL company, along with a scientist from the Institute of Nonferrous Metals and Materials Science of Siberian Federal University, performed a series of experimental investigations in recent years with varying the chemical composition of alloys and their treatment modes and fabricated pilot parties of cast and deformed semifinished products made of them [22].

The goal of this study was to determine the possibility of using the developed new economically alloyed scandium-containing alloy of the Al–Mg system to produce flat rolling with the required level of mechanical and operational properties.

EXPERIMENTAL

Flat ingots 560 × 1360 × 4520 mm in size made of the experimental aluminum alloy of the Al–Mg system containing 94% Al and 5% Mg, in which the scandium content varied in limits of 0.10–0.14%, were cast under conditions of the Bratsk Aluminum Plant. Templates for the fabrication of rectangular billets with milled faces for rolling were cut from ingots (Fig. 1a).

Billets were subjected to homogenizing annealing according to the following mode:

(i) heating in an electric furnace at a rate of 1.16 K/min to 350°C;

(ii) holding at this temperature for 11 h;

(iii) repeated heating to 425°C with a rate of 1.25 K/min;

(iv) holding at this temperature for 8 h;

(v) cooling in air.

In order to select the optimal rolling mode, we varied initial billet sizes and magnitudes of reduction. Nevertheless, the general deformation scheme included hot rolling of a billet with a thickness of up to 40 mm, heated to 450°C, and cold rolling of hot-rolled strip to a thickness of 3 mm (Fig. 1b). The billet width varied from 120 to 200 mm. We used the DUO 330 mill as an equipment for rolling, having the following technical characteristics:

Electric motor power, kW	90
Three-phase main voltage, V	380
Current frequency, Hz	50
Roll barrel width, mm	520
Roll diameter, mm	330
Maximal roll set, mm	70
Roll rotation frequency, rpm	10
Maximal rolling effort, MN	1.55
Maximal rolling moment, MN m	0.82

Mechanical properties of metal (temporary tensile strength (σ_u), yield strength ($\sigma_{0.2}$), and relative elongation (δ)) were determined for the samples made of deformed and annealed strips.

RESULTS AND DISCUSSION

One variant of treatment modes of the pilot alloy is presented in Table 1. When analyzing the results of experimental investigations of deformation and power-energy parameters, we can notice the following. The summary deformation degree during rolling to a thickness of 3 mm was $\varepsilon_\Sigma = 92.5\%$. Drawing from the passage varied in limits $\mu = 1.04–1.2$.

An analysis of deformation and power rolling parameters showed that rolling efforts and moment do not reach admissible magnitudes; therefore, rolling under such reduction modes is realizable at the specified power-energy load of the equipment. Fabricated strips 3 mm in thick were annealed at 350°C and holding time of 3 h.

Investigations into the mechanical properties of metal after rolling and annealing by the tension

Table 1. Rolling parameters of the experimental alloy

Passage number	Unity drawing coefficient λ_{un}	Sample temperature t, °C	Strain resistance σ_s, MPa	Rolling effort P, MN	Rolling moment M, MN m
1	1.02	450	276.8	0.45	0.042
2	1.03	426	282.9	0.47	0.050
3	1.03	402	290.1	0.50	0.063
4	1.04	378	295.4	0.51	0.063
5	1.04	354	300.5	0.51	0.064
6	1.04	332	305.3	0.50	0.064
7	1.04	312	309.9	0.50	0.064
8	1.04	292	314.3	0.50	0.063
9	1.04	274	318.4	0.50	0.063
10	1.05	257	322.4	0.50	0.062
11	1.05	241	326.1	0.50	0.062
12	1.05	226	330.4	0.50	0.065
13	1.06	212	333.9	0.50	0.064
14	1.06	199	337.3	0.50	0.064
15	1.06	187	340.6	0.50	0.063
16	1.07	176	343.7	0.50	0.063
17	1.07	165	346.8	0.50	0.062
18	1.08	156	349.9	0.50	0.061
19	1.09	148	353.3	0.51	0.063
20	1.10	140	356.7	0.52	0.063
21	1.11	134	360.3	0.54	0.059
22	1.12	129	363.8	0.56	0.058
23	1.14	124	367.6	0.59	0.058
24	1.16	120	371.9	0.63	0.056
25	1.21	117	377.1	0.68	0.057
26	1.12	20	387.3	0.188	0.030
27	1.14	20	401.2	0.190	0.031
28	1.14	20	415.3	0.207	0.033
29	1.14	20	450.1	0.215	0.034

method were performed using an LFM400 test machine by the effort of 400 kN according to *GOST 1497–84*. Results of tests of mechanical properties of the samples of various thicknesses in the deformed and annealed states are presented in Table 2.

Regularities of varying the mechanical properties of deformed semifinished products during rolling are presented in Fig. 2.

The analysis of mechanical properties of semifinished products showed that the level of strength and plastic characteristics is rather high, notably, for cold-deformed samples; the temporary tensile strength reaches 453–481 MPa, the metal yield strength is 429–457 MPa, and the relative elongation is 3.8–5.0%. The difference in strength properties of rolled samples (Table 2) is caused by the application of various unity drawings during rolling and, correspondingly, varying metal strengthening during the cold deformation.

According to the results of our investigations, we can conclude the following:

(i) when rolling the strips made of the experimental scandium-containing aluminum alloy with an increase in the summary degree of deformation, the temporary tensile strength and metal yield strength rise, while the relative elongation decreases, which corresponds to the general notions of the theory of metal forming;

Table 2. Mechanical properties of the samples of sheet rolling made of the experimental alloy

Sample no.	Thickness, mm	State	Mechanical properties		
			σ_u, MPa	$\sigma_{0.2}$, MPa	δ, %
1	10	Hot-deformed	369	266	15
2	3	Cold-deformed	481	457	3.8
3	3	Annealed	380	264	16
4	8	Hot-deformed	372	280	15
5	3	Cold-deformed	466	436	4.5
6	3	Annealed	386	276	15
7	6	Hot-deformed	387	312	12
8	3	Cold-deformed	453	429	5
9	3	Annealed	390	277	14

(ii) the application of annealing after cold rolling made it possible to attain good plastic properties of metal (the relative elongation increases and reaches 14–16%) at a sufficiently high yield strength (up to 277 MPa);

(iii) the level of mechanical properties allows us to fabricate deformed semifinished products in the form of sheet rolling made of experimental alloy ingots with a sufficiently low scandium content for the needs of shipbuilding and automobile industries.

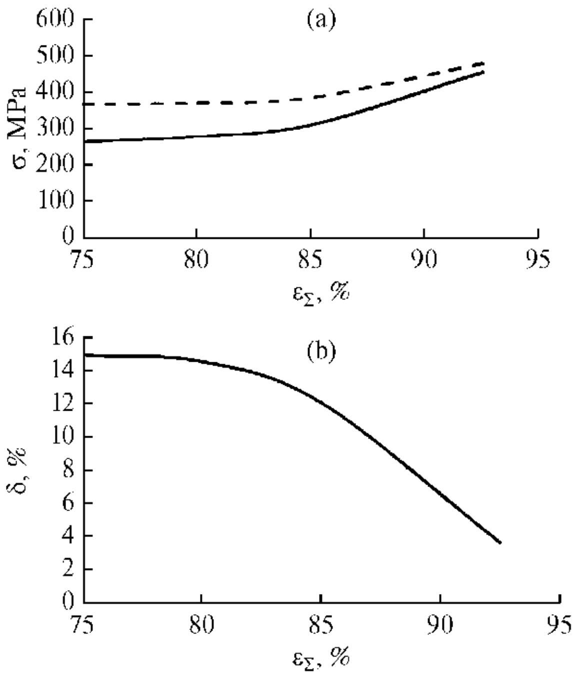

Fig. 2. Influence of the degree of deformation on (a) strength and (b) plastic properties of deformed semifinished products made of the pilot alloy.

CONCLUSIONS

Thus, our investigations allowed us to develop casting, rolling, and annealing modes to fabricate semifinished products made of a new alloy of the Al–Mg system containing scandium in comparatively small amounts (0.10–0.14%) and determine the level and regularities of varying mechanical properties depending on the summary degree of deformation when fabricating sheet rolling in various states (hot-rolled, cold-rolled, and annealed). The application of such alloys makes it possible to decrease the product prime cost herewith retaining high operational characteristics and required strength properties of metal. Our data will be in-demand when approving casting and treatment technologies of these alloys in industrial conditions.

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