Structure and Mechanical Properties of Ingots and Rolled Sections of Aluminum Alloy Based on the Al–Mg–Mn System

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Abstract—Commercial ingots and hot-pressed rolled sections of Al–Mg–Mn alloy doped with zinc, scandium, zirconium, chromium, and vanadium have been studied using optical microscopy, thermal analysis, electron microscopy, and electron-probe microanalysis. The compositions of the phase constituents and aluminum matrix of the alloy are determined. The sensitivity of the alloy to the formation of complex intermetallic compounds during solidification is revealed. The mechanical properties of ingots and rolled sections are determined.

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INTRODUCTION

Non-heat-treatable Al–Mg–Mn alloys are widely applied as structural materials for modern engineering [1, 2]. One of the promising wrought aluminum alloys is Al–Mg–Mn alloy 1580 developed at the Kamensk-Uralsk Metallurgical Plant [3]. This alloy is doped with several transition metals in order to use it for the production of hot-pressed rolled sections with a high (up to 320 MPa) yield strength.

The purpose of this work is to study the structure and properties of the grade 1580 alloy ingots and rolled sections.

EXPERIMENTAL

The grade 1580 alloy was produced in a gas furnace using two heats. The chemical composition of the metal of both heats (Table 1) was determined by atomic emission spectroscopy using a Spectrolab spectrometer.

Ingots 270 mm in diameter were produced by semi-continuous casting with homogenizing annealing at 360–380°C for 8 h. Transverse templates from the top of the cast were sampled in order to analyze the structure and properties of the ingots. After removal of a

5-mm-thick surface layer by grinding, the ingots were cut into pieces 850 mm in length, which were used for preparing rolled sections with a cross section of 50 × 100 mm. The samples for studying the structure and properties were taken from the exit (E) and pulling-down (P) ends of hot-pressed rolled sections.

The phase transformation temperatures of the grade 1580 alloy were determined by thermal analysis with subsequent numerical differentiation with respect to the heating curve time [4]. To reveal the macrostructure of the ingots and rolled sections, we used an aqueous solution of NaOH (10–15%). The grain structure of anodized polished sections was studied using polarized light on an OLYMPUS GX-71 optical microscope. The microstructure and composition of phase constituents were analyzed with a JSM 5900LV scanning electron microscope equipped with a microanalyzer. The mechanical properties of the ingots and hot-pressed rolled sections were tested by conventional methods.

RESULTS AND DISCUSSION

Cold shuts with a depth of 2–3 mm and a period of 20–25 mm along an ingot are visible on the surface of the as-cast ingots (270 mm in diameter). The structure

Table 1. Chemical composition of grade 1580 alloy*

Heat	Element content, wt %										
	Mg	Mn	Zn	Sc	Zr	Cr	V	Cu	Fe	Si	Be
1	6.3	1.0	0.8	0.25	0.09	0.12	0.014	0.18	0.07	0.07	0.0006
2	6.3	1.1	0.5	0.23	0.10	0.11	0.015	0.10	0.06	0.06	0.0004

* Aluminum for balance. The hydrogen content in the alloy is 0.46 cm³/100 g.

Fig. 1. Structure of an ingot 270 mm in diameter made of the grade 1580 alloy.

Fig. 2. Cross-section macrostructure of a grade 1580 alloy ingot 270 mm in diameter.

of the ingots is homogeneous, fine-grained, and close to a polyhedral pattern (Fig. 1).

The average grain size increases linearly from 30 to 40 μm from the surface region of an ingot to the central part. In the cross section of the ingot, a heterogeneity of macrostructure is revealed in the form of a bright region (Fig. 2). An analysis of the distribution of alloying and impurity elements over the cross section of the ingot showed that 1.3% Mn and 6.2% Mg are contained in the bright region and 1.0% Mn and 6.5% Mg are present in the peripheral dark region. Therefore, the central region contains a higher amount of manganese and a lower amount of magnesium in comparison with the peripheral region. The distribution of the other elements over the ingot cross section is uniform.

Separate coarse particles and clusters of intermetallic compounds $\text{Al}_6(\text{Mn}, \text{Cr}, \text{Ti}, \text{V})$ and $\text{Al}_6(\text{Mn}, \text{Fe}, \text{Cr})$ of a variable chemical composition are observed in the microstructure of the ingots (Fig. 3, Table 2; points 1, 1a, 1b). The particle sizes of these intermetallic compounds are from 35×42 to $90 \times 230 \mu\text{m}$, and some clusters contain up to 16 intermetallic particles. In addition, the microstructure also contains fine spherical particles (Fig. 3, Table 2; points 3, 3a), which consist of intermetallic compound $\text{Al}_5(\text{Sc}, \text{Zr}, \text{Ti})$. These particles exist in the form of clusters along grain boundaries and on the surface of intermetallic compounds $\text{Al}_6(\text{Mn}, \text{Cr}, \text{Ti}, \text{V})$ and $\text{Al}_6(\text{Mn}, \text{Fe}, \text{Cr})$.

Fig. 3. Micrograph of part of the polished section from the central layers of a grade 1580 alloy ingot 270 mm in diameter taken with backscattered electrons: EPMA points are given in Table 2.

Several regions of the polished section contain a complex eutectic (Fig. 3, Table 2, points 5, 5a) in the form of layers along grain boundaries. However, the volume fraction of the eutectic layers is insignificant.

α_{Al} solid solution grains contain 6.12–6.26% Mg, 0.61–0.81% Mn, 0.08–0.13% Cr, 0.19–0.22% Sc, 0.16–0.19% Cu, 0.09% Zr, and 0.04–0.05% Fe.

To determine the phase transformation temperatures, we used thermal analysis of the grade 1580 alloy in a heating mode. The obtained thermogram (Fig. 4) shows that the melting temperature range of the non-equilibrium eutectic (nonequilibrium solidus) is 466–477°C, the equilibrium solidus temperature is 536°C, and the liquidus temperature is 621°C.

To find the temperature range of the maximum plasticity of the grade 1580 alloy ingots, we determined the temperature dependence of the mechanical properties of samples (Fig. 5). The samples were cut in a radial direction. The data obtained evidence that relative elongation δ and relative reduction of area ψ of

Fig. 4. Heating thermogram of a sample cut from a homogenized grade 1580 alloy ingot 270 mm in diameter.

the samples are maximal at 430°C. At this temperature, the alloy is characterized by a yield strength $\sigma_{0.2} = 38\text{--}39$ MPa and ultimate tensile strength $\sigma_u = 43\text{--}44$ MPa.

Taking into consideration that the plastic properties (δ , ψ) of the ingots in the temperature range are maximal, this temperature range was chosen as the upper temperature range for hot pressing of rolled sections. In addition to hot pressing in this temperature range, the rolled sections were also pressed at lower temperatures (Table 3).

The macrostructure of all pressed sections is characterized by heterogeneity, which consists in the fact

Fig. 5. Temperature dependences of (a) relative elongation δ and (b) relative reduction of area ψ of a grade 1580 alloy ingot 270 mm in diameter: (○) heat 1 and (▽) heat 2.

that their central part is bright as compared to the periphery. This peculiarity of the macrostructure of the rolled sections is inherited from the ingot.

Table 2. EPMA results for the composition of the phase constituents of grade 1580 alloy ingots

Point (see Fig. 3)	Element content, wt %											Compound
	Al	Mn	Cr	Mg	Fe	Ti	Sc	Cu	Zr	Si	V	
1	72.98	17.72	6.60	—	0.56	0.72	—	—	—	—	0.37	$\text{Al}_6(\text{Mn}, \text{Cr}, \text{Ti}, \text{V})$
1a	67.32	18.76	2.03	—	4.92	—	—	—	—	—	—	$\text{Al}_6(\text{Mn}, \text{Fe}, \text{Cr})$
1b	65.79	17.31	1.54	—	5.41	—	—	—	—	—	—	$\text{Al}_6(\text{Mn}, \text{Fe}, \text{Cr})$
2	91.62	0.81	0.08	6.12	0.04	—	0.22	0.16	0.09	—	—	α_{Al} -solid solution
2a	91.68	0.61	0.13	6.26	0.05	—	0.19	0.19	0.09	—	—	"
3	58.15	—	—	—	—	1.83	16.37	—	21.51	—	—	$\text{Al}_5(\text{Sc}, \text{Zr}, \text{Ti})$
3a	59.36	—	—	—	—	1.46	19.43	—	18.06	—	—	$\text{Al}_5(\text{Sc}, \text{Zr}, \text{Ti})$
4	25.64	—	—	43.69	—	—	—	—	—	27.83	—	Mg_2Si
5	49.06	—	—	26.43	—	—	—	10.71	—	13.12 Zn	—	Eutectic of complex composition
5a	49.24	—	—	26.52	—	—	—	11.16	—	12.67 Zn	—	The same

Table 3. Mechanical properties of 50 × 100 mm rolled sections of the grade 1580 alloy as a function of pressing temperature t_{pr}

$t_{\text{pr}},\text{ }^{\circ}\text{C}$	Rolled section	Sample*	Mechanical property		
			σ_{u}	$\sigma_{0.2}$	$\delta, \%$
			MPa		
300—350	1	1E	433	282	15.0
		1P	435	296	15.0
350—400	2	2E	445	304	15.5
		2P	452	307	14.0
	3	3E	426	280	16.0
		3P	439	290	14.5
400—450	4	4E	436	288	13.5
		4P	444	307	14.5
	5	5E	439	304	12.5
		5P	434	288	15.0

Note: The container temperature is 400–420°C, and the pressing rate is 0.4 m/min.

* E is the exit end of rolled section, and P is the pulling-down end of the rolled section.

The microstructure of hot-pressed 50 × 100 mm rolled sections contains fragmented intermetallic compounds located as lines along the pressing direction (Fig. 6). Electron-probe microanalysis (EPMA) of these coarse particles showed that they consist of the $\text{Al}_6(\text{Mn}, \text{Cr}, \text{Ti}, \text{V})$ and $\text{Al}_6(\text{Mn}, \text{Fe}, \text{Cr})$ intermetallic compounds, which are identical to those in the ingots. In addition, the microstructure of the samples contains lines of fine particles of intermetallic compound $\text{Al}_5(\text{Sc}, \text{Zr}, \text{Ti})$.

The results of testing the mechanical properties of the exit and pulling-down ends of the rolled sections at room temperature are summarized in Table 3. An analysis of the tabulated data shows that the level of mechanical properties of the alloy 1580 rolled section is actually independent of the temperature of their

pressing, all other things being equal. However, commercial tests revealed that cracks formed in the corner zones during hot pressing of the rolled sections in the temperature range 350–400°C because of the insufficient technological plasticity of the alloy. Cracks formed most frequently in pressing of the rolled sections in the temperature range 300–350°C.

Therefore, the plastic properties of the ingots in the temperature range of their pressing and the mechanical properties of the rolled sections can be improved by means of preventing the formation or a significant reduction of the volume fraction of intermetallic compounds $\text{Al}_6(\text{Mn}, \text{Cr}, \text{Ti}, \text{V})$, $\text{Al}_6(\text{Mn}, \text{Fe}, \text{Cr})$, and $\text{Al}_5(\text{Sc}, \text{Zr}, \text{Ti})$ in their structure. This can be achieved by correcting the chemical composition of the alloy in the content of transition metals and by increasing the cooling rate of an ingot in the temperature range of alloy solidification.

CONCLUSIONS

(1) Homogenized ingots of the grade 1580 alloy 270 mm in diameter have a fine-grained macrostructure. The central zone of the ingots contains macroheterogeneity, which is caused by a high manganese concentration and a low magnesium content in comparison with the peripheral zone. It was found that the microstructure of the ingots contains coarse particles of intermetallic compounds $\text{Al}_6(\text{Mn}, \text{Cr}, \text{Ti}, \text{V})$ and $\text{Al}_6(\text{Mn}, \text{Fe}, \text{Cr})$ and fine globular particles of compound $\text{Al}_5(\text{Sc}, \text{Zr}, \text{Ti})$. The plasticity properties of the ingots at testing temperatures of 400–430°C are insufficient for hot pressing of rolled sections without cracking in them.

Fig. 6. Microstructure of hot-pressed 50 × 100-mm rolled sections in the longitudinal direction.

(2) The macrostructure of hot-pressed rolled sections is characterized by the macroheterogeneity inherited from the ingots. The microstructure of the rolled sections contains fragments of intermetallic compounds, which formed during pressing. They are located in the form of lines oriented along the pressing direction. As a consequence, the yield strengths of the rolled sections are below the expected level.

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