Physical Modeling of Semi-continuous Casting for Developing an Industrial Technology of Producing Ingots From New Deformable Aluminum Alloys

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Abstract

A physical model of a semi-continuous casting unit (SCCU) has been manufactured and tested, designed to develop a technology for casting flat and cylindrical ingots from experimental aluminum alloys for subsequent metal forming. The SCCU includes two induction melting furnaces with a tilting mechanism, a rotary mixer, a metal path system, a vertical casting machine, a jib crane, water supply, power supply, monitoring and control systems. SCCU testing was carried out on six heats of alloy 1580 of the Al-Mg system with the addition of scandium. In the first three ingots the scandium content was 0.05% (wt.). In the second series of three heats ingots with 0.075% (wt.) scandium were cast. The ingots had a high surface quality, did not have casting defects, and there were no inclusions of primary intermetallic compounds $\text{Al}_3(\text{Sc}, \text{Zr})$ in the structure of the ingots. The bottom and runner parts of the ingots were cut off, all faces were milled and subjected to homogenization annealing in a two-stage mode: the first heating at 350 °C, 3 h, the second heating for 1 h to 425 °C, 4 h. Then the billets were hot rolled from 40 to 5 mm, annealed at 380 °C, 1 h, rolled at room temperature to a thickness of 1 mm and annealed at 350 °C, 3 h. After that, tensile mechanical properties were tested. The results of modeling ingot casting were tested in industrial conditions when casting a large ingot with a cross section of 2100×500 mm. A template was cut from the ingot with the dimensions of a billet for rolling, as that obtained from an experimental ingot cast at the SCCU. The billet was subjected to hot and cold rolling according to the conditions used for rolling the experimental ingot. At the same time the modes of heat treatment of sheet semi-finished products were also repeated. The mechanical properties of sheets of alloy 1580 rolled from experimental and industrial ingots practically did not differ. This proves the reliability of casting modes for ingots obtained at the SCCU and tested for casting industrial ingots.

1 Introduction

Alloys of the Al-Mg system have significant advantages, such as satisfactory strength, high corrosion resistance, and good weldability [1–9]. Despite the fact that these alloys are not subject to hardening due to heat treatment [10–17], they are widely used in various industries, such as rocketry, aviation, shipbuilding and automotive [18–25]. The most promising alloys for use in these high-tech industries are Al-Mg alloys with additions of scandium (1515, 1523, 1545, 1545K, 1570, 1570C), to which many works are devoted [4–6, 22, 25–30]. Despite the huge potential of the Al-Mg-Sc system alloys developed in industry, scandium remains very expensive and rather difficult to obtain metal [31–33]. Therefore, research by various scientists around the world is aimed at studying the possibility of reducing the amount of scandium in aluminum alloys [34, 35].

The main method for producing large-sized ingots from aluminum alloys for the subsequent production of semi-finished products by metal forming is semi-continuous casting [27]. At the stage of mastering the technology for producing ingots from new alloys, knowledge of the optimal casting modes is required. The most accurate casting parameters can be given by experiments using industrial equipment designed for the production of these products. However, studies carried out in the conditions of existing production have the following disadvantages:

- - the need to withdraw industrial equipment and maintenance personnel from the current production process for the duration of the experiments;
- - high energy and material costs;

- - the impossibility or high cost of varying the investigated process parameters in wide ranges;
- - the likelihood of an accident and failure of production equipment, etc.

The most promising way out of this situation is modeling, which allows experiments to be carried out under laboratory conditions. This approach makes it possible to find acceptable boundaries for changing technological parameters, or to establish a range of parameters that would lead to the achievement of the best ratio of research costs and profit obtained from the introduction of new technology.

It is believed that of all types of modeling for the development of modes of semi-continuous casting of ingots from aluminum alloys, physical modeling is the most relevant. Therefore, the purpose of this work was to develop and test a physical model of a semi-continuous casting unit (SCCU) for aluminum alloys. To achieve this goal, the following tasks were solved in the work:

- - creation of a physical model of the SCCU;
- - conducting experimental testing of the casting modes of a new aluminum alloy at the SCCU;
- - study of the structure and properties of semi-finished products obtained at the SCCU;
- - study of manufacturability during metal forming of ingots manufactured at the SCCU;
- - testing the obtained experimental modes of modeling in industrial conditions.

2 Method Of Carrying Out Research

The physical model of the unit for semi-continuous casting of aluminum alloys was designed and manufactured with the support of the Ministry of Higher Education and Science of the Russian Federation, RUSAL Bratsk and the Russian Foundation for Basic Research (RFBR) at the Siberian Federal University (SFU) in 2020 [27]. The purpose of the SCCU is the development and testing of technologies for casting flat or cylindrical ingots from standard or new aluminum alloys intended for subsequent metal forming. The general view of the SCCU is shown in Fig. 1.

The SCCU includes two induction melting furnaces with a hydraulic tilt mechanism, an electrically heated rotary mixer, a metal track system, a vertical casting machine, a cantilever crane, water supply, power supply, monitoring and control systems. The main equipment and tooling of the SCCU are mounted on a frame, which is a steel frame structure.

The work of the SCCU is organized as follows (Fig. 2). In induction crucible furnaces 1, the charge is melted to prepare an alloy of a given chemical composition. Then the melt is poured through the metal track 2 into a rotary electrically heated mixer 3, in which it is subjected to settling, modification and refining with argon. After that, due to the tilt of the mixer, the melt with a predetermined temperature is fed through the metal path to the filtration section, which is a chamber 4 with a ceramic foam filter. Further, the molten metal enters the vertical casting machine 5, which, with the given casting parameters, forms an ingot in the mold 6. The section of the ingot can be round in diameter up to 190 mm or rectangular in size 60×200 mm. The complex also includes a cantilever crane designed to service the main equipment.

1 – induction crucible furnaces; 2 – metal track with heated lid; 3 – rotary electrically heated mixer; 4 – filtration section; 5 – vertical casting machine; 6 – mold

The main technical characteristics of the SCCU are given in Table 1.

Table 1
– Main technical characteristics of SCCU units

Unit of SCCU name	Main characteristics
Low frequency induction furnace IAT-0.16 (2 pcs)	- maximum temperature 1050°C; - capacity of one furnace no more than 55 kg (for aluminum); - weight of one furnace no more than 1000 kg; - power per one furnace 80 kW; - argon degassing mechanism.
Transport chute system – metal track	- casting troughs with the possibility of heating before casting.
Rotary electrically heated mixer	- maximum temperature 850°C; - capacity not more than 160 kg (for aluminum); - weight no more than 700 kg; - power up to 30 kW; - argon degassing mechanism.
Filtration section	- the ability to filter the melt; - complete heating system for filtration plant.
Vertical casting machine	- casting speed from 1 to 250 mm/min; - ingot length up to 1100 mm; - ingot weight no more than 100 kg; - drive power 2 kW;
Molds	- section of the obtained ingots: 60×200, 80×180, Ø190 mm; - coolant volume from 0.1 to 15 m³; - type of lubricant: oil, lubricants, etc.

The SCCU is controlled from the local operator panel, on which the main parameters of the casting, entering the database, are set and controlled. The database provides for their issuance in a format convenient for loading into computer programs, which will allow simulating various casting modes.

To test the operation of the SCCU a new Russian alloy 1580 of the Al-Mg system was used with the addition of scandium, which was studied in [27, 28, 36–50]. The mechanical properties of the obtained deformed semi-finished products were studied in [27, 39–48]. Also, computer simulation was carried out to study the modes of rolling of a new alloy [36–39]. The modes of sheet annealing were investigated [45, 48–50], as well as the

properties of welded joints from alloy 1580 [48, 49]. Corrosion properties were studied in [48, 50]. In this alloy the scandium content should be 0.05–0.14% (wt.). To reduce the content of expensive scandium in the alloy, its concentration should be taken closer to the lower limit of the allowable range in the alloy grade. During testing six heats were carried out. In the first three heats, the task was to obtain ingots with scandium content close to the lower limit of the specified interval – 0.05% (wt.). In the second series of three heats it was necessary to obtain alloys with a scandium content of 0.075% (wt.). This corresponds to the middle of the interval of this element in the alloy grade. Alloys were prepared in an IAT-0.16 induction furnace in an amount of 50 ± 0.1 kg using A85 grade aluminum. The analysis of alloys for compliance with the planned chemical composition was carried out on an optical emission spectrometer "Foundry master lab". Upon reaching the required chemical composition, the resulting alloys were poured from the furnace into a rotary mixer, held, and then the Al-5Ti-1B master alloy was added.

Alloy 1580 is mainly used for the production of sheets of different thicknesses [27, 37–39, 42, 43, 45–48]; therefore, the alloy was poured from a rotary mixer into the mold of a casting machine with a rectangular cross section of 60×200 mm in order to use an ingot for sheet rolling. The tilt speed of the mixer was synchronized with the casting speed of the ingot and the level of metal in the mold. All ingots were cast at the same temperature and speed parameters. The temperature of the alloys was: in an induction furnace $800 \pm 8^\circ\text{C}$; in the mixer $750 \pm 5^\circ\text{C}$, on the mold of the casting machine $700\text{--}705^\circ\text{C}$. The chemical composition of the alloys is given in Table 2.

Table 2
– Chemical composition of alloys for testing SCCU

Alloy number	Mass fraction of elements, %					
	Sc	Fe	Mn	Mg	The sum of other	Al
1	0.055	0.19	0.52	4.98	0.30	basis
2	0.054	0.17	0.52	5.01	0.35	basis
3	0.053	0.17	0.62	5.21	0.32	basis
4	0.077	0.20	0.61	5.16	0.30	basis
5	0.075	0.22	0.51	5.42	0.32	basis
6	0.075	0.18	0.61	5.22	0.30	basis

Preparation of ingots for rolling included cutting the bottom and gating parts (at least 100 mm), milling all edges to a depth of 2–3 mm, and homogenizing annealing. The annealing regime was carried out according to a two-stage regime: the first heating at 350°C and holding for 3 h, the second heating for 1 h to 425°C and holding for 4 h [47]. The view of the ingot prepared for rolling is shown in Fig. 3.

Hot rolling was carried out in the laboratory of the Department of Metal Forming of the Siberian federal university on a two-roll mill with a roll diameter of 330 mm and a barrel length of 520 mm. To carry out hot rolling ingots with dimensions of 40×120×170 mm were heated to 450°C and rolled in the casting direction to a thickness of 5 mm with single reductions of 5–10%. The total rolling reduction was 88%. Then the sheets were annealed at 380°C for 1 h. After that, the hot-rolled sheets were rolled at room temperature on a two-roll mill with

a roll diameter of 200 mm and a barrel length of 400 mm, brand LS 400 AUTO manufactured by Mario Di Maio (Italy) to a thickness of 1 mm with single reductions of 2–5%. The total reduction rate was 80%. Cold-rolled sheets were annealed at 350 °C for 3 h, and samples were cut from them for research.

The microstructure of the alloys was analyzed using an Observer A1m light microscope, Carl Zeiss. The processes of recrystallization of alloys were studied in the polarized light mode after deposition of an oxide film on the samples.

The mechanical properties of hot and cold rolled sheets were determined by tensile tests at room temperature on a Walter + BaiAG LFM 400 kN universal testing machine in accordance with State Standard 1497-84.

3 Results And Discussion

At external examination the ingots of alloy 1580 obtained at the SCCU were characterized by a high surface quality. Foundry equipment and general view of the ingot are shown in Fig. 4.

After cutting the bottom and gating parts of the ingots, as well as after milling all surfaces of the ingots, no casting defects in the form of cavities and inclusions were found, which indicates the correct selection of technology.

The microstructure of cast ingots, which was carried out before and after homogenization annealing is shown in Fig. 5.

On the microstructure of alloy No.1 with a Sc content of 0.055% (wt.) in the cast state, there is grains of an α -solid solution with chemical inhomogeneity over the cross section of dendritic cells (Fig. 5a). Along the boundaries of the cells, inclusions of the nonequilibrium phase $\beta(\text{Al}_8\text{Mg}_5)$, the Mg_2Si phase, and a large number of phases containing iron $\text{Al}_6(\text{Fe}, \text{Mn})$ and $\text{Al}_{15}(\text{Fe}, \text{Mn})_3\text{Si}_2$ were also found. In this case, the structure of the ingots did not contain inclusions of primary intermetallic compounds $\text{Al}_3(\text{Sc}, \text{Zr})$ [47]. Consequently, scandium and zirconium in the alloy were only in a supersaturated solid solution and the cooling mode during casting was chosen correctly.

In the two-stage annealing of ingots, according to [21], two processes occur: homogenization and heterogenization of the structure. For this alloy, upon homogenization, the dissolution of the nonequilibrium phase $\beta(\text{Al}_8\text{Mg}_5)$, partly of the Mg_2Si phase, and elimination of chemical inhomogeneity over the cross section of the dendritic cell and grain occurred. Heterogenization of the alloy led to the decomposition of the aluminum solid solution supersaturated with respect to Sc, Zr, Mn with the release of dispersed particles $\text{Al}_3(\text{Sc}, \text{Zr})$ and Al_6Mn and proceeded in two stages. At the first stage, at 350 °C, a homogeneous decomposition of a solid solution of scandium and zirconium occurred with the formation of particles of a stable coherent $\text{Al}_3(\text{Sc}, \text{Zr})$ phase several nanometers in size and with a high distribution density. At the second stage of annealing at a temperature of 425 °C, the decomposition was completed with a small coarsening of dispersed particles of the hardening phase $\text{Al}_3(\text{Sc}, \text{Zr})$. Also at this stage, the manganese solid solution decomposed with the formation of secondary precipitates.

The microstructure of alloy No.1 in the annealed state (Fig. 5b) practically did not differ from the cast structure, and insignificant differences in the microstructure can be explained by dissolution during annealing of the nonequilibrium $\beta(\text{Al}_8\text{Mg}_5)$ phase and partial dissolution of the Mg_2Si phase.

Analysis of the microstructure of alloys in polarized light showed (Fig. 5c, d) that the grain size of the alloys in the annealed state practically does not change in comparison with the cast state. Studies of the microstructure of the ingot of alloy No.5, containing 0.75% (wt.) Sc, did not reveal any noticeable differences from the microstructure of the ingot of alloy No.1.

The average values of the results of testing the mechanical properties of tensile samples cut from hot-rolled and annealed sheets are given in Table 3. Analysis of these data showed that alloys Nos. 1-3 with a scandium concentration of 0.055% (wt.) Are similar in their properties. Alloys Nos. 4-6 containing 0.075 have a higher level of strength properties, especially in terms of yield strength R_p , which can be explained by a higher content of scandium. At the same time, the ductility of all six alloys is at the same level.

Table 3 – Mechanical tensile properties of hot-rolled sheet semi-finished products 5 mm thick after annealing at 380 °C for 1 h

Alloy number	Sc, % (wt.)	Mechanical properties					
		Longitudinal direction			Cross direction		
		R_m , MPa	R_p , MPa	A , %	R_m , MPa	R_p , MPa	A , %
1	0.055	343	214	17	344	216	20
2	0.054	338	213	19	338	212	18
3	0.053	345	216	20	350	219	19
4	0.077	366	244	16	368	244	18
5	0.075	364	249	17	364	237	18
6	0.075	365	241	18	367	243	17

The average values of the results of testing the mechanical properties of tensile samples cut from cold-rolled and annealed sheets are given in Table 4.

Table 4 – Tensile properties of cold-rolled sheet semi-finished products 1 mm thick after annealing at 350 °C for 3 h

Alloy number	Sc, % (wt.)	Mechanical properties					
		Longitudinal direction			Cross direction		
		R_m , MPa	R_p , MPa	A , %	R_m , MPa	R_p , MPa	A , %
1	0.055	356	219	15	365	232	16
2	0.054	362	234	14	363	242	18
3	0.053	359	224	15	368	230	20
4	0.077	406	295	12	408	302	13
5	0.075	393	287	14	384	286	11
6	0.075	403	305	12	401	301	11

The analysis of these data showed that in alloys Nos. 4-6 the level of strength properties exceeds the level of alloys Nos. 1-3 by approximately 10-12%. But at the same time the plasticity of alloys Nos. 1-3 in the transverse direction significantly exceeds the plasticity of alloys Nos. 4-6.

The results of modeling the casting of ingots from alloy 1580 were tested in the industrial conditions of a Russian metallurgical enterprise when casting a large ingot with a cross section of 2100×500 mm. The aim was to obtain an ingot in which the scandium content, as in the experimental ingots, should be in the range from 0.05 to 0.075% (wt.). A general view of the industrial casting tooling and the large-sized ingot obtained on it is shown in Fig. 6.

The chemical composition of a large ingot made of alloy 1580 is presented in Table 5.

Table 5 – The chemical composition of a large-sized industrial ingot made of alloy 1580

Mass fraction of elements, %					
Sc	Fe	Mn	Mg	The sum of other	Al
0.067	0.25	0.51	5.10	0.30	basis

From Table 6 it follows that the casting modes obtained during physical modeling at the SCCU, which were recommended for industrial testing, ensured the production of a large-sized ingot with a given scandium content. Upon external examination of the ingot and after its milling to a depth of 5-10 mm, defects of casting origin were not detected, and in the study of the microstructure, the precipitation of primary intermetallic compounds $Al_3(Sc, Zr)$ was not detected. From the ingot subjected to homogenization annealing under industrial conditions, a template was cut with a thickness of 40 mm and dimensions in plain view of 120×170 mm, which repeated the dimensions of a billet for rolling, obtained from an ingot cast at the SCCU. The ingot was subjected to hot and cold rolling on the equipment of the laboratory of the Department of Metal Forming of the Siberian federal university according to the modes used for rolling experimental ingots. At the same time, the modes of heat treatment of sheet semi-finished products were also repeated. The mechanical properties of 1580 alloy sheets rolled from an industrial ingot are presented in Table 6.

Table 6 – Mechanical tensile properties of semi-finished sheet products obtained by rolling a template cut from a large-sized ingot 1580, casted under industrial conditions

Billet characteristics	Mechanical properties					
	Longitudinal direction			Cross direction		
	R_m , MPa	R_p , MPa	A , %	R_m , MPa	R_p , MPa	A , %
Hot-rolled 5 mm thick, after annealing at 380 °C, 1 h	358	236	17	355	236	16
Cold-rolled 1 mm thick, after annealing at 350 °C, 3 h	400	285	12	398	295	13

Comparison of the data given in Table 3, 4 and 6, allows concluding that the tensile properties of experimental and industrial ingots are approximately between the level of properties of alloys Nos. 1-3 and alloys Nos. 4-6, which corresponds to the average content of scandium in the industrial ingot between these groups of experimental alloys.

Summary

The studies carried out allowed concluding the following. The use of physical modeling of the process of semi-continuous casting of aluminum alloys on the SCCU experimental installation makes it possible to develop casting modes for new alloys. Industrial testing of the casting modes of ingots from the new alloy 1580, obtained at the SCCU, showed that the structure, as well as the mechanical properties of sheet semi-finished products from experimental and industrial large-sized ingots, practically did not differ. This proves the reliability of the modes of casting ingots obtained at the SCCU and the validity of their application to the industrial conditions of semi-continuous casting of ingots from aluminum alloys.

Declarations

Ethical Approval

The work contains no libelous or unlawful statements, does not infringe on the rights of others, or contain material or instructions that might cause harm or injury.

Consent to Participate

The authors consent to participate.

Consent to Publish

The authors consent to publish.

Authors Contributions

The authors declare that they are all participants in the work and none of them performed only administrative functions.

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Competing Interests

The authors declare about the absence of competing interests.

Availability of data and materials

Not applicable.

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Figures

Figure 1

General view of the SCCU

Figure 2

The main units of the SCCU: 1 – induction crucible furnaces; 2 – metal track with heated lid; 3 – rotary electrically heated mixer; 4 – filtration section; 5 – vertical casting machine; 6 – mold

Figure 3

Ingot for rolling from alloy 1580

a

b

Figure 4

Casting equipment of the Hot-top type for physical modeling (a) and an ingot made of alloy 1580 (b) obtained by casting at the SCCU (the cross section of the ingot)

a

b

c

d

Figure 5

Microstructure of alloy 1580 with a scandium content of 0.055% (wt.) in the cast (a, c) and annealed (b, d) state: a, b – brightfield image; c, d – polarized light image

a

b

Figure 6

Industrial casting equipment WaggStaff (a), large-sized flat ingot (slab) from alloy 1580 with cut-off bottom and runner parts (b)