Investigation of rolling modes, structure, and properties of aluminum-magnesium alloy plates with a reduced scandium content

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Abstract

Investigations of the rolling modes of plates from an experimental aluminum-magnesium alloy with a scandium content of 0.10–0.11 wt.%, corresponding to the chemical composition of the 1580 alloy, were carried out in laboratory and industrial conditions. It has been found that alloying of this material with scandium within the indicated limits leads to a significant grain refinement in the cast ingot and an increase in the strength properties of deformed semi-finished products. Based on the results of physical modeling of the rolling process, rational reduction modes are proposed, which made it possible to obtain deformed semi-finished products with the required level of mechanical properties. Based on the results of physical and computer modeling of the rolling process, rational reduction modes are proposed for pilot studies, which made it possible to obtain deformed semi-finished products with the required level of mechanical properties. At the same time, the power parameters of rolling did not exceed the allowable values of the force and rolling moment for the QUARTO 2800 rolling mill. To assess the formation patterns of the metal structure necessary to obtain high-quality plates, a metallographic analysis of the structure of cast and deformed semi-finished products from an experimental alloy was carried out. The results were used to test the reduction modes during sheet rolling and to adjust the casting parameters of experimental ingots. Annealing has practically no effect on the level of mechanical properties of plates obtained under production conditions in a hot-deformed state, while the ultimate tensile strength in the longitudinal direction is 388–389 MPa, the yield strength is 245–247 MPa, and the elongation to failure is 18.0–18.8%. After cold rolling, the plates have the following mechanical properties: ultimate tensile strength 413–414 MPa, yield strength 386–372 MPa, and elongation to failure 5.2–6.6%. Based on the results of the research, recommendations were formulated for the development and implementation of an industrial technology for rolling plates from alloy 1580 with a thickness of 31.5–45 mm from ingots with a thickness of 300–450 mm.

Keywords Aluminum alloys · Scandium · Casting · Rolling · Structure · Mechanical properties

1 Introduction

In many industries, especially in transport engineering (shipbuilding, rail transport, automotive industry, etc.), aircraft, and space engineering [1–7], rolled sheets from aluminum alloys of the Al–Mg system are widely used for the manufacture of technical products. To obtain it, traditional technologies and equipment for hot and cold rolling are used [3, 6]. The disadvantages of this technology is the presence of a large number of passes during rolling, associated with the need to use small single reductions, especially when processing alloys characterized by low ductility.
An innovative method for solving this problem is to increase the level of mechanical characteristics of alloys of the Al–Mg system by alloying them with rare earth metals such as scandium and zirconium which ultimately requires the selection of a rational processing mode. To improve the strength characteristics of these alloys, alloying with rare earth metals, such as scandium and zirconium, has recently been used. It has been found that additions of scandium lead to the formation of a subgrain structure in alloys and the occurrence of precipitation hardening due to the high degree of dispersion and distribution density of thermally stable Al₃Sc particles in the solid solution matrix [8–11]. In addition, scandium also effectively prevents recrystallization, which makes it possible to increase the degree of deformation during the deformation-heat treatment of these alloys.

Therefore, such alloys are characterized by high workability during pressure treatment and an increased level of strength properties, as well as high corrosion resistance and weldability. Depending on the type of design of technical products, these alloys are subject to additional requirements for a set of properties [4, 5]. In non-heating structures, alloys with high static strength characteristics (shear resistance, yield strength, ultimate tensile strength), satisfactory ductility, and low density should be used. For a number of parts and assemblies, the increased rigidity of the material is important, i.e., high modulus of elasticity and shear modulus.

One of these alloys is alloy 1580, the chemical composition of which meets the requirements of the State Standard 4784–2019 (Russian Federation). This alloy contains a minimum amount of scandium compared to similar alloys. This leads to a significant reduction in the cost of cast and deformed semi-finished products made from it. In addition, for the same reason, it is expedient to use this alloy for producing large mass slabs with a thickness of up to 600–800 mm and for manufacturing massive flat products in the form of plates with a thickness of 31.5–60 mm. At present, ingots with a thickness of not more than 300 mm are mainly used at domestic plants for the manufacture of flat-rolled products from aluminum alloys. Therefore, it is economically beneficial to maximize the thickness of ingots, taking into account the possibility of casting and rolling equipment of a particular enterprise.

Assessing the effect of scandium on the structure and properties of aluminum alloys, the following advantages should be noted:

- Significant grain refinement in the cast ingot and the formation of a non-dendritic structure, a small addition of scandium to aluminum alloys makes it possible to grind the grain of ingots to 25–50 microns.
- Reduction or complete suppression of surface recrystallization during deformation of alloys.
- Increase in the strength of semi-finished products by 20–25%.
- Reduction (complete suppression) of crack formation in welds.
- Increase in the strength of the welded joint and increase in fatigue life by 200%.

Thus, despite the fact that numerous works [12–18, 20–25, 38–42, 44–50] are devoted to the study of the properties and structure of semi-finished products from alloys of the Al–Mg system with different contents of scandium, the search for rational compositions of such alloys and technologies for their processing is an urgent scientific problem. Depending on the purpose of the alloy, various additives (Zr, Li, Cu, Mn, Zn) are used in alloys of the Al–Mg-Sc system. In work presented addition Ca in alloys Al–Mg–Sc. It has been shown that only binary phases Al₃Ca, Al₃Sc, and Al₃Mg₂ can be in equilibrium with the aluminum solid solution [23]. The effect of adding scandium on the structure of alloys is described in [12, 14, 16–23, 35, 44, 49, 50]. Various heat treatment regimes are considered in [13, 27, 30, 36, 38]. The heat treatment of the investigated alloys is carried out mainly at temperatures of 300–560 °C with different holding time (up to 32 h). Hot rolling of cast billets activates the process of precipitation of particles of the Al₃(Sc, Zr) phase on dislocations, the distribution density of which increases significantly. This also leads to a decrease in the size of Al₃(Sc, Zr) particles to 5 nm and an increase in their volume fraction to 1%. The mechanical properties of deformed semi-finished products from alloys of the Al–Mg system, sparingly alloyed with scandium, significantly exceed the properties of alloys without scandium, having the same magnesium content [14, 15, 19, 24, 25, 27–29, 31, 34, 35, 37, 50]. The properties are practically on the same level as industrial alloys (ultimate tensile strength \(R_u = 390–550\) MPa, yield strength \(R_p = 260–386\) MPa, elongation to failure \(\Delta = 6–20%\), but could be 740% in the conditions of superplasticity [15]), in which the content of scandium is 2–3 times higher [39–43]. Modeling of the casting [51, 52] and rolling process of 1580 alloy was studied in [7, 26, 32–34, 36]. These alloys are widely used mainly for the production of plates and sheets by hot and cold rolling.

Also, the rolling of plates in modern production conditions requires the provision of high accuracy of the existing theoretical model when predicting the rolling force. A thorough analysis of the law of change in the metal flow in the deformation zone is required. These tasks have been successfully solved by developing high-precision models in the works of Zhang S.H. and authors [53, 54].

Therefore, the aim of the work was to study the modes of obtaining plates from large-sized semi-continuously cast flat ingots of alloy 1580 (Fig. 1a) to form a metal structure that provides the required level of properties.
The objectives of the research were the following:

- Development of modes of hot and cold rolling of plates with a thickness of 31.5–45 mm from large-sized ingots of alloy 1580 with a thickness of up to 300 mm
- Analysis of the possibility of rolling slabs with one heating under different modes of single reductions in the course of physical modeling of the process in laboratory conditions at the DUO 330 mill
- Carrying out experimental studies to obtain pilot batches of plates from alloy 1580 in industrial conditions at the QUARTO 2800 mill
- Study of the structure and determination of the mechanical properties of the obtained semi-finished products in the deformed and annealed states

## 2 Materials and method

Metallographic studies of semi-finished products were carried out using a Carl Zeiss Stemi 2000C light microscope (macroanalysis) and an EVO 50 scanning electron microscope (microanalysis). To observe the structure of semi-finished products in polarized light, samples were etched and oxidized. Determination of the mechanical properties of the metal was carried out on a universal machine Walter + Bai AG LFM 400 kN in accordance with State Standard 1497–84 (Russian Federation), using the method of uniaxial tension of three samples, which were used to calculate the average values of ultimate tensile strength, yield strength, and elongation to failure.

The chemical composition of the experimental alloy is presented in Table 1.

Before carrying out experimental studies, it was necessary to determine the reduction modes and evaluate the shape change of the metal and the temperature parameters of the roll. To this end, the process of rolling plates from alloy 1580 was simulated on a QUARTO 2800 mill using the DEFORM-3D software package [7, 32, 36], the results of which are partially presented in Table 2.

The allowable rolling force was 30 MN, and the allowable rolling moment was 2.8 MN·m.

At the first stage of experimental studies in laboratory conditions, rolling (Fig. 2a) of billets with milled edges 50×130×330 mm in size (Fig. 1b) from an experimental 1580 alloy was simulated (Table 3). The given parameters of the rolling process were the following: the initial thickness of the billet $H_0 = 50$ mm, and the final thickness of the plate $H_0 = 30–35$ mm. Billet temperature $T = 430 \pm 10$ °C. The total deformation during rolling is up to 40%. As equipment

| Table 1 | The chemical composition of the experimental alloy 1580 (State Standard 4784–2019) |
|---------|----------------------------------------------------------------------------------|
| Si      | Fe       | Cu  | Mg   | Mn    | Cr    | Zn    | Ti    | Zr    | Sc    | Other elements | Al    |
| 0.12    | 0.15    | 0.1 | 4.96 | 0.56  | 0.13  | 0.20  | 0.12  | 0.1   | **0.10–0.11** | 0.15  | Basis          |
for rolling, a two-roll laboratory mill DUO 330 was used. The technical characteristics of DUO 330 mill are given in Table 3. In the course of rolling, samples were taken to test the mechanical properties and study the structure of the metal.

Brinell hardness tests were carried out on an Emcotest universal hardness tester. Hardness test conditions are as follows: indenter was hard alloy ball with a diameter of 2.5 mm; load was 62.5 kgf; and the number of measurements is 3.

3 Results and discussion

An assessment was made of the possibility of rolling plates from one heating under various modes of single reductions, a study of the structure and determination of the mechanical properties of the resulting deformed semi-finished products.

Two workpieces were rolled (Fig. 3) with a change in the reduction value, selecting rational processing modes.

The first workpiece heated to a temperature of $430 \pm 10 ^\circ C$ was rolled to a thickness of 30 mm with a minimum single reduction of 2%, after which cracks began to appear on the side faces (Fig. 4). The total degree of deformation was 40%, and the number of passes was 21. The temperature of the metal after the last pass was $350 ^\circ C$. An analysis of the rolled workpiece showed that the metal flow for a given reduction scheme is uneven, while the peripheral layers are ahead of the central ones (Fig. 3a). This caused the appearance of significant tensile stresses and, as a result, with a decrease in the temperature of the metal by the end of rolling, the appearance of cracks on both side faces of the workpiece. It should also be noted that for given single reductions, the energy-power parameters of rolling did not exceed the allowable ones for DUO 330 rolling mill (Table 3).

The second workpiece was rolled in a similar temperature regime but with maximum reductions during rolling (Table 4) after which the billet opened at its end. The total deformation was 37%. The temperature of the metal after the last pass was $370 ^\circ C$. It can be noted that a more uniform metal flow and the absence of cracks were observed during rolling (Fig. 3b), which indicates the development of both peripheral and central layers of the workpiece. Exceeding the permissible values of the energy-power parameters in this mode of compression was also not observed.

The mechanical properties of the obtained semi-finished products are given in Table 4.

For metallographic studies, samples were cut from the fracture surface of the workpieces for fractographic studies. The analysis showed that the fracture surface of the workpieces has a matte, non-oxidized surface without visible defects of foundry origin (large pores and non-metallic

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Table 3 Technical characteristics of the sheet rolling mill DUO 330

| Parameter                           | Value |
|-------------------------------------|-------|
| Electric motor power, kW            | 90    |
| Roll barrel length, mm              | 520   |
| Roll diameter, mm                   | 330   |
| Maximum roll separation, mm         | 70    |
| Roll rotation frequency, rpm         | 10    |
| Maximum rolling force, MN           | 1.55  |
| Maximum rolling moment, MN-m        | 0.82  |

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inclusions). A significant amount of light inclusions is observed along the fracture cross section of the workpieces.

X-ray microanalysis (XRSA) of the second workpiece revealed the presence of intermetallic inclusions, as well as cracks along the grain boundaries (Fig. 5). Intermetallics are observed in lamellar form containing Al, Zr, Sc, and Ti (Fig. 5, spectrum 1, 2) and in the form of polyhedra containing Al, Fe, Mn, and Cr (Fig. 5, spectrum 3). Intermetallic...
compounds have sizes of 10–60 microns, and single inclusions reach 150 microns.

The study of workpiece fracture on a scanning electron microscope showed that the fracture surface is mainly characterized by ductile fracture elements in the form of ridges and pits of various sizes and shapes (Fig. 6). The fracture also contains elements of brittle intergranular fracture in the form of flat facets.

Additional studies of the microstructure of the sample prepared from the transverse section of the destroyed workpiece showed that the propagation of cracks occurred along the accumulations of intermetallic inclusions located mainly along the grain boundaries (Fig. 7). The intermetallic compounds present in the structure of the workpieces are predominantly of crystallization origin.

The results of the experimental studies for test ingots made it possible to draw the following conclusions:

- It is necessary to improve the technology of casting large-sized ingots, since the presence of heterogeneity of the grain structure and intermetallic compounds does not allow for the same reduction of its entire surface, while cracks in the metal during rolling begin to form in the area where large intermetallic compounds are located.
- With reductions in the passages of about 9–11% and billet heating temperatures of $430 \pm 10 \degree C$, the deformation of the metal proceeds evenly without defects and the metal is worked out over the entire thickness.
- At large individual degrees of deformation, rolling with a minimum number of passes is possible and limited only by the allowable values of the rolling force and moment.
- For the studied experimental ingots of the 1580 alloy, the critical technological parameters that limit the possibility of deformation are as follows: the heating temperature of the billets is $420–450 \degree C$; the minimum temperature of the metal after rolling is not lower than $350–370 \degree C$; and the total degree of deformation is not more than 40%.

The results obtained during computer and physical modeling of the rolling process of 1580 alloy plates were used to test the reduction modes during metal deformation and to adjust the casting parameters of experimental ingots in order to obtain a high-quality metal structure necessary for rolling.

![Fig. 5](image)

**Table 4** Mechanical properties of samples from plates for an experimental alloy 1580

| Workpiece number | Ultimate tensile strength $R_{\text{m}}$, MPa | Yield strength $R_{p0.2}$, MPa | Elongation to failure $A$, % |
|------------------|------------------------------------------|-----------------------------|----------------------------|
| 1                | 405                                      | 343                         | 9                          |
| 2                | 410                                      | 379                         | 8                          |

| Spectrum        | Mg  | Al  | Si  | Sc  | Ti  | Cr  | Mn  | Fe  | Zr  | Total |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| Spectrum 1      | 2.35| 71.00| 6.30| 5.78|      |     |     |     |     | 100.00|
| Spectrum 2      | 1.08| 59.66| 3.38| 4.79|      |     |     |     |     | 100.00|
| Spectrum 3      | 68.87|     |     |     | 0.76| 10.99| 19.39|     |     |       |
| Spectrum 4      | 100.00|     |     |     |     |     |     |     |     |       |
| Spectrum 5      | 6.74| 88.65| 4.61|     |     |     |     |     |     |       |
For experimental studies at the second stage, billets 300×1445×2200 mm in size with milled edges were made from a large-sized experimental ingot of 1580 alloy 445 mm thick (Fig. 1a), which were subjected to rolling on an industrial QUARTO 2800 mill (Fig. 2b). At the same time, the technology for manufacturing plates under industrial conditions included homogenization annealing, hot rolling, intermediate annealing, and cold rolling.

The workpieces were subjected to homogenization annealing according to the following regime: heating with a furnace at a rate of 1.16 °C per minute to 350 °C; exposure at this temperature for 11 h; reheating to a temperature of 425 °C at a rate of 1.25 °C per minute; exposure at this temperature for 8 h; and air cooling [27].

The macrostructure of the 1580 alloy ingot was studied on templates cut from the peripheral and central zones along the thickness of the ingot after preliminary etching in a 15% NaOH solution for 30 min and subsequent clarification in nitric acid.

Metallographic studies have shown that the macrostructure over the cross section of the templates is uniform fine-grained with a grain size of up to 1 mm. Defects of metallurgical origin in the form of cracks, porosity, oxide films, non-metallic inclusions, and intermetallic compounds were not found. The depth of the surface zone of liquates reached 3 mm.

The microstructure of the metal in the cast state (Fig. 8) is represented by an aluminum-based α-solid solution and inclusions of excess phases located along the boundaries of dendritic cells. In the central zone of the ingots, porosity was found with pore opening up to 0.02 mm (Fig. 8a) and intermetallic compounds up to 0.05 × 0.23 mm in size. In the process of homogenization, the dissolution of the phase components along the boundaries of the dendritic cells and the decomposition of the solid solution with a uniform release of dispersed particles over the volume of the solid solution occurred (Fig. 8b). The study of the microstructure in polarized light (Figs. 9 and 10) showed that in the peripheral zone of the ingot, there is an inhomogeneous structure with a grain size of 167 to 330 µm.

As can be seen from Fig. 10 that after both hot and cold rolling, the 1580 alloy retains its non-recrystallized structure. This confirms the studies carried out by the authors of [19], which show that the hardening mechanism in alloys of the Al–Mg system with Sc additives consists in the preservation of the subgrain structure due to the deceleration of low-angle boundaries by Al3(Sc, Zr) nanoparticles, which are revealed only with the help of SEM.

The central part of the ingot is characterized by a more uniform grain structure; the average grain size is 250 µm (Fig. 9a).
The results of measuring the mechanical properties and hardness of ingots in its various zones are given in Table 5.

Hot rolling of plates with dimensions of $45 \times 2230 \times 7600$ mm was carried out on a QUARTO 2800 mill [7, 32, 36]. The degree of deformation was 85%. The thermal deformation parameters of rolling were chosen on the basis of simulation results. The ingot heating temperature was $430 \pm 10 \, ^\circ C$.

The obtained values of the mechanical properties of the deformed and annealed semi-finished products are given in Table 6. Intermediate annealing of the slabs was carried out at a temperature of $320 \pm 10 \, ^\circ C$ for 6 h. From Table 6, it can be seen that annealing has practically no effect on the mechanical properties of hot-rolled semi-finished products.

The microstructure of hot-rolled plates was studied on microsections cut from the central part of the plates in the longitudinal and transverse directions (Fig. 11).

Metallographic analysis showed that the microstructure is typical of an aluminum alloy in a hot-deformed state.
state. Against the background of the $\alpha$-solid solution, lines elongated in the direction of rolling and separate chains of fragmented fine phases are observed (Fig. 11a, b). An analysis of the grain structure in polarized light showed that the structure of all the studied samples was fibrous, non-recrystallized (Fig. 9b). It should also be noted that the microstructure of plate samples after hot rolling and annealing is similar to the structure of plates in the hot-rolled state.

**Table 5** Mechanical properties of the studied samples from cast ingot

| Sampling location       | Ultimate tensile strength $R_{m}$, MPa | Elongation to failure $A$, % | Hardness, HB |
|-------------------------|----------------------------------------|-----------------------------|--------------|
| Ingot peripheral zone   | 305                                    | 5.2                         | 74.7 ± 0.8   |
| Ingot central zone      | 290                                    | 6.5                         | 72.1 ± 0.9   |

**Table 6** Mechanical properties of plates from 1580 alloy at different condition

| Sample cut direction | Ultimate tensile strength $R_m$, MPa | Yield strength $R_p$, MPa | Elongation to failure $A$, % | Hardness HB, kgf/mm$^2$ |
|----------------------|--------------------------------------|---------------------------|-----------------------------|-------------------------|
| Hot-rolled plates    |                                      |                           |                             |                         |
| after rolling        |                                      |                           |                             |                         |
| Longitudinal         | 389                                  | 247                       | 18.0                        | 123 ± 0.9               |
| Transverse           | 358                                  | 234                       | 12.0                        |                         |
| Hot-rolled plates    |                                      |                           |                             |                         |
| after annealing      |                                      |                           |                             |                         |
| Longitudinal         | 388                                  | 245                       | 18.8                        | 118 ± 0.9               |
| Transverse           | 351                                  | 238                       | 12.6                        |                         |
| Cold-rolled plates   |                                      |                           |                             |                         |
| after rolling        |                                      |                           |                             |                         |
| Longitudinal         | 414                                  | 386                       | 6.6                         | 140 ± 0.9               |
| Transverse           | 413                                  | 372                       | 5.2                         |                         |

**Fig. 11** Microstructure of hot-rolled (a, b) and cold-rolled (c, d) plates from experimental alloy 1580: a, c center; b, d periphery, × 200
Cold rolling of plates was carried out to a thickness of 31.5 mm, while the degree of deformation reached 30%. It was noted that at the degree of deformation close to 30% cracks appeared on the side edges of the plates. The mechanical properties of cold-rolled plates with dimensions of 31.5 × 2000 × 7500 mm are also presented in Table 6.

An analysis of the metal microstructure of cold-rolled plates showed that lines and separate chains of crushed fine phases are observed in the rolling direction, which located along the grains of the α-solid solution (Fig. 11c, d). The structure of plates in the cold-deformed state is non-recrystallized in the form of fibers elongated along the rolling axis (Fig. 10a).

4 Summary

Thus, based on the data of physical modeling in laboratory conditions, a thermal deformation mode of processing alloy 1580 was proposed, which provides for the homogenization of cast ingots, their hot rolling at a temperature of 430 ± 10 °C with reduction ratios up to 85% and cold rolling with reductions up to 30%. This processing mode makes it possible to obtain under industrial conditions plates from alloy 1580 with dimensions of 31.5 × 2000 × 7500 mm. An analysis of the microstructure of test samples of plates obtained in laboratory and industrial conditions showed that it has a fibrous texture and consists of elongated grains of α-solid solution and inclusions of intermetallic compounds arranged in lines along the grain boundaries. As a result of mechanical tensile tests of samples of the obtained sheet materials from the 1580 alloy having this structure, it was found that the strength and plastic properties of the metal in the hot, cold, and annealed states have the required level and allow rolling with large degrees of deformation. It has been found that in the hot-deformed state, annealing has practically no effect on the mechanical properties, while the ultimate tensile strength in the longitudinal direction is 388–389 MPa, the yield strength is 245–247 MPa, and the elongation to failure is 18.0–18.8%. After cold rolling, the plates have the following mechanical properties: ultimate tensile strength is 413–414 MPa, yield strength is 386–372 MPa, and elongation to failure is 5.2–6.6%.

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Data availability Not applicable.

Declarations

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

Consent to participate The authors consent to participate.

Consent for publication The authors consent to publish.

Competing interests The authors declare no competing interests.

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