Investigation of Rolling Modes, Structure and Properties of Aluminum-Magnesium Alloy Plates With a Reduced Scandium Content

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Research Article

Keywords: Aluminum alloys, Scandium, Casting, Rolling, Structure, Mechanical properties

Posted Date: February 16th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1334066/v1

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. 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. 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.

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 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 Al_3Sc 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, 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 the Russian alloy 1580, the chemical composition of which, in accordance with the standard in force in Russia (State Standard 4784-2019) is given in Table 1. This alloy contains a minimum amount of scandium compared to similar alloys, which 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.

Table 1
– The chemical composition of the alloy 1580

Mass fraction of the element, %											
Si	Fe	Cu	Mg	Mn	Cr	Zn	Ti	Additional instructions	Other elements		Al
									Each	Sum	
0.06-0.16	0.12-0.18	0.1	4.9-5.3	0.4-0.8	0.08-0.18	0.25	0.15	**Sc: 0.05-0.14** Zr: 0.06-0.18 Ca: 0.0005 Na: 0.0003 Be: 0.003	0.05	0,15	Basis

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%.

These conclusions are confirmed by the data in Table 2, which presents the mechanical properties (ultimate tensile strength R_m, yield strength R_p, and elongation to failure A) of alloys of the Al-Mg system with scandium [11].

Table 2
– Mechanical properties of industrial aluminum alloys

Alloy grade	**Chemical composition**	**Mechanical properties**		
		R_m, MPa	**R_p, MPa**	**A, %**
1515	Al – 1% Mg – 0.22 Sc – 0.1 Zr	250	160	16
1523	Al – 2% Mg – 0.22 Sc – 0.1 Zr	275	200	16
1535	Al – 4% Mg – 0.22 Sc – 0.1 Zr	360	280	20
1545	Al – 5% Mg – 0.22 Sc – 0.1 Zr	380	290	16
1570	Al – 6% Mg – 0.4 Mn – 0.22 Sc – 0.1 Zr	400	300	15

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. The effect of adding scandium on the structure of alloys is described in [12, 14, 16, 18–23, 35, 44, 49, 50]. Various heat treatment regimes are considered in [13, 27, 30, 36, 38]. Hot rolling of cast billets activates the process of precipitation of particles of the Al_3(Sc,Zr) phase on dislocations, the distribution density of which increases significantly. This also leads to a decrease in the size of Al_3(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, 17, 19, 24, 25, 27–29, 31, 34, 35, 37, 50]. The properties are practically on the same level as industrial alloys, in which the content of scandium is 2-3 times higher [39–43]. Modeling of the rolling process of 1580 alloy was studied in [7, 26, 32, 33, 34, 36]. These alloys are widely used mainly for the production of plates and sheets by hot and cold rolling.

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

2 Method Of Carrying Out Research

Metallographic studies of semi-finished products were carried out using a CarlZeiss 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 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 3.

Table 3
– The chemical composition of the experimental alloy 1580

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

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 4.

Table 4
– Reduction mode and power parameters of plates rolling from an experimental alloy 1580

Thickness, mm	Single reduction,%	Total reduction, %	Rolling force, MN	Rolling moment, MN·m
45.0	10.0	10.0	25.4	1.20
41.5	7.8	17.0	29.2	1.26
38.0	8.4	24.0	29.8	1.32
34.5	13.2	31.0	29.9	1.33
31.5	8.7	37.0	29.9	1.24

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

3 Results And Discussion

At the first stage of experimental studies in laboratory conditions, the rolling of billets with milled edges 50×130×330 mm in size (Fig. 1b) from the experimental alloy 1580 was simulated (Table 3). 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. 2) with a change in the reduction value, selecting rational processing modes. The general scheme of deformation included hot rolling of a billet 50 mm thick, heated to a temperature of 430°C, with different values of a single reduction. As equipment for rolling, a two-roll laboratory mill DUO 330 was used, the technical characteristics of which are given in Table 5. In the course of rolling samples were taken for testing the mechanical properties and studying the structure of the metal.

Table 5
– Technical characteristics of the sheet rolling mill DUO 330

Parameter	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

The first workpiece heated to a temperature of 430±10°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. 3). 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°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. 2a). 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 (Table 5).

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 degree of deformation was 37%. The temperature of the metal after the last pass was 370°C. It can be noted that a more uniform metal flow and the absence of cracks were observed during rolling (Fig. 2b), 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 6.

Table 6
– Mechanical properties of samples from plates for an experimental alloy 1580

Workpiece number	Ultimate tensile strength R_m, MPa	Yield strength R_p, MPa	Elongation to failure A, %
1	405	343	9
2	410	379	8

For metallographic studies samples were cut from the fracture surface of the workpieces for fractographic studies (Fig. 4a, *b*). 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 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, Ti (Fig. 5, spectrum 1, 2) and in the form of polyhedra containing Al, Fe, Mn, Cr (Fig. 5, spectrum 3). Intermetallic compounds have sizes of 10-60 microns, 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, 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±10°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: the heating temperature of the billets is 420-450°C; the minimum temperature of the metal after rolling is not lower than 350-370°C; 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.

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). 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 hours; reheating to a temperature of 425°C at a rate of 1.25°C per minute; exposure at this temperature for 8 hours; 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 (Fig. 9) showed that in the peripheral zone of the ingot there is an inhomogeneous structure with a grain size of 167 to 330 μm.

The central part of the ingot is characterized by a more uniform grain structure, the average grain size is 250 μm (Fig. 9a).

Hot rolling of ingots with dimensions of 45×2230×7600 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±10°C.

The obtained values of the mechanical properties of the deformed and annealed semi-finished products are given in Table 7. Intermediate annealing of the slabs was carried out at a temperature of 320±10°C for 6 hours. From Table 7 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. 10).

Table 7
– Mechanical properties of plates from alloy 1580

Sample cut direction	**Ultimate tensile strength R_m, MPa**	**Yield strength R_p, MPa**	**Elongation to failure A, %**
Hot rolled plates after rolling			
longitudinal	389	247	18.0
transverse	358	234	12.0
Hot rolled plates after annealing			
longitudinal	388	245	18.8
transverse	351	238	12.6
Cold rolled plates after rolling			
longitudinal	414	386	6.6
transverse	413	372	5.2

Metallographic analysis showed that the microstructure is typical of an aluminum alloy in a hot-deformed state. Against the background of the α-solid solution, lines elongated in the direction of rolling and separate chains of fragmented fine phases are observed (Fig. 10a, *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.

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 7.

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 are located along the grains of the α-solid solution (Fig. 10c, *d*). The structure of plates in the cold-deformed state is non-recrystallized in the form of fibers elongated along the rolling axis (Fig. 9c).

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 with the required level of mechanical properties.

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.

Funding

The research was carried out within the framework of the state assignment of the Ministry of Science and Higher Education of the Russian Federation (scientific theme code FSRZ-2020-0013).

Acknowledgements

Use of equipment of Krasnoyarsk Regional Center of Research Equipment of Federal Research Center «Krasnoyarsk Science Center SB RAS» is acknowledged.

Competing Interests

The authors declare about the absence of competing interests.

Availability of data and materials

Not applicable.

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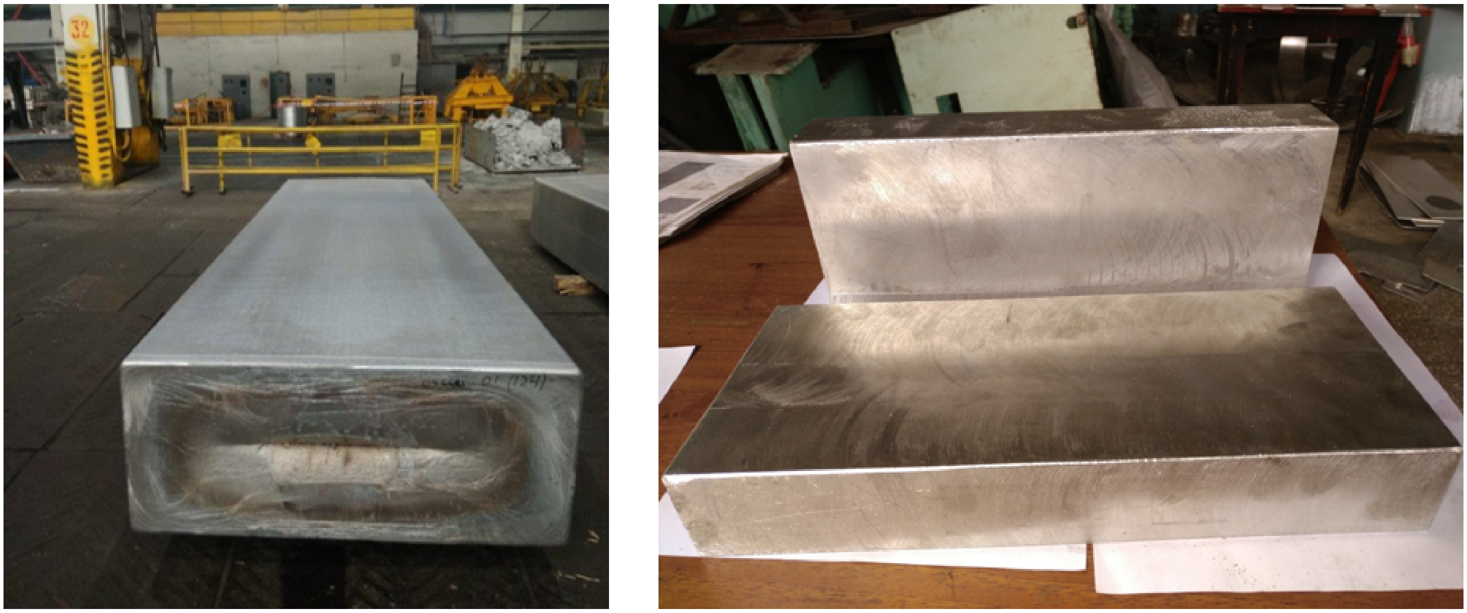
Figures



a *b*

Figure 1

View of the ingot obtained under industrial conditions (*a*) and billets from it (*b*)

a *b*

Figure 2

View of the side surface of the workpiece after rolling:

a – first workpiece; *b* – second workpiece

Figure 3

Type of cracks on the edges of the rolled billet

Figure 4

Fracture macrostructure in the middle of workpieces:

a – first workpiece; *b* – second workpiece

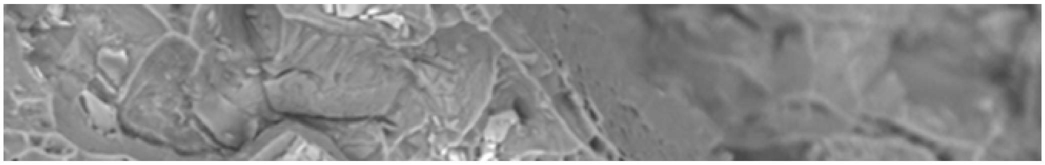


Figure 5

Electronic image and MRSA results of the second workpiece

Figure 6

Microstructure of workpiece fracture in secondary electrons: *a* – ×1000; *b* – ×500

Figure 7

Fracture microstructure of workpieces: *a* – fracture edge, *b* – fracture middle, ×500

Figure 8

Microstructure of ingots of experimental alloy 1580 in cast (*a*) and annealed (*b*) states, ×200

Figure 9

Microstructure of cast and deformed semi-finished products from experimental alloy 1580 in polarized light: *a* – ingot (periphery); *b* – ingot (center); *c* – hot-rolled plate; *d* – cold-rolled plate, ×100

Figure 10

Microstructure of hot-rolled (*a*, *b*) and cold-rolled (*c*, *d*) plates from experimental alloy 1580: *a*, *c* – center; *b*, *d* – periphery, ×100