

# STUDY OF STRENGTH PROPERTIES OF SEMI-FINISHED PRODUCTS FROM ECONOMICALLY ALLOWED HIGH-STRENGTH ALUMINIUM-SCANDIUM ALLOYS FOR APPLICATION IN AUTOMOBILE TRANSPORT AND SHIPBUILDING

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## Abstract

The results of study strength properties of rolled products from aluminium alloys doped with scandium under various processing conditions of hot and cold rolling are presented. The regularities of metal flow and the level of strength properties of deformed semi-finished products from aluminum-scandium alloys are established, depending on the total degree of deformation and the various modes of single reduction during rolling. It is shown that when using one heating of a cast billet to obtain high-quality semi-finished products, the temperature during the rolling process should not be lower than 350-370 °C, and the total degree of deformation does not exceed 50-60%. It is found that the semi-finished products from alloys with a content of scandium in the range 0.11-0.12% in the deformed state have elevated values of ultimate tensile strength and yield strength of the metal, which allows recommending them for industrial production of sheet metal products.

**Keywords:** *aluminium alloys, scandium, rolling, deformed semi-finished products, total degree of deformation, temporary tensile strength, yield stress of metal.*

## Introduction

Recently, much attention has been paid to research in the field of creating processing technologies and studying the properties of cast and deformed semi-finished products from aluminium alloys alloyed with rare-earth metals, in particular, by scandium [1-10]. This is because such alloys, along with corrosion resistance and good performance properties, can have high strength characteristics. Alloys of the Al-Mg system that do not contain scandium (for example, alloy 5083) are widely used in industry, and alloys with a high scandium content (up to 0.24%), for example, 01570 alloy, having a high cost due to the use of expensive scandium ligature. Therefore, an urgent task is the development of new alloys, economically alloyed with scandium, having increased strength.

With the purpose of deeper studying the patterns of formation of mechanical and operational characteristics of products made of such high-strength aluminium-scandium alloys, the employees of «RUSAL» together with the scientists of the School of Non-Ferrous Metals and Materials Science of the Siberian Federal University conducted a number of experimental studies to obtain cast and deformed semi-finished products and study their properties. The results of some of these studies are given below.

The article is based on the report presented at the IX International Congress “Non-ferrous metals and minerals-2017”.

## Methods

In the first stage of research, flat ingots of 8 alloys of the Al-Mg system with different scandium content varying in the range of 0.10-0.24% and 1 ingot of the 5083 alloy, which was basic and did not contain scandium, were cast in experimental industrial conditions. They were subjected to homogenization annealing in the following manner: heating with an oven at a rate of 1.16 °C per minute to 350 °C; holding at this temperature for 11 hours; reheating to temperature  $T = 425$  °C at a rate of 1.25 °C per minute; holding at this temperature for 8 hours; cooling in air. For the design of the processing route for experimental alloys, a deformation scheme was adopted that included hot

rolling of 28 mm thick preforms heated to 450 °C to a thickness of 10 mm, and then cold rolling of these strips to a final thickness of 1 mm (Table 1).

Table 1 – Route of rolling all investigated alloys

Route number	Primary thickness $h_0$ , mm	Final thickness $h_i$ , mm	Draw ratio $\lambda$		Degree of deformation $\varepsilon$ , %	
			Single $\lambda_s$	Total $\lambda_t$	Single $\varepsilon_s$	Total $\varepsilon_t$
1.	28.0	27.5	1.02	1.02	1.96	2.0
2.	27.5	26.8	1.03	1.05	2.48	4.4
3.	26.8	25.9	1.03	1.08	3.36	7.6
4.	25.9	25.0	1.04	1.12	3.48	10.8
5.	25.0	24.1	1.04	1.16	3.60	14.0
6.	24.1	23.2	1.04	1.21	3.74	17.3
7.	23.2	22.3	1.04	1.26	3.88	20.5
8.	22.3	21.4	1.04	1.31	4.04	23.7
9.	21.4	20.5	1.04	1.37	4.21	26.9
10.	20.5	19.6	1.05	1.43	4.40	30.1
11.	19.6	18.7	1.05	1.50	4.60	33.3
12.	18.7	17.7	1.05	1.58	5.09	36.7
13.	17.7	16.8	1.06	1.67	5.36	40.1
14.	16.8	15.8	1.06	1.77	5.66	43.5
15.	15.8	14.9	1.06	1.88	6.01	46.9
16.	14.9	13.9	1.07	2.01	6.39	50.3
17.	13.9	13.0	1.07	2.16	6.82	53.7
18.	13.0	12.0	1.08	2.33	7.32	57.1
19.	12.0	11.0	1.09	2.53	8.07	60.5
20.	11.0	10.0	1.10	2.78	8.87	64.0
21.	10.0	9.1	1.11	3.09	9.93	67.6
22.	9.1	8.0	1.12	3.47	11.03	71.2
23.	8.0	7.0	1.14	3.96	12.39	74.8
24.	7.0	6.0	1.16	4.61	14.14	78.3
25.	6.0	5.0	1.21	5.60	16.50	82.1
26.	5.0	4.4	1.12	1.12	11.0	84.3
27.	4.4	3.9	1.14	1.28	11.9	86.0
28.	3.9	3.4	1.14	1.45	12.2	87.8
29.	3.4	3.0	1.14	1.66	12.5	89.2
30.	3.0	2.6	1.14	1.89	12.3	90.7
31.	2.6	2.3	1.14	2.16	12.1	91.8
32.	2.3	2.0	1.14	2.45	12.1	92.8
33.	2.0	1.8	1.14	2.79	12.3	93.6
34.	1.8	1.6	1.13	3.16	11.7	94.3
35.	1.3	1.4	1.12	3.55	10.8	95.0
36.	1.4	1.3	1.10	3.91	9.2	95.4
37.	1.3	1.2	1.08	4.24	7.8	95.7
38.	1.2	1.1	1.07	4.55	6.8	96.1
39.	1.1	1.04	1.06	4.81	5.5	96.2
40.	1.04	1.00	1.04	5.00	3.8	96.4

When developing the rolling modes of experimental aluminum alloys, the methods and software described in [11, 12] were used to calculate deformation and force parameters and used the dependences characterizing the change in their strength characteristics from the degree of deformation obtained in the course of studying mechanical properties.

For the study, 8 alloys of the Al-Mg system with Cr 0.15 to 0.20%, Si 0.20%, Zn 0.1%, Cu 0.1%, Fe 0.2% and different scandium content from 0.10 to 0.24% were chosen (Table 2). The DUO 330 mill was used as the equipment for hot rolling, and the MDM ARIETE LS 400×240 mill for cold rolling. As a result of rolling with the use of intermediate heating preheaters, hot-rolled strips were obtained, which were then rolled to specified thicknesses with  $\varepsilon_t$  up to 97%.

Table 2 – The chemical composition of ingots from experimental alloys with a reduced content of Mn and Cr of the Al-Mg system

Alloy number	Main elements, %				
	Al	Mg	Mn	Sc	Zr
0	Basis	5.0-5.2	0.8	-	-
1		5.0-5.2	0.6	0.24	0.10
2		5.0-5.2	0.6	-	0.20
3		5.0-5.2	0.6	0.10	0.20
4		5.0-5.2	0.3	0.10	0.20
5		5.0-5.2	0.75	0.10	0.20
6		5.0-5.2	0.6	0.10	-
7		5.0-5.2	0.6	0.10	0.10
8		5.0-5.2	0.6	0.15	0.20

In the course of rolling, samples were taken for mechanical testing and determined for their tensile strength and yield strength of the metal by means of a universal machine LFM 400. The obtained 3 mm thick strips were annealed at  $T = 350$  °C and a holding time of 3 hours. Data on the mechanical properties of semi-finished products from the experimental alloy in comparison with the alloy-analogue 5083, which does not contain scandium, are shown in Fig. 1 (for the reference point for  $\varepsilon = 0$ , the values of  $\sigma_B$  for the cast preform are taken). Analysis of the dependencies on the graph allows us to conclude that, with an increase in the degree of deformation, the values of the temporary fracture resistance ( $\sigma_B$ ) for all investigated alloys increase and at  $\varepsilon_t = 96.8\%$  reach values of the order of 500-550 MPa. The regularities of the change in the values of the yield strength ( $\sigma_{0.2}$ ) of the metal are of a similar nature, and their values reach 360-478 MPa. It was also found that with the increase in the amount of scandium in the alloy, the strength characteristics of the metal also increase.

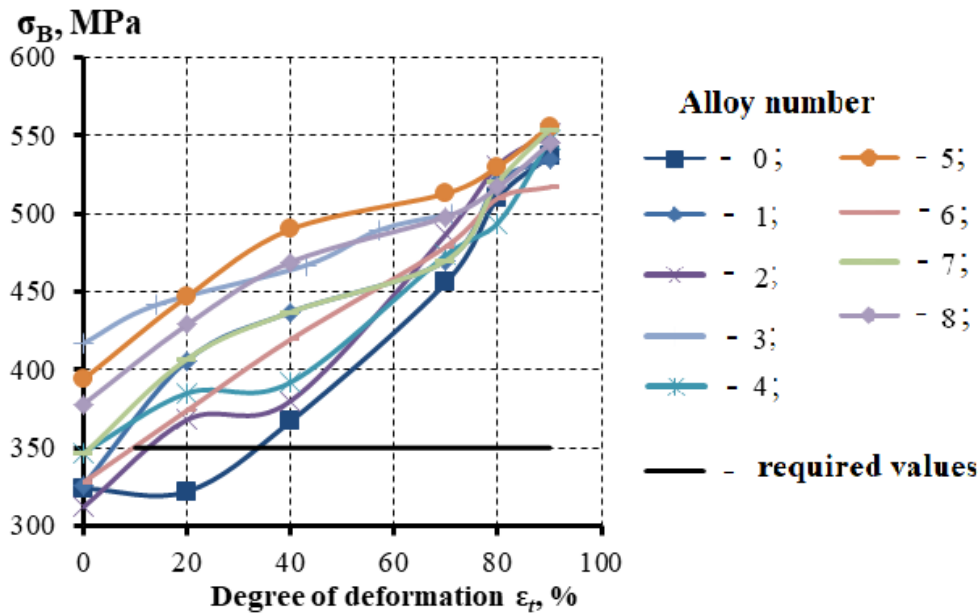


Fig. 1. The change in the tensile strength for the investigated alloys

At the second stage of the research in the industrial conditions of the Bratsk aluminium smelter on the basis of alloy 5083, flat ingots 560×1360×4520 mm in size (Fig. 2) were cast from an aluminium alloy in which the scandium content was in the range of 0.11-0.12%. The templates were cut off from the ingots, from which samples were prepared for testing the mechanical properties of the cast metal and the workpiece with milled faces for rolling with dimensions of 40×120×200 mm (Fig. 3).

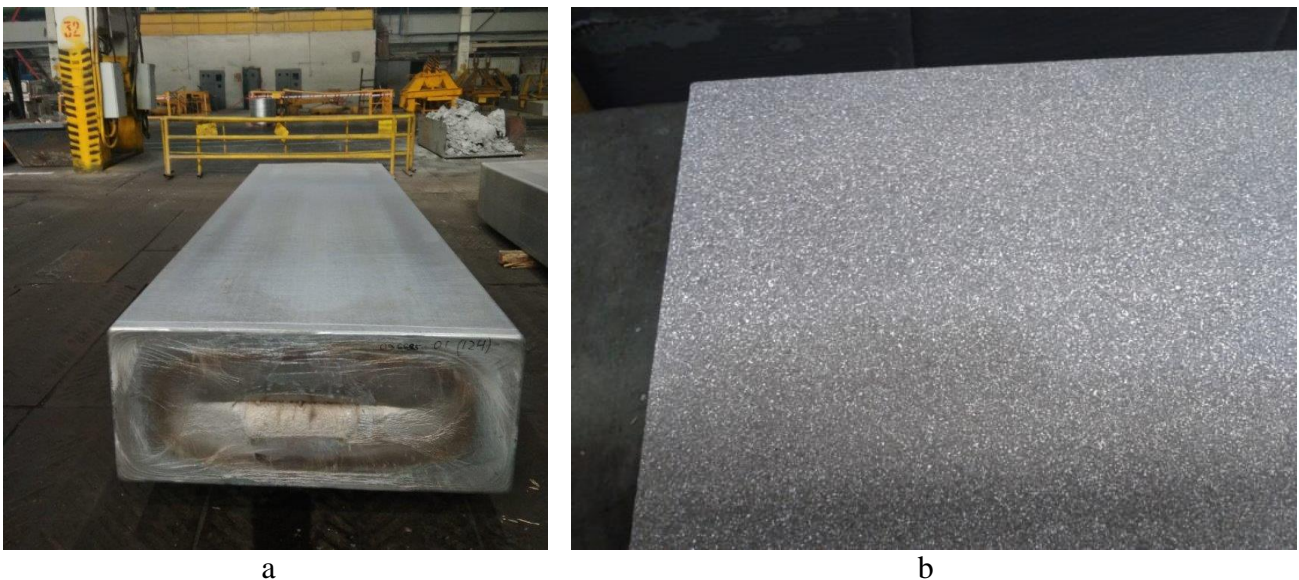


Fig. 2. The type of ingot (a) obtained under the industrial conditions of the Bratsk aluminium smelter, and its macrostructure (b)

Further, according to the previously developed regimes, the homogenized preforms were hot rolled in a DUO 330 mill up to a thickness of 10 mm, and the obtained strip was rolled to a thickness of 3 mm in the cold state. In the course of rolling, samples were taken for mechanical testing and determined for them a temporary tensile strength, yield strength and elongation. The resulting 3 mm thick strips were annealed at  $T = 350\text{ }^{\circ}\text{C}$  and a holding time of 3 hours.

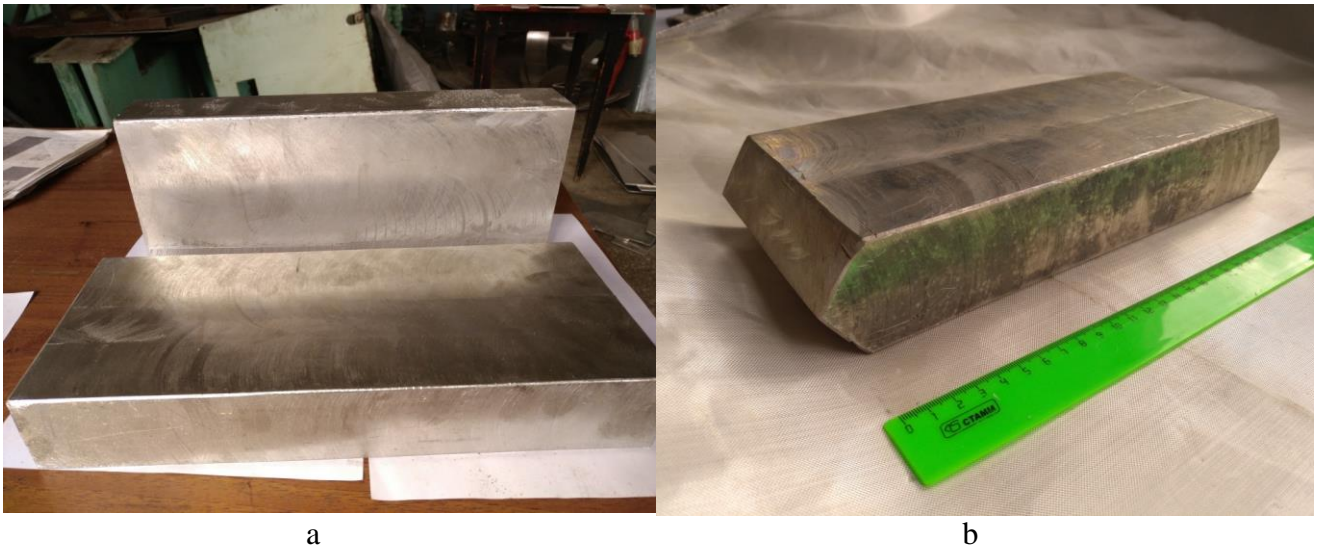


Fig. 3. View of cast billets from the investigated alloys after milling

Data on the mechanical properties of semi-finished products from the experimental alloy in comparison with the analog alloy 5083, which does not contain scandium, are given in Table 3 and showed that  $\sigma_B$  for deformed semi-finished products increased by an average of 17%, and  $\sigma_{0.2}$  of the metal by 29%, for annealed, respectively, by 29 and 49.8%.

Table 3 – Strength properties of samples of rolled products from experimental alloys

Sample number	Thickness $h_i$ , mm	Condition	Strength properties, MPa			
			alloy 5083		experimental alloy	
			$\sigma_B$	$\sigma_{0.2}$	$\sigma_B$	$\sigma_{0.2}$
1	10	hot deformed	297	196	356	232
2	8	hot deformed	305	217	372	280
3	6	hot deformed	318	213	387	312
4	3	cold deformed	394	373	453	429
5	3	annealed	277	139	390	277

In the third stage of the research, the possibility of rolling cast billets from an alloy with scandium content from one heating without additional metal heating during the rolling process and the strength properties of the obtained deformed semi-finished products were analyzed.

Rolling of the first billet with dimensions of 53×130×330 mm was carried out after homogenization with a single reduction of 2% until cracks appeared on the lateral faces that appeared at a thickness of 30 mm. The total degree of deformation was 43.4%, and the number of passes was 21. The analysis of shortcomings showed that the metal flow for a given compression pattern is uneven: the peripheral layers outstrip the central ones (Fig. 4). This caused the appearance of significant tensile stresses and, as a consequence, at a low metal temperature, the appearance of cracks on both sides of the workpiece.



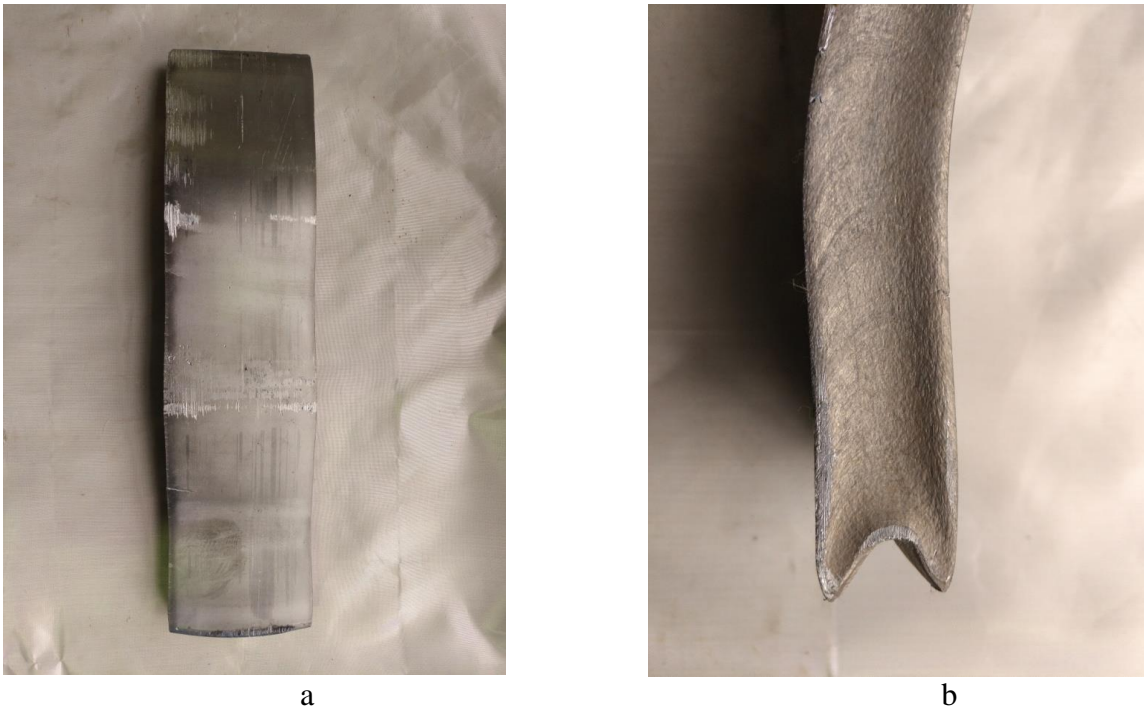


Fig. 4. View of the first billet after rolling: a - from above; b - on the side

The second billet (Fig. 5) was rolled under heating under a similar regime and the maximum reduction at rolling in the scheme 53-48-43-38-35-32-31.2 (6 passes), after which the billet was exposed at its end. The total degree of deformation was 41.1%. It can be noted that during rolling a more uniform flow of metal was observed and the absence of cracks on one of the faces (Fig. 5b), which indicates that both the peripheral and central layers of the preform are being worked through. However, large values of single compression led to the disclosure of the billet.

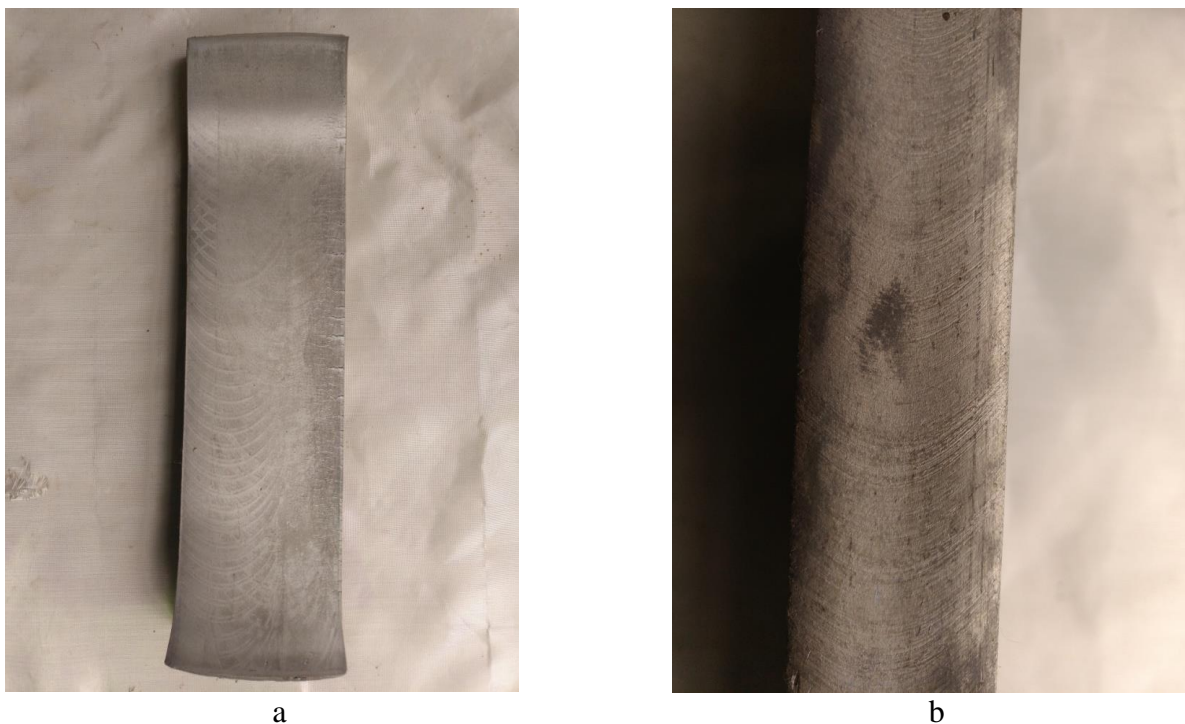


Fig. 5. View of the second billet after rolling: a - from above; b - on the side

Rolling of the third billet (Figure 6) with a thickness of 40 mm was done with an aluminium cladding of two large facets with a 1 mm thick plate and a length of 0.75 of the sample length at  $T =$

450 °C. The modes of reduction and the temperature of the metal are given in Table 4. The total degree of deformation  $\varepsilon_t$  was 75% (final thickness  $h_t = 11$  mm), during the rolling process, 4 intermediate heating of the metal had to be used.

Table 4 – Modes of reduction and temperature of metal along the passes during rolling

Pass number	$\Delta h$ , mm	Reduction, %		Temperature before pass $T$ , °C	Temperature after pass $T$ , °C	Note
		Single $\varepsilon_s$	Total $\varepsilon_t$			
1	5	12.5	12.5	450		
2	3	8.5	20	445	418	
3	2	6	25	418	395	
4	2	7	30	395	370	
5	2	7	35	370	350	heating
6	3	11.5	42.5	400	386	
7	2	9	47.5	386	357	
8	1	5	50	357	350	
9	1	5	52.5	350		heating
10	3	16	60	440	415	
11	2	12.5	65	415	360	
12	1	7	67.5	360		heating
13	2	15	72.5	430	360	heating
14	2	18	75	415	360	

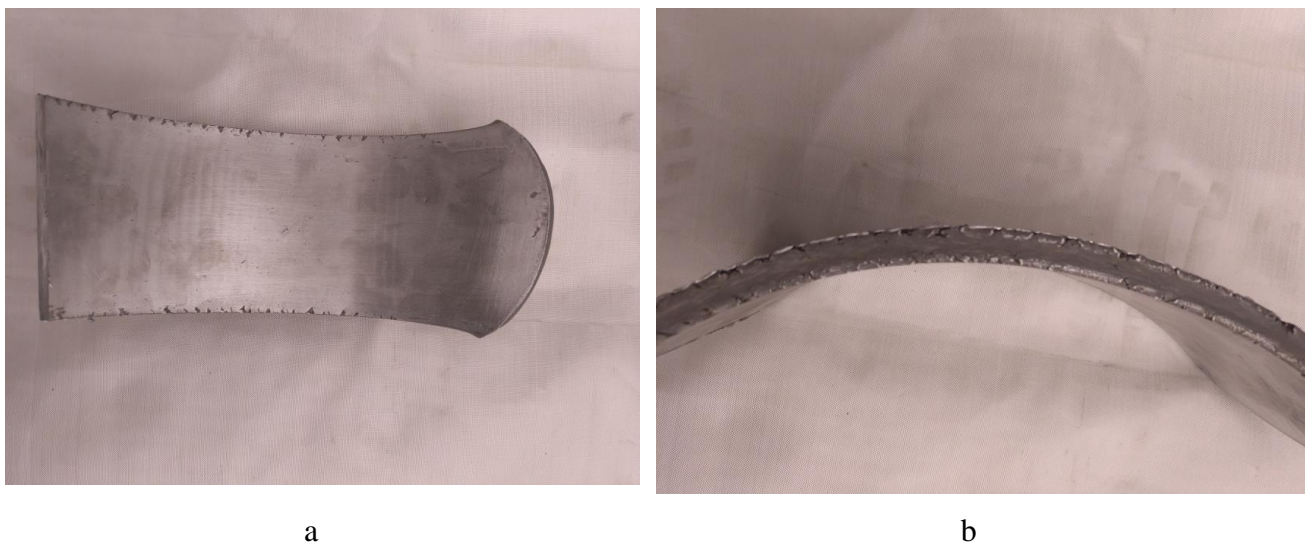
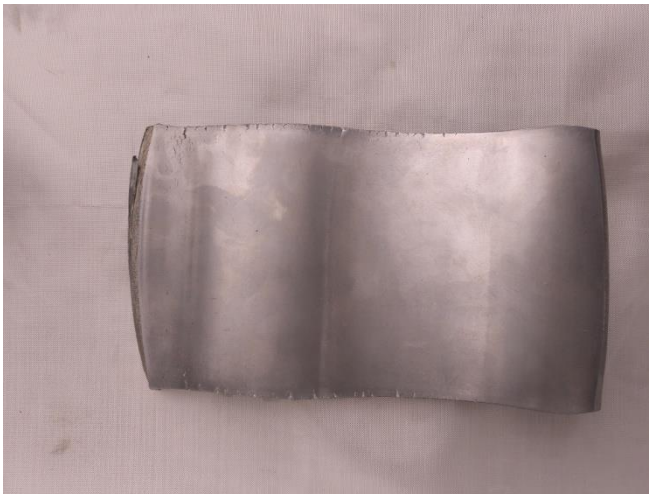


Fig. 6. View of the third billet after rolling:  
a - from above; b - on the side

The fourth blank with a thickness of 26 mm with a Petrov lock (Fig. 7 b) on one side was rolled from one heating at  $T = 450$  °C in 45 passes. Rolling was carried out with small crimps (1-2%), the total reduction  $\varepsilon_t$  was 57.6%.

The temporary tensile strength  $\sigma_B$  for the obtained semi-finished products varied within 343-379 MPa, which corresponds to the strength characteristics for hot deformed semi-finished products from the alloy studied earlier (Table 4).



a



b

Fig. 7. View of the fourth billet after rolling:  
a - from above; b - on the side

### Conclusions

Thus, the conducted studies made it possible to establish the regularities of the metal flow and the level of strength properties of deformed semi-finished products from aluminium-scandium alloys, depending on the total degree of deformation and the various modes of single reduction during rolling. The distribution of the compressions along the passes for the ingots is not important, since even when rolling with single compressions  $\varepsilon_s$  of the order of 10-15% at processing temperatures of 420-450 °C, the metal deformation proceeds evenly without defects, and the metal is worked through the entire thickness. The most important technological parameters are the temperature of strip and the total reduction: the temperature is not lower than 350-370 °C; the total degree of deformation  $\varepsilon_t$  is not more than 50-60%. Semi-finished products from aluminium alloys with scandium content in the range of 0.11-0.12% in the deformed state have increased values of the tensile strength and yield strength of the metal, which are on average 17-29% higher than the strength parameters for base alloy 5083, in the composition of which there is no scandium. The obtained research results will be used in the development of casting technologies for rolling these alloys in industrial conditions and obtaining products in the form of sheet products for the needs of automobile and shipbuilding.

### Acknowledgment

The publication was prepared using the results of works carried out during the project 03.G25.31.0265 "Development of economically alloyed high-strength Al-Sc alloys for use in road transport and navigation" as part of the Program for the implementation of complex projects for the creation of high-tech production approved by the RF Government Decree of April 9 2010 № 218.

### Nomenclature

- $h_0$  primary thickness, [mm]
- $h_i$  final thickness, [mm]
- $T$  temperature [°C]
- $\Delta h$  absolute reduction, [mm]
- $\varepsilon_s$  single degree of deformation (reduction), [%]
- $\varepsilon_t$  total degree of deformation (reduction), [%]
- $\lambda_s$  single draw ratio, [-]
- $\lambda_t$  total draw ratio, [-]
- $\sigma_B$  tensile strength, [MPa]
- $\sigma_T$  yield strength, [MPa]



## References

1. Pedro Henrique R. Pereira, Ying Chun Wang, Yi Huang, Terence G. Langdon, Influence of grain size on the flow properties of an Al-Mg-Sc alloy over seven orders of magnitude of strain rate, *Materials Science & Engineering*, 2017, A685, 367-376.
2. S. Mondol, T. Alamb, R. Banerjee, S. Kumar, K. Chattopadhyay, Development of a high temperature high strength Al alloy by addition of small amounts of Sc and Mg to 2219 alloy, *Materials Science & Engineering*, 2017, A687, 221-231.
3. Mengjia Li, Qinglin Pan, Yunjia Shi, Xue Sun, Hao Xiang, High strain rate superplasticity in an Al-Mg-Sc-Zr alloy processed via simple rolling, *Materials Science & Engineering*, 2017, A687, 298-305.
4. Yu. Buranova, V. Kulitskiy, M. Peterlechner, A. Mogucheva, R. Kaibyshev, S.V. Divinski, et al., Al<sub>3</sub>(Sc, Zr) - based precipitates in AlMg alloy: Effect of severe deformation, *Acta Materialia*, 2017, 124, 210-224.
5. Fuller C.B., Temporal evolution of the nanostructure of Al(Sc,Zr) alloys: Part II coarsening of Al<sub>3</sub>(Sc<sub>1-x</sub>Zr<sub>x</sub>) precipitates, *Acta Materialia*, 2005, 53, № 20, 5415-5428.
6. Ryset Ryum N., Scandium in aluminum alloys, *International Materials Reviews*, 2005, 50, No. 1.
7. L.S. Toropova, D.S. Eskin, M.L. Kharakterova, T.V. Dobatkina, *Advanced Aluminum Alloys Containing Scandium: Structure and Properties*, Amsterdam: Gordon and Breach Science Publishers, 1998, 175.
8. Filatov Yu.A. *Razlichnye podkhody k realizatsii uprochnyayushchego effekta ot dobavki skandiya v deformiruemyykh splavakh na osnove sistemy Al-Mg-Sc* [Various approaches to realization of the strengthening effect resulted from scandium addition made to wrought Al-Mg-Sc system based alloys], *VILS: Tekhnologiya legkikh splavov*, 2009, 3, 42-45.
9. Kuznetsov G.M., Pobezhimov P.P., Nefedova L.P., Belov E.V. *Osobennosti formirovaniya struktury i svoystv liteinykh Al-Mg-splavov, legirovannykh skandiem* [Features of the formation of the structure and properties of cast Al-Mg alloys doped with scandium], *Metallovedenie i termicheskaya obrabotka metallov / VIAM*, 1996, No. 6.
10. Drits M.E., Kadaner E.S., Dobatkina T.V., Turkina N.I. *O kharaktere vzaimodeystviya skandiya s alyuminiem v bogatoi alyuminiem chasti sistemy* [On the nature of the interaction of scandium with aluminum in the aluminum-rich part of the system], *Izv. AN SSSR*, 1973, No. 4, 213-217.
11. S.B. Sidelnikov, I.L. Konstantinov, D.S. Voroshilov, *Rolling technology: a textbook*. – 3rd ed., Ext. and revised. – Krasnoyarsk : SibFU, 2016, 180 p.
12. Baranov V. N., Sidelnikov S. B., Bezrukikh A. I., Zenkin E. Y., Research of rolling regimes and mechanical properties of cold-rolled, annealed and welded semi-finished products from experimental alloys of Al-Mg system, economically alloyed by scandium, *Tsvetnye Metally*, 2017, No. 9, 83-88.