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Influence of Scandium Content, Additional Alloying Elements and Strain Parameters on Properties of AlMgSc System Alloy Products

Boris V. Ovsyannikov

Kamensk Uralsky Metallurgical Works (OAO KUMZ), 5 Zavodskaya St.,
Kamensk Uralsky, Sverdlovsk Region, 623405, Russia

The main results of scandium addition to aluminium alloys are as follows: increase of strength properties (ultimate strength and yield strength) by 100-180 MPa, notable improvement of weldability, lower anisotropy of properties, considerable increase of both general corrosion resistance and exfoliation corrosion and stress corrosion resistance. These effects are especially typical for AlMgSc system alloys.
This article summarizes the results of series of research work which analysis has facilitated in identifying basic mechanism of influence of scandium addition on structure and properties of AlMgSc system aluminium alloys. The regularities have been used as a basis for choosing contents of new industrial alloys and optimization of temperature and time parameters of all the process flow (starting with melting and casting and ending with heat treatment of semi-finished products).
Both commercially produced alloys and some experimental alloys have been the objects of the research work.
We have determined the influence of temperature and degree of strain on tensile properties of these alloys. We have studied the influence of such additional alloying elements as Mn, Cr, Cu, Fe, Ni.
We have developed some new AlMgSc system alloys having 290-300 MPa of yield strength in hot-extruded condition and 320-360 MPa of yield strength in cold-worked condition.

Key Words: *AlMgSc alloys, composition, rods ,strain parameters, properties*

1. Introduction

Scandium modifies alloy structure, contributes to subgrain structure in semis and provides additional hardening [1]. This fact is provided by the following regularities:

1. Scandium reacts with aluminium according to eutectic type diagram with variable solubility. Scandium inclines to form oversaturated solid solutions in nonequilibrium state even at low rate of crystallization.
2. Al_3Sc intermetallic compound that is formed as a result of scandium and aluminium interreacting has some positive quality: its lattice is almost identical to aluminium lattice in size and structure. This lattice property has a strong influence on alloys structure and properties.

Thus, due to these properties scandium addition makes it possible to get ingots/billets and welded seams with non-dendritic structure and, as a result, with improved performance properties [2]. Inter alia, scandium addition in alloys enables strength increase by 29 – 50 MPa [3].

Industrial aluminium alloys alloyed with small content of scandium (tenths and even hundredth percent) are developed and manufactured [2]. These alloys are confirmed to combine unique properties: good weldability, workability at superplastic ductility, good tensile properties etc. [8, 9]. They are used in complex load-carrying structures with minimum flight weight [4], in assemblies designed for aerospace structures [3], in weld-fabricated structures operated in liquid oxygen [5].

Al-Mg system alloys alloyed with scandium fully meet the requirements to vessel materials meant for fast-speed dynamically supported ships [6]; they can be used as skin-plating in aircraft building [10], in addition, semi-finished product yield strength is 1.5-2.0 times higher than the same of standard alloys.

2. Test material

We have tested some of AlMgSc system alloys (1545, 1570, 1575 and 1597) commercially produced by Kamensk Uralsky Metallurgical Works [4]. Actual chemical composition of tested commercially produced alloys is given in Table 1.

***Table 1** Chemical composition of standard alloys*

Alloy	Element content, %									*Reference*
	Al	Si	Fe	Cu	Mn	Mg	Cr	Zr	Sc	
1545	base	0.07	0.12	0.03	0.3	4.7	0.02	0.10	0.21	7
1570	base	0.08	0.14	0.02	0.4	5.94	0.02	0.07	0.28	7
1575	base	0.08	0.14	0.03	0.50	5.6	0.17	0.09	0.24	6
CB1597*	base	0.07	0.10	0.03	0.60	5.77	0.18	0.09	0.44	6

* Alloy for welding wire

We have cast billets of various chemical compositions to determine possibility to improve tensile properties of AlMgSc system alloys by means of additional strengthening phases introduced to alloys and to determine influence of temperature and extrusion ratio on tensile properties. We have manufactured bars and pipes of various diameters from the experimental billets. Actual chemical composition of experimental alloys is given in Table 2.

***Table 2** Chemical composition of experimental alloys*

Experiment No.	Element content, %										
	Mg	Mn	Sc	Zr	Zn	Cr	Cu	V	Fe	Si	Ni	others
1	6.3	1.0	0.25	0.09	0.8	0.12	0.18	0.014	0.18	0.07	-	Be 0.0005
2	6.52	0.97	0.25	0.12	0.57	0.12	0.18	0.017	0.058	0.04	-	Be; Ce 0.0005
3	5.92	0.76	0.41	0.14	0.32	0.09	0.096	0.012	0.056	0.037	-	Be
4	6.3	0.89	0.24	0.12	0.62	0.11	0.20	0.012	0.058	0.04	-	Be; Ca 0.15
5	6.7	0.15	0.25	0.10	0.04	0.13	0.025	-	0.74	0.15	1.0	Be
6	7.1	0.02	0.22	0.12	1.1	0.02	0.18	-	0.8	0.21	1.0	Be
7	7.8	0.21	0.2	0.12	1.0	0.02	0.13	-	0.7	0.16	1.0	Be; Ca 0.05
8	6.6	0.84	0.21	0.11	0.54	0.11	0.01	-	0.05	0.03	-	Be; Ag 0.56
9	6.5	1.0	0.21	0.09	0.58	0.13	0.19	-	0.05	0.03	-	Be; Ag 0.69
10	6.2	0.8	0.27	0.10	0.5	0.09	0.2	0.003	0.14	0.07	-	-
11	6.7	0.2	0.28	0.11	0.6	0.13	0.05	0.005	0.8	0.22	0.9	-

3. Results and discussion

3.1. Influence of scandium content on properties of AlMgSc system alloys

We have extruded bars of 1575 and CB1597 alloys that differed only in scandium content to determine scandium influence. Billet extrusion temperature was 350-400^{0}C, flow rate was 0.5 m/min. We have tested tensile properties of extruded bars without further heat treatment and machining. The results are given in Table 3.

Table 3 Average values of tensile properties of extruded bars of 1575 and CB1597 alloys

Alloy	Ultimate strength, MPa	Yield strength, MPa	Elongation, %	$\sigma_{0.2}/\sigma_в$ ratio
1575	419	279	19	0.66
CB1597	414	280	16.5	0.68

This experiment revealed that scandium content increase in AlMgSc system alloys by more than 0.25% when zirconium content is at least 0.08% does not influence tensile properties of products of this alloy. We got the same result for extruded bars of experimental alloys (Table 7).

3.2. Influence of billet size and extrusion ratio

Considering that alloying of AlMg system aluminium alloys with scandium results in subdendritic structure formation at casting, grain size directly depends on cooling rate. In existing system of semi-continuous casting of billets cooling rate is a function of billet section size. For example, in 400 mm diameter billet of 1545 alloy average grain size is 40.8 µm and in 600 mm diameter billet it is 53.2 µm. We have extruded a rod of 150 mm diameter from 400 mm billet and 155x235 mm bar from 600 mm billet. Tensile properties of extruded rods/bars are shown in Table 4. Apparently, it has been extrusion ratio that influenced the tensile properties most, at the same time is it reasonable to seek to obtain as small grain size as possible by means of billet size optimization.

Table 4 Tensile properties of extruded rods/bars of 1545 alloy

Billet diameter, mm	Average size of billet grain, µm	Extrusion ratio	Ultimate strength, MPa	Yield strength, MPa	Elongation, %
400	40.8	7.1	390	270	18.0
600	53.2	4.3	375	250	20.5

3.3. Influence of temperature and extrusion ratio

We have extruded pipes of different diameters of 1570 alloy to determine influence of temperature and extrusion ratio on properties of extruded semis. Tensile properties of extruded pipes of 1570 alloy without additional heat treatment are given in Table 5. Specimens 1 and 2 are taken from different areas of one pipe with variable section.

The results have revealed that under otherwise equal conditions extrusion ratio increase makes it possible to improve pipe tensile properties; however increase of strain temperature over 400^{O}C results in properties deterioration.

Table 5 Tensile properties of extruded pipes of 1570 alloy depending on their temperature and extrusion ratio

Specimen No.	Billet temperature, ^{o}C	Extrusion ratio	Ultimate strength, MPa	Yield strength, MPa	Elongation, %
1	380	9.7	428-447	292-320	16.5-17.5
2	380	22.2	429-454	303-336	16.5-21.5
3	405	140	383-405	268-291	17.5-21.0

3.4. Influence of repeated strain

On account of available data on influence of strain on AlMgSc system alloys, an issue of influence of repeated strain on these alloys' properties is of concern. In this respect we conducted an experiment and manufactured forgings of 1570 alloy directly of the billet and of preliminary extruded rod. The tensile properties of forgings manufactured of a billet and of a preliminary extruded rod are given in Table 6. The tensile properties of forgings manufactured directly of a billet are lower than properties of those manufactured of extruded rod. It is related to less favorable strain pattern of forging manufacturing. At the same time manufacturing of a forging of a preliminary extruded blank enables higher tensile properties.

Table 6 Tensile properties of forgings of 1570 alloy

	Ultimate strength, MPa	Yield strength, MPa	Elongation, %
Forging made from a billet	383-405	268-291	17.5-21.0
Rod made from a billet	429-454	303-336	16.5-21.5
Forging made from a rod	428-447	292-320	16.5-17.5

3.5. Research of possibility to improve AlMgSc alloys properties by addition of Cu, Mn, Cr, Ni, Fe, Ag

Experimental alloys of compositions from 1 to 9 have been cast into Ø 260 mm billets. The bars of 31.8x139.7 mm cross-section have been extruded from these billets. The extrusion practice (temperature and extrusion speed) has been modified within certain limits to determine if it is possible to improve properties through strain. The tensile and corrosion properties of the bars have been tested. The bars have not been stretched or the residual stress after stretching was minimal (up to 1%), because the main purpose of the experiment was to obtain as high as possible properties in large-size pipes. At the second stage of the experiment (experiments 10, 11) hollow billets of Ø610x370 mm and Ø745x370 mm were cast. We have extruded the pipes of Ø430.6x37.5 mm cross-section from them. The results are given in Table 7.

The experiments showed that copper and zinc introduction together with iron content increase did not result in considerable improvement of tensile properties in comparison with 1570 alloy (experiments 1, 2, 4). Scandium content increase up to 0.41% together with zirconium content increase up to 0.14% (experiment 3) did not give an anticipated result. We got the same results for extrusion of CB1597 alloy (Table 3). On the other hand, this chemical composition allowed for the highest corrosion properties. The better properties in this experiment were obtained after stretch straightening with 3% residual stress. Introduction of iron-nickel phase made it possible to improve tensile properties (experiments 5, 6), though corrosion resistance of the alloy substantially decreased.

Table 7 Extrusion practice, tensile properties and corrosion resistance of experimental alloys of AlMgSc system

Exp. No.	Extrusion Practice				Ultimate strength, MPa	Yield strength, MPa	General corrosion, mm/year
	Extrusion ratio	Temperature of an billet/ container, °C	Extrusion speed, m/min	Stretch straightening $\varepsilon_{ост}$, %			
1	12	450-400/420 400-350/400 350-300/400	0.3-1.5 0.3-1.5 0.3-1.5	1 1 1	428 429 437	278 290 287	- - -
2	12	380/400 340-310/380	0.2-0.8 0.1-1.0	- 1	425 430	277 279	0.2607 0.2165
3	12	340/380 290/380 270/380	0.2-0.8 0.05-0.2 0.1-0.4	1 1 1 3	420 430 415 440	252 278 271 321	0.0007 0.0053 0.0096 -
4	12	380/400 310/380 290-260/380	0.2-1.0 0.2-1.0 0.05-0.4	1 - 1	420 425 425	276 283 280	0.2835 0.2827 0.3219
5	12	400/400 400/400 350/400	0.5 1.0 1.1	- - -	435 405 415	305 255 315	1.2752 1.1029 1.1125
6	12	395/360 370/360 310/380 295/380	0.7 1.2 1.0 1.0	- - - -	395 410 400 400	290 305 305 300	1,370 1,4243 1,3796 -
7	12	395/330 310/360	0.8 1.0	- -	345 355	135 125	1,4764 1,3642
8	12	390/400 370/400	0.5 1.0	- 1.0	412 418	270 275	- -
9	12	370/400	0.8	2.0	420	345	-
10	4.85	340/400 325/400	0.5 0.1	- -	425 430	275 280	- -
10	8.41	400/400	0.55	-	420	241	0,5064
11	4.85	325/400 330/400	0.4 0.5	- -	420 420	295 290	- -
11	8.41	405/400	0.4	-	400	246	1,8826

When magnesium content in AlMgSc alloy was increased and Fe-Ni phase up to 7.8% (7) was introduced, properties of the bars deteriorated. Apparently, it is related to separation of AlMg excess phase at grain boundary. Chrome addition into composition from 1 to 5 did not influence the alloys' properties. We have added calcium to composition 4 and 7 which increases ductility of AlMg and AlMgSi system alloys as determined by OAO KUMZ. However, in this case increased metal ductility could reduce properties increase by means of strain hardening. We made an attempt to improve tensile properties in compositions 8 and 9 by stabilization of phase composition through silver addition to the alloy similar in composition with 1575 alloy. The properties remained the same without stretch straightening. However, stretch straightening with 2% residual stress increased yield strength by 25% which reached 345 MPa.

We have chosen chemical compositions with the best balance of tensile properties to manufacture large-size pipes (experiments 10, 11). When we have extruded the pipes of Ø610x370 mm billet, we approached our goal as much as possible – yield strength in extruded condition reached 300 MPa. Unfortunately, the press power (maximum power of the press is 12,000 ton-force) was not sufficient to extrude Ø745x370 mm billet. To increase billet ductility we have had to increase its temperature over 400^{O}C, which resulted in tensile properties deterioration.

4. Summary

Scandium addition in amount of up to 0.18-0.25% in AlMg system alloys substantially increases tensile properties. Further increase of scandium addition under otherwise equal conditions does not improve tensile properties.

Addition of copper, iron, and nickel results in some improvement of ultimate strength and slight increase of yield strength, but greatly decreases corrosion resistance of products.

Optimum temperature for aluminium-magnesium-scandium alloys extrusion is 320-380^{O}C. Extrusion temperature increase over 400^{O}C results in great deterioration of tensile properties.

Additional strain after extrusion results in yield strength increase by 10-20%. Forgings produced of preliminary extruded material have higher tensile properties.

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