SCANDIUM IN ALUMINIUM ALLOYS OVERVIEW: PHYSICAL METALLURGY, PROPERTIES AND APPLICATIONS

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Abstract

The use of scandium as an alloying element in aluminium has gained an increasing interest even though scandium is difficult to extract, which makes the metal very expensive. The three principle effects that can be obtained by adding scandium to aluminium alloys are (i)grain refinement during casting or welding, (ii)precipitation hardening from Al_3Sc particles and (iii)grain structure control from Al_3Sc dispersoids. Addition of scandium in combination with zirconium is particularly effective, and the reason for this is linked to the recently discovered core/shell structure of the $Al_3(Sc,Zr)$ dispersoids. The effects that can be obtained from a Sc addition are to a large extent dependent on the alloy system to which it is added, and an overview of some effects in all the major classes of wrought aluminium alloys is given. Industrial use of Sc-containing aluminium alloy is so far limited to a few aerospace applications and to sporting equipment, further use is dependent on a price reduction of scandium.

Riassunto

L'introduzione dello scandio tra gli elementi di lega per l'alluminio sta suscitando crescente interesse malgrado l'elevato costo del metallo dovuto alle difficoltà nell'estrazione. L'aggiunta dello scandio nelle leghe di alluminio produce i seguenti effetti: i) affina il grano durante la solidificazione o la saldatura, ii) indurisce la lega per precipitazione del composto Al_3Sc, iii) stabilizza la struttura del grano ad alte temperature per mezzo di Al_3Sc. Inoltre l'aggiunta di Sc in combinazione con Zr è di particolare efficacia; il motivo è legato alla struttura "core-shell" dei dispersoidi $Al_3(Sc,Zr)$. Gli effetti che possono ottenersi dall'aggiunta dello Sc dipendono in gran parte dal sistema di lega alla quale è aggiunto. Vengono presentati in rassegna alcuni effetti prodotti dallo Sc nelle più importanti classi di leghe di alluminio da lavorazione plastica. Al presente, le leghe di alluminio contenenti Sc trovano limitate applicazioni nel settore aerospaziale e in pochi articoli sportivi; il loro sviluppo industriale per impieghi più diversificati è legato alla riduzione del costo.

INTRODUCTION

There has been an increasing interest for studying the potential of scandium (Sc) as an alloying element in aluminium (Al) alloys over the last two decades. Hundreds of scientific papers have been published describing various improvements in properties that can be achieved, and one text book [1] and a string of reviews or other overview articles [2-13] are written on this subject. A good indicator of the development of the interest in the scientific community is the amount of papers published at the ICAA-series of conferences, a biennial conference on the physical and mechanical properties of aluminium alloys. Figure 1 shows the number of papers related to Sc-containing Al alloys published in the conference proceedings over the years. The scientific interest in Sc-alloying is twofold. The most common motivation for the executed research is the improvement in properties that can be achieved by a Sc addition. The second motivation is related to the use of Al-Sc as a model system for studying basic principles of physical metallurgy. It turns out that Al-Sc alloys are particularly suitable for this purpose. However, even though the scientific interest for Sc in Al alloys has been considerable for several years the commercial use of such alloys is very limited. This is more than anything connected to the price and availability of Sc.

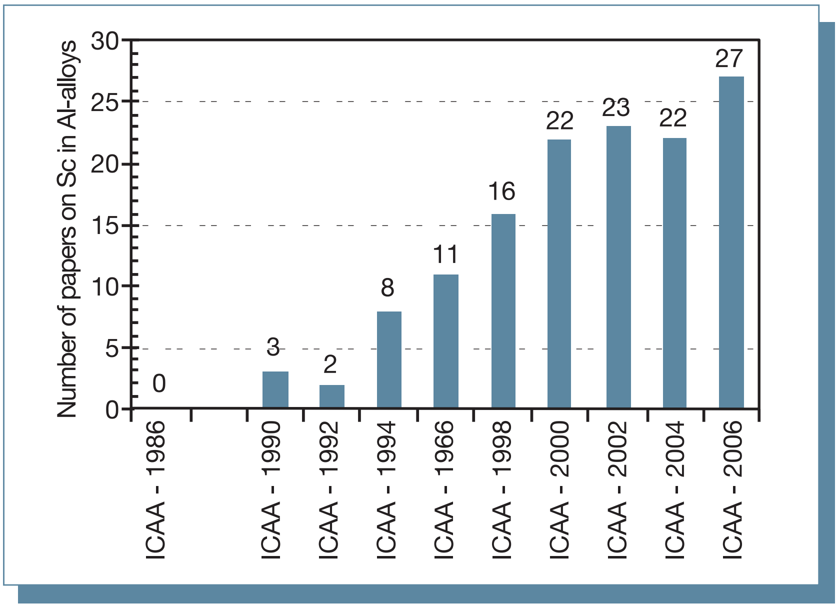

Fig. 1: Increasing interest in Sc as an alloying element in aluminium alloys expressed by the number of presentations related to this topic given at the ICAA-conferences over the years.

SCANDIUM

In a recent reader survey of the materials science journal JOM, the greatest moment in materials science was voted to be when Mendeleev constructed his periodic table of elements [14]. One of the advantages of Mendeleev's table over contemporary attempts to systemize the elements was that it made it possible identify yet undiscovered elements, and scandium was one of four elements quite accurately predicted by Mendeleev in the late 1860's. Sc was discovered a few years later, in 1876, by Lars Fredrik Nilsson. The fact that Sc had remained undiscovered up to this point reflects that it is rarely concentrated in minerals and ores. Despite being the 31st most abundant element in the earth's crust, half as abundant as copper, twice as abundant as lead and 10 times more abundant as tin [15], there are no known Sc-resources that are explorable for the Sc by itself. Sc gets concentrated in the by-products from processing of ores of other metals such as W, Sn, U and Al, and contemporary Sc extraction is based on such Sc-enriched tailings.

Scandium is a light metal, the density is approx. 3 g/cm^3 and the melting point is rather high, 1540°C. This is a combination of properties that could make Sc-based alloys an interesting candidate for lightweight high-temperature applications, but little, if any, research has been done in this field. There is no known commercial use of metallic Sc, and the global yearly demand for metallic Sc is very small.

AL-SC MASTER ALLOYS

When adding alloying elements to an aluminium melt, this can be done either by adding the pure elements or by adding the elements in the form of master alloys. Adding pure Sc to the melt is technologically feasible. From the binary phase diagram in Figure 2 [11, 16] it is evident that unless the melt is heated to a temperature higher than approx. 1185°C a sequence of phase transformations will have to take place before metallic Sc can dissolve in the melt, and that the rate of dissolution will be controlled by the slowest of the transformations. Dissolution of gram-size pellets at 800°C is reported to take more than 1h [17], this time is expected to decrease with increasing melt temperature.

However, metallic Sc is excessively expensive, which is due to both the scarceness of ores and a complicated extraction process. It turns out that it is possible to dissolve Sc in an Al melt simply by reducing the Sc oxide Sc_2O_3 directly in the melt [18]. Sc_2O_3 is considerably less expensive than metallic Sc. Thus, by preparing Al-Sc master alloy by this method the cost of adding Sc to an aluminium alloy is reduced by approx. an order of magnitude. The most common Sc-concentration of the master alloys available on the market is 2 wt.%, but contents in the range 1 – 20 wt.% are offered for sale.

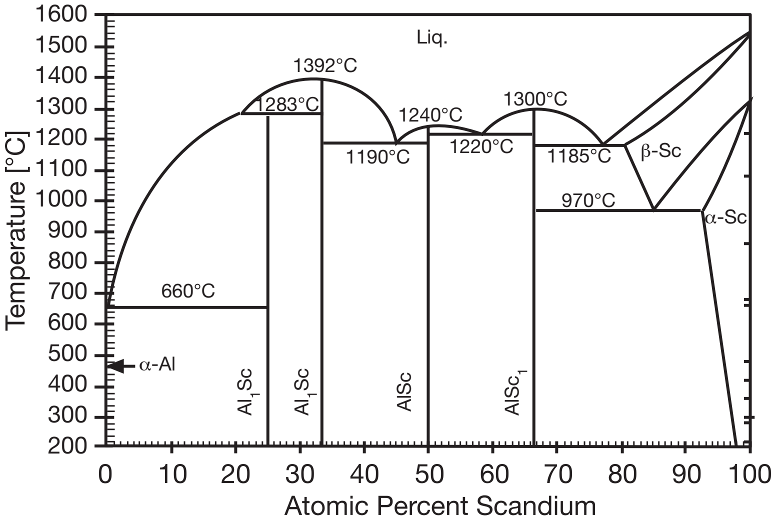

Fig. 2: A sketch of the Al-Sc phase diagram [11]. The sketch is largely based on data in Ref. 16.

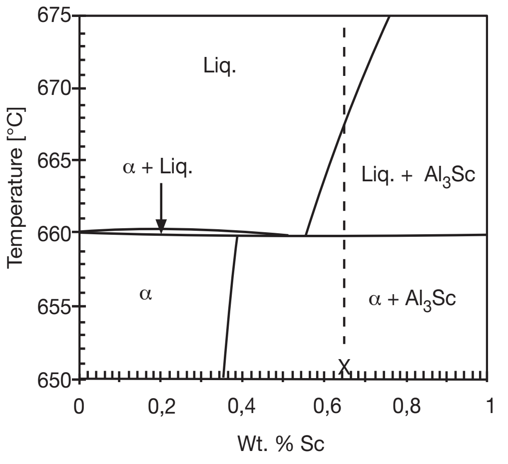

Fig. 3: Sketch of the Al-rich side of the Al-Sc phase diagram. The symbol X indicates an arbitrary hypereutectic composition.

THE EFFECT OF SC IN ALUMINIUM ALLOYS

There are three main reasons for adding Sc to aluminium alloys. All of these effects are related to the formation of particles of Al_3Sc, the phase that is in equilibrium with Al.

1 – GRAIN REFINEMENT DURING CASTING AND WELDING.

Consider the sketch of the Al-side of the Al-Sc phase diagram in Figure 3. There is an eutectic point at approx. 0.6 wt.% Sc and 659°C. If an alloy melt with the hypereutectic composition x as indicated in the figure is slowly cooled the first phase to form in the melt will be Al_3Sc. The lattice parameter of Al_3Sc is close to that of Al, and at a temperature of 659°C they are approx. 0.414nm [19] and 0.412nm [20] respectively, representing a lattice mismatch of approx. 0.5%. Due to the similarities of the atomic structures, the Al_3Sc particles are effective nuclei for solidification of aluminium crystals upon further cooling below the eutectic temperature [21]. It has been shown that the grain refining effect is further enhanced when adding Ti along with Sc in the melt. This leads to formation of $Al_3(Sc,Ti)$ particles that apparently are even more effective nuclei for Al during solidification [22]. There are few comparative studies between Sc and more common grain refiners such as TiB_2, TiC and SiC. The available studies indicate that Sc may perform equally well as [23, 24] or better than [25, 26] common grain refiners.

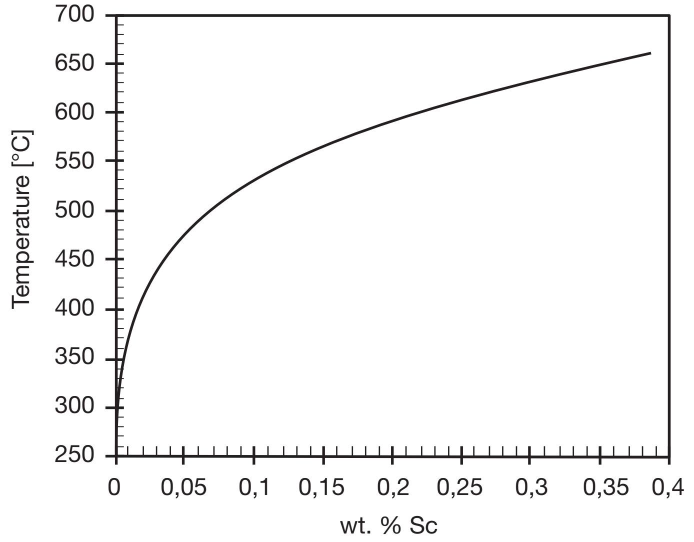

Fig. 4: The solvus line of Sc in Al [27].

2 – PRECIPITATION HARDENING

Figure 4 shows the solvus line on the Al-side of the binary Al-Sc phase diagram [27]. The maximum solubility of Sc is approx. 0.38 wt.%. However, it is relatively easy to obtain higher supersaturated solutions of Sc in Al-alloys by fast cooling during solidification. At a cooling rate of 100°C a supersaturation of 0.6 wt.% is achieved [28], and by quenching the liquid with a rotating mill device a supersaturation in excess of 5 wt.% has been reported [29]. The Sc in supersaturated solution may precipitate as finely dispersed Al_3Sc particles in the temperature range 250°C – 350°C [30, 31]. It has been shown that binary Al-Sc alloys with 0.1 wt.% Sc or more may give significant precipitation hardening [32, 33]. The hardness increase from Al_3Sc precipitation is somewhat lower than what is normally associated with precipitation hardened alloys, typically in the order of 100 MPa. It is not straightforward to combine precipitation hardening of Al_3Sc with precipitation hardening of the common heat treatable alloys (2xxx, 6xxx and 7xxx series). Figure 5 shows the typical temperatures for solution heat treatment and precipitation hardening of the common heat treatable alloys as well as the temperature regime for precipitation of Al_3Sc. It appears to be impossible to design a thermomechanical process route by which one can obtain full precipitation hardening from Al_3Sc in the common heat treatable alloys. It may be more feasible to use Sc for precipitation hardening in the non-heat treatable alloys of the 1xxx, 3xxx and 5xxx series.

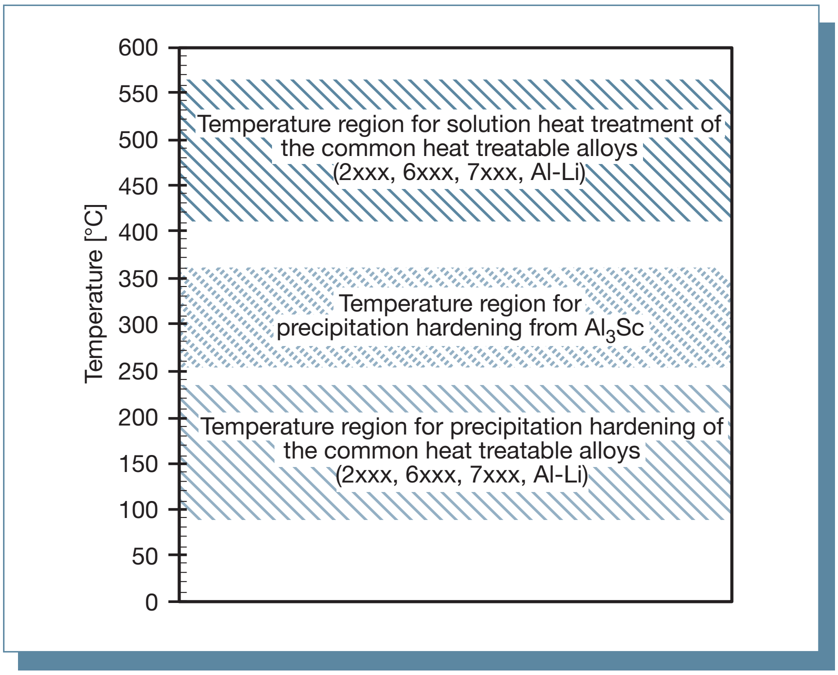

Fig. 5: Typical temperature regions for solution heat treatment and precipitation hardening of the common heat treatable alloys, and for precipitation hardening from Al_3Sc.

3 – GRAIN STRUCTURE CONTROL.

Precipitation of Al_3Sc may also take place at the temperatures used for homogenisation, or for solution heat treatment of common heat treatable alloys [11]. The Al_3Sc particles formed under these conditions, normally termed dispersoids, will usually be of too low number density for giving a strong contribution to the alloy strength. However, it is frequently found that the Al_3Sc dispersoids are very effective in impeding the movement of grain boundaries in the material. This leads to a good recrystallisation resistance of the material after forming operations such as rolling, extrusion and forging [11]. A non-recrystallised structure may improve properties such as strength, ductility, formability and corrosion resistance. A second advantage is related to superplastic forming. Superplastic forming is facilitated by a small grain size, and the Al_3Sc dispersoids are found to be effective in preserving the fine-grained structure during superplastic deformation.

CORE/SHELL $AL_3(SC,X)$ PARTICLES

It was discovered more than 20 years ago that the beneficial effects of adding Sc to Al alloys, and in particular those related to grain structure control, are enhanced when Sc is added in combination with Zr to the alloys. The improvement is related to a lower coarsening rate of the dispersoids, thus leading to a higher particle number density after exposure to high temperatures. Figure 6 a) shows the Al-rich corner of the 600°C-isotherm of the Al-Sc-Zr phase diagram, redrawn from [34]. It is found that the Al_3Sc phase solves significant amounts of Zr. This means that when Sc and Zr are added together in an aluminium alloy only a certain fraction, if any, of the Zr will form Al_3Zr particles, whereas the rest of the Zr will be solved in the Al_3Sc particles, which now should more correctly be designated $Al_3(Sc_{1-x}Zr_x)$ particles, or simply $Al_3(Sc,Zr)$ particles. The impact this has on the precipitation kinetics is illustrated in Figure 6 b) [11, 35], which shows C-curves for 10% and 60% completion of the precipitation reaction in Al-0.4wt.%Sc and Al-0.4wt.%Sc-0.15wt.%Zr. The addition of Zr does not influence on the start of the precipitation, but leads to a much slower reaction in the later stage. The reason for this was revealed recently by 3-dimensional atom-probe investigations [36, 37] and by computer simulation [38]; the precipitation starts with nucleation and growth of practically pure Al_3Sc, whereas Zr enters the particles at a later stage. This is explained by the much lower diffusivity of Zr compared to Sc, and leads to a core/shell structure where the nucleation and initial growth of the Al_3Sc core is controlled by Sc diffusion whereas the late growth and coarsening stage of the $Al_3(Sc,Zr)$ shell is controlled by Zr diffusion [39]. It should be mentioned that core/shell structures have also been observed earlier, in Al-Li based alloys where Al_3Li particles are observed to nucleate on and encapsulate pre-existing Al_3Sc

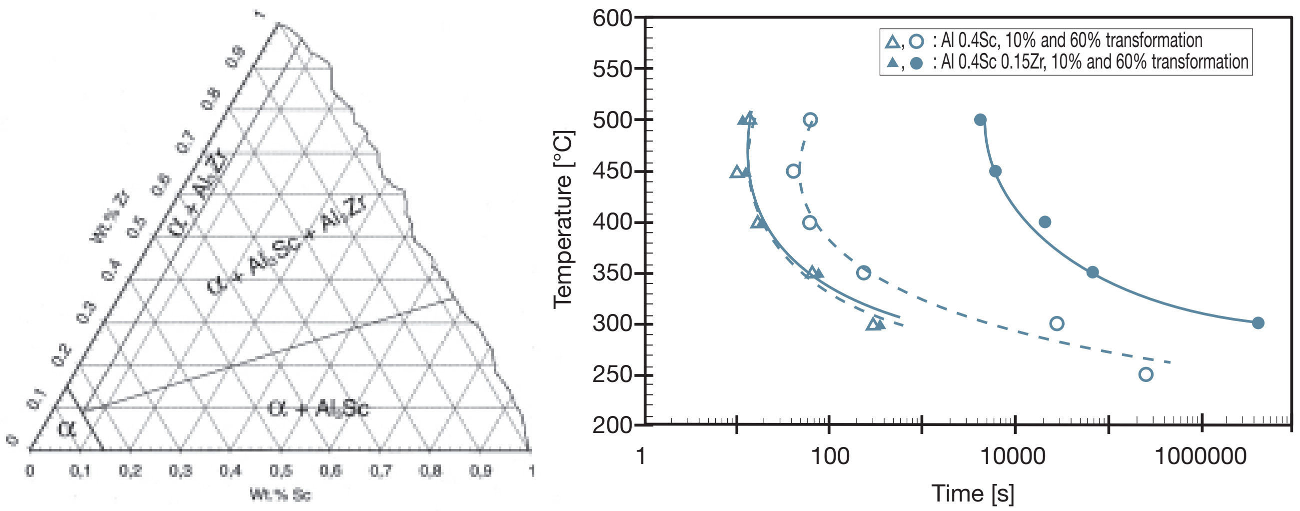

Fig. 6: a) The Al-rich corner of the 600°C-isotherm of the Al-Sc-Zr phase diagram, redrawn from Ref. 34.
b) Precipitation kinetics in Al-0.4Sc and Al-0.4Sc-0.15Zr, based on Ref. 35.

[40] or Al$_3$Zr [41] particles. However, in this case the core and the shell are of distinctly different phases (even though the crystal structures are equal and lattice parameters quite similar) and not a gradual change in composition within the same phase as is the case for the Al$_3$(Sc,Zr) particles.

Some efforts are being made of further exploiting the possibilities of using additional elements for creating core/shell Al$_3$(Sc,X) particles by including Ti [42], Hf [43] and a number of rare earths [44, 45].

PROPERTIES OF AL-ALLOYS CONTAINING SC

Giving a complete overview over the effects that can be expected from Sc-addition to all aluminium alloys is a rather exhaustive task, but some general observations can be made for the different classes of wrought aluminium alloys. In short one may state that for the non heat treateable alloys a significant increase in strength is possible with precipitation hardening from Al$_3$Sc particles, whereas for the heat treatable alloys a strengthening from Sc will depend on a combined effect of a small particle strengthening from Al$_3$Sc dispersoids, strengthening from a refined grain/subgrain structure and possibly on effects of Sc on the precipitation hardening in the alloy.

1XXX – PURE AL

According to the AA (Aluminum Association) designation system, aluminium of 99% purity or higher is classified as a 1xxx alloy. These alloys are used for packaging, electrical conductors, heat exchangers and architectural applications[46]. It is possible to add significant amounts of Sc to aluminium alloys within the 1xxx classification. The 1xxx alloys are categorised as unalloyed and non heat treatable, but a deliberate Sc addition will clearly give a precipitation hardening potential in these alloys. It is thus appropriate to consider whether otherwise unalloyed Al with Sc should still fall within the 1xxx series or whether the 8xxx series should be used. Even though binary Al-Sc is the most frequently investigated Sc-containing Al-alloy, no references to commercial 1xxx alloys with Sc are found in the literature.

Some properties that may be obtained in binary Al-Sc alloys[47] are listed in Table 1.

2XXX – AL-CU

The Al-Cu alloys are age hardenable, comprising some of the strongest aluminium alloys available. If Cu is the only element for precipitation hardening the precipitation sequence is apparently rather simple [48]:
sss → GPI → GPII → θ' → θ (Al_2Cu).
GP indicates Guinier-Preston zones, precursors to precipitates. The strength is normally highest when the GPII or θ' precipitates are predominant. Comparison of Sc-free with Sc-containing alloys do not indicate any strong effect of Sc on the precipitation kinetics of θ' [49].
Addition of Mg together with Cu leads to a faster and stronger age hardening. The presence of Mg leads to a different precipitation reaction[48]:
sss → GP → S'(Al_2CuMg) → S(Al_2CuMg).
It has been reported that Sc may lead to refined S' precipitate structure and thus to a higher strength in Al-Cu-Mg alloys[50, 51]. Some properties of Sc-containing Al-Cu and Al-Cu-Mg based alloys[50]

sss = Supersaturated solid solution

Table 1: Literature data on the effect of Sc on the strength of the various classes of wrought aluminium alloys

Alloy system	Ref.	Alloy	R_{p02} [Mpa]	R_m [Mpa]	Comment
1xxx	47	Al	15	48	Cold rolled material (89%), aged 288°C/8 h
		Al-0.23Sc	198	208	
		Al-0.38Sc	240	264	
2xxx	50	2618	~ 260	~ 330	Rolled sheet, solution heat treated, aged to peak hardness at 200°C (16-20h)
		2618 + Sc,Zr	~ 340	~ 390	
3xxx	53	Al-0.5Mn-0.2Mg-0.15Zr	87	140	As-extruded flat bar
		Al-0.5Mn-0.2Mg-0.15Zr-0.11Sc	119	173	
		Al-0.5Mn-0.2Mg-0.15Zr-0.21Sc	152	198	
		Al-0.5Mn-0.2Mg-0.15Zr-0.26Sc	168	207	
5xxx	54	Al-1Mg	50	120	As hot worked or annealed condition
		Al-1Mg- Sc (1515)	160	250	
		Al-2Mg-Mn	90	190	
		Al-2Mg-Sc (1523)	200	270	
		Al-4Mg-Mn	140	270	
		Al-4Mg-Sc (1535)	280	360	
		Al-5Mg-Mn	170	300	
		Al-5Mg-Sc (1545)	290	380	
		Al-6Mg-Mn	180	340	
		Al-6Mg-Sc (1570)	300	400	
	47	Al-5.3Mg	147	259	Cold rolled material (50%) w/intermediate anneals at 343°C, aged 288°C/8 h
		Al-5.3Mg- 0.3Sc	368	401	
6xxx	61	6082	333 / 338	351 / 357	Extruded rods, T5 age hardening at 185°C/ 4h (1st value) and 165°C/24h (2nd value)
		6082 + Sc,Zr	329 / 333	362 / 366	
	62	6060 + Zr	81	163	Extruded rods, T1 condition
		6060 + Zr,Sc	182	247	
	63	1370	380	430	Rolled sheet, T6 condition
7xxx	68	7017	400	475	Hot rolled plate, solution heat treated + aged to max. hardness at 120°C
		7017 + 0.25Sc	415	490	
	69	Al-8.6Zn-2.6Mg-2.4Cu-0.1Zr	649	672	Extruded rod, T6 condition
		Al-8.6Zn-2.6Mg-2.4Cu-0.1Zr-0.2Sc	689	715	
Al-Li	77	1420 (= 1421 without Sc)	270 / 280	440 / 450	Rolled sheet. Strength in longitudinal direction (1st value) and transverse direction (2nd value)
		1421	320 / 340	460 / 480	
		1423	350 / 330	460 / 460	
		1424	320 / 320	475 / 425	

are listed in Table 1. The 2xxx series alloys are frequently used for structural aerospace applications [46], and a Sc-containing 2xxx alloys for this purpose, 2023, has recently been developed by Alcan. The composition limits of 2023 [52] are given in Table 2. It appears that this alloy has not been put into use for any applications yet.

3xxx – Al-Mn

The Al-Mn alloys are normally classified as non-heat treatable, and are used for beverage cans, cooking utensils, heat exchangers and architectural applications [46]. It has been shown that additions of Sc can give significant strength increases within this alloy class, as indicated in Table 1[53], but no specifications for 3xxx alloys with Sc intended for commercial use appear to have been developed.

4xxx – Al-Si

Al-Si wrought alloys are classified as non heat treatable, and are most commonly used for welding wire or as a brazing alloy [46]. A very limited number of investigations of Sc-addition to these alloys has been done. When Sc is added to aluminium alloys with high Si contents there is a tendency for forming a ternary phase, $AlSc_2Si_2$, rather than the desired Al_3Sc phase [11]. This is probably the reason why little efforts have been put into investigating Sc-additions to 4xxx alloys.

5xxx – Al-Mg

This alloy system comprises the strongest of the non heat treatable aluminium alloys, and common uses are for beverage cans and for architectural, marine and automotive applications [46]. Second to binary Al-Sc alloys, the Al-Mg-Sc alloys are the Sc-containing alloys that have been most extensively studied. Some examples of properties [54] are listed in Table 1. These alloys have been evaluated for aerospace applications, amongst other for the Airbus 380, but are not put into use yet. One AA-designation for a 5xxx alloy with Sc, 5025, exists but it is currently inactive. The 5025 alloy is intended for use as welding wire, and the composition limits [52] are given in Table 2. A series of Al-Mg-Sc alloys for structural applications were developed in the former Soviet Union. The complete composition limits for these alloys do not appear to be available in the open literature, but the limits for Mg, Sc and Zr [55] are given in Table 2.

TABLE 2: COMPOSITION OF SOME COMMERCIAL ALUMINIUM ALLOYS CONTAINING SCANDIUM

Alloy system	Alloy	Ref.	Si	Fe	Cu	Mg	Li	Zn	Zr	Sc	Other
2xxx	2023	[52]	0.10 max	0.15 max	3.6-4.5	1.0 – 1.6	–	–	0.05 – 0.15	0.01 – 0.06	Mn < 0.30, Cr < 0.10. Ti < 0.05
5xxx	5025	[52]	0.25 max	0.25 max	0.10 max	4.5 – 6.0	–	0.25 max	0.10 – 0.25	0.05 – 0.55	Mn < 0.20, Cr < 0.20, Ti 0.05 – 0.20, Be < 0.0008
	1515	[55]				0.9 – 1.4			0,05 – 0.15	0.20 – 0.40	REM
	1523					1.8 – 2.4			0.10 – 0.20	0.20 – 0.40	V, REM
	1535					3.9 – 4.5			0.05 – 0.15	0.30 – 0.50	Be, REM
	1545					4.6 – 5.7			0.05 – 0.15	0.30 – 0.50	Be, REM
	1570					5.3 – 6.3			0.05 – 0.15	0.15 – 0.35	Be
	1571					5.8 – 6.8			0.05 – 0.15	0.30 – 0.50	Cr, Be, B, REM
7xxx	1970	[5]			0.35*	2.0*		5.4*	0.1*	0.25*	Mn 0.3*
	1975				0.25*	2.0*		5.4*	0.1*	0.08*	Mn 0.3*
Al-Li	1421	[78]	0.10 max	0.15 max	–	4.8 – 5.2	1.9 – 2.2		0.08 – 0.10	0.12* [77]	
	1423	[77]	0.1 max	0.15 max		3.5*	1.9*	0.1*	0.12*	0.08*	
	1430	[79]	0.1 max	0.15 max	1.5 – 1.8	2.5 – 3.0	1.5 – 1.9		0.08 – 0.14	0.02 – 0.3	Ti 0.02 – 0.1, Be 0.02 – 0.2, Y 0.05 – 0.25
	1460	[80]			2.6 – 3.3	0.05 - 0.10	2.0 – 2.5		0.06 – 0.15	0.05 – 0.14	Mn 0.05 – 0.10

* = Nominal value or example value
\- = No deliberate addition
Empty cell = no information available

6XXX – AL-MG-SI

Due to a favorable combination of strength, formability, weldability and other properties the 6xxx alloys are the most popular wrought aluminium alloys for structural applications. Typical uses are for architectural and automotive applications. The precipitation sequence of these alloys is commonly given as

$sss \rightarrow GP \rightarrow \beta'' \rightarrow \beta' \rightarrow \beta(Mg_2Si)$.

It appears that Sc additions have only limited, if any, influence on the precipitation hardening response [56, 57]. If Cu is added to Al-Mg-Si alloys the precipitation sequence shifts to

$sss \rightarrow GP \rightarrow q' \rightarrow Q(Al_5Cu_2Mg_8Si_6)$.

The effect of Sc on the precipitation hardening response of Al-Mg-Si-Cu alloys also seems to be small [58]. There appears to be a delay in the overageing of the alloy when Sc is present.

A limited amount of research has been performed on Sc-addition to these alloys, probably due to the risk of forming $AlSc_2Si_2$ rather than the desired Al_3Sc phase. It has however been shown that a high number density of $Al_3(Sc,Zr)$ dispersoids may form in these alloys [57, 59, 60], giving some indication that the improved microstructural control obtained by Sc addition in many Al-alloys may also be taken advantage of in the 6xxx alloys. Some literature data on the influence of Sc on the strength of 6xxx alloys [61-63] are given in Table 1. A Sc-containing Al-Mg-Si-Cu alloy, 1370, has been developed in the former Soviet Union. The alloy is stated to be analogous to the AA6056 alloy but with additions of Ni, Sc and Zr [63].

7xxx – Al-Zn-Mg

Strictly speaking the 7xxx series is identified as Al-Zn alloys, but practically all 7xxx alloys contain significant amounts of Mg and are heat treatable. The Al-Zn-Mg(-Cu) alloys represent the strongest aluminium alloys commercially available, and are therefore extensively used in aerospace applications and for automotive structural parts. Depending on the Zn/Mg ratio of the alloys two different precipitation sequences may be observed [48]:

sss $\rightarrow$ GP $\rightarrow \eta' \rightarrow \eta$ ($MgZn_2$).

sss $\rightarrow$ GP $\rightarrow$ T' $\rightarrow$ T ($Al_2Mg_3Zn_3$).

Reports on how Sc influences the precipitation behaviour in 7xxx are somewhat contradictory, both slower [64] and faster [65] precipitation has been observed, as well as no particular effects [66, 67].

Table 1 contains some data on the influence of Sc on the mechanical properties of some 7xxx alloys [68, 69]. At least 4 Sc-containing 7xxx-alloys were developed in the former Soviet Union, with the designations 1970, 1975, 1981 and 1987. The full composition limits are not available, but some examples of compositions [5] are given in Table 2.

Al-Li alloys

The Al-Li based alloys do not belong to a particular series in the AA designation system. If Li is the alloying element with highest concentration (wt.%), numbers of the 8xxx-series are used. Most of the Al-Li alloys that do not belong to the 8xxx series have a higher Cu than Li content, and thus belong to the 2xxx series. One alloy with a high Mg content belongs to the 5xxx series. Within the 2xxx, 5xxx and 8xxx series the penultimate digit 9 indicates that it is an Al-Li based alloy. The development of the Al-Li alloys has been driven by a wish for improved alloys for the aerospace industry [46].

In binary Al-Li the precipitation sequence is simple:

sss $\rightarrow \delta'$(Al_3Li) $\rightarrow \delta$ (AlLi).

The presence of Sc leads to a significantly reduced size of the d' precipitates, but has a limited effect on the precipitation kinetics and on the resulting strength in the binary Al-Li system [70, 71]. However, the coarsening of the δ' precipitates is considerably slower in the Sc-containing alloys.

In Al-Li-based alloys with Cu and Mg a range of other Li-containing phases (Al_2MgLi, Al_2CuLi, Al_6CuLi_3 and Al_7Cu_4Li) and their precursors may also precipitate depending on composition and thermomechanical processing [72]. However, the d' and d phases remain the main phases for precipitation strengthening of these alloys [72]. The reported influence of Sc on the precipitation hardening response in the more complex alloys ranges from negative [73] through rather neutral [74] to positive [75, 76]. Some literature data on the strength of Sc-containing Al-Li based alloys [77] are included in Table 1.

A range of Al-Li based alloys with Sc were developed in the former Soviet Union. The alloy designations known to the author are 1421, 1423, 1424, 1430, 1460, 1461 and 1464. Unfortunately no open source for the composition windows is found, but a collection of composition data from the literature [77-80] is given in Table 2.

USE OF Sc-CONTAINING ALUMINIUM ALLOYS

The use of Sc as an alloying element in aluminium alloys was first investigated by scientists of the former Soviet Union, who developed several Sc-containing Al-alloys during the 1980's and 1990's. Much of the alloy development that took place appears to be intended for aerospace applications. One alloy, 1421, is used for fuselage stringers of large cargo aircrafts [77], and some parts of the MiG 29 military aircrafts are also made of Sc-containing Al-Li based alloys. It is also claimed that some parts of the international space station (ISS) are made from alloys with Sc.

Ashurst Technology, a company that specialized in technology transfer between the former Soviet Union and the western world, developed a series of alloys for sporting equipment in cooperation with Kaiser Aluminum of USA.

PRICE AND AVAILABILITY OF SC

Al-2%Sc alloys can be bought at a price in the order of US$50/kg, which translated to a Sc price of US$2500/kg. If 0.2 wt.%Sc is going to be added to an alloy this will add US$5/kg to the material cost which, depending on the alloy, represents a doubling to quadrupling of the material cost. It is obvious that with such prices the use of such alloys is very limited. Further use of Sc in aluminium alloys depends to a large degree on a development of less expensive sources for Sc. Current scandium production is to a large extent based on stockpiles of Sc_2O_3 of the former Soviet Union. These stockpiles are bound to be exhausted within the foreseeable future, and alternative sources are sought. One particularly promising option is to extract Sc_2O_3 from "Red mud"[84], the residues of the Bayer process for extracting Al_2O_3 from bauxite. Preliminary analyses indicate that this process route may lead to a reduction in Sc_2O_3 price with approx half an order of magnitude. Such a price reduction will probably lead to a more widespread use of Sc in aluminium that what is the situation today.

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