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Review
The weldability of lithium-containing aluminium alloys

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Lithium-containing aluminium alloys have reduced density and increased elastic modulus compared with conventional aluminium alloys. Many such alloys are currently under development for aircraft applications, which usually involve mechanical fastening. Consequently, the weldability of lithium-containing aluminium alloys is currently receiving relatively little attention. The weldability of lithium-containing aluminium alloys is reviewed. The vast majority of the welding studies performed have been on the Soviet Al–5 wt% Mg–2 wt% Li alloy, 01420. Alloy 01420 and other lithium-containing aluminium alloys are indeed fusion weldable, and weldments having high joint efficiencies have been made.

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1. Introduction

Besides beryllium, which is extremely toxic, lithium is the only alloying element that both decreases the density and increases the elastic modulus of aluminium [1]. Each increment of 1 wt % Li alloyed with aluminium decreases density by about 3% and increases Young's modulus (*E*) by about 6% [2]. Lithium-containing aluminium alloys are being developed for use in applications where weight reduction can lead to savings in fuel costs and to increased performance. In fact, several studies have concluded that Al–Li alloys can dramatically reduce aircraft weight [3–5]. For an Al–3 wt % Li alloy, structural weight savings of 10% on affected structures could be realized by direct substitution, and 16% by design modification [4]. Each pound (454 g) of material saved from a commercial airliner saves the airline company about $250 in fuel over the life of the aircraft at today's fuel prices [4]. Because of this great cost-saving incentive, most Al–Li alloy development has been aimed towards the aircraft industry where, most often, aluminium alloys are mechanically fastened. Consequently, relatively little research and development has been performed on other means of joining Al–Li alloys, such as fusion welding. For these alloys to be used in a wider range of applications, weldable alloy variants should be developed. Such variants might serve in marine applications, lightweight pressure vessels, and armoured land vehicles.

The present paper reviews the published literature on weldable lithium-containing aluminium alloys. Although some welding research on Al–Li binary, Al–2.5 Mg–0.6 Li and Al–3 Li–*X* alloys has been uncovered, most of the research has been on the Soviet Al–5 Mg–2 Li commercial Alloy 01420.* The weldability of these various lithium-containing alloys will be discussed in detail.

2. High-purity binary Al–Li alloys

Cross *et al.* [6] investigated the weldability of high-purity Al–Li binary alloys by the varestraint test to assess their hot-tearing susceptibility. Hot-tearing is cracking in the weld zone caused by the inability of the liquid region to

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*All alloy compositions in this review are in weight per cent.

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TABLE I Comparison of ingot and weld metal lithium contents* [6]

Nominal ingot composition (wt %)	Measured ingot composition (wt %)	Measured weld composition (wt %)
1	0.9	0.9
2	1.6	1.7
3	2.8	2.9
4	3.8	3.6
5	4.7	4.4

*Impurities (wt %): 0.04 Si, 0.10 Fe, 0.001 Ca.

support the strain imposed by solidification shrinkage [6, 7]. In the varestraint test, a constant bending strain, in this case 4%, is imposed during welding. The total crack length that forms in the weld zone is taken as a measure of the hot-tearing susceptibility of the alloy. Autogenous gas tungsten arc (GTA) welding was performed using straight polarity, constant 100 A/16 V direct current, helium cover gas, and travel speeds of 2.1, 4.2 and 6.3 mm sec^{-1}, which generated heat inputs of 760, 380 and 250 kJ m^{-1}, respectively. The compositions of the five Al–Li alloys investigated are contained in Table I.

Hot-tearing susceptibility varied with lithium content and exhibited a steep peak at 2.6% Li (Fig. 1). Depth of penetration increased with increasing heat input, as is observed in other aluminium alloys [7]. However, depth of penetration increased with lithium concentration, which Cross *et al.* [6] found somewhat surprising. They suspect that the decrease in thermal conductivity that accompanies increasing lithium content may cause this increase in penetration.

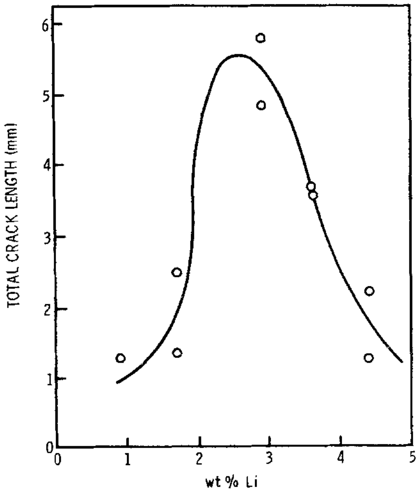

Figure 1 Peak hot-tearing susceptibility of high-purity Al–Li binary alloys occurs at 2.6% wt % Li (Cross *et al.* [6]). Travel speed 4.2 mm sec^{-1}.

When the lithium content was low, cellular dendrites grew perpendicular to the weld direction, whereas at high lithium contents they grew parallel to the weld direction. The spacing of the cellular dendrites increased with increasing heat input, and decreased with increasing lithium content. In all cases, the lithium content in the weld nearly equalled that in the bulk (see Table I).

Cross *et al.* [6] showed that high purity Al–Li alloys are readily weldable and have good resistance to hot-tearing. Even at the most susceptible composition, 2.6% Li, hot-tearing susceptibility was less than that observed in weldable Al–4.4% Mg commercial alloy, 5083.

3. Swiss Al–2.5 Mg–0.6 Li–0.55 Mn–0.14 Ti alloy

Sperry and Mardigo [8] of Swiss Aluminium Ltd patented a lithium-containing aluminium alloy with the London Patent Office. This alloy was claimed to have excellent formability, moderate strength (see Table II), good elevated temperature strength, and favourable weldability characteristics. As is generally the case with composition patents, it claimed an overly broad composition range and specified additions of

TABLE II Tensile properties of Swiss Alloy in cold-rolled and annealed conditions [8]

Condition	Orientation*	Yield strength		Tensile strength		Elongation (%)
		(MPa)	(ksi)†	(MPa)	(ksi)	
Cold rolled	L	330	47.9	347	50.3	2.5
	LT	338	49.0	370	53.7	3.0
Partially annealed	L	199	28.8	275	39.9	11.0
	LT	207	30.0	281	40.7	14.3
Fully annealed	L	117	17.0	239	34.7	19.5

*L = longitudinal, LT = long transverse.

†1 ksi = 10^3 psi.

TABLE III Electrical conductivity of Swiss Alloy [8]

Alloy composition (wt %)	Conductivity (% IACS)*
Al–2.52 Mg–0.60 Li–0.55 Mn–0.14 Ti	22.5
Al–2.50 Mg–0 Li–0.54 Mn–0.15 Ti	32.3

*Per cent of the conductivity of annealed copper.

numerous possible minor alloying elements. The lithium range claimed was from 0.3 to 1.0 wt % and the composition in the preferred example in the patent is Al–2.52 Mg–0.60 Li–0.55 Mn – 0.14 Ti [8].

The lithium addition is claimed to decrease electrical conductivity (see Table III), which facilitates resistance or "spot" welding. This is consistent with resistivity work by Noble *et al.* [9] on Al–Cu–Li alloys and with previously unreported work by Pickens [10] on mechanically alloyed Al–Li binary alloys (see Fig. 2). The lithium is also claimed to contribute to ductility and formability [8]. (Presumably, in this case, the lithium does not adversely affect ductility and formability because it exists in solid solution, not as the coherent δ' precipitate, which is known to impair ductility by promoting heterogeneous, i.e., "planar" slip [11–15].)

This alloy appears to have advantages for automotive applications in which spot welding is a cost-effective method of joining. As an ancillary benefit, the alloy has a slightly lower density than other automotive alloys such as Alloy 7021. Interestingly, for spot welding this alloy, the lithium actually improves weldability.

4. Soviet Al–Mg–Li Alloy 01420

Most of the welding research performed on lithium-containing aluminium alloys has been on Soviet Al–5 Mg–2 Li–*X* Alloy 01420 which, in fact, is the only weldable aluminium–lithium alloy in widespread commercial use. Consequently, a brief description and history of this alloy will be presented before reviewing its welding characteristics.

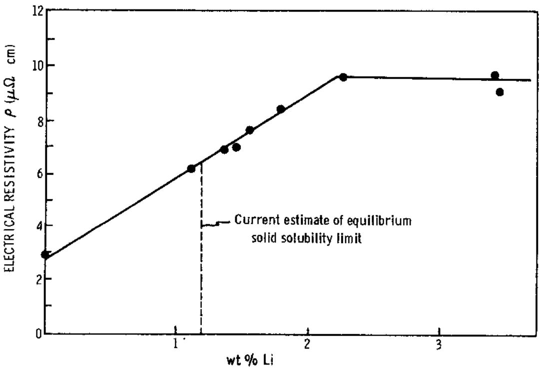

Figure 2 The electrical resistivity of mechanically alloyed Al–Li binary alloys increases with lithium content beyond the equilibrium solid solubility limit.

4.1. Background and physical metallurgy of Alloy 01420

Alloy 01420 was developed by Fridlyander and co-workers [16–18] during the early 1960s and has a nominal composition of Al–5 Mg–2 Li – 0.1 Zr. Variants of this composition also bear the 01420 designation, e.g. Al–5 Mg–2 Li–0.4 Mn, and both this manganese-containing variant and the zirconium-containing variant with ancillary alloying additions such as titanium. The composition ranges claimed by Fridlyander in his patent [16] are 4–7% Mg, 1.5–2.6% Li, 0.2–1.0% Mn and 0.05–0.3% Zr. Several zirconium-free versions in the above compositional ranges containing 0.05–0.3% Cr or 0.05–0.15% Ti or 0.05–0.3% Cr plus up to 0.1% Ti were also claimed.

The physical metallurgy and microstructures of various lithium-containing aluminium alloys including the Al–Mg–Li system have recently been reviewed extensively [19–23]. In addition, a recent review by Rogers [24] describes the metallurgy of Alloy 01420 and a paper by Balmuth and Schmidt [25] contains a brief review of the alloy's development. Some of the following physical metallurgy discussion is taken from relevant sections of these reviews.

The zirconium in Alloy 01420 is effective in refining grain size and, despite the fact that it decreases magnesium and lithium solubility in aluminium [24], it has been shown to improve corrosion resistance. Manganese also refines the grain size and increases the corrosion resistance of Alloy 01420, although not as effectively as zirconium. In addition, the manganese-containing variant has a lower solvus temperature than the zirconium variant.

Silicon is claimed to increase the yield strength of Alloy 01420, improve corrosion resistance, and decrease the embrittlement often attributed to sodium impurity. Consequently, the silicon content, usually present as an impurity element, is kept above 0.1%.

Sodium is well known as a cause of edge

cracking in Al–Mg alloys [26–29] and is claimed to have an embrittling effect on Alloy 01420. Talbot and Ransley [26–28] showed that bismuth additions reduced edge cracking in commercial Al–Mg alloys caused by sodium impurity. Likewise, Soviet researchers claim that bismuth additions reduce the embrittling effect of sodium on Al–Mg–Li Alloy 01420 [24].

Vasudevan *et al.* [30] studied the effect of sodium impurity on the ductility and toughness of an Al–3.2% Li alloy containing manganese for grain refinement. They added controlled amounts of sodium ranging from 0 to 600 atomic ppm to alloys that were then homogenized, rolled, solutionized, cold water–quenched, and aged at 204° C for 0, 4 and 48 h. Tensile and Charpy slow-blend tests were performed and secondary ion mass spectroscopy (SIMS) was used to detect sodium on specimens fractured under ultra-high vacuum.

For the as-quenched and for the underaged (4 h at 204° C) specimens, an increase in bulk sodium content caused an increase in grain boundary sodium content, resulting in a decrease in toughness. Embrittlement was detected at sodium contents as low as 7 atomic ppm. Furthermore, the intergranular nature of the fractures in these two tempers increased with increasing bulk sodium content. On the other hand, the toughness of peak aged specimens (48 h at 204° C) was largely insensitive to bulk sodium content. Vasudevan *et al.* [30] explain these results as follows. Sodium has an embrittling effect on Al–Li alloys which is apparent in the as-quenched and underaged conditions, where the tendency towards planar slip is slight. In the peak aged condition, the tendency towards slip planarity increases and dominates the fracture mechanism, so any embrittling effect of sodium becomes insignificant in comparison [30]. Thus, sodium can embrittle Al–Li alloys and sodium embrittlement might occur in the weld zone in areas having thermal histories that produce underaged microstructures.

Beryllium has been shown to reduce the loss of lithium from Alloy 01420 during solution heat treatment or homogenization [31]. Tarasenko *et al.* [32] claim that 0.2 wt % Be promotes the formation of protective oxides, such as $MgAl_2O_4$ and $BeAl_2O_4$, which prevent lithium loss.

Alloy 01420 is heat-treatable, and typical conditions for high strength are: solution heat treat at 450° C, water quench, and age at 120° C for 12 to 24 h [33, 34]. It should be noted, however, that considerably different ageing conditions have been claimed to produce peak strength, e.g. 8 to 16 h [35] and 16 to 24 h [35] at 170° C (note inconsistency in the same reference). In addition, ageing at 120° C for 12 to 48 h has been claimed to improve the ductility of Alloy 01420 [35]. High-strength conditions for Alloy 01420 generally range from 440 to 490 Mpa (64 to 71 ksi) tensile strength, and 290 to 350 MPa (42 to 51 ksi) yield strength. Mironenko *et al.* [36] have demonstrated attractive cryogenic tensile properties for Alloy 01420 at temperatures as low as − 196° C.

A survey of available commercial aluminium alloys revealed that Alloy 01420 has the lowest density (2.47 g cm^{-3}) of any widely-used aluminium alloy. Both magnesium and lithium decrease density, although the former decreases Young's modulus [1]. Lithium is well known for its ability to increase modulus [1, 2], and Alloy 01420 has a Young's modulus of about 73.4 GPa (10.7×10^6 psi) [17], compared with about 71.7 GPa (10.4×10^6 psi) for high-strength Al–Zn–Mg alloys and 70.3 GPa (10.2×10^6 psi) for high-strength Al–Mg alloys [37].

Alloy 01420 reportedly is "widely used in airplane and rocket construction" [24]. Fridlyander *et al.* [35] claim a weight reduction of 11% in compression-critical applications and 20% in stiffness-critical applications compared with conventional Soviet alloys. In addition, Paretskii *et al.* [38] have claimed 12 to 20% weight reduction from using Alloy 01420. Furthermore, the alloy has a good corrosion resistance similar to that of Al–6% Mg. Its usefulness stems from its low density, attractive specific mechanical properties, and its weldability characteristics, which will now be reviewed in detail.

4.2. Weldability of Alloy 01420

4.2.1. Filler wires used for Alloy 01420

Mironenko *et al.* [39] studied the weldability of Alloy 01420 using various filler wires, the compositions of which are contained in Table IV. They used argon-arc welding on 2 mm thick sheet that was solutionized at 450° C, air cooled,

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[†] 1 ksi = 10^3 psi.

TABLE IV Composition of filler wires used by Mironenko *et al.* [39] to weld Alloy 01420

Filler wire	Composition (wt %)								
	Mg	Mn	Ti	Zr	Be	Cr	Li	Impurities	Al
01420	5.0	0.01	0.0015	0.11	–	–	2.2	0.08 (Fe + Si)	Balance
Sv–AMg6	6.5	0.6	0.10	–	0.0037	–	–	0.61 (Fe + Si + Cu + Zn)	Balance
1557	5.32	0.4	–	0.21	0.0021	0.09	–	0.25 (Fe + Cu + Si)	Balance
Sv–AMg5	5.4	0.69	0.10	–	0.0032	–	–	0.62 (Fe + Si + Cu + Zn)	Balance

and aged for 12 h at 120° C – a high-strength condition. To prevent porosity, they chemically milled 0.2 to 0.3 mm from the alloy surface in 20 to 30% NaOH aqueous solution at 40 to 60° C, followed by a cleansing etch in a 30% HNO_3 solution. This surface-preparation technique will be described in greater detail later.

Mironenko *et al.* [39] claim that all the filler wires examined contributed to the high hot-tearing resistance observed during the welding of Alloy 01420. The fillers were ranked in order of combined increasing grain refinement in the weld and increasing weld ductility as follows: Alloy 01420, Sv–AMg6, Sv–AMg5, and Alloy 1557. The strengths of the welds made from the latter three fillers were similar and that of the weld made using Alloy 01420 filler was 15% lower. In addition, the welded joints made using the Alloy 1557 and Sv–AMg5 fillers were resistant to stress-corrosion cracking at stresses up to 195 MPa (28.4 ksi) [39]. Based on the many welding observations made during the filler wire study, it was concluded [39] that Alloy 01420 has "good weldability".

4.2.2. Weld-zone porosity and pre-welding surface preparation

Numerous Soviet researchers have noted that weld-zone porosity is often a problem with Alloy 01420 [36, 39–47]. As will be discussed later, one reason for the high porosity is the surface reactivity of Alloy 01420 with ambient moisture, which makes pre-welding surface preparation for this alloy critically important. In a systematic study of surface-preparation techniques, Fedoseev *et al.* [40] examined the following seven methods:

(a) Degreasing with organic solvents followed by cleaning with a scraper.

(b) Chemically pickling in a 5% NaOH solution followed by a rinse in HNO_3 to remove reaction products.

(c) Chemically pickling such that a passive film results.

(d) Chemically pickling followed by mechanical scraping.

(e) Mechanically milling up to 0.5 mm from the surface.

(f) Chemically milling up to 0.3 mm in a 200 g l^{-1} alkaline solution (a more alkaline solution than (b) above).

(g) Vacuum degassing followed by mechanical scraping.

Tungsten Inert Gas (TIG) welding was performed using filler wires of Sv–AMg6 (see Table IV) and Sv–AMg6TsVCh (composition unclear). They measured porosity in the weld zone using optical microscopy over a region 100 mm in length.

Material welded after undergoing surface-preparation techniques (a) to (d) contained numerous pores, mostly at the fusion line, with very few pores at the centre of the weld, whereas preparation techniques (e) to (g) successfully prevented pore formation [40]. Furthermore, Fedoseev *et al.* [40] noted that of the latter group, the chemical milling technique (f) is generally the most practical because it can be performed on a wide variety of shapes, e.g. wide sheets and complex extrusions, where mechanical scraping is difficult. They noted a marked drop in porosity after removing a 0.05 mm layer from the surface, and recommend removing 0.2 to 0.3 mm from sheets of less than 2 mm thickness to ensure that weld zone porosity will be virtually eliminated.

Fedoseev *et al.* [40] also studied the effect of arc energy on porosity in 2 and 6 mm Alloy 01420 sheets prepared by technique (b). Porosity decreased with arc energy from 880 to 4390 J cm^{-1} for 2 mm sheet and from 7240 to 21 550 J cm^{-1} for 6 mm sheet, and then increased slowly in both cases (Fig. 3). They attribute the minima in these curves to the competition

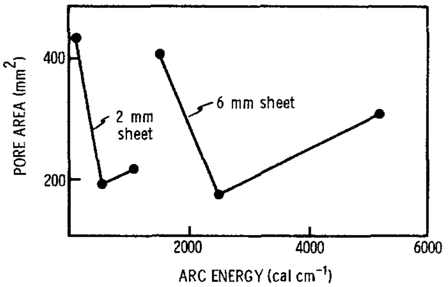

Figure 3 Effect of arc energy on Alloy 01420 weld porosity for 2 mm and 6 mm sheet (from Fedoseev *et al.* [40]); 1 cal = 4.187 J).

between growth of gas bubble nuclei and gas trapping in the weld.

Fedoseev *et al.* [40] obtained excellent strength in the weld zone – 82% of base metal properties (i.e. 82% "joint efficiency")‡ – and observed that Alloy 01420 has a low susceptibility to hot-tearing. However, Fedoseev *et al.* [40] demonstrated that extreme care must be exercised during surface preparation to eliminate weld porosity.

Fridlyander [18] discussed reasons for the susceptibility of Alloy 01420 to weld-zone porosity. He claimed that lithium-containing compounds such as LiO_2, LiOH, Li_2CO_3 and Li_3N form in the surface layer of Al–Mg–Li alloys and that these phases are instrumental in promoting adsorption of ambient moisture on to the Al–Mg–Li alloy surface, which can lead to hydrogen penetrating into the weld pool. In addition, lithium-containing aluminium alloys generally have a higher bulk hydrogen content from casting than do other aluminium alloys, although this source of hydrogen is not believed to be as much a problem in welding as that contained in the region within 0.2 mm of the surface.

Kainova and Malinkina [41] studied the weldability of Alloy 01420 using argon-TIG welding and Alloy 01420 filler. They observed small, spherical pores in the weld zone that had shiny internal surfaces indicating a gaseous origin. They cite work by Galaktionova [48] claiming that the absorption of hydrogen by lithium begins at 420° C, and cite the observations made by Shamrai [49] that LiH formation is particularly intense at 710 to 720° C and that at higher temperatures LiH dissociates.

Kainova and Malinkina [41] developed the following chemical milling parameters to remove the surface layer on Alloy 01420: immerse in 110 g l^{-1} NaOH aqueous solution at 60 to 70° C for 10 to 15 min, at which point 0.05 mm has been removed from the surface. Using specimens prepared in this fashion to study surface film formation as a function of temperature, they found that a lithium-containing film formed only on those heated above 420° C. Furthermore, those specimens on which the film formed exhibited weld-seam porosity when subsequently welded. Kainova amd Malinkina [41] emphasize that 420° C is the same temperature at which Galaktionova [48] observed the onset of LiH formation.

Alloy 01420 is generally solutionized at 450° C, which is above the threshold for hydrogen adsorption. Thus, it is during solution heat treatment in the presence of moisture that hydrogen is most likely adsorbed, which subsequently can cause weld-zone porosity. Consistent with the findings of Fedoseev *et al.* [40], the moisture-containing surface can be effectively removed by chemically milling in an NaOH aqueous solution [41]. Kainova and Malinkina [41] also note that Alloy 01420 adsorbs moisture at room temperature, and have observed weld porosity using material that was chemically milled 16 days prior to welding.

4.2.3. *Use of vacuum heat treatment to reduce weld-zone porosity*

From the numerous investigations discussed above, it is apparent that Alloy 01420 is particularly susceptible to weld-zone porosity, but that it can be eliminated by chemically milling 0.2 to 0.3 mm from the surface in NaOH aqueous solutions prior to welding. In more recent work, Mironenko *et al.* [36] explored the use of vacuum heat treatment (VHT) to reduce weld-zone porosity in Alloy 01420. Specifically they examined the effect of VHT prior to welding on both argon-TIG and electron beam (EB) weld-zone porosity, as well as on hot-tearing susceptibility and weld strength.

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‡In some of the Soviet references, the investigators state that they machined the weldment into a standard tensile specimen, thereby properly measuring the strength of the welded material. However, in many references, this point is not addressed, so it is not clear that the thicker weld bead was indeed machined to the same thickness as the rest of the test section.

The TIG welding was performed on 2 mm sheet at a current of 180 to 200 A and a speed of 24 m h^{-1}. The EB welding employed a current of 25 to 27 mA on 6 mm sheet and 40 to 45 mA on 10 mm sheet; speed in both cases was 35 to 40 m h^{-1}. The EB was modulated along the joint axis with a frequency of 400 Hz and an amplitude of 2 mm, and its focal plane was midway through each workpiece.

Vacuum heat treatment was performed at 450° C for 24 h at a vacuum of 10^2 to 10^3 torr. The VHT samples and non-VHT samples used for comparison were air-quenched from 450° C and aged at 120° C for 12 h.

The VHT appreciably reduced weld-zone porosity for both TIG and EB welding. Non-VHT material had continuous chains of pores in the fusion zone, whereas VHT material had only isolated pores less than 0.2 mm in diameter. In addition, VHT increased the tensile strength and ductility (measured by bend angle) of the weldments, had no effect on impact toughness, and increased the joint efficiency from 70 to 80%. In other work, Mironenko and Kolgarova [44] demonstrated that VHT in the temperature range 450 to 500° C at a vacuum not less than 1.33 Pa greatly reduced EB weld-zone porosity. For the porosity decrease to be substantial, the VHT had to reduce the hydrogen content to $\leqslant 0.2\,\text{cm}^3$ per 100 g alloy. Bokshtein *et al.* [45] found that VHT at 450° C for 6 h at a rather good vacuum of 10^{-5} torr virtually eliminated porosity in Alloy 01420 that was subsequently argon-TIG welded. Thus, VHT appears to be an effective prewelding preparation technique for reducing weld-zone porosity in Alloy 01420.

4.2.4. Joint efficiencies and other weldability studies

Alloy 01420 can exhibit high joint efficiencies when welded by a number of techniques. For example, in their work on argon-TIG welding of Alloy 01420 using Alloy 01420 filler, Kainova and Malinkina [41] found no susceptibility to hot-tearing and typically observed joint efficiencies of 80% when re-ageing after air cooling, subsequent to welding. By repeating the entire heat treatment – solutionize, water quench, age – 92 to 100% base metal properties were obtained. Ishchenko and Chayun [50] also observed high joint efficiency for Alloy 01420 obtaining, for example, joint efficiencies of 80% in argon-TIG welds of Alloy 01420 that were not heat treated after welding. In this study, Alloy 01420 filler was not used, but rather an Al–6.3 Mg–0.5 Mn–0.22 Zr alloy. In addition, Fridlyander *et al.* [51] obtained joint efficiencies of no lower than 70% in argon-TIG welds without post-welding heat treatment and a 99.6% joint efficiency by re-solutionizing, air cooling, and artificial ageing. Note that the ability of Alloy 01420 to be "air quenched" from welding temperatures and naturally aged to 80% of base metal properties enables it to be used in structures where re-solutionizing, water quenching, and/or artificial ageing are not practical.

Mironenko *et al.* [42] studied the weldability of 2, 6, and 10 mm Alloy 01420 sheet by both argon-arc (AAW) and electron-beam welding (EBW). The AAW was performed using Sv–AMg6 filler and the EBW was performed without filler. The filler wire was pickled to remove surface impurities and the sheet chemically milled in a 20 to 30% NaOH aqueous solution until 0.2 to 0.3 mm was removed. The welding parameters used are summarized in Table V. (Chayun *et al.* [52] and Rabkin *et al.* [53] discuss argon-TIG and EBW parameters in detail.)

The strength, ductility and toughness of the argon-arc welds decreased with both increasing sheet thickness and increasing heat input. For heat input less than 2510 J cm^{-1}, joint efficiency was 70% of the base metal strength. The strength of the EBW sheets, on the other hand, actually increased slightly with thickness, although toughness decreased in some cases. Joint efficiencies of 75 to 85% of the Alloy 01420 base metal were obtained. Despite these high joint efficiencies, fine porosity was observed in both the argon-arc and electron-beam weld-zones.

Stress-corrosion cracking (SCC) tests were performed on the various weldments in a 3 wt % NaCl aqueous solution. The weldments were examined in both the air-cooled and re-aged, and water quenched and re-aged conditions. The EBW weldments always showed at least equivalent, and generally superior, resistance to SCC. For both types of weldments, air cooling as opposed to water quenching showed no clear trend in SCC resistance (see Table VI). However, Mironenko *et al.* [42] conclude that an increase in SCC resistance generally results from a decrease in welding heat input.

TABLE V Argon-arc welding (AAW) and electron-beam welding (EBW) parameters used by Mironenko *et al.* [42] on Alloy 01420 sheet

Method of welding	Sheet thickness (mm)	Welding current (A) (mA for EBW)			Welding speed ($\mathrm{m\,h^{-1}}$)	Heat input ($\mathrm{J\,cm^{-1}}$)	Length of weakened zone from weld axis (mm)	Comment
		I_1	I_2	I_{work}				
AAW	2	–	–	190	24	2430	15 to 22	Single-phase welding
	6	–	–	390	19	6300	25 to 30	
	10	420	310	460	13	13 400	50 to 60	Three-phase welding
EBW	6	–	–	26	38	1340	10 to 20	The beam was modulated with a frequency of 400 Hz and an amplitude of 2 to 3 mm
	10	–	–	43	38	2180	10 to 20	

In the previously mentioned work on VHT, Mironenko *et al.* [36] also examined the effect of VHT on SCC susceptibility of EB and argon-TIG welds. They performed constant-immersion SCC tests in a 3% NaCl aqueous solution on specimens loaded to 70 to 80% of the 0.2% yield strength (YS = 282 MPa, 41 ksi). Although the number of specimens tested was not noted, VHT increased the time to failure in several cases (Table VII).

Ol'Shanskii *et al.* [54] studied the EB welding of Alloy 01420 circular joints (i.e. "shells"), and the welding parameters they used are reproduced in Table VIII. Alloy 01420 sheets that were fabricated into circular shells 510 mm in diameter with a wall thickness of 15 mm were solutionized, water quenched and aged to a UTS of 427 MPa (62 ksi). The surface was prepared by mechanically scraping off the surface oxide film that formed during heat treating. The electron beam was focused 5 to 7 mm below the surface, and the EB gun was 90 mm from the workpiece.

TABLE VI SCC data on electron-beam welded (EBW) and argon-arc welded (AAW) Alloy 01420 in a 3 wt % NaCl aqueous solution (Mironenko *et al.* [42])

Thickness (mm)	Quenching	Welding medium	Mean time to corrosion decay of welded joints (days)
2	Air	AAW	38
	Water	AAW	45*
6	Air	AAW	33
		EBW	45*
	Water	AAW	27
		EBW	27
10	Air	AAW	2
		EBW	45*
	Water	AAW	14
		EBW	45*

*Specimens did not fail during the test.

The EB welds produced were free from cracks and inclusions, but contained porosity, typically 15 pores 0.2 to 1.0 mm in diameter per 100 mm of weld. Note that the Alloy 01420 did not receive the chemical milling preparation technique shown to reduce weld porosity in other investigations [40, 41].

The weldments were machined into tensile and impact specimens and tested without post-welding heat treatment. Joint efficiencies of 83 to 85% of base metal tensile strength were achieved, and the impact strength of the welds actually increased by 40% with respect to the parent metal.

4.2.5. Electromagnetic stirring

Electromagnetic fields have been used to improve welds in Alloy 01420. For example, Abralov *et al.* [47] have applied square-wave, alternating current pulses through an electromagnetic coil placed near the molten weld pool. The applied field decreased weld-zone porosity by a factor of two, increased the strength of the weld by 15%, and also improved ductility. Post-welding heat treatment increased the strength of the weld by an additional 10 to 15%. Chayun *et al.* [46] found that electromagnetic agitation decreased porosity in argon-TIG welds by 67 to 75%, increased weld strength by 20 to 30 MPa and increased ductility by 30 to 40%. The benefits of the applied electromagnetic field increased until the argon shielding of the weld deteriorated under the influence of the field.

4.2.6. Flux for Alloy 01420

Abralov *et al.* [55] developed a flux paste,

TABLE VII SCC data from Alloy 01420 specimens that received vacuum heat treatment (VHT) or conventional heat treatment (No VHT) (Mironenko *et al.* [36])

Specimen thickness (mm)	Stress		Mean time to failure (days)	
	(MPa)	(ksi)†	No VHT	VHT
2	225	32.7	38	35
6	196	28.4	34	45*
	196	28.4	32	45*
10	196	28.4	45*	45*

*Did not fail during 45-day test period.
†1 ksi = 10^3 psi.

TFA–3, that improves the quality of Alloy 01420 weldments. Although its exact composition was not presented, the flux was said to contain fluorine, calcium, lithium, magnesium, strontium, beryllium and zirconium. The flux is applied in a 0.2 to 0.5 mm layer after removal of the surface oxide film from Alloy 01420. It is claimed to decrease penetration depth during argon-TIG welding, so welding parameters should be modified. Abralov *et al.* [55] also claim that using TFA–3 increased joint efficiency from 60 to 74%, decreased mean pore size from 460 to 105 μm, decreased pore density from 190 to 52 pores per millimetre of weld, and also decreased hot cracking susceptibility.

4.2.7. Flash-welding Alloy 01420

Sakhatskii and Melnikov [56] have successfully flash-welded Alloy 01420 by using high current densities and rapid deformation velocities. As is the case with other aluminium alloys, the strength of the flash welds is a function of sheet thickness. For example, with no post-welding heat treatment, joint efficiencies of 89 to 92% were obtained from 2 to 4 mm sheet. On 10 mm sheet, joint efficiency dropped to 65%. Nevertheless, after re-heat treatment of the weldments, the strength and ductility of all the flash welds were restored to those of the base metal.

4.2.8. Spot-welding Alloy 01420

Ryazantsev *et al.* [57] demonstrated that Alloy 01420 can be spot-welded. They point out that the lower electrical and thermal conductivity effected by alloying with lithium facilitates spot-welding, which was also noted by Sperry and Mardigo [8]. Ryazantsev *et al.* [57] found that the force required for successfully spot-welding Alloy 01420 is lower than for other aluminium alloys. Moreover, the time period during which the spot-welding force can be applied is longer, and consequently the alloy is more forgiving to changes in spot-welding parameters than other aluminium alloys.

Alloy 01420 has been successfully welded by TIG, EB, resistance-welding and spot-welding, and extensive information concerning surface preparation and welding parameters is in the literature. Although different joint efficiencies have been obtained by various investigators, it is clear that joint efficiencies of 80% can be obtained without post-welding heat treatment, because of the quench insensitivity of the alloy. Furthermore, joint efficiencies of 100% have been obtained by re-heat treating the alloy after welding.

5. Aluminium–lithium alloys made by rapid solidification

Rapid solidification (RS) can be used to refine metallurgical features such as grain and constituent particle size, to extend solid solubility limits, and to improve mechanical and corrosion properties. The advantages of RS in producing superior alloys have been extensively reviewed elsewhere [58–60].

Al–Li alloy development is proceeding most

TABLE VIII Electron-beam welding parameters used by Ol'Shanskii *et al.* [54]

Welded joint number	Size of gap in joint (mm)	Accelerating voltage (kV)	Beam current (mA)	Focal current (mA)	Welding speed ($\mathrm{m\,h^{-1}}$)	Welding technique	Ratio of depth to width*
1	0 to 0.1	27	130	71	35	Vertical down	3:1
2	0 to 0.1	26	130	71	35	Vertical down	3:1
3	0 to 0.1	26	150	71	36	Vertical up	5:1
4	0 to 0.1	26	145	71	37	Vertical up	5:1
5	0 to 0.1	26	150	71	37	Vertical up	5:1
6	0.3	26	150	71	37	Vertical up	5:1

*(Penetration depth)/(size of heat-affected zone).

TABLE IX Compositions (wt %) of Al–3 Li–*X* RS–P/M alloys and mechanical properties of the alloys before and after welding (all specimens were heat-treated to peak strength before tensile testing). From Bowden and Meschter [61]*

Alloy	Base Metal					Weld					Joint efficiency (%)	
	YS (MPa)	YS (ksi)†	TS (MPa)	TS (ksi)	Elongation (%)	YS (MPa)	YS (ksi)	TS (MPa)	TS (ksi)	Elongation (%)	YS	TS
Al–3 Li	312	45.3	388	56.3	5.7	209	30.3	272	39.4	6.3	67.0	70.1
Al–3 Li–0.2 Zr	418	60.6	481	69.8	8.2	317	46.0	365	52.9	1.4	75.8	75.9
Al–3 Li–1 Co	–	–	–	–	–	241	35.0	298	43.2	2.0	–	–
Al3 Li–2 Mg–0.2 Zr	444	64.4	556	80.6	7.9	314	45.5	340	49.3	1.2	70.7	61.1
Al–3 Li–2 Cu–0.5 Zr	507	73.5	569	82.5	5.4	314	45.5	355	51.5	1.2	61.9	62.4

*YS = yield stress, TS = tensile strength.

† 1 ksi = 10^3 psi.

rapidly by ingot metallurgy (I/M), because existing casting equipment can be modified and used for producing Al–Li I/M alloys. Nevertheless, RS combined with powder metallurgical (P/M) consolidation techniques offers potential improvements in the properties of Al–Li alloys. Bowden and Meschter [61], for example, performed a preliminary investigation on the weldability of RS–P/M Al–Li alloys, the compositions of which are contained in Table IX. They fabricated several RS Al–Li–*X* extrusions made from vacuum-atomized powder. Electron beam bead-on-plate welds were made at a beam current of 125 mA, an accelerating voltage of 15 V, and a welding speed of 0.18 m sec^{-1} at a vacuum of less than 1.3×10^{-2} Pa. Welding was performed in the F (i.e. as-extruded) temper, and the welded plates were heat treated to peak strength as follows: 560° C solution heat treatment for 1 h, quenching, and ageing at 177° C for 16 h. Tensile tests were performed on the as-welded plates and compared with similar tests performed on peak-strength plates that were not welded.

The joint efficiencies ranged from about 61 to 76% of base metal properties (see Table IX). Bowden and Meschter [61] noticed that strength was lost in the weld zone primarily by the destruction of substructure caused by the melting that accompanied welding. P/M alloys often realize a significant contribution of strengthening from substructure that results from the thermomechanical processing used to form the product [58]. The oxides and other fine dispersoids introduced by P/M processing probably contribute to the formation of this substructure. Unfortunately, fusion welding appears to reduce the magnitude of these benefits. Nevertheless, the RS–P/M Al–Li–*X* alloys were weldable and the Al–3 Li–0.2 Zr alloy displayed an acceptable joint efficiency of just over 75%.

6. Al–Cu–Li–Mn–Cd Alloy 2020

In the late 1950s, the Aluminum Company of America (Alcoa) developed Al–4.5 Cu–1.1 Li–0.5 Mn–0.2 Cd Alloy 2020 for applications requiring high room temperature strength, improved tensile properties at 200° C and/or improved specific modulus [62–64]. The alloy was designed for aircraft applications which are usually mechanically fastened, so weldability was not an alloy design criterion. Nevertheless, weldability trials were performed on this alloy.

TIG-welded butt joints using 1.6 mm sheet produced weld strengths of only 227 MPa (33 ksi), for parent material having a tensile strength of 580 MPa (84 ksi) [64]. However, a complete heat treatment of the weldment restored the strength to about 500 MPa (72.5 ksi).

A recent attempt to weld Alloy 2020 made by RS gave rise to weldments experiencing grain boundary liquation at the fusion line, and a large amount of porosity [65]. The investigators concluded that Alloy 2020 has "marginal weldability". It is possible that the problems associated with welding this RS alloy resulted from the powder processing and degassing, and did not result from the inherent composition of the alloy.

7. Concluding remarks

Lithium-containing aluminium alloys can exhibit good weldability as evidenced by studies on high-purity Al–Li binaries, and Al–Li–Zr and Al–Mg–Li alloys. Most of the welding research on lithium-containing aluminium alloys has been on Soviet Al–5 Mg–2 Li–0.1 Zr

Alloy 01420. This alloy displays attractive welding characteristics by both TIG and EB welding, similar to those observed for commercial Al–4 wt % Mg alloys. However, extreme care must be exercised when using surface-preparation techniques because a hydrated surface layer forms on the alloy that must be removed to prevent weld-zone porosity. Soviet investigators claim that the best way to remove this layer is to chemically mill 0.2 to 0.3 mm from the surfaces by immersion in a 100 to 110 $g l^{-1}$ NaOH aqueous solution at 60 to 70° C for 10 to 15 min.

The good weldability and quench insensitivity of Alloy 01420 enables joint efficiencies to be typically 80% of base metal tensile properties, without post-welding heat treatment. Joint efficiencies of up to 100% have been claimed for material re-heat treated after welding.

7.1. Recommendations

The moderate-to-high strength, good corrosion resistance, low density, and weldability of Alloy 01420 provide the alloy with potential for use in a variety of marine and aerospace applications. Weldability trials and subsequent mechanical property evaluations should be performed in the Western World to better assess the alloy's potential usefulness.

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