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Review
Recent developments in the weldability of lithium-containing aluminium alloys

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The weldability of aluminium–lithium alloys is reviewed with emphasis on alloys that are being commercialized: 2090, 8090 and Weldalite™ 049. These alloys are weldable, although hot-cracking susceptibility has been reported for 2090 and 8090 when welded with certain conventional filler alloys. Mechanical property data from weldments made by several techniques are emphasized. Weld-zone porosity problems, discussed at length in a 1985 review in this journal, have largely been controlled by proper weld pretreatment and gas shielding. Interest in the weldability of aluminium–lithium alloys has taken on increased significance because of their potential to reduce the weight of space launch systems, whose fabrication most often involves welding.

1. Introduction
The benefits of alloying lithium with aluminium alloys are now well known, consisting of a decrease in density and an increase in elastic modulus [1]. Furthermore, Al–Cu–Li and Al–Cu–Li–Mg alloy compositions have been identified that rival those in the Al–Zn–Mg–Cu subsystem as the highest strength aluminium alloys [2–6]. Most Al–Li alloy development efforts have sought to replace alloys such as 7075 and 2024 for aircraft applications, which most often involve mechanical fastening. Consequently, the leading Al–Li alloys were not designed to be weldable, and relatively little emphasis has been placed on assessing weldability compared with other alloy properties.

Aluminium–lithium alloys suffer a price disadvantage which has previously been estimated as two to three times the price of high-strength conventional aluminium alloys in the same mill product form. More recent estimates now suggest that this price multiplication factor may be three to four [7]. In either event, there is a strong economic driver for the new Al–Li alloys to compete for applications that can support a significant price premium.

Many space systems are welded, particularly tankage for fuel and oxidizer storage on launch systems. For example, two major systems made by the Martin Marietta Corporation involve extensive welding – the *Titan* family of missiles and the external tank of the space shuttle. The *Titan* family uses Al–Cu–Mg alloy 2014 as its main structural alloy, which is welded primarily with Al–Si filler 4043 (nominal welding filler compositions are shown in Table I). The external tank, which is essentially huge cryogenic tankage for liquid hydrogen and liquid oxygen, is mostly made of Al–Cu alloy 2219 welded with Al–Cu filler alloy 2319. Each of these alloys is ~ 35 years old and the potential weight savings of using Al–Li alloys to replace 2014 and 2219 induced the present author in 1983 to review the weldability of lithium-containing alloys, which led to a review published in 1985 [8]. The essential findings of this earlier review are that lithium-containing aluminium alloys can be fusion welded, but the alloys are quite susceptible to weld-zone porosity. However, the porosity problem could be alleviated by chemical or mechanical milling of the surface prior to welding.

Most of the weldability research uncovered in the review [8] was performed in the Soviet Union on Al–5Mg–2Li (wt %, unless stated otherwise) alloy 01420, developed by Fridlyander [9]. Soviet researchers reported chemical and mechanical milling pretreatment parameters that reduce weld-zone porosity to tolerable limits and also reported reasonable joint strengths [10–12]. These claims were essentially corroborated in a study conducted in the West [13].

The launch cost to put a pound of payload into low-earth orbit is approximately US $7900 per kg [14]. This expense provides a tremendous incentive to reduce vehicle weight and presents an opportunity where the cost premium of using Al–Li alloys is likely to be acceptable. In addition, the 1985 space shuttle disaster has renewed interest in existing expendable launch systems as well as future designs such as the Advanced Launch System. These factors have stimulated weldability research on the existing Al–Li alloys that were designed for non-welded applications, as well as on the design of new alloys with weldability as a first-tier alloy design property.

In the present review, the author endeavours to update the aforementioned 1985 review [8] with emphasis on weldability for space launch systems. Although much weldability data is proprietary, enough information has been published or acquired through private communication to assess the ability of the leading Al–Li alloys to be welded without

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TABLE I Nominal compositions of conventional aluminium-base filler alloys (wt %) used in Al–Li welding studies

Alloy	Cu	Mg	Si	Mn	Ti	Zr	V	Cr	Al
1100	–	–	–	–	–	–	–	–	> 99
2319	6.3	–	–	0.3	0.15	0.18	0.10	–	Balance
4043	–	–	5.2	–	–	–	–	–	Balance
4047	–	–	12.0	–	–	–	–	–	Balance
4145	4.0	–	10.0	–	–	–	–	–	Balance
5356	–	5.0	–	0.12	–	–	0.12	0.12	Balance
5556	–	5.1	–	0.8	0.12	–	0.12	0.12	Balance

unacceptable hot-cracking susceptibility, and to approximate the joint strengths that can be expected. Many of the welding parameters and know-how techniques are proprietary, so the weldment property data will be emphasized.

2. Recent research on the weldability of Al–Li alloys

Weldability is often defined as the resistance of an alloy or alloy/filler metal combination to hot cracking during welding. Hot cracking is a difficult entity to quantify because it is heavily influenced by the amount of constraint imposed during the welding operation. An alloy could display no hot cracking in weld-parameter development studies and then display significant cracking when welded under the conditions of high constraint that often occur when large structures are "fit up" to be welded. An attempt will be made to assess hot-cracking susceptibility of the leading commercial aluminium–lithium alloys as qualitatively accurately as possible, although the inherent difficulty in doing so is clearly recognized. (An excellent review describing the hot-cracking susceptibility of Al–Li and other aluminium alloys has been written by Cross [15].)

Good hot-cracking resistance alone is not sufficient to enable an alloy to compete with established weldable alloys for demanding applications. Combinations of mechanical and corrosion properties of weldments often must be superior to those of in-service alloys to induce designers to effect an alloy change, even when parent alloy properties are clearly superior. Only joint strength data were uncovered to any great extent in this review and they will be highlighted; however, corrosion, stress-corrosion, fatigue, toughness, and cryogenic properties of weldments are necessary before a new alloy will replace an existing one in many demanding applications.

2.1. Weldable Al–Mg–Li alloys for fusion reactors

Several Japanese investigators [16–18] have been developing weldable Al–Mg–Li alloys for the vacuum vessel in a fusion device. These alloys are apparently lower lithium modifications of Soviet alloy 01420 and were designed to meet or exceed the weldability and the tensile strength of 5083-0 (about 300 MPa). The lithium additions were selected because of the additional alloy design goal of increased electrical resistivity.

Kamada *et al.* [16] developed an Al–4Mg–1Li alloy that has parent properties of 310 MPa (45 × 10^3 p.s.i.) ultimate tensile strength (UTS), 172 MPa (25 × 10^3 p.s.i.) 0.2% yield strength (YS), and over 20% elongation. The alloy was said to be fusion weldable with 5356 filler, but joint properties were not presented.

Namba and Sano [17] investigated Al–4.7Mg–(0.3 to 1.3)Li alloys for the aforementioned reactor application and performed gas tungsten arc (GTA, also called tungsten inert gas, or TIG, welding) and electron-beam (EB) welding evaluations. The susceptibility to hot cracking during GTA welding was said to be similar to that of 5083, which is quite low. GTA weldment strengths, with the weld beads removed, were reported as high as 274 MPa (39.8 × 10^3 p.s.i.) for the 1.3% Li alloy variant in the as-welded condition. The parent properties were 350 MPa (50.8 × 10^3 p.s.i.) UTS, 205 MPa (29.7 × 10^3 p.s.i.) yield strength (YS), and 20% elongation. Consequently, the joint efficiency (i.e. UTS weldment/UTS parent) is ~ 80%, which is similar to that obtained on 01420 [12]. GTA weldment strengths as high as 358 MPa (52 × 10^3 p.s.i.) were obtained with the weldment reinforcement on.

Weld-zone porosity was a problem in the GTA weldments, but it was reduced by trailing inert gas shielding, backing inert gas shielding, and "scarfing" of 0.2 mm off the surface prior to welding. A weldment tensile strength of 324 MPa (47 × 10^3 p.s.i.) and a yield strength of 172 MPa (25 × 10^3 p.s.i.) were reported for the autogeneous EB weldment. (The YS and % elongations of weldments are actually "apparent" YS and "apparent" elongation because, although most plastic deformation is in a localized region, the larger specimen gauge length is used to compute the 0.2% offset YS or the engineering elongation.)

Namba and Sano [17] measured the contents of magnesium and lithium in the weld bead for the three experimental alloys that were GTA welded using 5356 (Al–5Mg) filler (see Tables I and II). Dilution caused the lithium content of the weld bead to be lower than that of the parent. Namba and Sano suggested that using a lithium-containing filler could increase the lithium content of the weld zone and might result in greater strength.

Additional work on Al–Mg–Li alloys for the fusion reactor vessel application was performed by Saida and Matsumoto [18]. Gas metal arc (GMA, also called metal inert gas, or MIG) welding using 5356 filler was performed; parent alloy compositions and weldment properties are shown in Table III. The weldments displayed high tensile strengths, up to 295 MPa, which is commensurate with that of the best Al–Mg alloys, and excellent elongations.

TABLE II Parent-filler mixing of GTA weldments made with 5356 [17]

Nominal parent alloy composition (wt %)	Composition of weldment (wt %)		Decrease in Li content (%)
	Mg	Li	
Al–4.7Mg–0.3Li	4.8	0.19	37
Al–4.7Mg–0.8Li	5.0	0.42	47
Al–4.7Mg–1.3Li	4.9	0.70	46

TABLE III GMA welding of experimental Al–Mg–Li alloys made using 5356 filler displayed attractive weldment properties [18]

Alloy	Composition (wt %)					Weldment properties				
	Mg	Li	Zr	V	Cr	UTS		YS		El.* (%)
						MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)	
A	4.9	1.3	0.05	0.06	0.01	272	(39.5)	137	(19.9)	19.6
B	4.6	0.8	0.13	0	0.08	289	(41.9)	168	(24.4)	16.4
C	4.7	0.8	0.09	0.07	0.01	295	(42.8)	163	(23.7)	23.0

*Gauge length not provided in translation.

The Japanese investigators have developed experimental Al–Mg–Li alloys that are lower lithium modifications of 01420. Their hot-cracking resistance is claimed to be similar to that of 5083 and their behaviour during fusion welding and weldment properties obtained are quite similar to those of 01420 [10–13].

2.2. Al–5Mg–2Li alloy 01420 and dispersoid-modified 01420-type alloys

The weldability of Soviet alloy 01420 was reviewed in detail previously [8, 19]. The key points contained in the Soviet literature are that 01420 has "good" weldability with Al–Mg and parent alloy fillers, but is susceptible to weld-zone porosity. However, chemical milling of up to 0.3 mm in a 200 g l^{-1} alkaline solution, or mechanical milling of up to 0.5 mm from the surface prior to welding, reduces weld-zone porosity to low levels [10]. Furthermore, joint efficiencies of 80% are obtainable without post-weld heat treatment and, with re-solution heat treatment, i.e. quenching, and artificial ageing, joint efficiencies of 100% have been obtained.

Pickens *et al.* [13] studied the weldability of the Al–5Mg–2Li–0.1Zr 01420 variant using GTA welding with parent or 5356 filler. The 01420 was cast and extruded at what is now International Light Metals (Torrance, California) into 7.6 cm × 0.6 cm (3 in. × 0.25 in.) flat bar; tensile properties in the long transverse (LT) orientation in an underaged temper were 425 MPa (61.7 × 10^3 p.s.i.) UTS, 263 MPa (38.2 × 10^3 p.s.i.) YS, and 16.9% el. Chemically milling 0.25 mm (0.010 in.) in a 30% NaOH (6.5 M) aqueous solution at 50 to 60° C, followed by rinsing in a 30% HNO_3 aqueous solution (4.8 M), reduced porosity to acceptably low levels. In addition, machining 0.13 mm (0.005 in.) from the surface weldment prior to welding was equally successful in reducing porosity. Tensile strengths as high as 272 MPa (39.4 × 10^3 p.s.i.) were obtained with no post-welding heat treatment and as high as 363 MPa (52.7 × 10^3 p.s.i.) after the full heat treatment was repeated on the weldment. Although joint efficiencies were not as high as those reported in the Soviet literature, they were sufficiently high in this preliminary welding study for Pickens *et al.* to recommend further research on the alloy in the West. In addition, secondary ion mass spectroscopy (SIMS) studies performed in the weld zone indicated that both lithium and hydrogen depletion occurred. It is interesting that the lithium and hydrogen profiles followed the same trend; one possible explanation for this is that an Li–H complex was forming.

Academecian Fridlyander, the inventor of alloy 01420, was contacted privately for any recently published work on the weldability of 01420. Although no such work was cited, he provided a paper [20] that reviews the physical metallurgy of the alloy. He also indicated that a new, weldable aluminium–lithium alloy has been developed with attractive cryogenic properties.

Alloy 01420 was used as a matrix material for ceramic reinforcement [21]. TiB_2 particles, made by Martin Marietta's proprietary XD™ [22] technique, were introduced at 4.9 and 8.9 vol % into 01420 castings, which were extruded to 10.2 cm × 0.95 cm (4 in. × 0.375 in.) plate. Tensile and yield strengths of the 4.9 vol % TiB_2 01420 parent alloy are similar to those of unreinforced 01420 [13], indicating that little or no significant strengthening was provided by the TiB_2 particles (Table IV). However, the 8.9 vol % TiB_2 01420 did obtain a boost in yield strength from the reinforcement.

GTA weldments were fabricated in the orientation parallel to the extrusion direction using 5356 and 01420 TiB_2 fillers. The GTA weldments were made using a 75° V groove with four passes. Weldment tensile properties were scattered because of failure at TiB_2 agglomerates. Nevertheless, several attractive properties were obtained (Table V). With weldment tensile strengths as high as 374 MPa (54.3 × 10^3 p.s.i.) with post-weld ageing (no solution treatment), alloy 01420 appears to have potential as a matrix material for weldable metal-matrix composites.

Pickens *et al.* [23–25] have designed weldable aluminium alloys to be fabricated by rapidly solidified (RS) powder metallurgy (P/M) processing. One of these alloys is a modification of Soviet alloy 01420 that contains a high volume fraction of dispersoids, which is made possible by RS–P/M processing. The nominal composition of this alloy is Al–5Mg–2Li–0.5Zr. Zirconium was selected as the dispersoid-forming element because of its ability to refine parent alloy grain size, its potent ability as a recrystallization inhibitor, and its beneficial effects in weldable Al–Zn–Mg alloys in terms of refining the weld-bead microstructure [26]. This RS–P/M alloy is designated MML 15.

TABLE IV Tensile properties of 01420-TiB_2 extruded plate in a near peak-strength temper [21]

TiB_2 (vol %)	Orientation	YS		UTS		El. (%)
		MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)	
4.9	L	296	(42.9)	427	(61.9)	8.5
	LT	290	(42.0)	403	(58.4)	3.5
8.9	L	360	(52.2)	454	(65.8)	3.7
	LT	345	(50.0)	436	(63.2)	2.2

TABLE V Best properties of 01420-TiB_2 metal matrix composite GTA weldments [21]

Parent alloy	Filler	Weld bead on/off	Post-weld heat treatment	Apparent				El. (in 2.5 cm) (%)
				YS		UTS		
				MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)	
01420 + 4.9 vol % TiB_2	Parent	Off	AW-NA*	184	(26.7)	338	(49.1)	8.3
01420 + 4.9 vol % TiB_2	Parent	On	SHT/WQ/160 (24)†	286	(41.5)	342	(49.6)	1.9
01420 + 4.9 vol % TiB_2	Parent	On	160 (24)‡	292	(42.4)	374	(54.3)	2.8
01420 + 4.9 vol % TiB_2	5356	Partial	AW-NA	168	(24.3)	339	(49.2)	11.8
01420 + 8.9 vol % TiB_2	5356	Partial	AW-NA	172	(24.9)	316	(45.9)	7.1
01420 + 8.9 vol % TiB_2	5356	On	SHT/WQ/160 [17]	165	(23.9)	312	(45.3)	5.0

*As-welded and naturally aged.
†Solution heat treated, water quenched, artificially aged 24 h at 160° C.
‡Post-weld artificially aged 24 h at 160° C.

Typical parent properties of 5.8 cm × 1.35 cm (2.3 in. × 0.53 in.) extruded bar are significantly higher than those of ingot metallurgy 01420 containing 0.1 wt % Zr (see Table VI). Although the typical tensile strength of several extrusions was 551 MPa (81 × 10^3 p.s.i.), one 10 kg heat had a tensile strength of 600 MPa (87 × 10^3 p.s.i.). (Alloy MML 15 received 3% cold stretch prior to artificial ageing. Although artificially aged strengths in the stretched versus unstretched conditions were not compared, the peak strength will be referred to as T8, i.e. it is assumed that the stretch increased peak strength.)

As a preliminary assessment of weldability, a bead-on-plate, i.e. "melt run", was performed. The tensile strength of this autogeneous weldment was extremely high at 441 MPa (63.9 × 10^3 p.s.i.) in the as-welded condition. Re-solution heat treating, quenching, and ageing the alloy raised the strength to 490 MPa (71.1 × 10^3 p.s.i.).

Only limited further work was performed on this alloy because of the success of an Al–Zn–Mg alloy variant [23, 27]. Nevertheless, the potential for improving the strength of a weldable Al–Li alloy by using RS–P/M processing to refine grain size and effect dispersion strengthening was demonstrated.

2.3. 8090 weldability

Although Al–2.5Li–1.2Cu–0.7Mg–0.12Zr alloy 8090 was designed for mechanically fastened applications, several studies have been performed to assess its fusion weldability. For example, Gittos [28] performed GTA and GMA studies on 8090 using 5556A (a slight modification of 5556), 4043, 2319, and parent filler. Gittos mechanically milled the plate surfaces prior to welding and used inert gas backing to reduce weldment porosity. No hot cracking was observed with 5556A, but hot cracking was observed with each of the other three fillers. For example, fusion line cracking was observed with 4043. Cracking was also observed with 2319, and the weldments made with parent filler displayed the most hot-cracking susceptibility. Using the Houldcroft [29] test to assess the inherent hot-cracking susceptibility of 8090, Gittos ranked it as similar to 6082 – a hot-cracking-sensitive alloy.

Weld-zone porosity was observed, but its extent was reduced by the inert gas backing employed. Nevertheless, some attractive mechanized-TIG weldment strengths were obtained. For example, as-welded strengths were obtained as high as 349 MPa (50.6 × 10^3 p.s.i.) with parent filler, and as high as 414 MPa (60.5 × 10^3 p.s.i.) after re-solution heat treatment, quenching, and artificial ageing.

Gittos [28] concluded that lithium is not a neutral addition to Al–Cu–Mg alloys in terms of influencing hot cracking because its presence changes the normal ranking of filler alloys compared to their performance on conventional Al–Cu–Mg alloys.

Wilner and colleagues at Lockheed Missiles and Space Co., Inc., have expended significant effort in developing welding parameters for 8090. The applications, welding parameters and weldment properties are proprietary. Nevertheless, Wilner [30] indicates that a weldment tensile strength design-allowable of 228 MPa (33 × 10^3 p.s.i.) is attainable with proper welding procedures using an Al–Mg filler, zirconium-modified NG-61 (composition not provided) [30].

Edwards and Stoneham [31] performed an 8090 T6 weldability study using the bead-on-plate (i.e.

TABLE VI Properties of RS–P/M Al–5Mg–2Li–0.5Zr alloy MML 15 extruded bar and autogeneous EB "melt run" [24]

Orientation	Condition/temper	YS		UTS		El. (in 2.54 cm) (%)
		MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)	
L	Parent T8	496	(72)	558	(81)	6
LT	Parent T8	469	(68)	445	(79)	4
LT	EB melt run:					
	AW	356	(51.6)	441	(63.9)	–
	SHT/WQ/Age	454	(65.9)	490	(71.1)	–
Ingot metallurgy 01420 (parent) extruded bar in slightly underaged temper [13]						
L	T8	291	(42.2)	425	(61.7)	16.6
LT	T8	263	(38.2)	425	(61.7)	16.9

TABLE VII Hot-cracking index of 8090 compared with conventional alloys [31]

Alloy	Hot-cracking index (%)
8090	62.5
2014	66.0
7017 T6	83.0
7079 T6	83.0

autogeneous) Houlcroft test to assess hot cracking, and also fabricated autogeneous EB weldments and GTA weldments using parent and Al–5Mg fillers. In this test, the lower the hot-cracking index, the lower the hot-cracking susceptibility. The hot-cracking susceptibility of 8090 was found to be similar to that of 2014, a hot-crack-sensitive alloy (Table VII). Nevertheless, it displayed lower hot-cracking susceptibility than did two difficult-to-weld 7xxx alloys.

The highest 8090 joint strengths (presumably from GTA weldments in all cases) were obtained using parent filler – 311 MPa (45.1×10^3 p.s.i.) weld tensile strength in the as-welded condition, 367 MPa (53.2×10^3 p.s.i.) after re-heat treating those weldments to the T6 temper (Table VIII). The EB weldments were used in a fractographic study but no mechanical properties were reported. Thus, Edwards and Stoneham [31] reported high weldment strengths with 8090, but also reported hot-cracking susceptibility. These results are consistent with those of Gittos.

Skillingberg [32] performed GTA and GMA weldability studies on 8090 and Al–2.7Cu–2.2Li–0.12Zr alloy 2090. The joint geometry selected was a single V groove with a 60° included angle. The edges of the plates were filed and degreased immediately prior to welding. Alloy 8090 was weldable using 1100, 4043, 5356, and parent filler, but significant hot cracking was observed using 2319. In fact, 2319 was judged to be an unacceptable filler for 8090. Subsequent metallographic evaluation revealed cracking in the 8090 weldments made using 5356. Tensile properties of 8090 welded with 4043 displayed the highest as-welded strengths: 301 MPa (43.7×10^3 p.s.i.) UTS, 223 MPa (32.4×10^3 p.s.i.) YS, 2.5% el. (see Table IX). Re-solution heat treatment, quenching, and artificial ageing of the weldments made with parent filler produced the highest weldment tensile strength, 447 MPa (64.9×10^3 p.s.i.), which was 85% of parent properties.

Skillingberg [32] also assessed the toughness of weldments by Charpy impact testing. Toughness data were scattered, but the 5356 filler produced the highest values for alloy 8090 weldments. Skillingberg's results on 2090 will be discussed in the following section.

Thus, it appears that 8090 is susceptible to hot cracking, but with proper care, quality weldments can be made. The alloy produces high weldment strengths with 4043, 5356, 5556 and parent filler. Whether cracking problems arise when large structures are fit up for welding is not addressed in the literature, but may be an area for concern.

Alloy 8090 displays a natural ageing response in the unstretched condition (T4) suggesting that a potential vehicle exists to restore strength in weldments. It would be interesting to make low-heat-input 8090 weldments with parent filler using copper chill bars to rapidly extract heat to determine whether weldment strength does indeed increase with time at ambient temperature after welding.

2.4. Weldability of 2090

Alloy 2090 was developed by Alcoa to replace the high-strength alloy, 7075-T6. To respond to questions concerning the weldability of 2090 by the makers of space launch systems, Alcoa initiated welding studies on the alloy.

Martukanitz *et al.* [33, 34] performed GTA, GMA and EB welding studies on 2090 T8E41. The plates were prepared for welding by either mechanical milling of 0.08 to 0.23 mm from the surface, or chemical milling of 0.04 to 0.15 mm from the surface in a 5 wt % NaOH aqueous solution at 49° C, followed by desmutting in a chromic–sulphuric acid solution. Prior to welding, the edges adjacent to all surfaces were mechanically scraped.

An inverted "T" joint, comprising GTA fillet welds on both sides of the joint, was used to assess hot-cracking susceptibility; butt weldments were fabricated to assess joint strength. The fillers investigated were 4043, 4047, 4145, 5556 and 2319 (compositions in Table I). In order of increasing hot-cracking susceptibility, the fillers were ranked 4047, 4145, 2319, 4043 and 5356, as shown schematically in Fig. 1. Only 5356 displayed sufficiently severe hot-cracking susceptibility to be considered beyond the limit for commercial weldability. Comparison of these results with those from inverted "T" tests on conventional weldable alloys indicated that 2090 T8E41 welded with 4047 or 4145 has a hot-cracking susceptibility similar to that of 6061-T6 welded with 4043. Hot-cracking susceptibility of 2090 T8E41 with 2319 was judged only slightly higher than that of 2219 T87 with the same filler [33].

TABLE VIII Tensile behaviour of 8090 weldments [31]

Filler	Apparent YS		UTS		El. (in 2.54 cm) (%)	Post-weld heat treatment
	MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)		
Al	137	(19.9)	165	(23.9)	5	AW
Al–5Si	165	(23.9)	205	(29.7)	3	AW
Al–5Mg	176	(25.5)	228	(33.1)	4	AW
Al–5Mg(+Zr)	183	(26.5)	235	(34.1)	4	AW
8090	285	(41.3)	311	(45.1)	2	AW
Al–5Mg(+Zr)	245	(35.5)	302	(43.8)	4	AW + T6
8090	315	(45.7)	367	(53.2)	4	AW + T6

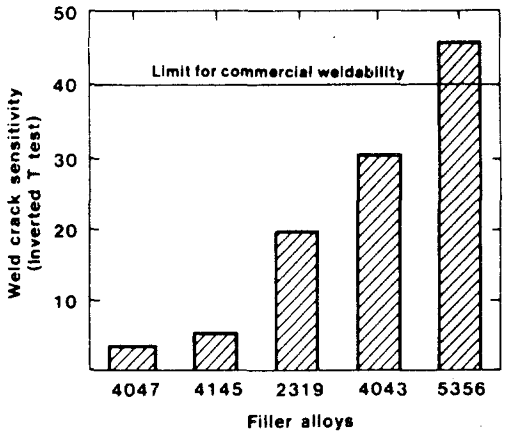

Figure 1 Weld crack sensitivity of 2090-T8E41 with various filler alloys [33].

Martukanitz *et al.* [33] observed objectionable porosity while welding sheet 3 mm (0.12 in.) thick and thinner, but not with thicker sheet. They attributed this effect to the greater surface area-to-volume of the thinner sheet which contributed more hydrogen per unit volume of weld.

GTA weldment properties of 2090 T8E41 welded with 2319 filler were 232 MPa (33.6×10^3 p.s.i.) UTS, 204 MPa (29.6×10^3 p.s.i.) YS, with 5.2% el. (in 5.1 cm). Welding 2090 in the T4 condition and inducing post-weld artificial ageing raised the weldment tensile strength to 258 MPa (37.5×10^3 p.s.i.), with brittle fracture occurring before apparent yield. Re-solution heat treating, quenching and artificial ageing of the T8E41 weldments increased the tensile strength to 386 MPa (56.1×10^3 p.s.i.), but fracture was also brittle with no measurable elongation. In addition, Martukanitz *et al.* [33] found that weldment strength increased linearly with the amount of material removed during pretreatment over the ranges investigated.

Autogeneous EB weldments on 12.7 mm (0.500 in.) 2090 T8E41 plate displayed as-welded tensile strengths as high as 322 MPa (46.8×10^3 p.s.i.) (see Table X). The strength increase apparently resulted from the plastic constraint provided by the relatively thick plate compared with the thin fusion zone, as is generally the case for EB weldments. Re-solution heat treating, quenching and ageing an EB weldment increased weldment tensile strength to 413 MPa (59.9×10^3 p.s.i.), but no elongation was measured.

Martukanitz *et al.* [33] concluded that 2090 can be welded with 4047, 4145, 2319 and 4043 filler, but highly restrained joints and low filler dilution may limit the choice of fillers to 4047, 4145 and 2319. The microstructures of 2090 weldments were also investigated; the heat-affected zone microstructure was found to be similar to that of conventional alloys [34].

At the Westec '88 conference, Gaw [35] presented the results of a welding study of 2090 and 8090 performed by Rockwell International personnel. The details of the study are included in a government report [36] whose dissemination is restricted by the International Arms Export Control Act. Consequently, only the data presented at Westec '88 can be reviewed here. Fortunately, this includes weldment strength data.

GTA weldments were made on nominal 0.32 cm (0.125 in.) 2090 sheet and 1.27 cm (0.50 in.) 2090 plate using several conventional filler alloys. A "staking fixture" with copper backup bars was used to maximize heat removal from the weldments. Pure helium was used as a root-shielding gas. The weldments with the 0.32 cm thick 2090 were square butt weldments and those with the 1.27 cm 2090 were 75° V-notch weldments. The tensile properties were obtained with the weld reinforcement intact.

As-welded tensile properties of the weldments that were made using the thinner sheet were significantly stronger (Table XI) than those reported by Martukanitz [33] or Skillingberg [32] (see Tables X and IX). Gaw attributes this to the heat removal effected by the

TABLE IX Tension test properties of Al–Li–Cu–(Mg)–Zr plate weldments [32]

Base plate	Filler	Test condition	Weld strength				El. (in 5.08 cm) (%)
			UTS		YS		
			MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)	
8090	1100	AW	192	(27.9)	151	(21.9)	4.0
8090	2319	AW	287	(41.7)	228	(33.1)	2.0
8090	4043	AW	301	(43.7)	223	(32.4)	2.5
8090	4043	SHT + A	281	(40.7)	249	(36.1)	1.25
8090	5356	AW	278	(40.3)	187	(27.1)	4.0
8090	5356	SHT + A	350	(50.8)	247	(35.9)	2.75
8090	8090	AW	283	(41.0)	173	(25.1)	1.0
8090	8090	PWA	318	(46.1)	314	(45.5)	0.5
8090	8090	SHT + A	447	(64.9)	378	(54.8)	2.25
8090	–	Base plate	527	(76.5)	423	(61.3)	9.2
2090	5356	AW	253	(36.7)	165	(23.9)	3.0
2090	5356	SHT + A	359	(52.1)	264	(38.3)	3.5
2090	2090	AW	230	(33.3)	123	(17.9)	4.0
2090	2090	SHT + A	381	(55.3)	292	(42.3)	3.5
2090	–	Base plate	474	(68.7)	387	(56.2)	7.5

AW, as-welded.
PWA, post-weld-aged only.
SHT + A, solution heat treated and aged after welding.

TABLE X Process parameters and mechanical properties for electron beam welding of 12.7 mm (0.500 in.) 2090 butt joints [33]

Alloy temper and condition	Beam current (MA)	Voltage (V)	Travel speed (cm sec^{-1})	Chamber environment	Beam deflection	UTS		YS		El. (in 5.1 cm) (%)
						MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)	
2090-T841 AW*	70	60	2.1	Hard vacuum	No	322	(46.8)		†	0
2090-T8E41 AW	70	60	1.3	Hard vacuum	Yes	298	(43.3)		†	0
2090-T8E41 Post-weld SHT and aged	70	60	1.3	Hard vacuum	Yes	413	(59.9)		†	0
2090-T8E41 AW	70	60	2.1	Partial vacuum	No	320	(46.5)		†	0
2090-T8E41 AW	100	175	2.1	Non-vacuum	No	245	(35.6)	210	(30.5)	5.2

*As-welded.
†Failure occurred before 0.2% offset was reached.

staking fixture [36]. However, the weldments made using the thicker material were not nearly as strong as those using the thinner material, apparently due to the much lower rate of heat extraction. Note in particular the ~ 50 MPa difference in apparent YS and 44 MPa difference in weldment UTS observed between the 2090/2319 weldments of different thickness (Table XI).

Gaw removed a residue on some weldments by wire brushing, revealing short cracks near the end of the weld bead. These cracks were intergranular, but whether they were hot cracks was not determined in this study.

Dvornak [37] performed hot-cracking studies on model 2090-like alloys using the trans-varestraint test. The alloys investigated were a ternary alloy with the same copper and lithium levels as 2090 (Al–2.7Cu–2.2Li) but without grain refiners, and the same alloy with titanium and zirconium grain-refining additions.

The Al–2.7Cu–2.2Li ternary alloy was found to be highly susceptible to hot cracking; however, the titanium and zirconium additions decreased susceptibility by refining the grain size and altering the shape and distribution of the eutectic phase in the weld.

The total crack length as a function of strain was measured for the Al–2.7Cu–2.2Li ternary and also conventional alloys 2024 and 5083. Alloy 2024 is generally considered unweldable because of its hot-cracking susceptibility and 5083 is considered to have good weldability. The Al–2.7Cu–2.2Li ternary displayed greater hot-cracking susceptibility than 2024, based on both total hot-crack length at a given strain and threshold strain for hot-crack initiation (Fig. 2; Table XII). Although the addition of grain refiners to the Al–2.7Cu–2.2Li alloy reduced hot-cracking susceptibility, trans-varestraint data comparable to those in Fig. 2 and Table XII were not provided for these alloys.

As mentioned earlier, Skillingberg's fusion weldability studies included both 8090 and 2090 [32]. Alloy 2090 was found to be weldable with both parent and 5356 filler, although cracking was observed on one of the metallographic cross-sections of 2090/5356 weldments. The 2090 weldments generally had higher porosity levels than did the 8090, particularly the 2090/5356 GMA weldment. Apparently, the filing pretreatment was not as effective as more extensive mechanical or chemical milling techniques.

The strengths of the 2090 weldments were lower than those of the 8090 weldments. For example, the as-welded strength with parent filler was 230 MPa (33.3×10^3 p.s.i.), compared with 283 MPa (41×10^3 p.s.i.) for 8090 welded with parent filler. Moreover, the highest as-welded strength for 2090 was 253 MPa (36.7×10^3 p.s.i.), obtained using 5356 filler, and the highest for 8090 was 301 MPa (43.7×10^3 p.s.i.), obtained using 4043. The Charpy impact energy of the 2090 weldments exhibited significant scatter [32].

Marsico and Kossowsky [38] performed a preliminary laser weldability study on Al–Cu–Li alloy 2090. Although some porosity was observed in the fusion zone, the alloy was found to be laser-weldable. In fact, Marsico and Kossowsky claim that the laser weldability of 2090 is better than that of most conventional aluminium alloys because of the lower thermal conductivity caused by the lithium addition.

TABLE XI Tensile properties of 2090 GTA weldments (each datum is the mean of three values; weld reinforcement intact [36])

2090 thickness (cm)	Filler alloy	YS		UTS		El. (%)	
		MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)	2.54 cm	5.08 cm
0.32	5180	219	(31.8)	299	(43.4)	5.3	2.7
0.32	5556	223	(32.3)	314	(45.5)	7.3	3.8
0.32	4145	236	(34.3)	285	(41.4)	4.5	1.5
0.32	2319	183	(26.6)	296	(43.0)	8.0	4.2
1.27	2319	134	(19.5)	252	(36.5)	1.5	7.2

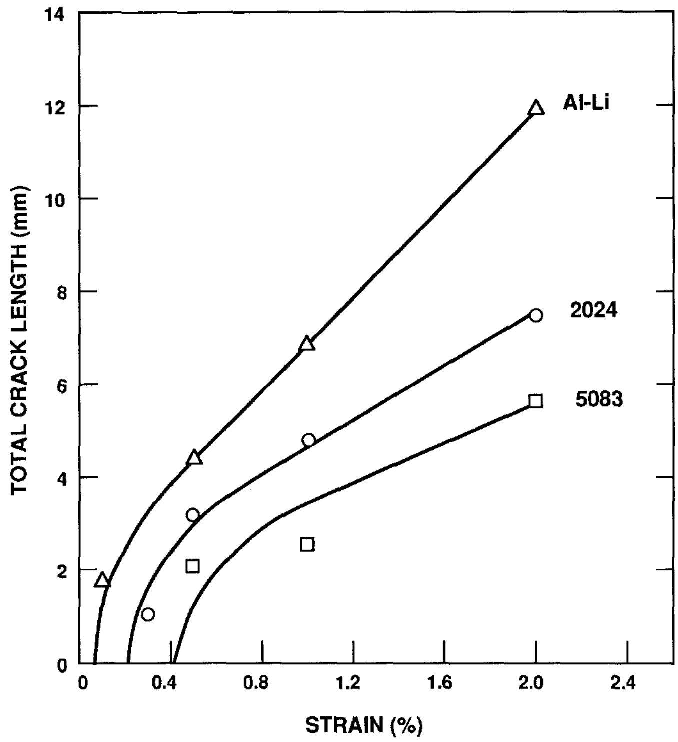

Figure 2 Comparison of the total crack length generated at various applied strains for the Al–2.2Li–2.7Cu, 2024 and 5083 alloys tested in the trans-varestraint test [37].

The autogeneous weldments were not particularly strong, with the best transverse weldment strengths being about 217 MPa (31.5×10^3 p.s.i.). Nevertheless, the laser weldability of 2090 was clearly demonstrated in this preliminary study.

Thus, 2090 is weldable, although hot cracking has been reported for 2090 that is welded with certain filler alloys and for a model 2090-type alloy fabricated without grain refiners. Weldments made with 2090 are generally not as strong as those made with 8090, although Gaw and co-workers demonstrated higher weldment strengths by increasing heat removal rates.

2.5. Weldalite™ 049

In the early 1980s, scientists and engineers at Martin Marietta Corporation endeavoured to interest their designers in using Al–Li alloys to reduce the weight of the space systems which the Corporation manufactures. In particular, the external tank of the space shuttle "flies" approximately 23 000 kg (50 000 lb) of aluminium alloys, most of it Al–6.3Cu alloy 2219. They argued that large potential weight and cost savings could be realized by building the external tank of the space shuttle with an Al–Li alloy.

Internal studies were performed to assess the properties of 2090, 8090 and 01420, with emphasis on weldability and cryogenic properties. The designers, conservative by nature, were not sufficiently impressed with the weldment strengths of these Al–Li alloys in relation to those of 2219 to incur the cost and risk of effecting an alloy change.

TABLE XII Threshold strain (ε_{min}) for hot-crack initiation by the trans-varestraint test [37]

Alloy	ε_{min} (%)
Al–2.7Cu–2.2Li	0–0.1
2024	0.1–0.3
5083	0.3–0.5

Pickens and co-workers [5, 6 39–41] at Martin Marietta Laboratories endeavoured to design an Al–Li alloy from first principles to be weldable and also to have high strength at room and cryogenic temperatures. Several alloys have been designed during the course of this research, but the leading alloy is called Weldalite™ 049 and was designed as a replacement for alloys 2219 and 2014. Weldalite™ 049 is an Al–(4.0–6.3)Cu–1.3Li–0.4Ag–0.4Mg–0.14Zr alloy that has extremely high strength in several tempers because, in part, of the enhanced precipitation behaviour caused by the Ag + Mg additions.

Weldalite™ 049 is significantly stronger [5, 6, 40, 42] than other aluminium alloys and has a typical (mean of over 22 heats) longitudinal T8 tensile YS of over 690 MPa (100×10^3 p.s.i.) from 10.24 cm × 2.3 cm (4 in. × 0.375 in.) extruded "plate". This exceptionally high strength in the T8 temper is due to an ultra-fine distribution of $T_1(Al_2CuLi)$ platelets, with no $\delta'(Al_3Li)$ present. Recent work by Huang and Ardell [43, 44] indicates that T_1 is an extremely potent strengthener, significantly more potent than δ'.

The natural ageing response of Weldalite™ 049 is extraordinary, typically providing 590 MPa (86×10^3 p.s.i.) longitudinal tensile strength in the T4 temper (i.e. no cold work) after 500 to 1200 h at ambient temperature. The mean properties of Weldalite™ 049 extruded plate in five technologically useful tempers are summarized in Table XIII. Because the alloy attains high strength from refined precipitation strengthening, contributions from fine grain (i.e. Hall–Petch) strengthening are of secondary importance. Tensile strengths > 690 MPa (100×10^3 p.s.i.) have been obtained from small-scale forgings and rolled 0.6 cm plate.

Weldalite™ 049 has been welded by EB, GTA, GMA and variable polarity plasma arc (VPPA) welding. No propensity to hot cracking has been observed in highly constrained weldments, and experienced

TABLE XIII Mean longitudinal tensile properties of Weldalite™ 049 in various tempers from extrusions [40]

Temper	Stretch (%)	YS		UTS		El. (%)
		MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)	
T3*	3	407	(59.0)	529	(76.7)	16.6
T4*	0	438	(63.5)	591	(85.7)	15.7
Reversion	0 or 3	331	(48.0)	484	(70.2)	24.2
T6	0	683	(99.1)	718	(104.1)	3.8
T8	3	696	(100.9)	715	(103.7)	5.5
2219-T81†	Minimum	303	(44.0)	421	(61.0)	6.0
	Typical	352	(51.0)	455	(66.0)	10.0

*500 to 1200 h.
† From same extruded geometry as Weldalite™ 049 data.

welders claim that the alloy welds similarly to 2219. A preliminary EB welding study was performed by the present author in conjunction with welders at The Welding Institute, Abingdon, UK. Extruded plate of Weldalite™ 049 measuring 10.2 cm × 0.95 cm (4 in. × 0.375 in.) in cross-section was mechanically abraded prior to the fabrication of autogeneous butt welds parallel to the extrusion direction. The resulting weldments were machined so that the weld-bead surface was flush with the base material, and tensile testing was performed in the LT orientation. In the as-welded condition, apparent yield strengths were extremely high, 417 MPa (60.5 MPa), with weldment tensile strengths 430 to 434 MPa (62.4 to 63.0 × 10^3 p.s.i.) (see Table XIV) [39]. The elongation of 0.3% is a manifestation of the confinement of deformation to the weld zone. Optical reduction-in-area measurements from the fracture surface indicated a true fracture strain of about 9%. After re-solution heat treatment, quenching and artificial ageing, an extremely high apparent yield strength of 527 MPa (76.4 × 10^3 p.s.i.) was obtained. Experiments are under way to determine whether the weldment strength increases with natural ageing time.

Both manual and automatic GTA weldments have been made on 10.2 cm × 0.6 cm or 10.2 cm × 0.95 cm extruded plate using 2319 filler, with the welding direction parallel to the extrusion direction. The plate was chemically milled in a 30% NaOH aqueous solution for 15 min at 60° C, followed by desmutting in a 30% HNO_3 solution for 15 min at ambient temperature. The side, top, and bottom surfaces adjacent to the joint were mechanically abraded just prior to welding. Some weldments exhibited porosity, but after some weld-parameter development, weldments having extremely low porosity and high strength were obtained, as reported in Table XV. Tensile strengths as high as that of the strongest weldable conventional aluminium alloys were obtained using conventional 2319 filler. Furthermore, these strengths are significantly higher than those typically obtained with 2219 using 2319 filler, the parent/filler combination the alloy was designed to replace (welding performed by G. Doherty, Martin Marietta Aero and Naval Systems, Baltimore, Maryland, USA).

Weldments were made using parent "cut rod" filler, and a specifically designed Weldalite™ filler that had been fabricated into wire and spooled. Weld-parameter development using both cut rod and this novel filler is under way by GTA, GMA and VPPA. The preliminary VPPA results are summarized below.

Weld-parameter development studies of Weldalite™ 049, 2219 and Al–Cu–Li alloy 2090 were performed by Hackett and MacFarlane [45] of Martin Marietta Manned Space Systems. A proprietary modified Weldalite™ 049 composition filler (049 filler hereafter), developed at Martin Marietta Laboratories and fabricated into 0.16 cm (0.063 in.) spooled wire, and conventional 2319 were used for the studies.

Hackett and MacFarlane [45] used VPPA welding to fabricate square-butt weldments. Because alloy 2219 VPPA-welded with 2319 filler is the standard weldment used to fabricate the external tank of the space shuttle, 2219/2319 weldments (i.e. 2219 parent plate, 2319 filler) were fabricated for comparison. All three alloys were welded with 2319 and the 049 filler. The mean tensile strength of 2219/2319 VPPA weldments was 273 MPa (39.6 × 10^3 p.s.i.) (Table XVI). After effective, although not optimal, parameters were established for 2219/049, the mean tensile strength increased to 325 MPa (47.1 × 10^3 p.s.i.). That is, the 049 filler increased 2219 weldment strength by 19% over that obtained using the conventional alloy's specifically designed filler. This result raises the possibility of improving existing designs by changing filler alloy, an easier task than changing the main structural alloy.

Alloy 2090 welded with 2319 had a mean VPPA weldment strength of 251 MPa (36.5 × 10^3 p.s.i.), which is greater than the GTA weldment strengths reported by Martukanitz [33]. Nevertheless, the weldment strength is still below that of 2219/2319, which has been a barrier to replacing 2219 with 2090 in space launch vehicles. However, the 049 filler causes the 2090 weldment strength to increase to 285 MPa (41.3 × 10^3 p.s.i.), which is comparable to that of 2219/2319.

The most significant development in the welding study by Hackett and MacFarlane is the exceptionally high VPPA weldment strength of Weldalite™ 049/049 weldments. The mean tensile strength was 372 MPa (54.0 × 10^3 p.s.i.), which is 36% greater than that of 2219/2319. This exceptional strength was obtained without optimization of welding parameters, since

TABLE XIV Autogeneous electron beam weldment strengths from Weldalite™ 049 0.95 cm extruded plate (LT) [39]

Post-weld condition	Apparent YS		UTS		El. (in 2.54 cm) (%)	RA* (%)
	MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)		
AW	417	(60.5)	430	(62.4)	0.3	9.0
AW	416	(60.4)	434	(63.0)	0.3	9.0
SHT/WQ/160° C (20 h)	527	(76.4)	529	(76.8)	0.2	6.0

*RA = reduction in area.

TABLE XV Tensile properties from automated, GTA square-butt weldments of Weldalite™ 049 extruded plate using 2319 filler (weld reinforcement machined flush) [40]

Current	Plate thickness (cm)	Post-weld temper	Apparent YS		UTS		El. (in 2.54 cm) (%)
			MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)	
DC	0.95	AW	219	(31.8)	327	(47.5)	5.7
	0.95	AW	262	(38.0)	344	(49.9)	2.7
	0.95	AW	241	(35.0)	338	(49.1)	3.4
	0.95	AW	234	(34.0)	343	(49.7)	3.6
		SHT/WQ/160 (24)	295	(42.8)	421	(61.0)	9.5
AC	0.64	AW	216	(31.3)	332	(48.2)	4.9
	0.64	AW	207	(30.0)	314	(45.6)	3.8
	0.64	AW	314	(45.6)	353	(51.2)	4.5

weldment elongation was only 3% in 2.54 cm. Thus, Hackett and MacFarlane have attained VPPA weldment strengths on 0.95 cm thick material that, to their knowledge, are higher than those on any other alloy [45].

Kramer *et al.* [41] recently performed a study comparing the hot-cracking susceptibility of Weldalite™ 049 containing different copper levels, 2090, and conventional alloys 2219 and 2014. The mini-varestraint test (moving electrode) was used to assess weld-zone cracking, and the spot varestraint test (stationary electrode) was used to assess heat-affected-zone (HAZ) cracking. The Weldalite™ 049 variants contained a nominal 6.2, 5.4 and 5.0 wt % Cu, levels over which peak strength does not vary [40] but ductility and toughness increase with decreasing copper content.

Alloy 2014 displayed the greatest weld-zone hot-cracking susceptibility, followed by alloy 2090 (Fig. 3). The three Weldalite™ 049 variants displayed lower hot-cracking susceptibility than 2090, with susceptibility generally decreasing with increasing copper content. Alloy 2219 had the lowest weld-zone hot-cracking susceptibility of the five alloys. On the other hand, the four aluminium–lithium alloys displayed greater resistance to HAZ cracking than both 2219 and 2014.

Kramer *et al.* [41] note that the mini-varestraint test properly ranks the hot-cracking susceptibility of the two conventional alloys. Alloy 2014 is difficult to weld and is welded in commercial environments using a "forgiving" filler alloy, such as 4043, to combat hot cracking. On the other hand, alloy 2219 is readily weldable with parent-modified filler 2319 and generally does not display cracking problems in even highly constrained structures.

The general trend toward reduced susceptibility to weld-zone hot cracking with increasing copper content in Weldalite™ 049 is consistent with trends observed in Al–Cu binary alloys. The higher copper content results in a larger volume fraction of primary particles, which provide eutectic liquid that has been claimed to heal weld cracks during solidification of Al–Cu alloys. The presence of lithium in Weldalite™ 049 results in a larger volume fraction of primary particles at a given copper level because of the higher solute content in the alloy. Consequently, good hot-cracking resistance is observed at copper levels lower than those required for good resistance in binary Al–Cu alloys.

The first tensile test on Weldalite™ 049 was performed in March 1987. The ultra-high strength of the alloy sparked the interest of Martin Marietta designers and motivated movement of the alloy rapidly into the development stage. Ten 180 kg ingots were direct-chill cast at Reynolds Metals Co. Research Laboratory (Richmond, Virginia), and rolled to sheet and plate in early 1988. Some of this sheet was used to fabricate a sub-scale, Weldalite™ 049 prototype cryogenic tank [42].

Sheet with a thickness of 0.5 cm was provided to Martin Marietta Space Launch Systems in the T4 temper. The sheet was roll-formed into barrel sections and artificially aged to the T6 temper, which provided 625 MPa (90.7×10^3 p.s.i.) YS, 660 MPa (95.8×10^3 p.s.i.) UTS and 5.2% elongation in the longitudinal orientation. Automated GTA weld-parameter development studies were performed on flat sections of the 0.5 cm sheet using 2319 filler. After acceptable welding parameters were developed under restraint conditions that could be expected on the welded panels of the tank, the tensile properties of the

TABLE XVI Mean VPPA, as-welded tensile properties of Weldalite™ 049, 2090 and 2219 square-butt weldments made with conventional and Weldalite™ filler [45]*

Base metal/ filler	Number of specimens	Thickness		Weld position	UTS		Apparent YS		El. (in 2.54 cm) (%)
		cm	(in.)		MPa	(10^3 p.s.i.)	MPa	(10^3 p.s.i.)	
2219/2319	(10)	0.95	(0.375)	60° horizontal	273	(39.6)	141	(20.4)	7.9
2219/049	(10)	0.50	(0.230)	60° horizontal	325	(47.1)	161	(23.4)	9.0
2090/2319	(24)	1.27	(0.500)	Vertical	252	(36.5)	156	(22.7)	8.6
2090/049	(10)	0.65	(0.255)	60° horizontal	285	(41.3)	147	(21.3)	7.1
049/2319	(3)	0.95	(0.375)	Vertical	274	(39.8)	248	(36.0)	1.5
049/049†	(5)	0.95	(0.375)	60° horizontal	372	(54.0)	290	(42.1)	3.0

*Data courtesy of W. M. MacFarlane and J. W. Hackett, Martin Marietta Manned Space Systems, Michoud, Louisiana. Weldalite™ filler wire was fabricated by J. R. Pickens and W. Precht, Martin Marietta Laboratories, Baltimore, Maryland.
†Naturally aged 800 h.

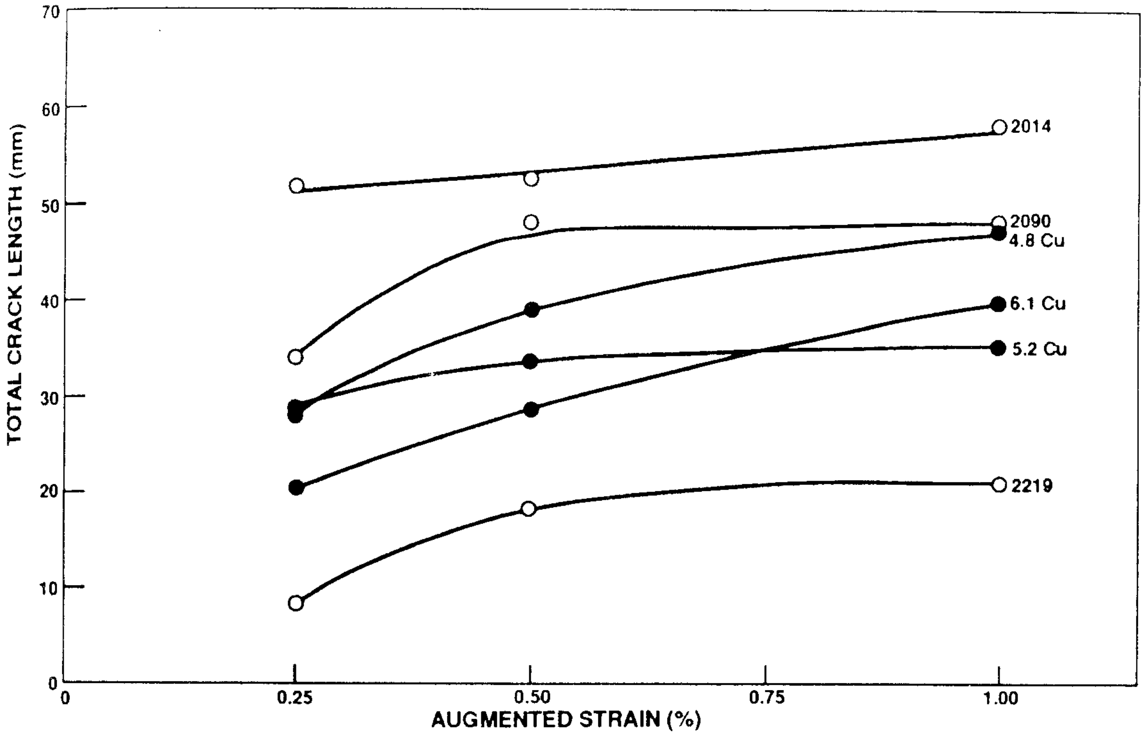

Figure 3 Total crack length within the weld plotted against augmented strain (%) for the alloys investigated. (●) Weldalite™ 049, (○) commercial alloys [41].

weldments were assessed. The mean tensile strength of the weldments was 311 MPa (45.1×10^3 p.s.i.) [42] with a standard deviation of 9.0 MPa (1.3×10^3 p.s.i.), i.e. excellent reproducibility. The barrel sections were then welded to form a cylindrical section measuring just under 1 m diameter. Weldalite™ 049 dome sections could not be fabricated in the allotted time, so an existing subscale tank with 2014 domes and a 2219 barrel was utilized for this project. The domes were removed 2 in. into the 2219 barrel so that the Weldalite™ 049 could be welded to the 2219, which was easily accomplished. This subscale prototype cryogenic tank involved 580 cm Weldalite™ 049-to-2219 welds and 500 cm Weldalite™ 049-to-Weldalite™ 049 welds, all made using 2319 filler (see Fig. 4) [42].

Figure 4 Prototype cryogenic tank fabricated using Weldalite™ 049 [42].

3. Concluding remarks

Interest in the weldability of lithium-containing aluminium alloys has increased since the previous 1985 review. This has occurred because of (1) the difficulties the new Al–Li alloys (e.g. 2090, 8090) are having in their competition with established, mechanically fastened aircraft alloys, which are significantly less expensive; (2) the need for lighter weight, weldable high-strength alloys for space launch systems; (3) the high cost to launch a kilogram of payload to low-earth orbit, which makes it easier for launch systems to tolerate the price premium of Al–Li alloys.

The porosity problems in welded Al–Li alloys have generally been overcome by proper pretreatment and careful welding process control. The leading Al–Li alloys designed for mechanically fastened applications, 2090 and 8090, are fusion weldable, but hot cracking has been reported with certain fillers. The strengths of 8090 weldments are generally superior to those of 2090 weldments.

A new Al–Cu–Li–Ag–Mg–Zr alloy has been designed to be fusion weldable and to attain ultra-high strength. This ingot metallurgy alloy, Weldalite™ 049, attains 700 MPa ($> 100 \times 10^3$ p.s.i.) tensile strengths from parent material. GTA weldment strengths as high as those from any conventional alloy have been attained using conventional 2319 filler. In addition, higher strengths have been obtained by VPPA welding using parent-modified Weldalite™ 049 filler. The viability of Weldalite™ 049 was demonstrated by construction of a subscale cryogenic tank.

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