JOURNAL OF MATERIALS SCIENCE 30 (1995) 4155–4160

Ageing behaviour of commercial aluminium–lithium welds

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The post-weld ageing behaviour of two commercial aluminium–lithium alloys, 2090 and 8090, was evaluated. Both a 2319 and 5556 filler material were used for preparing welds in Alloy 2090, while only the 5556 filler material was used with Alloy 8090. Welds with these filler metals were made at two dilution levels, nominally 35% and 65% dilution of the filler material by the base metal. The ageing behaviour of autogenous welds in each alloy was also evaluated. Post-weld heat treatments were performed at 325, 375 and 475 °F (163, 190 and 218 °C) for times up to 32 h. The ageing response was determined by performing hardness measurements at 4 h intervals. In general, dilution of the base metal by the filler metal reduced the ageing response of the combinations tested with autogenous welds in both 8090 exhibiting the highest peak hardness values. Ageing response curves for six base metal/weld metal/dilution combinations at two autogenous welds at three temperatures are presented.

1. Introduction

Aluminium alloys containing small amounts of lithium (1–3 wt%) have been the subject of active development for the past 15 years in an effort to provide high specific strength alternatives to conventional structural aluminium alloys, including 2219-T8, 2024-T6 and 7075-T6. Weight reductions up to 12% are possible through substitution with Al–Li–X alloys and, thus, these materials are being considered for use in both aircraft and space launch applications. Much of the effort with Al–Li–X alloys has focused on optimizing mechanical behaviour and characterizing the metallurgical behaviour during ageing. A relatively limited amount of work has been devoted to evaluating the welding characteristics and weldability of these alloys. Most of the welding studies published to date have focused on single alloys, usually in combination with dissimilar, lithium free filler materials. In general, these investigations have dealt with weldability issues such as cracking susceptibility [1–3] and porosity [4–6]. Relatively little information is available regarding the mechanical properties of Al–Li–X weldments, including the response of welds to standard post-weld ageing treatments.

The ageing response of Al–Li alloys is relatively complex and has been the subject of numerous studies [7–11]. A number of strengthening precipitates have been identified in the various Al–Li alloys including $\theta'(Al_2Cu)$, $T_1(Al_2CuLi)$, and $\delta'(Al_3Li)$ in Al–Li–Cu–Zr alloys such as 2090, and δ', T_1 and S' (Al_2CuMg) in Al–Li–Cu–Mg alloys such as 8090. Identification of the strengthening precipitates in these alloys in both tedious and time consuming and was outside the scope of the investigation.

Not unexpectedly, the use of compositionally dissimilar filler materials to join Al–Li alloys alters the ageing response of the unique weld metal composition that is created. The development of matching, or near-matching, lithium-bearing filler materials has been largely unsuccessful, primarily due to severe porosity problems associated with the use of these filler metals. As a consequence, standard commercial 2000- or 5000-series filler materials have generally been selected to join the Al–Li alloys.

In this investigation, two commercial Al–Li alloys were selected for evaluation, namely alloys 2090 and 8090. The filler materials selected included both 2319 and 5556, with the 2319 filler used in conjunction with alloy 2090 and the 5556 filler used with both base materials. The influence of dilution on the ageing response of these base/filler metal combinations is reported and compared with the behaviour of autogenous welds in these alloys. The influence of filler material selection and dilution on the weld solidification cracking susceptibility of these same combinations has been reported previously [3].

2. Experimental procedure

The chemical compositions of the 2090 and 8090 alloys evaluated during this study are provided in Table I. Alloy 2090 was in the form of 6.35 mm (0.25 in) plate in the −T8 temper condition (solution annealed, cold worked, artificially aged), while alloy 8090 was provided in 6 mm (0.236 in) thick plate in the −T851 temper condition (solution annealed, stretched 2.5% and aged at 190 °C (375 °F) for 16 h). Both alloys were welded in the as-received condition following appropriate cleaning. Gas tungsten arc welding (GTAW) procedures were developed for each alloy that would produce weld metal dilutions by the base metal of nominally 35% and 65%. Filler alloys

TABLE I Chemical composition (wt%) of base metals and weld metals

	Base metal							
	2090	2090	2090	2090	2090	8090	8090	8090
Filler metal[a]	None	2319	2319	5556	5556	None	5556	5556
Dilution (%)	100	65	35	65	35	100	65	35
Designation	2000	2265	2235	2565	2535	8000	8565	8535
Lithium	2.03	1.40	0.92	1.48	0.81	2.22	1.44	0.86
Copper	2.62	3.60	4.16	1.80	0.95	0.96	0.69	0.34
Magnesium	0.01	0.01	0.01	1.41	2.46	0.63	1.58	2.64
Iron	0.06	0.14	0.13	0.12	0.18	0.04	0.09	0.17
Silicon	0.05	0.06	0.06	0.06	0.07	0.02	0.04	0.06
Manganese	NA[b]	0.09	0.16	0.17	0.34	NA	0.14	0.35
Chromium	NA	0.01	0.01	0.03	0.06	NA	0.02	0.06
Zinc	0.02	0.02	0.03	0.01	0.01	0.02	0.01	0.01
Titanium	0.03	0.05	0.07	0.04	0.05	0.03	0.04	0.05
Vanadium	0.01	0.03	0.04	0.01	0.01	NA	0.01	0.01
Boron	0.0005	0.0009	0.0001	0.0005	0.0002	NA	0.0001	NA
Zirconium	0.13	0.13	0.13	0.09	0.05	0.12	0.09	0.04
Aluminium[c]	95.03	94.46	94.28	94.78	95.01	95.96	95.85	95.41

[a] Nominal 2319 composition: 6.3 Cu, 0.3 Mn, 0.15 Ti, 0.17 Zr; nominal 5556 composition: 5.1 Mg, 0.75 Mn, 0.12 Ti, 0.12 Cr.
[b] NA not analysed.
[c] Determined by difference.

ER5556 and ER2319 were used in conjunction with 2090, while ER5556 was used with 8090. The actual dilutions ranged from 61%–66% and 30%–36%. To produce approximately the same level of dilution through the thickness of the plate, a two-sided welding procedure was used for all welds. 35% dilution welds were made using a double V-groove joint design with a 70° groove angle and a 0.060 in (0.15 cm) root face. For the 65% dilution welds, a square butt with no root opening was employed. Just prior to welding, 0.005–0.007 in (0.013–0.018 cm) of material was removed (by dry machining) from the joint faces and from both plate surfaces to a distance 0.5 in (1.27 cm) from the centreline of the joint. This practice was employed to avoid weld porosity. The chemical composition of the variable dilution, filler metal welds is also listed in Table I.

Weld metal designations were developed which included the base metal, filler metal and dilution. For example, alloy 2090 welded with 2319 filler metal and 65% dilution was designated as weld metal 2265. These designations are listed in the third row in Table I.

The ageing response of both autogeneous and filler metal welds at two dilutions levels was determined at 325, 375 and 425 °F (163, 190 and 218 °C) for ageing times up to 32 h. The ageing response of the weld metal was monitored by hardness measurements at 4 h intervals up to 24 h with a final measurement after 32 h total ageing. The ageing heat treatments were performed in air in an electrically heated furnace fitted with an on/off-type temperature controller. Furnace temperature was monitored using a thermocouple attached to a base metal sample of similar thickness to that of the weld samples. Specimens were cooled from their respective ageing temperatures by quenching in water. Hardness measurements, using the Rockwell B-scale, (R_B), were recorded at a minimum of three locations within the weld fusion zone.

3. Results

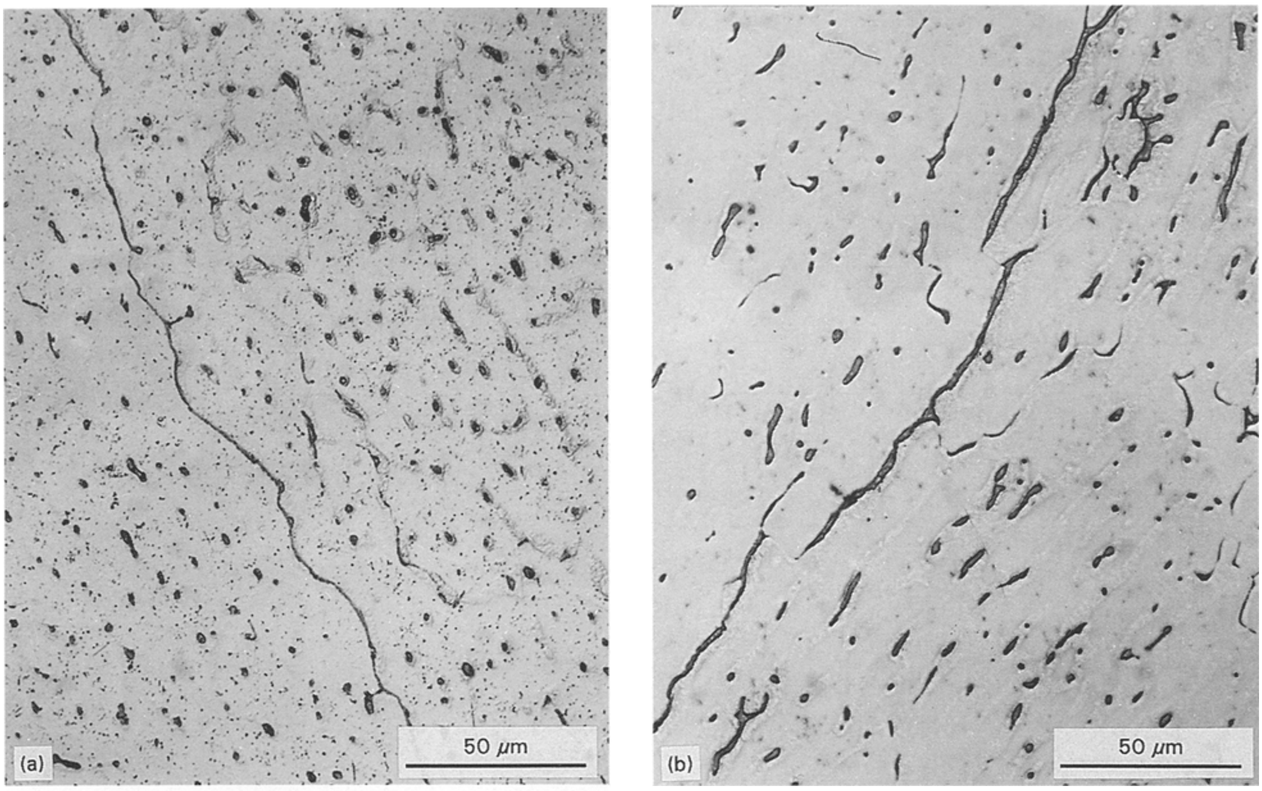
3.1. Weld metal microstructures

The as-deposited weld metal microstructures for the three base/filler alloy combinations consisted of a two-phase mixture of alpha aluminium and a eutectic constituent. Representative microstructures from the 2090/2319 combination are shown in Fig. 1. The volume fraction of eutectic was relatively uniform within a given weld, although significant variation in solidification substructure size was observed from point-to-point in the fusion zone. Autogenous welds in both alloys 2090 and 8090 exhibited nearly continuous eutectic networks along fusion zone solidification grain boundaries with distinctly discontinuous intragranular (subgrain) eutectic constituents. With the addition of 5556 filler metal, the volume per cent eutectic appears to decreased slightly relative to the autogenous welds in both alloys. In contrast, weld metal eutectic content increases with decreased dilution of 2319 filler metal by 2090 base metal (Fig. 1). (The absolute magnitude of this variation is difficult to quantify owing to the different etching responses of the weld metals. As a consequence, only a qualitative assessment is provided here.)

3.2. Post-weld ageing treatments

Base metal ageing response for both the 2090 and 8090 alloys are shown in Fig. 2. Note that alloy 2090 continues to harden at both 325 and 375 °F (163 and 190 °C) for ageing times up to 32 h. Both alloys exhibit a softening trend at 425 °F (218 °C). At 375 °F, alloy 8090 initially hardens and then softens at ageing times exceeding 16 h.

Weld metal ageing response for autogenous welds and heterogenous welds made with two levels of filler metal dilution are shown in Figs 3–5. The as-welded hardness was relatively low, generally less than 20 R_B, with the exception of combinations 2565 and 2235 (see



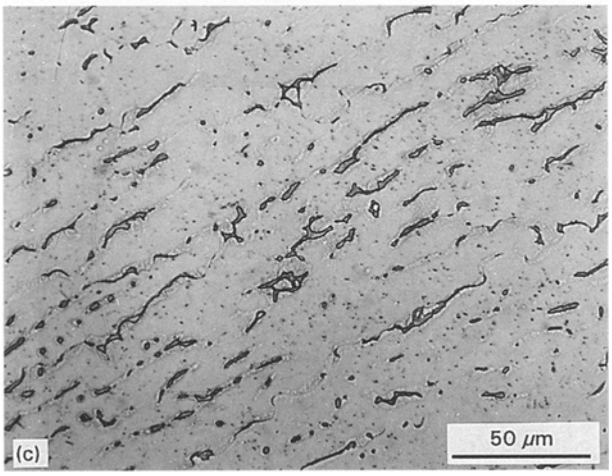


Figure 1 Weld metal microstructure of 2090/2319 combinations, (a) autogenous, (b) 65% dilution, (c) 35% dilution.

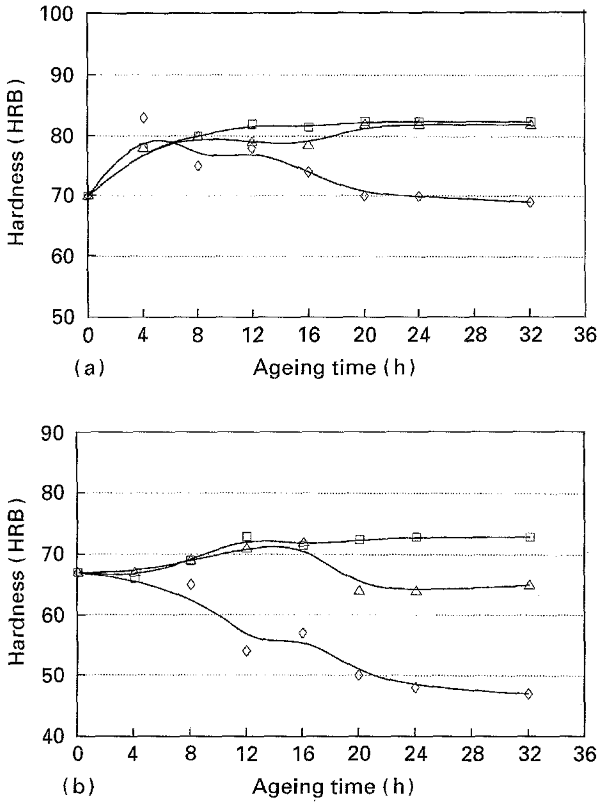


Figure 2 Ageing response of base materials at (□) 325, (△) 375, and (◇) 425 °F, (a) Alloy 2090, (b) Alloy 8090.

Table I, Row 4 for nomenclature). Hardness recovery in the autogenous welds of both alloys was rapid at all three ageing temperatures, reaching over 75% of the peak value after only 4 h. Alloy 8090 showed either a higher or equivalent hardness relative to alloy 2090 in the as-welded condition and for all ageing temperatures and times.

The ageing response of heterogenous welds made at two different levels in dilution was much more complex. In general, the response to ageing, in terms of peak hardness achieved, was less than that of the autogenous welds in the respective Al–Li base alloys. Table II lists the as-welded joint efficiencies, based on hardness data, for both autogenous and heterogenous welds. Note that, in general, joint efficiencies were less than 30%, with autogenous welds exhibiting less than 10% efficiency relative to the base metal under identical ageing conditions (Fig. 2).

Table III lists the peak hardness values and joint efficiencies for each base/filler/dilution combination. These data are presented in bar chart form in Fig. 6 for 2090/2319, 2090/5556 and 8090/5556 combinations. The highest hardness values were achieved in autogenous welds in both 2090 and 8090 after a 32 h

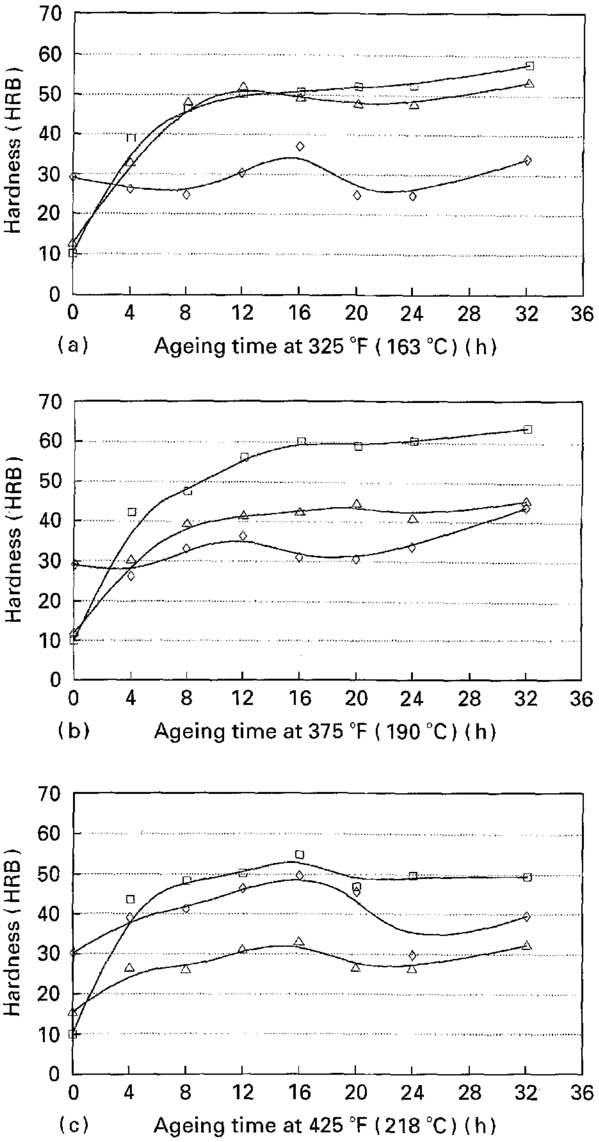


Figure 3 Ageing response of 2090/2319 combinations, (a) 325 °F, (b) 375 °F, (c) 425 °F, (□) Autogenous, (△) 65%, (◇) 35%.

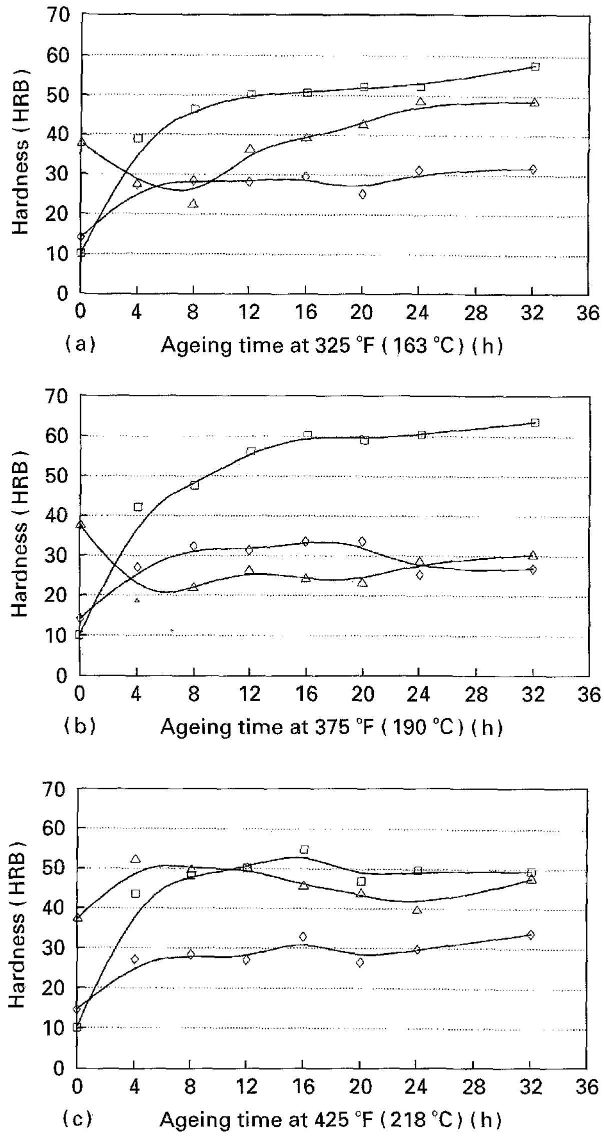


Figure 4 Ageing response of 2090/5556 combinations, (a) 325 °F, (b) 375 °F, (c) 425 °F, (□) Autogenous, (△) 65%, (◇) 35%.

ageing treatment at 375 °F (190 °C). In welds made with filler metal additions, 2090/2319 combinations exhibited the highest hardness values. This is not surprising because 5556 is generally not considered a heat-treatable filler material. Only a small difference in hardness was observed as a function of dilution in all three base/weld metal combinations, with more highly diluted weld metals exhibiting a slightly better ageing response.

4. Discussion

The ageing behaviour of Al–Li–X alloys is extremely composition dependent, with various precipitates forming as the proportions of lithium, copper and magnesium are altered. It was beyond the scope of this study to identify the precipitates and/or the precipitation kinetics. Alternatively, the hardness of welded and aged samples was used to determine the rate and relative magnitude of strengthening.

The primary focus of this investigation was to evaluate the ageing response of the weld metal in the as-welded condition. Solution treatment after welding was not employed, because for most applications such a heat treatment is not practical. It is recognized that a solution heat treatment after welding would, in most cases, result in additional improvement in strength over the welded/aged condition. It must also be emphasized that the weld metal ageing response is extremely microstructure dependent. The presence of eutectic solidification products essentially "robs" the matrix of the alloying elements which form the strengthening precipitates. Copper, lithium and magnesium are all known to partition to the liquid during solidification and, thus, are present in relatively high concentrations in the eutectic constituent. Recognizing this, it is not unexpected that aluminium alloy weldments containing eutectic constituents exhibit a lower strength than the base metal after ageing. A solution heat treatment is effective in dissolving this eutectic constituent, thus replenishing the surrounding matrix in the alloying elements that form the strengthening precipitates. Again, for many applications in which Al–Li alloys are proposed, such as large cryogenic tanks for space launch systems, a post-weld solution annealing heat treatment is not practical and

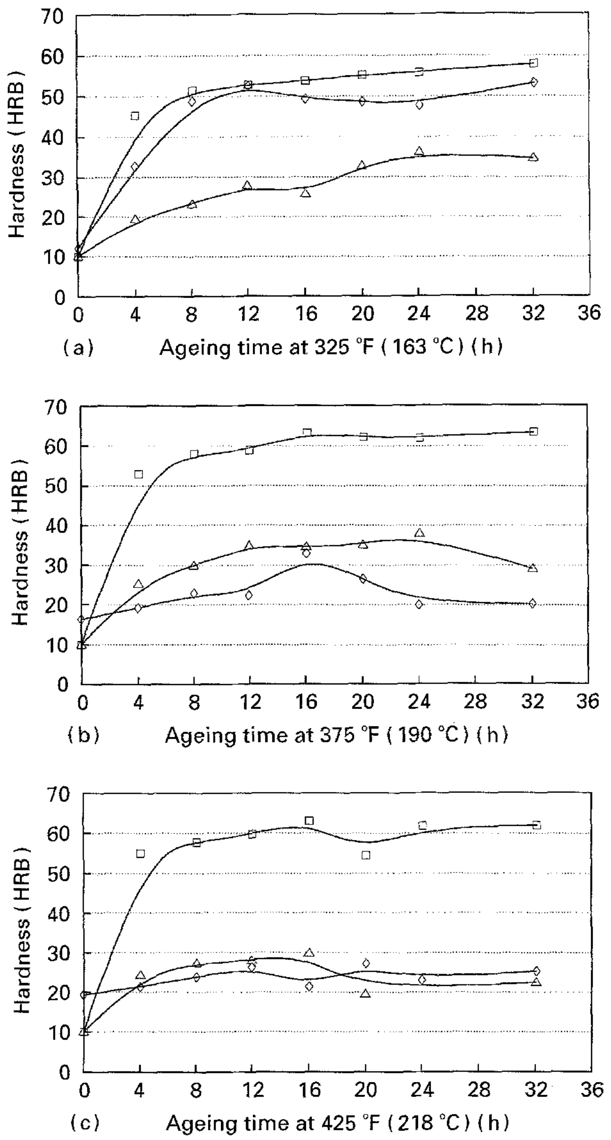


Figure 5 Ageing response of 8090/5556 combinations, (a) 325 °F, (b) 375 °F, (c) 425 °F, (□) Autogenous, (△) 65%, (◇) 35%.

TABLE II As welded joint efficiency[a]

Designation	Weld metal hardness, R_B	Joint efficiency (%)
2000	<10	<15
2265	13	18.6
2235	29	41.4
2565	37.5	53.6
2535	14.2	20.3
8000	<10	<15
8565	<10	<15
8535	17.5	26.1

[a] Joint efficiency $= \left(\frac{\text{weld metal hardness}}{\text{base metal hardness}}\right) \times 100$, Alloy 2090 = 70 R_B, Alloy 8090 = 67 R_B.

TABLE III Peak weld metal hardness values after ageing

Designation	Ageing treatment (°F/h)	Hardness, R_B	Joint efficiency[a] (%)
2000	375/32	63.7	78
2265	325/32	53.3	64
2235	425/16	49.7	67
2265	425/4	52.3	63
2535	375/20, 425/32	33.7	41, 49
8000	375/32	63.5	98
8565	375/24	38.0	60
8535	375/16	33.0	46

[a] Joint efficiency based on base metal hardness value after the same ageing treatment (Fig. 2).

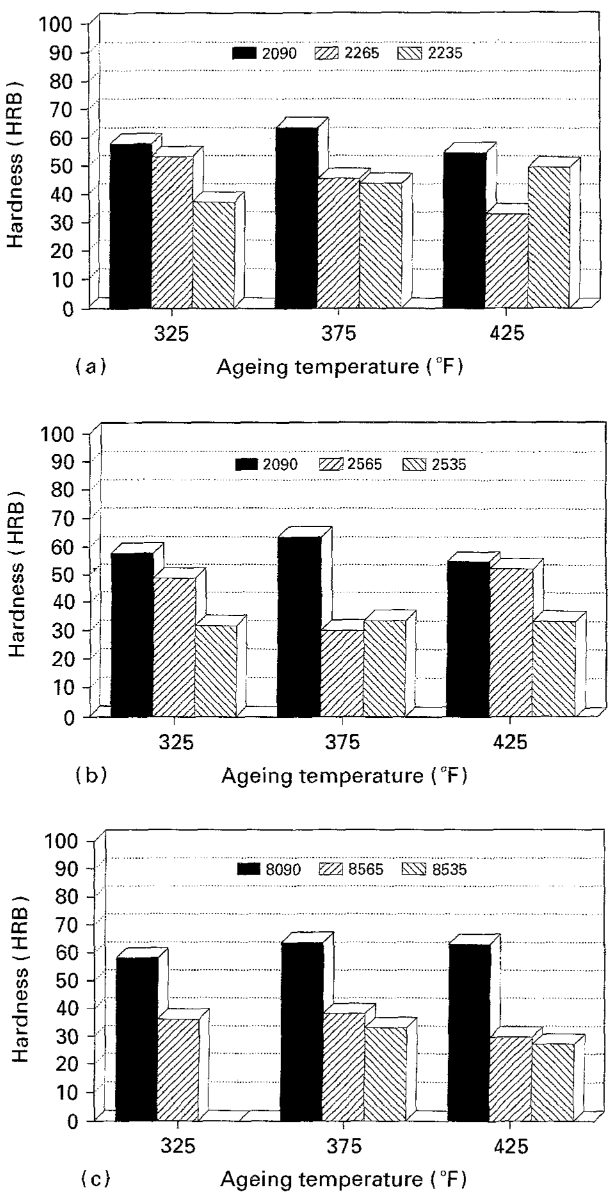


Figure 6 Peak weld metal hardness values at 325, 375 and 425 °F for (a) 2090/2319 welds, (b) 2090/5556 welds, (c) 8090/5556 welds.

thus the emphasis must be placed on optimizing post-weld ageing heat treatments.

The ageing curves presented in Figs 3–5 for the three ageing temperatures, 325, 375 and 425 °F (163, 190 and 218 °C), show considerable variation as a function of filler metal selection and dilution. A common feature of all the base/filler combinations at all ageing temperatures is that the addition of filler material results in a decrease in hardness (strength) relative to the autogenous weld. This difference is particularly pronounced in the 2090/5556 and 8090/5556 welds at the highest ageing temperatures (375 and 425 °F; 190 and 218 °C). At 325 °F (163 °C) highly diluted welds (weld metals 2565 and 8565) in these combinations exhibited an ageing response approaching that of the autogenous weld. The ageing response of the 2090/2319 welds was slightly improved relative to the autogenous weld behaviour, particularly at 375 and 425 °F (190 and 218 °C).

These results are perhaps not surprising, because the substitution of copper for lithium in the 2090/2319 welds should not seriously degrade the ageing response, while the substitution of magnesium in the 2090/5556 and 2090/5556 would be expected to retard the ageing response. The magnesium effect is most clearly manifested in Fig. 5b and 5c, showing that the peak hardness obtained under all ageing conditions was, in most cases, significantly less than the autogenous weld metal. In contrast, peak hardness of the 2090/2319 combinations (Fig. 5a) more closely approached the autogenous 2090 behaviour. The results clearly show that copper additions to the weld metal significantly affect the hardening response, while magnesium additions do not.

Often the most important measure of weld properties is not the absolute strength (hardness) of the weld, but rather the ratio of its strength relative to the surrounding base metal. This ratio is often termed "joint efficiency". The efficiencies measured in this investigation are reported in Tables II and III. Note that the as-welded joint efficiencies are extremely low, generally less than 30%. The exception to this are combinations 2235 and 2565 with 41.4% and 53.6% joint efficiencies, respectively. The explanation for the improved as-welded joint efficiencies in these combinations is not apparent, although it should be noted that the hardness of 2565 falls upon ageing, while 2235 shows little ageing response (Fig. 2 and 3).

Joint efficiencies after ageing are presented in Table III. These efficiencies have been calculated based on the concomitant ageing response of the base metal, i.e. the hardness of the adjacent base material exposed to the same post-weld ageing treatment (Fig. 2). Autogenous welds in alloy 8090 achieved nearly 100% joint efficiency after ageing at 375 °F (190 °C) for 32 h. This result is slightly misleading, however, because the hardness of the base material decreased slightly for the same ageing treatment relative to the as-received-T851 condition. In general, the highest weld metal strengths (hardnesses) and joint efficiencies were exhibited by the 2090/2319 welds with values in the range from 64%–68%. This result probably reflects the effectiveness of copper relative to magnesium in promoting the ageing response.

5. Conclusions

1. In general, addition of filler metal to either 2090 or 8090 reduces the ageing response of the weld metal in terms of peak weld metal hardness.

2. The as-welded hardness of autogenous welds in both 2090 and 8090 was extremely low, but ageing response was relatively rapid at all three ageing temperatures (325, 375 and 425 °F; 163, 190 and 218 °C). Alloy 8090 weld metal achieved nearly 100% joint efficiency.

3. Significant softening was observed in the heat-affected zone after welding. In general, the ageing response of this region was relatively rapid, with hardness approaching the level of the base metal.

4. Of the alloy/filler combinations tested, 2090/2319 welds demonstrated the best response to post-weld ageing. Joint efficiencies between 60% and 70% were achieved.

5. The addition of 5556 filler to both 2090 and 8090 severely reduced the ageing response and generally resulted in joint efficiencies of less than 50%.

Acknowledgements

This work was supported by Alcoa, Alcan and General Dynamics Space Systems. Special thanks are extended to Alcoa and Alcan for supplying the 2090 and 8090 alloys, respectively, and to the Alcoa Technical Center for performing the weld metal composition analyses. Sincere thanks are also extended to Dr Jeff Hou, Ohio State University, for reviewing the manuscript.

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Received 11 April 1994
and accepted 3 February 1995