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THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF VARIOUS ALUMINIUM-LITHIUM ALLOY PRODUCT FORMS FOR HELICOPTER STRUCTURES

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THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF VARIOUS ALUMINIUM-LITHIUM ALLOY PRODUCT FORMS FOR HELICOPTER STRUCTURES

by

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ABSTRACT

The benefits of reduced density and increased elastic modulus, characteristic of the new family of aluminium-lithium based alloys, have been quickly and widely recognised and evaluation quantities of the new alloys have been made available to many airframe manufacturers, including Westland Helicopters of England.

This paper describes the tests carried out and results obtained from various aluminium-lithium alloy product forms, including metallographic examination, mechanical property determination and conclusions drawn from heat treatment and component manufacturing trials. Particular emphasis will be placed upon aspects of behaviour and properties of aluminium-lithium which differ significantly from those of conventional aluminium alloys, together with features unique to the new material.

Finally, brief mention will be made of disadvantages, limitations and difficulties which may arise in the introduction of aluminium-lithium alloys for the manufacture of helicopter structures.

1. INTRODUCTION

Although structural weight reduction is a well recognised means of improving aircraft performance, its translation into benefit to the operator is dependent upon the type and function of the aircraft in question. In the case of a civil airliner, for example, the benefit may be measured primarily as an increase in the ratio of earned revenue to aircraft procurement and operating costs, while in military applications increased weapon load or extended time 'on station' may be of paramount importance. The latter is particularly relevant to helicopters acting in the search and rescue roles where even a relatively small increase in flying time may dictate the success of the mission. New developments in materials are, therefore, of continuous interest to aircraft designers and the 1980's will be remembered as the decade in which the emergence of a new family of lightweight aluminium alloys, containing lithium as a major alloying element, heralded a new phase in the battle between aluminium alloys and organic-matrix fibre composites for dominance in aircraft structures. Whilst the latter may afford greater weight reductions per se and their use in many aerospace applications is now undisputed, the economies of direct substitution for many metal structures are often disappointing or prohibitive when the total costs of development, complexity of manufacture and acquisition of new plant are included. This is particularly so considering the suitability of the new aluminium-lithium alloys for conventional metal production and forming routes.

Previous attempts to commercially exploit the reduced density and concommitant increase in elastic modulus of aluminium-lithium alloys have been largely unsuccessful, primarily due to notch sensitivity and fracture toughness deficiencies such as those encountered in the now obsolete 2020 'ingot metallurgy' alloy developed in the 1950s by the Aluminium Company of America (ALCOA) (1-3). Renewed research interests in these alloys in the 1970's centred mainly around alloy production via a 'powder metallurgy' route using Rapid Solidification Technology (4). However, parallel developments in improved melting and casting technologies, together with a greater understanding of aluminium-lithium metallurgy have progressed to the stage of imminent commercialization of 'ingot metallurgy' alloys manufactured independently by British Alcan Aluminium (UK), ALCOA (USA) and Cegedur Pechiney (France). Considerable success has additionally been achieved in the production of an aluminium-lithium based powder alloy by Novamet Aluminium (USA), a subsidiary company of INCO.

ALUMINIUM ASSOCIATION DESIGNATION	COMPANY OF ORIGIN	TRADE NAMES/ OTHER DESIGNATIONS	CHEMICAL COMPOSITION (weight per cent)											SUBSTITUTE FOR
			Li	Cu	Mg	Zr	Si	Fe	Cr	Ti	Zn	Mn	Al	
8090	Alcan/ Pechiney	F92 (RAE) DTD ---A (RAE) Lital A (Alcan) CP271 (Pechiney)	2.20 to 2.70	1.00 to 1.60	0.60 to 1.30	0.04 to 0.16	0 to 0.20	0 to 0.30	0 to 0.10	0 to 0.10	0 to 0.25	0 to 0.10	Bal.	2014-T6 & T651 2324-T39 7475-T73 7075-T73
8090	Alcan/ Pechiney	F92 (RAE) DTD ---C (RAE) Lital C (Alcan) CP271 (Pechiney)	AS ABOVE											2024-T3 & T351 2024-T4
X8090A	Alcoa	Alithalite A	2.10 to 2.70	1.10 to 1.60	0.80 to 1.40	0.08 to 0.15	0 to 0.10	0 to 0.15	0 to 0.05	0 to 0.15	0 to 0.10	0 to 0.05	Bal.	2024-T3 & T351
8091	Alcan	DTD ---B (RAE) Lital B (Alcan)	2.4 to 2.8	1.6 to 2.2	0.5 to 1.2	0.08 to 0.16	0 to 0.20	0 to 0.30	0 to 0.10	0 to 0.10	0 to 0.25	0 to 0.10	Bal.	7075-T76 7475-T76 7050-T7651 7010-T7651
X8192	Alcoa	Alithalite C	2.30 to 2.90	0.40 to 0.70	0.90 to 1.40	0.08 to 0.15	0 to 0.10	0 to 0.15	0 to 0.05	0 to 0.15	0 to 0.10	0 to 0.05	Bal.	Low density Medium strength
X8092	Alcoa	Alithalite D	2.1 to 2.7	0.5 to 0.8	0.9 to 1.4	0.08 to 0.15	0 to 0.10	0 to 0.15	0 to 0.05	0 to 0.15	0 to 0.10	0 to 0.05	Bal.	7075-T73
2090	Alcoa	Alithalite B	1.90 to 2.60	2.40 to 3.0	0 to 0.25	0.08 to 0.15	0 to 0.10	0 to 0.12	0 to 0.5	0 to 0.15	0 to 0.10	0 to 0.05	Bal.	7075-T6 7075-T73 (forgings)
2091	Pechiney	CP274.	1.70 to 2.30	1.80 to 2.50	1.10 to 1.90	0.04 to 0.16	0 to 0.20	0 to 0.30	0 to 0.10	0 to 0.10	0 to 0.25	0 to 0.10	Bal.	2024-T351 7475-T7351 7175-T731
-	Pechiney	CP276	1.90 to 2.60	2.50 to 3.30	0.20 to 0.80	0.04 to 0.16	0 to 0.20	0 to 0.30	0 to 0.10	0 to 0.10	0 to 0.25	0 to 0.10	Bal.	7050-T6 & T651 7010-T6 & T651
2020$^+$	Alcoa	-	0.9 to 1.7	4.0 to 5.0	0 to 0.03	0 to 0.05	0 to 0.4	0 to 0.4	0 to 0.05	0 to 0.10	0 to 0.25	0.30 to 0.80	Bal.	7075-T651
9052 XL *	Novamet (Inco)	-	1.3 to 1.6	0 to 0.50	4.0 to 4.50	0 to 0.10	0 to 0.2	0 to 0.3	0 to 0.10	0 to 0.10	0 to 0.10	0 to 0.10	Bal.	2014-T6 7075-T6 7010-T6 7050-T6 } forgings

$^+$ Obsolete alloy, also contained 0.10-0.35% Cd

* Mechanically alloyed, also contains nominally 0.8% O and 1.2% C

Table 1. Chemical compositions of current commercial Aluminium-lithium alloys (including the inactive 2020 alloy for comparison).

Evaluation quantities of the various aluminium-lithium based alloys developed by these organisations have been made available in various product forms to many aerospace companies, including Westland Helicopters Ltd of Yeovil, England (hereinafter referred to as WHL) where these materials are currently receiving considerable attention and active support. This paper reports some of the findings to date and attempts to present a balanced view of the new alloys by indicating both positive and negative aspects of their behaviour, as their development stands at present. It should be remembered throughout the paper that the information presented has been obtained from metal of pre-production quality and further improvements are being incorporated into production status material as it emerges in the near future.

2. ALLOY COMPOSITION AND DENSITY

The main aim of the current aluminium-lithium research programmes has been to develop a new range of alloys which, compared to 'conventional' aluminium alloys, exhibit an approximate 10% decrease in density together with a similar increase in elastic modulus without degradation of other properties. The alloy compositions currently under development and/or available in evaluation quantities have been selected with this principle objective and are detailed in Table 1. All 'ingot metallurgy' alloys to date are based upon the aluminium-lithium-copper system and are allocated a designation in the Aluminium Association 2xxx alloy series if copper is the major alloying addition (by weight) or in the

8xxx series if lithium predominates. The mechanically alloyed material is given a designation in the 9xxx series, previously unused but now employed for all mechanically alloyed aluminium materials, with or without lithium additions. With reference to 'other designations' in Table 1, it is noted that several of these are allotted to the 8090 alloy, due to the fact that the UK development of this composition by Alcan was essentially a scaling-up of the F92 alloy invented at the Royal Aircraft Establishment (9), and since this was very similar to the Pechiney alloy CP271, agreement was reached to marry both compositions under one designation, 8090.

The inter-relationship between composition and density has invariably been used to indicate the accuracy of chemical analysis of all aluminium-lithium materials received at WHL for evaluation, the composition being determined independently of, and compared to, that quoted on the metal manufacturer's release documents. Theoretical density values have been derived from the formula due to Peel et. al. $^{(10)}$ for material which has been solution treated (irrespective of any subsequent ageing):-

$$\text{Density} = 2.71 + 0.024\,\text{Cu} + 0.018\,\text{Zn} + 0.022\,\text{Mn} - 0.079\,\text{Li} - 0.01\,\text{Mg} - 0.004\,\text{Si}\ \text{gcm}^{-3}$$

where the atomic symbols represent the concentration of that element in weight per cent. Comparison with experimentally determined values is generally excellent, with agreement to ± 0.01 gcm^{-3} usually achieved and indicative of a relatively accurate chemical analysis. Where there have been significant differences in elemental levels (usually in lithium content) for a given metal sample, the above approach has been found useful in aiding determination of the source of the discrepancy, exemplified in the case of some early 8090 material in which differences of 0.2-0.5% in lithium content consistently occured. This was subsequently explained by the fact that the metal manufacturer was making his analysis from molten metal and elemental loss during casting modified the composition at the solid product.

Density measurements, so far obtained, have shown the desired 10% reduction in samples of the 'ingot metallurgy' alloys 8090, 8091 and 2091 received by WHL. Products in 8090, for example show values in the range 2.5300-2.5675 gcm^{-3} compared to 2.7725-2.8125 gcm^{-3} for 2014 alloy as indicated in fig. 1. It is important to note that this data refers to material which has undergone solution treatment (irrespective of any subsequent ageing), because the density in the as-fabricated (F) condition is significantly lower. In the case of the 8090 alloy, the density prior to solution treatment has been found to be typically 2.50-2.54 gcm^{-3} and this is attributable to the presence of a relatively large amount of second phase particles, fig. 2a. These have a complex structure of aluminium, lithium, copper and magnesium which necessitates a large unit cell of relatively low atomic packing factor and dissolution during solution treatment (fig. 2b) eliminates much of the space within, resulting in an overall reduction in material volume. The associated linear dimensional changes calculated from measured changes in density have shown excellent agreement with experimentally determined values, an isotropic contraction typically of ~0.28% occuring for 8090 sheet, fig. 3. The metal user is unlikely to find this problematic, however, since it is envisaged that the standard condition of supply of aluminium-lithium, like 'conventional' aluminium alloys, will be of solution treated material; subsequent re-solution treatment has been found to result in negligible further contraction.

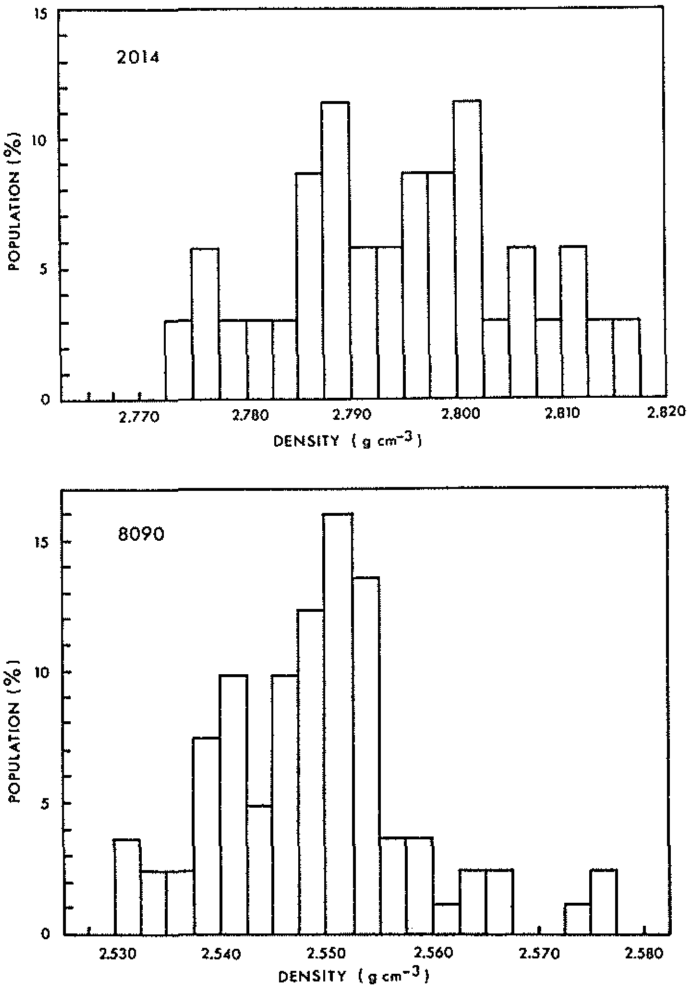
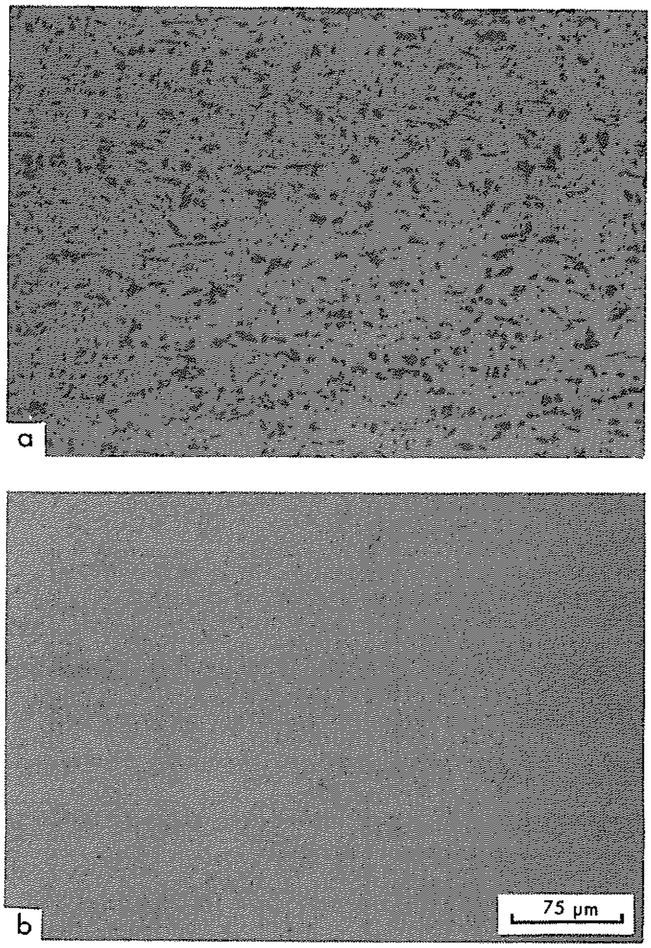


Figure 1. Measured density distributions in unclad 2014 and 8090 alloys.

3. SURFACE ELEMENTAL DEPLETION

Observations by WHL and other organisations have shown that, upon exposure to relatively high temperatures in the presence of air, aluminium-lithium alloys exhibit two unusual but related phenomena. Firstly, due primarily to their strong oxidising tendencies, depletion of elemental lithium and magnesium readily occurs from surface regions and, being essential to alloy strengthening by solid solution and/or precipitation hardening, is manifest as microhardness gradients at these locations. Being essentially diffusion controlled, the extent of depletion is a function of both time and temperature as illustrated for 8090 sheet by the family of curves in fig. 4, where the data for 510° and 530°C simulate up to three consecutive solution heat treatments, each of twenty minutes duration.

Secondly, the aforementioned effect may be accompanied by sub-surface pore-formation in a



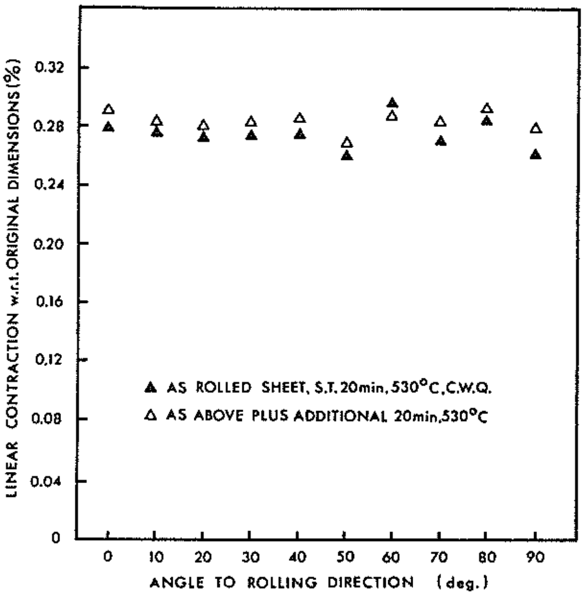


Figure 3. Effect of solution treatment upon dimensional stability of as-rolled 8090 1.6 mm sheet as a function of orientation to the rolling direction.

Figure 2. 8090 sheet (a) As fabricated (rolled), (b) solution treated.

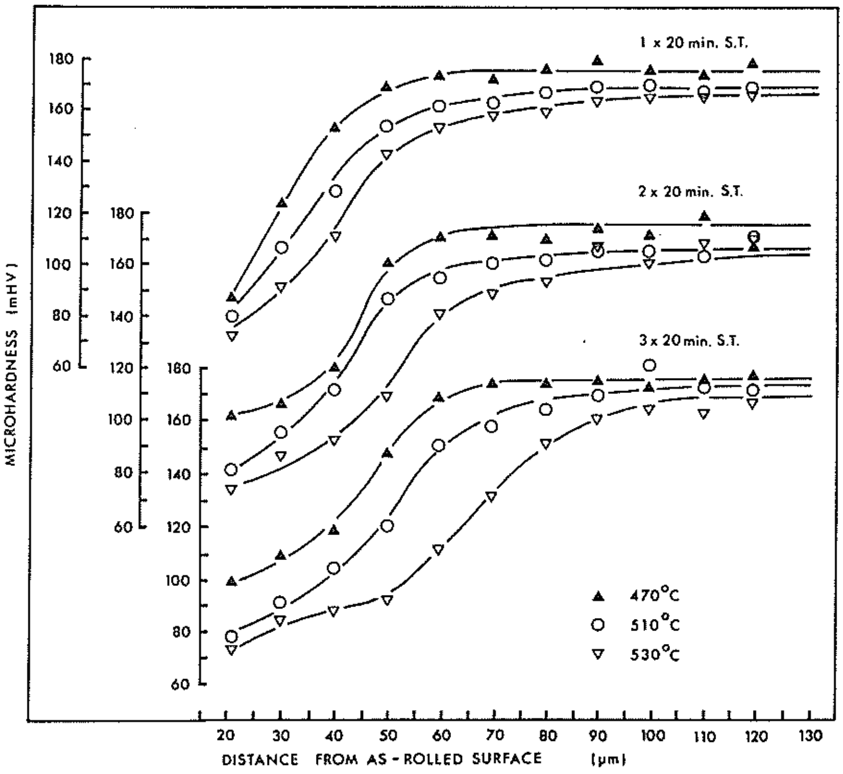


Figure 4. Typical lithium and magnesium surface depletion in 1.6 mm 8090-T6 sheet as a function of time and temperature.

band parallel to the metal surface, fig. 5. The depth at which this occurs increases as the depth of lithium and magnesium depletion increases from extended times at temperature, fig. 6. The origin of the pores is currently uncertain although one possibility is that they are due to vacancy agglomeration where the significantly slower diffusing aluminium atoms fail to reverse the vacancy flow into the metal which arises from the migration of lithium atoms to the surface. However, this hypothesis, if fundamentally correct, requires further refinements as the pore-free band adjacent to the metal surface is unaccounted for.

The ramifications of these features are clearly dependant upon the product form and dimensions. Total solution treatment times are unlikely to exceed 1h (with the possible exception of castings) for which figs. 4 and 6 indicate that both depleted layers and porosity bands occur at depths of up to ~90 μm and will, therefore, be removed from many components by machining or other finishing operations. However, their presence becomes more important in the case of product forms such as thin sheet or thin section extrusions where the as-fabricated surfaces are retained and the depth of depletion occupies a significant proportion of the section thickness. This has been investigated at WHL and typical results for 0.8 mm and 1.2 mm 8090 sheet solution treated in air are shown in fig. 7 where, the general decrease in strength values with increasing time at temperatures indicates the effect of progressive lithium and magnesium depletion. In these circumstances, the use of salt bath or inert gas solution treatments would be clearly beneficial as it has been shown that the exclusion of oxygen results in minimal elemental surface depletion and prevents corresponding pore-formation.

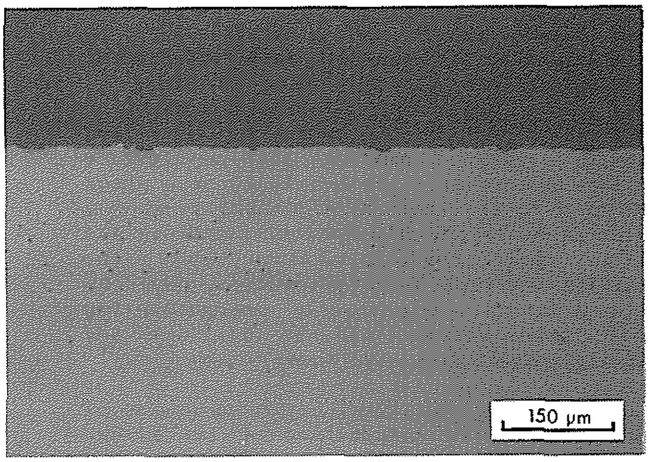


Figure 5. Sub-surface porosity in 8090 sheet after solution treatment in air.

4. PHYSICAL METALLURGY OF ALUMINIUM-LITHIUM ALLOYS

Although it is not the intention of the present paper to discuss in depth the various precipitation reactions which can occur in aluminium-lithium based alloys, it is, nevertheless, appropriate to mention briefly the role of the various alloying additions as they largely determine the resultant mechanical properties.

The 'ingot metallurgy' alloys so far developed consist of conventional precipitation hardening systems whereby the desired strength and associated properties are achieved by solution heat treatment and subsequent ageing schedules.

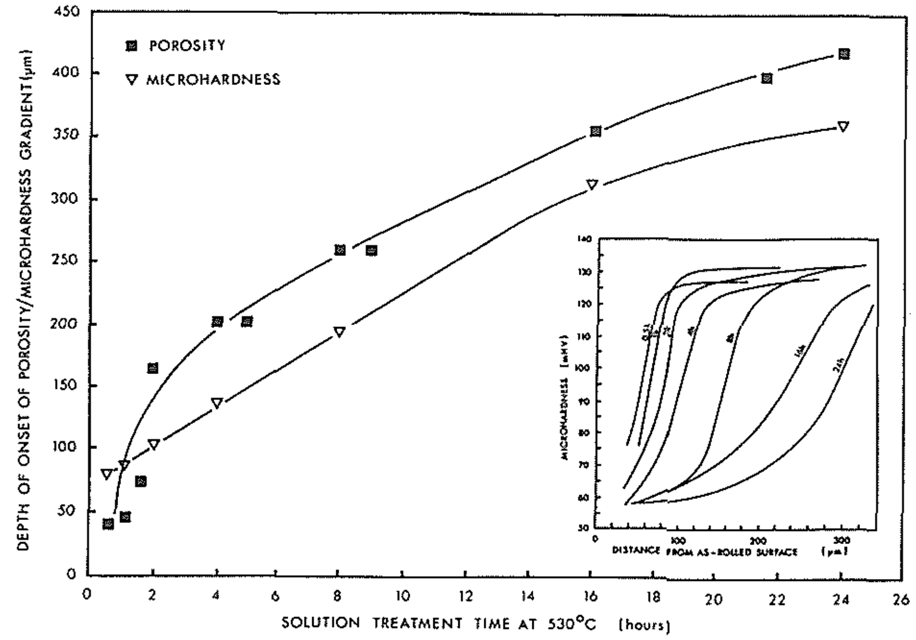


Figure 6. Depth of onset of sub-surface porosity and microhardness gradient as a function of solution treatment time; inset shows corresponding microhardness curves.

Alloy strengthening in the aluminium-lithium-copper based alloys is generally due to co-precipitation of two or more independent hardening phases. Precipitation hardening in binary aluminium-lithium alloys is due to the δ'-Al_3Li phase but in the more complex alloys currently being developed the precipitate comprises a core of Al_3Zr enveloped by a shell of Al_3Li (11,12). Both precipitates form as a regular distribution of spherical particles and due to their coherent nature and close similarity in unit cell parameters with the aluminium matrix, are primarily responsible for both increased strength and the relatively low ductility characteristic of these alloys.

The nature of the additional hardening phases is dependent upon the composition of the alloy, especially with regard to copper and magnesium levels. In the essentially magnesium-free 2xxx series aluminium-lithium alloys, additional hardening is generally due to the θ' ($CuAl_2$) and T_1 (Al_2CuLi) phases (13), while the S'(Al_2CuMg) phase predominates in the 8xxx series (14). For maximum strengthening these precipitates require to be homogenously dispersed as fine particles and this is achieved by the application to rolled and extruded products of a 1-3% cold stretch between solution and ageing heat treatments which has the effect of introducing, via a dislocation network, a significantly large number of nucleation sites. (Cold compression provides the analogous effect in forgings). In the absence of these stimuli, the precipitates form predominantly as relatively coarse particles which contribute little hardening, accounting for the lower properties of the stretch-free tempers where strengthening is almost solely due to δ'-Al_3Li precipitation. Additional strengthening is provided by grain size effects due to the presence of zirconium which, whilst being a highly efficient grain refiner, also acts as a recrystallisation inhibitor and is responsible for the flat 'pancake' shaped grains commonly seen in these alloys, fig. 8. However, the introduction of sufficient cold work may overcome these inhibiting effects as exemplified by the recrystallised, relatively equiaxed grains in extrusion corners and by the peripheral coarse grain on extrusion and sheet/plate surfaces, fig. 9.

Structural characteristics differing significantly from the above are exhibited in materials produced by mechanically alloying, a high energy dry milling technique, whereby the repetitive plastic deformation, cold welding and fracture of the powdered constituents results in highly homogenous powders of the desired composition. Excessive welding of the powders is prevented by the addition of organic lubricants which, during subsequent consolidation by vacuum hot pressing and extrusion, decompose to form a fine dispersion of Al_4C_3 particles. Together with Al_2O_3 particles derived from the original aluminium powder, these confer dispersion strengthening upon the matrix and with the stable, ultra fine grain size, constitute the main attractions of this material (5-8).

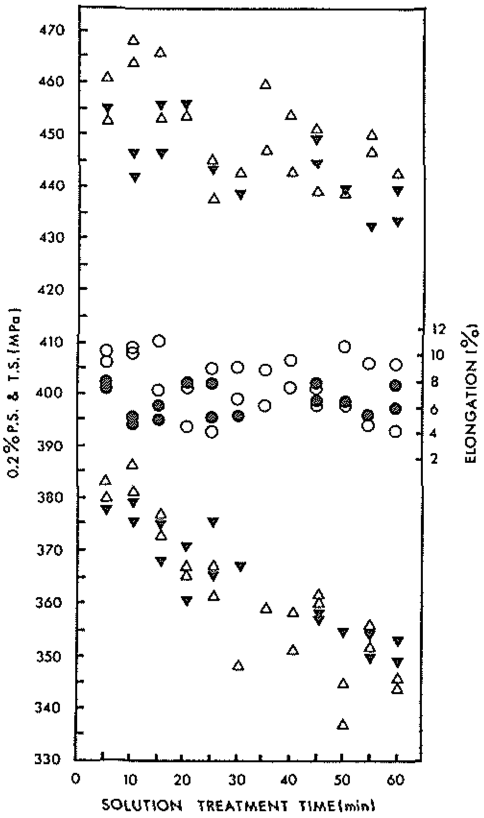


Figure 7. Effect of solution treatment times (at 530°C) upon transverse T6 mechanical properties of 0.8 mm (△○) and 1.2 mm (▼●) 8090 sheet.

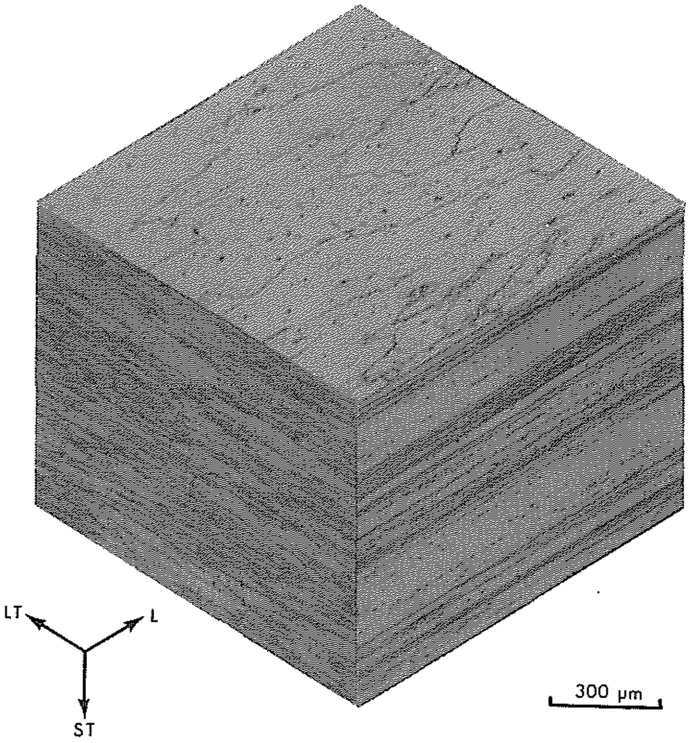


Figure 8. Grain structure of Zr-containing 'ingot metallurgy' aluminium-lithium alloys in plate and extruded form.

5. MECHANICAL PROPERTIES

5.1 Sheet

To facilitate initial usage on a substitutional basis, the philosophy behind the original concept of the new aluminium-lithium alloys was that, excepting density and elastic modulus, other properties should aim to match those of 'conventional' aluminium alloys (10). Accordingly, the properties of the 2xxx and 7xxx aerospace alloys have been generally adopted as standards against which to assess the new materials and this has particularly been the case with mechanical behaviour. (It should perhaps be mentioned here that care needs be exercised when direct substitution on a strength basis is being considered because the increase in elastic modulus implicit in using aluminium-lithium alloys may significantly alter the vibrational characteristics of the aircraft structure). In the case of sheet material comparison should strictly be made between material in the same clad/unclad condition. This is not always appropriate or possible when direct alloy substitution for existing designs is concerned. This is the case at WHL where unclad 8090 with its improved corrosion resistance typical of aluminium-lithium alloys has been, and is continuing to be evaluated with a view to replacement of widely used clad 2014A-T6 (BS L165-0.2% PS, TS and elongation of 345 MPa, 415 MPa and 7% respectively), notwithstanding the fact that the minimum properties of the new alloy are generally targetted at those of unclad 2014A-T6 (L159-0.2% PS, TS and elongation of 370 MPa, 430 MPa and 6% respectively). Considerable data has been generated from a series of solution heat treatment and ageing trials carried out on as-rolled 8090 sheet. Although some trends were apparent from slight experimental modifications using strict laboratory procedures, the general magnitude of property variations was considered to be no greater than the experimental scatter inherent in the random sample testing from different material batches and subject to typical industrial heat treatment practices. Fig. 10 shows histograms of the 8090 data and that from typical in-release testing of clad 2014A-T6 sheet. A noticeable difference in strength values is apparent although the majority of 8090

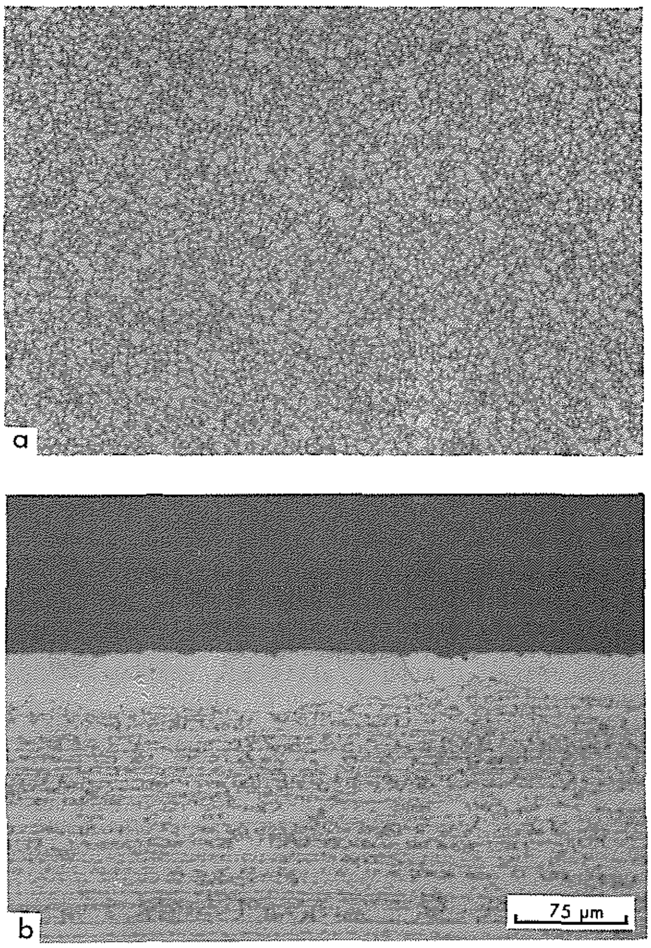


Figure 9. (a) Equiaxed grains at extrusion corners and
(b) peripheral coarse grain.

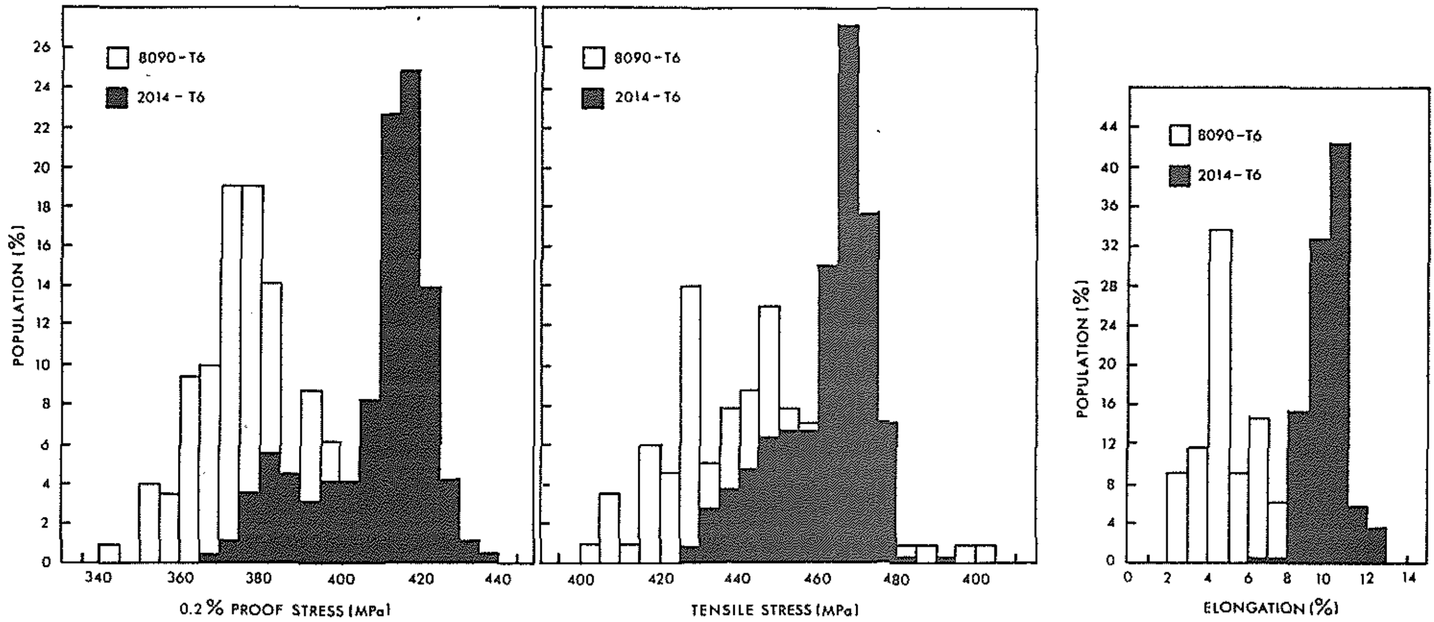


Figure 10. Transverse tensile properties of 8090-T6 and clad 2014A-T6 sheet.

data, especially in the long transverse direction, does achieve the minimum BS L165 specification requirements. It should be emphasised at this point, however, that the 8090 sheet, being relatively early development material, was produced on inappropriate plant and prior to optimisation of casting and fabrication procedures. Preliminary testing of current production route material has indicated some improvements and it now seems likely that property levels will match those of L165, but that they will struggle to achieve L159 levels, in the T6 temper. However, a different situation exists with material stretched subsequent to solution treatment (T351 temper) when 0.2% PS and TS properties in excess of 400 and 470 MPa respectively are readily achieved upon subsequent ageing, typically for 5-16h at 185°C (ie. T851 temper). In this respect, the virtual lack of natural ageing behaviour and good formability of 8090 sheet may enable forming to be carried out in the T351 temper in place of the W or T4 conditions usually employed for conventional aluminium-copper-based alloys; this is currently being investigated by WHL. It is of interest to note that aluminium-lithium based alloys are relatively quench insensitive and in the case of 8090 , still air cooling after solution treatment at 530°C results in only a 3-6% decrease in subsequent precipitated mechanical strength compared to what is obtained after cold water quenching and ageing.

A characteristic of many aluminium-lithium based alloys is the presence of pronounced crystallographic textures, manifest particularly as anisotropic mechanical behaviour, fig. 11. Modifications to process parameters and specifically the recent use of salt bath solution heat treatment will considerably lessen this effect in current and future production status material (15) although similar phenomena but of a lesser degree have been found in 2014 sheet as also shown in fig. 11.
All 8090 properties discussed so far have related to unrecrystallised material. However, sheet is now becoming available from British Alcan in which significant recrystallisation has been achieved, fig. 12, and work is currently in hand to incorporate the inherent lower strength but enhanced ductility and toughness into an aluminum-lithium replacement for the damage tolerant alloy 2024-T3. Alternatively, this requirement may be met by alloy 2091, developed by Cegedur Pechiney as CP274 which similarly exhibits high fracture toughness and good resistance to crack propagation (16). Greater isotropy in properties is also expected from recrystallised material and investigations are in hand.

5.2 Extrusions

Extruded sections in alloy 8090 in the form of rectangular bar and strip and simple thin sections have been examined by WHL and macrostructural studies have indicated no significant differences in extrusion behaviour compared to 'conventional' aluminium alloys. The central regions of all sections were essentially unrecrystallised after solution heat treatment while locations nearer the surface subjected to greater deformation during extrusion exhibited varying degrees of recrystallisation; peripheral coarse grain was evident in surface regions. Due primarily to

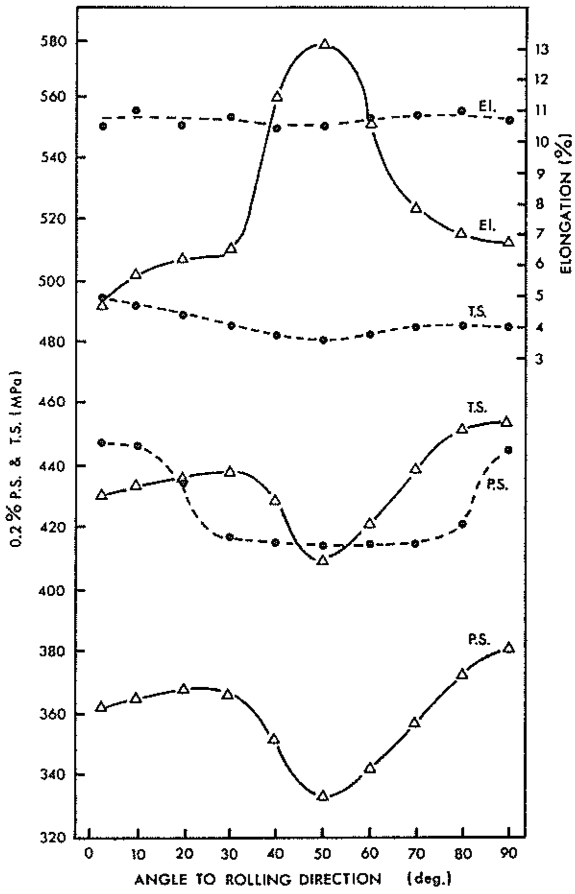


Figure 11. Anisotropy of mechanical properties of 8090-T6 (△) and 2014A-T851 (●) sheet.

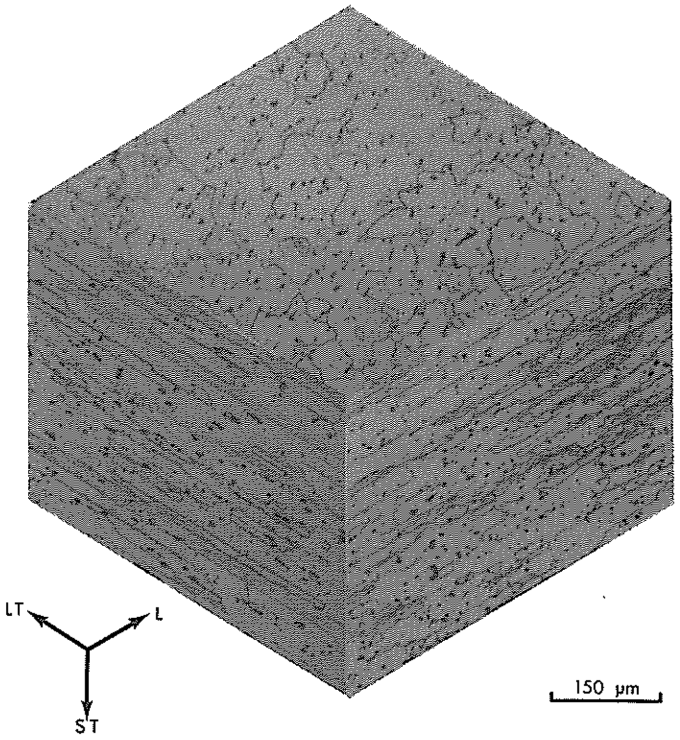


Figure 12. Partially recrystallised 8090 sheet.

grain size and texture variations, mechanical properties, particularly in bar and strip, were location-dependent with significant differences across the bar/strip, fig. 13, and throughout the bar thickness, fig. 14, although it is noted that longitudinal strength properties at all locations greatly exceed the minimum values required by the specifications 2014A-T6511 (L168-415 MPa, 460 MPa and 7% for 0.2% PS, TS and elongation respectively) and 7075-T73511 (L160-420 MPa, 485 MPa and 8% for 0.2% PS, TS and elongation respectively). Characteristically lower ductility values are also achieved. Property variations were similarly noted in channel sections of 1.6 mm wall thickness, where longitudinal 0.2% PS levels were 20-40 MPa higher from the flanges compared to locations within the middle of the extrusion, although TS values were relatively unaffected. No significant differences in properties from corresponding locations were apparent from the same section in alloy 7075-T75311 (L160) in which it was originally designed. 'Round the clock' tests in the bar showed significant anisotropy in strength properties, with 0.2% PS and TS values showing minimum levels of 340 MPa and 460 MPa respectively at an angle of 60° to the extrusion direction. It is interesting to note the anisotropic similarity in this stretched 19 mm thick extrusion with that in the previously mentioned unstretched 0.8-1.6 mm gauge sheet.

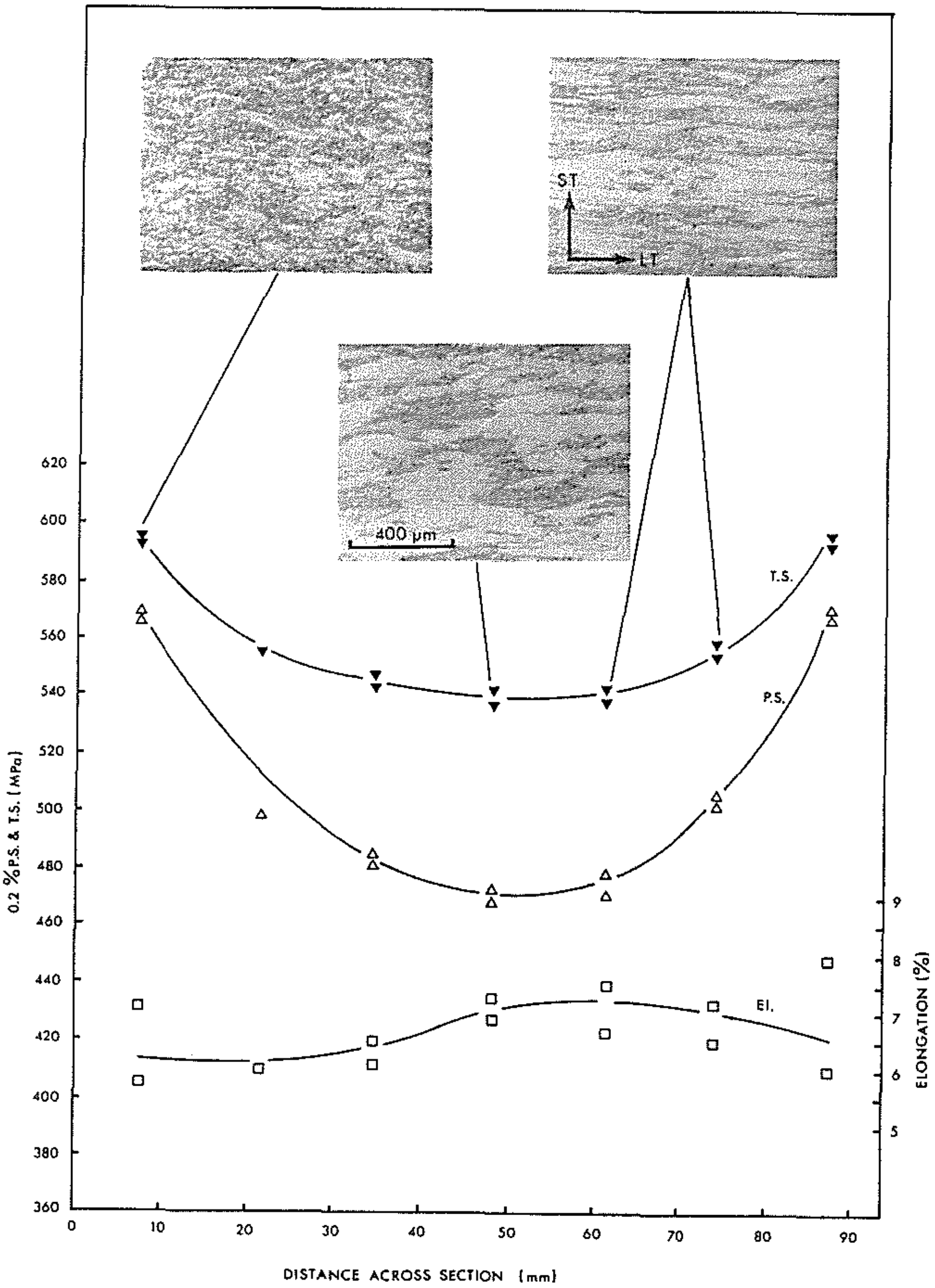


Figure 13. Longitudinal 8090-T6511 extrusion properties as a function of position across bar with associated grain structures.

Interest in aluminium-lithium at WHL has not been limited to alloys produced by the 'ingot metallurgy' route and the mechanically alloyed 9052XL material has been examined in extruded round bar of 98 mm diameter. Metallographic characterisation showed a very fine, uniform grain size typically of ~ 1 µm and x-ray diffraction studies indicated the presence of Al_4C_3 together with unidentified particles assumed to be complex dispersoids of aluminium, lithium, magnesium, oxygen and carbon. Heat treatment studies showed precipitation hardening effects to be absent and as-extruded properties were relatively unaffected by heating at 500°C for 0.5h to simulate thermal effects during a forging operation, consistent with the dispersion-strengthened nature of this material. Typical mechanical properties are illustrated in fig. 15 and, although not strictly equivalent due mainly to section size differences, they are comparable with those from the aforementioned 8090 extruded bar with noticeable improvements in transverse 0.2% PS values. From a practical point of view, this material is particularly attractive in that the ability to achieve adequate properties without solution treatment eliminates both the problem of residual quenching stresses and the need for a cold stretch prior to ageing, necessary to develop full strength in precipitation hardening aluminium-lithium alloys.

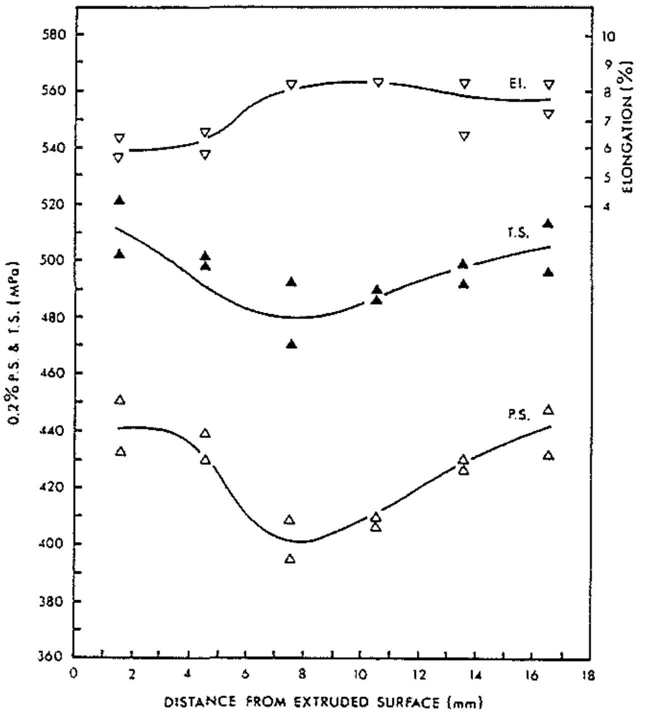


Figure 14. 8090 tensile properties through the extrusion thickness.

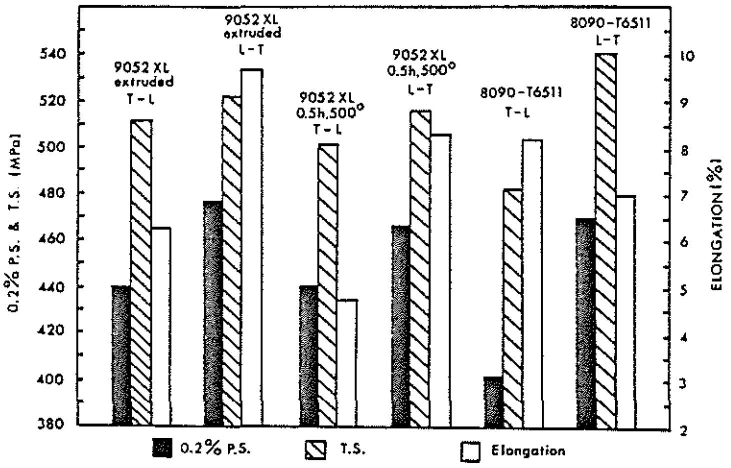


Figure 15. Mechanical properties of 9052XL (samples extracted from 98 mm dia. extruded bar) compared to those of 8090 (extracted from centre of 95x 19 mm rectangular extruded bar).

5.3 Plate

Due to the combined effects of the low material utilization typical of plate and the current high cost of aluminium lithium, little usage, at least initially, of these alloys in plate form is envisaged at WHL. Nevertheless, evaluation of aluminium-lithium plate has been carried out on 25 mm thick material in alloys 8090 and 8091 in the T651 temper.

8090 properties were found to be location-dependant throughout the plate thickness with maximum values occuring at the centre (½t) position, the converse of the 8090 extruded bar mentioned previously. Fig. 16 shows that both surface and centre (½t) longitudinal 0.2% PS properties of 8090 comfortably exceed both the corresponding minimum (410 MPa) and typical 2014-T651 (L93) levels. This is not the case for corresponding 8090 transverse properties where, although most of the samples tested reached the relevant L93 minimum of 400 MPa, the majority failed to match typical L93 values. However, all 8090 TS levels exceeded both corresponding minimum (450 MPa for both longitudinal and long transverse directions) and typical L93 levels. Elongation properties of 8090 were generally in the range 5-7% while those of L93 were 8-10% (typical) and 6% (specified minimum).

Compared to 8090 tensile properties, those from 8091 alloy were noticeably less dependant upon position throughout the plate thickness. The mechanical test results in fig. 17 show 8091 0.2% PS levels to comfortably exceed the corresponding 7075-T651 (L95) and 7010-T73651 (DTD 5130A) minimum values of 450 MPa and 425 MPa respectively for both longitudinal and long transverse directions. TS properties of 8091 comfortably exceeded 7010-T73651 minimum of 490 MPa and in all but a few instances exceeded the 7075-T651 minimum of 530 MPa. Also apparent in Fig. 17 is the fact that particularly in the case of the PS values the highest properties are achieved in the centre of the plate which is the reverse of what is found with the conventional alloys.
Elongation properties of 8091 were generally in the 3-6% range while those of 7075 were 8-10% (typical), 6% (specified minimum) and for 7010 the specified minimums are 8% (longitudinal) and 6% (long transverse).

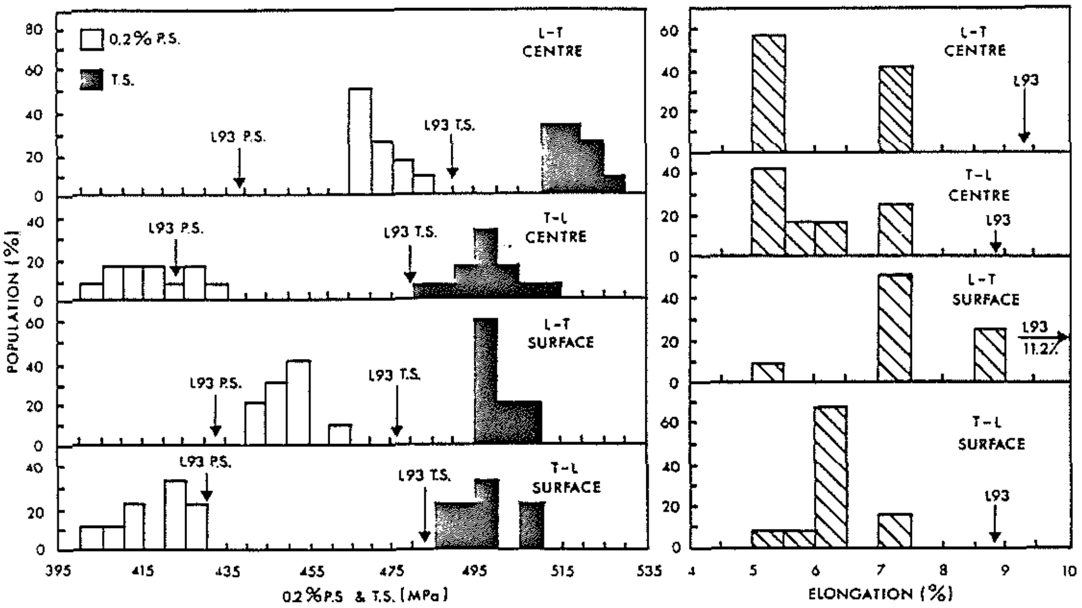


Figure 16. Histograms of 8090-T651 plate properties with measured L93 mean values.

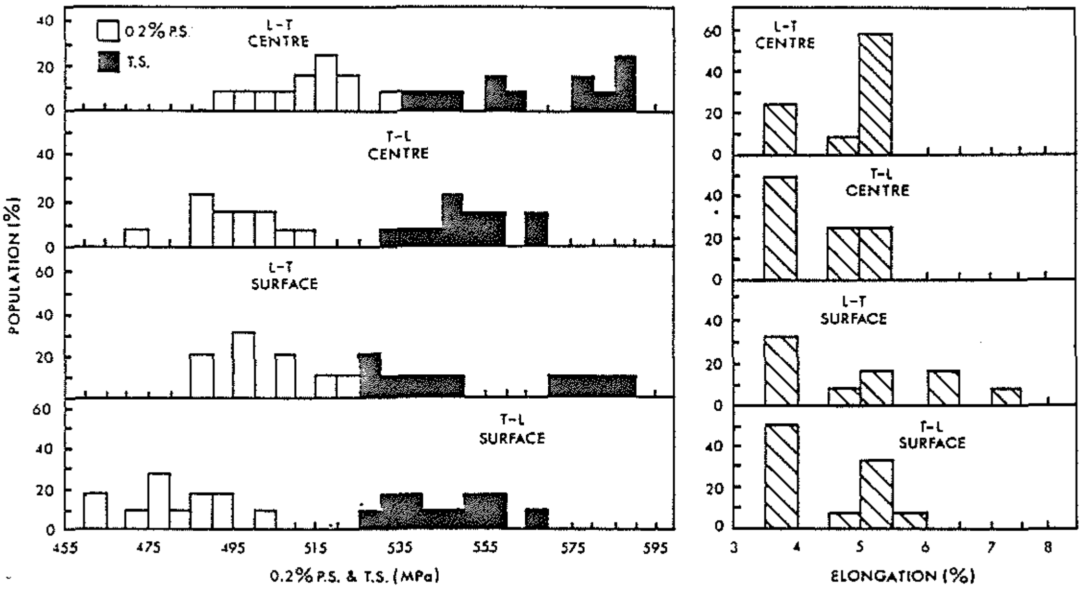


Figure 17. Histograms of 8091-T651 plate properties.

The above 8091 results were obtained from miniature tensile specimens. Properties were additionally obtained from larger tensile samples representing a greater proportion of the plate thickness and the resultant 0.2% PS values are compared with corresponding compression data in fig. 18. This indicates noticeably higher tension values in the longitudinal direction but lower corresponding compression levels due to relatively easy failure along grain boundaries elongated in the rolling direction; the converse situation occurs in the long transverse direction where compression properties are higher. The 2014-T651 (L93) minimum tension 0.2% PS level of 410 MPa is just achieved by 8090 in the longitudinal and long transverse directions in compression and tension respectively while the converse of this testing gives properties which clearly exceed this value. All 8091 0.2% PS values in both tension and compression comfortably exceed the corresponding tension minimums of 450 MPa and 425 MPa for 7075-T651 and 7010-T73651 respectively.

An important property of plate material employed in aircraft structures is fracture toughness, deficiencies in which were largely responsible for the withdrawal of the first commercial aluminium-lithium alloy 2020 as mentioned in the introduction to this paper. After initial trials to confirm a good correlation with directly measured K_{IC} values, a test method was adopted at WHL whereby this parameter was derived from the measured ratio of notched tensile stress/0.2% proof stress (17) using the notched tensile test specimen of ASTM E602/78.

As well as being relatively simple to perform, the method has the additional advantage that the small specimen sizes (~12 mm diameter) facilitate measurement at various positions through the plate thickness. Results from 8090 plate are shown in fig. 19 where longitudinal K_{IC} values at both surface and centre (½t) locations are generally higher than those from similarly tested 2014-T651 plate while 8090 transverse levels are slightly inferior. Fig. 20 shows K_{IC} data for 8091 and 7075-T651 and the former alloy appears to be universally inferior. However, this comparison is further complicated by the fact that L95 plate which was available for the comparative testing was significantly thicker than 8091 (100 mm and 25 mm respectively). Further, although the 8091 alloy was non-optimised and produced at a relatively early stage in the current development programme, it nevertheless exhibits K_{IC} values which are generally superior to those of 2020 alloy i.e. 22 and 16 MPa $m^{\frac{1}{2}}$ for longitudinal and transverse directions respectively(18).

6. FATIGUE

Fatigue testing of various aluminium-lithium product forms is continuing at WHL to obtain basic material data as well as in configurations to simulate actual material usage in helicopter structures. Results obtained so far have generally substantiated those reported from other workers which indicate the fatigue properties of the new alloys to match, and often exceed those of 'conventional' aluminium alloys. Notwithstanding this, a point of concern has arisen in testing of 8090 sheet which, although appearing superior to unclad 2014A-T6 sheet at peak stress levels of ≥ 250 MPa, has indicated inferior behaviour at lower stress levels, fig. 21. However, these results should be interpreted taking into consideration (a) the 8090 was of early origin and may not be truly representative of future production material, especially with regard to metal cleanliness where the presence of undissolved inclusions may result in premature fatigue failures (b) the static strength of 8090-T6 tested was significantly lower than 2014A-T6 and 8090-T851 and (c) the duplex solution treatment applied to 8090 to simulate both manufacturers and users treatments (in air) will have resulted in some lithium/magnesium surface depletion so that comparison should perhaps be more realistically made with clad 2014A. Although confirmatory tests have yet to be made a similar but less clear cut situation has been indicated in fatigue testing of riveted lap joints in 8090 sheet. However, bushed lugs in 8090-T651 plate have out-performed similar specimens in 7075-T73, while 9052XL samples exhibit very satisfactory properties (as shown in Fig. 21). In view of the particular relevance of fatigue to helicopter applications, a number of programmes have been initiated, including comparisons of plain and notched fatigue properties of 8090 and 2014A forgings and plain and riveted joints in 8090-T6511and 7075-T73511 extrusions.

7. MANUFACTURING ASPECTS

The new aluminium-lithium alloys have been manufactured in most product forms and the widely reported ease of fabrication has been confirmed at WHL where cold forming of 8090 sheet has been accomplished even more readily

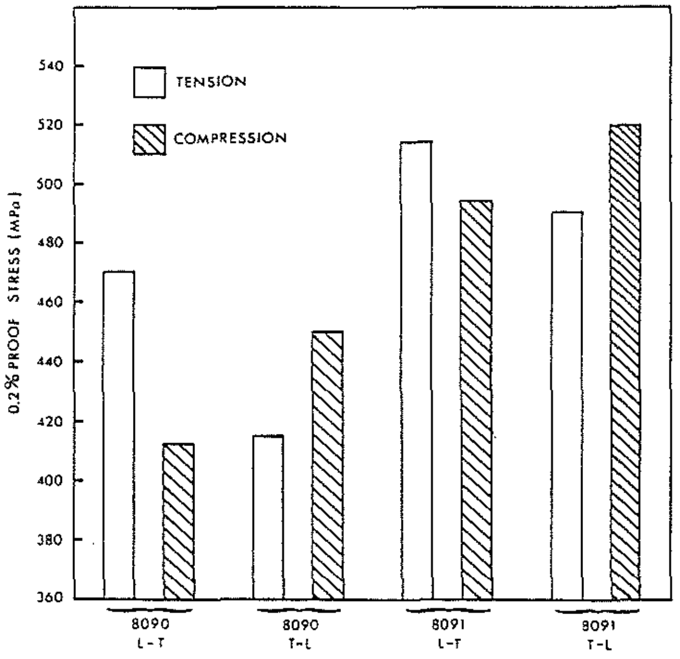


Figure 18. Tension and compression 0.2% PS of 8090 and 8091-T651 25 mm plate.

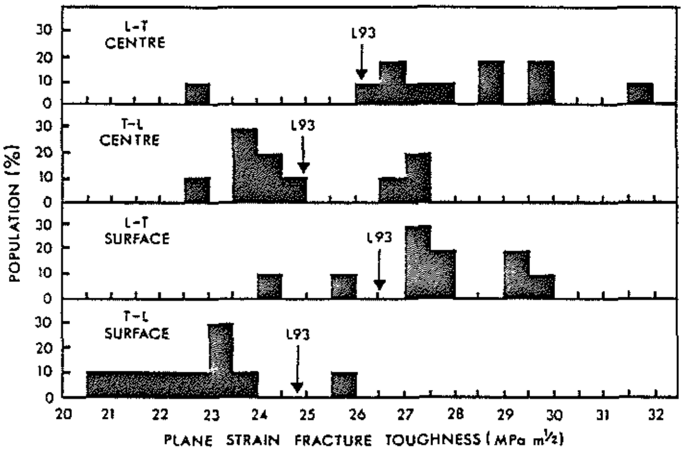


Figure 19. Histograms of plane strain fracture toughness of 8090-T651 plate with 2014-T651 (L93) mean values, both derived from σ_{nts}/σ_{ps} ratios.

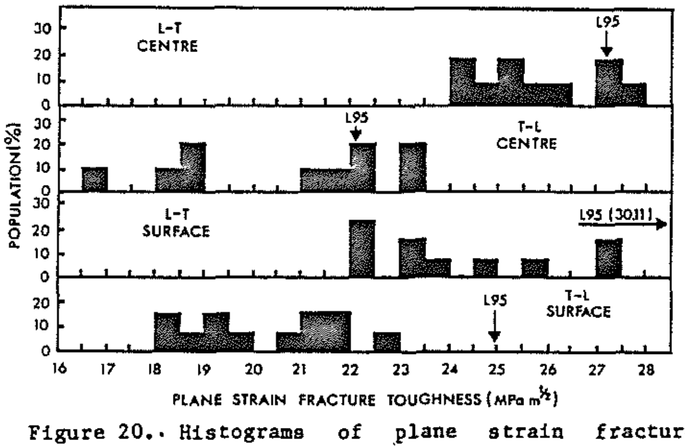


Figure 20. Histograms of plane strain fracture toughness of 8091-T651 plate with 7075-T651 (L95)mean values, both derived from σ_{nts}/σ_{ps} ratios.

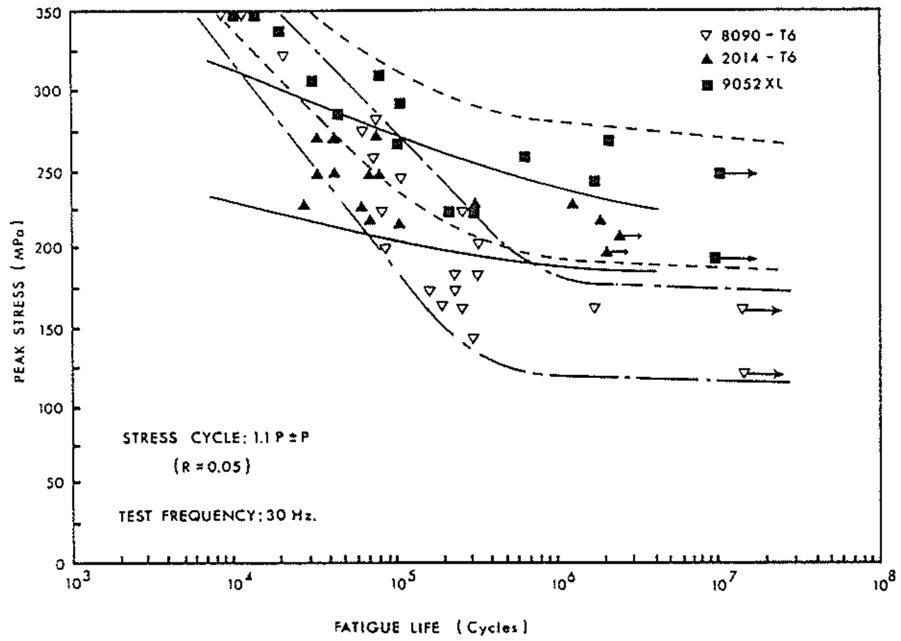


Figure 21. Comparison of axial fatigue behaviour of longitudinal samples of 0.7-2.0 mm 8090, 2014A and 9052XL alloys.

than with corresponding 2014A alloy while the machining characteristics of 8090, 8091, 2091 and 9052XL have been found to be indistinguishable from 'conventional' aluminium alloys. Aluminium-lithium extrudability is reported to be excellent with the implication that sections of greater complexity may be produced by this method although a negative aspect of these materials is the occasional increased difficulty of post-extrusion straightening arising from the inherently higher modulus. Forgeability is similarly good although there may be a need to introduce sufficient cold work to achieve post-ageing properties in some of the 'ingot metallurgy' alloys. Good drawing properties have enabled wire and tube to be produced, while the superplastic forming capabilities of these alloys are particularly attractive, especially in the relatively quench-insensitive 8090 alloy where a post-forming solution treatment prior to ageing may not be required to achieve adequate properties. The one area in which little effort has been devoted to date is in castings where a number of problems remain to be solved, particularly the high reactivity of molten aluminium-lithium with most mould sands. Additionally, it is most likely that specific casting compositions will need to be developed in which copper in particular will be absent as the significant contribution of this element to increasing density would largely negate the advantage of such alloys over most current casting alloys.

An important aspect of any material is that of joining. To date, two methods have been investigated at WHL i.e. spot welding and adhesive bonding.. No difficulties have been experienced with the former where many of the joints have been superior to those achieved in 'conventional' aluminium alloys. However, more work is required to develop suitable adhesive bonding methods, as bond strengths to date using standard chromic acid anodising as a pretreatment have been inferior to bonds achieved with 2014A alloy sheet. The use of alternative anodising procedures is indicated as failure appears to be associated with the premature detachment of the primer from the anodic film prior to cohesive failure of the adhesive. However, painting using conventional pickling and anodising treatments together with alochrom repair techniques have presented no problems.

8. CONCLUSIONS

Considerable work carried out at WHL during the past few years has critically examined some of the emerging aluminium-lithium based alloys in various product forms and, in general, favourable comparisons have been made with 'conventional' aluminium alloys. The prime target of an 8-10% density reduction has been achieved whilst maintaining other properties although a characteristic feature of many of the 'ingot metallurgy' aluminium-lithium alloys is the need for post-solution treatment cold work prior to ageing to achieve comparable and adequate strengths. The development of a lithium (and magnesium) depleted surface layer and associated porosity band after solution treatment in air is a phenomenon also typical of the 'ingot' alloys but is likely to only be problematic in thin sheet or extrusions and can be essentially eliminated by salt-bath or inert gas heat treatment. Quench sensitivity is generally significantly less than current aluminium alloys which has particular advantages when coupled with the superplastic forming capabilities of the new materials, enabling adequate properties to be achieved by directly ageing the as-formed component without the need for re-solution treatment. Texture effects, attributable to the zirconium additions in 'ingot metallurgy' alloys, result in noticeable anisotropy of mechanical properties although this may be significantly lessened in material processed to overcome the recrystallisation-inhibiting effects of this element. Corresponding strength reductions may be coupled with increased fracture toughness to produce a damage tolerant variant, particularly applicable to alloy 8090. Fatigue properties of 8090-T6 sheet have so far been disappointing at the low stress/high cycle end of the fatigue curve but it is encouraging that the 8090 alloy has out performed 7075-T73 in the form of bushed lugs. Additional work is in hand to evaluate fatigue properties of different product forms and configurations and it is hoped that the 'cleaner' metal now emerging from the metal producers (as a result of incorporation of efficient filtration systems in the casting process) will show improved fatigue characteristics.

The dispersion hardening nature of the mechanically alloyed 9052XL material has been confirmed and superior strength and fatigue properties to conventional 'ingot metallurgy' alloys have been exhibited and are relatively unaffected by exposure to the high temperatures which are encountered in forming operations such as forging. The absence of a solution treatment to achieve properties in this product form is particularly advantageous as induced quenching stresses are eliminated.

Excellent formability of 8090-T4 sheet has been demonstrated at WHL although the higher predicted final properties of material fabricated in the T351 temper have also aroused interest. No problems have been encountered in aluminium-lithium machinability and good forgeability and extrudability has been indicated by samples so far received.

Aspects of metal joining have been investigated and while excellent spot welds have been achieved, further work is required to establish optimum adhesive bonding procedures with particular attention being paid to anodising parameters.

In summary, it appears that the major deficiencies which led to the withdrawal of the previous commercial aluminium-lithium alloy 2020 have been overcome and while recognising that the new alloys have some differing characteristics compared to their currently used counterparts, their increasing use in aircraft structures is optimistically anticipated with the proviso that their increased costs are kept within economic bounds.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

1.	E.H.Spuhler	Alcoa Alloy X2020 Green Letter 156-9-58,(1958),27
2.	E.H.Spuhler, A.H.Knoll and J.G.Kaufmann	Lithium in Aluminium - X2020 Met.Prog. (1960), 79, 80-82
3.	E.S.Balmuth and R.Schmidt	A perspective on the development of aluminium lithium alloys. Proceedings of the 1st International Aluminium-Lithium Conference, Stone Mountain, Ga.May. 1980. Met.Soc.AIME 1981, 69-88.
4.	I.G.Palmer, R.E.Lewis and D.D.Crooks	The design and mechanical properties of rapidly solidified Al-Li-X alloys. Ibid, 242-262
5.	P.A.Lovett	Mechanical Alloying. The Metallurgist and Materials Technologist (1983), 15(9), 443-444
6.	J.S.Benjamin and M.J.Bomford	Dispersion Strengthened Aluminium made by Mechanical Alloying. Met.Trans.A, (August 1977), 8A, 1301-1305
7.	P.S.Gilman and S.J.Donachie	The Microstructure and Properties of Al-4Mg-Li Alloys prepared by Mechanical Alloying. Proceedings of the 2nd International Aluminium-Lithium Conference, Monterey, Ca. April 1983. Met.Soc. AIME, 1984, 507-515
8.	P.S.Gilman, J.W.Brooks and P.J.Bridges	High Temperature Tensile Properties of Mechanically Alloyed Al-Mg-Li Alloys. Proceedings of the 3rd International Aluminium-Lithium Conference, Oxford, July 1985. Inst. of Metals 1986, 112-120.
9.	C.J.Peel and B.Evans	U.K. Patent G.B. 2115 836B. February 1983.
10.	C.J.Peel, B.Evans, C.A.Baker, D.A.Bennett, P.J.Gregson and H.M.Flower	The Development and Application of Improved Aluminium-Lithium Alloys. Contribution to Reference 7, 363-394.
11.	F.W.Gayle and J.B.Vander-Sande	"Composite" Precipitation in an Al-Li-Zr Alloy". Scripta Met. (1984) 18, 473-478
12.	Ibid.	$Al_3(Li,Zr)$ or α' Phase in Al-Li-Zr system. Contribution to Reference 8, 376-385.

13.	R.F.Ashton, D.S.Thompson, E.A.Starke and F.S.Lin	Processing of Al-Li-Cu-(Mg) Alloys. Contribution to Reference 8, 66-77.
14.	P.J.Gregson and H.M.Flower	Microstructural Control of Toughness in Aluminium-lithium Alloys. Acta.Met. (1985), 33, 527.
15.	M.A.Reynolds, A.Gray, E.Creed, R.M.Jordan and A.P.Titchener	Processing and Properties of Alcan Medium and High Strength Al-Li-Cu-Mg Alloys in Various Product Forms. Contribution to Reference 8, 57-65.
16.	J.Moriceau, B.Dubost, G.LeRoy and P.Meyer	Aluminium-Lithium Alloys for the Aerospace Industry. Cegedur Pechiney, WESTEC-85. March 18, Los Angeles, CA, 1-7
17.	-	Rapid Inexpensive Tests for Determining Fracture Toughness. NMAB Pub. (1976), No. NMAB-328, 62-80.
18.	P.S.Pao, K.K.Sankaran and J.E.O'Neal	Microstructure, Deformation and Corrosion-Fatigue Behaviour of a Rapidly Solidified Al-Li-Cu-Mn Alloy. Contribution to Reference 3, 308-323.