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STRUCTURAL WEIGHT SAVINGS ON THE EH101 USING ALUMINIUM-LITHIUM ALLOYS

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ABSTRACT

In order to significantly reduce structural weight on the Anglo-Italian EH101 helicopter, extensive use will be made of the recently commercialised aluminium-lithium alloys as lightweight substitutes for extruded profiles, sheet and die forgings. An unacceptably high fly:buy ratio as well as the unavailability of thick sections has precluded the use of corresponding plate and bar, although numerous components originally designed in 'conventional' aluminium alloy plate and bar will now be manufactured in the form of aluminium-lithium die forgings.

This paper summarises the weight saving cost analysis associated with the planned introduction of these alloys into the EH101, and presents the results of some of the extensive studies carried out to assess their applicability and characteristics. It is shown that satisfactory properties can be achieved in the commercial 8090 and 2091 compositions although the former will be the preferred material. Joining may be effected by conventional adhesive bonding techniques whereas slight pre-treatment modifications are required for TIG welding. It is concluded that aluminium-lithium has reached the technical maturity to enable the EH101 to emerge as the Worlds first helicopter to be constructed extensively in these alloys.

1. INTRODUCTION

Whilst lightweight aluminium-lithium based alloys are currently being specified in new fixed wing aircraft designs and for space applications, the Anglo-Italian EH101 will represent their use, for the first time, in a helicopter airframe. Whilst observing certain cost effectiveness criteria, the prospective use of aluminium-lithium alloys for selected components in the forward and centre fuselage of this aircraft led initially to a minimum weight saving target of approximately 55 kg: complete replacement of all 'conventional' aluminium alloys at these locations, irrespective of cost, would yield an approximate 82 kg weight reduction. As testing of the new alloy has proceeded, however, the increasing confidence gained has widened the applications for which they will be employed and it is now the intention to incorporate them extensively throughout both the forward/centre fuselage (WESTLAND-designed and constructed) and the tail end (AGUSTA-designed and constructed). Nevertheless, two criteria must be fulfilled if an aluminium-lithium alloy is to be used in a particular application.

Firstly, adequate material properties must be demonstrated and although aluminium-lithium alloys may not always exhibit the same combination of properties as their currently used counterparts, this will not necessarily exclude their use, since the particular requirements of a specific application will be considered as well as the material characteristics of the alloy in which the component is currently designed. Secondly, the intrinsically higher material cost of aluminium-lithium alloys must be taken into account, in relation to the typical utilisation rates (fly:buy ratios) of various wrought aluminium alloy product forms, table 1, and the amount of actual weight saved. These factors may be combined into the following equation which represents a cost controlling criterion and which, in the case of the UK, is expressed in £ per kg:-

$$\frac{\text{Additional material cost of aluminium-lithium}}{\text{Weight saved} \times \text{material utilisation rate}}$$

Material form	Utilization rate
Conventional die forging	20%
Extruded profiles	90%
Plate/bar	7%
Sheet	50%

Table 1. Utilisation rates (fly:buy ratios) for wrought aluminium alloys.

It can be shown that the cost of weight saving for various product forms can be ranked in order of their material utilisation rates. Thus, extruded profiles (90% utilisation rate) represent the cheapest weight saving while plate (7% utilisation rate) is the most expensive. Further, when compared with a predetermined break-even cost of weight saving for the EH101 it is concluded that it is not cost-effective to incorporate aluminium-lithium alloys in plate and extruded bar forms and, accordingly, little work has been carried out by WHL on these products. However, aluminium lithium sheet, extruded profiles and conventional die forgings are cost effective and will therefore be used, subject to satisfactory material properties. In view of the acceptable weight-save costs of aluminium-lithium forgings, these will be substituted for numerous applications which currently use 'conventional' aluminium alloy plate, since it is predicted that the extra costs associated with the manufacture of forging dies will be approximately offset by reduced machining costs compared to plate and when amortised over 100 aircraft. In the case of extruded profiles, only those sections which use in excess of 0.7 metres per aircraft will be considered for replacement by aluminium-lithium. Small cleats, brackets and fittings in other categories will be excluded if there are insufficient quantities used per aircraft to effect significant weight reductions.

2. ALUMINIUM-LITHIUM ALLOY COMPOSITIONS

A previous ERF paper in 1986 (1) indicated a number of pre-production aluminium-lithium alloy compositions and designations which had, at that time, been identified by the aluminium producers as potential candidates for subsequent 'scaling-up' to full production status. Inevitably, some 'front-runners' have emerged and Table 2 details the three alloys now routinely manufactured commercially by the 'ingot' route, as distinct from powder metallurgy methods once believed to be the only way to produce these alloys on an industrial scale.

The properties of 'conventional' wrought aluminium alloys for use in the aircraft industry are generally divided into three main categories viz 'low strength/damage tolerant', 'medium strength' and 'high strength'. The development of aluminium-lithium alloys has been similarly guided by these requirements. Through processing and heat treatment variations, to be discussed later, both 8090 and 2091 alloys are capable of fulfilling the property requirements of the first two categories and as it is within these that the majority of EH101 structural property requirements fall, WESTLAND test programmes have been formulated accordingly. Results of testing the 'high strength' 2090 alloy will therefore not be presented in this paper. Table 3 details the possible use of 8090 and 2091 on the EH101, although due to current material availability, commercial aspects and the desire to keep to a minimum the number of alloys used, it is the current intention that 8090 will be the preferred alloy. In-depth evaluation of 2091 is nevertheless continuing.

Alloy	Company of origin	Chemical composition (weight per cent)					Other licenced billet producers
		Li	Cu	Mg	Zr	Al	
8090	British Alcan (UK)*/ Pechiney (F)	2.20 to 2.70	1.00 to 1.60	0.60 to 1.30	0.04 to 0.16	Bal	International Light Metals (USA) Pechiney (F) Alcoa (USA) Kaiser Aluminium (USA)
2091	Pechiney (F)	1.70 to 2.30	1.80 to 2.50	1.10 to 1.90	0.04 to 0.16	Bal	Alcoa (USA)
2090	Alcoa (USA)	1.90 to 2.60	2.40 to 3.00	0 to 0.25	0.08 to 0.15	Bal	Reynolds Aluminium (USA) Kaiser Aluminium (USA)

*- Prime licencees from original patent holders, RAE, Farnborough (UK)

Table 2. Current commercial aluminium-lithium alloys (ingot route)

All three compositions shown in Table 2 exhibit a 8-10% density reduction with a 8-10% increase in elastic modulus compared to current aluminium aircraft alloys, and being precipitation hardening systems, may be similarly heat treated to produce the required properties. Nevertheless, aluminium-lithium alloys 8090 and 2091 do differ from 'conventional' aluminium alloys in some respects and the following characteristics can account for the properties described later in this paper.

a) 'Conventional' age hardened aluminium alloys derive the majority of their strengthening by uniform precipitation of fine submicroscopic particles of <u>one</u> particular phase type in a given alloy. In the above three aluminium lithium alloys, strengthening is due to co-precipitation of at least <u>two</u> different phase types per alloy.

b) 'Conventional' age hardened aluminium alloys develop a uniform distribution of the relevant hardening phase by ageing the previously solution treated material. In the aluminium-lithium alloys above, one of the hardening phases (δ'-Al_3Li shown in fig. 1a) precipitates in a similar way. However, additional strength in 8090 and 2091 is due to the S'-Al_2CuMg phase, and in 2090 to the T-Al_2CuLi phase. Both these compounds will precipitate only in the form of sparsely distributed colonies of coarse particles if directly aged after solution treatment, hence providing minimal additional strengthing, unless numerous nucleation sites are introduced into the metal. This is generally achieved by generation of a dislocation network imparted by cold working the material between solution and precipitation heat treatments, thus making this operation a prime requirement if optimum properties are to be achieved. Figures 1b and 1c illustrate these effects upon S'-Al_2CuMg phase size and distribution in solution treated and aged 8090 with and without an intermediate cold working operation.

Product form	Alloy	Condition	Substitute for:
Sheet	8090 2091	Recrystallised Damage tolerant	2024-T3 (≡ BS L109)
Sheet	8090 8090/2091	Unrecrystallised, 'Medium strength' Recrystallised, 'Medium strength'	2014-T6 (≡ BS L157, L159, L165, L167)
Die Forgings	8090	Unrecrystallised, 'Medium strength'	7010-T7452 (forgings) 7010-T736 (forgings) 7010-T7451 (plate)
Extruded sections	8090	Unrecrystallised, 'Medium strength'	7075-T7411 (≡ BS L160)
Tube	8090	Unrecrystallised, medium strength	6082-T6 (≡ BS L114)

Table 3. Tentative aluminium-lithium variants for incorporation on the EH101.

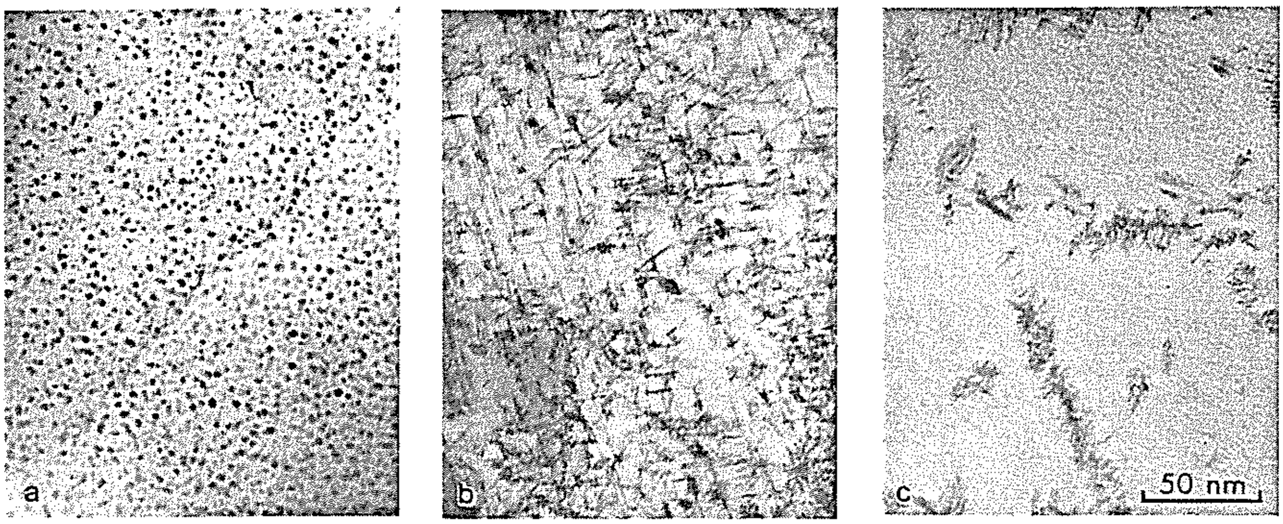

Figure 1. Typical Al-Li-Cu-Mg-Zr alloy TEM micrographs (a) δ'-Al_3Li precipitates (b) S'-Al_2CuMg precipitates in metal with cold working operation (c) S'-Al_2CuMg precipitates in metal without cold working operation.

c) 'Conventional' age hardening alloys generally exhibit a largely recrystallised grain structure giving relatively uniform properties irrespective of the testing orientation relative to the rolling/extrusion/forging direction, i.e. they are isotropic. In the case of the current aluminium-lithium alloys, zirconium additions generally act as recrystallisation inhibitors, and the inherent sub-grain boundaries present in the resultant unrecrystallised grain structures act as further nucleation sites for S'-Al_2CuMg and hence promote further strengthening. Concommitant with such structures is the retention of the rolling/extrusion texture which results in a relatively anisotropic metal as evidenced in a significant dependence of mechanical properties upon test direction. 8090A is the specific designation adopted when this particular alloy is used in the unrecrystallised condition to meet 'medium strength' properties. However, primarily in the case of sheet and thin plate, suitable processing conditions can overcome the effects of the zirconium and hence produce a recrystallised grain structure, albeit with lower strength but with the anisotropy reduced to varying degrees in static strength properties. It has been found that this grain structure is required in order to promote 'damage tolerant' properties wherein a characteristically lower P.S:T.S ratio is achieved compared to 'medium' strength levels: typical values are 0.66 for 2024-T3 c.f. ~0.86 for 2014-T6 i.e. a greater difference between P.S. and corresponding T.S. levels. When produced in the recrystallised condition, the designation 8090C is used. With regard to alloy 2091, this was originally developed to meet 'damage tolerant' requirements in the form of sheet and thin plate and is therefore produced almost entirely in the recrystallised condition for these products while thicker plate, extrusions and forgings tend to be unrecrystallised to achieve medium strength properties. Examples of unrecrystallised and recrystallised grain structures are shown in figures 2a and b.

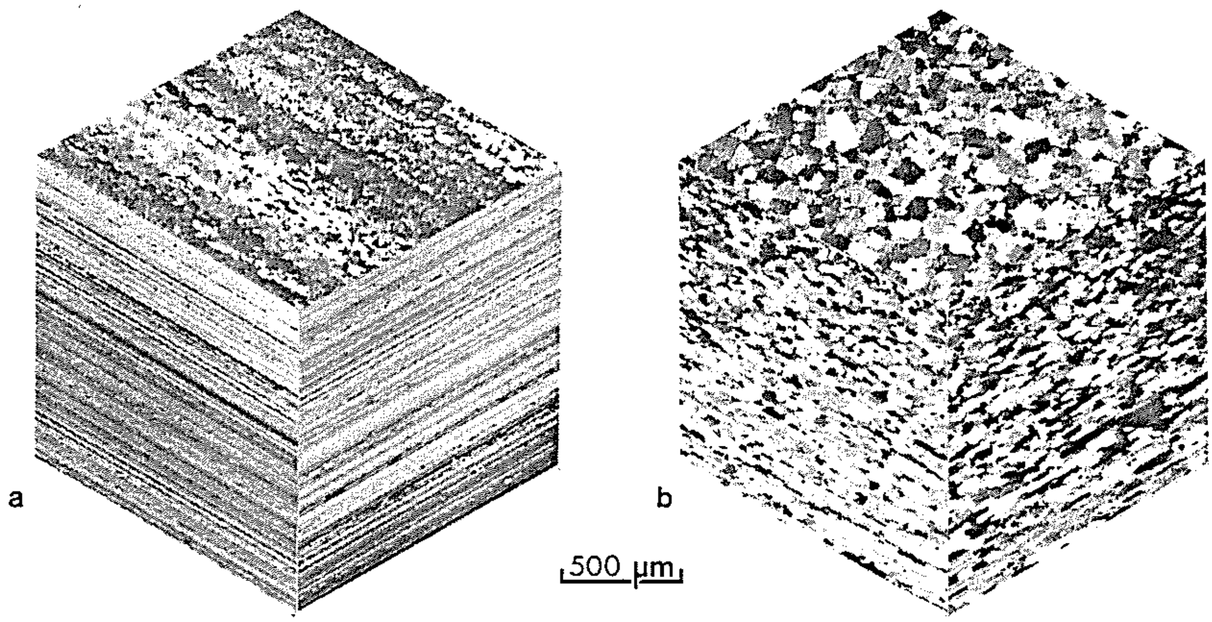

Figure 2. Aluminium-lithium alloy grain structures (a) Unrecrystallised (b) Recrystallised.

d) For a given strength level and particularly in the unrecrystallised form, *aluminium-lithium alloys generally exhibit lower ductility* values than their 'conventional' counterparts. This is primarily due to the ordered, coherent nature of the δ'-Al_3Li hardening phase and the resultant dislocation 'pile-ups' generated at grain boundaries after plastic deformation of the metal. This is exacerbated by the retention of crystallographic texture in unrecrystallised grain structures.

3. ALUMINIUM-LITHIUM SHEET

The majority of sheet used on the EH101 is for skinning and general presswork which, in the original design, called for the 'damage-tolerant' 2024-T3 (≡ BS L109) and 'medium-strength' 2014-T6 alloys, both in the clad condition. The aim of the WESTLAND work has therefore been to develop heat treatment schedules for, and to assess the properties of 8090 and 2091 as direct substitutes for the above alloys.

3.1 'Damage tolerant', 2024-T3 replacement

As mentioned in section 2, it has been found that a recrystallised grain structure is necessary in order to produce the relatively large difference in 0.2% PS and TS levels characteristic of metal fulfilling the 'damage tolerant' category. Further, in order to achieve properties comparable to 2024-T3, a significantly underaged condition is required. Ageing curves have been generated at 135°C and 150°C for 1.00 mm recrystallised 8090C and 2091 alloys in the solution treated and stretched, T3 temper. Table 4 summarises the static mechanical properties achieved in commercially viable ageing times of 12h and 20h.

	Ageing Temp °C	Ageing Time h	8090C			2091			L109 minima		
			0.2% PS MPa	T.S MPa	El %	0.2% PS MPa	T.S MPa	El %	0.2%PS MPa	T.S MPa	El %
LONGITUDINAL	135	12	284	372	14	358	434	17			
	135	20	298	388	13	364	440	15			
	150	12	310	394	15	364	444	15	270	405	15
	150	20	320	407	15	368	456	13			
TRANSVERSE	135	12	243	367	17	337	460	16			
	135	20	261	384	16	347	469	14			
	150	12	263	390	15	342	467	12	270	405	15
	150	20	276	405	15	350	476	12			

Table 4. Static mechanical properties of 1.00 mm 8090C and 2091 aged to 'damage tolerant' temper.

The following observations may be made from this data:-

i) For a given ageing temperature and time, 2091 shows higher strength than 8090C but with comparable ductility values. This is due to the greater propensity of the former alloy to develop the hardening S′-Al_2CuMg phase which arises from the higher Cu and Mg levels of this particular composition.

ii) Each of the four ageing schedules stated is capable of adequately achieving 2024-T3 (BS L109) minimum specified strength levels in alloy 2091 in both longitudinal and transverse directions. In the case of 8090C, ageing for 20h at 150°C only just achieves this.

iii) For both alloys and for all four ageing conditions investigated, 0.2% PS values are noticeably higher in the longitudinal direction than those cut transversely. In order to study this further, and using the 12h at 135°C and 20h at 150°C ageing schedules for 2091 and 8090C respectively, duplicate tensile tests were conducted on specimens cut at 10° intervals to the rolling direction. The results are shown graphically in figure 3, together with corresponding data for clad 2024-T3 (BS L109) sheet. All three alloys exhibit some degree of anistropy in P.S. values, with a gradual decrease in strength from 0° to 40° to the rolling direction, which then remains essentially constant in 8090C and L109. In the case of 2091, strength increases again from ~60° to 90° and may be indicative of differing processing conditions applied to the alloys by the manufacturers of the 8090C and 2091 sheet under study, ALCAN and PECHINEY respectively. However, these differences may also be due to the differing compositions of the two alloys. Higher strengths at all angles could be achieved by longer ageing times at the above temperature, but these would be uneconomical. Alternatively, higher ageing temperatures could be used, although there is evidence to suggest that a decrease in fracture toughness would ensue (2). However, although 2091 appears to be the stronger alloy, 8090C does achieve the L109 minimum specified P.S. although just fails to meet the corresponding T.S. minimum. Nevertheless, as far as EH101 alloy selection upon a static property basis is concerned, the two aluminium-lithium alloys may be regarded as equivalent. Fracture toughness testing is in progress and is concentrating upon the 12h at 135°C and 20h at 150°C ageing schedules for 2091 and 8090C respectively.

It is anticipated that the majority of components will be formable in the as-received T3 temper and selected trials in 2091 and 8090 have confirmed this. In the event that re-solution treatment is necessitated, tests on 2091 have shown this to have no significant effect upon strength after ageing for 12h at 135°C, producing a sufficiently underaged structure such that S′-Al_2CuMg is not formed and hence the metal does not require post solution treatment cold work for optimum nucleation. Strengthening in this case is due primarily to the homogeneously nucleated and uniformly dispersed δ'-Al_3Li phase (3).

In addition to static property tests, extensive fatigue testing of both 2091 and 8090C in 'damage tolerant' tempers is in progress. Preliminary results from 2091 aged 12h at 135°C are shown in figure 4, the S-N curves correlating with the static tests in that re-solution treatment prior to ageing has no noticeable effect upon fatigue behaviour. Further, at equivalent peak stress levels of $\leq$ 250 MPa, 2091 specimens exhibit significantly longer fatigue lives compared to L109 and is in accordance with the lower fatigue crack propagation rates generally claimed for aluminium-lithium based alloys (4,5).

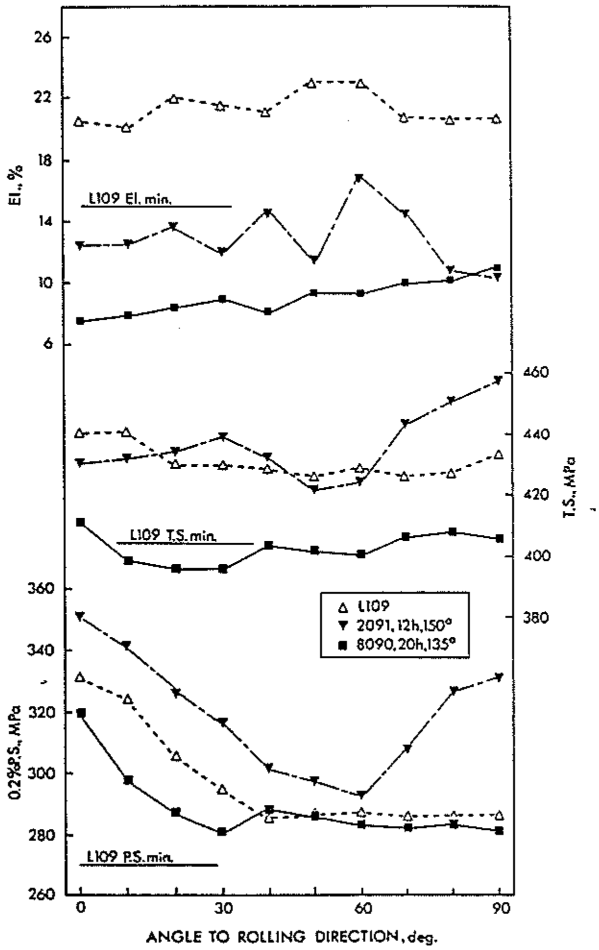

Figure 3. Anisotropy in 2091 and 8090C sheet aged to the 'damage tolerant' condition, with L109 data for comparison.

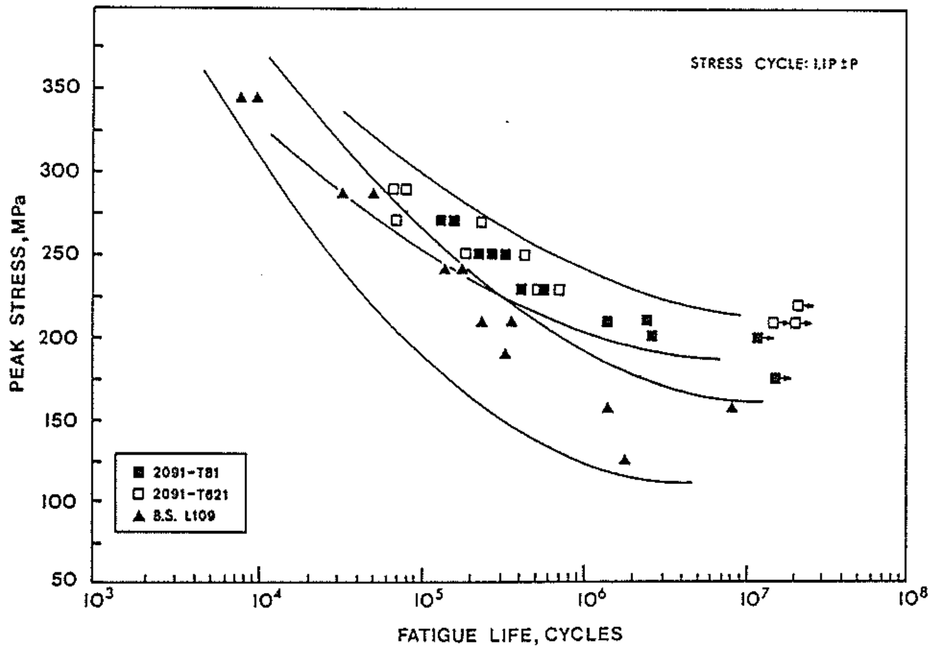

Figure 4. Comparison of fatigue behaviour of BS L109 sheet with that of (a) stretched and (b) re-solution treated recrystallised AA2091 sheet in the LT direction and aged 12h at 135°C.

3.2 'Medium Strength', 2014-T6 replacement

The first of the present generation of aluminium-lithium alloys to be developed specifically for the 'medium strength' category was 8090A, i.e. exhibiting an unrecrystallised grain structure. As mentioned in section 2, for a given alloy composition and ageing schedule, such a grain structure is capable of producing higher strengths than a corresponding recrystallised grain structure, but at the expense of greatly increased anisotropy in mechanical properties. Accordingly, WESTLAND work is currently in progress wherein attempts are being made to elucidate 'medium strength' ageing schedules for application to the recrystallised 2091 and 8090C variants originally developed for 'damage tolerant' properties. Figure 5 shows a representative 175°C ageing curve for longitudinal 8090A, 8090C and 2091 specimens from which the following points arise:-

i) As with the 'damage tolerant' ageing trials, 2091 shows higher strength than 8090C at equivalent ageing times.

ii) Ductilities in the recrystallised 2091 and 8090C alloys are significantly higher than in unrecrystallised 8090A.

iii) Minimum BS L165 strength properties can be achieved in all three alloys by ageing for commercially realistic times of ~20h. Corresponding L165 ductilities are attained in 2091 and 8090 C, but not in 8090A.

Figure 6 shows anisotropy curves for the above three alloys aged at 175°C. These confirm the marked anisotropy in unrecrystallised 8090A alloy, but show this to be significantly reduced in the recrystallised variants. In the case of 8090C and 2091, L165 minimum strength properties are achieved at all test angles. However, the 0.2% PS of 8090A marginally fails to attain these levels at angles between 45°-60° to the rolling direction. Nevertheless, as pointed out by Peel et al (6) the prescribed relationships between limit loads and ultimate design loads requires that the P.S.:T.S. ratio should be not less than 0.67 and 0.75 for civil and military aircraft respectfully. In the case of 8090A above, T.S. reaches a minimum value of 410 MPa at the 55° orientation. Taking military aircraft as the 'worst' case, the mandatory rules require that for this T.S., the corresponding minimum P.S. should be 275 MPa. Further, considering the 415 MPa minimum specified T.S. for L165, the corresponding minimum P.S. in this case is 311 MPa and this is clearly acceptable since this was the originally specified material for use on the EH101. As shown in fig. 6, 8090A exhibits a P.S. minimum of ~335 MPa and it may therefore be concluded that, on the basis of static strength levels, sheet in all three alloy variants may be considered as suitable lightweight replacements for L165. This is of particular importance to WESTLAND as it would appear that both 'damage tolerant' and 'medium strength' requirements may be met by one alloy in one condition, (8090C and/or 2091) thereby providing both commercial and inventory advantages.

Before the final sheet alloy choice can be made, testing of other material properties will be completed such as fracture toughness and fatigue evaluations of the three alloys. Results to date from 8090A are very encouraging and representative S-N curves for stretched sheet aged for 30h at 175°C are shown in fig. 7. These show that in the high cycle/low stress regime, the three testing directions may be ranked in decreasing order as longitudinal, 55° to the rolling direction and transverse. Also included for comparison is the corresponding unclad

2014-T6 (≡ BS L157) curve in the transverse direction and again indicates the very satisfactory fatigue properties of aluminium- lithium alloys. Since the alloy to be replaced is clad 2014-T6 (≡ BS L165), this would be expected to exhibit even lower fatigue properties, thereby accentuating further the superiority of aluminium-lithium and tests are in progress to confirm this. The effects of re-solution treatment prior to ageing 8090A have been investigated for 'medium strength' ageing schedules of 70h, 16h and 30h at 135°, 185 and 175°C respectively. In all cases, little significant effect upon fatigue behaviour was observed, with all results at least comparable to corresponding L157 specimens.

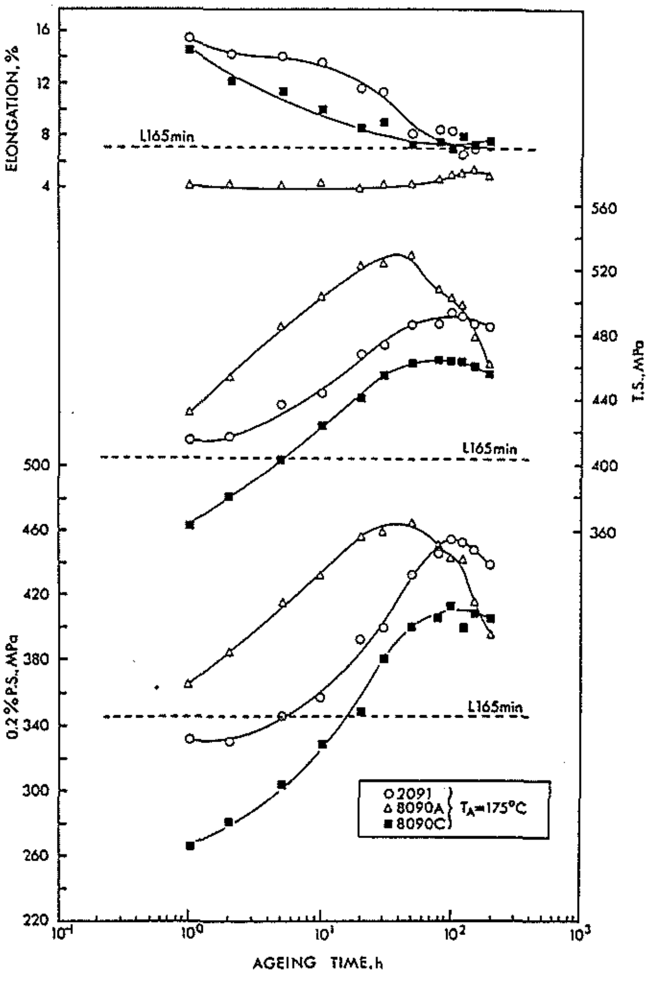

Figure 5. Ageing curves at 175° to achieve 'medium strength' properties in 2091, 8090A and 8090C.

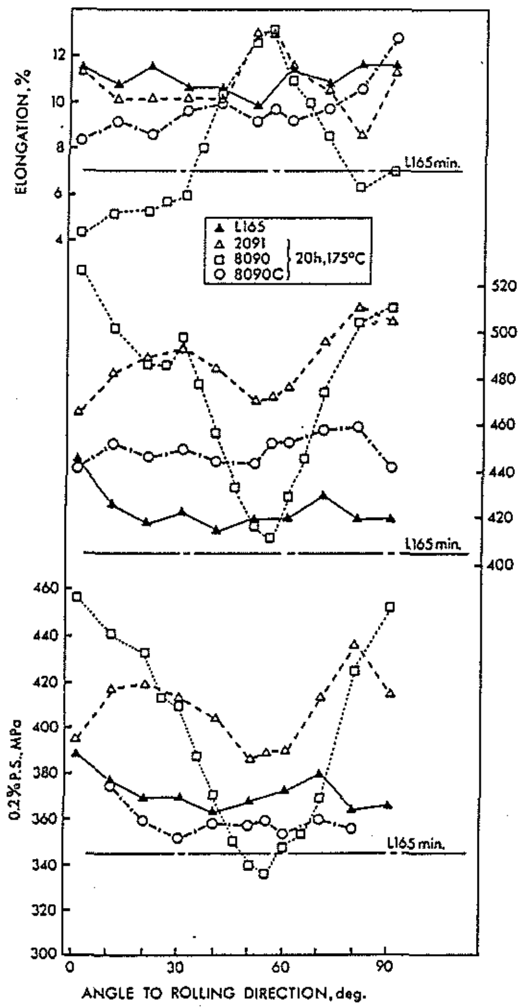

Figure 6. Anisotropy in stretched 2091, 8090A, 8090C sheet after ageing 20h at 175°C, with BS L165 for comparison.

4. ALUMINIUM-LITHIUM DIE FORGINGS

Significant potential weight savings have been identified in the EH101 airframe through replacement of large structural members currently machined from 'thick' (up to 125 mm) 7010-T7451 plate (DTD 5130A) with those from cold compressed aluminium-lithium die forgings. Two factors have prompted this change in product form:-

1) Whilst the (lost) value of metal in the form of scrap arising from the very low (7%) utilisation rate of 'conventional' aluminium alloy plate has been tolerated in the past, such a situation would be unacceptable for the intrinsically higher metal costs of corresponding aluminium-lithium plate. However, due to the greater utilisation rate of

forgings associated with their being closer-to-net shape, manufacture of such components in this way from aluminium- lithium is below the calculated break-even figure for EH101 weight saving.

2) Aluminium-lithium plate of thicknesses greater than 50 mm is not commercially available due to quench sensitivity problems which lead to particularly poor ST ductility and toughness.

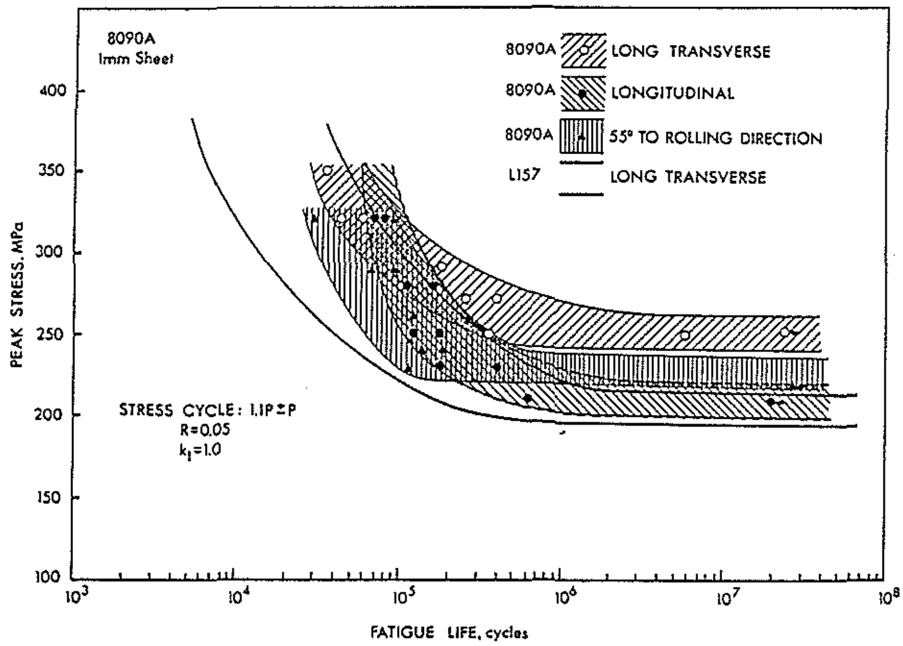

Figure 7. S-N curves of 8090A stretched sheet aged 30h at 175°C.

In order to assess the feasibility of such a change, trial die forgings of a selected EH101 main cabin lift frame side member were produced in alloy 8090, with similar components in the ALCAN higher strength (but yet to be fully commercialised) 8091 aluminium-lithium alloy and in 'conventional' 7010 aluminium alloy for comparison. All forgings were cold compressed subsequent to solution treatment in order to provide a degree of stress relief. In the case of the two aluminium-lithium alloys, this additionally acts as a means of providing nucleation sites for S'-Al_2CuMg precipitation during ageing, in an analogous way to stretching in mill products. Figure 8 shows the forgings before and after machining to the final shape and dimensions.

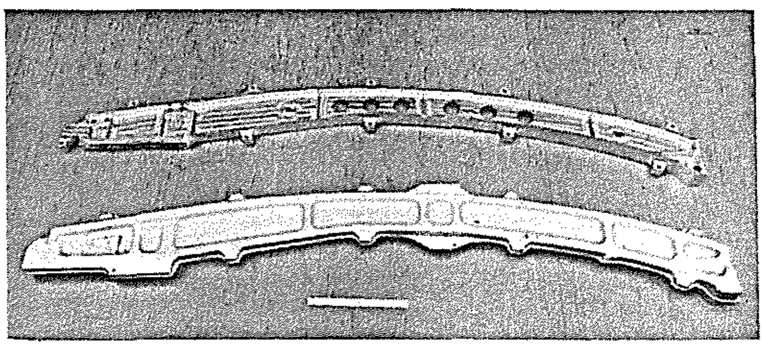

Figure 8. EH101 Cabin Frame forgings before and after machining.

Summaries of static tensile properties are shown graphically in two different forms in figures 9 and 10. These show that 0.2% PS and TS properties in 8090 and 8091 generally cover the same range as values in 7010 in the L and LT directions, although a greater number of results from the latter alloy lie at the higher end of the range. However, 8090 and 8091 strength values in the ST direction are noticeably inferior to those of 7010, as are the majority of ductilities. These figures generally show a greater spread in aluminium-lithium properties compared to 7010 and are due to variations in the degree of cold compression which are inevitable in a forging. These subsequently lead to variations in the size and uniformity of S'-Al_2CuMg precipitation in 8090 and 8091, in contrast to the uniform precipitation of the η-MgZn hardening phase in 7010 which occurs independently of cold compression (7).

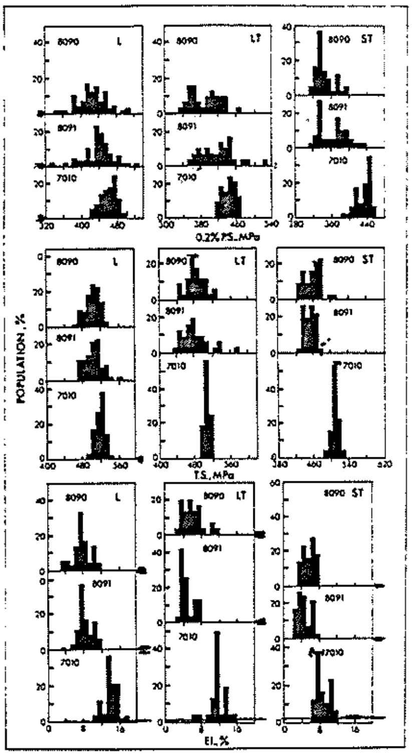

Figure 9. Histograms of static properties in 8090A, 8091 and 7010 frame forgings.

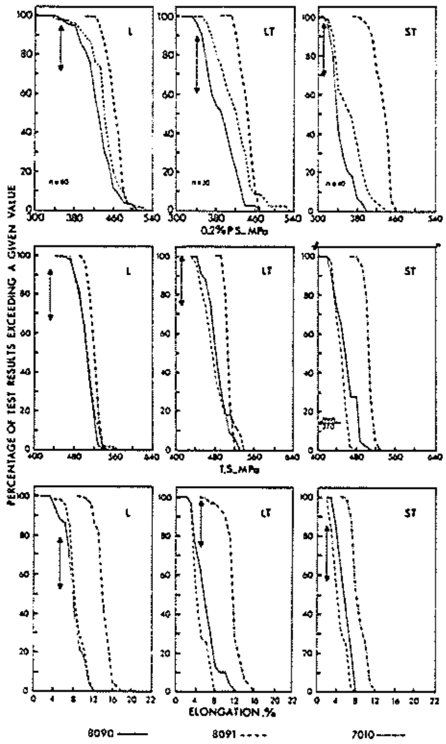

Figure 10. Proportion of forging static properties exceeding a given value.

Whilst 8090 static properties, in particular, do not entirely match those of 7010 forgings or plate, this does not preclude the use of aluminium-lithium in the manufacture of these components, since a survey of the EH101 airframe has shown that reduced strength levels can be tolerated partly as a consequence of the adoption of a multiple load path design philosophy and the fact that fatigue behaviour is of greater importance than static strength. The minimum required strength levels are indicated in figures 9 and 10 and it is apparent that these can be achieved in 8090 in the majority of cases. However, further property improvements may be anticipated in future forgings of this type for two reasons. Firstly, it has been shown that, within limits, mechanical properties in 8090/8091 alloys are a function of magnesium content (8,9). A level of 0.66% was used in the current forgings whereas future ALCAN billet will contain 0.8-0.9% while that from PECHINEY and ILM will be >1.00%. Enhanced properties would therefore be expected. Secondly, planned proprietary improvements to the manufacturing process by the forgemaster are intended to have additional beneficial effects upon properties.

Although the 8090 grain structure differed from that in 8091, it was concluded that both were generally unrecrystallised (7). As with un-recrystallised 8090 sheet discussed earlier, retained texture leads to significant property anisotropy and figure 11 shows minimum and similar 0.2% PS levels to occur at the 20-30° orientation in the centre plane of both 8090 and 8091 forgings. T.S. properties are affected to a lesser extent, while ductility is increased. Nevertheless, the 0.2% PS properties at 20-30° are only marginally lower than the minimum WESTLAND stress office requirements of 350 and 340 MPa for L and LT directions respectively and, again bearing in mind the likely effect of increasing the magnesium level, should be acceptable. With the 7010 plate and forgings, strength also decreases at angles between L and LT directions but to a much lesser extent and over a wider orientation range.

Fatigue properties have been measured and figure 12 compares the S-N curves obtained for 8090 and 7010. In the LT and ST directions, 8090 and 7010 fatigue lives are comparable at high stress levels whilst 8090 is superior at lower stresses. In the case of the L direction, 8090 alloy shows considerable scatter, with some results being comparable to

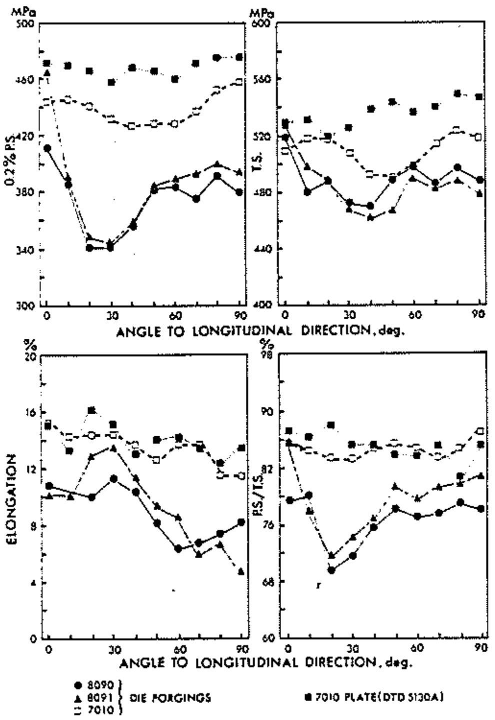

Figure 11. Anisotropy in 8090, 8091 and 7010 die forgings compared with 7010 plate.

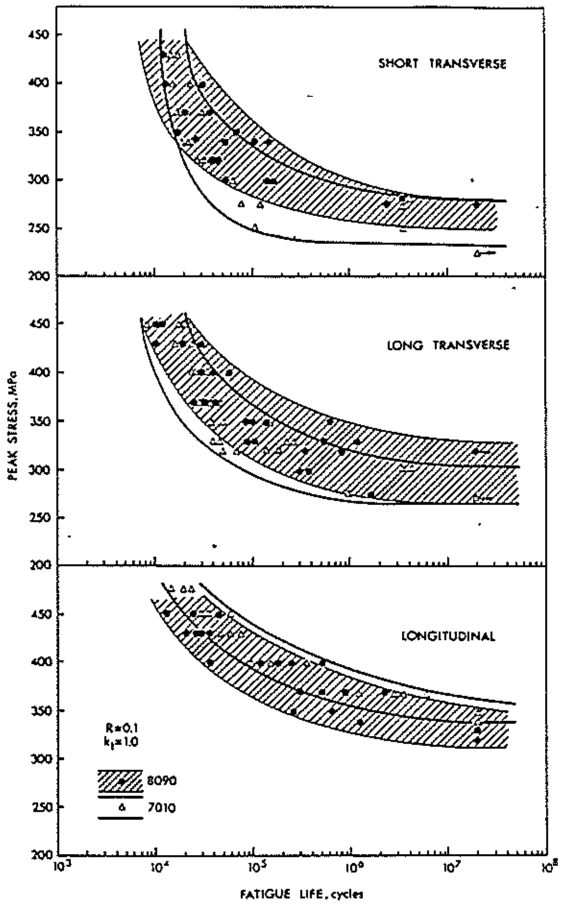

Figure 12. Comparison of 8090 and 7010 forging S-N curves in L, LT and ST directions.

7010 while others are inferior. However, it is interesting to note that superior 8090 properties over 7010 were exhibited by longitudinal specimens in the form of flat plates taken from machined forgings, these being more representative of the final component. The data in figure 12 was generated by round test pieces extracted from the unmachined forgings and may indicate a sensitivity to specimen shape and stressing conditions. These findings are currently being investigated.

A further batch of forgings from the above die has been made using Pechiney-supplied 8090 billet containing 1.0% magnesium. Test pieces will be taken from identical locations as those in the initial forgings above in ALCAN billet, in order to provide a direct comparison of the effects of magnesium content. Nevertheless, a full analysis of results from the current (ALCAN billet) forgings have confirmed the suitability of 8090 die forgings for use on the EH101 airframe and accordingly, a further 12 dies are being cut for similar main lift frame forgings which will be made in 8090 of magnesium content not less than ~0.8% and from which 38 different components will be machined. Due to optimised design, a significant improvement in utilisation rate will be achieved as it has been calculated that of the approximate 4 tonnes of 8090 billet required for forgings per aircraft, approximately 1.8 tonnes will fly, i.e. a utilisation rate of ~45% c.f. traditionally quoted figure of ~20%.

5. ALUMINIUM-LITHIUM EXTRUDED SECTIONS

Aluminium-lithium extrusions are perhaps the most straightforward product form in the new alloy as far as attaining properties are concerned. Forty three different EH101 extruded sections have been identified which will be produced in unrecrystallised 8090 alloy and will replace those designed originally in 7075-T7411 (≡ BS L160). Four different profiles in 8090 have been subjected to in-depth testing and prototype aircraft sets of 7m lengths have been delivered. As discussed in a previous paper (10), after some initial difficulty in meeting BS L160 strength, modifications in degree of stretch and ageing schedules now enable comparable properties (excepting ductility) to be consistently achieved. Comparable fatigue properties are also exhibited as shown in figure 13 which shows the results of specimens from a c-channel and seat track in alloy 8090 and the original L160, figure 14.

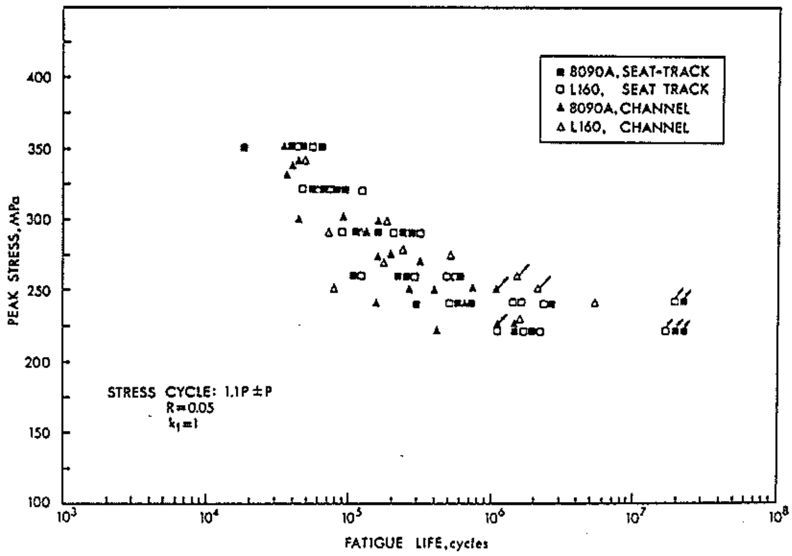

Figure 13. S-N curves for 8090 and BS L160 C-channel and seat track extrusions.

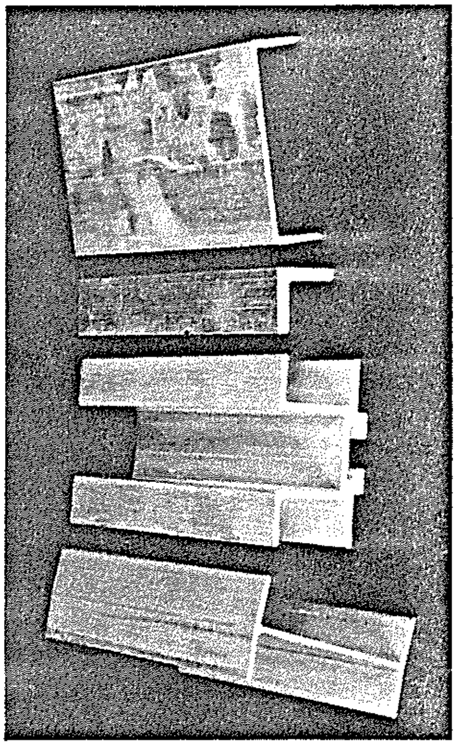

Figure 14. EH101 extrusions in 8090A alloy.

A further advantage of aluminium lithium is its enhanced extrudability compared to other 'strong' aluminium alloys. In practice, the seat track extrusion shown in figure 14 would have a further metal strip bonded onto the 'feet'. However, it has now been shown that this section can be extruded as a one-piece hollow section in 8090, thus effecting significant savings in time and cost: this was not possible with L160.

6. JOINING

Trials have been carried out to assess the feasibility of joining aluminium-lithium alloys by the two methods commonly employed in aircraft construction, viz adhesive bonding and TIG welding. The results of this work carried out on 1.0 mm 8090A sheet are summarised below:-

6.1 Adhesive bonding

Both chromic and phosphoric acid anodising pre-treatments have been assessed and with two types of adhesive, AF163-2K which is a 125°C curing epoxy film and EC9323, a room temperature curing, two-part epoxy paste. Comparative tests were conducted upon unclad 2014-T6 sheet (≡ BS L157) and all specimens were subjected to single overlap shear testing in order to assess the effectiveness of bonding. Three test conditions were used, (i) subsequent to bonding at room temperature i.e. "RT, Unaged" (ii) after 5000 hours exposure at 50°C in an environment of 95% Relative Humidity and was carried out to assess the effect of moisture upon the bond and (iii) testing at -40°C to simulate service conditions in cold climates. The results are summarised in Table 5, each result representing the mean of six tests per material and condition. The highest bond strengths in both alloys, particularly after ageing for 5000h at 95% RH and when tested at -40°C, appear to be exhibited after

Pretreatment	Material (substrate)	Adhesive	Mean Shear Strength (MPa)		
			RT Unaged	Aged 5000h at 50°C and 95% RH	-40°C
Chromic Acid Anodise	8090A	AF163-2K EC 9323	33 33	29 21	29 21
	2014 (BS L157)	AF163-2K EC 9323	32 34	27 23	38 23
Phosphoric Acid Anodise	8090A	AF163-2K EC 9323	34 30	37 26	40 23
	2014 (BS L157)	AF163-2K EC 9323	40 31	33 28	43 30

Table 5. Summary of adhesive bonding trials on 8090A and 2014.

phosphoric acid anodising and subsequent bonding with AF163-2K. However, chromic acid anodizing is routinely used at WESTLAND and since, for a given set of processing and testing conditions, 8090 shows comparable bond shear strengths to 2014, there is no intention or apparent need to change this, especially in view of the superior corrosion protection afforded by this method. Adhesive bonding of 8090 using existing processing practices is not therefore expected to be problematic.

6.2 TIG Welding

Published work (11) has indicated that the major problem associated with TIG welding of aluminium-lithium alloys is the occurrence of weld-zone porosity associated with the absorption of water vapour by oxide formation during hot rolling and/or solution treatment. The initial objective of the work carried out at WESTLAND was to ascertain the processing conditions necessary for optimum mechanical properties. The following observations were made:-

a) In addition to welding in a controlled, protective atmosphere, it was demonstrated that extended immersion (up to ~4h) in a chrome/sulphuric acid pickle prior to welding was a prerequisite to achieving minimal weld zone porosity. Surface metal removal by mechanical means or the use of the relatively short immersion times of conventional aluminium cleaning practices (typically 20 minutes) appeared to be inadequate in this respect.

b) Higher tensile strengths and a higher pass rate for 4t bend tests were achieved when using filler rod of aluminium alloy 5056A (former designation NG6) compared to a filler of parent metal, strips of which were cut from the sheet.

c) Due to the frequent impracticality of solution treating welded assemblies in production, emphasis was placed upon assessing properties in the 'as-welded and aged' conditions, notwithstanding the finding that solution treatment resulted in significantly higher tensile strength, albeit with reduced ductility. Post welding heat treatment conditions have yet to be optimised and are the subject of current work, but it is encouraging that the average tensile strength of a batch of 10 test panels in the 'as-welded' condition was 293 MPa, all data being within a range of 270-319 MPa. With regard to the EH101, the preferred aluminium alloy sheet for welding is 6061-T6 or 6082-T6 for which a minimum tensile strength of 290 MPa is specified but which would be expected to be lower after welding. Clearly, the results of welded 8090A sheet achieve these levels and as such, TIG welding will be used on the EH101 primarily for joining 8090 tube in the manufacture of numerous instrument cabinets and racking.

7. CONCLUSIONS

In order to reduce structural weight on the EH101 helicopter, extensive use will be made of the newly commercialised aluminium-lithium based alloys in the form of sheet, extruded profiles and die forgings, whilst plate and bar has been rejected due to a combination of higher intrinsic metal costs and relatively low material utilisation rate. However, numerous components originally designed in 'conventional' aluminium alloy plate will now be made as aluminium-lithium die forgings.

The 8090 composition is the preferred alloy for use on the EH101, although 2091 will be considered as an alternative. Extensive tests have shown these alloys to exhibit satisfactory mechanical properties, with fatigue behaviour, in particular, generally being significantly better than current alloys. The new materials are amenable to the same manufacturing techniques and practices as 'conventional' aluminium and trials have confirmed that adhesive bonding is not problematic: TIG welding can be satisfactorily carried out if certain metal pretreatments are adopted. It is concluded that aluminium-lithium has reached the technical and commercial maturity to enable the EH101 to emerge as the Worlds first helicopter to be constructed extensively in these alloys.

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