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THE APPLICATION OF IMPROVED ALUMINIUM-LITHIUM ALLOYS IN AEROSPACE STRUCTURES

C.J. PEEL, B. EVANS

Royal Aircraft Establishment
(Farnborough)
England

and

R. GRIMES, W.S. MILLER

Alcan International
(Gerrards Cross)
England

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by

C.J. Peel and B. Evans Materials and Structures Dept, RAE

and

R. Grimes and W.S. Miller Alcan International Ltd

ABSTRACT

Target property levels for improved low density, high stiffness lithium-containing aluminium alloys have been defined. These targets are based on existing medium and high strength 2000 and 7000 series alloys but with a density reduction of about 10% and stiffness increased by at least 10%. An Al-Li-Cu-Mg-Zr composition range aimed at meeting the medium strength requirement has been defined and mechanical property data generated on most product forms. Tensile, fatigue, fracture toughness and corrosion properties are encouraging. Work is progressing on problems identified with a slight deficiency in strength of unstretched sheet and with exfoliation corrosion in sheet aged for longer times. Extensive evaluation programmes on all product forms are underway aimed at the future acceptance of these alloys in both aerospace and other applications. The main attractions will continue to be relatively conventional production and forming routes and predicted weight savings of 13% which are competitive with levels currently claimed for carbon fibre composites in primary aircraft structures.

INTRODUCTION

This paper outlines the targets for the development of a series of improved aluminium-lithium alloys that have been pursued within the United Kingdom over the last five years. The paper presents the results of initial evaluations of factory fabricated lots of alloys to preferred compositions and indicates the deficiencies in these properties that require further research and development. The potential applications for the improved alloys are widespread and some examples are shown of trial products and a consideration is made of the mass savings likely to be achieved by the use of the new alloys. The whole concept of the alloy development was based upon the design of alloys that could be produced successfully by ingot metallurgy to enable large scale manufacture of relatively low cost products in the range of forms commonly used in aircraft structures.

Targets for the Alloy Development

The addition of lithium to aluminium reduces the density of the alloy by approximately 0.08 g/ml per weight per cent lithium and increases the stiffness of the alloy by approximately 3 GPa per weight per cent lithium. The requirements for the UK alloy development programmes sponsored by the Ministry of Defence are that the new alloys should have a density that is reduced to be not more than 90% of that of the commonly used 2000 and 7000 series aluminium alloys and a stiffness that is increased by at least 10%. It was decided that the other mechanical properties of the alloys such as strength, fracture toughness, fatigue and corrosion resistance should be optimised to match those of the conventional alloys already used in aircraft structures. The purpose of this philosophy is to enable the substitution of the lithium alloys for conventional alloys in existing structures with minimum design modifications yet producing at least 10% saving in mass of the rebuilt components. Future designs could exploit the improved specific stiffness of the lithium alloys to save up to 20% in mass. Three levels of strength have been prescribed to date, they have been coded DTD XXXA, XXXB and XXXC in draft DTD specifications. DTD XXXA is intended to replace 2014-T6 (and T651) sheet and plate commonly used in the UK and possibly to replace the more modern alloys of similar strength levels such as 2324-T39 and 7475-T73. Table 1 compares the minimum specified properties of DTD XXXA with those of the conventional alloys in plate form.

Table 1

Property Requirements (Medium Strength)

		Minimum 0.2% Proof Stress MPa	Minimum Tensile Strength MPa	Minimum Elongation %
DRAFT DTD XXXA	L	400	450	6
PLATE ($\ngtr$40 mm)	T	400	450	6
2014-T651 to	L	410	450	6
BS L93 ($\ngtr$40 mm)	T	400	450	5
2324-T39 ($\ngtr$32 mm)	L	386	455	10
	T	372	475	8
7475-T7351 ($\ngtr$80 mm)	L	-	-	-
	T	387	466	-
7010-T73651 to	L	425	490	8
DTD 5130 ($\ngtr$40 mm)	T	425	495	6

DTD XXXB is a higher strength requirement intended to replace 7475-T76 sheet material and 7475-T7651, 7010-T7651 and 7050-T7651 in plate form [Table 2]. Similar equivalent targets can be prescribed for the same alloys in forged and extruded forms. DTD XXXC is a low strength-high toughness condition intended to match the high damage tolerance properties of 2024-T3 sheet and plate.

Table 2

Property Requirements (High Strength)

		Minimum 0.2% Proof Stress MPa	Minimum Tensile Strength MPa	Minimum Elongation %
DTD XXXB	L	455	525	6
PLATE ($\ngtr$40 mm)	T	455	525	6
7475-T761	L	420	482	-
($\ngtr$6 mm)	T	413	489	9
7010-T7651 to	L	450	515	7
DTD 5120B	T	450	515	5
7050-T7651	L	455	524	8
($\ngtr$50 mm)	T	455	524	6

Metallurgical Background to the Alloy Development

The extensive alloy development conducted within the RAE and Alcan International has been based upon the published background of metallurgical knowledge[1,2,3,4]. Two types of aluminium-lithium alloys have previously been used in service. These were a Russian alloy, coded 01420, containing approximately 5.5 wt % Mg and 2.1 wt % lithium and an American alloy 2020 containing approximately 4.5 wt % copper and 1.3 wt % lithium. Extensive studies of the microstructure of Al-Li alloys and alloys in the Al-Mg-Li system such as 01420 have suggested that the addition of lithium produces a precipitation hardening system based upon the following series of reactions:

$$\text{Supersaturated solid solution} \rightarrow \delta'(Al_3Li) \rightarrow \delta(AlLi) \qquad - (1)$$

in magnesium-free alloys and

$$\text{Supersaturated solid solution} \rightarrow \delta'(Al_3Li + Mg) \rightarrow Al_2MgLi \qquad - (2)$$

in alloys containing magnesium[4]. The amount of magnesium involved in the δ' precipitate is in question. δ', the main hardening phase in these alloys forms as a spherical precipitate with an ordered $L1_2$ structure coherent with the aluminium matrix [Fig 1]. The equilibrium phase δ can form during casting, if the lithium content is sufficient and, being brittle and highly reactive, is considered undesirable.

Al-Cu-Li alloys such as 2020 produce at least two further types of precipitation reaction, namely:

$$\text{Supersaturated solid solution} \rightarrow \text{GP zones} \rightarrow \theta'' \rightarrow \theta' \rightarrow \theta\ (Al_2Cu) \quad -$$

$$\text{Supersaturated solid solution} \rightarrow T_1\ (Al_2CuLi) \quad - ($$

in addition to reaction (1). High Cu:Li ratios would favour reactio and high Li:Cu ratios reaction (4).

The present alloy development, initiated at RAE, has produced series of Al-Li-Cu-Mg alloys with compositions designed to optimise density, strength and fracture toughness. The combined addition of copper and magnesium produces a further precipitate reaction:

$$\text{Supersaturated solid solution} \rightarrow S\ (Al_2CuMg) \quad - (5)$$

It is clear that reactions (1), (4) and (5) can occur simultaneously. Fig 2 illustrates the combined precipitation of S and T_1 phases in an Al-Li-Cu-Mg alloy. Increasing the magnesium content favours the precipitation of S phase rather than T_1. It has been found[5] that the magnesium content affects the age hardening response critically.

The grain structure of the preferred alloys with optimised composition is controlled mainly by the addition of zirconium. This addition produces a typical 'pancake' grain structure in hot rolled plate [Fig 3] and an ultra-fine partially recrystallised grain structure in the same alloys in sheet form [Fig 4]. The very fine grain structure produces an alloy that is proving to be highly amenable to conventional hot working practices such as rolling, forging and extrusion and to be capable of super-plastic forming[6] when given the appropriate treatments. However, the powerful grain controlling effects of zirconium tend to result in the retention of a pronounced deformation texture even after cold rolling and solution treatment unless the processing is carefully controlled.

Properties of the Preferred Al-Li-Cu-Mg Alloys

It is stated that one of the requirements of the UK alloy development was to produce an alloy or series of alloys that were at least 10% lighter than the conventional 2000 and 7000 alloys that are in common use. Fig 5 plots the distribution of densities of commercially produced lots of alloy to draft specification DTD XXXA. The specified composition for DTD XXXA is given in Table 3 and is the subject of world wide patent applications as are the DTD XXXB composition and the fabrication practices for the two alloys.

Table 3

Chemical Composition, wt %

	Minimum	Maximum
Lithium	2.30	2.60
Copper	1.00	1.40
Magnesium	0.50	0.9C
Zirconium	0.10	0.14
Iron		0.30
Silicon	-	0.20
Sodium	-	0.002
Hydrogen	-	0.30 (ppm)
Others Each	-	0.10
Total	-	0.20
Aluminium	-	Remainder

Small variations in the lithium content make significant changes to the density and it can be seen that the population is concentrated on the heavy side of the target value of 2.525 g/ml reflecting a trend to be slightly below target in lithium content. The densities of conventional alloys such as 2014 and 7050 are typically 2.80 g/ml and 2.82 g/ml respectively.

An improvement of at least 10% in elastic modulus was also required. The conventional alloys have mean values of 73 GPa for 2014 and 70 GPa for 7075 or 7050 so that a value of 80 GPa is required from the aluminium-lithium alloys. Measurements of the moduli of sheet and plate versions of DTD XXXA alloy using optical extensometry indicate mean values of 80 GPa and 82 GPa respectively irrespective of test direction. Fig 6 compares the optical extensometer results for 1.6 mm sheet to DTD XXXA with those of an automated method employing transducer measurements of machine displacements. It is clear that the automated method produces lower results, a trend also found with the conventional control alloys.

Obviously the mechanical properties such as strength and fracture toughness depend upon the extent of age hardening that is applied. All the indications to date are that under-aged tempers produce the best combination of strength, toughness and resistance to certain forms of corrosion. For this reason ageing treatments are being optimised for all the alloys to produce the required balance in properties rather than the highest strengths. For example, Figs 7a, b and c show the age hardening responses of stretched sheet, plate and extrusion all to the draft DTD XXXA composition. Ageing times are chosen to maximise the fracture toughness at the required strength level. Little difficulty is found in producing the required properties in stretched material but sheet, formed into parts by repeated solution treatment and forming operations loses the beneficial effects of the stretching and requires a more careful optimisation.

Typical properties for the chosen heat treatments are given in Table 4.

Table 4

Specified and Typical Properties for DTD XXXA and DTD XXXB, T6 and T8

Product	Specification	Temper	0.2% PS MPa	TS MPa	Ef %
Sheet	DTD XXXA	T6 MIN	380	440	6
		T6 TYP	370	470	6
		T8 MIN	380	440	6
		T8 TYP	420	500	6
	DTD XXXB	T6 MIN	420	500	6
		T6 TYP	415	510	6
		T8 MIN	450	500	6
		T8 TYP	480	540	5
Plate	DTD XXXA	T651 MIN	400	450	6
		T651 TYP	425	480	7
	DTD XXXB	T651 MIN	455	525	6
		T651 TYP	520	560	5
Extrusion	DTD XXXA	T651 MIN	430	480	6
		T651 TVP	500	540	6
	DTD XXXB	T651 MIN	505	560	6
		T651 TYP	550	580	5

It can be seen that the values of 0.2% proof strength are below the specified requirements for sheet in both the XXXA and XXXB categories in the T6 temper.

The levels of fracture toughness obtained with sheet and plate versions of XXXA and XXXB are plotted [Figs 8 and 9] against the appropriate levels of 0.2% proof strength. Certain processing developments have produced a balance between longitudinal and transverse fracture toughness levels so that both L-T and T-L tests fit the populations plotted in Figs 8 and 9 but the transverse strengths tend to be slightly lower than their longitudinal equivalents. Short transverse fracture toughness levels in plate are considerably lower than the 'in-plane' values. Currently, values of 15 $MPa\sqrt{m} \pm 1 MPa\sqrt{m}$ are obtained at a level of 400 MPa for the 0.2% proof strength.

The resistance of the DTD XXXA alloy to fatigue cracking has proved surprisingly good to date, suggesting that a damage tolerant alloy may be possible. Fig 10 compares fatigue life data (R = 0.1 and at a frequency of 105 Hz) of DTD XXXA alloy with 7075-T73 alloy with similar strength levels. The resistance to fatigue crack growth at low values of stress intensity factor also proves to be good with possibly as much as an order of magnitude improvement in crack growth rates at low values of ΔK [Fig 11].

The resistance of the alloys to corrosion, exfoliation and stress corrosion cracking continues to be evaluated. Tests are being conducted in outdoor marine environments and in a selected number of accelerated laboratory tests. Target values for minimum short transverse threshold stresses for stress corrosion cracking in plate versions of the A and B alloys are 240 MPa and 175 MPa respectively in accord with current specified levels for 7010 alloy. Tests to date on DTD XXXA alloy indicate that threshold stress levels in excess of 240 MPa may be achieved, although variability between cast lots has occurred.

An unusual problem has been identified in thin sheet, that of exfoliation blistering, normally associated with thicker gauges of material. In neutral NaCl solution the Al-Li-Cu-Mg sheet has excellent corrosion resistance but acidified solution as used in EXCO tests or acidified salt fog tests can produce exfoliation. The susceptibility varies with the degree of ageing, the lightly aged versions being virtually immune, rated EA or better and the over-aged versions being highly susceptible. Fortunately, the under-aged tempers are preferred giving a better balance between strength and fracture toughness. Plate material appears much more resistant to exfoliation even when aged near to peak strength.

Potential Applications

Sheet and plate forms of the alloys are already under extensive evaluation. In particular, the forming of sheet parts has been evaluated. Fig 12 shows a selection of parts formed from 1.6 mm sheet and machined from thin plate. Little adjustment to conventional aluminium alloy practice has been required, although the use of salt baths for heat treatment has been prohibited until safety tests can be made. DTD XXXA has been produced as hand and die forgings [Fig 13] proving to be readily forged and has been extruded in a limited range of sections [Fig 14]. Extruded material has been found to be significantly stronger than the sheet and plate equivalents in accord with the normal behaviour of the wrought aluminium alloys. Seamless tube has been fabricated.

Since it begins to appear that a complete range of product forms will eventually be available in Al-Li alloys with a density reduction of approximately 10%, it would seem that their substitution for conventional aluminium alloys in aircraft structures will produce mass savings of 10% for the parts of structure that are changed. This requires that adequate strength and fatigue strength levels are achieved.

Further mass savings may be achieved by using the guaranteed 10% increase in stiffness or by using greater strength [Fig 15]. The current target strength levels match the commonly used 7000 series aluminium alloys and should produce 13% mass savings in structure designed to exploit the increased stiffness. This saving would appear to be competitive with levels currently claimed for carbon fibre reinforced composites in primary structure. The prediction of mass savings is dealt with in detail elsewhere[5,7].

Conclusions

Feasible targets for the design of a new series of aluminium-lithium alloys appear to be a 10% reduction in density, a 10% increase in stiffness, with similar strength levels to the conventional 2000 and 7000 aluminium alloys. Alloys achieving these targets have been produced and if successfully employed their use should produce mass savings of up to 13%. Several problems have been identified and to some extent overcome. These include achieving adequate levels of fracture toughness, producing material that is isotropic and that will age harden rapidly without prior stretching and the optimisation of strength levels and resistance to exfoliation. Sheet, plate, forgings and extrusions have been produced by factory routes and are under evaluation. The next significant step will be the production of the preferred alloys in large ingots typical of commercial practice.

Acknowledgements

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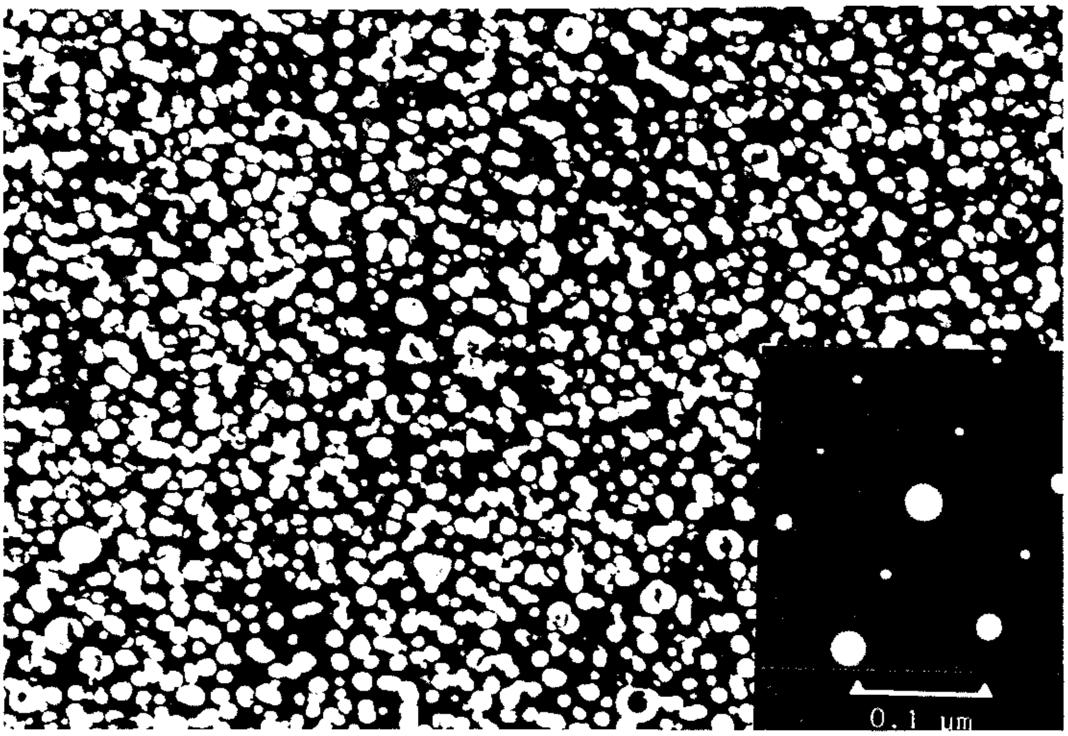

Fig 1 Dark field electron micrograph of the precipitation of δ' in Al-Mg-Li-Zr alloy

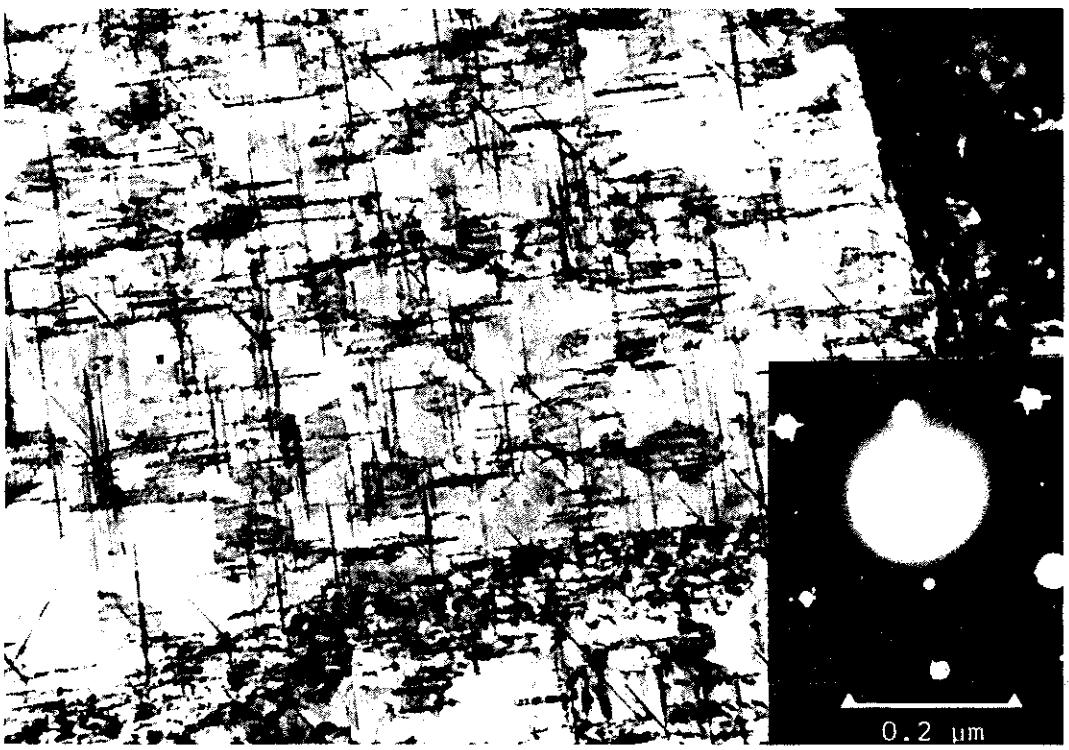

Fig 2 Bright field electron micrograph of the co-precipitation of T_1 and S phases in an Al-Li-Cu-Mg-Zr alloy to DTD XXXA

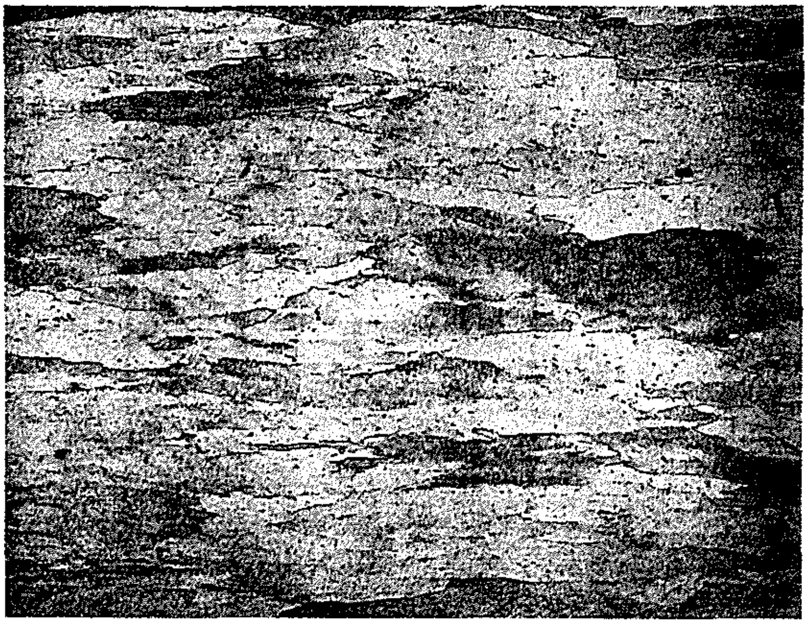

Fig 3 Grain structure of 25 mm plate to DTD XXXA. x200
Transverse section

Fig 4 Grain structure of 1.6 mm sheet to DTD XXXA. x500
Transverse section

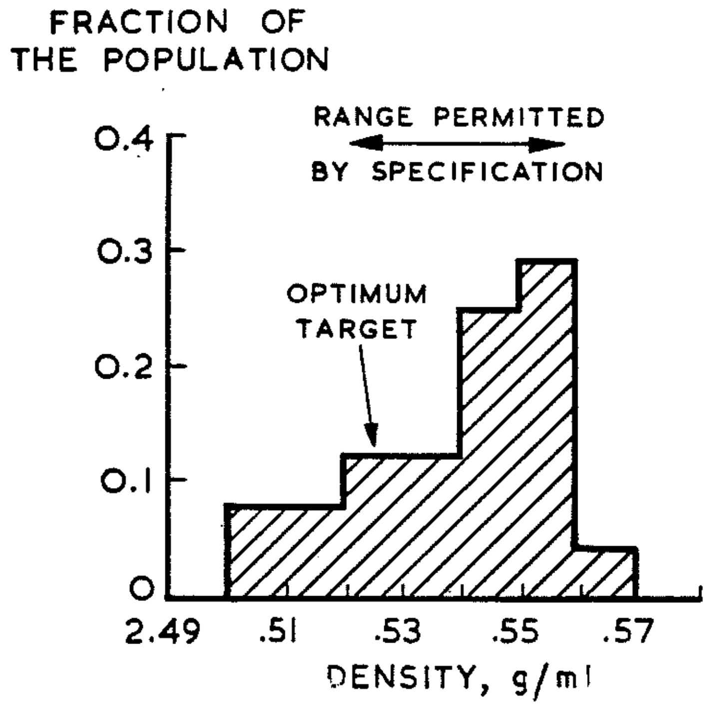

Fig 5 Density distribution of 25 lots of DTD XXXA alloy

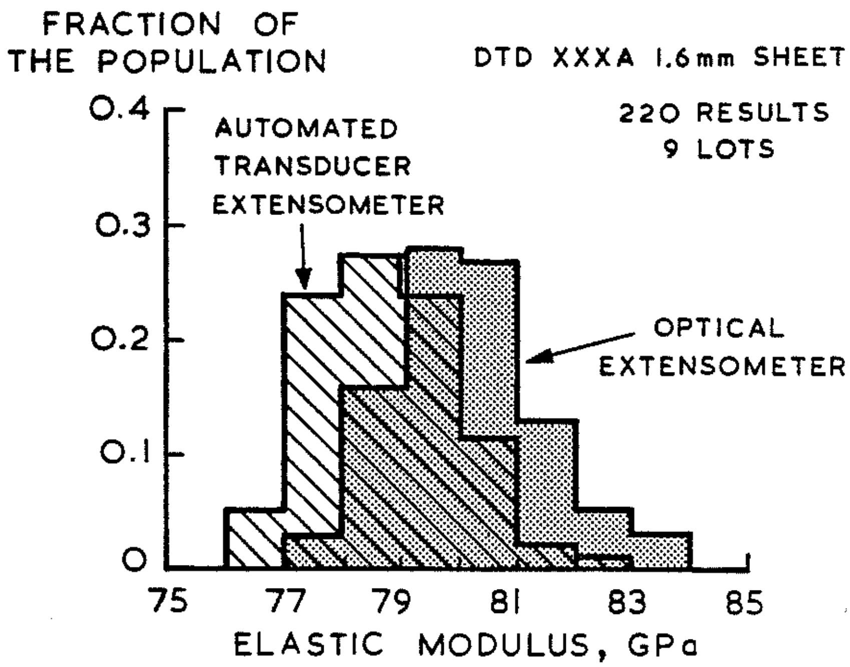

Fig 6 Distributions of elastic moduli of DTD XXXA determined by optical extensometry and by an automated technique

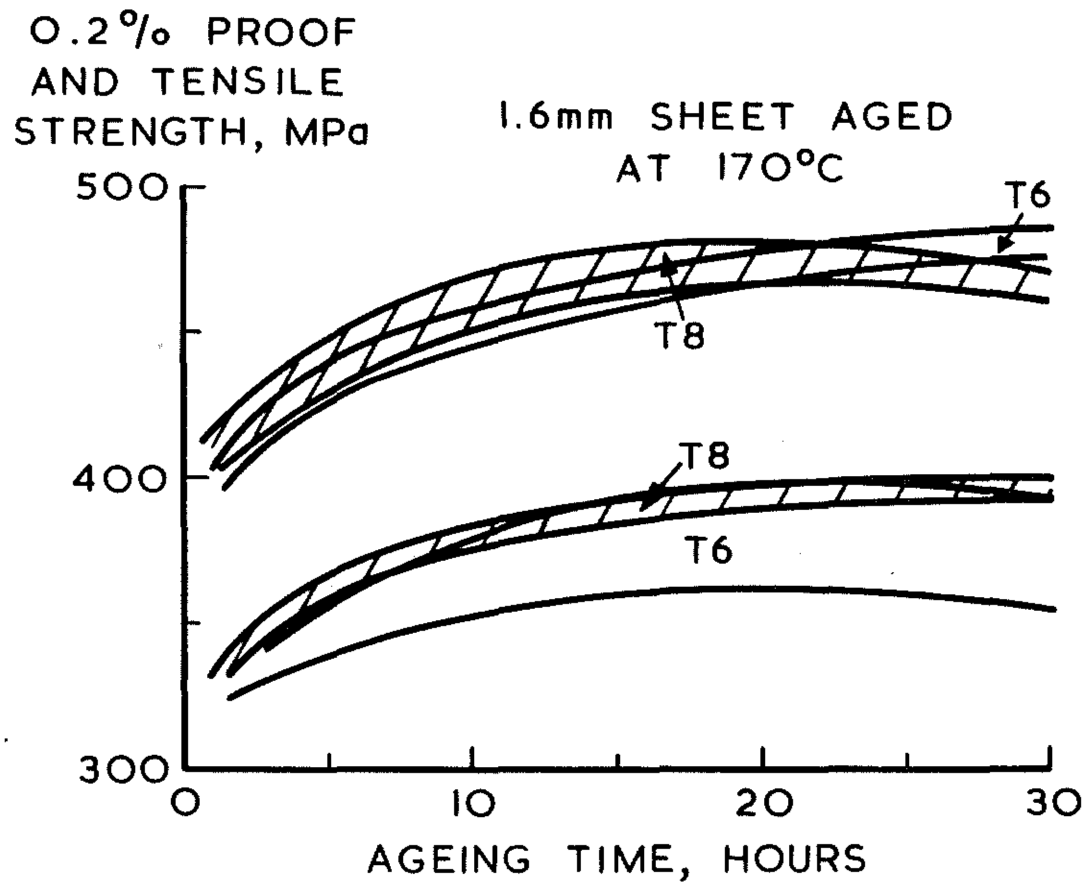

Fig 7a Age hardening curve for DTD XXXA sheet aged at 170°C with (T8) or without (T6) prior stretching

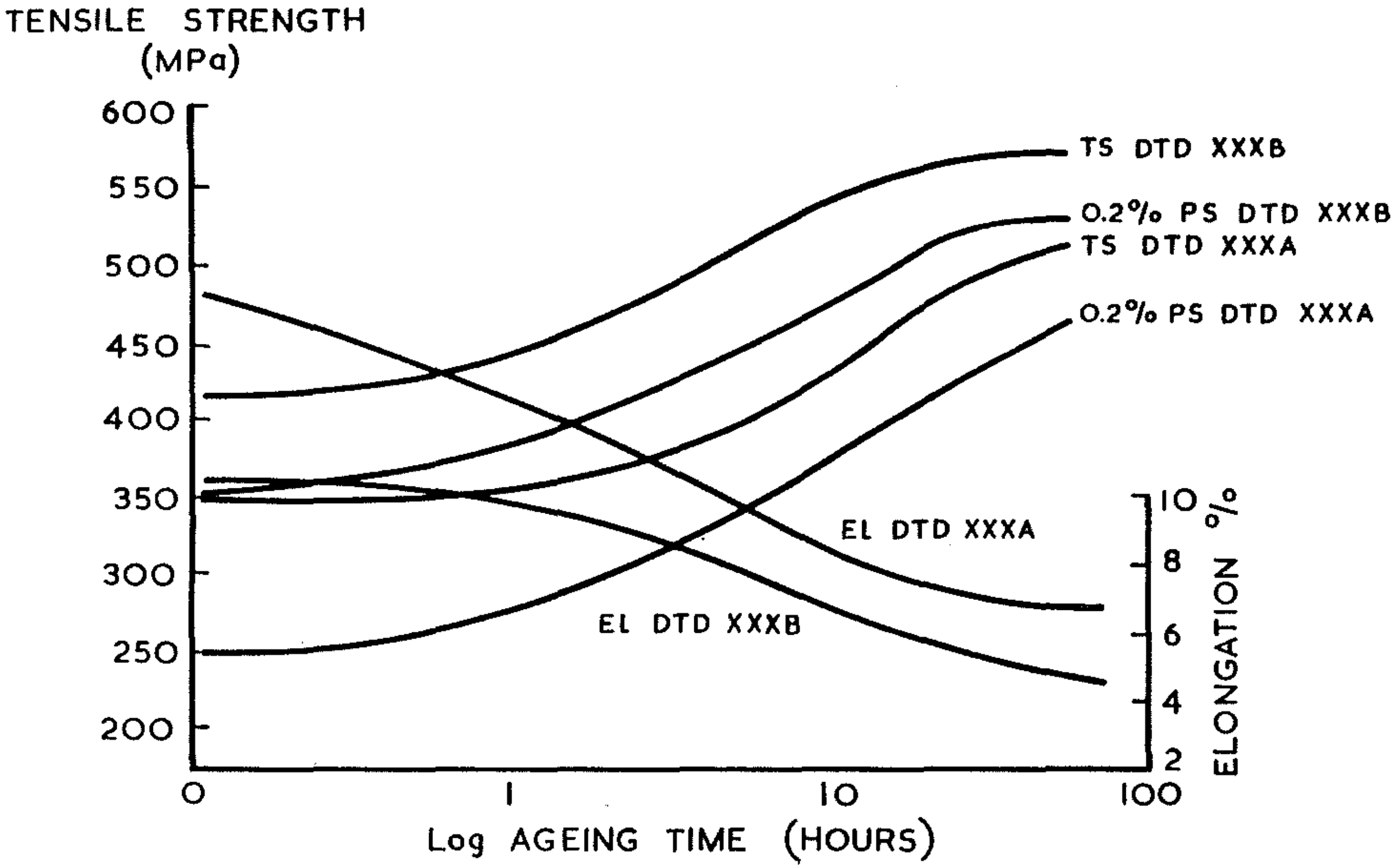

Fig 7b Age hardening curves for DTD XXXA and DTD XXXB plate aged at 170°C after 2.5% stretch

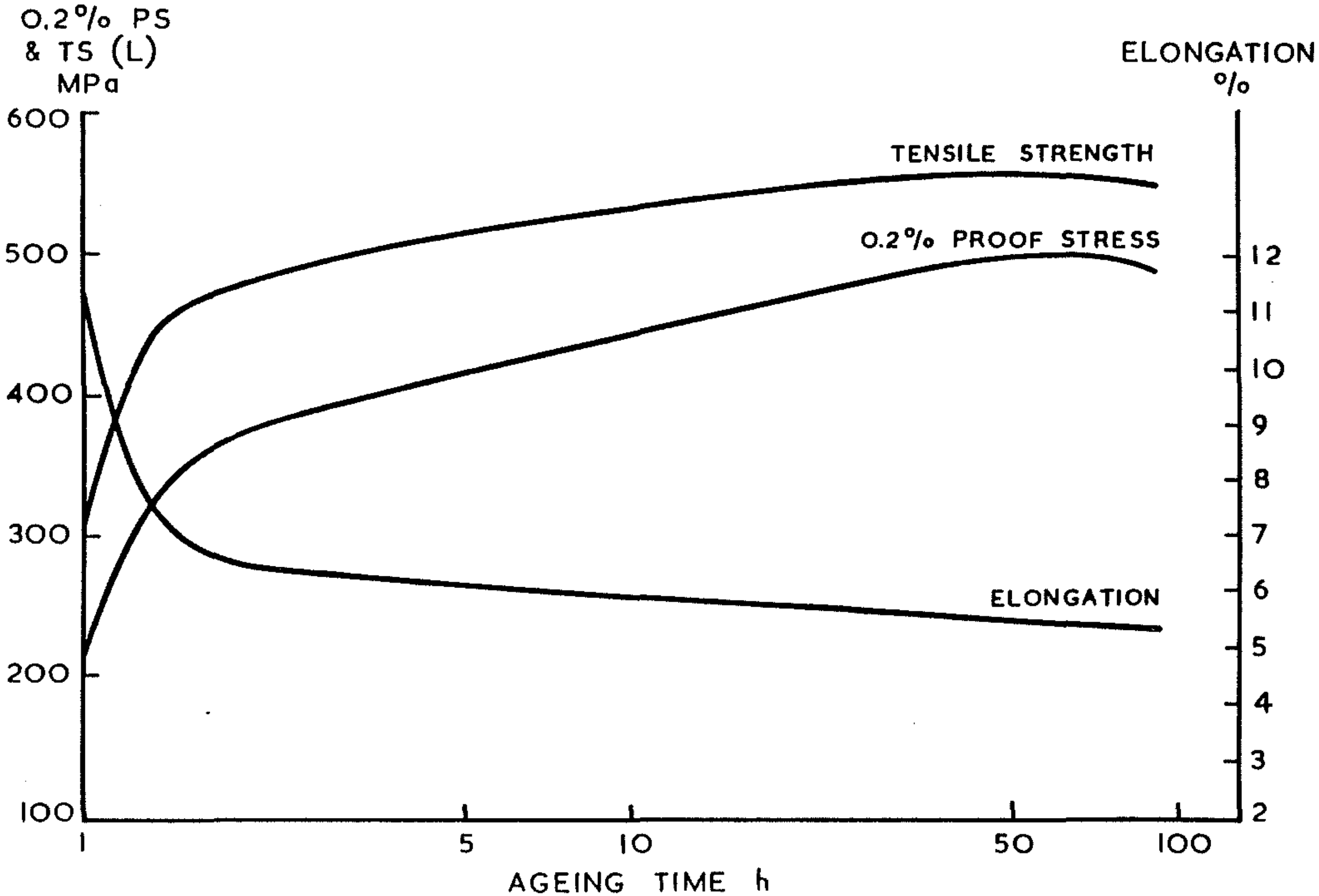

Fig 7c Age hardening curve for DTD XXXA rectangular extrusions aged at 170°C after 2% stretch

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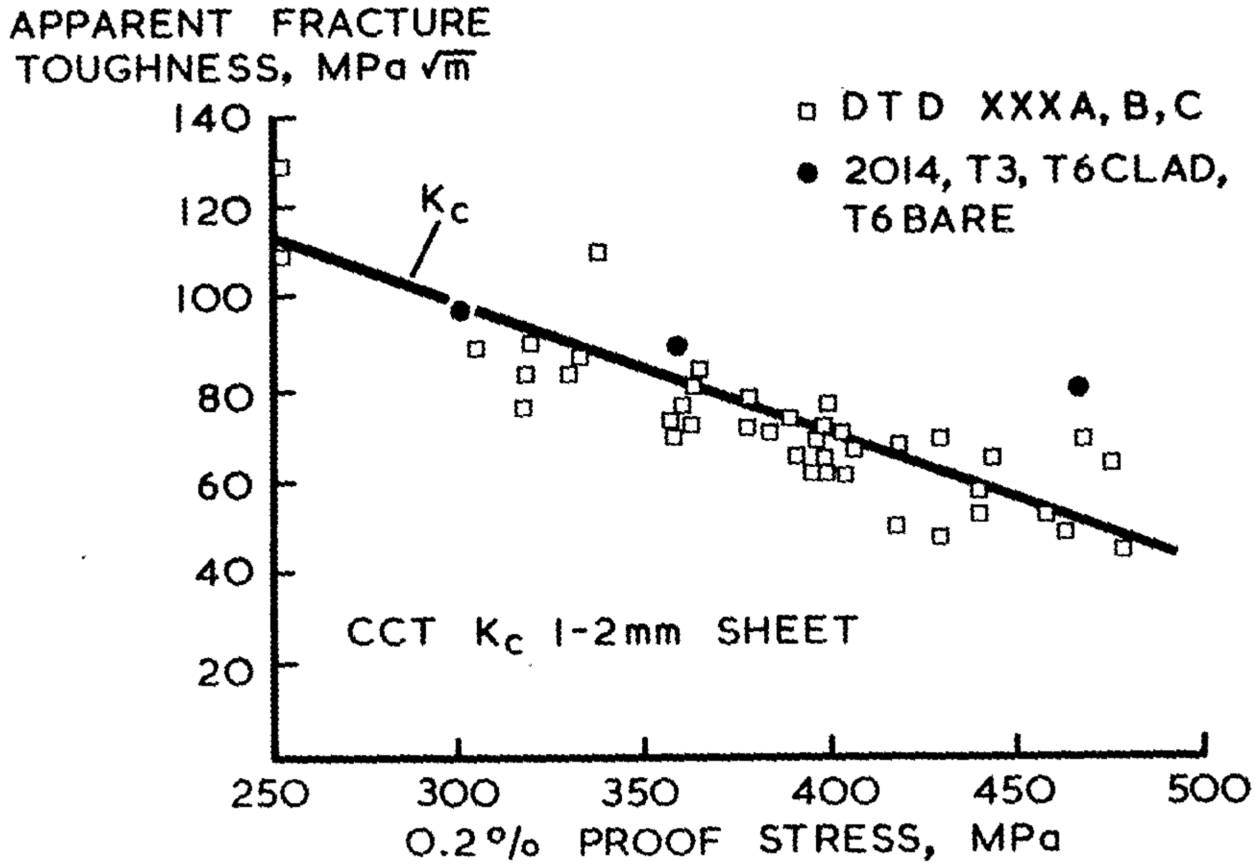


Fig 8 Plane stress fracture toughness (K_c) of DTD XXXA, XXXB and XXXC sheet L-T and T-L directions as a function of the appropriate 0.2% proof stress

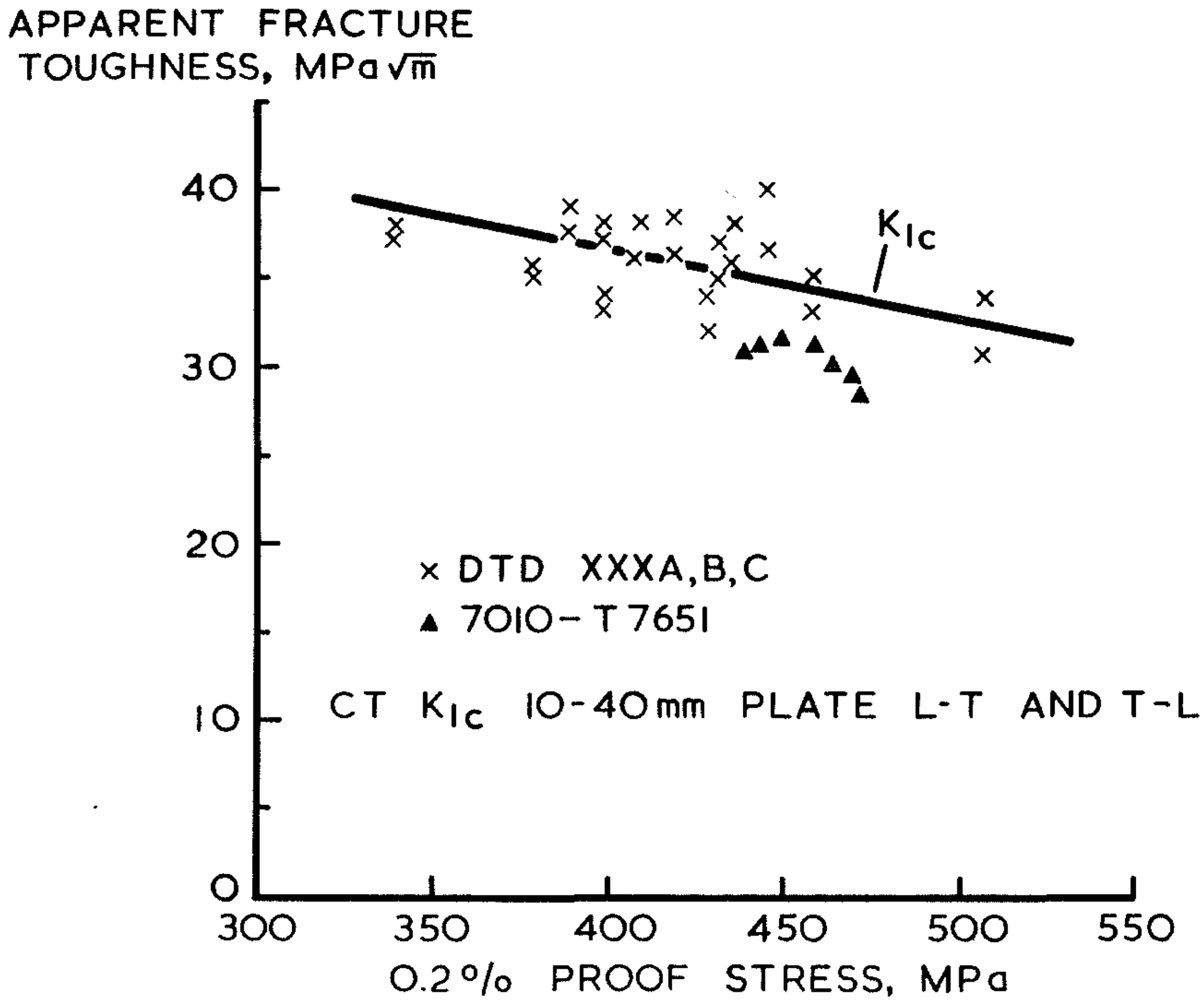


Fig 9 Plane strain fracture toughness (K_{1c}) of DTD XXXA, XXXB and XXXC plate L-T and T-L directions as a function of the appropriate 0.2% proof stress

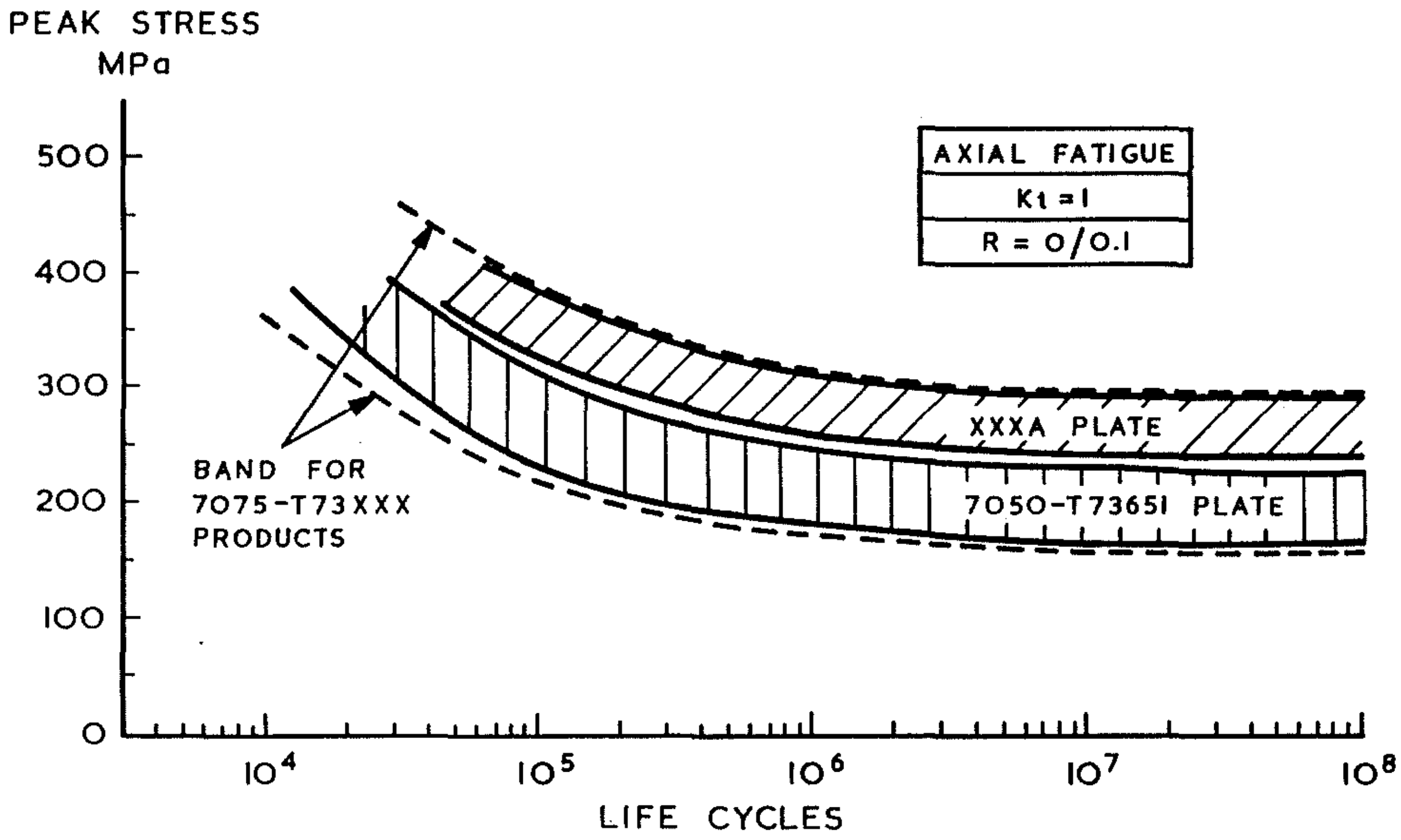


Fig 10 Fatigue life data for transverse samples of DTD XXXA plate compared with results for 7075 and 7050 alloys

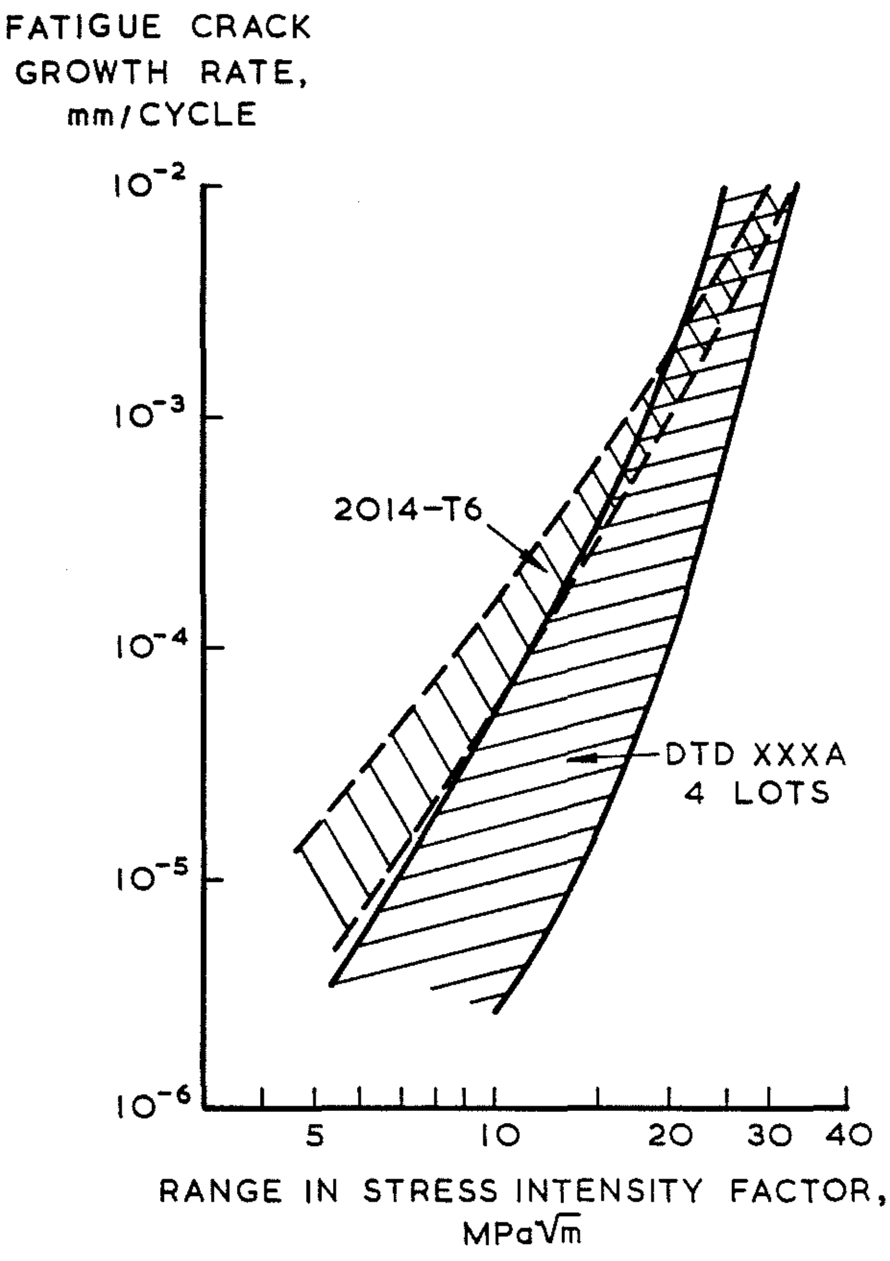


Fig 11 Fatigue crack growth data for four lots of DTD XXXA sheet compared with 2014-T6 sheet

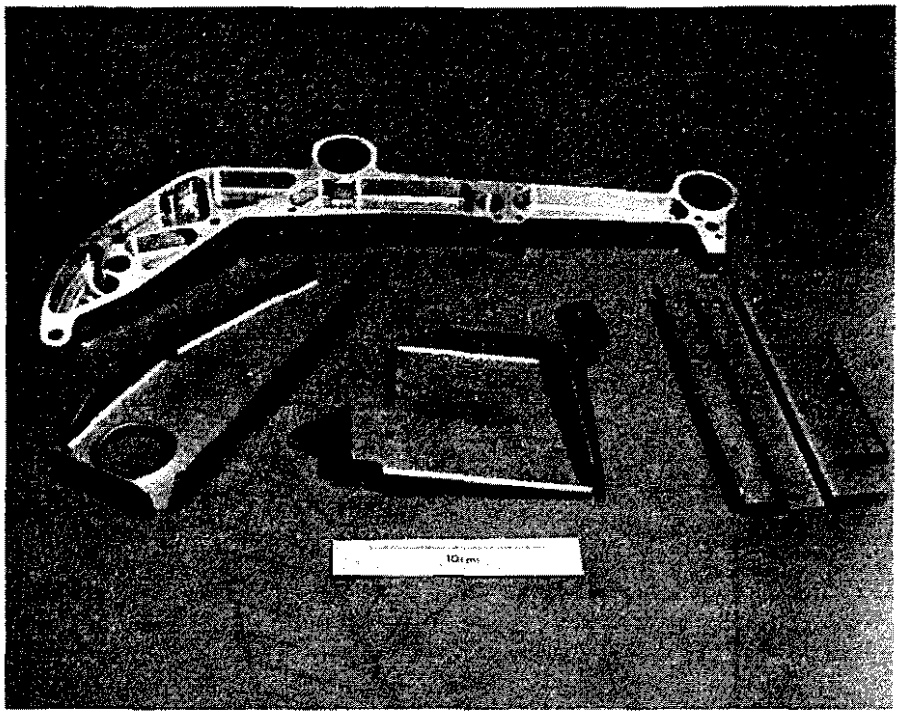
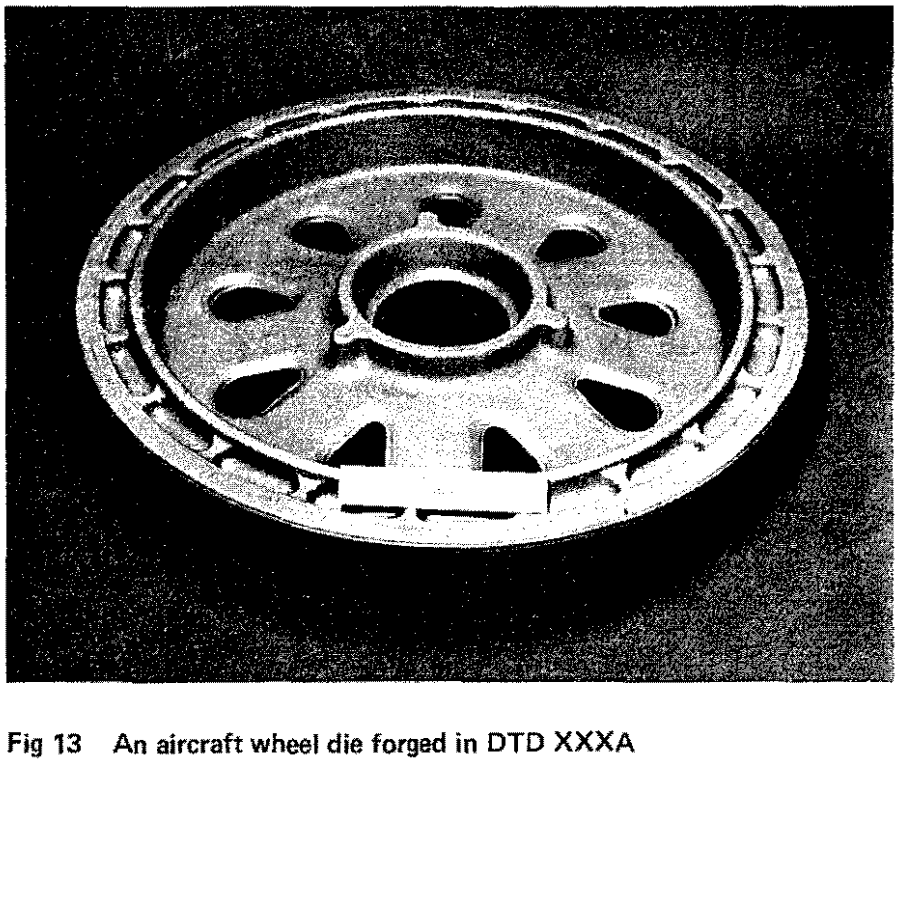


Fig 12 A range of aircraft components formed from DTD XXXA sheet or machined from thin plate to DTD XXXA



Courtesy of High Duty Alloy Forgings

Fig 13 An aircraft wheel die forged in DTD XXXA

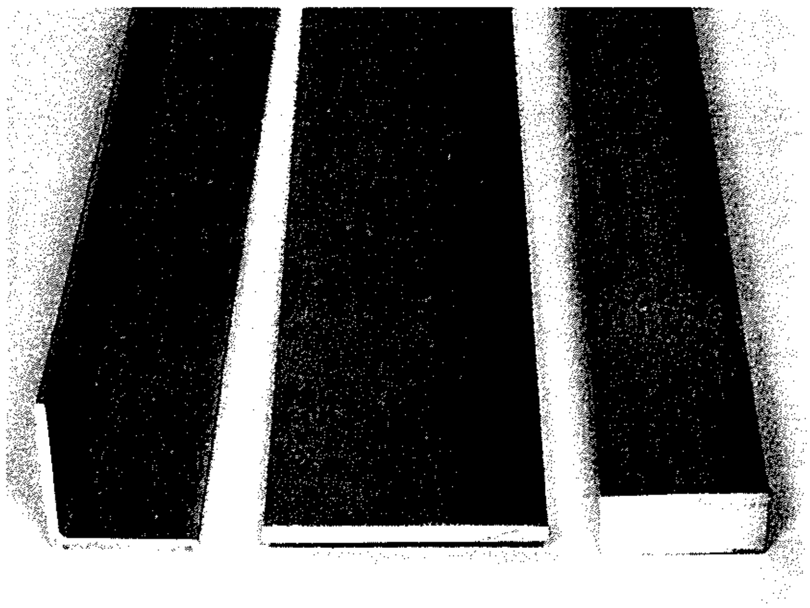


Fig 14 Extruded sections of DTD XXXA alloy

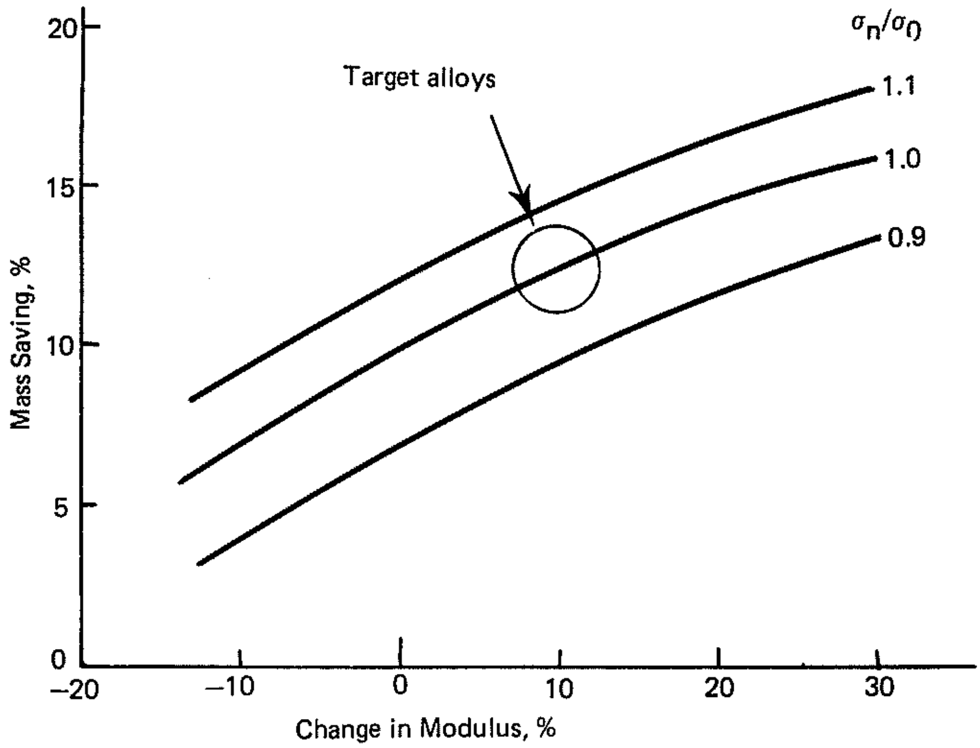


Fig 15 Mass savings predicted for components using an alloy with a density of 90% of the baseline alloy as functions of elastic modulus and strength level