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THE DESIGN OF AEROSPACE MATERIALS FOR THE FUTURE

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ABSTRACT

This paper outlines some of the progress now occurring in the development of materials for future aerospace structures with a particular emphasis on those based on lightweight aluminium alloys. A comparison of the performance of conventional aluminium alloys with that of competing materials such as carbon fibre reinforced composite reveals several areas for potential improvements in the aluminium-based metallic materials. Design studies immediately reveal the benefits accrued from density reductions achieved with the modern series of aluminium-lithium alloys now entering service and examples are given of their improved performance.

Aluminium based alloys can be further developed in three particular respects. These are the significant increase in stiffness possible by the incorporation of ceramic reinforcement in the alloys, an associated improvement in strength particularly at elevated operating temperatures and a potential for an improvement in the resistance to fatigue crack initiation and crack growth achieved by reinforcing the metallic alloys with ceramic particles and either ceramic or organic fibres . These improvements are particularly effective when the density of the material is again reduced.

The paper reviews the potential weight savings and performance improvements offered by these emerging materials and attempts to define optimum developments with particular reference to problem areas such as limited strain capability, notch sensitivity and thermal and environmental effects.

1. INTRODUCTION

It is very evident that the bulk of the structure of airframes of military and civil aircraft and of weapons and space systems is comprised of the high strength aluminium alloys. This has been the case for the last five decades, despite the emergence of competitive materials particularly the high strength titanium alloys and fibre reinforced non-metallic materials. It may be argued that aluminium alloys have been fully developed and that there remains little prospect for further improvement, signalling a decline in their dominant position in aircraft construction. This paper attempts to indicate how aluminium alloys and materials derived from them can further improve, with particular emphasis on properties that affect structural efficiency of airframes as opposed to long term reliability or manufacturing acceptability.

Two types of aluminium-based materials are considered, conventional alloys and metal matrix composites (MMC). The choice of improved conventional alloys is limited to those already on the market and will include the very high strength aluminium-zinc alloys of the 7150 type and the high stiffness aluminium-lithium alloys of the 8090 and 8091 types. Metal matrix composites based on aluminium alloys are clearly more speculative in nature. For the purposes of these designs considerations the performance of notional particulate-reinforced and fibre-reinforced versions are exemplified. In each case comparison is made between the emerging materials and conventional aluminium alloy, represented by aluminium-copper alloy 2014, and conventional carbon-fibre reinforced plastic (CFRP) represented by XAS fibres in an epoxy matrix.

Comparison of the metals with fibre reinforced composite is always complicated by the anisotropy in properties of the latter. For this reason comparisons of the metallic materials are made with nominal organic composite lay-ups containing 60% by volume fibre with selected proportions of the fibres aligned in the testing direction. A similar argument is presented for fibre reinforced metal with 55% by volume fibre where the fibre may be considered to be either silicon carbide or alumina, there being little difference in either's performance in terms of design parameters.

The properties selected for this comparative study are as follows:- tensile strength based on three quarters of the minimum specified ultimate tensile strength, that is the stress level allowed at limit load for the metallic materials, and the maximum allowed design strain (0.5%) for the composites; specific compressive strength, based on the 0.1% compressive proof stress for the metallic materials, and the maximum allowed compressive strain (0.4%) for the organic matrix composite materials; specific stiffness, based on typical moduli for all the materials and, similarly, specific buckling resistance based on the cube root of typical moduli. The more difficult comparisons of fatigue performance and high temperature strength rely on a perception of a realistic environmental requirement, e.g a prescribed fatigue lifetime or a maximum operating temperature-time envelope. Cut-off stresses are applied to the metallic materials and to the organic composites illustrating the relative performances of these two categories in two scenarios of a short-life high stress situation, perhaps typical of a military fighter aircraft and a long-life low stress application typical of a tansport aircraft pressure cabin. It would be premature to consider both the metal matrix composites and the organic composites for some of these applications, however. High temperature strength is simply represented as instantaneous strength at elevated temperature. The base property levels chosen for these design studies are listed in Table.1.

2a. COMPARISON OF STATIC STRENGTH

The specific tensile strengths of the selected materials are illustrated (Fig.1). It can be seen that the aluminium-lithium alloy offers a slight improvement over the conventional aluminium alloy and that a further improvement is achieved with the reinforcement of the 8090 with particulate SiC. However, the conventional titanium alloy shows matching specific strength and, at least in the direction of alignment, the best performance is offered by the reinforced composites whether of metallic or organic matrix. This comparison is unrealistic however because the simple metals are essentially isotropic in their performance and experience of real structure indicates that composite materials can be required to show high levels of both shear strength and transverse strength. To make a more balanced comparison, the isotropic metals are compared with carbon fibre reinforced plastic at selected levels of longitudinal reinforcement (Fig.2). That is, of the 60% volume fraction fibre in the CFRP at least 30% must be aligned in the test direction for equivalence with conventional aluminium alloy. This imposes some limitations on the shear and transverse performance so that, on balance, conventional metallic materials will produce lighter structures when isotropic strength is required. For example, a composite with a quasi-isotropic lay-up (25%0°,50%±45°,25%90°) would prove uncompetitive with conventional aluminium alloy, whilst a more tailored quasi-isotropic lay-up (such as 35%0°,50%±45°,15%90°) would be able to compete with even the high strength 7010 aluminium alloy. The effects of anisotropy apply equally well to fibre reinforced metal matrices and this is illustrated (Fig.3) in a similar manner to that of the organic based materials.

It will be noted that a tensile design allowable strain of 0.5% has been set for both the metal matrix and organic matrix fibre reinforced composites. Arguments may well be raised to the extent that higher strains might be permitted, particularly in the metal matrix composites with fibre reinforcement, if some ductility is demonstrated. It has been assumed that the particulate reinforced MMC will perform as a ductile metal since this has already been demonstrated (1).

A comparison of static compressive strengths leads to a similar conclusion except that the balance is even more in favour of the simple metallic materials (Fig.4) for two subtle reasons. Firstly, very high strength 7000 series aluminium alloys can be used in compressively loaded structures because fears over fatigue and corrosion problems are diminished and, secondly, fibre reinforced plastic composites demonstrate naturally low short transverse strengths leading to easy delamination when loaded in compression. This has led to a more severe strain limitation at 0.4%, although this may be subject to improvement. A question of vital importance to this argument is whether the metallic matrix composites need to be so limited. Indeed the major argument for the employment of the metallic matrix is the claimed improvement in transverse matrix strength. The importance of this argument is illustrated (Fig.5) by comparing the performance of a notional fibre reinforced aluminium alloy at a typical strength level (2) compared to that at a design imposed strain of 0.4%.

2b. COMPARISON OF STIFFNESS

High stiffness is of great importance in most aerospace designs and to make a comparison the elastic moduli of the emerging composite materials are compared with those of the control alloys. Effects of complications such as micro-plasticity or dual moduli are ignored in this simplistic comparison. Once again, to achieve a measure of the effects of alignment, both the organic and metallic matrix fibre reinforced composites are assessed at a selection of loadings in the test direction. It can be seen that the conventional composite material competes favourably with 2014 alloy at low alignment values of approximately 30%, 40% is required to outperform 8090 aluminium-lithium and more than 50% to equal an isotropic metal matrix composite based on 8090 and SiC (Fig.6). Since the specific stiffness presently offered by the fibre reinforced metals is very similar to that of the carbon fibre reinforced composites (Fig.6), the same argument applies to their competitive position.

The resistance to buckling is also very important to the designer concentrating on minimum weight structure. Whilst metallic structure is often allowed to buckle, post buckle design with composite materials carries with it the risk of catastrophic delamination. A comparison of buckling resistance is made in terms of the specific cube root of the selected moduli, representing the performance of a rectangular section such as a panel, ignoring the inherent advantages of the conventional metals in the post buckle regime. A distinct change in the relative ranking of the materials now emerges as the low density of the organic matrix composites begins to tell (Fig.7). Similarly, the advantages of the high modulus fibre reinforced metals are less pronounced because of their higher density

(Fig.7). Buckling is in itself a major design issue, this brief comparison only serves to reveal the inherent advantages of a low density material in this respect.

3. FATIGUE AND FRACTURE TOUGHNESS

Metallic structures are designed ab initio with degradation by fatigue in mind. Depending upon the required fatigue life, the operating environment and the type of structure, the nature of the restriction imposed by fatigue concerns will vary. It matters little whether the design is safe-life, fail-safe or damage tolerant, if a fatigue requirement is defined the effect is to constrain the operating stresses allowed and hence increase structural weight. The allowable stresses or strains depend upon the fatigue life required so that a simple comparison for the present purposes is difficult. However, a typical strain allowed for a transport aircraft pressure cabin skin might be as low as 0.15% and for an aircraft bottom wing skin 0.5%. The effects of these limits on the competitive performance of the metallic materials are shown (Fig.8). If the fatigue strengths of the new composites are increased in proportion to their improved moduli then there should be little change in the relative performances, but if the fatigue strength does not increase in proportion then the value of the increased moduli is somewhat negated. For example, a maximum working stress of 350MPa would be expected at a strain of 0.5% for conventional 2014 and of 550MPa for SiC reinforced 8090. Whilst there is some evidence that the improved moduli of the composite materials improves their fatigue strength it is suspected that local plasticity in the conventional matrices will prevent the full increase in fatigue strength that this argument requires. Interestingly the disproportionate improvement in stiffness over strength in the particulate MMC suggests that fatigue cut-off stresses may start to exceed the factored tensile design allowables, making them essentially immune to fatigue in design terms, at least for short life military applications.

A related aspect concerns the fracture toughness or damage tolerance of the materials in question. Metallic structures are expected to crack in service and it has become practice to monitor the growth of cracks and to contain the critical catastrophic failure condition by considerations of critical crack lengths at the design stage. For example, a typical requirement may be the containment of a crack of a length equal to the bay width of a pressure cabin at limit load. Assuming that levels of stressing and fracture toughness have been adjusted over years of use to produce the desired damage tolerance, the same balance can be required of the emerging composite materials. Thus an increase of operating stress level of 50% would require a matching increase in fracture toughness. This raises serious questions on the balance offered by the particulate reinforced metal matrix composites where, from currently available evidence, increases in stiffness and strength are achievable but fracture toughness may well be reduced. To illustrate this problem critical crack lengths are calculated for a notional metallic matrix material at operating stresses calculated for selected fractions of the ultimate tensile strength. To maintain the performance already offered by conventional alloys in a damage tolerant situation, the specific working stresses applied to a particulate reinforced composite will need to be reduced increasing the structural mass. (Fig.9). There seems little competition with aluminium-lithium alloys where both improved fracture toughness and reduced density are offered in combination with reduced rates of fatigue crack growth, even in aggressive environments (3) and it must be concluded that damage tolerance aspects may well limit the applicability of isotropic particulate metal matrix composites.

Composites based on organic matrices also suffer fatigue damage (4), but it is claimed that the strain limitations already imposed to offset notch sensitivity, environmental degradation and scatter in performance will allow a satisfactory fatigue life. However, this claim has yet to be substantiated by service experience and increases in fibre performance or allowed working strains, yet to be discussed, will possibly modify this situation. For the present, the allowable strain limit set for static tensile performance, namely 0.5%, is taken as the fatigue limit.

The performance of fibre reinforced composite materials with regard to damage tolerance is a more difficult situation because the modes of damage accumulation differ from those in the monolithic metal and the isotropic metal matrix composites. The present perception is that fibre reinforced composites with an organic matrix exhibit very low levels of fracture toughness or damage tolerance in the metallic sense but that they delaminate or craze in a manner characteristic of their construction rather than producing discrete pernicious cracks. There seems little prospect at present for the containment of damage by the metallic controlled crack growth techniques. The initial indications for the fibre-reinforced metal matrix composites are that similar problems may well arise with easy cracking transverse to the fibres but diffuse cracking modes or crack turning occurring when the composites are stressed longitudinally. In the absence of an ability to describe damage modes in a quantifiable manner, safe life techniques will presumably be applied. However, if it is shown that a small amount of damage will produce catastrophic failure, that is the materials are notch sensitive or damage intolerant, then a large safety factor will be applied to contain damage that might be built into the structure producing scatter in the strength of the structure. Whilst this scatter factor might be sufficient to contain in-service damage, analogous to the organic composite situation, safety factors as high as those applied to the organic matrix ccomposites would reduce allowable strains to perhaps 0.5% and the advantages of the fibre reinforced metal composites would entirely vanish.

4. PERFORMANCE AT ELEVATED TEMPERATURES.

Conventional aluminium alloys suffer a degradation in mechanical strength as the operating temperature is increased. This degradation stems from two mechanisms. At lower temperatures, similar to the levels used for precipitation hardening such as 170°C continued precipitation and precipitate coarsening occurs at rates determined by diffusion of the solute elements. This slow process leads to an operational limit for conventional 2000 series aluminium alloys typically of 160°C for times in excess of 1000 hours. Higher temperatures can be sustained for shorter times but as the temperature is raised towards the solution treatment values e.g 500°C the grain structure of the conventional alloys becomes unstable. Aluminium-lithium alloys suffer a similar degradation, performing as well as the best of the conventional aluminium alloys.

Metal matrix composites of both the particulate and fibre reinforced types offer scope for significant improvements in high temperature performance. This stems from the combination of replacement of a conventional cast grain structure with very fine alloy powder containing particulate boundaries which are stabilised by the ceramic additions and the supplementation of the conventional precipitate hardening with a significant contribution from hardening by the very stable ceramic reinforcement. This effect is particularly marked in the fibre reinforced variants. The potential improvement in high temperature performance is illustrated (Fig.10) in terms of specific strength. To compete with the metallic systems the non-metallic composites appear to require the development of systems based on thermoplastic matrices, requiring a change in manufacturing methodologies akin to that required with the fibre reinforced metal matrices. These methods have yet to be fully established.

5. POTENTIAL FURTHER IMPROVEMENTS.

It can be established that further improvements are developing, if not already available, for both the conventional composite materials and the established aluminium alloys. In particular higher strength aluminium alloys have been available for some time and higher modulus carbon fibres should also be considered. The value of these further developments is illustrated in terms of specific strength (Fig.11) for 7150 and 8091 alloys and an intermediate modulus carbon fibre. The original baseline materials are included for comparison. It can be seen that the relative improvements are approximately balanced and that the competitive performance of the composite relies on the ability of the designer to exploit anisotropic lay-ups.

6. THE BALANCE OF MATERIAL PROPERTIES

It is apparent that the improvements offered by the metallic composite materials will be offset by disadvantages and that a balance in property levels will need to be optimised. It has been illustrated that the metal matrix composites can provide very significant improvements in specific stiffness and smaller, but useable increases in specific strength, but that the damage tolerance properties may not follow producing a limit to their value in structures that require high fracture toughness. All the properties considered in this paper are important in limiting the mass of aerospace structures and to achieve sustained mass savings all these properties need to improve simultaneously. This has only been achieved with the use of lower density matrices exemplified by 8090 and MMC based on 8090, illustrating the powerful effect of density reductions.

It is frequently claimed that the organic matrix composites outperform the conventional metallic materials. These results show that this is strictly untrue for both existing and emerging CFRP when isotropic metals are compared with quasi-isotropic CFRP. When anisotropic performance can be exploited then the organic composites quickly begin to show their value. The lesson for the metallic materials would appear clear, deliberate controlled anisotropy must be developed to outperform the plastic matrix materials on every count. This approach is slowly becoming available with the emergence of stiffened isotropic sheet material coupled to aligned stringers. Ideally, the anisotropic aligned material should be produced by conventional extrusion rather than by expensive lay-up techniques with all the attendant composite problems of quality, joining and non-destructive evaluation.

7. CONCLUSIONS

To maintain their competitiveness against the emerging organic matrix composites aluminium alloys need to enhance certain features of their performance. In general terms the performance of isotropic materials leaves the balance firmly in favour of conventional alloys, with distinct improvements already in full development such as aluminium-lithium and ultra-high strength aluminium-zinc alloys and with particulate metal matrix composites begining to emerge. However. to achieve competitiveness in structures requiring anisotropic properties the development of cheap aligned products is required. The improved high temperature performance of the emerging metal matrix composites requires urgent quantification. Problems already perceived with the metal matrix composites stem from questionable levels of fracture toughness that may require detailed attention in both microstructural optimisation and development of mixed product forms.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

(1). J.WHITE, I.R.HUGHES, T.C.WILLIS, R.M.JORDAN "Metal matrix composites based on aluminium-lithium and silicon carbide." 4th International Al-Li Conference Paris 1987 Les Edition de Physique. 1987

(2). A.M.WALKER "Properties of Safimax MMCs" METAL MATRIX COMPOSITES: Structure and Property Assessment. The Institute of Metals and The Royal Aeronautical Society London Nov 1987.

(3) M.PETERS, V.BACHMANN, K.WELPMANN " Fatigue crack propagation behaviour of the Al-Li alloy 8090 compared to 2024." 4th International Al-Li Conference Paris 1987 Les Edition de Physique 1987

(4) P.T.CURTIS " A review of the fatigue of composite materials " RAE TR 87031 May 1987

TABLE. 1

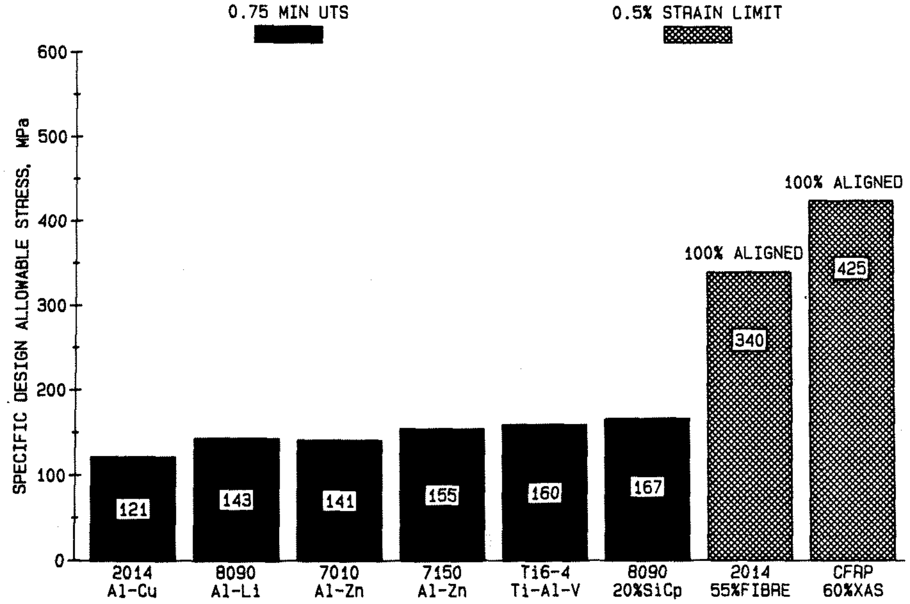
BASIC MATERIAL PROPERTIES

		2014	8090	7010	8090+SiC	2014+FIBRE '*	60%XAS *	60% IM *
ELASTIC MODULUS	GPa	72	80	69	110	195	138	168
TYPICAL STRENGTH	MPa	475	515	550	580	1000+	1750	2700
ALLOWABLE STRENGTH	MPa	338	355	395	410	975	690	840
FRACTURE TOUGHNESS	MPa/m	25	45	45	20	-	-	-
DENSITY	g/cc	2.80	2.53	2.81	2.61	2.90	1.62	1.60

* Properties of fully aligned composites
' Either silicon carbide or alumina fibre

FIG.1 SPECIFIC TENSILE DESIGN ALLOWABLE STRENGTHS

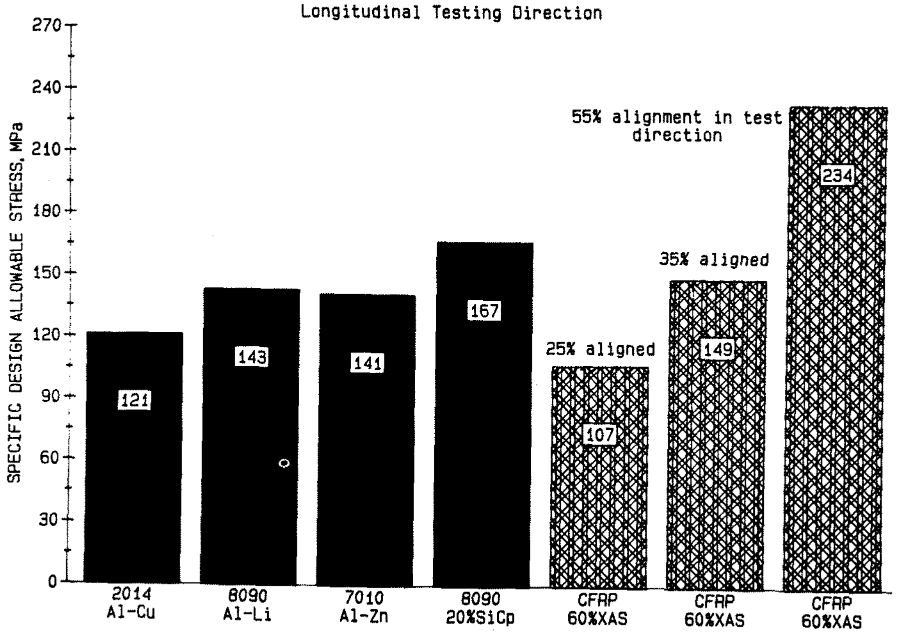
Longitudinal Test Direction



RAE MGS

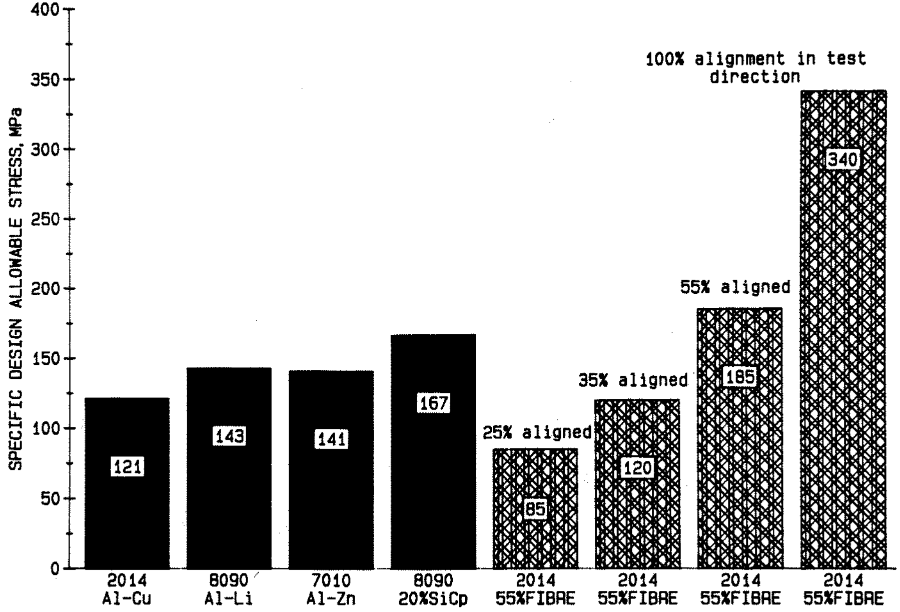
FIG.2 SPECIFIC TENSILE DESIGN ALLOWABLE STRENGTHS

Longitudinal Testing Direction



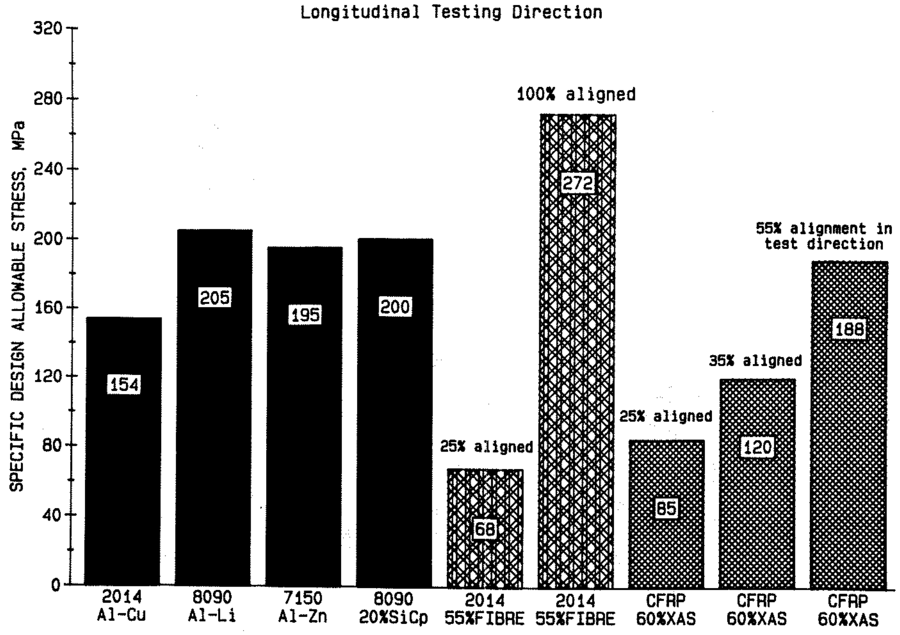
RAE MGS

FIG.3 SPECIFIC TENSILE DESIGN ALLOWABLE STRENGTHS
Longitudinal Testing Direction



RAE M&S

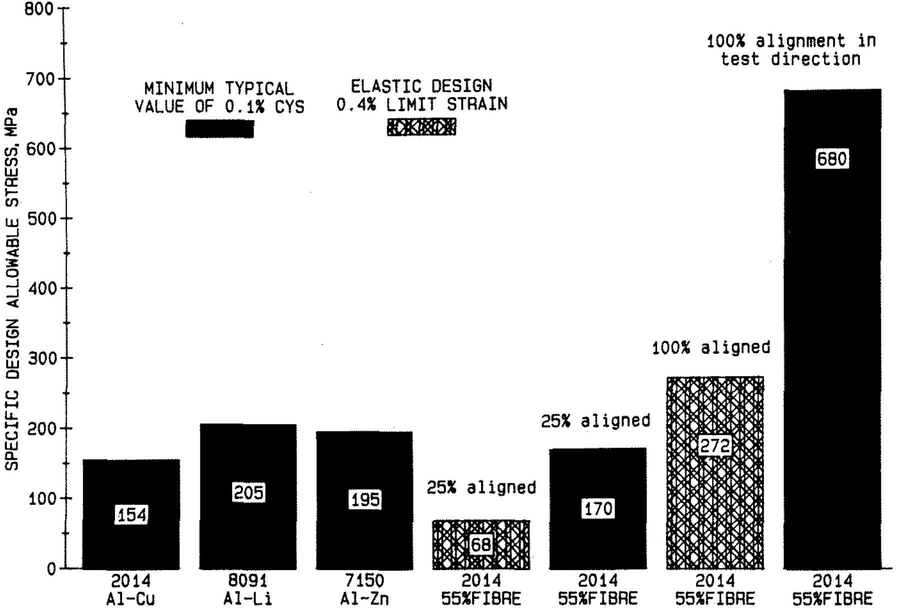
FIG.4 SPECIFIC COMPRESSIVE DESIGN ALLOWABLE STRENGTHS
Longitudinal Testing Direction



RAE M&S

FIG.5 SPECIFIC COMPRESSIVE DESIGN ALLOWABLE STRENGTHS

Longitudinal Testing Direction



RAE M&S

FIG.6 SPECIFIC ELASTIC MODULI

Longitudinal Testing Direction

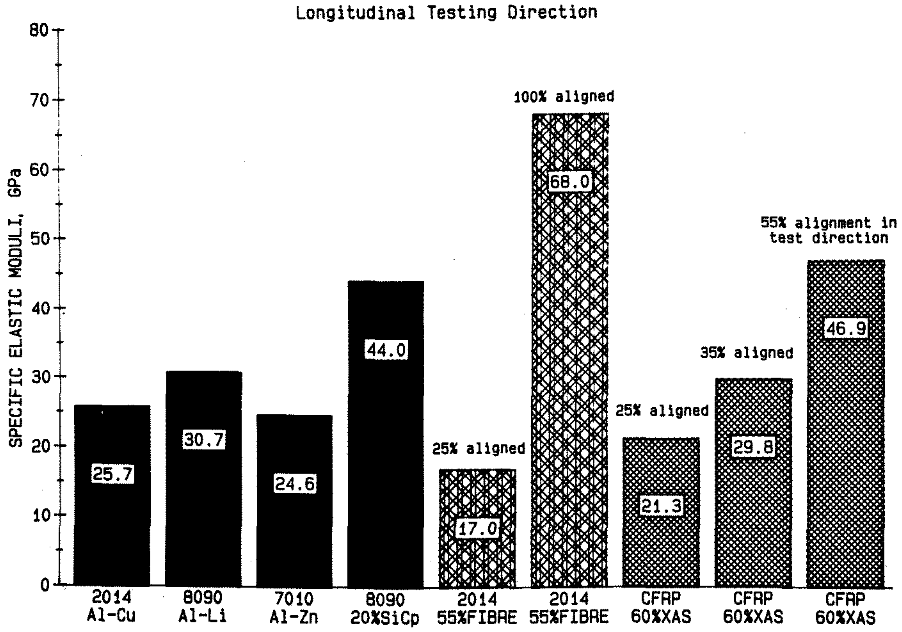


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FIG.7 SPECIFIC ELASTIC BUCKLING RESISTANCE

Longitudinal Testing Direction

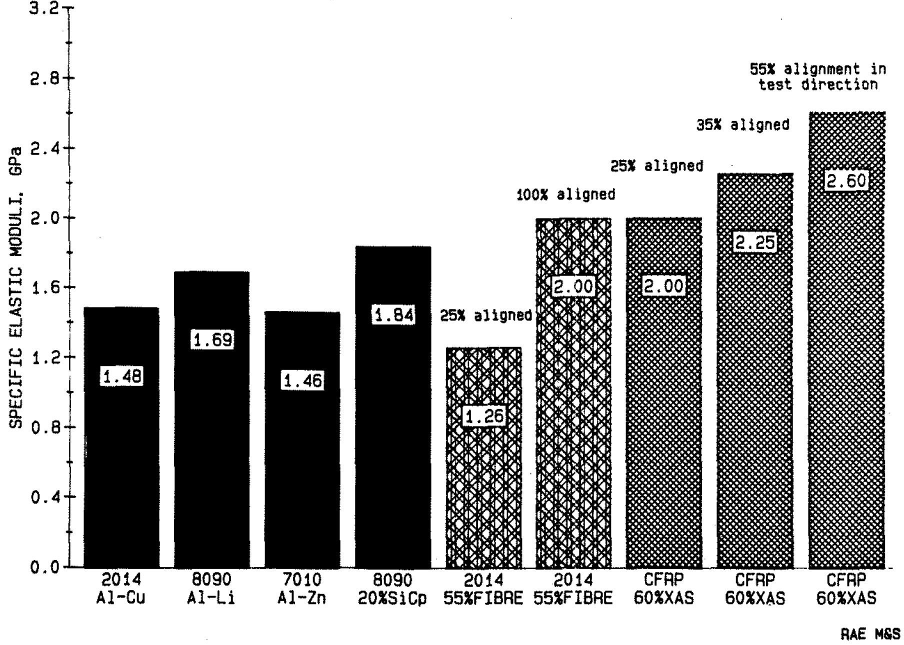

FIG.8 SPECIFIC TENSILE DESIGN ALLOWABLE STRENGTHS

Longitudinal Testing Direction

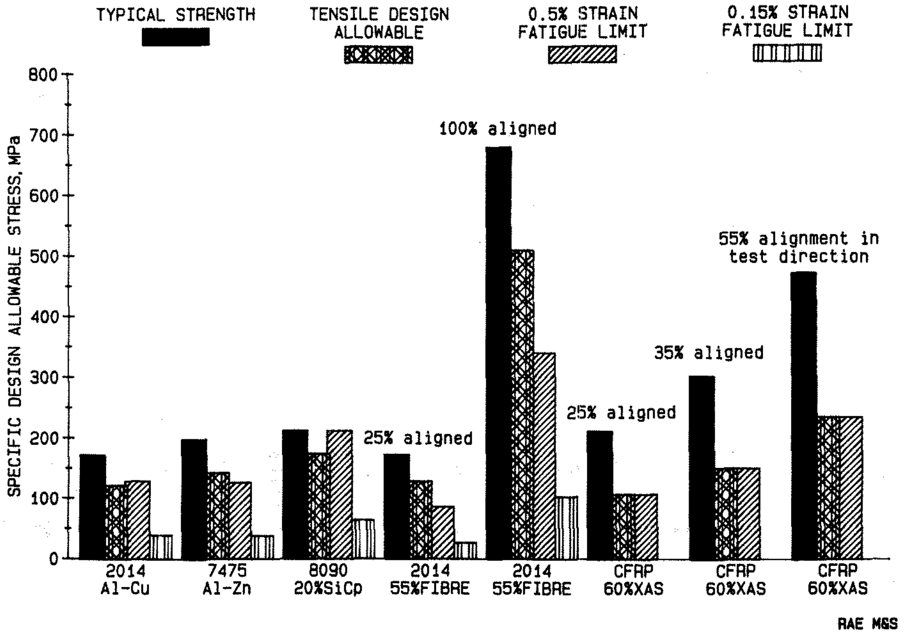

FIG.9 CRITICAL CRACK DEPTHS AT SELECTED APPLIED STRESSES

STRESS SELECTED AS A FRACTION OF THE ALLOWABLE TENSILE STRENGTH

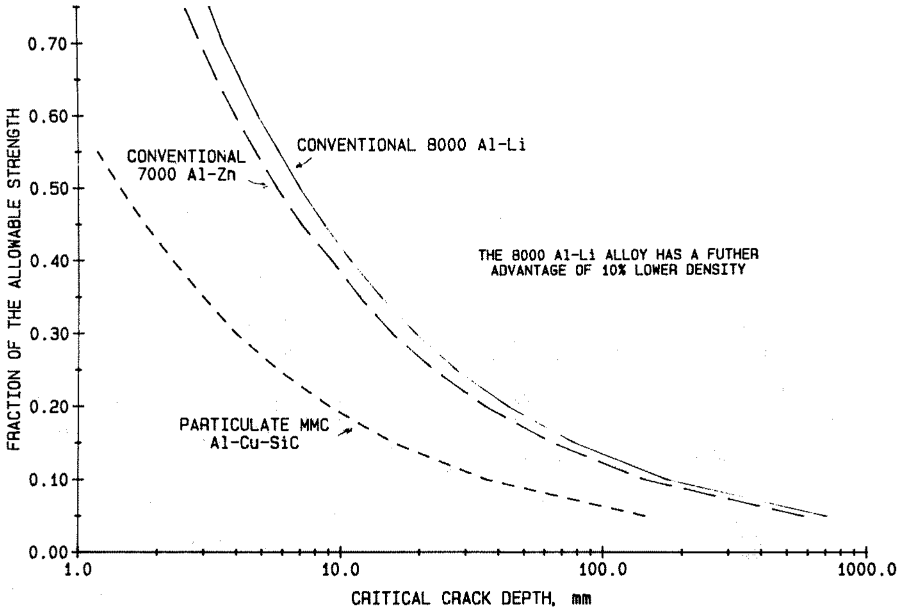

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FIG.10 SPECIFIC TENSILE STRENGTHS AT 250C

Estimated typical longitudinal values

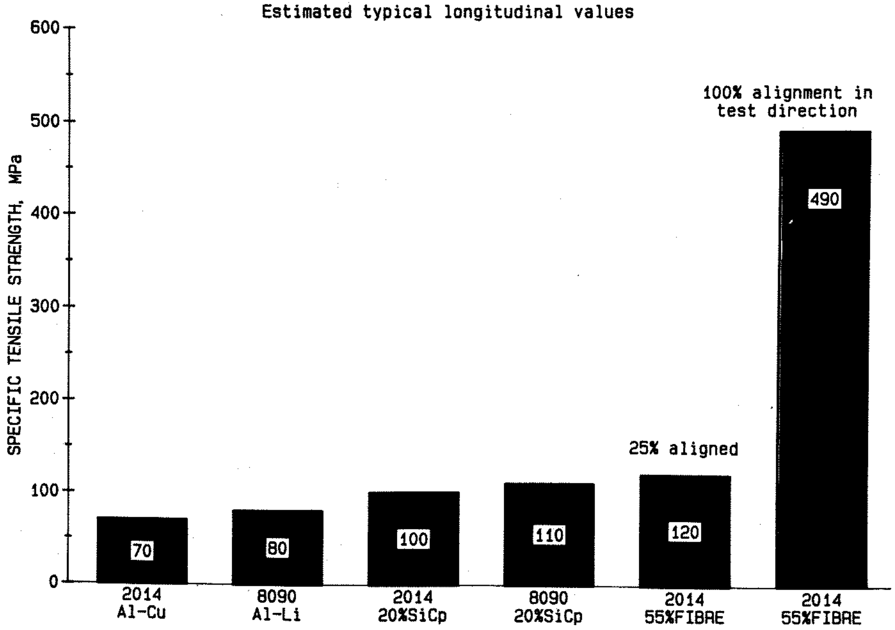

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FIG.11 IMPROVEMENTS IN SPECIFIC TENSILE DESIGN ALLOWABLES

Longitudinal Testing Direction