APPLICATIONS OF TITANIUM ALUMINIDES IN

GAS TURBINE ENGINE COMPONENTS

P J Postans[+], M T Cope[+], S Moorhouse[+] and A B Thakker*

[+] Rolls-Royce plc, PO Box 31, Derby, DE24 8BJ, UK
* Rolls-Royce Inc, 2849 Paces Ferry Road, Atlanta, GA 30339-3769, USA

Abstract

Titanium aluminide for the last two decades have offered the prospect of significant weight savings in gas turbine engines by the replacement of Ni base superalloys. As yet they have failed to deliver despite significant R&D effort. However, recent advances in chemistry and processing capabilities have now resulted in Ti aluminides standing on the threshold of commercial engine utilisation.

For this class of material to make the transition from research curiosity to a 'real' engine material the key property requirements must first be identified. Only then can the material be tailored to meet the engineering need.

To identify key properties targets for titanium aluminides, a series of design studies have been carried out for civil, military and helicopter gas turbine engines using current gamma and alpha2 material properties.

Gamma blades in the low pressure turbine of civil engines save over 100kg per engine compared to current cast nickel blades. The key requirements here are specific stiffness coupled with adequate tensile strength and resistance to damage and defects. Other attractive applications are compressor stator vanes and simple, non critical structures where conventional titanium can not be used because of the risk of titanium fires. Compressor blading is a further possibility. Large complex static structures and high integrity parts lifed by fracture mechanics are unsuited to current alloys.

Alpha2 alloys were for a long time the front runners for engine applications compared to gamma Ti aluminides. However their poor fire and environmental resistance has proved their Achilles' heel.

Further understanding is still required on the long term effect of operating environment on mechanical properties for titanium aluminides. In addition the effect of local stress concentrations, ie, defects or damage, on life particularly for the more brittle gamma alloys, need to be assessed. The applications for alpha2 would be significantly increased if its fatigue crack growth rate could be slowed down to that of conventional titanium, allowing its use as critical discs provided environmental resistance is adequate.

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Introduction

'Find out what the customer wants - then supply it' is the recipe for success in any business. Applied to titanium aluminides it should ensure the materials and manufacturing processes developed have the widest industrial application and benefit.

The present paper identifies key areas where improvements are required, based on recent Rolls-Royce design studies for civil, military and helicopter engines. The conclusions provide a good indication of general aeroengine industry needs, although there will be some detailed variations between different companies due to different engine operating conditions, technology base and personal opinion.

Titanium aluminide capabilities

Design studies identifying component applications and key materials and process properties are iterative with materials and process development. A first step is to assess current materials and process capability (Figures 1 and 2) and estimate likely future improvements (1)(2)(3)(4)(5).

There are also some basic conditions which a gas turbine engine material must meet. They are described below in no particular order since all are essential.

Material must be available in the right timescales

Maximum benefit from a new material or process accrues when it is designed into a component from the start, rather than being substituted within an existing engine configuration. Such design opportunities only occur every few years.

The engineering advantage must be high enough to justify development costs and any increase in component cost

When a new material or process allows the engine to be thermodynamically more efficient, ie, operate hotter or at higher pressure ratio, the benefit is usually greater than if it just saves weight. A general rule for civil gas turbine engines is that a reduction of 1kg in component weight saves £650 in direct operating costs (mainly fuel) over the life of an engine (2). Weight assumes more importance in military combat and space vehicle components.

The risk of unexpected component failure must be acceptably low

Components are divided into several categories, dependent on the consequence of failure. The most critical must have a very low risk of premature failure; it can increase somewhat for components where failure affects efficiency but not safety.

Component design studies for civil, military and helicopter gas turbine engines

The results of these studies are summarised in Figure 3, with more detail in Table 1 for gamma and Table 2 for alpha2.

Both gamma and alpha2 are also potential matrices in composite materials. Since materials and process requirements for matrices, are likely to be significantly different they are not considered here.

Compressor aerofoils

The requirements for all 3 types of engine are broadly similar despite differences in component size and cost/weight benefit.

Aluminides offer no benefit to the engine thermodynamic cycle as temperatures are limited by available disc materials.

Stator blades in gamma offer weight savings of 50% approx compared to steel or nickel. The risk of component failure is lower for stators compared to rotors as the likelihood of impact from foreign objects in the gas stream is low. Stators held at both the inner and outer annulus are expected to remain in place even if cracked.

Rotor blades in gamma offer little advantage compared to conventional titanium, improved fire resistance being offset by increased risk of foreign object damage. As a replacement for nickel the weight savings depend on allowable crushing stress, hence blade root design. A heavier disc rim could easily cancel the 45% reduction in blade weight.

Alpha2 is of little use unless its fire resistance can be markedly improved.

Turbine aerofoils

Many turbine aerofoils, including all those in military combat engines, run too hot for gamma aluminide. Those at suitable temperatures are civil engine low pressure turbine, LPT, aerofoils and helicopter engine power turbine aerofoils. The latter will probably demand low cost in preference to low weight and hence remain in nickel.

Civil LPT blades, offer no engine cycle advantage due to gamma but weight savings of 45% are expected by replacing nickel. Since civil LPT blades can be over 35cm long this translates to a saving of 80-120kg on a large turbofan engine. Reduced blade weight facilitates lighter discs and casings, saving an additional 30%, ie 70kg. As a result Rolls-Royce consider civil LPT rotor blades are the most important application for gamma aluminide, see Figure 4. It is understood other gas turbine engine companies share this view.

Civil LPT nozzle guide vanes, ie static aerofoils, show no engineering benefit in gamma since their key requirement is high strength.

Alpha2 has some application in civil LPT blades but its lower temperature capability and lower modulus (influencing vibration) make it less useful than gamma.

Engine structures

Applications for titanium aluminides are limited. Many casings require high 'plasticity' for containment of failed blades, which precludes gamma, and fire resistance, which precludes alpha2. Spoked engine support structures require neither of these properties but their complex shape is often beyond current titanium aluminide manufacturing capability. Military engine nozzles and some combustor casings are more promising.

Discs

In recent years there has been a move away from disc lives based on fatigue initiation. The alternative is fracture mechanics life based on a typical initial defect size and fatigue crack growth rate.

For both gamma and alpha2, it is likely that high lives to crack initiation can be obtained on 'defect free' material but both have a fairly fast crack growth rate which results in low fracture mechanics lives.

It is unlikely that fatigue crack growth rate can be slowed down sufficiently for either gamma or alpha2 to make them suitable for long life discs. Applications will therefore be limited to short life discs eg missile or some military engines, or certain turbine discs which are required to withstand a high overspeed criteria, hence tensile strength is the main requirement and fatigue stresses are relatively low.

Conclusions

Gamma has wider potential application than alpha2 due primarily to its fire resistance and reasonable temperature capability. Key areas for improvement are plasticity, both improving defect tolerance without detriment to other key properties and/or learning to effectively use material with limited plasticity; environmental stability; tensile strength and manufacturing capability.

Alpha2 alloys have limited application due to their lack of fire resistance and poor environmental resistance. Key areas for improvement are surface protection to improve temperature capability and ways of slowing fatigue crack growth rate. These would enable alpha2 to fill a useful, though small niche between conventional titanium and nickel alloys.

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Figure 1

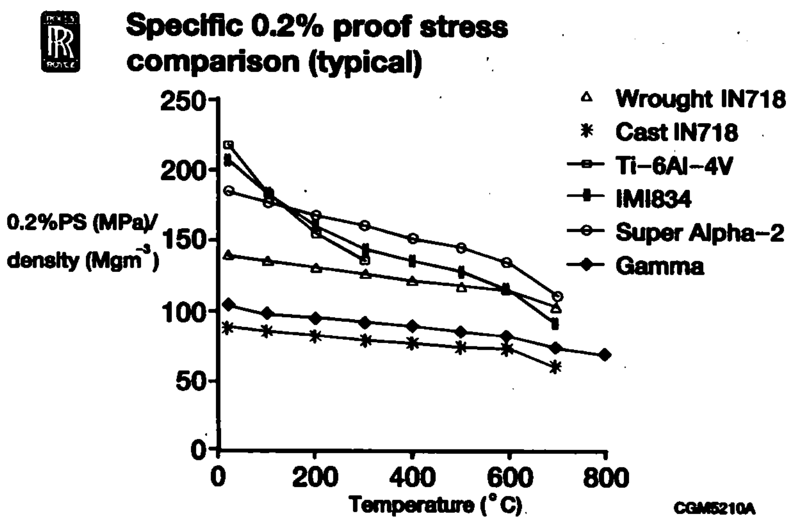

Figure 2

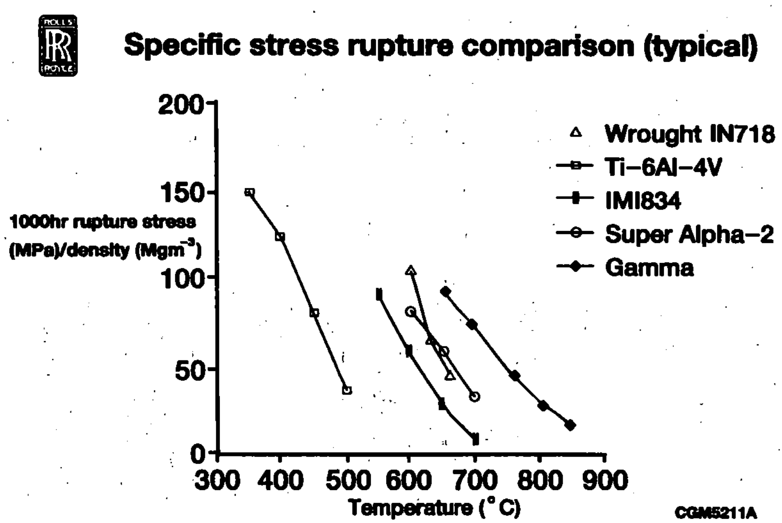

Figure 3

Potential applications of titanium aluminides in a large civil turbofan engine

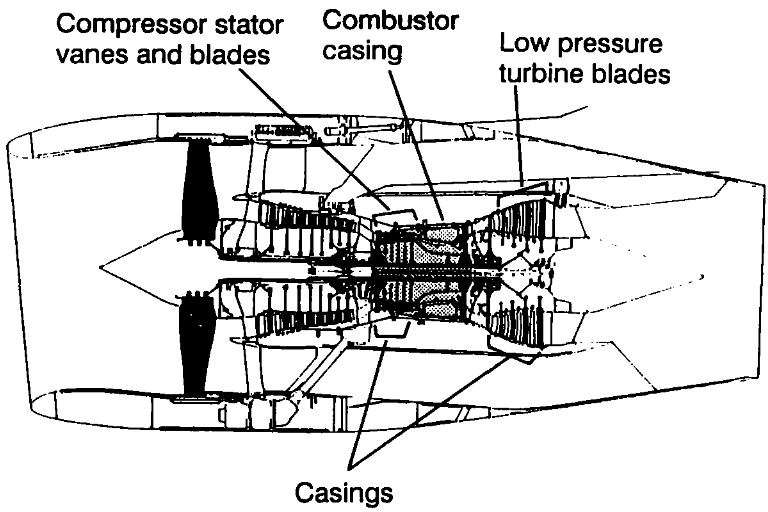

Figure 4

Table 1 Key Design Requirements for Gamma Titanium Aluminides

Design Requirement	Compressor Aerofoils		Turbine Aerofoils		Structure	Discs	Priority for improvement/research	
	Rotors	Stators	Rotors	Stators (NGVs)				
Tensile Strength	/	/	/	I	I	/	3	Note 1
Creep Strength	/	/	/	I	I	?		
Plasticity	I	/	I	/	I	?	1	Note 2
Modulus	/	/	/	/	/	/		
Fracture Toughness	/	/	/	/	/	/		
Crack Propagation	na	na	na	na	I	I	7	Note 3
Fire Resistance	/	/	/	/	/	na		
Environmental Stability	/	/	I	I	I	/	2	Note 4
Castability	/	/	/	/	I	na	6	Note 5
Forging/Extrusion	/	/	/	/	?	?		
Sheet	na	na	na	na	I	na		
Machining	/	/	/	/	?	?	5	
Welding/Bonding	na	?	na	?	?	?	4	Note 6
Engineering benefit of current or near future material	Moderate /Low	Moderate	High	None	Low	None		

/-Acceptable in current or near future material I-Significant improvement required ?-Don't know more information needed na-Not applicable

Note 1 - Need to improve to nickel strength levels

Note 2 - Need to learn how to design with limited plasticity material

Note 3 - Unlikely to achieve rates similar to conventional titanium

Note 4 - Aim 850 to 950°C

Note 5 - Imorovements needed for large complex structures

Note 6 - Cooling rate critical for fusion welds

Table 2 Key Design Requirements for Alpha2 Titanium Aluminides

Design Requirement	Compressor Aerofoils		Turbine Aerofoils		Structures	Discs	Priority for improvement/research	
	Rotors	Stators	Rotors	Stators (NGVs)				
Tensile Strength	/	/	/	/	/	/		
Creep Strength	/	/	/	?	?	/		
Plasticity	/	/	/	/	/	/		
Modulus	/	/	/	/	/	/		
Fracture Toughness	/	/	/	/	/	/		
Crack Propagation	na	na	na	na	I	I	2	
Fire Resistance	I	I	I	I	I	na		Note 2
Environmental Stability	I	I	I	I	I	I	1	Note 1
Castability	na	na	na	?	?	na		
Forging/Extrusion	/	/	/	/	/	/		
Sheet	na	na	na	na	/	na		
Machining	/	/	/	/	?	?		
Welding/Bonding	na	?	na	?	?	?	3	
Engineering benefit of current or near future material	None	None	Low	None	Low	Low/ Moderate		

/ Acceptable in current or near future material
? Don't know - more information needed
I Significant improvement required
na Not applicable
Note 1 Base alloy unlikely to be improved - need surface coating
Note 2 Increased fire resistance would extend applications but it is unlikely to be feasible