INTERMETALLIC COMPOUNDS FOR HIGH TEMPERATURE USE IN THE AEROSPACE INDUSTRY

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Abstract

Intermetallic compounds have emerged as a new class of "alternative" materials for advanced aerospace applications. These materials which are often lighter, stiffer and have a higher specific strength than most conventional alloys are potential candidates for various high temperature applications. This paper outlines the current state-of-the-art and draws attention on some promising areas of research on intermetallic compounds. Research and development effort on multiphase intermetallics is essential to achieve an overall balance of properties required in many structural applications. However, despite the progress made in the field of new compositions and processing techniques, many more years of effort will be necessary for a successful industrial utilization of such materials.

1. General considerations

The design requirements for advanced aerospace structures have driven the development of novel materials with improved mechanical properties and better environmental resistance. While selecting materials for airframe and propulsive systems a primary consideration is to keep weight to a minimum. Weight saving is of critical importance in civil aircraft where the airframe structural weight is of the order of half the empty weight.

The two main factors, in addition to costs, durability and environmental resistance, are the increase of the specific strength and stiffness, and also, in particular in the case of aeroengines, the increase of the high temperature capability since the turbine inlet temperature is the main parameter to contribute to the specific thrust of the engines, and has also a strong influence on their efficiency.

Separate materials are needed both in the engines and for the airframes since different parts will be heated to different temperatures. Generally, for each temperature range of interest, the objective is to select the lowest density material that can satisfy the overall requirements of strength and environmental resistance.

The potential of current conventional materials has been largely exploited. For example, both the nickel-base alloys and the titanium alloys have reached their upper temperature limit of utilization. The aerospace industry is therefore looking forward to the development of "alternative" materials which would be lighter, stronger and would have a higher temperature potential, compared to the presently available alloys.

In this context, considerable research and development effort is underway on a wide range of materials that may find eventual applications including intermetallic compounds (monolithic and composite), high temperature metallic composites, refractory metals, glass-ceramic and ceramic/ceramic composites.

This paper will be devoted to reviewing the status, advantages and problem areas of the intermetallic compounds (IC) and intermetallic matrix composites (IMC's).

2. Intermetallic Compounds

2.1. Introduction and background

The intermetallic compounds may be defined as phases or compounds between metallic atoms with either well defined integral atomic ratios or having a limited range of possible compositions. Those which are of interest for applications at elevated temperature under high stresses are alloys of high chemical stability, with high melting temperatures and high elastic moduli. This stability is the result of very strong interactions between unlike metal atoms. In most cases, bonding retains its metallic character. As a consequence, at last when the sizes of unlike atoms are not too different, the memory of usual metallic arrangements is preserved, and the compounds are ordered derivatives of usual metallic close-packed structures (simple face-centred cubic, body-centred cubic or hexagonal). The occurrence of a particular ordering arrangement is governed by electronic structure and statistical thermodynamics laws which are now fairly well understood, at least qualitatively[1]

These alloys remain ordered up to the melting point, or may disorder at a lower characteristic temperature. Deviation from the stoeichiometry may have a profound effect on the mechanical properties.

Most intermetallic compounds have high strength and relatively good oxidation and corrosion resistance, and relatively low specific gravity. The work-hardening rate of some of these ordered alloys is also quite high compared to those of the disordered alloys. Unfortunately, at least at low temperatures they show a brittle behaviour. Low ductility and fracture toughness constitute a serious but not unsurmountable barrier to their successful use as structural materials.

There is ample experimental evidence available today to show that the mechanical performance (especially the creep strength, ductility and fracture toughness) of multi-phase alloys is better than that of monolithic intermetallics[2]. This is particularly true for Ni_3Al-based intermetallics and the titanium aluminides. It should be in particular remembered that modern Ni-based superalloys contain up to 70% of the γ, Ni_3Al-type phase inserted in a fcc., Ni-based solid solution. This awareness has led to an increasing interest in both phase manipulation in intermetallics by compositional and process control and by the manufacture of synthetic intermetallic matrix composites. More speculative work is also being carried out to identify "exotic" intermetallics which have a very high temperature potential. Among the vast number of

Table 1. Some potential intermetallic compounds.

Compound	Advantages	Disadvantages
Advanced potential candidates		
Ti_3Al	Density	Oxidation
TiAl	Density	Ductility
FeAl	Ductility, oxidation	Melting point, density
NiAl	Melting point, oxidation	Ductility
Far term application (speculative)		
Ti_5Si_3	Density	Ductility
Nb_5Si_3	Melting point	Ductility, oxidation
Nb_3Al	Melting point	Ductility, oxidation
$NbAl_3$	Melting point, density	Ductility, oxidation
$TiAl_3$	Density	Ductility
$MoAl_2$	Melting point	Ductility, oxidation
Nb_2Be_{17}	Melting point	Ductility, oxidation
$ZrBe_{13}$	Melting point	Ductility, oxidation

intermetallics identified up to now, very few have been considered for structural applications (Table 1).

The intermetallics for structural applications can be divided into three major categories:

- nickel aluminides (Ni_3Al and NiAl),
- titanium aluminides (Ti_3Al, TiAl and $TiAl_3$),
- other intermetallics.

2.2. Nickel aluminides

2.2.1. Ni_3Al-based intermetallics

A considerable amount of research effort has been devoted to Ni_3Al and Ni_3Al-based γ' intermetallics. The main reason is that Ni_3Al is the principal strengthener in many nickel-base superalloys. This intermetallic with the $L1_2$ ordered structure is important because it exhibits an increasing flow stress with increasing temperature up to 600-800°C. The increase in flow stress with temperature of some Ni_3Al-base single crystals is shown in Fig.1 but the polycrystalline Ni_3Al also shows a very similar behaviour. Although this property is useful as a base for high temperature structural applications, the binary compound in the polycrystalline state exhibits brittle intergranular fracture with zero ductility at ambient temperature. On the other hand, single crystals of the binary compound are ductile in all orientations even at low

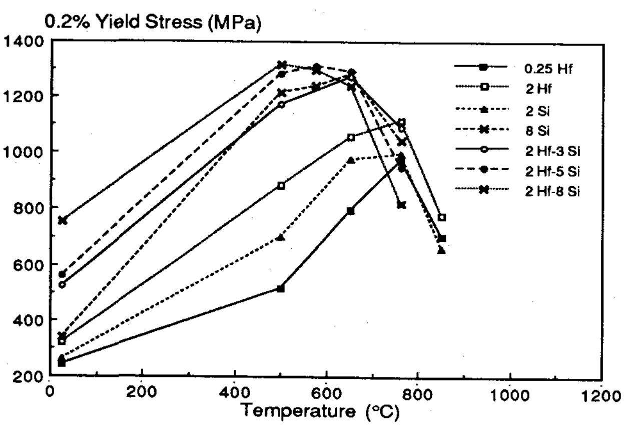

Figure 1. Effect of temperature and macroalloying on the 0.2% yield stress of Ni_3Al-based [001] single crystals.

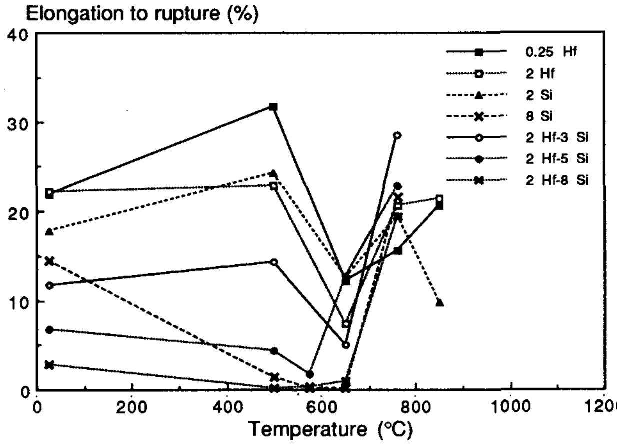

Figure 2. Variation with temperature of the tensile ductility of Ni_3Al-based [001] single crystals.

temperatures. It is, however, worth mentioning that even in the single crystal form, some single phase γ' alloys may become extremely brittle around a temperature which coincides with the peak in flow stress (Fig.2).

A major advance in improving the ductility of this polycrystalline material was made with the discovery of a very strong micro-alloying effect of boron by Aoki and Izumi [3]. However a cumbersome environmental effect was found in the temperature range 600-1000°C on ductility which drops to almost zero on tensile tests conducted in air. This problem could only be solved by Liu and Sikka [4] by the addition of chronium (≈ 8%) which resulted in a material which is no longer single-phase but contains an appreciable amount of disordered γ phase along grain boundaries.

Besides, the γ-γ' interfaces seem to play a major role in improving the creep strength of superalloys compared with the intrinsic resistance of the intermetallic phase. This is illustrated on figure 3 where are compared the creep curves of the γ-γ' "CMSX-2" superalloy and of the constituent γ' phase of this alloy. The two-phase system is far more creep-resistant, although the tensile curves of the

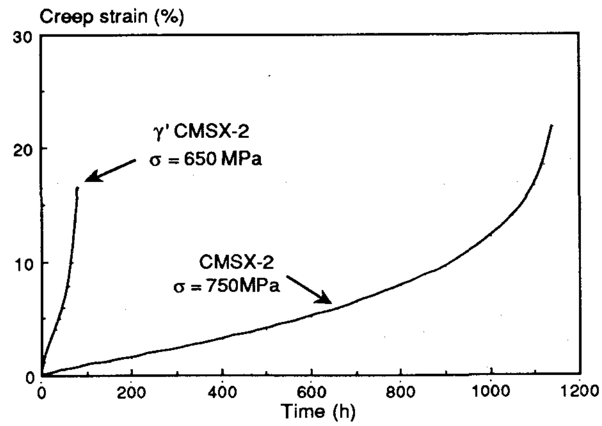

Figure 3. Creep curves at 760°C of [001] CMSX-2 and γ' CMSX-2 single crystals.

two materials at 760°C are almost identical (fig.4).

The potential of Ni_3Al-based alloys for structural applications has been recently reviewed [2], and it is now apparent that such alloys cannot replace the currently available high strength superalloys.

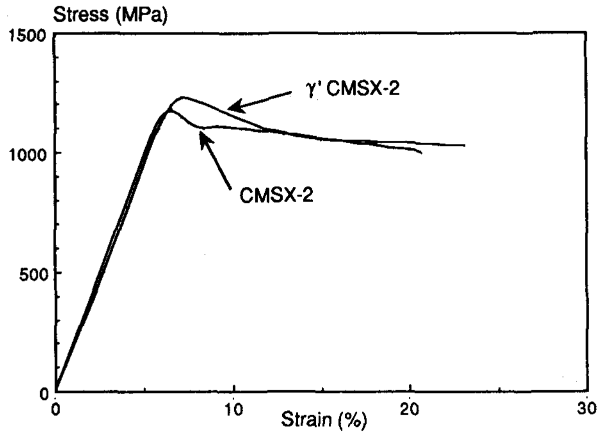

Figure 4. Tensile curves at 760°C of [001] single crystals.

2.2.2. NiAl-based nickel aluminides

The NiAl compound has been recognized as an important intermetallic because it is a major constituent of high temperature, oxidation resistant coatings. It has a B2 ordered structure, melts at 1638°C, has a high modulus (189GPa), a low density (~6g/cm^3) and a wide solubility range. The compound is extremely stable (enthalpy of formation of ~14.8Kcal/mol) and it has excellent cyclic oxidation resistance up to 1300°C especially when alloyed with small amounts of rare earths [5].

Single crystals of NiAl of suitable orientations are ductile but the polycrystalline material is brittle around room temperature. Contrary to the case of Ni_3Al, the brittleness of NiAl is not due to a weakness of the grain boundaries but due to the lack of sufficient number of slip systems. Indeed, this compound deforms primarily by {110}<100> slip which provides only three independent slip systems [6-8].

The brittle-ductile transition temperature of the polycrystalline material is found to be in the temperature range 300-600°C; the exact temperature depends upon the stoichiometry and grain size. The best results have been obtained apparently with the stoichiometric composition giving about 2% elongation in bend tests.

Both the strength and the ductility of the binary compound in the monolithic form are too low to render NiAl a competitive high temperature material compared to the high strength superalloys. Several attempts to increase the ductility either by alloying, in order to favour <111> slip [9], or by rapid solidification, in order to reduce the grain size [10,11], have not proved to be satisfactory enough. However, multiphase alloys based on NiAl intermetallic show substantial promise. In order to make this material of any practical use, it is therefore extremely important to study the effect of ternary and higher order additions. Previous work has already shown some spectacular results, in terms of creep strength, obtained with the Ni-

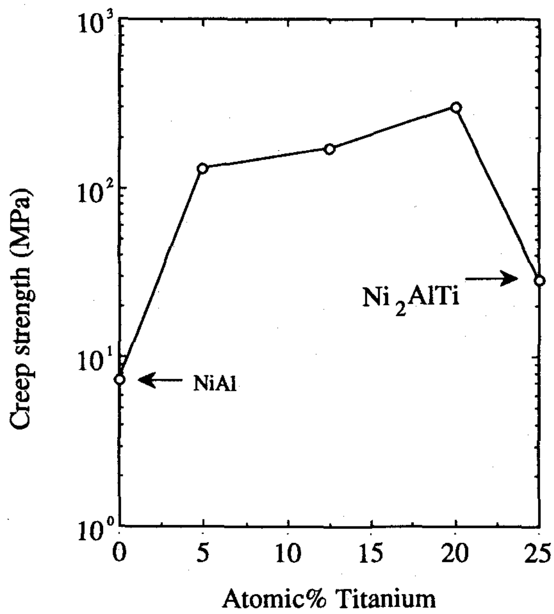

Figure 5. Creep strength as a function of Ti content for alloys along the NiAl-Ni_2AlTi tie line.

Al-Ti system. Indeed, Strutt et al.[12] showed fourteen years ago that remarkable creep strength can be obtained with the NiAl-Ni_2AlTi two-phase intermetallics up to very high temperatures. The two phases β (NiAl) and β' (Ni_2AlTi) which are derived both from the ordering of the bcc lattice are in epitaxy and the lattice parameter of the former is about half of the lattice parameter of the latter. The two phases are therefore crystallographically quite "compatible". This type of two-phase structure bears a certain resemblance to the γ-γ structure of superalloys, although the β-β' structure is composed of two brittle intermetallic phases instead of a disordered ductile γ phase containing an intermetallic γ phase. The creep strength of the NiAl-Ni_2AlTi alloys is shown in Fig.5 as a function of the Ti content. More interestingly, Fig.6 shows that the creep strength of the two-phase material is considerably higher than that of the

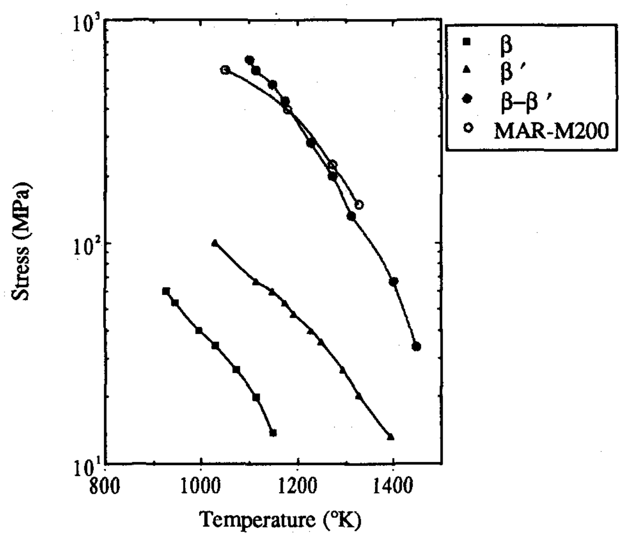

Figure 6. Creep strength, defined as the stress to maintain a creep rate of 10^{-7}/sec, vs.temperature for β, β', β-β' and Mar-M200 [12].

individual constituents NiAl and Ni_2AlTi. Apparently, the presence of semi-coherent interfaces between these two phases renders the plastic deformation much more difficult compared to the situation in the individual monolithic phases and it becomes possible to attain a creep strength equivalent to that of a high strength superalloy, MAR-M200, used as a turbine blade material in the aerospace industry.

The major problem is still the extreme brittleness of the NiAl-Ni_2AlTi alloys and all attempts, including directional solidification, have not resulted in imparting a reasonable ductility to this system. However, this work provides a particularly interesting example of the potential offered by the NiAl-based multi-phase alloys, in terms of creep strength. The manufacture of such multi-phase alloys seems to be the only hope for obtaining practically useful materials which may provide an overall balance of properties such as tensile strength, creep resistance and fracture toughness (and perhaps ductility).

In this context, considerable effort is presently underway at General Electric USA on NiAl-based multi-phase single crystal alloys in order to replace the current γ-γ' turbine blade superalloys. The benefits of such a material are evident: the use of NiAl-based turbine blades with a much lower density (the density of NiAl is about 6g/cm^3 compared to 8.5g/cm^3 for superalloys) would lead to a substantial weight saving and much lower stresses on the turbine disc. A further asset would be the excellent oxidation resistance of NiAl. The ductility problem would, however, have to be solved to make turbine blades out of such a material. The study of directionally solidified NiAl-based multi-phase intermetallics is actively being pursued at ONERA and it is clear from the preceeding discussion that the emphasis should be placed on multi-phase material rather than the single-phase ones.

2.3. Titanium aluminides

In this category of intermetallics, there are three types of aluminides: Ti_3Al, TiAl and $TiAl_3$. Titanium aluminides and especially Ti_3Al are the ones which have been the subject of an extensive sustained effort during the past many years. Most of the research and development work on titanium aluminides has been carried out in the USA under Air Force contracts. The activity has been particularly intense on Ti_3Al and its origins can be traced back to the 1960's. The investigations on TiAl and $TiAl_3$ are much more recent. Most of the effort on such materials is motivated by advanced propulsion programmes and airframe structures for hypersonic vehicles.

2.3.1. Ti_3Al-based aluminides

The Ti_3Al intermetallic has an ordered hexagonal (or DO_{19}) structure. The stoichiometric compound has a density of 4.2g/cm^3 but when alloyed with other elements, it is closer to that of the titanium alloys (~4.7g/cm^3). Clearly, this type of intermetallic, the so-called α_2 phase which is the ordered form of the α (hexagonal) titanium phase, is much lighter than Ni_3Al and NiAl which have a density of 7.5 and 6 respectively. Ti_3Al-based alloys are not expected to provide any density advantage over the Ti-based alloys but they can extend the temperature capability of the currently used titanium alloys, which is about 600°C.

The two-phase alloys based on this compound have, compared to the conventional titanium alloys, higher strengths at elevated temperatures, higher elastic moduli and greater resistance to oxidation. Here again, the multi-phase microstructures lead to better overall properties compared to the single-phase material. However, the problem of relatively limited ductilities, low fracture toughness and impact resistance at lower temperatures is still of great concern. Another major problem area which has often been ignored is that extensive surface originated microcracking occurs during the plastic deformation of some Ti_3Al-based alloys in air around 600-700°C temperature range [13]. A protective coating would therefore be required for such alloys to be used around 650-700°C.

In order to produce a useful Ti_3Al-based material, it is necessary to achieve a microstructure which has a ductile second

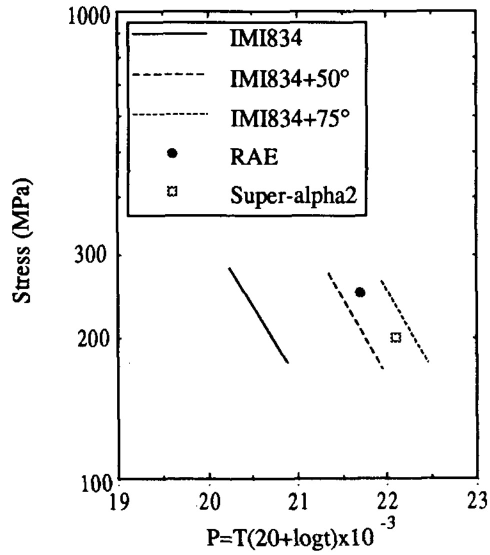

Figure 7. Larsen-Miller plot showing that the creep strength of the RAE alloys is similar to that of the TIMET Super α_2 alloy [14].

phase. This can be achieved by adding β-stabilizing elements to produce an α_2+β microstructure [14]; the β phase will provide the ductility.

The elements that can be added to titanium to produce a β phase are niobium, molybdenum and vanadium. Although the latter element may lead to interesting results in terms of ductility, the alloys are not acceptable due to a poor oxidation behaviour. Most developments are based on niobium, the latest versions being the TIMET (USA) "super α_2" alloys (Ti-25Al-10Nb-3V-1Mo (at.%) and the alloys under investigation at the Royal Aerospace Establishment (UK) [14] (Fig.7).

The balance of properties (creep, ductility, fracture toughness, tensile strength...) for use as engine components requires that the volume fraction of β phase be kept to a certain minimum. In general, elevated temperature strength, creep resistance and environmental resistance are improved by a high aluminium content, the presence of β stabilizers (in moderate amounts). The effect of composition on yield strength is illustrated in Fig.8. For a good room temperature ductility and fracture toughness, the aluminium content should be rather low and Nb additions should be favoured over Mo. Most importantly, the interstitial level and especially the oxygen content should be kept as low as possible: it has recently been shown that in an α_2+β processed alloy (Ti-25Al-14Nb) containing 250ppm of oxygen, up to 7% ductility and a tensile strength of over 1000MPa can be achieved at room temperature after the fully heat treated condition (1107°C/1h/S.Q.+ 815°C/30min/A.C.).

Morphologically, Ti_3Al-based alloys bear a strong resemblance to the conventional α+β titanium alloys and their response to heat treatments is also very similar. Various thermo-

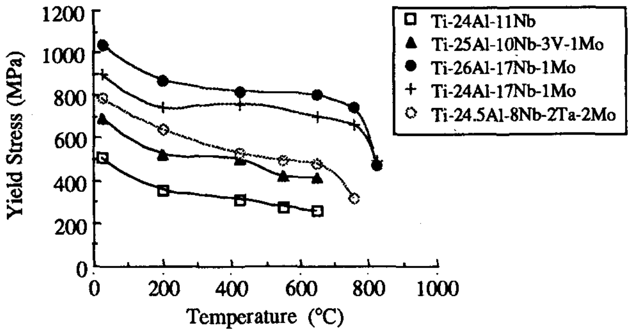

Figure 8. Effect of composition on the yield stress of α_2 alloys [15].

mechanical treatments and the cooling rates lead to a variety of microstructures and the mechanical properties depend both on the morphology and the volume fraction of the ductile β phase.

Although microstructures produced by heat treatments in the α_2+β phase region have recently been investigated because of their potential for increased room temperature ductility and toughness [15], - it is desirable to have a topological situation where the α_2 phase does not percolate - transformed β microstructures have been the most widely studied to date because they have been considered necessary to achieve the best balance of room temperature ductility and elevated temperature properties.

Some applications of Ti_3Al-based intermetallics are being considered in the USA both for static and rotating components. Examples are: exhaust seals, after burner nozzle seals and other non-fracture-critical components. Critical applications such as compressor and turbine casings, shrouds and support rings, compressor blades and vanes etc. will require improvements in both creep resistance and fracture toughness [16] (Table 2). It is clear that as yet, there is no commercially available alloy of the Ti_3Al-based intermetallic which has successfully combined the high temperature capability of the ordered intermetallic and an acceptable balance of properties to produce an engineered material. It is anticipated that

Table 2. Optimum Ti_3Al-Nb microstructure for various properties[16].

Mechanical Property	Magnitude of Microstructure Effect	Optimum microstructure
Tensile strength	Strong	Fine Widmanstatten
Tensile Ductility	Strong	Intermediate Widmanstatten α_2+β
Creep Resistance	Strong	Intermediate Widmanstatten β
Fatigue Crack Growth	Strong	Coarse Aligned Laths β
High Cycle Fatigue	Weak	Fine Widmanstatten α_2+β
Fracture Toughness	Unknown	Unknown

such alloys will first be used as non-critical static components before their use is extended to rotating parts. Further alloy development activities are necessary but a substantial effort should be focussed both on the processing parameters and the effect of interstitials. Methods such as plasma arc melting are being developed to process these intermetallics. Specifications will be needed to establish required purity levels for starting materials. Today, it is clear that a few years additional effort is necessary to produce a useful Ti_3Al-based alloy for critical structural applications in the temperature range 650-700°C.

2.3.2. TiAl-based aluminides

The TiAl-based alloys, developed up to now, contain 46 to 52 at.% of aluminium and can be divided into single phase γ alloys and two-phase γ+α_2 alloys. The γ TiAl has the ordered $L1_0$ structure. It remains ordered up to its melting point of about 1450°C and its density is 3.8g/cm^3.

The strength, the modulus and the oxidation resistance of such alloys are much higher than those of the Ti_3Al (α_2) type alloys. The single phase alloys are extremely brittle but the two-phase binary alloy Ti-48at.%Al shows a ductility of about 2%. A Japanese group from Kawasaki is the first to have evaluated the potential of Ti-48Al binary alloy for the manufacture of cast automotive turbocharger rotors [17]. This material has a specific strength superior to both Inconel 713 superalloy and the Si_3N_4 ceramic. Compared to the Ti_3Al intermetallic, the development of TiAl alloys is much more recent but the temperature potential of such alloys is up to about 950°C for structural applications. The major concerns regarding the mechanical properties are with respect to high fatigue crack growth rates (compared with superalloys for example), low fracture toughness and impact resistance at lower temperatures. Although the fracture toughness increases with increasing temperature, the values at room temperature for most of these alloys are in 12-15MPa·$m^{1/2}$ range. Creep resistance of TiAl-based alloys can be high but it strongly depends on alloy chemistry and the microstructure, as shown in Table 3. As a guide, the specific

Table 3. Mechanical properties of γ titanium aluminide alloys [19].

Alloy	RT strength (MPa) YS	UTS	El. (%) RT	800°C	BDT (°C)[a]	K_{IC} (MPam$^{1/2}$)	Creep life (hr) 815°C/103MPa 1%	Rupture
Ti-54Al	490		<1	10	700			
Ti-52Al	350		0.1-1.1	20	600			
Ti-50Al			1.8			7.7	111	602
Ti-48Al	390/520	483	0.3-2.1[b]	40	550		10	128
Ti-46Al	501	592	0.7				6	110
Ti-44Al	748	748	0.3				8	176
Ti-50Al-1V			1.3					
Ti-48Al-1V	400	507	2.3				27	398
Ti-48Al-1V-0.1C*	385	507	1.5			12.5	15[c]	198[c]
Ti-48Al-(1-3)V	520		1.5-3.5		550			
Ti-44Al-1V	754		0.6					
Ti-48Al-(1-2)Mn	500		1.5-3.5					
Ti-48Al-(1-3)Cr	520		1.5-3.5					
Ti-48Al-2W	547	616	1.3				75[d]	430[d]
Ti-48Al-(1-3)X (X=Nb, Ta, Hf)			<1.8					

a : Brittle-ductile transition temperature.
b : El.=2.7% for high purity (300ppm O_2).
c : 815°C/173MPa. d : 815°C/207MPa.
* : The impact resistance of Ti-48Al-1V-0.1C is 1.4 Joule.

creep strength of TiAl is compared with that of a titanium alloy, Ti_3Al and a well-known superalloy, often used in the hot compressor end section of some aeroengines (Fig.9).

One of the important problems in creep of some of these alloys seems to be a rather high primary creep strain and this aspect has often been ignored while comparing with superalloys. The time for 1% creep strain is usually very short, a factor of at least 6 lower compared to the rupture life. To improve the creep resistance, high aluminium content and/or the addition of refractory elements seems to be necessary but then the ductility is lowered. It is important to understand the origin of high primary creep observed in titanium aluminides on which no information exists in the literature.

Several alloying elements can be introduced to obtain a better overall balance of properties, and considerable research and development work is presently underway in the USA to improve both ductility and fracture toughness. Additions of V improve ductility to some extent but at the expense of oxidation resistance. Adding Mn enhances twinning [18] and also the ductility. It seems that the addition of Mn, Ta and Nb improves the room temperature ductility without substantially altering the yield strength [19,20]. The oxidation resistance can be apparently improved through additions of Ta and Nb.

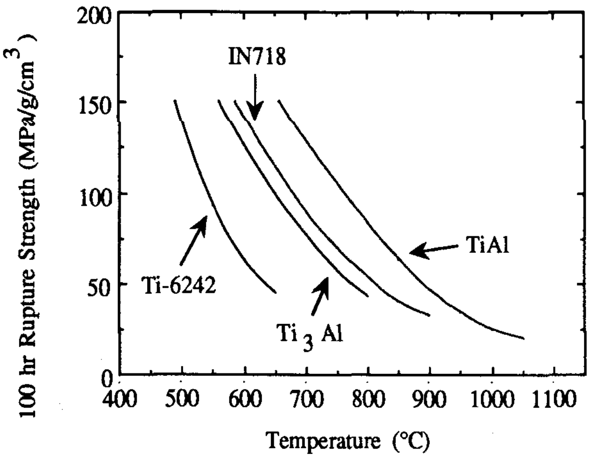

Figure 9. Variations of 100 hr specific rupture strength with test temperature for TiAl and other alloys [19].

These alloys can be processed both via ingot metallurgy and powder metallurgy routes. Thermomechanical processing of these alloys (isothermal forging or extrusion), which is the preferred route, is much more difficult than for Ti_3Al-based alloys because of their higher mechanical strength (hence poorer workability) at high temperatures. Hot working on TiAl alloys is usually performed at temperatures close to 1100°C. Some work indicates, however, that for large pieces much higher temperatures are necessary to obtain a sound product with a reasonably high strain rate [21].

A variety of microstructures can be obtained in the two-phase alloys (47-49at.%Al). Phase transformation studies in the two-phase region are important in order to facilitate processing and to understand ductility related problems. These alloys require two-step heat treatments [19], and the maximum ductility is apparently achieved with about 10% of α_2 phase.

To sum up, the TiAl-based alloys have considerable potential for high temperature structural applications but many problems have to be solved. Many more years of research and development effort are required on this intermetallic before it can be used in the hot section of turbine engines.

2.3.3. $TiAl_3$-based intermetallics

$TiAl_3$ is a compound which has a melting point of 1340°C. Its main interest lies in its very low density (3.37), which leads to very high specific elastic moduli, and yield strength, in addition to an excellent oxidation resistance.

But its extreme brittleness both in polycrystalline and single crystal forms has not yet been overcome; all attempts to reach a reasonable ductility either by alloying [22] or by changing the crystal structure to a higher symmetry (DO_{22} to cubic $L1_2$; our own work) have not proved to be successful.

2.4. Other intermetallics

In this section, we will briefly deal with much more speculative intermetallics which show potential for exceeding the performance of high temperature superalloys. This is obviously a very difficult challenge since none of the intermetallics that we have considered up to now is intended for applications much above 1000°C; a possible exception could be the NiAl-based alloys which have a potential up to 1050°C. Besides, it should be remembered that in the case of turbine blades, the ability of superalloys to sustain high-temperature stresses has permitted the successful use of cooled blades, where the maximum metal temperature is only 950-1050°C while the gas temperature is 1450°C. The cooled configuration is not likely to be applicable to intermetallics, which would then be required to retain mechanical properties up to approximately 1500°C. Otherwise, they would only be of interest if uncooled blade design is preferred (small site aero-engines for instance).

Judicious screening tests are essential for identifying potentially interesting intermetallics. In addition of the problems related to the lack of low temperature ductility and the low level of fracture toughness, which are a general concern in the case of intermetallics, the oxidation resistance is important for many high temperature applications and therefore special considerations should be given to those systems which have a high content in aluminium, chromium and silicon in the hope of obtaining protective scales. The choice of the crystal structure is important both for obtaining some plasticity and for achieving two-phase alloys. In general, high symmetry structures offer a better hope for obtaining reasonable ductility and therefore attention should be focussed on them.

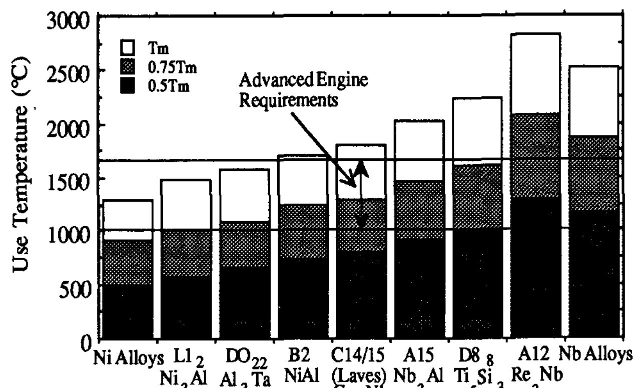

Figure 10. A representation of the temperature capabilities of intermetallic compounds with various types of crystal structures [23].

To achieve useful strengths in the temperature range 1000-1600°C, high melting points are required. Assuming that most materials retain a significant strength up to 0.5-0.6 of their melting

Table 4. Classification of high-temperature intermetallic compounds [23].

Stoichiometry	Crystal Structure	Groupe Name	Example	Melting Point (°C)	Density (g/cm^3)
A_3B	$L1_2$		Ni_3Al	1397	7.41
			Pt_3Al	1556	17.47
	DO_{19}		Ti_3Sn	1670	5.29
	DO_{22}		Ni_3Ta	1547	11.8
			Al_3Nb	1607	4.52
			Al_3Ta	1550	6.9
	A15		Nb_3Al	1960	7.29
			Mo_3Si	2025	8.97
			V_3Si	1925	6.47
			Cr_3Si	1770	6.46
	A12	α-Mn	Re_3Nb	2700	17.6
A_2B	C1		$CoSi_2$	1326	4.98
	$C11_b$		$MoSi_2$	2030	6.31
	C14	Laves phases	Cr_2Hf	1870	10.24
			Cr_2Nb	1720	7.68
	C15	Laves phases	W_2Hf	2512	-
			Co_2Nb	1520	9.0
			Co_2Zr	1560	8.23
			Fe_2Zr	1645	7.69
	C36	Laves phases	Mo_2Hf	2170	11.4
	$D8_b$	σ phases	Nb_2Al	1871	6.87
A_5B_3	$D8_m$		Mo_5Si_3	2180	8.2
	$D8_8$		Ti_5Si_3	2130	4.38
A_7B_6	$D8_5$	μ Phases	Nb_6Fe_7	1620	-
			W_6Co_7	1689	-
AB	B2		NiAl	1640	5.88
			CoHf	1640	12.5

temperature, one can think of evaluating intermetallics with melting points (T_m) in the temperature range 1600-2700°C. The temperature capabilities of some intermetallics with various crystal structures (including low symmetry structures)are shown in Fig.10. and they are compared to the Ni-base and Nb alloys.

After extensive literature survey and based on some pertinent selection criteria, Anton et al.[23] propose a list of potentially useful compounds shown in Table 4. This list provides an indication about the compounds on which further work should be pursued. Based on the various studies conducted at different laboratories, it is highly improbable that a simple binary compound will satisfy the balance of properties required for many industrial applications.

3. Intermetallic Matrix-based Composites (IMC's)

Due to the inherent brittleness and low fracture toughness of intermetallic compounds, the reinforcement of such materials with strong fibres and/or hard refractory particles is being considered. Such composite materials offer a considerable potential for various future aerospace applications, since both the temperature capability and the specific strength and moduli can be substantially increased. Depending upon the application, both the fibre-reinforced and the particulate composites are of interest.

Although investigations are underway on many different IMC's, we will only briefly deal with titanium aluminide composites. It has been shown that the use of a titanium aluminide matrix offers a significant improvement in strength over the monolithic materials [24]. The specific strength of a Ti_3Al-based composite reinforced with 33vol.% of SiC fibres is compared with that of a number of other alloys in Fig.11.

One of the basic problems in producing titanium aluminide composites is to incorporate fibres (SiC, TiB_2) into the matrix while avoiding chemical reaction at the fibre-matrix interface. The conventional method for fabricating the composite is to lay fibres between sheets of the intermetallic matrix, followed by hot pressing. The metal flows between the fibres ensuring bonding and the end component is a sandwich structure. However, this sheet-fibre-sheet sandwich, in spite of some recent success obtained by Texas Instruments in manufacturing Ti_3Al sheets through a hot-rolling process (TIGERR), does not seem to be very attractive partly because of the difficulties encountered in making sheets from the intermetallics. The titanium aluminides have poor formability

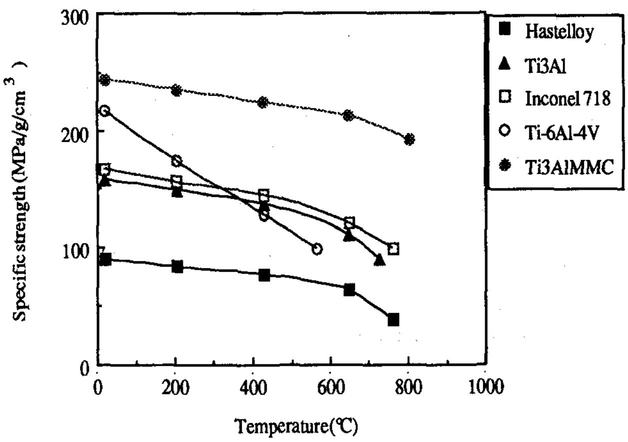

Figure 11. Variations of specific yield strength with temperature for a Ti_3Al-based composite and other alloys [24].

characteristics, they interact with the fibres during consolidation at high temperatures and there is a thermal expansion mismatch between the fibres and the matrix. Cracking occurs in the matrix during cooling or during thermal cycling.

An alternative approach for consolidation has been developed at General Electric using a rapid solidification plasma deposition. In this case, the matrix material is a powder which is fed through a plasma arc to melt it. The molten droplets are immediately deposited onto fibres that are wrapped on a drum inside a vacuum chamber where they are rapidly quenched to a solid state. By

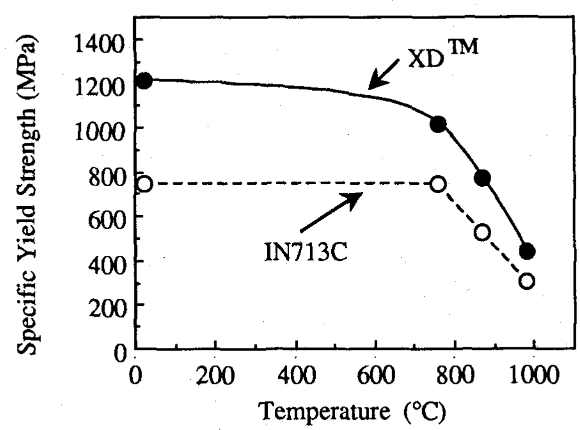

Figure 12. Variations of specific yield strength with temperature for the XD™ Ti-48Al-2V+7 vol%TiB_2 alloy and the IN713C superalloy.

rotating and translating the drum, one can obtain a "monotape" of matrix material between and on the fibres. After stripping off the drum and hot pressing, one can obtain a multilayer Ti_3Al-based composite reinforced with SiC fibres. Attempts are underway to adapt the process for making TiAl composites which are more difficult to produce but it seems that the chances are better with this approach compared with the sheet-fibre-sheet technique.

Fibres other than SiC are being tried, such as TiB_2 and TiC. These fibres have a better thermal expansion match and they are expected to have a better chemical compatibility than the SiC fibres at the high temperatures required for consolidation.

Another promising process for manufacturing titanium aluminide composites is the so-called XD process (Exothermic Dispersion). This process was developed by Martin Marietta Research Laboratories. It produces a material containing a fine dispersion of a second phase, typically TiB_2. Fig.12 shows that the TiAl reinforced with 7vol.% of TiB_2 results in a significantly higher yield strength of this material compared to the IN713 superalloy, up to about 980°C. However, the room temperature ductility is about 1% and the fracture toughness does not exceed $15MPa{\cdot}m^{1/2}$. The creep properties at 760°C for various TiAl-based composites are shown in Table 5 [25]. The interesting part of this process is that a large variety of dispersions, ranging from spherical to long needles, can be produced in-situ with a clean and well-bonded interface. The composite material can be worked into various product forms and the process has been scaled up to 115kg ingots.

Table 5. Constant stress creep data on XD_{TM} TiAl alloys [25]. Material tested at 760°C.

Alloy (atomic %)	σ (ksi)	t to 1%	ε_{min} (hrs.$^{-1}$)	Test length	Elong. Termin. (%)
Ti-45Al+TiB_2 (H.T.)	10	308	$3x10^{-5}$	352	1.1
Ti-45Al+TiB_2	10	114	$4x10^{-5}$	128	1.1
Ti-45Al+TiB_2	15	45	$1x10^{-4}$	49	1.1
Ti-45Al-2V+TiB_2	10	79	$1x10^{-4}$	92	1.1
Ti-45Al+TiN+TiB_2	10	1750	$2x10^{-6}$	1850	1.02
Ti-45Al-2V+TiB_2 (H.T.)	15	≈ 287	≈ $3x10^{-5}$	≈ 317	1.1

4. Conclusions and Future Prospects

The intermetallic compounds have a considerable potential for future aerospace applications and possibly for some ground based applications. Up to now, the major problems with virtually all intermetallics of practical interest are their low ductility, inadequate fracture toughness and low impact resistance. Although the major emphasis in terms of research and development has been on the aluminides, some other well selected intermetallics must also be considered for very high temperature applications.

It seems quite clear that single-phase intermetallic compounds will not be satisfactory to achieve an overall balance of properties required for most structural applications. Therefore, the research and development effort must be primarily focussed on multi-phase intermetallic or composite materials.

Recent research at ONERA has shown that it is possible to produce multi-phase microstructures in a number of materials comprising a ductile matrix and a high volume fraction of an intermetallic phase. One such example obtained at ONERA is shown in Fig.13 in which a "compatible" intermetallic phase could be incorporated in an iron matrix. As opposed to the conventional synthetic composites, the multi-phase material approach is based on producing a coherent or semi-coherent second phase (or phases) which is a consequence of phase transformations. This type of approach is inspired by the γ-γ' microstructure obtained in superalloys and has the advantage of producing a multi-phase microstructure where there is a "compatibility" between the different phases.

For a successful development of these "alternative" intermetallic materials, it is highly desirable that a closer relationship be established with the potential users in order to identify their needs and requirements. A multidisciplinary approach has now become necessary for the development of an industrially useful material. It is indeed important to create a strong interaction between the "alloy developers" (who must take into account the composition, microstructures and the fabrication route) and the designers who have the task of incorporating the new material as a component.

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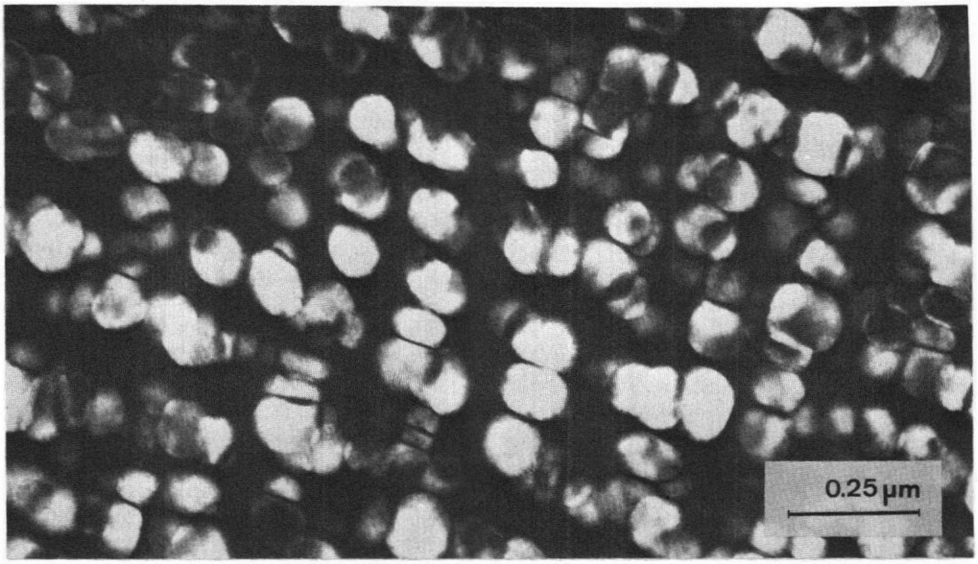

Figure 13. Microstructure observed in an iron base alloy containing a "compatible" intermetallic phase.