PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Multiphase Intermetallics [and Discussion]

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Multiphase intermetallics

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Ordered intermetallic compounds, notably the aluminides of nickel, titanium, iron and niobium, have been under intensive investigation for the past two decades as prospective load-bearing materials for high temperatures, with special emphasis on aerospace applications. The stronger of these phases are all catastrophically brittle at and near ambient temperature and this difficulty has proved obdurate. A promising solution appears to be to alloy such phases in such a way that the result is a two-phase or multiphase material. The extra phases may be disordered and intrinsically ductile: the presence of such phases lowers the high-temperature strength but is apt to enhance the plastic deformability of the material even at ambient temperature. There are also instances of multiphase alloys in which all the phases are ordered intermetallics, some stronger and more brittle, others weaker and more ductile, and the end-result can be a promising combination of strength and ductility, as well as good creep resistance.

1. Introduction

An intermetallic, an abbreviated term which has come into universal use, is an ordered compound between two or more metals, in simple numerical atomic proportions. Intermetallics fall into two large families: weakly ordered ('reversible') ones like Cu_3Au or CuZn which become disordered on heating before they melt, and strongly ordered ('permanent') ones like NiAl, TiAl or Nb_3Al which remain ordered up to the melting temperature. The physical features of such phases, and the ordering transformation, have been investigated since the 1930s, but mechanical properties and their relation to microstructure have only been studied since the 1950s; at first, reversibly ordered phases were examined so that ordered and disordered states of the same compound could be compared, then attention shifted to permanently ordered ones, the aluminides of nickel, titanium, iron and niobium in particular. This latter kind of research became intensive in the mid-1970s and nowadays is probably the most active branch of physical metallurgy. The motive force for this great flood of research has been the hope that certain permanently ordered intermetallics might become prime contenders for high-temperature structural applications, in jet engines in particular, with a view to raising service temperatures and reducing weight. This kind of application is my main concern in this paper: it requires a high creep resistance at temperatures well above 700 °C with reasonable resistance to brittle failure at ambient temperature.

Westbrook (1993), who has worked on intermetallics since the 1950s, has published a systematic account of the history of these researches in the context of

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their times. The complex crystal chemistry of intermetallics has been surveyed by Ferro & Saccone (1993). A good account of the early studies of the plastic behaviour of intermetallics was published by Lawley (1967). Among the numerous overviews of recent researches on the mechanical behaviour of potentially usable, permanently ordered intermetallics, the following can be recommended as being particularly informative: the single articles by Fleischer *et al.* (1989), Yamaguchi & Umakoshi (1990), George *et al.* (1994) and Sauthoff (1995); the multiauthor compilations by Liu *et al.* (1992) and Fleischer & Westbrook (1994); and the conference proceedings in which Westbrook's (1993) paper appears. Fleischer & Westbrook's recent two-volume work is the most comprehensive, while Sauthoff's book chapter is the most thorough overview by a single author or group of authors. All of these treatments cover a wide range of intermetallics; there are many others that focus on particular families of compounds, such as the titanium aluminides, and there are also numerous conference proceedings from 1985 onwards, several of which (e.g. Whang *et al.* 1990; Izumi 1991) contain important overview papers. A fine critical survey, by a panel of experts, of current scientific issues in connection with the mechanical behaviour of intermetallics has been published by Yoo *et al.* (1993).

As a broad generalization, it is safe to say that the strength and also the resistance to high-temperature creep of intermetallics increases as the ordering energy increases. This quantity is a measure of the energy required to destroy the long-range order and replace it by a random distribution of atoms on the lattice. The reversible intermetallics all *ipso facto* have small ordering energies; FeAl, Ti_3Al and the very important Ni_3Al phase have intermediate ordering energies; phases such as NiAl, TiAl and Nb_3Al have high ordering energies. At the same time (and subject to complications arising from environmental effects), the brittleness, especially at ambient temperatures, increases in line with the ordering energies, and a great deal of recent research has been addressed to this problem, as it affects NiAl and TiAl in particular. This paper focuses on one promising approach for moderating the brittleness of strongly ordered intermetallics, which is the replacement of single-phase (also called 'monolithic') intermetallics by multiphase alloys.

2. Some practically important intermetallic phases

I shall emphasize two phases: Ni_3Al and NiAl. The first of these has received more attention than any other intermetallic, though its intrinsic importance for aerospace uses is now seen to be slight; NiAl has recently moved to the top of the agenda as a possible base intermetallic for jet engine blades and discs, while TiAl is seen as increasingly promising for other jet engine components and possibly for discs; it is also under development for automotive 'supercharger' turbine blades. Iron aluminides, though they have received much attention, are not strongly enough ordered to be of interest for jet engine temperatures and they are primarily targeted at terrestrial uses at modest temperatures, while the niobium aluminides, (with or without titanium added) though very strongly ordered and recently much studied, have not yet reached the stage at which their promise can be reliably assessed (see brief overviews by George *et al.* (1994) and Dimiduk *et al.* (1993)). TiAl, possibly the most important phase in present estimation, is briefly treated in a separate section.

Ni_3Al This cubic phase, with $L1_2$ structure, is the ordered component of conventional superalloys (see McLean's paper in this collection): such superalloys consist principally of an oriented, coherent and stable dispersion of Ni_3Al cuboids in a disordered matrix of almost the same lattice parameter. Ni_3Al has the striking property of a yield stress that rises with increasing temperature up to about 650 °C (the anomalous yield point effect). This important characteristic has been the subject of a great deal of theory based on dislocation dynamics, and while the general outlines of an interpretation are agreed, details are still being vigorously debated. Experimental facts are set out in a general survey of the properties of Ni_3Al (Stoloff 1989) while the development of theoretical models is mapped out by Yamaguchi & Umakoshi (1990). A very clear early joint survey of both experimental and theoretical aspects of anomalous yield was published by two of the principal investigators in this field, Pope & Ezz (1984).

There are several other important aspects of this phase. Single crystals have long been known to be be ductile, but polycrystals were perceived as intrinsically brittle until in 1978, in a study which has become a classic, Aoki & Izumi in Japan discovered that doping with small amounts of boron, which segregates to grain boundaries, can confer ductility on Ni_3Al polycrystals; later it was found that this benefit only obtains when there is a little more nickel than corresponds to stoichiometry. The origin of this ductilizing effect, and the related question whether grain boundaries in the pure compound are *intrinsically brittle*, has generated a huge literature, which is excellently summarised in the review by George *et al.* (1994). George *et al.* (1993), as part of an extensive research on environmental effects, found a way of making wholly uncracked Ni_3Al polycrystals and were able to prove that these were highly ductile in a high vacuum, but if moisture was present at a partial pressure of as little as a millionth of an atmosphere, atomic hydrogen was generated by seepage along grain boundaries and reaction with Al, which embrittles the grain boundaries. (This phenomenon of environmental embrittlement was found by Liu to be common to several intermetallics). Substantial chromium additions overcome the problem. Alloying with iron reduces the ordering energy and enhances the ductility (Horton *et al.* 1987); in fact, Flinn took out a patent as long ago as 1962 for a Ni_3Al alloy ductilized by iron (Flinn 1962).

The upshot of all this is that with proper precautions, Ni_3Al is intrinsically ductile in both single crystal and polycrystalline form. Its intrinsic strength as a single phase is insufficient for most uses beyond about 600 °C, though as remarked it is the crucial constituent in (always multiphase) superalloys. A family of advanced nickel aluminides was developed by Liu and his colleagues in the early 1980s by alloying the binary phase with Cr, Fe and small amounts of several other metals. These are stronger, as well as being reasonably ductile; they have found several applications, including use in fuselage fasteners in aircraft. The real value of Ni_3Al will probably be recognised as residing in its potential for conferring some ductility on other, stronger phases.

NiAl This very strongly ordered cubic phase (the *virtual* critical temperature for disordering, far above the melting temperature, has been estimated as being above 4000 °C), with the simple B2 structure, has excellent high-temperature strength and a considerably lower density than both Ni_3Al and superalloys, and so (after many years of mild academic concern) it has received an unparalleled measure of attention during the last decade, especially since the late 1980s. The

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outcome of this research has been collected in an outstanding review by Miracle (1993), which incorporates 337 literature citations. While strong, light, oxidation-resistant and with good creep resistance and outstanding heat conductivity, the phase is extremely brittle at and some way above ambient temperature. Much of the recent research has addressed this recalcitrant problem. Darolia in America has been the industrial leader in this research; his large team at GE's engine factory has aimed directly at the production of *single-crystal* gas-turbine blades, as set forth in a very informative overview (Darolia *et al.* 1992). Single-crystal applications are immune from the generalization that multiphase alloys are to be preferred to single-phase ones.

Single crystals of favourable orientations show some ductility even at room temperature, and this ductility is considerably enhanced by small (*ca.* 0.1 at%) alloying additions of Fe, Mo or Ga; at larger solute contents the benefit disappears. The preferred interpretation of this at present is that the solute acts as a scavenger of unintended, embrittling interstitial solutes.

Polycrystalline NiAl in general is brittle, but in an important study, Hahn & Vedula (1989) discovered that very close to stoichiometry only, some 2% of tensile ductility can be achieved even at ambient temperature; the reasons remain mysterious. One tentative suggestion is that interstitial solute content is apt to be smaller for the stoichiometric alloy, and interstitials have also been adduced to account for indications that brittleness can be reduced by low-temperature heat-treatment. The normal brittleness of the polycrystalline alloy is attributed to the prevalence of ⟨100⟩ slip vectors, which imply that insufficient independent slip systems are available to enable individual grains to follow an externally imposed shape change; sustained attempts to alter the preferred slip vector by alloying have been unsuccessful. ⟨111⟩ slip is possible but suffers from a very high critical shear stress; it is not clear whether the problem is one of a lack of dislocation sources with this geometry or whether the Peierls–Nabarro stress for dislocation propagation is very high. Grain sizes below 20 μm also create some ductility.

Cotton *et al.* (1993*a*, *b*) have systematically studied the effect of various solutes on the behaviour of NiAl; substantial further hardening was found for some solutes, but no ductilization.

In the next section, various efforts to alleviate the brittleness of NiAl by introducing other, less brittle, phases will be outlined.

3. Multiphase alloys: generalities

Apart from the brittleness problem, there is a further crucial reason for preferring the multiphase version of an intermetallic to the monolithic (single-phase) form. When the microstructure is right, the creep resistance of the multiphase form (and this is what matters most in jet engine applications) is much better than that of the monolith. This is, after all, why the standard γ/γ' superalloy structure has held its own for so many years. The essential microstructural feature is the stable dispersion of small ordered γ' particles in an epitaxial relationship to a disordered γ matrix; dislocations are restricted to the narrow matrix channels between the particles. Naka *et al.* (1992) demonstrated the superiority of such a microstructure very clearly with the measurements in figure 1, taken from their paper. A 'single crystal' of an advanced superalloy, CMSX-2 (consisting actually of a single orientation of disordered matrix with a dispersion of γ' particles all in

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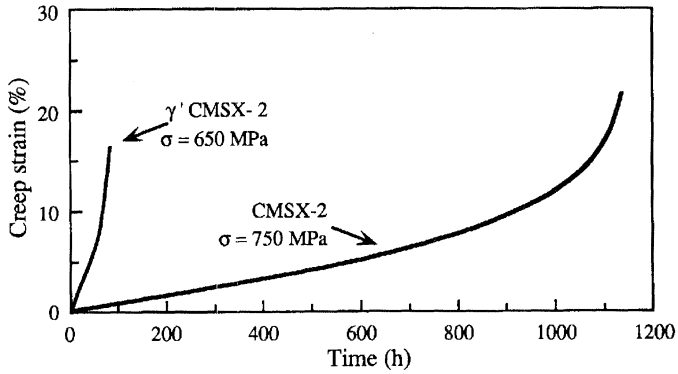

Figure 1. Creep curves at 760 °C for [001]-oriented single-phase CMSX-2 and two-phase γ'/CMSX-2 single crystals. After Naka *et al.* (1992).

parallel orientation) is compared in creep with another crystal consisting of monolithic γ', at 760 °C. Although the stress acting on the superalloy crystal is 15% higher, yet its creep rate is much lower than that of the monolithic γ' crystal. (The tensile strengths of the two crystals at the same temperature are virtually identical.) In their investigation, Naka *et al.* go on to examine other, novel alloy systems which have similar microstructures (dependent on having almost the same lattice parameter for the two epitaxial phases), but use a (disordered) body-centred cubic matrix instead of the usual face-centred cubic one. They obtained interesting high-temperature properties for Fe–Ni_2AlTi and Nb(+Cr)–Ti_2AlMo alloys which possess this type of microstructure. This paper deserves careful study.

In a very recent paper, entitled 'The superiority of superalloys', Nabarro (1994) makes essentially the same point, though his argument is centred on TiAl–Ti_3Al alloys, which are to be discussed below. He cites an excellent paper (Nathal *et al.* 1989) which presents extensive evidence for Ni-base alloys along the same lines as that in figure 1. In his paper, he discusses at some length the deformation mechanisms which confer upon superalloys their exceptional creep resistance.

The general point can be made, in the light of Naka's and Nabarro's arguments, that the strategy of replacing monolithic by multiphase alloys does not necessarily entail a sacrifice of high-temperature creep resistance for the prize of enhanced room-temperature ductility. It is quite possible in principle to design alloys which combine both these benefits. One might object that the end-result of many years' research on intermetallics might then merely be a renewed emphasis on two-phase (disordered + ordered) alloys; the chemistry but not the microstructural principle would change from traditional superalloys. This is not necessarily so: as we shall see in the next section, improved alloys can consist of two or more ordered intermetallic phases, or of two ordered intermetallic phases plus one disordered phase. Indeed, most such alloys have an *ordered* (*o*) *matrix*; if such a matrix were associated with a disordered (d) epitaxial dispersoid, the result would be a mirror-image of a traditional superalloy, but quite generally, it is appropriate to regard an alloy with an ordered matrix as an intermetallic.

4. Multiphase alloys based on NiAl

No one has yet made a multiphase alloy with a NiAl matrix combined with a parallel epitaxial dispersion of another phase, but several alloys with other kinds

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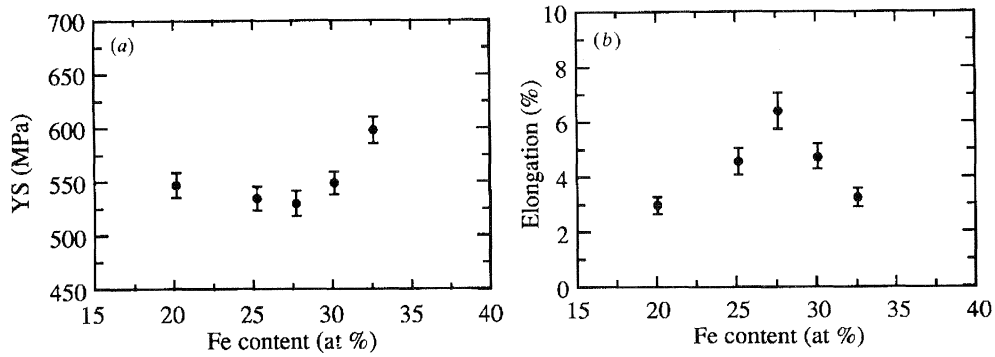

Figure 2. Plots of (*a*) yield stress and (*b*) elongation as a function of iron content for Ni(Al,Fe) alloys. After Tsau *et al.* (1992).

of epitaxy have been reported. Numerous metallurgists have examined multiphase alloys based on a major NiAl constituent, and some of them have most interesting properties—good strength combined with some ductility at ambient temperature. Few creep tests have been done as yet. The alloys examined hitherto fall into the following categories: (1) $\beta+\gamma'$; (2) $\beta+\gamma+\gamma'$; (3) $\beta+\beta'$; (4) $\beta+\beta'+\gamma'$. Here β represents (o) NiAl, γ represents a (d) FCC phase, γ' represents an (o) Ni_3Al-type phase, and β' represents an (o) Heusler phase such as Ni_2AlTi. Here there is space to mention only a few of the studies published in recent years.

(1) $\beta+\gamma'$ and (2) $\beta+\gamma+\gamma'$. If some of the aluminium in NiAl is replaced by iron, the alloy can have one or other of these phase structures, according to the iron content. Emphasis has been on Ni–20 at%Al–30 at%Fe, which consists of roughly equal amounts of rather finely divided β and $(\gamma+\gamma')$, the latter being a dispersion of minute γ' particles in a disordered matrix; there is some disagreement between investigators concerning the amount of disordered γ in this alloy, and this may depend upon details of heat treatment. The most detailed and recent study is by Guha *et al.* (1991). They compared the Ni–20Al–30Fe alloy with Ni–30Al–20Fe and with Ni–12Al–40Fe. The first had an ambient yield strength of 850 MPa (compared with a typical value of 250–450 MPa for pure polycrystalline NiAl) with up to 20% elongation; the second (an almost single-phase β alloy) had 800 MPa but only 2% elongation; the third (very like a normal γ/γ' superalloy) had 500 MPa and 28% elongation.

Figure 2 shows yield strength and elongation values measured for similar alloys by Tsau *et al.* (1992). They agree with Guha *et al.* in observing maximum elongation near 30 at% Al, but find lower yield stresses. The latter clearly depend upon the processing: Guha's alloys had been extruded, Tsau's were in cast form. These various alloys, incidentally, contain considerably more iron than Flinn's early patented alloys.

An earlier study (Pank *et al.* 1990) focused on $(\gamma+\gamma')$ alloys made by replacing Al in NiAl with 8–9 at%Co. Their alloys contain 'necklaces' of γ' surrounding the β grains and these alloys had 3–4% of elongation at room temperature. This kind of necklace structure is clearly not as effective as the more intimate phase mixture of the Ni–Al–Fe alloys.

Gibala and his collaborators have made important contributions to an understanding of how the extra phases in Ni–Al–Fe alloys are able to ductilize the alloys. Two important papers (Noebe *et al.* 1990; Misra *et al.* 1991) start from

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research done in the 1970s in Gibala's laboratory on the enhancement of ductility of BCC metals by the use of surface films and also by preparing BCC and FCC two-phase alloys. They are among the very few who have examined Ni–Al alloys between 25 and 50 at% Al: they directionally solidified ($\beta + \gamma'$) $Ni_{70}Al_{30}$ and $Ni_{60}Al_{40}$ alloys and obtained up to 10% elongation as well as substantial strength rising with temperature to 600 °C, the best qualities of the two phases combined. They showed that the β phase contains many more dislocations than in single-phase β because of injection of dislocations from the γ' phase. Similar enhancement of dislocation populations in the β phase in $Ni_{50}Al_{30}Fe_{20}$ was also observed. Likewise, oxide surface films on single-phase NiAl crystals injected additional mobile dislocations into the bulk. This injection was recognized to be facilitated in the Ni–Al–Fe alloy because the β and $(\gamma + \gamma')$ phase fields were mutually oriented according to the Kurdyumov–Sachs relationship and this caused the glide planes in adjacent phase fields to be virtually parallel. Finally, the fine dispersion of γ' in the $(\gamma + \gamma')$ phase field served to arrest cracks originating from the β phase. (Guha *et al.* had also shown this.)

There is one other remarkable study of the behaviour of multiphase Ni–Al–Fe alloys, this time with Fe contents between 50 and 85 at%Fe. Jung & Sauthoff (1989) examined creep in alloys containing various Ni/Al/Fe proportions. Some of these were single-phase β (B2), others had either an α-iron matrix with β precipitates or else a β matrix with almost pure α-iron precipitates. An alloy of the latter kind was compared with a single-phase β alloy of the same composition as the matrix in the two-phase alloy (an interpolation method was used to make the comparison). The creep resistance of the $(\beta + \alpha)$ alloy was higher than that of the single-phase β alloy, even though the α-iron precipitates were much softer than the β phase! The two-phase alloy was found to possess a threshold stress for creep: this threshold was successfully interpreted in terms of a model according to which the dislocation energy of a climbing matrix dislocation near the particle is reduced in the matrix–particle interface because of relaxation processes in the interface. This implies that the dislocation is attracted by the particle, and the overcoming of this attraction results in the threshold stress. Thus a soft disordered phase can enhance the creep resistance of an intermetallic matrix.

Generally, creep of intermetallics, especially multiphase alloys, has had rather less than the degree of attention it merits, and a recent critical overview of the theme by Sauthoff (1993) is therefore particularly welcome.

(3) $(\beta + \beta')$ and (4) $(\beta + \beta + \gamma')$. Many years ago, Polvani *et al.* (1976*a*, *b*) discovered what was in effect a superalloy based on a BCC lattice, but with both matrix and dispersoid in the form of ordered intermetallics, in the Ni–Al–Ti system. The matrix was β, that is, Ni(Al,Ti), while the dispersoid consisted of the strongly ordered Heusler phase, Ni_2AlTi, also denoted β', which has the $L2_1$ structure. The high-temperature creep resistance of the dispersion was much greater than that of either constituent in single-phase form, consistently with the generalization made later by Nathal, Naka and Nabarro (quoted above). However, the alloy was hyperbrittle and development was soon aborted.

Recently, Yang *et al.* (1991, 1992*a*, *b*†) embarked on an alloy development pro-

† A very recent study related to Yang *et al.* (1992*b*) by Hsiung & Bhadeshia (1995) has shown that the ductility of these alloys can be further improved by extruding mixtures of the three single-phase powders.

gramme, based upon the hypothesis that the incorporation of a third, weaker and more ductile intermetallic phase, the γ' phase based on Ni_3Al, might serve to ductilize the $(\beta + \beta')$Ni–Al–Ti alloy without weakening it much. (Small amounts of quaternary additions (B or Cr or Fe) were also tried.) Figure 3*a* shows the three-phase $(\beta + \beta' + \gamma')$ field at 900 °C as determined in the 1992*a* paper, while figure 3*b* shows the room-temperature stress–strain characteristics in compression, compared with the unimproved $(\beta + \beta')$ alloys, and with a 'state-of-the-art' disc superalloy, U 720. The combination of strength and moderate ductility of the three-phase alloys, one of the most effective to be made up entirely of intermetallic phases, is clear. Several of the three-phase alloys proved to remain stronger than the U 720 up to about 650 °C (the anomalous yield characteristic of γ' helped in bringing this about). Figure 4 shows an example of the three-phase microstructure: this one has a β' matrix with β dispersoid; other alloys, nearer the NiAl corner of the three-phase triangle, have a β matrix with β' dispersoid. The β and β' are in parallel epitaxy, while the γ' is in Nishiyama–Wassermann orientation relationship with the matrix; this is not very different from the Kurdyumov–Sachs relationship found by Gibala's team in Ni–Al–Fe alloys. Microstructural analysis showed two things: dislocations were injected from the γ' into the β or β' phase, helped by a favourable orientation relationship (figure 5), and dislocations were more mobile in the very hard β' phase when it was in the form of a fine dispersoid than in the massive β' phase. No tensile or creep tests have as yet been performed.

The studies on the various Ni–Al–Fe and on Ni–Al–Ti alloys together make it clear that the strategy of marrying strong and brittle intermetallics with weaker and more ductile phases, in an intimate phase mixture to combine high-temperature strength with reasonable ambient ductility, works effectively. The Jung & Sauthoff paper suggests also that this strategy can be effective in enhancing creep resistance.

5. Multiphase alloys based on TiAl

Three titanium aluminides, all non-cubic, have all been intensively examined in recent years: Ti_3Al (reversibly ordered), TiAl and $TiAl_3$ (both permanently ordered). The view has gradually gained ground that alloys based on TiAl have the best overall prospects. In the very limited space available, it is only possible to make a few short comments on the multiphase aspects of TiAl.

TiAl has the $L1_0$ structure characteristic of CuAu. If the Al content is reduced slightly below 50 at%, then a two-phase structure including the hexagonal phase, Ti_3Al results. Such an alloy can either form a lamellar ('polysynthetic') structure, in which the two phases are in epitaxy within each grain, or by different heat treatments the alloy can be turned into a divorced, 'equiaxed' form. Other heat treatments can produce an intermediate structure. Grain size can also be varied within wide limits. The balance of ductility, toughness, strength and creep resistance varies according to the microstructure type, and recent researches have examined these trade-offs in great detail; thus, lamellar microstructures have better creep resistance and also higher toughness than equiaxed ones, in spite of having a lesser ductility. Dislocation 'injection' does not seem to have been specifically examined. The most recent concise survey is in George *et al.* (1994). An excellent survey of the effect of processing, and especially of heat-treatment,

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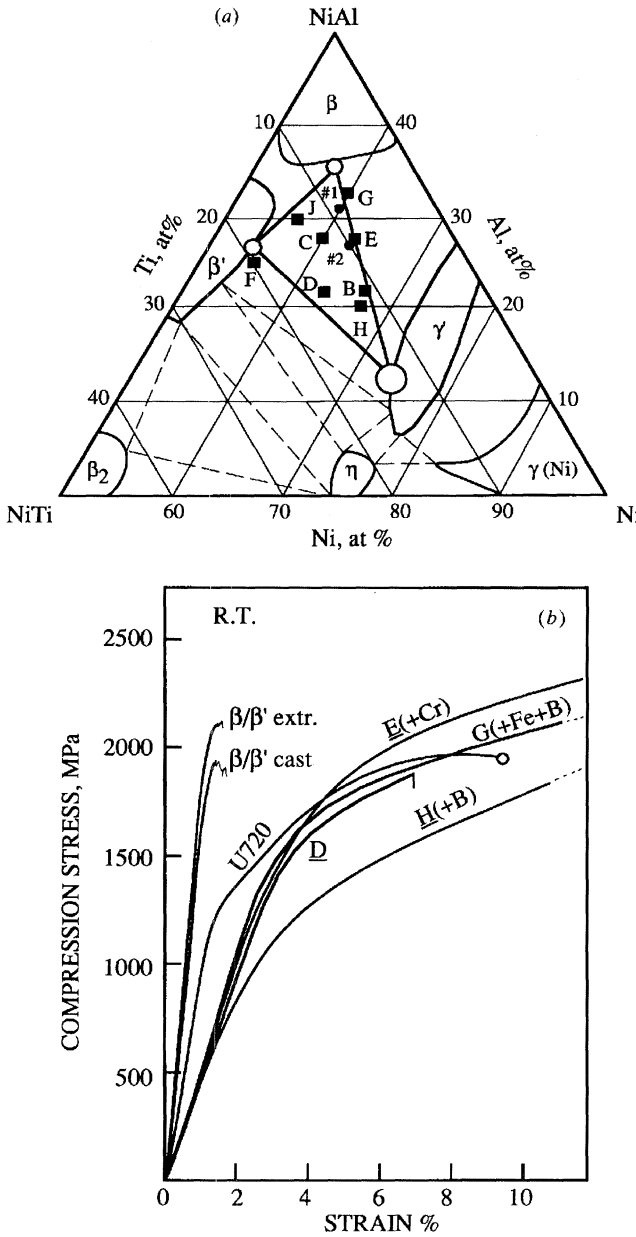

Figure 3. (*a*) The three-phase ($\beta + \beta' + \gamma'$) field in the Ni–Al–Ti system at 900 °C; the circles represent estimates of experimental inaccuracy in locating the corners of the three-phase triangle. Compositions of alloys examined are shown. After Yang *et al.* (1992*a*). (*b*) Compressive stress–strain curves at room temperature for several Ni–Al–Ti alloys, binary and ternary, and of a commercial superalloy (U 720). Some of the alloys contain small quaternary additions of other elements. After Yang *et al.* (1992*b*).

on the microstructureof (TiAl + Ti_3Al) alloys is by Martin *et al.* (1993), while a paper by Yamaguchi & Inui (1953) focuses on properties. Nabarro (1994) has examined in detail the ways in which TiAl–Ti_3Al alloys resemble conventional

Figure 4

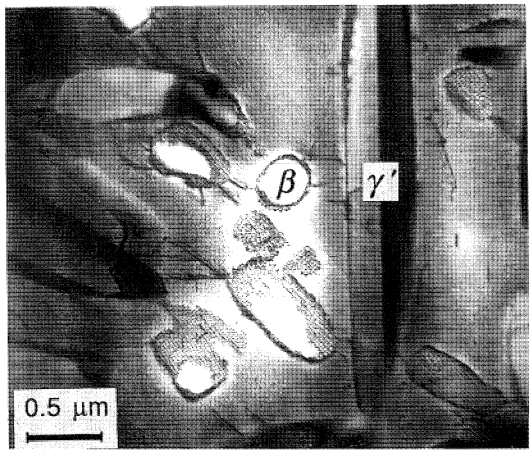

Figure 5

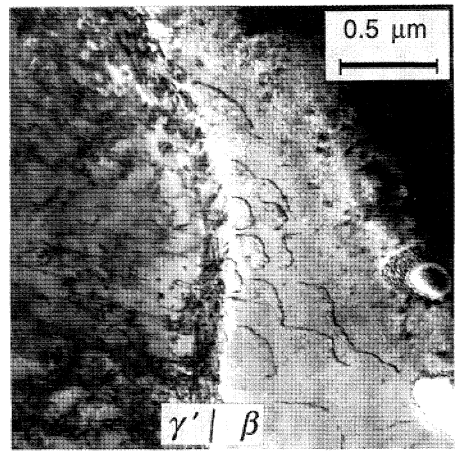

Figure 4. Electron micrograph of alloy D (see figure 2*a*) showing a twinned γ' lath and β islands (in parallel epitaxy) in a β' matrix. After Yang *et al.* (1992*b*).
Figure 5. Dislocations 'injected' from the γ' phase into the β' phase across a semicoherent boundary. After Yang *et al.* (1992*b*).

superalloys. The emphasis on the effects of minutely varied heat treatments, as noted in recent TiAl research, has yet to be seen in research on NiAl-based multiphase alloys.

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Discussion

D. R. F. West (*Imperial College, London, UK*). In the TiAl-based alloys there is considerable interest in the addition of other elements in relatively small amounts. Is there beginning to emerge a clearer role of such additions and how they act to influence alloy properties?

R. W. Cahn. Yes, a picture is beginning to emerge about the role of ternary or quaternary additions to TiAl. For an excellent, concise discussion of this see Huang & Chesnutt (1994). The efficacy of any alloying additions depends on careful control of the Ti/Al ratio, to ensure the right two-phase microstructure. When this is right, V, Mn, and Cr generally enhance ductility. Arguments based on stacking-fault energy or c/a ratios do not seem to be helpful, and the most convincing arguments bear on the tendency of these additives to substitute preferentially for Al, thereby 'reducing the covalency of the Ti–Al bond', especially when there is a two-phase microstructure. Other additives, Nb in particular, help to enhance oxidation resistance, while still others (notably Er) mop up excessive dissolved oxygen. One has to hope that the different functions of additives do not interfere with each other!

D. J. Dunstan (*University of Surrey, UK*). Professor Cahn remarks that it is surprising that the iron dispersoid strengthens the material because the iron would be very soft. Could there not, however, be size effects? Semiconductors which are very soft at crystal growth temperatures can support high elastic strains (over 1%), provided the strained layer is very thin. Perhaps similar size effects strengthen the iron?

M. McLean (*Imperial College, London, UK*). Professor Cahn suggests that intermetallics can be strengthened by the incorporation of entrained soft, disordered phases. The ultimate soft, disordered phase is a gas (or void). Is there evidence that a porous intermetallic is stronger than the fully dense material?

J. W. Martin (*Oxford University, UK*). There are two further points about strengthening by voids: firstly, in the absence of applied tensile stress they are essentially soluble at high temperature and will slowly disappear by sintering.

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Secondly, in the presence of a sufficient tensile stress they will grow, possibly until the specimen fractures by void coalescence. So their presence in a microstructure may lead to impaired creep ductility. The presence of a dispersion of an insoluble soft phase will not necessarily be deleterious to creep ductility in the same way, as the particles, when sheared, would be unlikely to fracture and thus generate a microvoid. Only when particle–matrix decohesion occurred would impairment of ductility be a possibility by this mechanism.

R. W. Cahn. Voids can certainly strengthen a metal or alloy if they are small enough, and they are able to trap grain boundaries and prevent softening by recrystallization. If they are coarse, they are bad news: thus in intermetallics made by self-sustaining high-temperature synthesis, incomplete densification is apt to embrittle the product beyond its normal degree. But as voids become smaller, the extreme is reached when a void becomes a lattice vacancy. Recently, Chang *et al.* (1993) demonstrated that the hardness and the (unusually large) vacancy concentration in FeAl are closely correlated.

D. Morris (*University of Neuchâtel, Switzerland*). We should note that most probably useful intermetallics are multiphase, but not all. The multiphase concept is perhaps required for strengthening but most probably for ensuring creep resistance and toughening. For iron aluminides, however, the situation is different. While not aerospace materials, these have high potential, and indeed are already being used, as high-temperature, oxidation- and corrosion-resistant structural steels. The materials under development, whether disordered Fe/16%Al, DO_3 ordered Fe/25–28%A1 or B2-ordered Fe/35+%Al, are essentially single-phase alloys, where strengthening is achieved by the ordered state, by grain refinement, and by solute additions (including perhaps vacancies). At the same time, dislocation multiplication and mobility is sufficiently good that plasticity, including at notch tips, is sufficient for the single-phase materials to be used as engineering materials.

R. W. Cahn. Yes, indeed, I quite agree. But then, the iron aluminides are relatively weakly ordered, and the brittleness problem is apt to be really obstinate only in those intermetallics which are strongly ordered, so then the multiphase solution becomes imperative.

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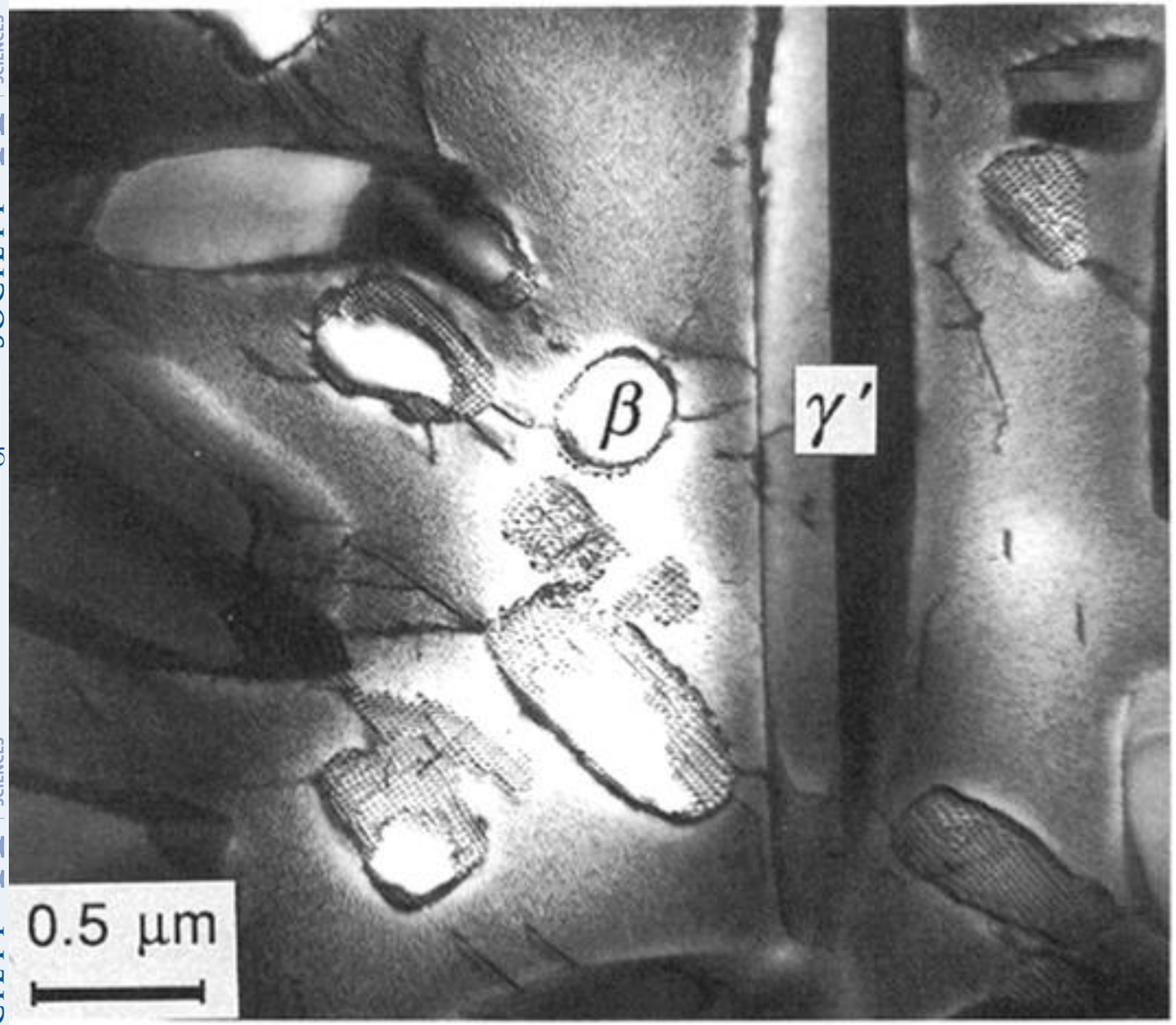

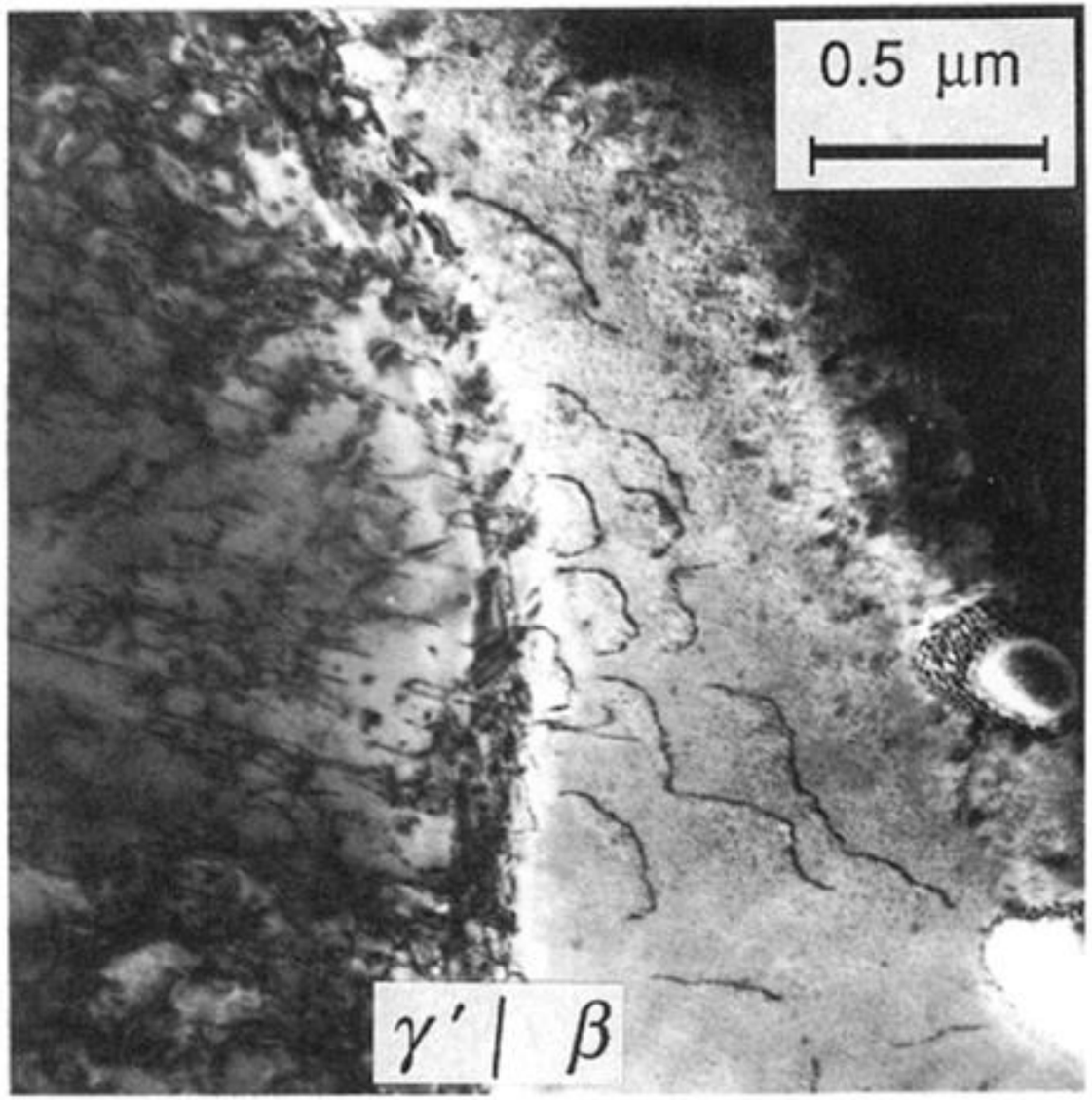

igure 4. Electron micrograph of alloy D (see figure 2*a*) showing a twinned γ' lath and β islands n parallel epitaxy) in a β' matrix. After Yang *et al.* (1992*b*).

igure 5. Dislocations 'injected' from the γ' phase into the β' phase across a semicoherent oundary. After Yang *et al.* (1992*b*).