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The thermal stabilities of alloy composites in an accelerational field

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A theoretical investigation has been made of the high-temperature stabilities of alloy composites in the presence of an accelerational field. Under these conditions discrete precipitates are predicted to migrate down the accelerational potential gradient with velocity proportional to the difference in density between precipitate and matrix. This phenomenon is shown to lead, by a variety of mechanisms, to an enhanced rate of morphological breakdown in systems such as aligned eutectic and eutectoid materials and conventional dispersion-hardened alloys. It is shown that this accelerated coarsening is likely to be important in the high-temperature application of metallic composites to rapidly revolving components such as turbine blades.

1. Introduction

A major problem associated with the high-temperature employment of alloy composites is the prevention of precipitate coarsening or degeneration under the driving force of capillarity. Consequently, much attention has been devoted to investigating the isothermal morphological stability both of systems such as directionally transformed eutectics and eutectoids, e.g. [1-7], and of the more conventional dispersion-hardened alloys, e.g. [8]. Nevertheless, recent work has shown that it is not sufficient to study morphological stability under simple isothermal conditions when assessing the suitability of alloys for high-temperature applications. For example, the author has shown that the imposition of a temperature gradient results in a greatly increased rate of structural breakdown in the case of aligned composite alloys [9-11]; and it has been shown [9-11] that this effect is likely to seriously limit the life of components (such as integrally cooled turbine blades) subjected to large heat fluxes.

Another potentially important factor in many high-temperature applications is the presence of large accelerational forces generated by rapid rotational motion. However, no account as yet appears to have been taken of the effect of such forces on microstructural stability as distinct from conventional creep phenomena. Accordingly, the present paper is devoted to investigating theoretically the effect of rotational forces on the thermal stability of a representative selection of high-temperature composite alloys.

2. Basic considerations

Recent experimental work has shown, e.g. [12-14], that liquid inclusions entrained in a crystal of density unequal to that of the inclusions will migrate through the crystal under the influence of large accelerational fields. Although not yet observed experimentally, an analogous effect would be anticipated for the case of solid precipitates entrained within an alloy matrix; and it would be expected that the migration of alloy particles in an accelerational field would provide a mechanism for changing the morphology of a composite alloy. Accordingly this section is devoted to deriving approximate figures for the rates of migration expected of precipitate particles under conditions typical of high-temperature practice.

For the common case where the precipitate particles are approximately spherical, we may write [15]

$$V = (-\,2D_\mathrm{i}\delta/kTr)F_\mathrm{m}\,, \qquad (1)$$

where V = velocity of precipitate relative to the free surface of the specimen; D_i = diffusivity of matrix material in the precipitate/matrix interface; δ = thickness of high-diffusivity layer at interphase interface; k = Boltzmann's constant; T = absolute temperature; r = particle radius; F_m = net force exerted on each atom of the matrix by the accelerational field. Throughout the present treatment it will be assumed that diffusion in the bulk phases may be ignored (as should be the case for materials having high melting points) and thus Equation 1 refers to particles moving through the matrix by mass transport in the interphase boundary. Equation 1 also assumes that the driving forces required to cause dissolution or precipitation at the particle/matrix boundary may be neglected. Finally, the matrix material is assumed to consist of a simple atomic species unrelated to any of the constituents of the precipitate.

It may be shown readily that

$$F_{\mathrm{m}} = -\,\Omega_{\mathrm{m}}(\rho_{\mathrm{p}} - \rho_{\mathrm{m}})a\,. \qquad (2)$$

Ω_{m} is the atomic volume of the matrix, ρ_{p} and ρ_{m} are the densities of precipitate and matrix, and a is the acceleration imposed on the system. Thus, from Equations 1 and 2, we have

$$V = 2D_{\mathrm{i}}\delta\Omega_{\mathrm{m}}(\rho_{\mathrm{p}} - \rho_{\mathrm{m}})a/kTr\,. \qquad (3)$$

Typical values for D_{i}, δ, Ω_{m} and T are 10^{-3} $\mathrm{mm^2\ sec^{-1}}$ [5], 0.5 nm, $7 \times 10^{-6}\ \mathrm{m^3\ mol^{-1}}$ and 10^3 K. $\rho_{\mathrm{p}} - \rho_{\mathrm{m}}$ is usually $\sim 4\ \mathrm{Mg\ m^{-3}}$ for high-temperature materials [16, 17]. In many applications (for instance turbine blading) a is $\sim 10^9$ $\mathrm{mm\ sec^{-2}}$. Thus V is typically $\sim 0.007\ \mathrm{nm\ sec^{-1}}$ for a particle of radius 0.5 μm, or $0.07\ \mathrm{nm\ sec^{-1}}$ for an inclusion 0.05 μm in radius. These velocities are such that, after a hundred hours, a typical precipitate particle will have moved between 2.5 and 25 μm through the matrix. In the following sections we shall investigate the effect of this degree of movement on the morphologies of typical eutectic, eutectoid, and dispersion-hardened composites.

3. Dispersion-hardened alloys

In a typical dispersion-hardened alloy, where precipitates are likely to be small ($r \sim 0.05$ μm), the latter will migrate over distances comparable to the inter-particle spacing in times as small as 2 h. Thus any differential migration of precipitates will quickly lead to the contact and coalescence by interfacial diffusion of precipitate particles, with attendant rapid coarsening of the microstructure. Differential migration may arise as a result of an initial spread in the distribution of particle radii manifested in the form of Equation 3. Moreover, variations in particle radius associated with precipitate coalescence will sustain further differential migration. After a time the overall increase in r generated by the coarsening process will lead, via Equation 3, to a progressively smaller rate of precipitate migration; and this, coupled with an increasing interparticle spacing, will eventually lead to a rapid decrease in the net rate of particle coalescence.

Differential migration of precipitates may also arise if a certain degree of interfacial control is present; in this case the rate of particle migration may not be markedly decreased, but variations in the interfacial driving forces from one particle to another may lead to significant variations in V. Such kinetic variations may arise when interfacial motion requires the presence of crystallographic defects [18], or when impurities are randomly adsorbed at the interphase interfaces.

In many systems precipitates will not necessarily migrate strictly parallel to the imposed rotational forces but may, in the event again of some interfacial control, move along more kinetically preferred, crystallographic, directions in the matrix. In such circumstances, additional particle coalescence may result from particles moving on collision courses along symmetry-related crystallographic directions.

Finally, by analogy with work [19] on the temperature-gradient migration of gas bubbles through organic solids, grain boundaries should strongly catalyze the coalescence of migrating precipitates.

4. Aligned fibrous alloys

Much attention has recently been devoted to developing aligned, fibrous eutectic alloys for use as turbine-blade materials, e.g. [16]. When employing these alloys, turbine blades may be solidified unidirectionally, yielding an *in situ* composite microstructure with reinforcing fibres of eutectic material aligned parallel to the service-generated accelerational field. The latter may influence the thermal stability of the eutectic microstructure by the following main mechanisms.

Consider first the common case where capillarity causes a fibre to break down into a row of uniform equidistant spheres by means of surface diffusion, e.g. [2, 5]. In this situation further coarsening may ensue (see Fig. 1) if coalescence of spheres occurs due to the effects of interfacial kinetics (see Section 3). In typically fine eutectic microstructures such spheres will usually be ~ 1 μm in size, and should migrate up to 2.5 μm ($\sim$ the inter-sphere spacing) in

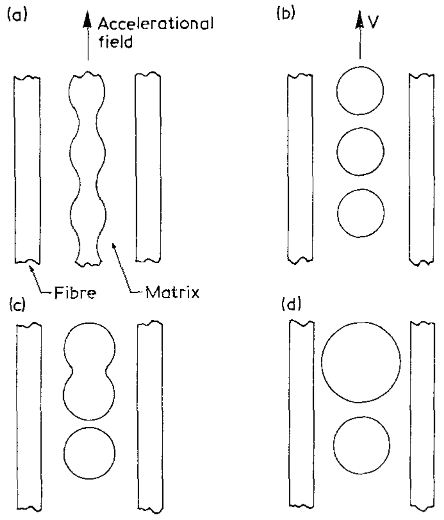

Figure 1

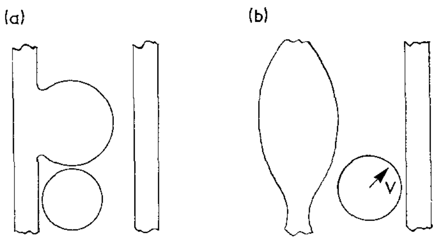

Figure 2

Figures 1 and 2 Sequence illustrating how, in an accelerational field, the periodic spheroidization of fibrous precipitates can lead to additional microstructural coarsening.

approximately a hundred hours. Thus significant additional coarsening should often be caused by typical rotational forces after sensible lengths of time.

In the case of alloys having a relatively large volume fraction of fibres, the above type of coalescence should rapidly lead to the situation shown in Fig. 2; and the shape perturbation thus generated on an otherwise perfect fibre will catalyze further periodic spheroidization [3]. This type of instability may also, in general, result from the diagonal migration of an eutectic sphere (see Section 3) in the direction of an adjacent fibre (Fig. 2b); and additional coarsening may be catalyzed by eutectic spheres created during the spheroidization of fibre terminations [1].

In principle it is possible for complete fibres to migrate in the direction of the accelerational field; and in the present case – where the field is parallel to the fibre axis – the motion of fibres may be described by Equation 3, with r as the fibre radius. If the microstructure is well aligned, fibre migration need not lead to appreciable coarsening, but may result in undesirable effects at grain boundaries or free surfaces.

Lastly, the above mechanisms of enhanced coarsening should also in principle apply to analogous systems such as aligned, fibrous eutectoids and dendritically-reinforced composites.

5. Aligned lamellar alloys

In the absence of diffusion in the bulk phases, aligned lamellar alloys normally spheroidize only at terminations of, or imperfections in, the lamellae [4, 6]. In the usual case where the growth direction of the alloy is parallel to the applied accelerational field, the latter may lead to enhanced coarsening by encouraging particle coalescence as above (see also Fig. 3). In addition, diagonal migration of such particles towards adjacent lamellae (see Fig. 3b) will lead to a certain degree of lamellar thickening. As in the case of fibrous alloys, the lamellae should in principle migrate bodily in the direction of the rotational forces; but again this need not lead to any microstructural degeneration in the bulk of the specimen.

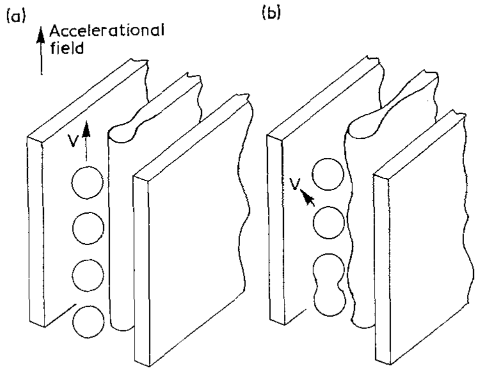

Figure 3 Sequence showing how, in an accelerational field, the spheroidization of lamellar precipitates can lead to further coarsening of the microstructure.

In general, the low density of lamellar faults and imperfections in most alloys of the type indicates that lamellar structures should be appreciably more stable than fibrous morphologies in an accelerational field.

6. Discussion

It is clear from the above that the imposition of an accelerational field should result in the exaggerated morphological breakdown of many composite materials. The effect is likely to be most pronounced for fine dispersion-hardened systems, but is also of potential importance in the case of fibrous composites. It is noteworthy that coarsening due to rotational forces can occur even in systems which would normally be perfectly stable at elevated temperature (e.g. dispersion-hardened systems with negligible bulk diffusivities). If the above treatment is modified to allow diffusion in the bulk phases as well as in just the interphase interfaces, the effect of the accelerational field should be increased correspondingly.

Structural stability under the present circumstances may often be improved markedly if the kinetics of interfacial motion are very sluggish. In this case small precipitates will migrate only slowly, and processes such as particle coalescence and spheroidization will themselves be suppressed. If, however, precipitates become larger in the direction of migration, the driving force on the precipitate will become greater relative to the driving force required for interfacial motion. Thus larger precipitates will be less obstructed by interfacial constraints than smaller particles.

Finally, the effect of the accelerational field may be reduced most directly by minimizing the difference in density between precipitate and matrix.

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References

1. F. A. NICHOLS and W. W. MULLINS, *J. Appl. Phys.* **36** (1965) 1826.
2. *Idem, Trans. Met. Soc. AIME* **233** (1965) 1840.
3. H. E. CLINE, *Acta Metallurgica* **19** (1971) 481.
4. Y. G. NAKAGAWA and G. C. WEATHERLY, *Met. Trans.* **3** (1972) 3223.
5. D. R. H. JONES, *J. Mater. Sci.* **9** (1974) 989.
6. *Idem, J. Crystal Growth* **22** (1974) 34.
7. J. D. LIVINGSTON and J. W. CAHN, *Acta Metallurgica* **22** (1974) 495.
8. G. R. SPEICH and R. A. ORIANI, *Trans. Met. Soc. AIME* **233** (1965) 623.
9. D. R. H. JONES, *Metal Sci.* **8** (1974) 37.
10. *Idem, Mat. Sci. Eng.* **15** (1974) 203.
11. D. R. H. JONES and G. J. MAY, *Acta Metallurgica* in press.
12. T. R. ANTHONY and H. E. CLINE, *Phil. Mag.* **22** (1970) 893.
13. *Idem, ibid* **24** (1971) 695.
14. W. R. WILCOX, *J. Crystal Growth* **13/14** (1972) 787.
15. P. G. SHEWMON, *Trans. Met. Soc. AIME* **230** (1964) 1134.
16. F. D. LEMKEY and E. R. THOMPSON, *Met. Trans.* **2** (1971) 1537.
17. C. J. SMITHELLS, "Metals Reference Book" (Butterworths, London, 1967) pp. 685, 923.
18. P. J. MORRIS, D. KIRTISINGHE and R. F. STRICKLAND-CONSTABLE, *J. Crystal Growth* **2** (1968) 97.
19. T. R. ANTHONY and R. A. SIGSBEE, *Acta Metallurgica* **19** (1971) 1029.

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