Metal matrix composites produced from yttrium based or high yttrium content alloys

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Abstract

This paper surveys the author's production of metal matrix composite from yttrium or high yttrium content alloys. Composite materials have been produced by directional solidification and/or cooling in the yttrium–oxygen system. Additionally, metal–metal matrix composites were produced by deformation processing. These materials have been produced in the yttrium–titanium system and in the yttrium–niobium system are analogous to those formed in copper–niobium alloys. Here a precursor alloy is cold worked such that both phases co-deform. This produces a fine filamentary reinforcing phase within a continuous matrix phase. Both methods produce materials with interesting microstructures and possible new methods for the production of structural materials from yttrium, scandium or the other rare earth metals.

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1. Introduction

Rare earth metallurgy is noted for many contributions to modern technology; however, rare earth-based structural alloys are noticeably absent. The high cost of the rare earth metals in addition to their limited availability has restricted the development of structural alloys of these materials. This is particularly unfortunate in the case of yttrium and scandium, which have very attractive physical properties. Although metal cost is still a problem, the technological maturity of other low-density high-tech structural alloy material, *e.g.* alloys of beryllium and titanium, warrants this new investigation. The rare earths are essentially unexplored territory for the development of new structural materials.

Our focus of research into new structural rare earth alloys has followed two concurrent paths: [1] rare earth metal matrix composites produced by directional solidification or heat treatment with compound-forming non-metals, as modeled by the yttrium–oxygen system, and [2] rare earth–refractory metal alloys that are deformation processed to produce *in situ* metal–metal matrix composites. In both processes, it is desired to produce a rare earth metal matrix that is reinforced by the presence of a large volume fraction of fibers or particles of a second phase [1].

2. Directionally thermally processed composites

Our preliminary work has been done on the yttrium–oxygen system, the phase diagram of which is shown in Fig. 1 [2]. Two approaches have been made to the formation of metal matrix composites. The first approach was through directional solidification of alloys of eutectic composition, 37.4 at.% oxygen. To produce these composites yttrium and yttria, Y_2O_3, were combined as ingot metal and oxide powder in a tantalum crucible and directionally solidified by the Bridgeman technique. The alloy liquid alloy was homogenized at 1770 °C for 20 min and a thermal gradient of 1000 °C cm^{-1}. This was done at withdrawal velocities of 1, 10, 100 and 500 $\mu m\ s^{-1}$. The microstructures were all similar to that shown in Fig. 2 for a withdrawal velocity of 100 $\mu m\ s^{-1}$. Eutectic yttria appears to grow with a very

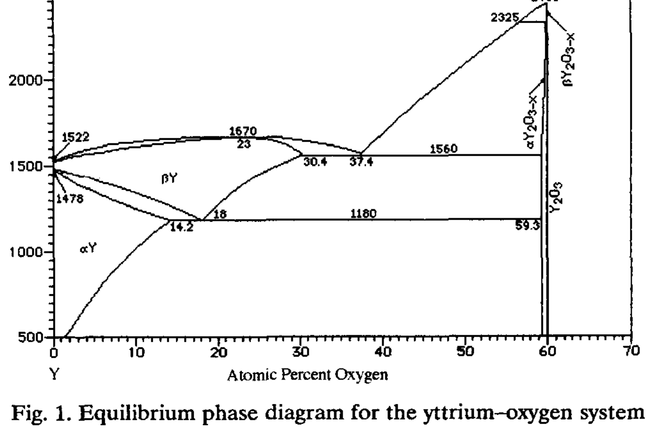

Fig. 1. Equilibrium phase diagram for the yttrium–oxygen system.

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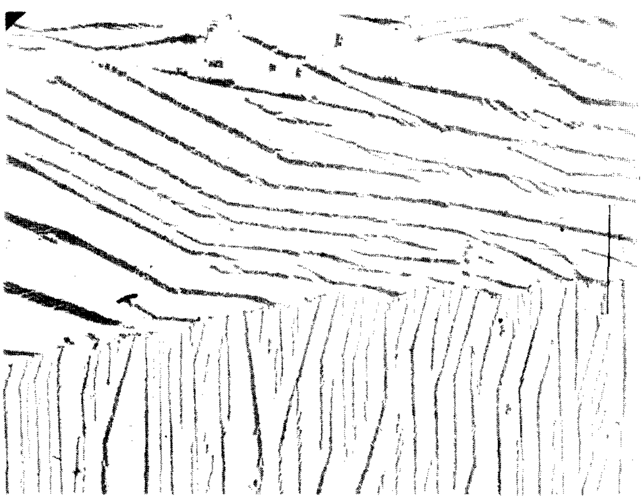

Fig. 2. Microstructure yttrium–yttria eutectic directionally solidified at 100 μm s^{-1}.

faceted morphology which is to be expected. Eutectic spacings were found to vary from 350 μm to 100 μm over the velocity range explored. This spacing was felt to be too large to provide significant strengthening. Therefore, attention was refocused on the eutectoid reaction present at a composition of 18.0 at.% oxygen.

The feasibility of strengthening by controlled eutectoid growth in this system was accomplished by performing a Jominy test on a bar of eutectoid composition, *i.e.* 18.0 at.% oxygen [2]. Jominy tests are very commonly used to evaluate the hardenability of steel alloys [3]. To perform a Jominy test, a bar of 2.5 cm diameter and 10.5 cm length is solutionized to assure uniform composition in our experimental work at 1400 °C for 2 h, which is then quenched by the impingement of a water stream at one end. This provides for essentially unidirectional heat flow with the cooling rate varying from an infinite quench at the jet end to a very slow cool on the opposing end. To evaluate the hardenability, hardness measurements are made along the length of the bar. This was done in our experimental work using a Vickers indentor and a 50-kg load. In Fig. 3 the measured Vickers hardness is plotted versus distance.

By observation, one finds that the results are rather random until approximately 7.0 cm from the quenched end, where a regular reduction of hardness with distance is found. This type of two-region curve is not uncommon in some steels where retained austenite, the high temperature fcc allotrope of iron, is retained through the quenching process.

Although the actual processes that produce this variability in the hardness at high cooling rates need further investigation, it is apparent that solutionizing and controlled cooling can lead to hardening in this system. The microstructure of this material, as done by optical microscopy, is shown in Fig. 4. Generally, the microstructure consists of a yttrium matrix phase with yttria precipitating out either as a eutectoid product intragranularly or on grain boundaries. Precipitation on grain boundaries is not desirable in view of results obtained in cast irons. Grain boundary precipitation leads to yttria, or to carbon in the case of cast iron, as the continuous phase. Continuous precipitates on grain boundaries can lead to very poor tensile properties. However, as is the case in cast iron alloys, additions of other elements may suppress grain boundary precipitation and the subsequent problems.

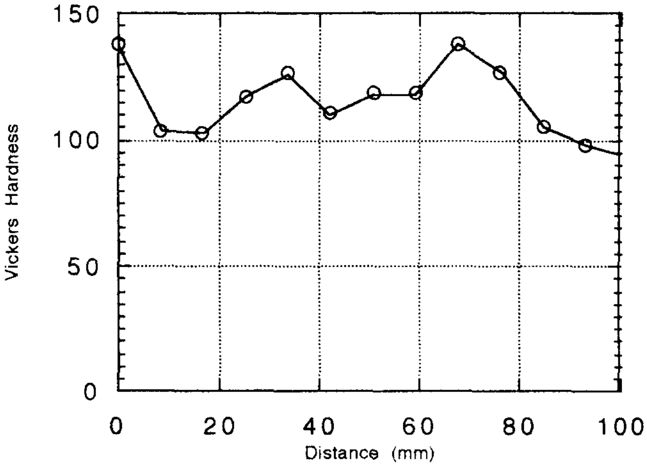

Fig. 3. Vickers hardness versus distance from the quenched end for a yttrium–18.0 at.% oxygen Jominy test bar.

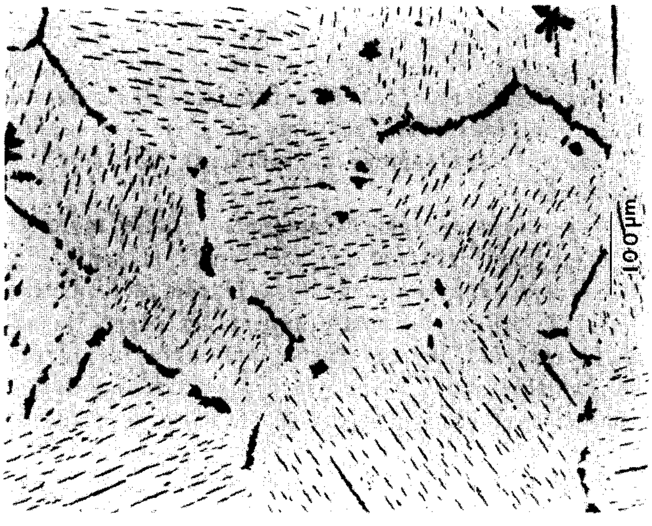

Fig. 4. Microstructure of a yttrium–18.0 at.% oxygen 7.0 mm from the quenched end.

3. Deformation processed composites

Deformation processing of immiscible yttrium-refractory metal alloys, *e.g.* titanium, niobium, vanadium, chromium, molybdenum, has proven to be a new method for the production of rare earth based structural alloys. Some of the fundamentals of this type of composite have been previously presented [4–6]. Deformation processing of a two-phase immiscible alloy, for example the yttrium–titanium phase diagram presented in Fig. 5, produces a microstructure consisting of a continuous matrix phase and a high aspect ratio fibrous phase. The particular microstructure that defines a deformation-processed metal–metal matrix composite, DMCs, is unique in terms of structure and processing. Common polymer matrix composite materials have a continuous polymer matrix which is reinforced by the presence of fibers of inorganic or organic material. In DMCs, a continuous metallic matrix phase is reinforced by a high aspect ratio non-continuous metallic reinforcing phase; the fibrous morphology of the reinforcing phase is produced by the co-deformation of the matrix and reinforcing phases. Therefore, the fibrous morphology of the reinforcing phase is formed *in situ* during deformation of the material, a distinction that separates these materials from the wide range of non-metallic reinforced metal matrix materials, *e.g.* SiC fibers in aluminum.

A prototypical microstructure for these materials formed upon deformation processing is shown in Fig. 6 for a yttrium–titanium alloy. During deformation, both the reinforcing phase and matrix phase become highly textured. Texture development limits the number of available slip systems which produces the ribbon-shaped cross-section to the filaments as seen in Fig. 5.

As shown in Fig. 7 for two titanium–yttrium alloys, 20 and 50 vol.%, the ultimate tensile strength (UTS) increases as a function of η. A copper–20 vol.% niobium alloy is shown for comparison. [6] η is defined as the natural log of the ratio of the reduction in area, $\eta = \ln(A_f/A_i)$, where A_f is the final cross-sectional area and A_i is the initial cross-sectional area. The ultimate tensile strength of these alloys is increased from approximately 250 MPa at $\eta = 0$, to 950 MPa at $\eta = 8$. Following the copper–niobium example, increasing the value of η should lead to much larger increases in UTS of these alloys. These experiments, however, have proved the validity of this approach for producing high strength alloys based on yttrium.

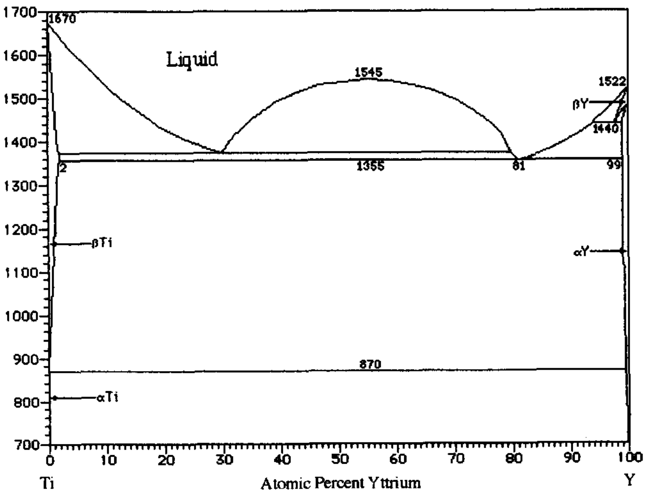

Fig. 5. Equilibrium phase diagram yttrium–titanium system.

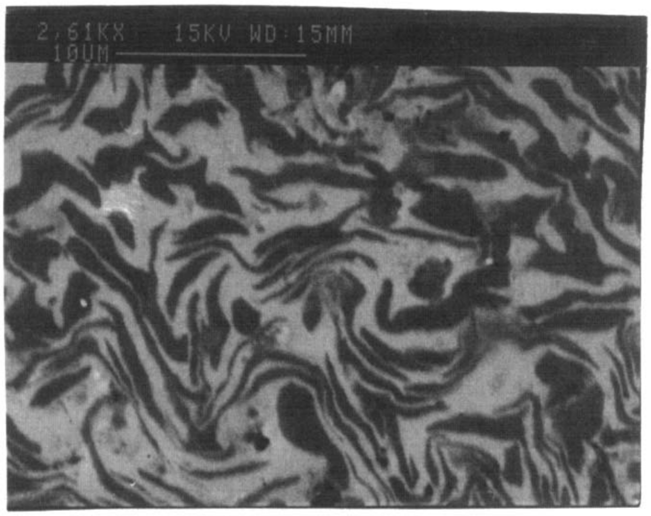

Fig. 6. Microstructure of deformation processed titanium–50 vol.% yttrium.

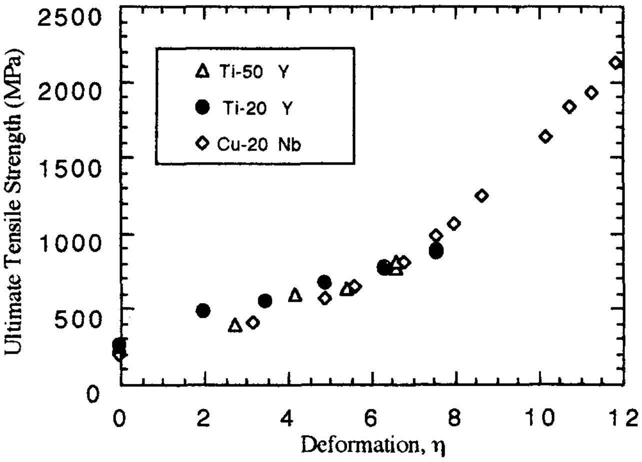

Fig. 7. Ultimate tensile strength alloy, titanium–20 vol.% yttrium, yttrium–50 vol.% titanium and of a copper–20 vol.% mobium versus η.

4. Conclusion

The objective of this survey was to investigate the feasibility of using yttrium, and by analogy the other rare earth elements, as the primary phase of metal matrix composite materials. This has been done by two different methods; firstly, the growth of yttria fibers within a yttrium matrix by manipulation of the eutectic and eutectoid reaction; secondly by deformation processing of yttrium–refractory metal alloys in a manner analogous to that undertaken in copper–refractory metal alloys.

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