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Directional Eutectoid Decomposition in Cu-11.8 wt % Al

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Directional eutectoid decomposition in a Cu-11.8 wt % Al alloy at a rate of 7 × 10^{-5} cm/sec produced eutectoid colonies several inches in length, with lamellae parallel to the temperature gradient. Average lamellar spacing was 4000 Å. Significantly faster driving speeds produced martensitic structures. The maximum rate of eutectoid decomposition and the spacing observed were in agreement with earlier data from isothermal studies.

1. Introduction

Many investigators have successfully produced aligned composites by directional control of eutectic solidification. However, Kraft [1] reports that several attempts to produce aligned composites by directional control of eutectoid decomposition, in particular the pearlite reaction in Fe-C, have been unsuccessful. Recently, Bolling and Richman [2] have moved a cylinder of austenite at constant velocity through a steep temperature gradient, and thereby achieved a relatively planar transformation front. However, many fine colonies were produced, and only a small fraction of the pearlite appeared to be aligned along the temperature gradient.

The most extensively studied of the non-ferrous eutectoid reactions is that occurring at Cu-11.8 wt % Al [3]. In this reaction, the high-temperature β-phase (bcc) decomposes into α (fcc, 9.4 wt % Al) plus γ_2 (γ-brass structure, 15.6 wt % Al), with a eutectoid temperature of 565° C. Asundi and West [4] have reported the transformation rates and interlamellar spacings observed for isothermal decomposition at various temperatures below 565° C. It was decided to attempt to produce an aligned composite structure by transforming a Cu-Al eutectoid alloy in a high temperature gradient.

Recently, Carpay [5] reported the production of aligned composite structures by directional control of several solid-state phase transformations. In the case of Cu-11.8 wt % Al, he reported eutectoid colonies several mm in length.

2. Experimental

An alloy of Cu-11.8 wt % Al was made from elements of 99.999 % purity and formed into a rod 0.175 in. in diameter. The alloy was melted in argon in a graphite crucible 5 in. long with 0.250 in. outer diameter and 0.035 in. walls, and directionally solidified in an apparatus described in detail previously [6]. Samples were driven at constant velocity through a temperature gradient of approximately 300 °C/cm.

Samples were subsequently polished for metallographic examination of a complete longitudinal section. Selected regions were thinned for transmission electron microscopy using a cooled solution of 50 % conc. nitric acid, 50 % methanol.

Samples driven at 2.8 × 10^{-4} cm/sec and faster, were completely martensitic in structure. A sample driven at 1.4 × 10^{-4} cm/sec was mostly martensitic, but also included several large, unaligned eutectoid colonies.

Samples driven at 7 × 10^{-5} cm/sec showed only eutectoid structures. (We except the initial end of the sample, which also showed pro-eutectoid α, and the final end, which showed pro-eutectoid γ.) In each of six samples transformed at this velocity, several unaligned colonies were seen in the first cm of length. However, in each sample one colony subsequently became successfully established and continued for several inches with the eutectoid lamellae lying nearly parallel to the temperature gradient (figs. 1, 2). Transformation was eventually interrupted by a sudden quench which revealed the eutectoid transformation front (fig. 3).

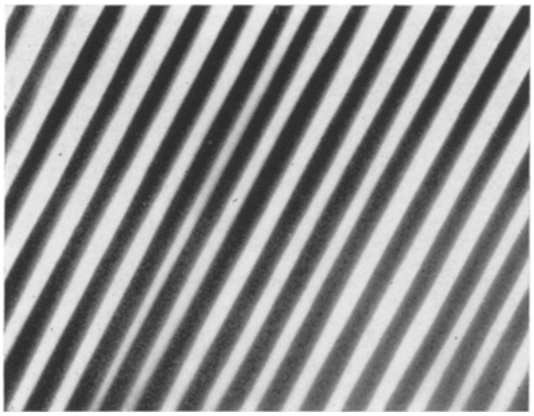

Figure 1 Transmission electron micrograph of transverse section of directionally-transformed Cu-11.8 wt% Al alloy. Light phase is α-phase (× 11 600).

Figure 2 Longitudinal section of directionally-transformed Cu-11.8 wt % Al alloy. Temperature gradient vertical (× 665).

The major departure from alignment was in the form of small regions of fairly abrupt change in lamellar direction. These regions appeared to be related to cusps in the transformation front (fig. 3). In a given sample, the lamellae in all of these misaligned regions have the same orientation.

From optical and electron microscope observations on transverse sections, the average interlamellar spacing was found to be 4000 Å.

3. Discussion

It was suggested by Livingston *et al* [7] that high-speed directional control of eutectoid decomposition and cellular precipitation might be used to produce aligned composites finer than those attainable by eutectic solidification. This prediction overlooked the fact that the maximum velocities at which such solid-state phase transformation fronts can advance are much lower than the attainable rates of solidification. For the Cu-Al eutectoid reaction, Asundi and West [4] observed a maximum velocity of 1.25×10^{-4} cm/sec in isothermal tests. This is in excellent agreement with the present results, in which a speed of 7×10^{-5} cm/sec successfully produced eutectoid decomposition, but a speed of 1.4×10^{-4} cm/sec produced mostly martensite. Carpay [5] reports that only speeds below 1.4×10^{-4} cm/sec produced aligned composite structures in Cu-11.8 wt % Al. The maximum transformation velocity corresponds to a minimum lamellar spacing observed to be about 2000 Å by Asundi and West [4]. Although this spacing is far finer than that produced by eutectic solidification at the same velocity, eutectic solidification at rates above 10^{-1} cm/sec can produce spacings of 1000 Å and finer [7].

As discussed by Bolling and Richman [2], in most studies of solid-state transformation the temperature is fixed experimentally and velocity is a "free" variable. The present type of experiment fixes the average velocity of the transformation front, and interface temperature becomes a "free" variable. From the velocity versus temperature data of Asundi and West [4], we estimate that in our samples driven at 7×10^{-5} cm/sec, the temperature at the advancing eutectoid interface was about 535° C, an undercooling of about 30° C below the equilibrium eutectoid temperature. Asundi and West found an interlamellar spacing of about 4000 Å at this temperature, in good agreement with our observations.

The irregularity of the advancing interface (fig. 3) presumably results from inhomogeneities in the β-phase. Because of such inhomogeneities, and because the variation of velocity with temperature is much less extreme for solid-state

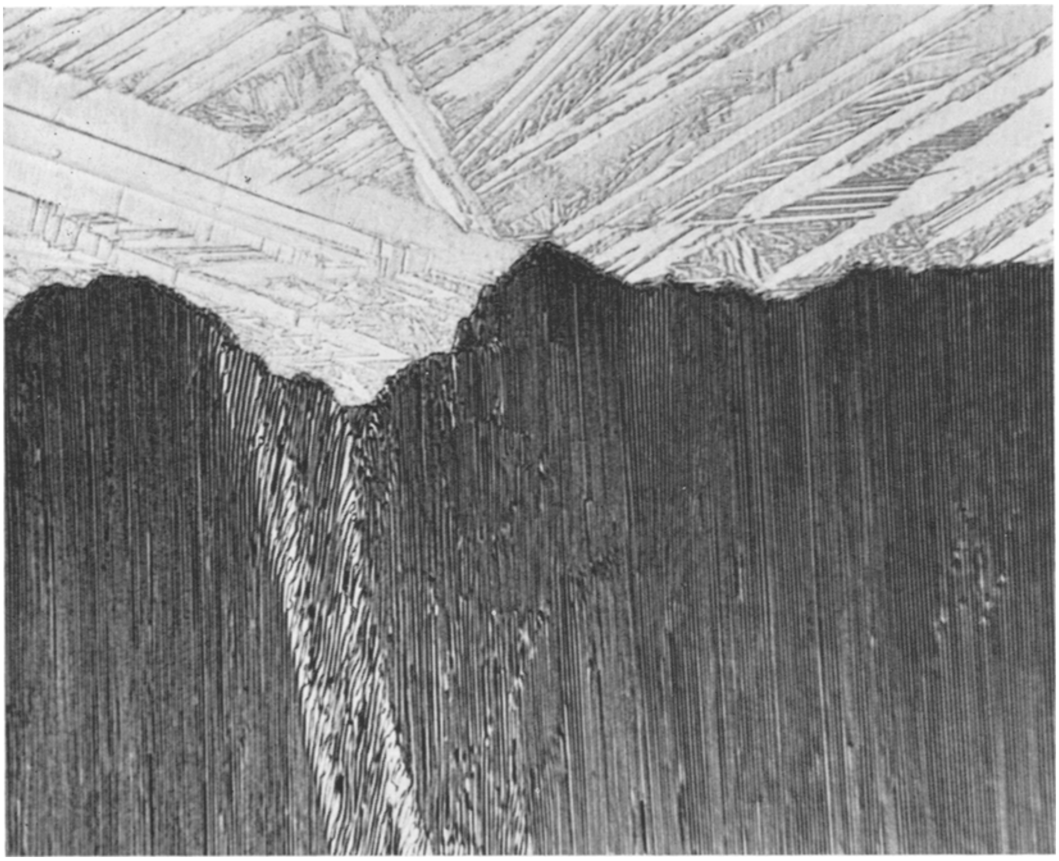

Figure 3 Eutectoid transformation front as revealed by sudden quench. Structure ahead of interface is martensitic, induced by quench. Temperature gradient vertical (× 1000).

transformations than for solidification, it is likely that much higher temperature gradients will generally be necessary to maintain a planar front for solid-state transformations than for solidification. In the present case, a fairly well aligned structure was obtained despite the irregular interface, apparently because of a strong crystallographic preference for a particular lamellar plane. Rather than changing orientation freely to remain perpendicular to the front, the lamellae change orientation only severely and abruptly, presumably to another low-energy orientation. This strong tendency for preferred lamellar planes in the Cu-Al eutectoid was noted previously by Smith [8], who also reported that the abrupt changes in lamellar orientations were accompanied by twins in the α or γ_2 phase. Crystallographic data in this system are needed, and a detailed study is currently under way.

Before directional transformation, Carpay [5] prepared his samples by chill casting followed by a homogenising anneal slightly below the melting point. The ultimate size of the eutectoid colonies subsequently produced was presumably limited by the β-phase grain size. In our experiment, in which directional solidification and directional transformation occurred in a single run, we probably produced single-crystalline or nearly single-crystalline β. Because of the lack of transverse grain boundaries, we were able to produce eutectoid colonies that extended along the entire length of the sample.

The observation of pro-eutectoid α and γ_2 at the initial and final ends, respectively, of the sample indicates that solidification has introduced a slight segregation of aluminium. Chemical analysis revealed a composition of 11.2 wt % Al at the initial end and 12.1 wt % Al at the final end.

Directional control of solid-state phase transformations may become an important alternative technique to that of eutectic solidification for the production of aligned composites. Aligned composites are now possible for many new alloy compositions, and composite structures may be produced, if desired, after the sample has been machined to final shape. However, application must of course be limited to temperatures below the eutectoid temperature.

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