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The effect of a magnetic field upon directional solidification of Sn-Cd and Sn-Pb alloys

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Eutectic alloys of Sn-Cd and Sn-Pb were solidified vertically under a transverse magnetic field of 23000 Oe. Analysis of the data indicated that the magnetic field had no effect upon the lamellar spacing of the eutectic or the orientation of the lamellae relative to the magnetic field. This result indicates that the effect of the magnetic field upon the liquid diffusion coefficient is too small in these systems to allow control of lamellar spacing by means of an applied magnetic field.

1. Introduction
Directional solidification of eutectic forming alloys offers a promising technique for the preparation of aligned composite materials. The size of the aligned fibre phase is determined by the rate of solidification. Theory [1, 2] shows that the fibre spacing and, hence, the fibre size should be proportional to the minus $\frac{1}{2}$ power of the solidification rate, and this prediction has been fairly well substantiated by experiment [3]. The theory also shows the fibre size to be proportional to the liquid diffusion coefficient to the $\frac{1}{2}$ power. Therefore, if one could exercise some control over the liquid diffusion coefficient, one would have an additional means of control of the fibre size in the preparation of aligned composites. In a recent series of papers Youdelis [4-6] has presented some theoretical and experimental evidence showing that the diffusion coefficient may be decreased by the presence of a moderately high magnetic field. Experiments on solid Al-Cu alloys showed a 25% decrease of the diffusion coefficient in a magnetic field of 30000 Oe. A definite effect of magnetic field upon solute redistribution during dendritic [5] and plane front [6] solidification was also observed. These results indicate that if this magnetic field effect is large enough in liquid metals, one could reduce the diffusion coefficient and, hence, the fibre spacing by applying a magnetic field to directional solidification experiments on eutectic alloys. The magnetic field would have the added advantage of reducing fluid flow in the liquid and thereby reducing the chances of banding which is often encountered in preparation of aligned composites by directional solidification. The present investigation was undertaken to determine if a moderately high magnetic field would be effective at reducing the spacing of the eutectic lamellae in Sn-Pb and Sn-Cd eutectic alloys.

2. Experimental
The ingots were prepared by melting the eutectic compositions under helium or vacuum and then casting into 8 mm o.d. × 6 mm i.d. quartz tubes using a vacuum casting technique. The starting metals had quoted purities of 99.999%. The quartz tubes containing the alloy were placed in the solidification apparatus shown in Fig. 1. The furnace was made from stainless steel and the windings were wound in such a way as not to affect the magnetic field. A stainless steel tube was used to assist in producing unidirectional heat flow down between the pole faces of the magnet. The furnace temperature was adjusted to position the solid-liquid interface at the centre of the poles faces.

After the system was at temperature the ingot was raised in the furnace and any gas bubbles removed with a tantalum stirrer. The ingot was then quenched a length of 3 in. to provide good thermal contact with the lower water jacket. After a 15 min equilibration the ingots were

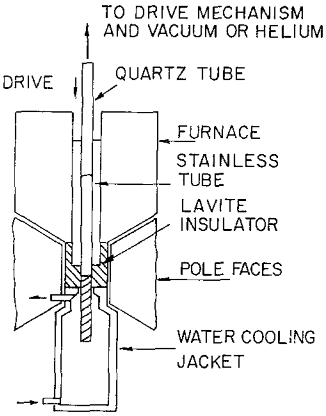

Figure 1 Experimental apparatus.

directionally solidified for a length of 2.5 to 3 in. In the Sn-Pb alloys the first half of the ingot was solidified with the magnet off and the second half with the magnet on. In the Sn-Cd alloys the magnet was on only for the central third of the solidified distance. The final solid-liquid interface was determined by a rapid lowering of the tube which quenched the remaining liquid.

A 12 in. electromagnet with 3 in. pole faces separated $1\frac{15}{16}$ in. was used in this study. The field was measured using a rotating coil gaussometer with the furnace, steel cylinder, and water jacket in place. The field readings were unaffected by applying current to the furnace windings. The field was found to vary from 23000 Oe on the centre line to 22600 Oe at 1 cm off the centre line.

The temperature gradient in the liquid was determined with a Chromel-Constantine thermocouple encased in a tantalum tube. Using this as a probe it was determined that the solid liquid interface remained fixed relative to the pole faces during a run, and consequently, the solidification rate was taken as the rate at which the tube was driven downward into the water jacket. Metallographic examination revealed the quenched solid-liquid interface to be planar, which indicates that unidirectional heat flow down the ingot was obtained.

The eutectic spacing was determined at several transverse sections along each ingot using standard metallographic techniques. Each spacing was determined as the average of around twenty-five measurements which, on the Sn-Pb alloys, were taken from random points on the transverse section. The central grains of the Sn-Cd alloys were found to contain fewer faults in the lamellae than the grains near the outer edges on the sections. In agreement with a recent study [7] the lower fault density grains had a slightly smaller spacing, and in these alloys all measurements were taken from grains having the lower fault density. The measured lamellar spacings on both Sn-Cd and Sn-Pb agreed very well with literature values [3].

TABLE I Experimental data on Sn-Cd. Temperature gradient = 50° C cm^{-1}

Rate (μm sec^{-1})	Field (Oe)	Spacing (μm)	$t_{0.05}\, S/\sqrt{n}$ (μm)
1.06	0	5.47	± 0.10
1.06	23000	5.46	± 0.15
1.06	0	5.48	± 0.10
2.12	0	4.27	± 0.082
2.12	23000	3.92	± 0.086
2.12	0	3.93	± 0.086
5.30	0	2.66	± 0.093
5.30	23000	2.55	± 0.075
5.30	0	2.56	± 0.061

TABLE II Experimental data on Sn-Pb. Temperature gradient = 50° C cm^{-1}

Rate (μm sec^{-1})	Field (Oe)	Spacing (μm)	$t_{0.05}\, S/\sqrt{n}$ (μm)
0.93	0	5.94	± 0.11
0.93	16400	6.08	± 0.24
9.3	0	1.40	± 0.071
9.3	22000	1.47	± 0.013
18.9	0	1.97	± 0.034
18.9	16400	1.99	± 0.034
18.9	22000	1.98	± 0.050

3. Experimental results

The experimental results on the lamellar spacing measurements are given in Table I for Sn-Cd and Table II for Sn-Pb. The final column of the tables lists the 95% confidence interval as determined from the student *t*-distribution. The number of measurements in most cases was twenty-five. The difference in the no-field spacing versus the field spacing falls within the 95% confidence interval in all cases except for one of the no-field measurements at 2.12 μm sec^{-1} on Sn-Cd. Since the upper no-field measurement in this experiment agreed with the field measurement it seems likely that the high value of 4.27 μm was owing to experimental error. The data were also analysed by calculating the t-statistic for the comparison of two means [8]. This test showed that there was no significant difference between the no-field spacing versus the field spacing at the 95% confidence level for all of the data except for the above mentioned value on Sn-Cd. Consequently, it is concluded that a magnetic field of 22000 to 23000 Oe had no effect upon the measured lamellar spacing of Sn-Cd and Sn-Pb eutectics within the precision of our measurements, which averaged 2.5% of the measured spacings as determined by the 95% confidence interval. Because of the square root relationship between lamellar spacing and diffusion coefficient we conclude that the effect of the magnetic field upon the liquid diffusion coefficient in Sn-Pb and Sn-Cd was probably less than 5% of its value and certainly less than 10%.

If the magnetic field did affect the diffusion coefficient one would expect the effect to be a maximum for diffusion perpendicular to the field and to be zero for diffusion parallel to the field. Therefore, since diffusion would be easier parallel to the field one might expect the lamellae to prefer to align themselves perpendicular to the magnetic field. To check this possibility specimens of Sn-Cd and Sn-Pb were solidified for $2\frac{1}{2}$ in. under a field of 23000 Oe. Sections from the final solidified end were examined metallographically to determine, (1) if the grains rotated to line up the lamellae relative to the magnetic field, and (2) if the plate spacing was a function of the angle between the lamellae and the magnetic field. Histograms were prepared for the number of grains versus the angle of their lamellae with the magnetic field and for the lamellar spacing versus the angle of the lamellae with the magnetic field. Fifty grains were examined in Sn-Cd and fifty-four grains in Sn-Pb. No correlation could be seen of either the lamellar direction or lamellar spacing with the magnetic field direction. This result supports the conclusion that the magnetic field produced no observable effect upon the diffusive transport at the eutectic growth front.

4. Discussion

Cahoon and Youdelis [9] have suggested two restrictions under which one would not expect a magnetic field to affect diffusive transport. (1) If the two metals have similar valences the free electron gradient associated with the concentration gradient would perhaps be too small to allow an effect from the magnetic field. (2) If the length to width ratio of the diffusion field is large, as in conventional capillary reservoir experiments, the Hall field will build up and cancel the Lorentz force on the free electrons thereby inhibiting the magnetic field effect. The present experiments are not subject to restriction (2) but the Sn-Pb experiments are subject to restriction (1). Therefore, although the theory [4, 5] would predict the magnetic field effect would be quite limited in Sn-Pb, there does not appear to be any *a priori* reason for a similar prediction on Sn-Cd.

Recent experiments [10-12] have clearly shown that a magnetic field significantly reduces fluid flow in liquid metals. Therefore, in addition to any possible constraint on liquid diffusion, a magnetic field will affect solidification experiments by reducing fluid flow. In the present experiments very little fluid flow was present near the interface because of the vertical linear heat flow. In addition, fluid flow does not significantly affect the lamellar spacing of eutectics [13]. Hence, one would not expect the influence of the magnetic field in suppressing fluid flow to affect the measurements made here. However, in the solidification experiments which claim to show that a magnetic field inhibits liquid diffusion in Al-Cu alloys [5, 6] fluid flow was known to be present and, therefore, it is not clear in those experiments that the measured effects of the magnetic field are due only to constrained liquid diffusion and not to suppression of the fluid flow.

5. Conclusions

Application of a moderately high magnetic field to the directional solidification of Sn-Pb and Sn-Cd alloys does not affect the lamellar spacing sufficiently to be measurable by standard metallographic technique Statistical analysis of the data indicates that the effect of magnetic fields of 23000 Oe upon the liquid diffusion coefficient is probably less than 5% and certainly less than 10%. These results indicate that the effect of the magnetic field upon suppression of liquid diffusion in Sn-Cd and Sn-Pb is less than expected, based on the measurements of Youdelis *et al* [5, 6] on Cu-Al alloys. It seems very questionable that application of moderately high magnetic fields will allow one to reduce the fibre spacing during directional solidification of aligned composite eutectics.

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References

1. W. A. TILLER, "Liquid Metals and Solidification" (ASM, Cleveland, Ohio, 1958) p. 276.
2. K. A. JACKSON and J. D. HUNT, *Trans. Met. Soc. AIME* **236** (1966) 1129.
3. L. M. HOGAN, R. W. KRAFT, and F. D. LEMKEY, "Advances in Materials Research," Vol. 5 (John Wiley, New York, 1971).
4. W. V. YOUNDELIS, D. R. COLTON, and J. CAHOON, *Canad. J. Phys.* **42** (1964) 2217.
5. *Idem*, *ibid* **42** (1964) 2238.
6. W. V. YOUDELIS and R. C. DORWARD, *ibid* **44** (1966) 139.
7. J. E. GRUZLESKI and W. C. WINEGARD, *J. Inst. Metals* **96** (1968) 301.
8. R. A. FISHER, "Statistical Methods for Research Workers", 14th Edn. (Oliver and Boyd, Edinburgh, 1970) p. 122.
9. J. R. CAHOON and W. V. YOUDELIS, *Canad. Met. Q.* **8** (1969) 39.
10. D. R. UHLMAN, T. P. SEWARD, and B. CHALMERS, *Trans. Met. Soc. AIME* **236** (1966) 527.
11. H. P. UTECH and M. C. FLEMINGS, in "Crystal Growth," Ed. H. S. Peiser (Pergamon Press, New York, 1967) 651.
12. D. T. J. HURLE, *ibid*, p. 659.
13. J. D. VERHOEVEN and R. H. HOMER, *Met. Trans.* **1** (1970) 3437.

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