JOURNAL OF MATERIALS SCIENCE 16 (1981) 1367–1373

Electrical anisotropic property of some unidirectionally solidified eutectic alloys

I. H. MOON, Y. L. KIM, I. S. AHN*
Department of Materials Engineering, Han Yang University, Seoul, Korea

The eutectic systems of Cd–Pb, Bi–Cd and Bi–Zn were alloyed using chemically pure raw materials in an electric furnace. The electrical resistivities were determined at room temperature in terms of the microstructures of the eutectic alloys. Electrical resistivities measured parallel and perpendicular to the unidirectional microstructure at different solidification rates were quite distinctive. The electrical resistivities measured were consistent with calculated values. The present study indicates qualitatively that unidirectional solidification of ideal conductor–insulator eutectic systems could produce electrical anisotropic materials.

1. Introduction

Eutectic microstructures are classified as regular (normal) or irregular forms. Regular eutectics are lamellar or rod-like in nature, and frequently demonstrate more interesting physical and mechanical properties than their irregular form which is usually shown as broken lammelar or dendritic structures.

Since 1950 numerous investigations have been documented concerning the mechanism of eutectic solidification and the relationships between microstructure and growth rate in eutectic alloys. The impetus for such studies is the potential use of such alloys as high strength structural materials [1]. The structure against mechanical properties of eutectic alloys has been extensively investigated.

Although it is expected that the anisotropic microstructure associated with eutectics should produce interesting electrical properties, few studies on electrical properties have been reported. Since 1970 Ondracek [2–4] has extensively investigated the dependance of electrical resistivity on directional features of microstructures and respective phase volume fractions in numerous ceramic–metal eutectics [2–4]. As a result of these studies, a number of phenomelogical equations relating electrical resistivity to the microstructure of eutectics were developed.

The present study is an extension of these efforts to other unidirectionally solidified eutectic systems. The subjects studied were selected on the basis of several criteria as noted below: (1) The systems should have low melting points for experimental convenience; (2) One phase in the eutectic should have a markedly greater electrical resistivity than the other, because it allows easier detection of the effect of microstructure; (3) In the systems chosen, the microstructure as related to growth conditions should be well understood.

Using the above criteria the following three systems were selected: (1) Cd–Pb, a prototype of a regular eutectic alloy; (2) Bi–Cd, a prototype of a quasi-regular eutectic alloy; (3) Bi–Zn, a prototype of an irregular eutectic alloy.

2. Experimental procedure

The raw materials used for the present investigation were Bi of 99.99% purity, produced by Korea Tungsten Mining Co., and Pb, Cd and Zn all of 99.9% purity. High purity zinc (99.999%) was used for some specimens to determine the impurity effect. Alloying was achieved by melting the pure materials in an electric furnace for 1 h. During alloying the liquid alloy was covered with an epoxy resin layer in order to prevent or minimize oxidation of the melt.

The specimens were vacuum sealed in glass tubes of 10 mm diameter and about 100 mm length

*Present address: Korean Air Force Academy, Korea.

0022–2461/81/051367–07$02.70/0

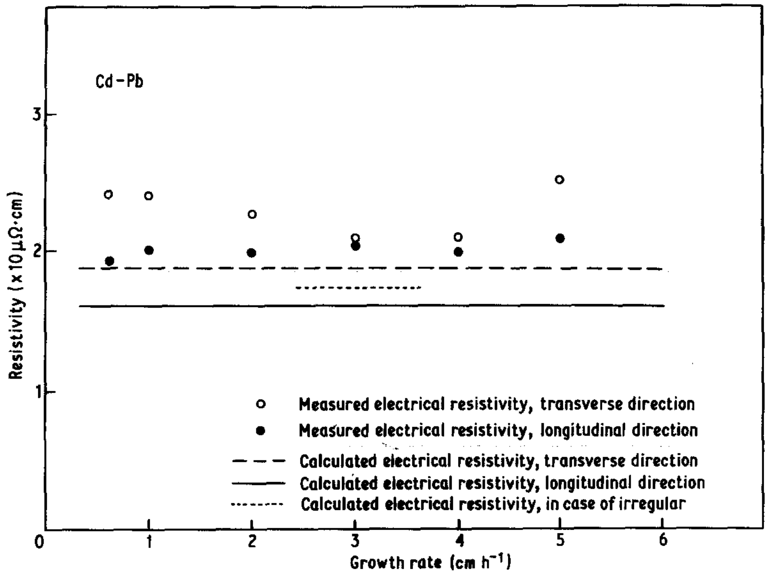

Figure 1 Relationship between growth rate and electrical resistivity in Cd–Pb eutectics.

prior to unidirectional solidification. After insertion into a Bridgman-type furnace, the alloy was held at the eutectic temperature for 1 h in order to obtain alloy homogeneity. The homogenized alloy was then unidirectionally solidified at rates from 0.63 to 9.1 cm h^{-1}. The temperature gradient was about 25° C cm^{-1}.

Specimens of length from 10 to 20 mm were cut from the middle of the unidirectionally solidified bar. Microstructures of polished and unetched specimens were observed under a reflective microscope. The lamellar space of the microstructures was determined in the conventional manner. Specimens of rectangular cross-section of dimensions small compared with the length were used for electrical resistance measurements. Specimen end faces were polished carefully to minimize contact resistance. At room temperature electrical resistance was measured with a Kelvin double bridge.

3. Results and discussion

The variation of electrical resistivity with growth rate for the various eutectic alloys is shown in Figs 1 to 3. The solid and dashed lines represent the calculated values of the resistivity for the pertinent systems. The phenomenological equations used to determine the values are given in Table I and the data listed in Table II are used for the

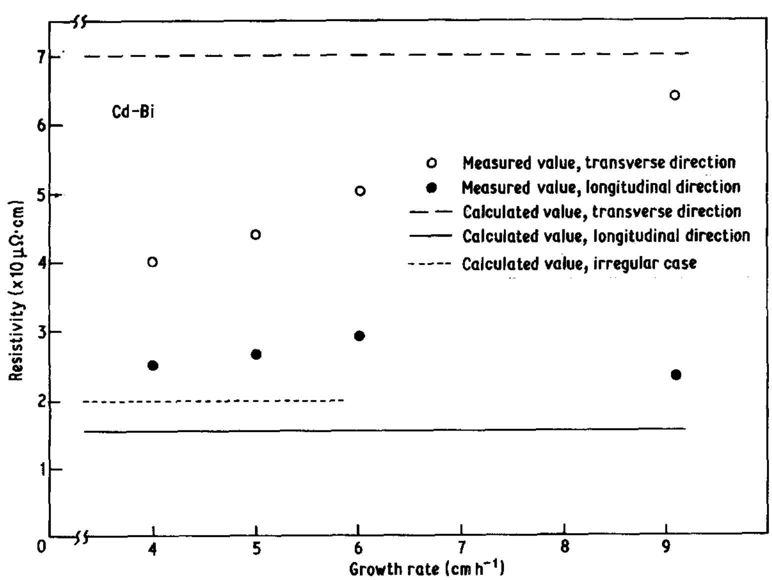

Figure 2 Relationship between growth rate and electrical resistivity in Bi–Cd eutectics.

TABLE I Equation relating electrical resistivity to microstructure for some special cases

Type of structure	Electrical resistivity parallel to the solidification direction		Electricial resistivity perpendicular to the solidification direction		Electrical resistivity for a random distribution	
Lamellar	$\rho_e = \dfrac{\rho_1 \cdot \rho_2}{\psi_1 \rho_2 + \psi_2 \rho_1}$	(1)	$\rho_e = \psi_1 \rho_1 + \psi_2 \rho_2$	(2)	$1 - \psi_2 = \dfrac{\rho_2 - \rho_1}{\rho_1 - \rho_2} \quad \dfrac{\rho_2 + 2\rho_1}{\rho_2 + 2\rho_e}$	(3)
Rod-like	$1 - \psi_1 = \dfrac{\rho_1(\rho_e - \rho_2)}{\rho_e(\rho_1 - \rho_2)}$	(4)	$1 - \psi_1 = \dfrac{\rho_e \cdot \rho_e}{\rho_1 - \rho_2} \cdot \dfrac{\rho_1}{\rho_e}{}^{1/2}$	(5)	$1 - \psi_2 = \dfrac{\rho_1(\rho_e - \rho_2)}{\rho_e(\rho_1 - \rho_2)} \cdot \dfrac{\rho_e(\rho_1 + 5\rho_2)}{\rho_1(\rho_e + 5\rho_2)}{}^{2/5}$	(6)

where ρ_1 and ρ_2 are the electrical resistivities of eutectic constituents 1 and 2, respectively; ψ_1 and ψ_2 are the volume fractions of eutectic constituents 1 and 2, respectively; and ρ_e is the electrical resistivity of the eutectic alloy.

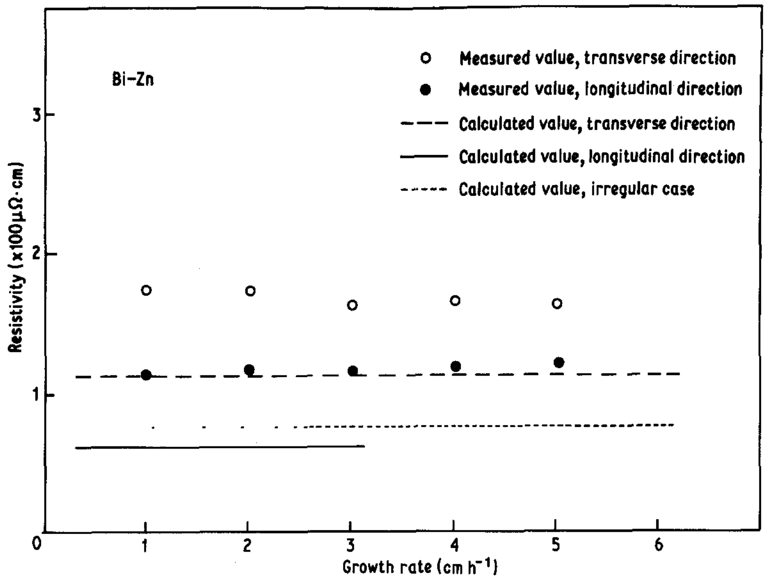

Figure 3 Relationship between growth rate and electrical resistivity in Bi–Zn eutectics.

calculation. Calculated values were assumed independant of growth rate for a given system, although differences in size and space of the lamellae may be expected to effect electrical resistivity.

3.1. Cd–Pb system

As shown in Fig. 1 electrical resistivities of Cd–Pb eutectics, which are parallel to the solidfication direction, are generally lower than resistivities in the transverse direction. This, however, does not hold for Cd–Pb alloys solidified at a growth rate of $3\,\mathrm{cm\,h^{-1}}$. Microstructural examination of the alloys (Figs 4 and 5) shows that the eutectic structure has "broken down" at this growth rate, as indicated by the lack of preferential lamellar alignment with the solidification direction. Such a break-down has previously been observed in this system [8]. Calculated resistivity, therefore, using Equation 3 may be more reliable. The values calculated in this way are shown by the dotted line in Fig. 1.

A systematic difference of about $5\,\mu\Omega\,\mathrm{cm}$ between measured and calculated values of electrical resistivities in Cd–Pb eutectics exist. This is believed to be due to the impurity level or contact resistance of the experiment.

3.2. Bi–Cd system

Fig. 2 shows the relationship between electrical resistivity and growth rate in Bi–Cd eutictics. The eutectic structure of Cd–Bi has been known as "quasi-regular" [7]. This type of structure is also observed in the present study (Fig. 6). The measured and calculated values of electrical resistivity for Bi–Cd eutectic approached each other with increasing growth rate. As shown in Fig. 6 lamellar alignment with the solidification direction becomes more pronounced with increasing solidification rate. This microstructural features make it reasonable to calculate the resistivity of a specimen grown at $9.1\,\mathrm{cm\,h^{-1}}$.

It should be noted that in Bi–Cd system the resistivity measured transverse to the solidfication direction is always lower than the calculated one. This may be due to the oversimplification in the calculation in which the microstructure is assumed to be the regular lamellar type although irregularities exist to some extent.

TABLE II Ancillary data used for calculation of composite electrical resistivity

System	Electrical resistivity [5] ($\mu\Omega$ cm)	Volume fraction of constituent 2 [6]	Remarks [6, 8]
Cd–Pb	7.4 20.6	0.19	Regular (lamellar or rod-like)
Bi–Cd	116	0.43	Quasi-regular
Bi–Zn	5.9	0.004	Broken lamellar

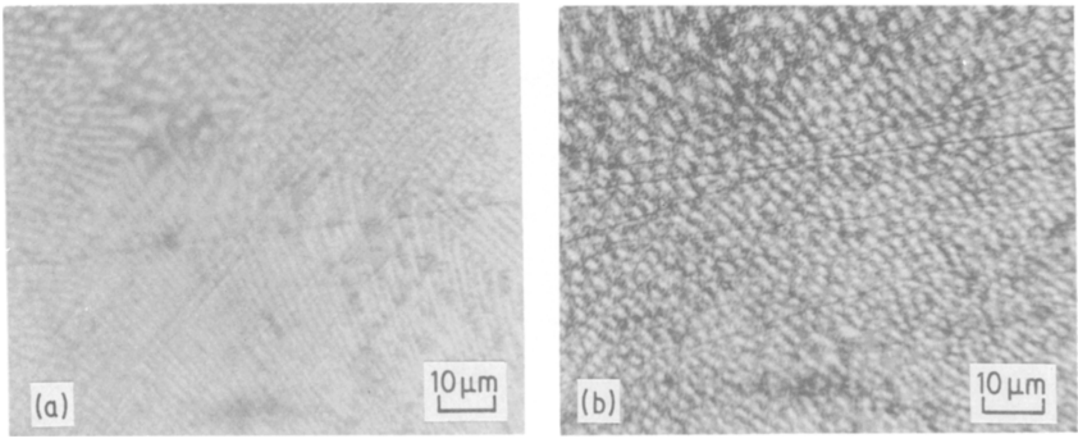

Figure 4 Microstructures of Cd–Pb eutectics perpendicular to the solidification direction at growth rates of (a) 3 cm h^{-1} and (b) 0.63 cm h^{-1}.

3.3. Bi–Zn system

The relationship between the electrical resistivity and growth rate in Bi–Zn eutectics is shown in Fig. 3. The measured values of electrical resistivities parallel to the solidification direction are generally lower than those of resistivities in the transverse direction. The differences of the measured electrical resistivity between the transverse and longitudinal direction slightly decreased with increasing solidification rate. This might be attributable to the micro structure of the pertinent eutectic system.

The eutectic structure of Bi–Zn has been classified as irregular. However, the stable Zn phase is formed as broken lamellar. The lamellar direction is alligned to the solidification direction at a relatively lower growth rate (Fig. 7a). This broken lamellar structure, however, becomes unstable, and changed to an irregular fibre structure at an increased growth rate (Fig. 7b), which was generally expected [9]. In Bi–Zn eutectics, however, the electrical resistivity was rather independent of growth rate since the good conductor phase. Zn, was only 0.4% of the total volume of the eutectics, and this phase forms a broken lamellar structure.

In eutectics of Bi and high-purity Zn systems, similar results were obtained. Therefore the effect of impurity content as a minor constituent is not believed to be significant.

Finally the lamellar spaces observed in these systems investigated were also compared with those in the literature. Table III shows the dependance of lamellar space on growth rate, in which the lamellar spaces may be calculated using the

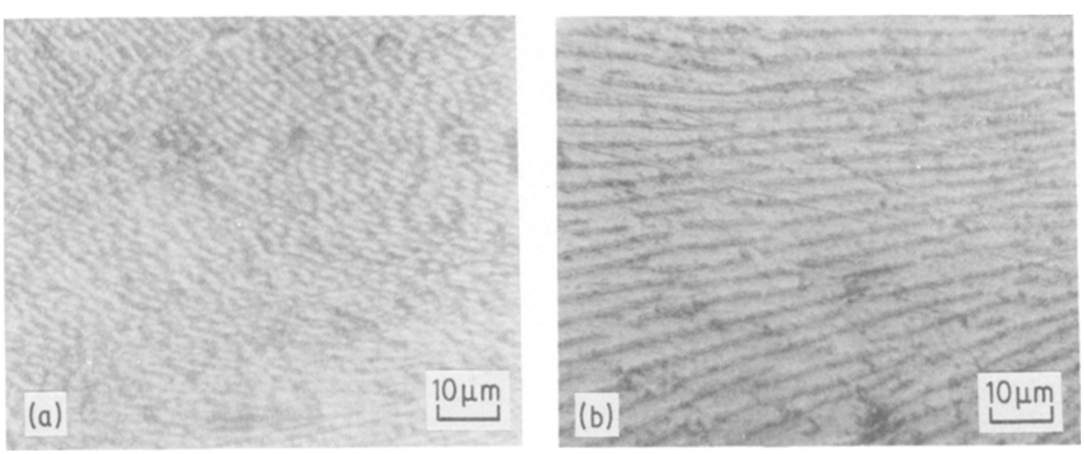

Figure 5 Microstructures of Cd–Pb eutectics parallel to the solidification direction at growth rates of (a) 3 cm h^{-1} and (b) 0.63 cm h^{-1}.

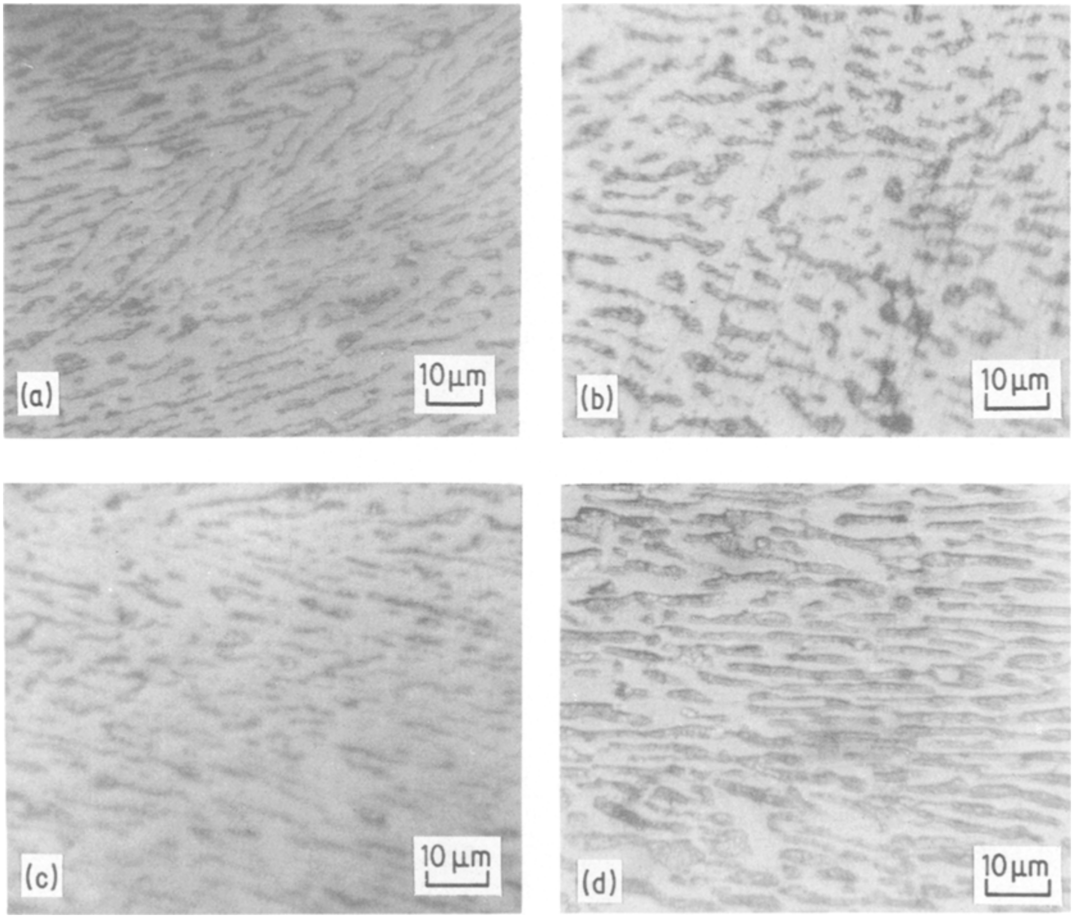

Figure 6 Microstructures of Cd–Bi eutectics parallel to the solidification direction at various growth rates: (a) 4 cm h^{-1}. (b) 5 cm h^{-1}, (c) 6 cm h^{-1} and (d) 9.1 cm h^{-1}.

TABLE III The dependance of lamellar spaces on growth rate

System	Growth rate (cm h^{-1})	Lamellar space, calculated (μm)	Average lamellar space observed (μm)
Cd–Pb	0.63	3.5	3.7
	1	2.7	2.5
	2	1.8	1.7
	3	1.6	1.5
	4	1.3	1.4
	5	1.1	1.0
Bi–Cd	4	3.0	3.3
	5	2.7	2.7
	6	2.4	2.5
	9.1	2.0	2.1

general relationship between lamellar spacing (λ) and growth rate (v) of

$$\lambda = A \cdot v^{-n}, \qquad (1)$$

and inserting A and n values quoted from the literature [10, 11]. As shown in Table III, the lamellar spacings observed were consistent with those calculated.

4. Conclusions

From the above results it may be cautiously concluded that if the unidirectional solidification technique could be applied to an ideal system, suitable electrically anisotropic materials might be produced which could be applicable to practical use.

Acknowledgement

The authors are indebted to Professor T. H. Courtney for his help with the final draft of the manuscript.

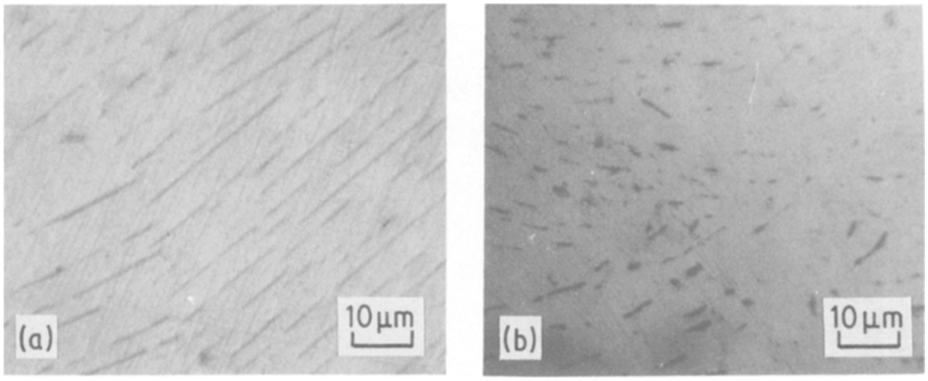

Figure 7 Microstructures of Bi–Zn eutectics parallel to the solidification direction at growth rates of (a) 1 cm h^{-1} and (b) 9.1 cm h^{-1}.

References

1. R. ELLIOTT, *Intern. Met. Rev.* (1977) 161.
2. G. ONDRACEK and B. SCHULZ, *Ber. Dt. Keram. Ges.* **48** (1971) 525.
3. G. ONDRACEK, *Z. f. Werkstofftechnik* **5** (1974) 416.
4. *Idem, ibid.* **8** (1977) 240.
5. C. J. SMITHELLS, "Metal Reference Book", Vol. 2, (Buterworths, London, 1967).
6. W. KURZ and P. R. SAHM, "Gerichtet Eratarrte Eutektische Werkstoffe", (Springer Verlag, Berlin, 1975).
7. M. N. CROKER, R. S. FIDLER and R. W. SMITH, *Proc. Roy. Soc.* **A335** (1973) 15.
8. B. C. PAI, C. V. SHASTRY and E. S. DWRAKADASA, *Indian J. Technol.* **11** (1973) 701.
9. W. C. WINEGRAD, "An Introduction to the Solidification of Metals", (Institue of Metals, London, 1964).
10. V. de L. DAVIES, *J. Inst. Met.* **93** (1964/5) 10.
11. B. L. JONES, *J. Australian Inst. Met.* **14** (1969) 111.

Received 10 September and accepted 18 November 1980.