Title
SPECIMEN PREPARATION AND MECHANICAL PROPERTIES OF DIRECTIONALLY SOLIDIFIED Al-Si EUTECTIC COMPOSITE

Author
Justi, Stefan

Publication Date
1977-05-01

Submitted to Metallurgical Transactions

LBL-6238
Preprint c.2

SPECIMEN PREPARATION AND MECHANICAL PROPERTIES OF DIRECTIONALLY SOLIDIFIED Al-Si EUTECTIC COMPOSITE

Stefan Justi and Robert H. Bragg

May 1977

Prepared for the U. S. Energy Research and Development Administration under Contract W-7405-ENG-48

LBL-6238

SPECIMEN PREPARATION AND MECHANICAL PROPERTIES OF DIRECTIONALLY SOLIDIFIED Al-Si EUTECTIC COMPOSITE

Stefan Justi and Robert H. Bragg

Materials and Molecular Research Division, Lawrence Berkeley Laboratory,
and Department of Materials Science and Minerals Engineering,
University of California, Berkeley, California 94720

ABSTRACT

Al-Si eutectic alloys have been directionally solidified in a horizontal resistance heated furnace. The temperature gradient, G, ahead of the solid/liquid interface was kept fairly constant at 80°C/cm, while the growth rate, R, was varied between 0.1 and 47 cm/h. Microstructural studies show a definite alignment of the rod-like Si at low growth rates. At growth rates higher than 5.0 cm/h the microstructures appear irregular, although some preferential orientation of the Si rods parallel to the growth direction can be observed. Tensile tests show higher values in both yield and ultimate strengths than was found in previous investigations, most likely due to the careful sample preparation prior to testing in the present work. The yield strength increases with the growth rate up to about 5 cm/h, and only a slight increase is observed at higher rates. The ultimate strength also increases with the growth rate, but shows less tendency toward saturation. Superposition of hardness and yield data show excellent correlation, while comparison between hardness and ultimate strength shows higher hardness than ultimate values with decreasing growth rates.

INTRODUCTION:

Directional solidification of eutectic alloys has been widely acknowledged as a way to improve the strength, thermodynamic stability, creep and corrosion resistance of materials at both room and elevated temperatures. Although there have been numerous publications on directional solidification of eutectics in recent years, not much has been reported about their mechanical properties. Most investigators discuss the mechanical properties of directionally solidified (d.s.) eutectics in terms of composite materials composed of an aligned strengthening phase embedded in a soft matrix. The properties are calculated using the Rule of Mixtures (RoM) for a first approximation.

The mechanical properties of d. s. Al-Si eutectic which is an important commercial material have been reported in several investigations[1-3], but the results differ from each other. In this paper we are reporting tensile properties of d. s. Al-Si eutectic grown at different rates. Our results will be compared with those of the previous investigators[1-3]. We will also compare them with Vickers hardness measurements[4].

EXPERIMENTAL:

As described elsewhere[4], ingots with the dimensions 25.4 cm x 2.54 cm x 1.43 cm were directionally solidified at nine different growth rates, R, ranging from 0.1 cm/h to 47 cm/h in a horizontal, resistance heated furnace. The temperature gradient, G, ahead of the solid/liquid interface was kept fairly constant at about 80°C/cm.

After solidification, the ingots were cut as shown in Fig. 1, based upon observations using standard metallographic techniques. Typically region A had a multigrain microstructure and was not used in further investigations. Optical micrographs taken from Regions B and D showed that a single grain eutectic crystal was predominant. Region C was sliced as shown in Fig. 1, and three subsize sheet type tensile specimens were prepared for each growth rate. The specimens had an overall length of 40mm and a width of 6mm, the gauge section was 22 mm in length and 4mm in width, and the thickness was 1.65mm. The stress axis was parallel to the growth axis. After machining the specimens were held at 450°C for 30 minutes to eliminate possible cold working effects. They were then carefully polished to reduce surface defects. The testing was carried out on an INSTRON testing machine at room temperature at a cross-head speed of 0.05 mm/min. Elongations were measured by a 13 mm INSTRON extensometer. For the purpose of obtaining accurate data for the 0.2% offset yield strength[5], load and elongation were recorded with the highest possible sensitivities, up to approximately 0.35% elongation. Thereafter lesser sensitivities were used to record maximum load and elongation.

RESULTS

Optical micrographs taken from region B are shown in Fig. 2 a-f. It can be seen that at the slow growth rate there is an alignment of the Si-phase with the growth direction. The flaky Si grows dendritically, but due to the high G/R ratio there is only little evidence of side branching (Fig. 2a). As the growth rate increases, the particle size of the Si-phase becomes finer, the spacing between the Si flakes decreases, and more side branching occurs (Fig. 2c). At a growth rate of 4.6 cm/h and higher the Si phase forms non-aligned irregular dendrites in the

Al matrix, which have been found to be interconnected.[6] Fig. 2e shows, however, that there is still a preferential orientation of the Si dendrites with the growth axis.

Typical engineering stress-strain curves for samples grown at three different rates are shown in Fig. 3 (the sections of the curves with strains up to 0.35%, which were recorded at a higher sensitivity, were redrawn to fit into this plot). The tensile data are summarized in Table 1. After calculating the means and standard deviations for each growth rate, the stresses were plotted versus $R^{1/4}$ for the same reasons as in Ref. 4.*

The yield strength (YS), which was taken from the 0.2% elongation offset point[5], versus $R^{1/4}$ is shown in Fig. 4. Two different regions can be seen. At growth rates lower than 5 cm/h the yield strength increases linearly with $R^{1/4}$ while at growth rates higher than 5 cm/h no significant increase of the yield strength is observed.

Fig. 5 shows the ultimate tensile strength (UTS) versus $R^{1/4}$. In the lower growth rate region an increase of the UTS with $R^{1/4}$ can be observed similarly to the behavior of YS in Fig. 4, but at the higher growth rates there is less tendency toward saturation over the range of growth rates examined.

DISCUSSION

The microstructures shown in this work confirm earlier reports[1-4] that with increasing growth rates there is a gradual structural change

---

*It has been found that a Hall-Petch type relationship exists in d.s. eutectics with λ, the interparticle spacing substituting for grain size d. It has also been found that in the Al-Si eutectic a $\lambda^2 R$ = constant relationship is maintained. Thus an appropriate variable to test the yield stress for Hall-Petch behavior is $R^{1/4}$ instead of d. A more detailed explanation is given in Ref. 4.

of the eutectic Si-phase from a rod-like (Fig. 2a) to a branched dendritic (Fig. 2c) to an irregular form (Fig. 2e). The growth rates employed here were not high enough to show the transition to the fibrous form of Si which has been of interest to many workers[7]. For purposes of comparison the data of the previous investigators[1-3] were plotted on to Figs. 4 and 5. It can be seen that the tensile data obtained in this work are considerably higher than those reported earlier. Steen and Hellawell[1] report data for only two growth rates. The material for their tensile test samples was grown under different conditions (larger dimensions) than that for their microstructural characterization. Thus the possibility of growth defects in their tensile specimens which are conducive to fracture at low stresses cannot be excluded.

The data reported by Sahoo and Smith[2-3] show that both yield and ultimate strengths increase with the growth rate, but it is difficult to draw two smooth curves which have consistent trends owing to the scattering of the data. As with the data of Steen and Hellawell, the data of these investigators indicate lower properties than obtained in the present work.

As early as 1921 it was found that cracks propagate through the flaky form of Si[8]. Cracks spread easily because the cleavage plane of Si is {111}, which often is the plane of faceted flakes in which the parallel twins are also {111}. Steen and Hellawell[1] make this way of crack propagation responsible for the sensitivity of tensile specimens to surface defects and scratches. This might account for the differences noted herein, because in this work the specimens were not only machined as in Refs. 1-3, but were carefully polished before testing, thus reducing surface defects, and the results obtained show indeed a noticeable increase in strength. Further proof that the tensile properties are very sensitive to the surface treatment was found in preliminary tests. Material taken from the same ingots as in this investigation was machined but not polished, and exhibited lower yield strength.[9]

A similar behavior of the strength as in Figs. 4 and 5, i.e. monotonic increase at slow and no dramatic change at high growth rates, has recently been found for the d.s. Cd-Zn eutectic[10] which is of the regular type but has the same volume fraction of the reinforcing phase as the Al-Si system.

It can be assumed that at low growth rates the alignment of the Si-phase does not contribute to higher strength. To support this, Gangulee and Gurland[11] have found that the fracture probability increases with the Si particle size. At high growth rates the reason for the relatively small increase in strength is most likely the same as in the case of the Cd-Zn eutectic, i.e. the misalignment of the reinforcing phase. Only if the Si changes into the fibrous form can further increase of strength be obtained.

The results found here are supported by hardness data. Chadwick states[12] that "despite the reservation that can be placed on the hardness test as providing a measure of the stress-strain behavior, hardness data and the yield stress of single crystal eutectics correlate quite well where both techniques have been employed." The HV1 hardness data obtained earlier[4] were superimposed on the YS and the UTS. The superposition was done through multiplication of the hardness numbers by constant factors 0.13 for the YS and 0.3 for the UTS, respectively. As can be seen in Fig. 4 the correlation between YS and hardness is excellent. Figure 5 shows that in the lower growth rate region the hardness is higher than the UTS. This is in agreement with higher compression than tensile data[2]. It also supports the finding that in case of tension the crack propagation is made easier with an increasing size of Si particles[11].

CONCLUSIONS

1. Increasing growth rates change the morphology in the directionally solidified Al-Si eutectic from rod-like to branched dendritic to irregular flakes.

2. YS and UTS increase monotonically with increasing growth rates, R, but at rates R greater than approximately 5 cm/h saturation is reached in YS, while the UTS continues to rise with a monotonic decreasing slope.

3. Hardness data correlate excellently with YS, thus proving that in this system hardness is a valuable measure to obtain mechanical property data where dimensions of the test material limit tensile measurements.

Work performed under the auspices of the U. S. Energy Research and Development Administration.

REFERENCES

1. Steen, H. A. H. and Hellawell, A., Acta. Met. 20, 1972, p. 363.
2. Sahoo, M. and Smith, R. W., Met. Sci., 9, 1975, p. 217.
3. Sahoo, M. and Smith, R. W., Canad. Met. Q.15, 1976, p. 1.
4. Justi, S. and Bragg, R. H., Met. Trans. 7A, 1976, p. 1954.
5. American National Standard Z 168.23-1971, American National Standards Institute.
6. Day, M. G. and Hellawell, Proc. Roy. Soc. A., 1968, Vol. 305, p. 473.
7. Smith, R. W., "The Solidification of Metals", Iron and Steel Institute Pub. No. 110, 1968, p. 226.
8. Pacz, A., U. S. Patent 1,387,900 (1921).
9. Morrow, D., "Mechanical Properties of Directionally Solidified Al-Si Eutectic", M. S. Thesis, UCBLBL Report No. 6063, Lawrence Berkeley Laboratory, 1977.
10. Sahoo, M., Porter, R. A. and Smith, R. W., J. Mat. Sci. 11, 1976, p. 1680.
11. Gangulee, A. and Gurland, J., Trans. AIME 229, 1967, p. 271.
12. Chadwick, G. A., Acta. Met. 24, 1976, p. 1137.

TABLE 1: Room Temperature Tensile Properties of Directionally Solidified Al-Si Eutectic

gradient °C/cm	growth rate cm/h	0.2% off-set yield strength kg/mm^2	ultimate tensile strength kg/mm^2	uniform elongation %
80.6	0.1	6.4	8.6	2.6
		5.2	7.6	1.0
		4.9	8.7	1.7
78.0	0.25	5.5	9.4	4.0
		5.6	10.6	4.5
		6.3	9.2	2.2
74.8	1.0	6.6	11.9	3.9
		5.9	13.4	5.7
		6.0	13.0	5.7
79.1	2.4	7.0	13.0	-
		7.2	14.0	3.5
		6.3	14.1	5.0
88.5	4.6	6.8	14.8	5.7
		7.3	15.1	5.0
		7.5	15.8	8.0
78.0	4.9	7.0	15.4	5.1
		7.8	15.4	5.5
		7.3	15.7	7.5
78.0	9.7	7.9	15.8	8.6
		7.1	16.9	8.1
		7.9	16.2	7.0
101.5	23.2	7.9	17.9	8.9
		7.2	17.6	6.0
		7.6	17.4	6.6
50.2	47.0	8.3	17.0	6.7
		7.8	17.7	11.1
		7.0	18.7	9.8

FIGURE CAPTIONS

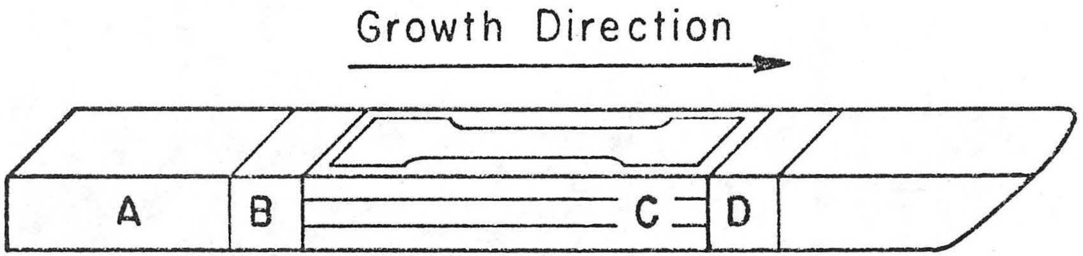
Fig. 1: Position of tensile specimen in d.s. Al-Al_2Cu ingot.

Fig. 2: Optical micrographs of d.s. Al-Al_2Cu eutectic.

Fig. 3: Typical engineering stress-strain curves (three different growth rates).

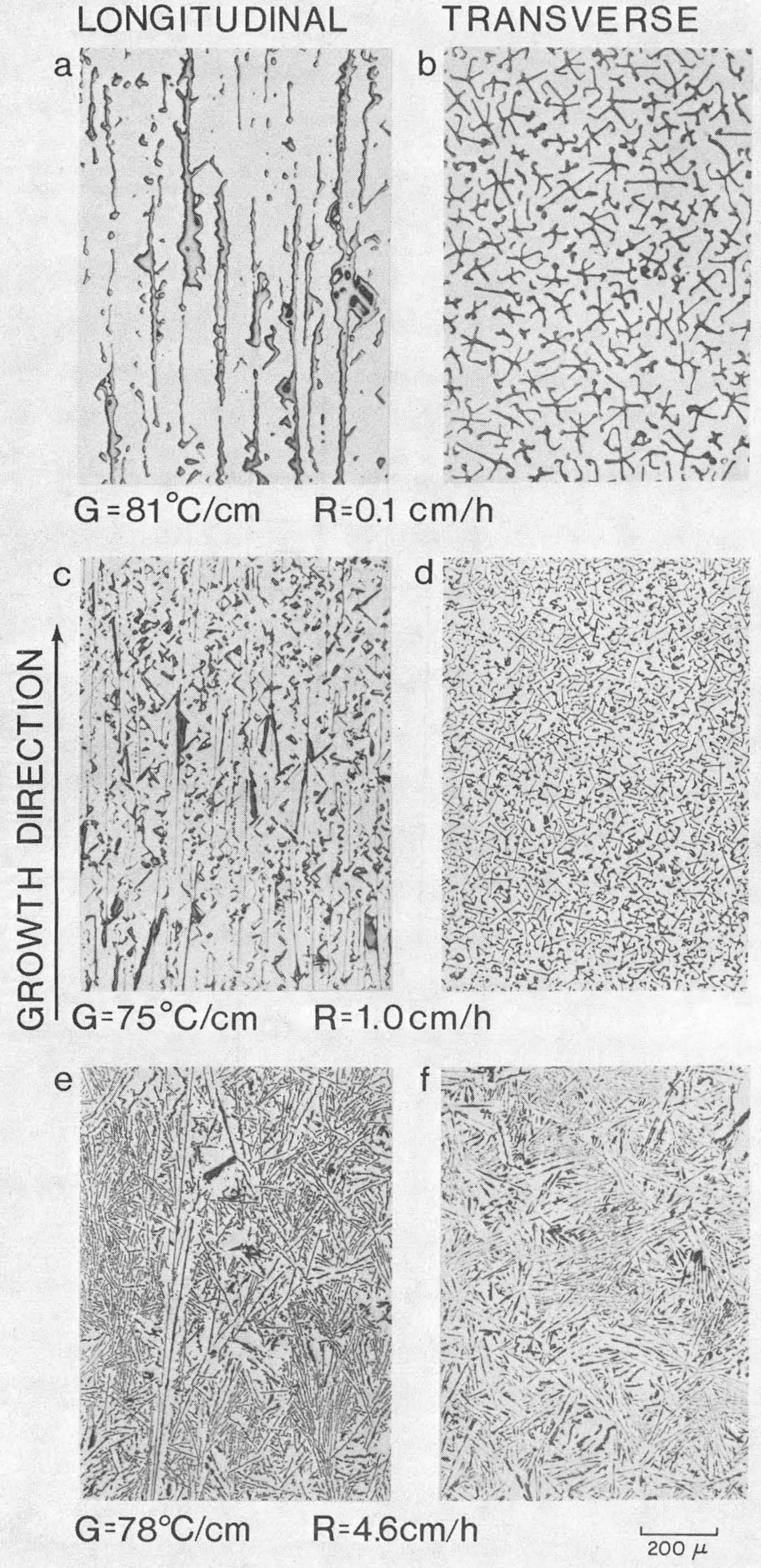
Fig. 4: Yield strength YS vs. growth rate $R^{1/4}$.

Fig. 5: Ultimate tensile strength UTS vs. growth rate $R^{1/4}$.



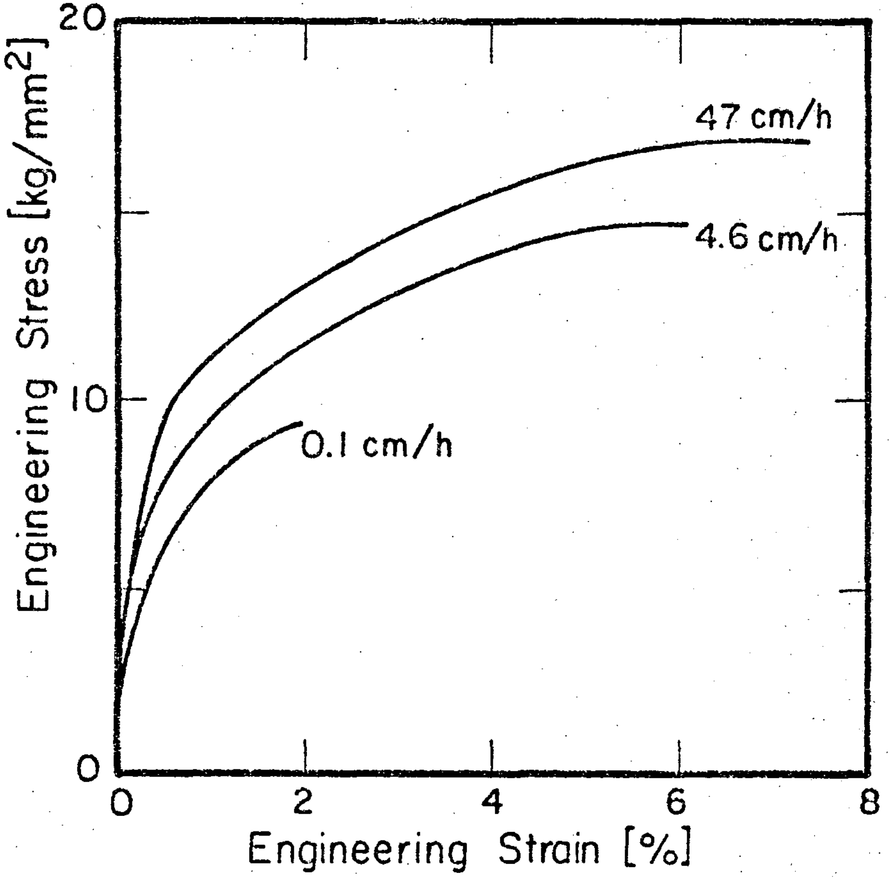
XBL 774-5398

Fig. 1



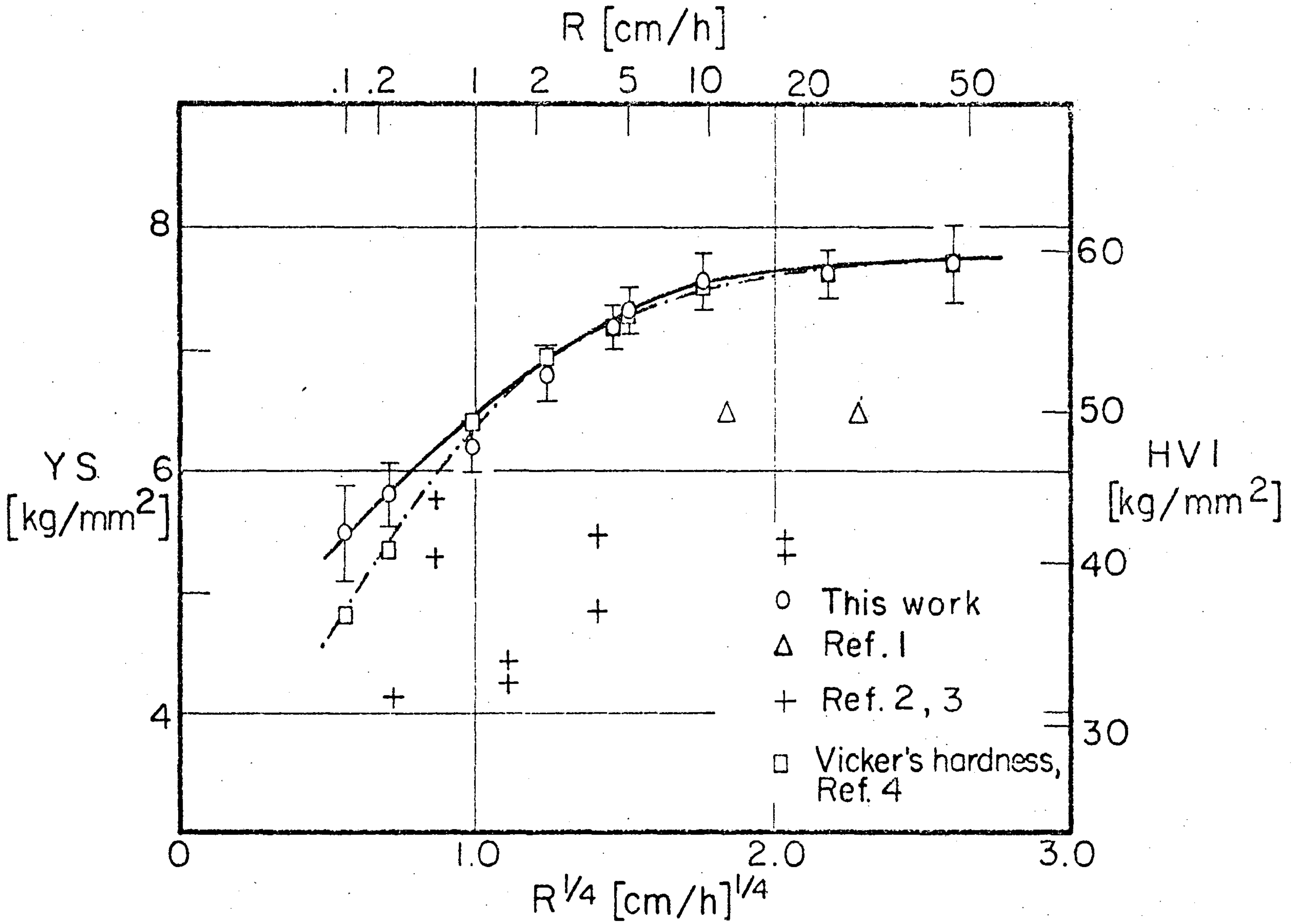
XBB 774-3600

Fig. 2



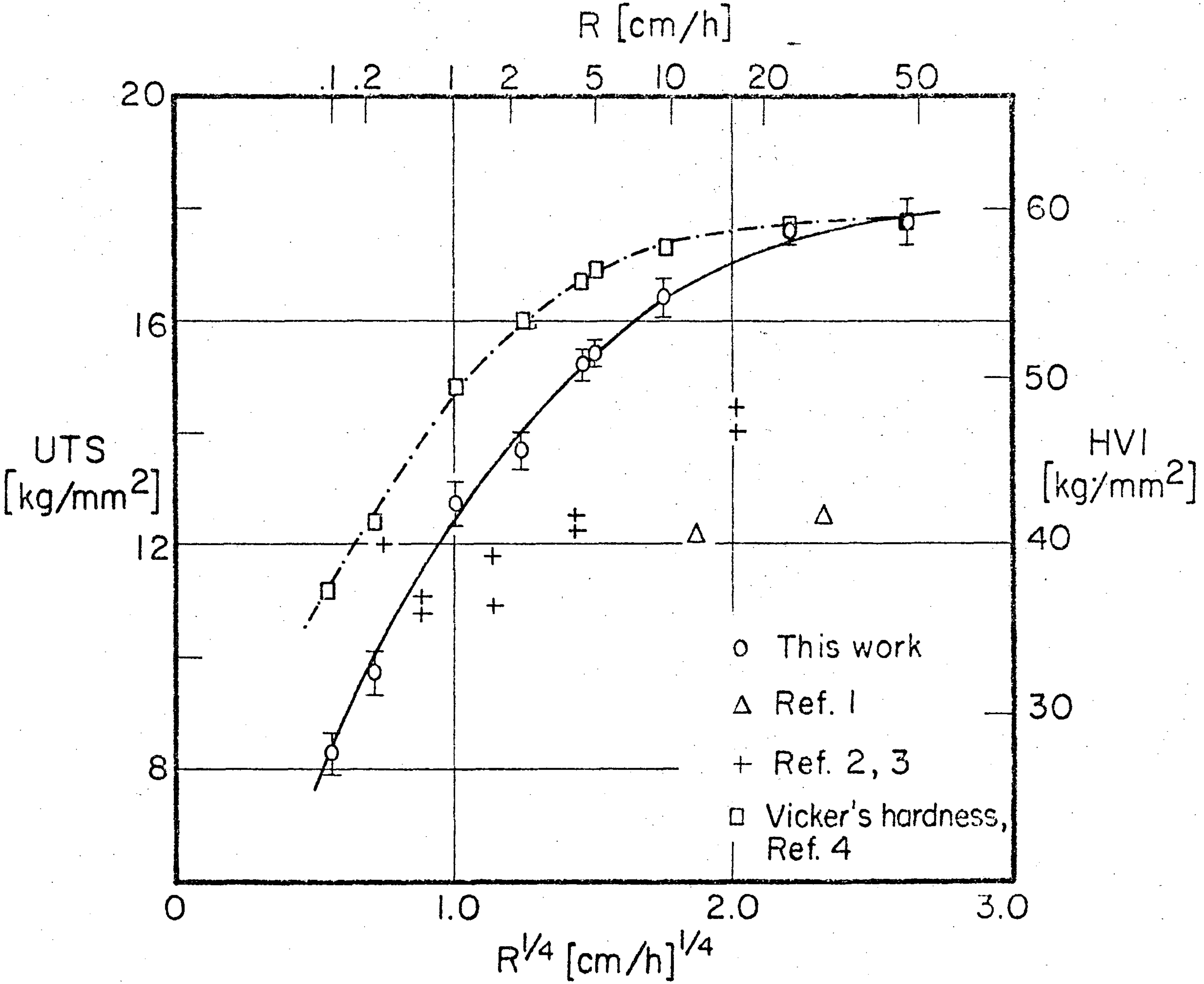
XBL 774-5399

Fig. 3



XBL 774-5400

Fig. 4



XBL774-5401

Fig. 5

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720