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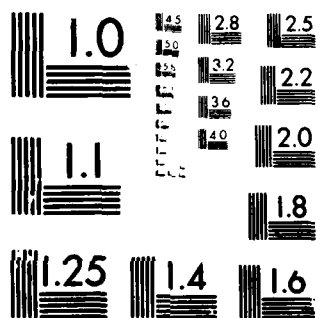
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This paper describes the effect of melt-spinning process parameters such as orifice diameter, ejection pressure, and wheel speed, in determining the ribbon dimensions of Pb-Sn eutectic and low content Al alloys.

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MELT SPINNING OF CRYSTALLINE ALLOYS

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Rapid solidification techniques have been studied ever since
the early experiments of Duwez et al (1,2). In recent years,
the melt-spinning process (sometimes known as chill block cast-
ing) has been of particular interest because of the possibility
of manufactoring iron-based amorphous alloys for magnetic appli-
cations (2). Liebermann and Graham (3) and Kavesh (4) have
discussed the effect of melt spinning process parameters on
the dimensions of melt-spun ribbons of amorphous $Fe_{40}Ni_{40}B_{20}$.
This note describes the results of an investigation into the
effect of melt spinning process parameters on the ribbon dimen-
sions of two other materials, namely Pb-Sn eutectic and Al
containing small quantities of Fe and Mn. The main objective
was to determine whether the conclusions of Liebermann and
Graham and Kavesh can be applied over a wide range of materials.
Thus, Pb-Sn and Al-(Fe,Mn) were chosen because they have very
different melting points from $Fe_{40}Ni_{40}B_{20}$, and because they
solidify in a crystalline rather than amorphous form.

Master alloys of Pb-Sn eutectic, Al-2 wt%Fe. and Al-2wt%Mn
were prepared by induction melting 99.99% pure components in
recrystallised alumina crucibles under a dynamic argon atomsphere
Melt-spun ribbons were produced as follows. Each specimen of
2-3g was placed in a 9mm diameter quartz tube at the bottom of
which was a small orifice. After flushing the tube with argon
the specimen was induction melted, and then ejected by argon
slightly above atmospheric pressure on to a rapidly rotating,

highly polished copper drum to produce a melt-spun ribbon.
Ribbons were prepared with ejection pressures in the range
$\sim$ 5-40 kPa above atmospheric pressure with orifice diameters
from $\sim$ 0.75-1.50mm, and with drum surface velocities between
$\sim$ 4-30 ms^{-1}.

The resulting melt-spun ribbons of Pb-Sn eutectic consisted
of equiaxed Pb and Sn rich grains $\sim$ 4μm in diameter, and
exhibited superplastic behaviour when subjected to a tensile
stress. The microstructure and mechanical properties of melt-
spun Pb-Sn eutectic ribbons have been discussed in detail else-
where (5). The microstructure of melt-spun Al alloys was not
investigated, but x-ray diffractometry showed the presence of the
Al together with a small amount of an unidentified second phase.
To determine the effect of melt spinning process parameters on
ribbon dimensions, the width of Pb-Sn and Al alloy ribbons was
determined with a travelling microscope. The Pb-Sn eutectic
ribbons had sufficiently smooth surfaces that a satisfactory
measurement of their thickness could be obtained by direct
measurement with a micrometer. For the Al alloys however, the
surfaces were too rough so that the thickness had to be measured
by weighing a known length of ribbon and using the expression
t = W/lwρ where l,w,t are ribbon length, width and thickness, ρ
is density (2.71.10^3 Kgm^{-3}), and W is the measured weight.

Liebermann and Graham (3) applied Bernoulli's equation,
essentially an energy balance, to the column of liquid metal
during ejection from the orifice. Bernoulli's equation is
$V_J{}^2$ = 2P/ρ where V_J is the velocity of the liquid jet leaving
the orifice and P is the ejection pressure, and the continuity

equation for an incompressible fluid gives the volumetric flow
rate $Q = A_R V_R = A_J V_J$ where A_R, A_J are cross-sectional areas of
ribbon and jet respectively and V_R is the ribbon velocity. These
two equations can be combined, putting the ribbon velocity V_R
equal to the surface velocity of the drum, V_S, and taking the cross-
sectional area of the jet $A_J = \pi\emptyset^2/4$ where $\emptyset$ is the orifice dia-
meter. This leads to:

$$A_R = \pi\emptyset^2 P^{\frac{1}{2}}/2^{3/2} V_S \rho^{\frac{1}{2}} \tag{1}$$

Equation (1) can be generalised to allow for energy losses in
the orifice by incorporating a discharge co-efficient C_D so
that $V_J^2 = 2C_D^2 P/\rho$ and:

$$A_R = \pi C_D \emptyset^2 P^{\frac{1}{2}}/2^{3/2} V_S \rho^{\frac{1}{2}} \tag{2}$$

Liebermann and Graham found a good fit to equation (2) for
amorphous ribbons of $Fe_{40}Ni_{40}B_{20}$ taking $C_D = 1$. The present
results for Pb-Sn eutectic and Al-2%(Fe,Mn) are shown in figure
1 as a plot of A_R versus $\emptyset^2 P^{\frac{1}{2}}/V_S$. The results agree quite well
with the linear relationship expected from equation (2), although
there is some scatter in the Pb-Sn data possibly because of the
poorer method of measuring thickness. Linear regression
analysis gives a slope for Pb-Sn eutectic of $1.23.10^{-2} m^{3/2} Kg^{-\frac{1}{2}}$
with a correlation coefficient of 0.90; for the Al alloys the
slope is $1.63.10^{-2} m^{3/2} Kg^{-\frac{1}{2}}$ with a correlation coefficient of
1.00. Taking the density of Pb-Sn eutectic as $8.45.10^3 Kgm^{-3}$
gives a discharge coefficient of $C_D = 1.02$; this value is
sufficiently close to unity that the results are virtually
identical to those obtained by Liebermann and Graham. Taking

the density of Al as $2.71.10^3$ gives $C_D = 0.76$ and this rather low value may reflect the rather poor flow characteristics which were exhibited by the Al alloys during melt spinning.

Kavesh (4) used a more detailed analysis of thermal and momentum transport during melt-spinning to obtain independent equations for the width and thickness of melt-spun ribbons:

$$\ln_e(wV_S) = c + n \ln_e(QV_S) \tag{3}$$

$$\ln_e(tV_S) = -c + (1-n)\ln_e(QV_S) \tag{4}$$

where c is a constant depending upon the thermal characteristics of the solidifying material, and n is a constant in the range 0.75 - 1.00. Data for amorphous $Fe_{40}Ni_{40}B_{20}$ agreed well with equation (3) and somewhat less well with equation (4), with n $\sim$ 0.85. The present results for Pb-Sn eutectic and Al-2%(Fe, Mn) are shown in figures 2 and 3. Once again, there is good agreement in figure 2 for the width variation predicted in equation (3), but poorer agreement for the thickness data shown in figure 3. Linear regression analysis of the Pb-Sn width data gives n = 0.81 and c = 5.4 with a correlation coefficient of 0.99; the thickness data for Pb-Sn also gives n = 0.81 and c = 5.4 with a correlation of only 0.80. For the Al alloys, width measurements give n = 0.93 and c = 6.4 with a correlation coefficient of 0.95; however, the thickness results do not agree so well, giving n = 0.75 and c = 3.8 with a correlation of 0.80. Once again, the poorer results for Al alloys may be a result of their poor flow characteristics and a tendency for fibrilation during melt spinning.

Liebermann (6) has recently pointed out that there is an empirical relationship between ribbon width w and volumetric flow rate Q in a variety of melt-spun Fe-Ni based amorphous alloys:

$$w = w_o + Q \, \nu p^{-1} \qquad (5)$$

where w_o and νp are constants. Liebermann interpreted νp as an average dynamic viscosity in the solidifying liquid, and found that its value was approximately constant at $1.0\text{-}1.1.10^{-3} m^2 s^{-1}$ for the range of alloys that he studied. Data for Pb-Sn eutectic and Al-2%(Fe,Mn) are shown in figure 4, and for both types of alloy agreed with equation (5) within a correlation coefficient of 0.96. The values of νp are $0.66.10^{-3} m^2 s^{-1}$ for Pb-Sn and $0.77.10^{-3} m^2 s^{-1}$ for Al-(Fe,Mn), in both cases lower than the values found by Liebermann. However, this difference is not unreasonable; in an amorphous alloy the liquid viscosity rises sharply just ahead of the solidification front, but there is no equivalent increase in viscosity ahead of a crystallising interface.

The present results can be summarised as showing that the analyses of Liebermann and Graham, Kavesh, and Liebermann can be extended reasonably well from amorphous Fe-Ni based alloys to the rather different cases of crystalline Pb-Sn eutectic and low content Al alloys. However, there are three reservations. Firstly, a discharge coefficient must sometimes be included in Liebermann and Graham's analysis of ribbon cross-sectional area, to allow for inefficient ejection at the orifice. Secondly, there is considerable scatter in the variation of ribbon

thickness, although the average trend is still in quite good agreement with Kavesh's analysis. Thirdly, the liquid viscosity in Liebermann's empirical relation for ribbon width is considerably lower in a crystallising alloy compared to the amorphous alloys studied previously. The authors would like to thank the U K Science Research Council and U S Office of Naval Research (N-00014-789-0048) for providing financial support for this research programme, and Professor R W Cahn for providing laboratory facilities.

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FIGURE CAPTIONS

Fig. 1. Cross-sectional area A_R of melt-spun Pb-Sn eutectic
and Al alloy ribbons as a function of orifice diameter
$\emptyset$, ejection pressure P, and surface velocity of the
drum V_S, following the analysis of Liebermann and
Graham (3). The points are experimental data and the
lines show the least-squares best fit.

Fig. 2. Ribbon width w for melt-spun Pb-Sn eutectic and Al
alloys as a function of volumetric flow rate Q and
surface velocity of the drum V_S, following the
analysis of Kavesh (4). The points show the experimental
data and the lines show the least-squares best fit.

Fig. 3. Ribbon thickness t for melt-spun Pb-Sn eutectic and
Al alloys as a function of volumetric flow rate Q
and surface velocity of the drum V_S, following the
analysis of Kavesh (4). The points show the experimental
data and the lines show the least-squares best fit.

Fig. 4. Ribbon width w for melt-spun Pb-Sn eutectic and Al
alloys as a function of volumetric flow rate Q,
following Liebermann's empirical relationship (6). The
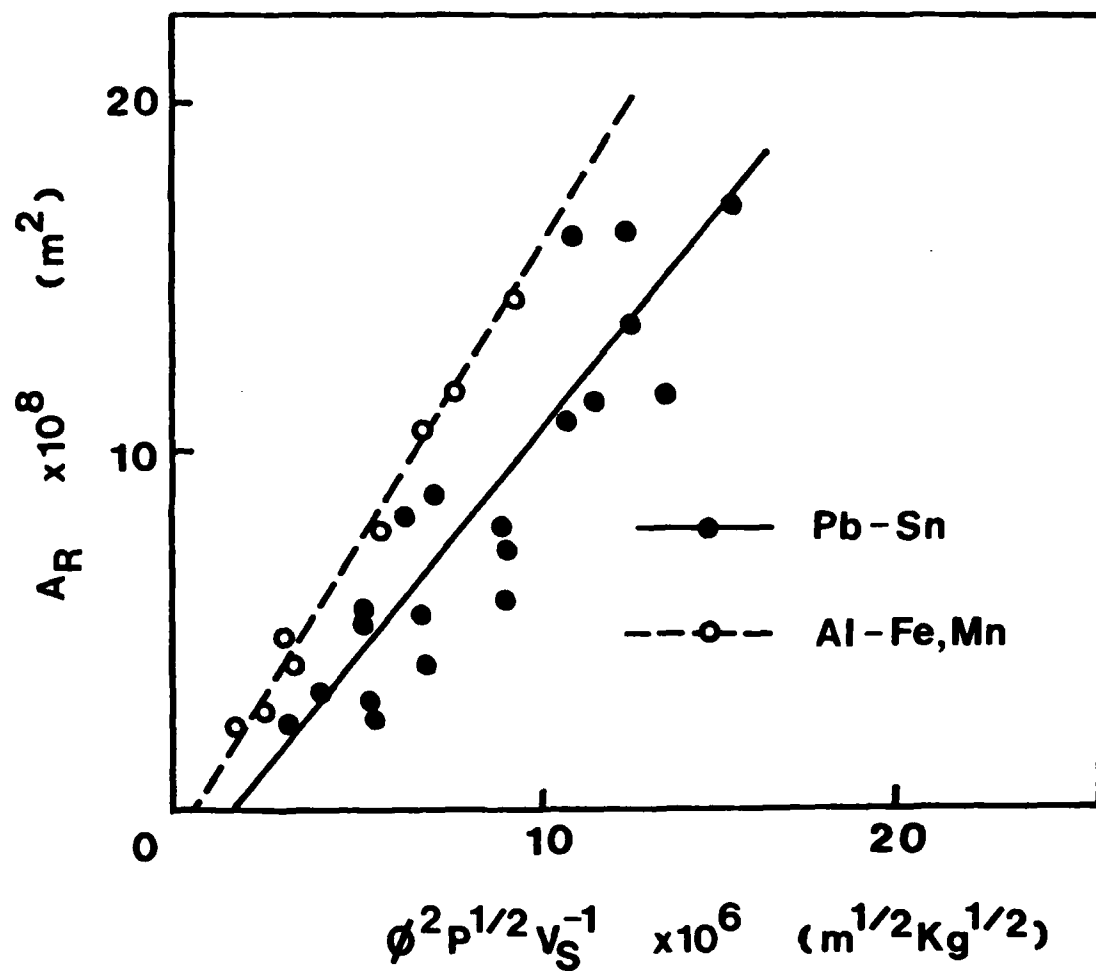points are the experimental data and the lines show the
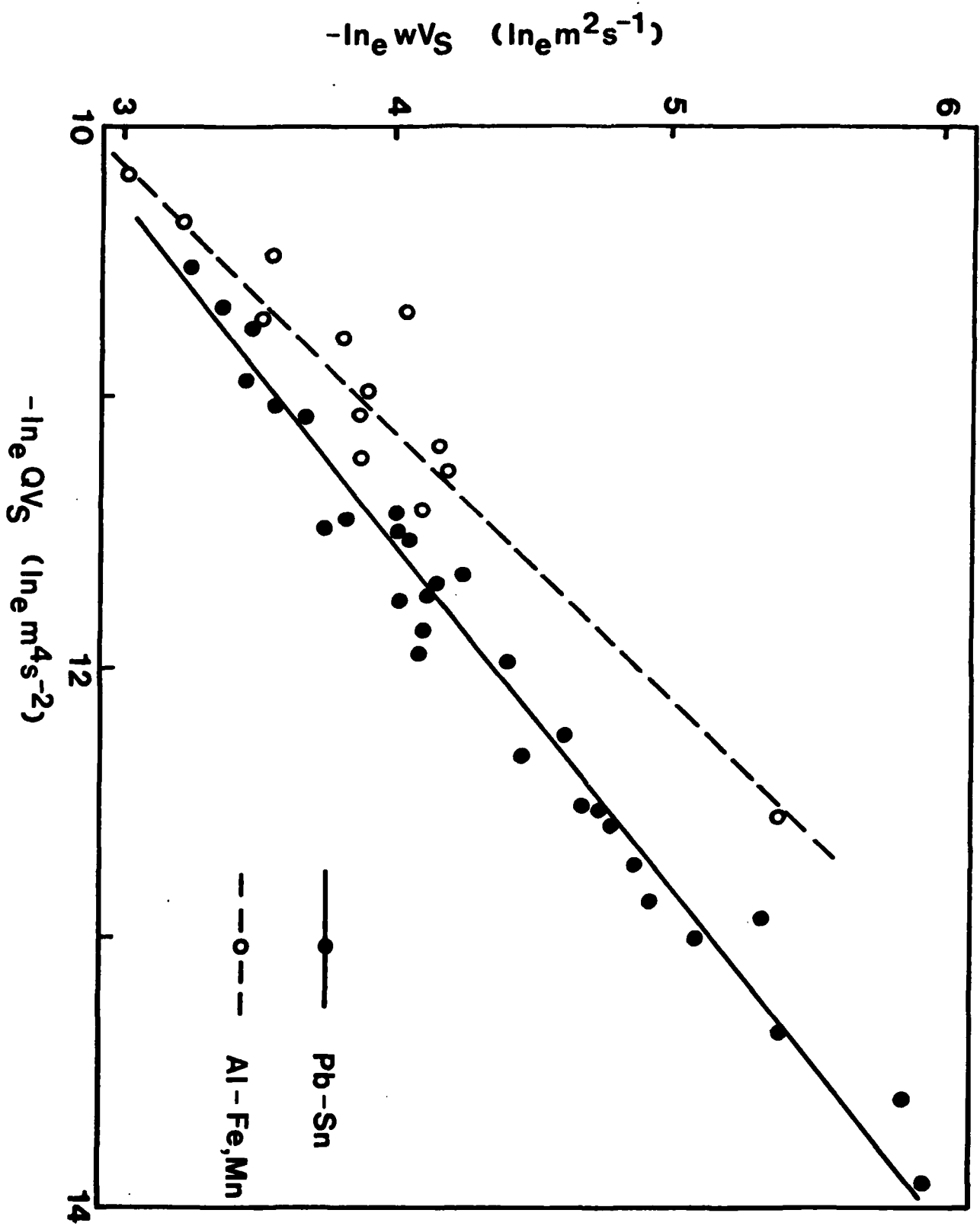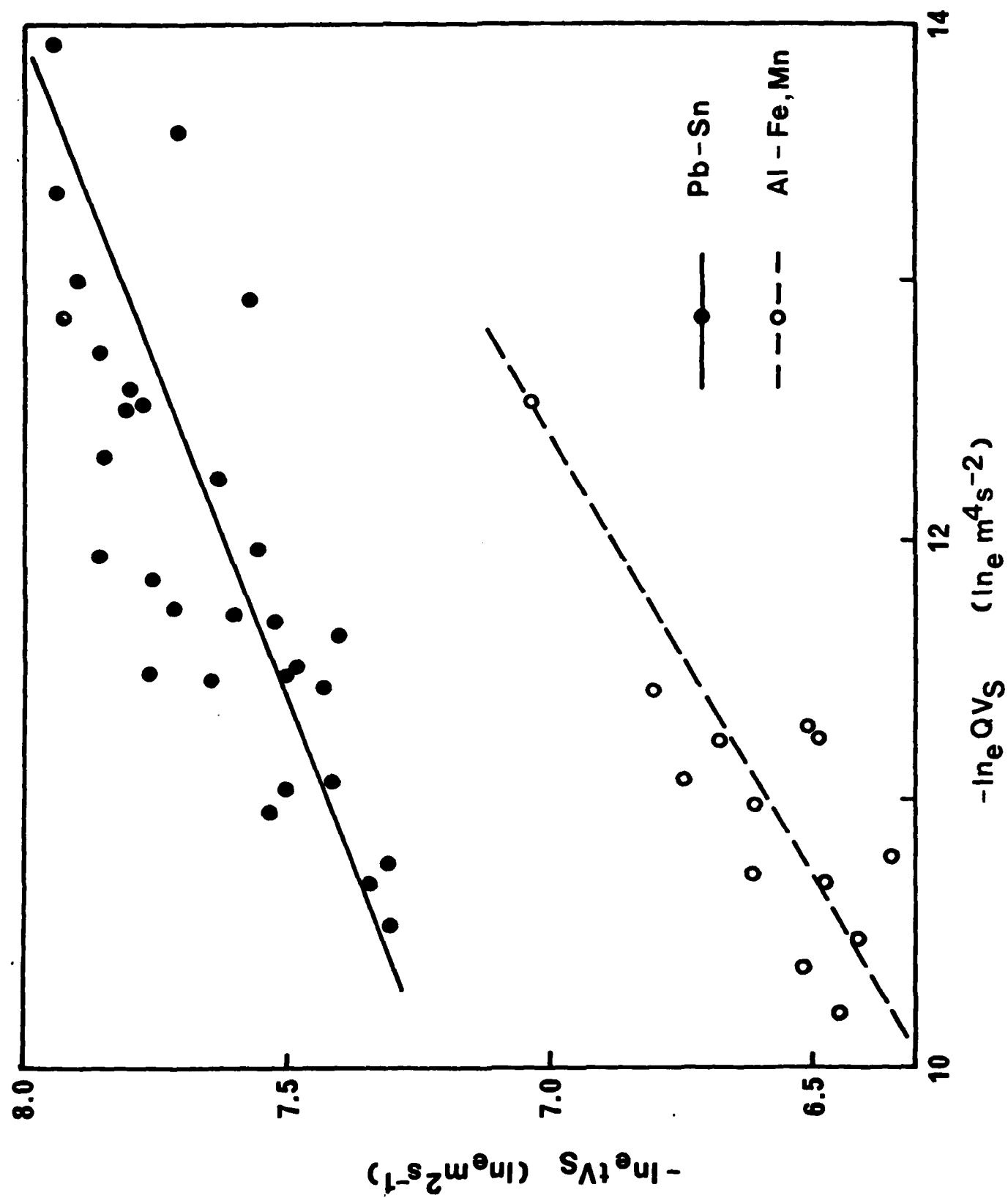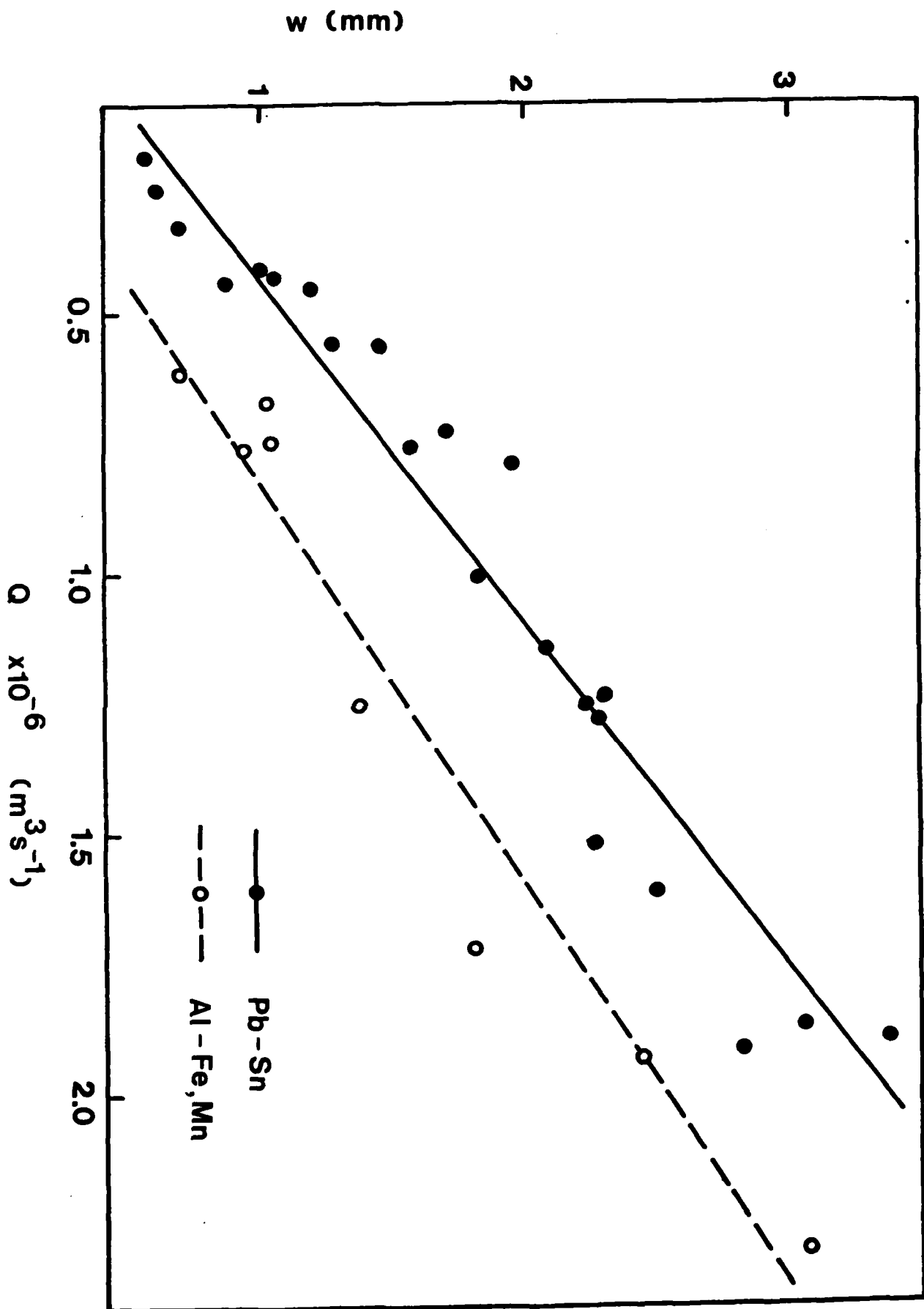least-squares best fit.

FIG. 1

FIG. 2

Pb–Sn ●——

Al – Fe,Mn ○---

$-\ln_e QV_S$ $(\ln_e \, m^4 s^{-2})$

$-\ln_e \, tV_S$ $(\ln_e \, m^2 s^{-1})$

FIG. 4