MELTING OF A METAL WIRE BY HEAVY CURRENT PULSES

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Melting has been observed for wires of Cu, Au, Cd, Zn, Pb, Pt, and Ni in response to current pulses of duration 100-450 μsec. The voltage and current waveforms have been used to calculate the resistance and enthalpy of the solid and liquid phases near the melting point; the results for all the metals except lead agree well with published values. It is found that wires of Pt, Ni, Au, and Cu begin to melt from the surface, the melting front moving radially towards the axis with a mean speed of several m/sec. The other metals have the interphase boundary moving radially and axially. It is found that solid Pb becomes superheated, and also that superheating occurs when some liquid is present, the excess temperature being about 40°K.

The melting of metals at high heating rate can give valuable information on the melting kinetics, about which little is known [1]. We have used continuous pulse heating of a wire specimen with waveform recording for the current and voltage [2]. The current pulses were obtained by discharge of banks of electrolytic capacitors or by line shaping; in the latter case, the waveform was nearly rectangular.

Figure 1 shows the current I and voltage U for zinc as recorded with a double-beam oscilloscope type DÉSO-1 when a bank of capacitors was discharged at the wire. The voltage waveform has kinks corresponding to the following points in time: t_1 onset of melting, t_2 end of melting, and t_3 start of failure of the liquid specimen. The melting range was similarly identified for the other metals.

Table 1 gives the parameters of the specimen (r_0 is radius and l is length at 25°C), together with the parameters of the pulse heating, which include not only t_1 and t_2 but also I_1 and the heating power P_1 at the start of melting. The behavior of r_0 during the melting interval t_2-t_1 may serve to characterize the mean speed of the interphase boundary.

The waveforms were processed with a Minsk-22 computer, which printed out not only the time dependence of the relative resistance R/R_0 (R_0 is the initial resistance of the specimen at 25°C) and the enthalpy H relative to 25°C, but also the plot of the first against the second. The coefficient of variation in H was 6% and that in R/R_0 was 4%.

Table 2 gives the values for R_1/R_0 and H_1 for time t_1 and corresponding values for t_2; the first set of values refers to the solid states, while the second refers to the liquid during melting. Here also we give the latent heat of fusion H_2-H_1 and the ratio $\gamma = R_1/R_2$, which characterizes the resistance change in the metal on melting and also the specific resistance ρ_0 of the metals at 25°C, as measured in the usual way. The values for all the metals except Pb agree well with those given in [1, 3].

Fig. 1

We examined the mode of melting from the waveforms from t_1 to t_2 (Fig. 1); the following assumptions were made:

1) the heat goes only to melt the metal during melting;

2) one can neglect the volume change during melting;

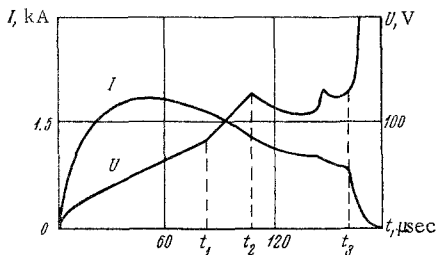TABLE 1

Metal	r_0, mm	l, mm	t_1, μsec	t_2, μsec	$\dfrac{r_0}{t_2-t_1}$, m/sec	I, kA	P_1, MW/g-atom
Cu	0.155	54	108	165	2.72	2.7	240
Au	0.245	50	198	240	5.75	3.4	260
Cd	0.255	54	70	90	12.8	2.65	350
Zn	0.25	54	95	125	8.33	2.75	265
Pb	0.597	84	354	446	6.5	2.50	46
Pt	0.245	60	320	395	3.27	1.55	280
Ni	0.25	60	350	420	3.57	1.75	240

TABLE 2

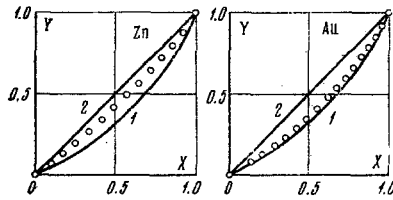| Metal	Purity	ρ_0, μΩ cm	$\dfrac{R_1}{R_0}$	$\dfrac{R_2}{R_0}$	$\gamma = \dfrac{R_1}{R_2}$	H_1, kJ/g-atom	H_2, kJ/g-atom	H_2-H_1, kJ/g-atom
Cu	99.95	1.73	5.6	11.5	0.487	30	43.7	13.7
Au	99.95	2.29	5.4	12.0	0.450	29.0	41.8	12.8
Cd	99.95	7.84	2.4	4.25	0.565	8.7	15	6.3
Zn	99.975	6.10	2.8	5.75	0.487	11.1	18.5	7.4
Pb	99.9995	21.22	2.4	4.38	0.548	9.6	14.5	4.9
Pt	99.93	10.89	5.7	8.5	0.670	55	77	22
Ni	99.93	7.50	8.0	11.2	0.714	50	67	17

Fig. 2

3) the electric field lines within the specimen are almost parallel to the axis.

It is assumed that a solid begins to melt from the surface, since nucleation of the liquid phase is not accompanied by an increase in the Gibbs free energy. On this basis we assume that the solid–liquid interphase takes the form of a cylinder, whose radius r varies smoothly from r_0 to 0 (melting model 1). Then r for a given time t is expressed in terms of R by

$$\frac{1}{R} = \frac{\pi r^2}{\rho_1 l} + \frac{\pi (r_0^2 - r^2)}{\rho_2 l}$$

where ρ_1 and ρ_2 are the specific resistance of the solid and liquid phases, respectively. Then

$$r = \frac{r_0}{\sqrt{1-\gamma}} \sqrt{\frac{R_1}{R} - \gamma} \tag{1}$$

The expression for r in terms of H is

$$r = r_0 \sqrt{1 - \frac{H - H_1}{H_2 - H_1}} \tag{2}$$

We equate the right sides in (1) and (2) to get

$$y = \frac{\gamma x}{1 - (1-\gamma)x} \quad \left(y = \frac{R - R_1}{R_2 - R_1}, \ x = \frac{H - H_1}{H_2 - H_1}\right) \tag{3}$$

where y is the relative resistance change on melting, while x is the relative heat consumed in melting in time $t - t_1$.

Analogous arguments may be applied when the interphase boundary moves only along the axis (melting model 2), which gives the linear relationship between y and x:

$$y = x \tag{4}$$

Figures 2 and 3 show $y = f(x)$ in the melting region for Zn, Au, Pt, and Ni; curve 1 has been calculated from (3), while curve 2 has been derived from (4) with the values for R_1, R_2, H_1, H_2 of Table 2; the points correspond to $y = f(x)$ in the melting region as derived from the waveform processing. One can
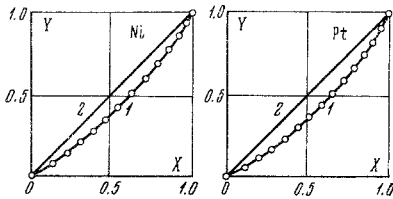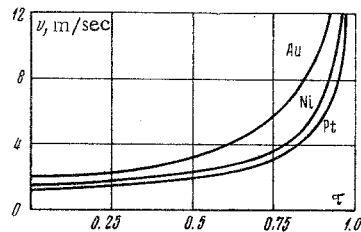
Fig. 3

Fig. 4

compare curves 1 and 2 with the experiment to show that the observed points for Cd and Pb resemble those for Zn (Fig. 2) in lying between curves 1 and 2; i.e., the melting in these metals does not follow either model. This means that Cd, Zn, and Pb wires melt with the interphase boundary moving axially as well as radially, because the nuclei of the liquid phase can arise at different points of the surface at different times. Also, it is possible for liquid nuclei to arise within the volume, e.g., at boundaries between grains. This mode of melting may be due to films of oxide on the surface, which would represent an energy barrier for surface nuclei.

An analogous comparison for Pt and Ni (Fig. 3) gives good agreement with (3), which means that these metals begin to melt from the surface, and the melting front moves towards the axis with a speed roughly the same in all parts of the specimen. This is possible on account of the absence of an oxide film on these metals. This mode of melting predominates for Au and Cu (Fig. 2).

Then the melting of Pt, Ni, and Au allows one to determine the speed $v = dr/dt$ for the interphase boundary, which can be derived by differentiating the $r - t$ relationship found from experiment by means of (1); Fig. 4 shows the results, where $\tau = (t-t_1)/(t_2-t_1)$ is the relative melting time; $v > 10$ m/sec at the end of melting. On this basis one finds the ratio $r_0/(t_2-t_1)$ (Table 1) for Pt, Ni, Au, and Cu as a mean, while the values for the other metals are purely nominal.

The solid—liquid system has to be heated above the phase equilibrium temperature T_m in order to maintain a high speed in the interphase boundary; this superheating [4] is defined by

$$\frac{T - T_m}{T_m} = \frac{3\pi v\lambda^2 \eta N}{f(H_2 - H_1)} \tag{5}$$

where λ is the length of the jump performed by an atom on passing through the interphase boundary, η is the viscosity of the melt at superheating T, N is Avogadro's number, and f is the proportion of sites in which one gets elementary axial transition. Satisfactory agreement has been obtained [4] between this formula and observed $(T-T_m)/T_m$ and v for melting of P_2O_5 crystals on the assumption that $f = 1$ and that λ = the length of a P—O bond. If by analogy with this we assume that $f = 1$ and $\lambda = a$, where a is the interatomic distance at T_m, then for Ni, Cu, and Au with $v = 10$ m/sec we get $(T-T_m)/T_m$ of the order of unity, which conflicts with the experimental results (Table 2). Comparison of the H_2 for Ni and Cu with the results of [3] gives for $(T-T_m)/T_m$ a value not more than 3%, which lies within the limits of error of measurement for H. If we assume for Ni and Cu that $(T-T_m)/T_m = 3\%$, we need in order to get such a value from (5) to assume for λ a value equal to about half the vibration amplitude Δa for the atoms at T_m [5].

The H_1 for Pb exceed the results of [3] by 1.14 kJ/g-atom, while for H_2 they exceed the latter by 1.27 in those units, these discrepancies being larger than the experimental error for H. The first difference indicates scope for heating of the solid Pb above T_m, which is possible if nuclei of the liquid phase have difficulty in arriving, e.g., on account of a film of oxide. The magnitude of the superheating can be estimated from the excess enthalpy of 1.14 kJ/g-atom and the specific heat near T_m at about 40°K. The excess H_2 indicates that the solid—liquid system has about this superheating during the melting of lead.

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