Polymorphic transitions of tin in shock compression and dilatation waves

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A manganin pressure probe was used to record a two-wave configuration of a shock front in tin, demonstrating a polymorphic transition under a pressure of 8.9 GPa. A dilatation wave traveling along tin shock-compressed to 10.4 GPa, revealed a shock-induced transition. The amplitude of the dilatation shock wave was 7.8 GPa. Therefore, recrystallization of tin in a dilatation wave began at a pressure much lower than the critical pressure for the polymorphic transition in the compression wave, and a hysteresis of this transition was observed.

A polymorphic transition due to shock compression of a solid usually splits the shock front and produces a two-wave structure in a certain range of pressures. Then, under shock loading conditions we can expect the same polymorphic transitions which occur also under static compression. It has been shown on several occasions that when a first-order phase transition occurs during unloading (dilatation), for example, in ionic KCl and KBr crystals,[1] in slate,[2] in iron,[3] and in bismuth[4] the amplitude of a shock dilatation wave is considerably less than the critical polymorphic transition pressure for these substances in a compression wave.

The results obtained by the present authors in a study of polymorphic transition processes in tin should be of interest. It is known that tin undergoes a polymorphic transition at a pressure of 9.4 GPa when it is compressed statically at 25 °C. A two-wave profile of a shock-wave front in tin (Fig. 1) indicated that the polymorphic transition occurred under dynamic loading conditions. The critical transition pressure was, as usual, equal to the amplitude of the first compression wave P_1 formed as a result of splitting of the front. The kinetics of the polymorphic transition could be judged on the basis of the broadening time t_1 of the front of the second compression wave. Low-temperature recrystallization of tin, which took a fraction of a microsecond, was supported by an earlier conclusion[1] that an athermal martensitic mechanism of the polymorphic transition predominated under shock loading conditions.

A detailed structure of the compression front and of the dilatation wave in tin was determined by a method[4] utilizing a manganin pressure probe bonded with an epoxy resin between two plates (Fig. 2) of chemically pure tin whose density was $\rho_0 = 7.30$ g/cm^3. The manganin probes were bifilar spirals with a diameter of ~ 4.5 mm and they were insulated from the tin by mica or a mylar spacer ~ 0.03 mm thick. The probe thickness was 0.03 mm. The total thickness of the package with the probe and the insulator was 0.12–0.15 mm. The probes were excited with pulses ~ 10 μs before the moment of arrival of a shock dilatation wave. Each probe had four identical copper leads, which made it possible to ignore the resistance of these leads. One pair was used to supply a voltage to the probe. The recorded signal was passed to the other pair of leads and reached directly the deflection plates of an S9-4 oscilloscope. Fuller utilization of the working part of the oscilloscope screen and an improvement in the precision of our measurements were ensured by applying a rectangular voltage pulse of 10 V amplitude after ~ 1 μs from the triggering of the recording apparatus; this rectangular pulse was supplied by a G5-15 generator and it deflected the beam toward the zero level line. The frequency of the calibration sinusoid in the oscillograms was measured with a Ch3-34 frequency meter.

The shock pressure P applied to tin was deduced from the measured value of the electrical resistance R of a manganin probe in its compressed state, calculated from

$$R=R_0(Z_0-Z_1+Z)Z_0^{-1},$$

where R_0 is the initial resistance of the probe amounting to ~ 1.5 Ω; Z_0, Z_1, and Z are the amplitudes of the deflection of the beam in the oscillogram. Conversion from R/R_0 to P was made using the dependence of the electrical resistance of manganin on the shock pressure $P=f(R/R_0)$ taken from Ref. 4.

The critical polymorphic transition pressure of tin $P_1 = 8.9$ GPa was practically identical with the corresponding pressure of tin compression conditions,[5] which was not a

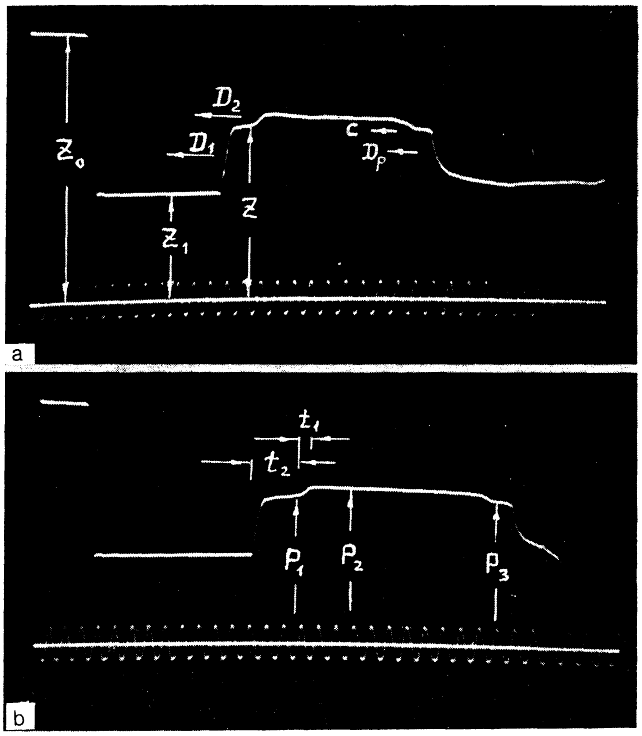

FIG. 1. Profiles of the compression and dilatation waves in tin: D_1 and D_2 are the shock compression waves, C and D_p are the elastoplastic and shock dilatation waves; $P_1 = 8.9$ GPa, $P_2 = 10.4$ GPa, $P_3 = 7.8$ GPa; the frequency of the calibration sinusoids is 5 MHz; a) $L_1 = 6$ mm, $L_2 = 3.9$ mm, $t_2 = 0.36$ μs; b) $L_1 = 9.15$ mm, $L_2 = 4.68$ mm, $t_2 = 0.54$ μs.

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TABLE I.

U_1, km/s	D_1, km/s	ρ_1, g/cm^2	U_2, km/s	D_2, km/s	ρ_2, g/cm^2
0,36	3,37	8,17	0,43	2,98	8,39

trivial result in view of the difference between the steady hydrostatic pressure P_{hydr} inducing a polymorphic transition and the pressure $P = P_{\text{hydr}} + (2/3)\,Y_d$, which was normal to the shock-wave front and included a contribution due to the dynamic strength Y_d of shock-compressed tin, and also in view of the difference between the mechanisms (diffusion–diffusion martensitic) of formation of the dense phase of tin by static and shock compression.

Using the known value of the mass velocity of the copper screen of the loading device ($U_{\text{Cu}} = 0.35$ km/s) and the pressure in the second compression wave ($P_2 = 10.4$ GPa), we determined (Fig. 3) the mass velocity $U_2 = 0.43$ km/s in tin beyond the front of the second compression wave.

It follows from the laws of conservation that

$$P_1=\rho_0 U_1 D_1,$$
$$P_2=P_1+\rho_1(D_2-U_1)(U_2-U_1)$$
$$=P_1+\rho_0 D_1(D_2-U_1)(U_2-U_1)(D_1-U_1)^{-1}.$$

and we obtain the equation

$$t_2=L_1(D_1-U_1)[D_1(D_2-U_1)]^{-1}-L_1D_1^{-1},$$

where D and U are values in the laboratory system of coordinates.

The solution of these three equations with three unknowns, in combination with the knowledge of ρ_0, the thickness of the sample L_1, the time interval t_2 between the moments of departure toward the probe of the first and second compression wave, the pressures P_1 and P_2, and the mass velocity U_2, allows us to obtain the following expressions for U_1, D_1, and D_2:

$$U_1=P_1[\rho_0 L_1 U_2-t_2(P_2-P_1)](\rho_0 L_1 P_2)^{-1},$$
$$D_1=P_1(\rho_0 U_1)^{-1},$$
$$D_2=U_1+(P_2-P_1)[\rho_1(U_2-U_1)]^{-1}.$$

We shall now determine the density of tin behind the fronts of the first and second compression waves:

$$\rho_1=\frac{D_1}{D_1-U_1}\rho_0,\qquad \rho_2=\frac{D_2-U_1}{D_2-U_2}\rho_1.$$

The results of these calculations are presented in Table I.

We checked the correction of our calculations in special experiments by determining experimentally (with the aid of piezoelectric transducers located at the copper–tin interface and on the free surface of a tin sample) the velocity of propagation in tin of the first compression wave $D_1 = 3.37 \pm 0.01$ km/s, which agreed with the value given in Table I.

It is quite clear from the oscillograms in Fig. 1 that the dilatation wave in tin caused a clear shock transition. The amplitude of the shock dilatation wave P_3 was ~ 7.8 GPa. This value was corrected for the hysteresis of manganin in the dilatation wave.[6,7] Using the ideas put forward in Ref. 8, we concluded that the initial pressure for the recrystallization of tin in a dilatation wave was even smaller. The results of our experiments showed therefore that the recrystallization of tin in a dilatation wave occurred at pressures much lower than the critical pressure needed for the polymorphic transition of tin in a compression wave.

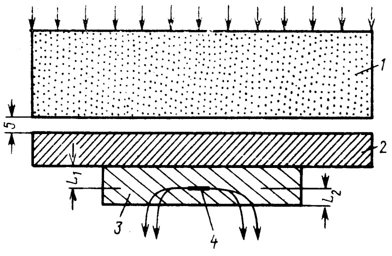

FIG. 2. Schematic representation of the configuration of a shock compression front and of the profile of a dilatation wave in tin: 1) explosive (TNT) charge 120 mm in diameter and 40 mm high; 2) copper screen 10 mm thick; 3) sample of tin; 4) manganin pressure probe.

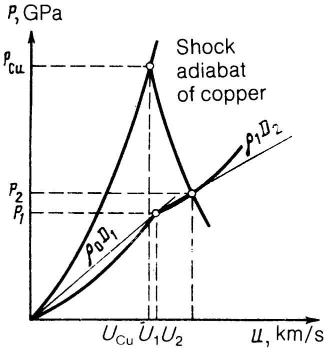

FIG. 3. Method of construction of the P–U diagram.

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