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Anomalous Effect of Temperature on Shock-Wave Propagation in Cu–Zn

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Shock-wave measurements at initial temperatures from 20° to 450°C reveal shock-wave propagation in ($\beta+\alpha$) brass is appreciably affected by alloy preheating. The shock-velocity value measured in the alloy at 20°C is decreased ~20% at 450°C for equal incident pressures. The anomaly is attributed to a disorder–order rearrangement occurring in Cu–Zn alloys of near stoichiometric composition.

To determine values of the Grüneisen parameter from compressibility changes and, therefore, define a more complete equation of state, we have studied the effects of thermal changes on the shock-wave compression of several alloy materials. Since brass has been frequently used as a material of known shock-compression characterestics, we performed a series of experiments in which specimens of this alloy were subjected to compression by shock pressures to 1 Mbar at initial temperatures in the range of 100°–450°C. This paper reports data that show that this initial temperature elevation appreciably affects the shock-compression characteristics of Cu–Zn alloys of near stoichiometric composition.

An analysis of the composition of the brass gave 59.00 at.% copper and 40.50 at.% zinc with a maximum impurity of ~0.5%, principally Sn and Fe. The alloy, of density 8.4 g/cm^3, was formed into short cylinders, 0.318-cm high and 1.27 cm in diam. These cylinders were mounted on 20.3-cm-diam specimen plates of the same alloy composition. Heat was supplied to the specimens indirectly by beaded nichrome coils which were wrapped and cemented around the circumference of the specimen plate. The specimen plate arrangement is shown in Figs. 1 and 2. The heated specimen–specimen plate system then was loaded with the plane shock waves from thin steel driver plates. The initial high temperatures, to 450°C, required the use of a heat-resistant explosive as an explosive insulation between the driver plate and the plane-wave explosive system which uses conventional explosives that can melt and become hazardous.

The driver-plate velocity, shock-wave velocities, and free-surface velocities of the Cu–Zn specimens and specimen plate were measured using a modification in the reflected light-smear camera technique described previously.[1] In the experimental arrangement (Fig. 2) the driver plate, when propelled across the gap, strikes the tantalum foil and produces a shock wave in the specimen plate. This shock wave is transmitted essentially flat-topped to the specimens. A glass window 1.1-cm wide and 6-cm long was inserted partially through the specimen plate for viewing the light-intensity changes produced by the driver plate's impact of the tantalum foil and the foil's arrival at the window. The window was spaced far enough from the specimens to prevent rarefactions from affecting the shock-velocity measurements. The time at which the foil was impacted and the time required for the foil to traverse the thin air gap between the foil and the window was measured to determine the driver-plate velocity.

The driver-plate velocity measurements gave good checks (~5%) to the specimen-plate–free-surface velocity which is approximately twice the particle velocity. The shock velocities of the specimens and the particle velocities obtained from the driver-plate measurements are listed in Table I. These data also are plotted in Fig. 3.

The dashed curve in Fig. 3 represents measurements by McQueen and Marsh.[2] Their brass (density 8.6 g/cm^3) contained ~36 at.% Zn, with the composition by weight, Cu/Zn/Pb/Fe: 61.5/36.0/2.5/<0.2.

The 20°C data are represented by a curve which, in accordance with reported results for most materials, should extrapolate, at zero particle velocity (U_p), to a shock velocity (U_s) equal to the adiabatic bulk sound speed. This result occurs because under high shock pressures the behavior of materials becomes fluid like. Our 20°C data include a shock velocity of 3815 m/sec plotted at $U_p=0$. This value corresponds to a shock pressure <50 bar and was measured by a weak-shock aquarium technique.[3] It may be considered as an elastic wave velocity approximately equal in magnitude to the bulk sound speed.

Theoretical considerations[4] show that in cubic metals, thermal-expansion changes cause the shock-wave-velocity–particle-velocity curves to be nearly parallel and spaced according to differences in the adiabatic bulk sound speeds. This result is only partially confirmed

[1] N. L. Coleburn, J. Chem. Phys. **40,** 71 (1964); T. P. Liddiard, Jr., and B. E. Drimmer, J. Soc. Motion Picture Television Engrs. **70,** 106 (1961).

[2] R. G. McQueen and S. P. Marsh, J. Appl. Phys. **31,** 1253 (1960).

[3] N. L. Coleburn and T. P. Liddiard, Jr., J. Chem. Phys. **44,** 1929 (1966).

[4] D. Pastine and D. Piacesi, J. Phys. Chem. Solids **27,** 1783 (1966).

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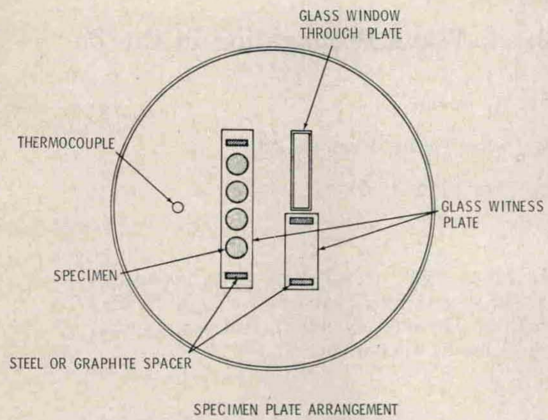

FIG. 1. Specimen-plate arrangement.

by the linear fits to the data in Fig. 3, primarily, we believe, because of limited data and data scatter.[5] The curves for shock propagation at 200° and 400°C, however, are nearly parallel to the 20°C curve. A more surprising result of these measurements though was that the free-surface velocities were largely unchanged beyond the measuring error (~3%) when the specimens were shocked by a constant-shock driver system but the initial temperature was varied. The shock velocities, however, showed a large decrease amounting to ~20% when the Cu–Zn alloy was shocked at ~400°C. This decrease greatly exceeds the experimental error and is not predicted by the normal decrease of ~3% in the bulk sound speed as calculated for most metals changing in temperature from 20° to 450°C.

The large displacements in the U_s–U_p curves may be examined by considering the possibility of a phase transition in Cu–Zn alloys as indicated by significant changes in their elastic modul with temperature. The elastic moduli of 40.3 at.% Zn have not been measured. (This composition at low temperatures is in the $(\alpha+\beta')$ region of the brass phase diagram).[6] However, large changes in the moduli with temperature normally are not expected. For example, from measurements[7] of the longitudinal and transverse wave velocities of sound in 9.7 at.% Zn (α brass) we calculate a ~2.4% decrease in the bulk sound speed (3820–3730 m/sec) for a change from 300° to 700°K. The adiabatic compressibility thus decreases by 8%. McManus,[8] however, has measured the temperature variation of the elastic moduli for compositions ranging from 45 at.% Zn to the stoichiometric Cu–Zn alloy (β brass) with 50 at.% Zn. He finds a large variation in the shear constants with composition and a substantial change in these constants near the critical temperature, the Curie temperature for order in β brass. For example, from 300° to 750°K, the shear

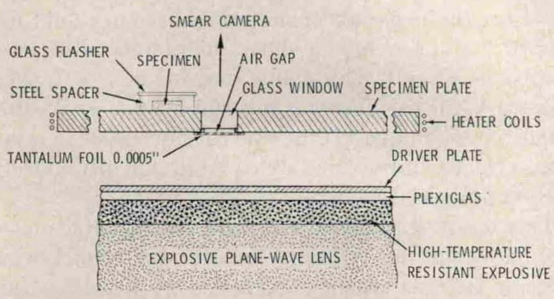

FIG. 2. Experimental arrangement for producing a plane shock wave and measuring shock propagation in the specimens and the driver-plate velocity.

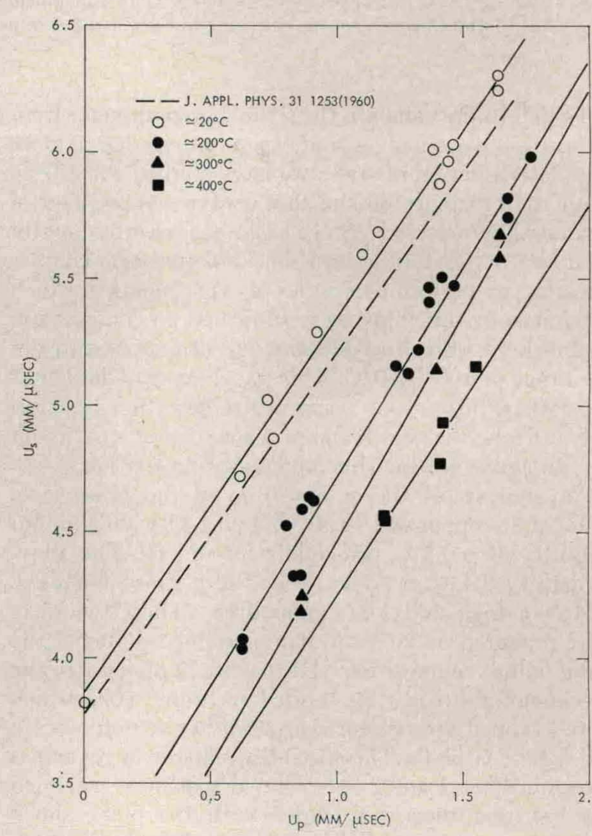

FIG. 3. Shock velocity U_s vs particle velocity U_p for brass at several initial temperatures.

[5] Some of the scatter is due to variations in the initial temperature at compression. For example, the plotted data for ~300°C includes data obtained at temperatures ranging from 285° to 325°C.

[6] M. Hansen, *Aufbau der Zwoistofflegierung* (Julius Springer–Verlag, Berlin, 1936); G. Shinoda and Y. Amano, Trans. Japan Inst. Metal. **1**, 54 (1963); R. P. Elliott, *Constitution of Binary Alloys* (McGraw-Hill Book Co., Inc., New York, 1965), First Suppl., p. 390.

[7] Y. A. Chang and R. Hultgren, J. Phys. Chem. **69**, 4162 (1965).

[8] A. M. McManus, Phys. Rev. **129**, 2004 (1963).

TABLE I. Summary of shock-wave measurements in $(\beta+\alpha)$ brass for several initial temperatures.

T_i (°C)	U_s (m/sec)	U_p (m/sec)
20	3815	0
20	4720	618
20	4860	750
20	5020	709
20	5290	913
20	5590	1100
20	5670	1170
20	5870	1400
20	5960	1440
20	6010	1380
20	6030	1450
20	6240	1640
20	6300	1640
195	5410	1370
195	5470	1370
200	4520	798
200	4590	864
200	4620	905
200	4630	893
205	4040	633
205	4070	633
205	4330	837
205	4334	867
205	5110	1290
205	5150	1240
205	5730	1680
205	5810	1680
210	5970	1760
215	5210	1320
215	5470	1460
215	5500	1410
305	5590	1650
305	5690	1650
340	4190	863
340	4250	863
365	5150	1400
385	4930	1420
430	4540	1180
430	4560	1190
430	4760	1410
440	5150	1550

constant C_{44} changes by 22%. This occurrence is consistent with an order–disorder transformation.

Presumably this transformation begins below 300°C and continues until ~480°C. A transition also is indicated by the specific-heat vs temperature curves of Cu–Zn alloys in the above composition ranges. These curves[9] show a sharp peak at $T_c \approx 480$°C, indicating a transition of β brass to an ordered structure. Thus the electrical resistance, specific heat, and elastic moduli of near stoichiometric Cu–Zn alloys are appreciably affected by temperature changes. The isentropic compressibility and isothermal compressibility also increase with increasing temperature.

In our experiments heating the brass specimens to ~400°C and then adding heat from the shock compression should facilatate an α (fcc)$\rightarrow\beta$(bcc) structural transformation in the alloy. The thermal and shear effects of the shock compression may produce a decrease in the electron concentration of the α phase by diffusion to a point where additional electrons can be accommodated in the β phase. This change, however should be indicated by a cusp in each of the U_s–U_p curves (Fig. 3) similar to the results that are obtained in the shock-induced, first-order transition of iron and its alloys. Since no inflections are indicated, the observed behavior is principally due to a change in order. The extremely rapid deformation by the shock destroys order in the alloy. The change to disorder is facilitated by heating, but it is not accompanied by a volume change and generates no heat of transformation. It is therefore considered a second-order phase transition[10] analogous to the disappearance of ferromagnetism at the Curie point. It is doubtful, however, that the anomaly in the shock propagation is indicative of a transition in Cu–Zn by melting under shock compression. Calculations indicate, e.g., that a 0.5-mbar shock produces a temperature increase exceeding 650°C in Cu–Zn specimens, initially at 450°C. However, no change of state due to alloy melting is indicated by the volume changes in the shock compression results at 450°C. The absence of a discontinuity in these results supports the view that melting of Cu–Zn in this compression range is a longer process than ~1 μsec, the duration of our shock observations. The structural changes then are indicated primarily by substantial displacements of the U_s–U_p curves with increasing temperature. These displacements perhaps are indicative of the degree of disorder in the alloy at the different temperatures.

[9] H. Mosev, Physik 2, **37**, 737 (1936); F. Seitz, *The Modern Theory of Solids* (McGraw-Hill Book Co., Inc., New York, 1940), p. 37.

[10] W. Boas, *An Introduction to the Physics of Metals and Alloys* (John Wiley & Sons, Inc., New York, 1949), p. 167.