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

N. L. COLEBURN AND J. W. FORBES

U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland 20910

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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/cm³, 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/cm³) 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).

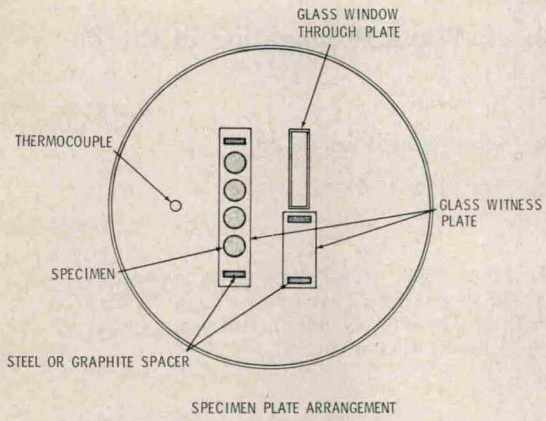

FIG. 1. Specimen-plate arrangement.

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

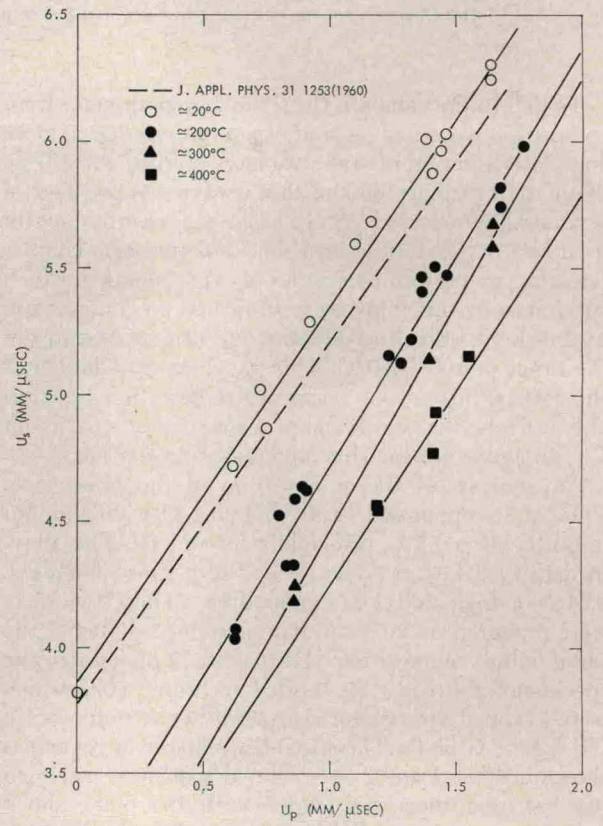

FIG. 3. Shock velocity U_s vs particle velocity U_p for brass at several initial temperatures.

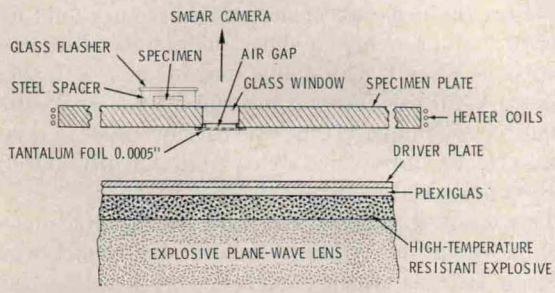

FIG. 2. Experimental arrangement for producing a plane shock wave and measuring shock propagation in the specimens and the driver-plate velocity.

[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).