STUDY OF THE UNLOADING OF STEEL SHOCK-COMPRESSED ABOVE THE PHASE-TRANSITION POINT

Yu. V. Bat'kov, A. G. Ivanov, and
S. A. Novikov

UDC 532.593

It was experimentally established in [1] that the adiabatic curve for shock compression of iron has an inflection point at a pressure of about 13.0 GPa. The sudden increase in compressibility at this point for iron and different steels based on α-iron is due to a first-order phase transformations from the α-phase (bcc lattice) to the ε-phase (hexagonal lattice). The presence of the inflection point results in a situation whereby a pressure pulse in iron and steels is propagated as two successive compression waves in the pressure range from 13.0 to 36.0 GPa. Studies of the structure of the waves [2] show that the front of the second wave is quite eroded (the width of the front is about 0.3 μsec) due to relaxation occurring with the transition of iron from one phase to another during shock compression.

The opposite phase transition occurs during the unloading of iron subjected to shock compression above a pressure of 13.0 GPa. The Poisson adiabatic curve also has an inflection point at the point transition. Generally speaking the inflection point during loading corresponds to the beginning of the phase transition, i.e., the adiabatic curve should have a section corresponding to a mixture of the two phases (the end of the phase transition has not been experimentally fixed on the Hugoniot curve of iron). During unloading, the inflection point on the Poisson curve corresponds to the end of the $\varepsilon \to \alpha$-transition. The reverse phase transition should also be accompanied by a certain relaxation process.

The inflection in the compressibility curve is the special limiting case of the anomalous section of an adiabatic curve with a negative second derivative $\partial^2 p/\partial V^2 < 0$ (p is the pressure and V is the volume). As was first shown in [3], a low-pressure shock wave (LSW) is formed during the unloading of such a medium. The condition of stability of the LSW is expressed geometrically by the tangency of the wave ray determining the velocity of the LSW to the two branches of the Poisson curve [4]. Figure 1 schematically shows the shock-compression adiabatic curve (a) and the Poisson adiabatic curve (b) of iron. Also shown is the profile of the pressure pulse, including two shock compression waves (p_1, p_3) and an LSW (p_2). Point 1 corresponds to the beginning of the $\alpha \to \varepsilon$-transition, point 4 corresponds to the end of the reverse $\varepsilon \to \alpha$-transition, and points 2 and 5 correspond to the point of tangency of the wave ray to the two branches of the Poisson curve.

The first experimental proof of the existence of an LSW was the formation of cleaved sections from a smooth surface in tests involving the explosive loading of iron and steep specimens [5, 6]. The introduction of manganin pressure transducers in gasdynamic experiments made it possible to directly record an LSW in iron and several other materials [7-11]. The pressure corresponding to the beginning of the polymorphic phase transition $\alpha \to \varepsilon$ in Armco iron p_1 is 12.6 ± 0.4 GPa according to [10] and 13.6 ± 0.25 GPa according to [11], these pressures having been determined with a manganin transducer. The quantity $p_1 = 14.7 \pm 0.5$ GPa according to a recording of changes in the velocity of the free surface of specimens after the passage of a shock wave, the measurements here having been obtained with a capacitive transducer [12]. According to the data in [13], obtained with a laser interferometer, $p_1 = 12.8$ GPa. This value is 15.2 GPa for steel St3 [7]. As the pressure corresponding to the beginning of the reverse $\varepsilon \to \alpha$-transition in iron in [9-11, 13], the authors took a value of pressure ahead of the LSW front p_2 equal to 12.3 ± 0.4 GPa [10], 10.0 ± 0.25 GPa [11], and 9.8 ± 0.4 GPa [13]. Thus, the pressure hysteresis $\Delta p = p_1 - p_2$ of the $\alpha \rightleftarrows \varepsilon$-transition in iron and steels has not been unambiguously determined and is found in the range from 0.3 to 3.6 GPa. Under static loading conditions, the hysteresis is about 5.0 GPa [14].

Here we present results of studies of the pressure profile in steel St3 obtained in explosive tests with a manganin transducer. We also present results of measurement of the

---

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 142-144, November-December, 1985. Original article submitted August 7, 1984.

0021-8944/85/2606-0890$09.50

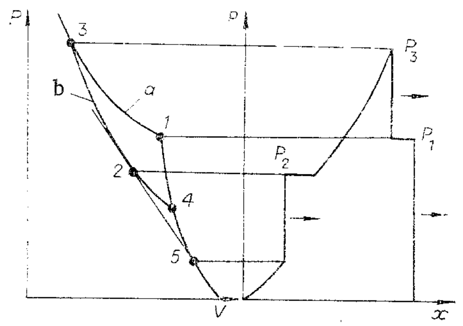

Fig. 1

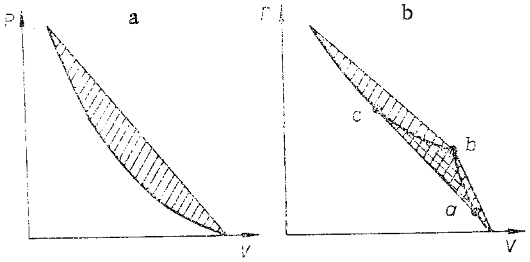

Fig. 3

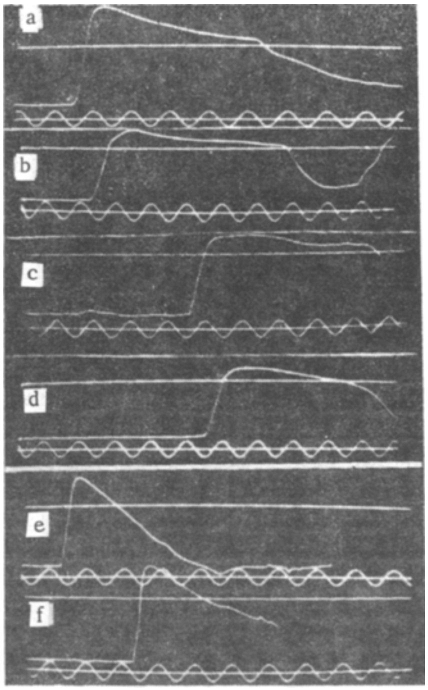

Fig. 2

residual temperature of the steel after shock loading, making it possible to evaluate the hysteresis of the phase transition.

In the first series of tests, a shock wave was created in steel specimens 120 mm in diameter and about 60 mm thick by a plane detonation wave in a charge of pressed trotyl ($\rho_0 = 1.51$ g/cm^3, ϕ 90 × 40 mm). Profiles of pressure p(t) normal to the shock front were recorded in two sections of the specimen with manganin wire transducers [15]. To the detriment of the time resolution of the equipment, the total thickness of the transducers together with the fluoroplastic insulating liners was made equal to 0.3-0.5 mm in order to ensure the necessary lifetime for the transducer (about 10-15 μsec). The calibration dependence of the relative change in the resistance of the wire transducer $\Delta R/R_0$ on pressure p in the range 1.5-20.0 GPa, obtained in preliminary experiments, is described by the formula $p = (0.32 + 35.395\Delta R/R_0)$ GPa and agrees well with the data in [9, 10, 16].

Figure 2a-d shows typical oscillograms of the pressure profiles p(t) in the specimen at distances of 10, 20, 25, and 35 mm from the loading surface. To demonstrate the difference in unloading processes, we also show pressure profiles in an aluminum specimen (AD1) at distances of 10 and 25 mm (Fig. 2e, f) obtained in a similar experiment. The frequency of the scale sine curve in the oscillograms is 1.0 MHz. In contrast to [7], in our tests we detected no distortion of the recorded signal in the steel from electromagnetic interference connected with the change in the magnetic permeability of iron. This was avoided in [7] by the use of a special bifilar magnetic transducer. Results of analysis of the tests (2-3 tests per section) are shown in Table 1. It can be seen from the oscillograms of the pressure profiles in Fig. 2 that all of the features of a pressure pulse typical of steel initially compressed above the phase transition level (two compression wave, simple low-pressure wave and an LSW) are quite visible 20 mm from the loading surface (Fig. 2b). The amplitude of the second shock wave p_3 decays at distances of 10-25 mm from the loading surface from 17.0 to 13.0 GPa. The pressures p_1 and p_2 determined at distances of 10-35 mm from the loading surface are 12.5 ± 0.5 and 10.2 ± 0.5 GPa for steel St3, respectively. The value of p_1 nearly (with allowance for the 10% measurement error) coincides with the data in [10, 11, 13]. The value of p_2 is in good agreement with the results in [11, 13] and is significantly below the value 12.3 ± 0.4 GPa from [10].

It was found in the tests with iron and steel specimens that the temperature of the fragments within the so-called "shock zone" — the sharp boundary of which is formed by the sudden reduction in pressure on the front of the shock wave when it catches up to the LSW [17] — is appreciably higher than the temperature of the other specimen fragments. It is natural to suggest that this difference is connected with features of the unloading of iron

TABLE 1

H, mm	Pressure, GPa		
	p_1	p_2	p_3
10	13,5	10,0	17,0
20	12,5	11,0	14,0
22,5	12,5	11,0	13,5
25	12,0	10,0	13,0
35	12,0	9,0	—

TABLE 2

No. of test	L, mm	h, mm	T, °C	
			Expt.	Calc.
1	65	43	205	150
2	130	50	240	200
3	130	49	250	200
4	130	51	240	200

in an LSW. As is known, with the assumption of the coincidence of the shock-compression and Poisson adiabatic curves, the increase in the temperature of the material after its unloading is determined in the coordinates p–V by the area of the hatched segment in Fig. 3a. In the case of unloading with the participation of an LSW, there is additional heat liberation corresponding to the area abc in Fig. 3b. The temperature of the material after unloading is determined in this case by the total area of the hatched region.

In the second series of tests, we measured the residual temperature of fragments in the form of "cores" formed in the interaction of an LSW in cylindrical specimens and located in the phase-transition zone [6, 17]. The setup of the tests was similar to that used in [6]. The specimens were placed on dry sand, the temperature of the "core" was measured with a calorimeter, and the time interval from the moment of explosion of the charge to the moment the fragment was dropped into the calorimeter was no greater than 1 min.

Table 2 shows calculated and experimentally measured (after the tests) values of the temperature of the "cores," where L is the length of the explosive charge, h is the height of the "core," and T is the temperature of the core. The mean temperature of the core after unloading was calculated from the x–t curve of the flow formed when the plane detonation wave was reflected from the face of the iron specimens. Here, it was assumed that the Hugoniot (shock-compression) and Poisson curves coincided. It can be seen from Table 2 that the difference between the calculated and measured temperatures is about 40°C and is large enough to be an explanation for the measurement errors; the most probable explanation is the hysteresis in the reverse phase transition. The hysteresis of the $\alpha \rightleftarrows \varepsilon$ transition can be evaluated form the above-noted temperature difference. This reduces formally to the introduction of the missing area in the p–V diagram. (In obtaining the estimates, we constructed the upper branch of the Poisson adiabatic curve as a continuation of the branch of the Hugoniot adiabatic curve to the initial volume corresponding to the ε-phase.) The estimates showed that the point of inflection on the iron curve during unloading should be at a pressure of about 9.0 GPa. Such an estimate (Δp = 4 GPa) should be considered excessively high, since heating of the iron due to the conversion of strain energy to heat was not taken into account in the calculations.

It should also be noted that the pressure p_2 on the front of the LSW does not characterize the beginning of the reverse phase transition during unloading. This follows from the above-noted "tangency" condition (Fig. 1). The pressure on the front of an LSW formed in iron and steels should always be above the inflection point on the Poisson adiabatic curve. Here, the value of p_2 depends on the maximum pressure p_3 on the front of the shock-compression wave.

Thus, the pressure difference $\Delta p = p_1 - p_2$ does not determine the amount of hysteresis of the $\alpha \rightleftarrows \varepsilon$-transition in iron and steels during shock compression. The values of p_2 determine only the amplitude of the LSW formed in iron and steels under the given loading conditions. Thus, the pressure evaluated from the residual temperatures of the specimens (about 4 GPa) should be closer to the true value of the phase-transition hysteresis in iron than in [10].

LITERATURE CITED

1. D. Bancroft, E. I. Peterson, and S. Minshall, "Polymorphism of iron at high pressure," J. Appl. Phys., 27, No. 3 (1956).
2. S. A. Novikov, I. I. Divnov and A. G. Ivanov, "Study of the structure of shock-compression waves in iron and steel," Zh. Eksp. Teor. Fiz., 47, No. 3(9) (1964).
3. Ya. B. Zel'dovich, Theory of Shock Waves and Introduction to Gasdynamics [in Russian], Izd. Akad. Nauk SSSR, Moscow (1946).

4. A. G. Ivanov and S. A. Novikov, "Low-pressure shock waves in iron and steel," Zh. Eksp. Teor. Fiz., 40, No. 6 (1961).
5. A. G. Ivanov, S. A. Novikov, and Yu. I. Tarasov, "Cleavage phenomena in iron and steel caused by the interaction of low-pressure shock waves," Fiz. Tverd. Tela, 4, No. 1 (1962).
6. J. O. Ercman, "Smooth spalls and the polymorphism of iron," J. Appl. Phys., 32, No. 5 (1961).
7. A. V. Anan'in, A. N. Dremin, and G. I. Kanel', "Structure of shock waves and rarefaction waves in iron," Fiz. Goreniya Vzryva, 9, No. 3 (1973).
8. M. N. Pavlovskii and V. V. Komissarov, "Features of the phase transformation in bismuth in a rarefaction wave," Zh. Eksp. Teor. Fiz., 83, 6(12) (1982).
9. G. E. Duval and R. A. Graham, "Phase transitions under shock wave loading," Rev. Mod. Phys., 49, No. 3 (1977).
10. A. V. Anan'in, A. N. Dremin, and G. I. Kanel', "Polymorphic transformation in iron in a shock wave," Fiz. Goreniya Vzryva, 17, No. 3 (1981).
11. Z. Rosenberg, Y. Partom, and D. Yaziv, "Determination of the dynamic $\alpha \rightleftarrows \varepsilon$ transformation in iron using manganin stress gauges," J. Phys. D, 13, 1489 (1980).
12. S. A. Novikov, I. I. Divnov, and A. G. Ivanov, "Phase transition in iron during shock compression," Fiz. Met. Metalloved., 21, No. 2 (1966).
13. L. M. Barker and R. E. Hollenbach, "Shock wave study of the $\alpha \rightleftarrows \varepsilon$ phase transition in iron," J. Appl. Phys., 45, No. 11 (1974).
14. P. M. Gilles, M. N. Longenbach, and A. R. Marder, "High-pressure $\alpha \rightleftarrows \varepsilon$ martensitic transformation in iron," J. Appl. Phys., 42, No. 11 (1971).
15. Yu. V. Bat'kov and E. D. Vishnevetskii, "Equipment for measuring impulsive pressures with piezoresistance transducers in the range 0.1-20 GPa," in: Summaries of Documents of the Second All-Union Symposium on Impulsive Pressures, VNIIFTRI, Moscow (1976).
16. G. I. Kanel', G. G. Vakhitova, and A. N. Dremin, "Metrological characteristics of manganin pressure transducers under conditions of shock compression and unloading," Fiz. Goreniya Vzryva, 14, No. 2 (1978).
17. S. A. Novikov, I. I. Divnov, and A. G. Ivanov, "The nature of the 'shock zone' in iron and steel," Fiz. Met. Metalloved., 20, No. 1 (1965).

PARAMETERS OF AN ELASTOPLASTIC DILATATION MODEL FOR EARTH MATERIALS

S. M. Kapustyanskii and V. N. Nikolaevskii

UDC 622.011.4:622.023

Strength and dilatation coefficients were taken as a function of the hardening (softening) parameter from data from triaxial tests of specimens of earth materials in compression. It was found that there is a significant change on cohesion, internal friction, and dilatation rate with a change in pressure and initial porosity. The results obtained make it possible to perform numerical calculations of geodynamic processs with multiple internal fractures.

1. The closed mathematical model of the elastoplastic deformation of earth materials includes the momentum balance equation

$$\rho dv_i/dt = \partial S_{ij}/\partial x_j - \partial p/\partial x_i + F_i,$$

where ρ is density; v_i, mass velocity; S_{ij}, stress tensor-deviator; p, pressure; F_i, the body forces and the governing relations characteristic of earth materials. An important element of the latter is allowing simultaneously for internal friction and dilatation.

The laws of flow with hardening used below [1] will be represented in the form

$$\tilde{d}S_{ij}/dt = 2G(\varepsilon_{ij} - \varepsilon\delta_{ij}/3 - \xi S_{ij}),\ \tilde{d}p/dt = -K(\varepsilon - 2\xi\Lambda\tau),$$

Leningrad. Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 145-150, November-December, 1985. Original article submitted June 4, 1984.

0021-8944/85/2606-0893$09.50