Shock compression of ultralow density nickel

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Results are given of a study of the compressibility of nickel with initial density $\rho_{00}=0.44$–0.89 g/cm^3, at pressures up to 35 GPa. Comparison of the results is made with known results corresponding to initial densities above 1 g/cm^3. The new experimental results correspond to a region of the phase diagram hitherto unexplored.

INTRODUCTION

Experiments on shock compression of porous matter are of interest from the point of view of equations of state in two main related areas:

First–directly for the determination of the relations between thermal pressures and energies (in the procedure for finding the Grüneisen coefficient);

Secondly–as test data for verifying (and constructing) models of matter for the region of thermodynamic parameters not readily accessible to other types of experiments.

From this point of view the region of the P–ρ–T diagram of special interest has the following parameters: pressure (P) > 20–30 GPa, density (ρ) < units of g/cm^3 and temperature (T) > 30 000 K. This region is a "blank spot" on the phase diagram where experimental results are absent or where there are no reliable numerical evaluations, since theoretical models of matter are inapplicable in this region.

We reproduce here with minor modifications the phase diagram drawings from Al'tshuler *et al.*[1] in the coordinates of energy (kJ/g) and volume (mole/l) used there. The region of concern here is the shaded rectangle in the center of the diagram. The right hand part of the diagram is the region well studied by dynamic methods; it also includes theoretical models for dense states of matter. The left-hand part corresponds to the gaseous state region and the theoretical description according to the Saha model. The shock adiabats of Xe, Au, and Ni and the energetic curves of cold compression of metals are shown on the diagram. It can be seen that it is impossible to reach the shaded region by shock compression of elements with normal initial density. The measurements of compressibility of porous metals by Trunin *et al.*,[2] Kormer *et al.*[3] and Krupnikov *et al.*,[4] also do not solve this problem, although the results of these investigations are also in the immediate vicinity to the boundary of the region which interests us.

Al'tshuler *et al.*[1] suggested using pulsed isochoric heating to solve the problem, making possible the study of states of matter up to $E\simeq 10^3$ kJ/g. In the variant of the method described, the energy of powerful particle beams falling on the specimen and heating it up is measured directly. However, the accuracy requirements in determining the beam energy of these particles is difficult to achieve at present, which is one of the reasons why the method is not applied in practice.

The other principal possible route is a study of the compressibility of dense vapors in strong shock waves. However, such experiments are technically difficult to carry out.

These difficulties can be overcome by carrying out experiments on shock compression of highly porous specimens. Estimates show that experiments in which metal powders with initial density tenths of g/cm^3 are subjected to pressures $P>20$ GPa would solve these problems.

In the present work we consider the results of the first such investigations.

EXPERIMENTAL RESULTS AND DISCUSSION

For the investigations we chose specimens of nickel, a metal resistant to oxidation. However, attempts to obtain porous specimens with the density we required ($\rho_{00}<1$ g/cm^3) using commercial powders were unsuccessful. Also, the existing means of obtaining low density specimens artificially, based in particular on hydrogenated metals with subsequent dehydrogenation did not yield the required result.

It was possible to prepare the necessary specimens in the present case by using specially prepared finely divided nickel powders with dimensions of the individual grains $\lesssim 200$ Å.[1)] The bulk density, i.e. that which is obtained on filling a measured volume with a given weighed quantity of essentially unpressed powder was $\rho_{00}=0.444$ g/cm^3 (porosity $m=\rho_0/\rho_{00}=20$). Smaller values of the porosity (larger density) were obtained by pressing the powder under different loads.

X-ray structural methods showed that the powder consisted of particles of pure nickel with no oxide component.

As is usual, we used the reflection method[5] in our investigations, with an array of explosive measuring devices with shock wave calibrated parameters in aluminum shields. In the majority of experiments the electric-contact method of measuring wave velocities was used. Signals from the response of the sensors were recorded with SUPI-23 type digital recorders with 5 ns time resolution.

Since the loading pressures on specimens in part of the experiments were relatively low (5–10 GPa) the wire electrical sensors usually used here work unstably in such conditions and for greater reliability in the results piezoelectric time markers were used. For the same purpose for each measuring arrangement, i.e., for each state of the shock

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TABLE I.

ρ_{00}, g/cm^3	D, km/s	U, km/s	P, GPa	ρ, g/cm^3
0,887	1,922	1,636	2,8	5,96
	2,355	2,044	4,3	6,72
	4,07	3,42	12,3	5,55
	5,29	4,31	20,2	4,79
	6,41	5,11	29,1	4,37
	7,15	5,65	35,8	4,23
0,592	1,111	0,993	0,61	3,70
	1,902	1,690	1,9	5,31
	2,345	2,125	2,9	6,31
	4,03	3,61	8,6	5,68
	4,10*	3,64	8,8	5,27
	5,29	4,58	14,3	4,41
	5,30*	4,58	14,3	4,36
	5,77	4,91	16,8	3,97
	6,51	5,44	21,0	3,60
	7,27*	6,07	26,1	3,59
	8,02	6,56	31,1	3,25
0,444	4,07	3,72	6,7	5,16
	5,37	4,73	11,3	3,72
	6,61	5,65	16,6	3,05
	7,56	6,28	21,1	2,62
	8,19	6,81	24,7	2,63

*) Results obtained on pumping air out of the specimens.

wave in the shield a series of measurements of wave velocities in the powder was carried out, consisting of 3–6 separate experiments. The whole set of experimental results obtained is shown in Table I and in Figs. 2–4 with coordinates D–m, D–U, and P–ρ (D is the shock wave velocity, U the mass velocity of the matter behind the shock front, P is the pressure, ρ the density).

The uncertainty in determining the relative density of

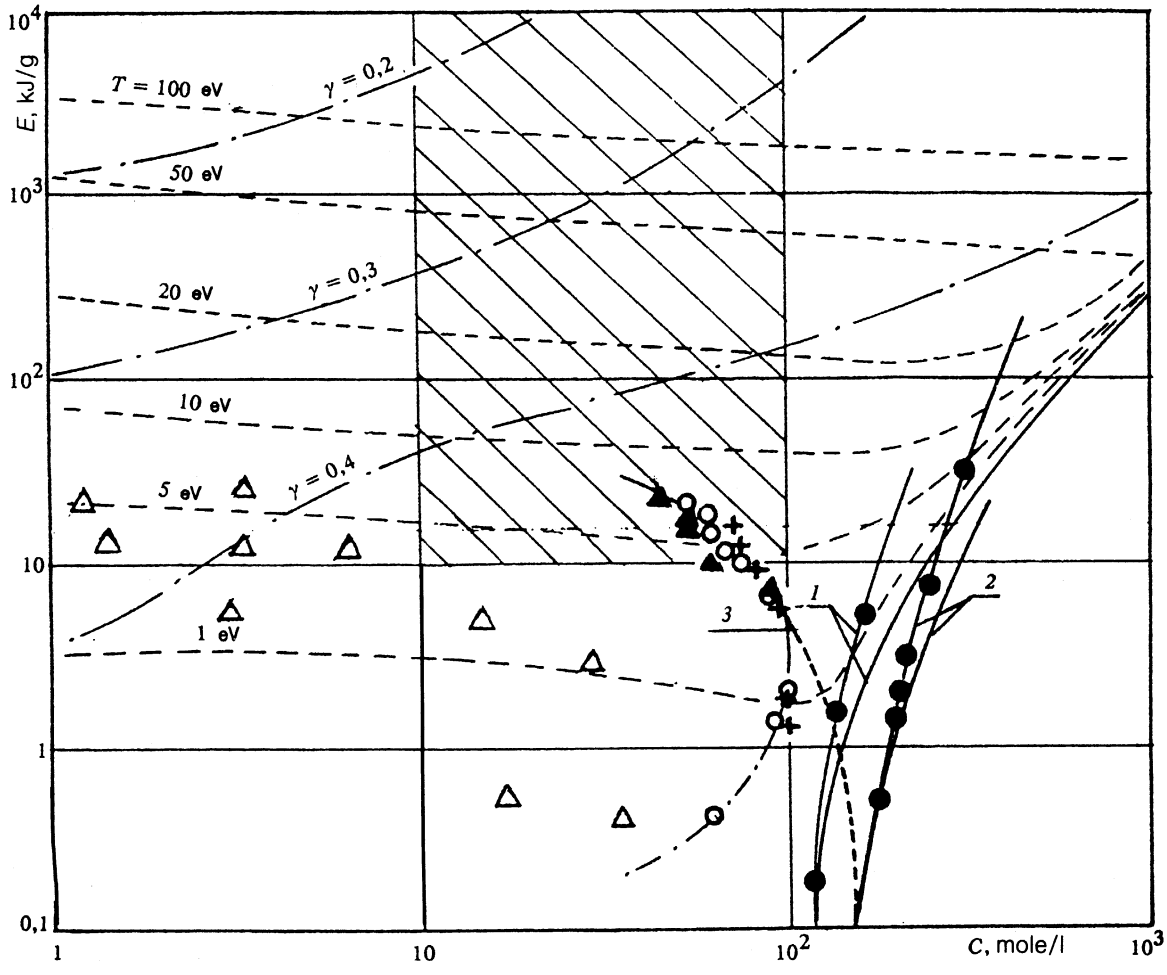

FIG. 1. Phase diagram. *1*—shock adiabat and isotherm ($T=0°$) for gold: *2*—the same for nickel, *3*—shock adiabat of porous nickel +) $m=10$, ○) $m=15$, ▲) $m=20$. △) data for Xe (Ref. 9).

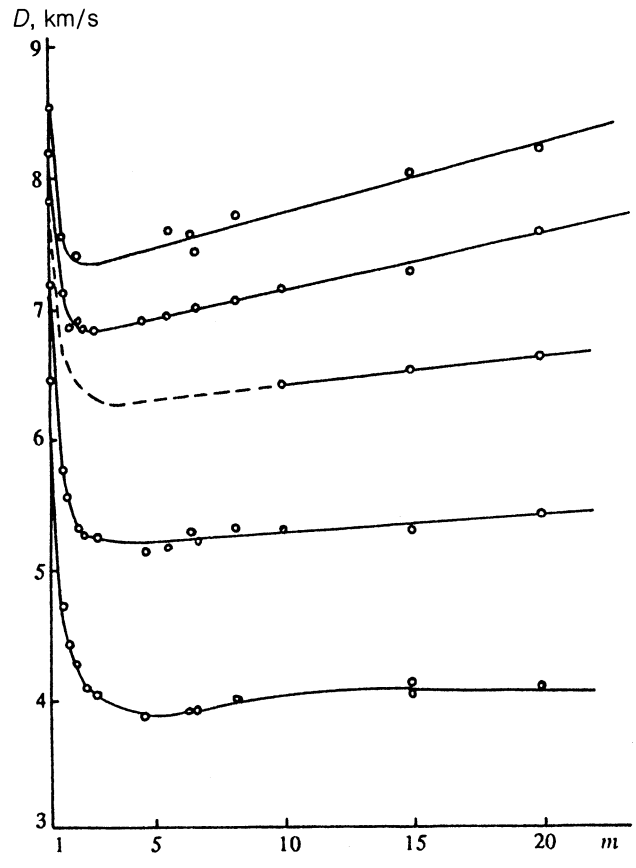

FIG. 2. Experimental $D(m)$ relation.

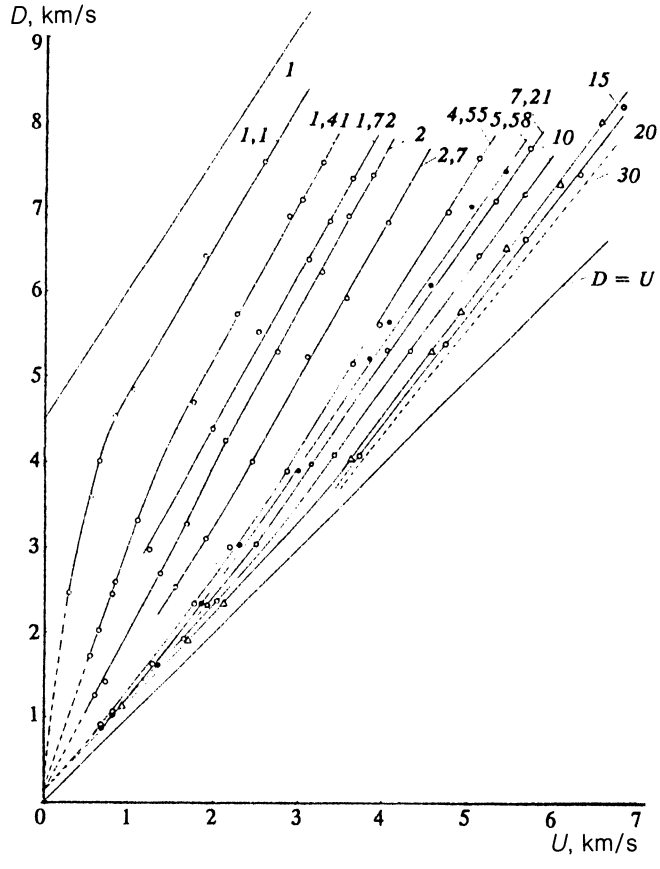

FIG. 3. D–U diagram for nickel.

the shock compression $\Delta\rho/\rho$ at small pressures ($P<5.0$ GPa) is ~5–8% for individual points, so that exact quantitative conclusions can not be drawn from them. These are only possible on the basis of the whole set of the functions describing the average of the experimental measurements for the ρ_{00} considered. Even in this case, however, the position of the shock adiabats in the early sections (for $m>4$) are evidence of qualitative rather than of quantitative relationships.

The question of the possible effect of air filling the pores between the metal particles on the results of measurements of wave velocity was important in connection with the methodology. This problem was solved by direct experiments in which air was pumped out of the measuring unit to a pressure of 1–5 torr.

The experiments were carried out with specimens of density 0.59 g/cm^3 for three loading pressures—9, 14, and 26 GPa. They showed that within the limits of relative experimental errors the results of "with-air" and "without-air" experiments agreed among themselves (see Table I). This considerably simplified the experiments since its was no longer essential to introduce the complications associated with pumping air out of the measuring system.

We turn to consideration of the results obtained. The $D(m)$ relation, Fig. 2, shows the so-called "single-charge lines", i.e., each of the curves is the change in wave velocity as a function of m for fixed parameters of the wave in the shield, i.e., for a chosen measuring system. The form of the curves is different for different charges, but there are also general features: for small m the wave velocities drop sharply; they are observed to grow or level out starting at $m\simeq 2.0$. The D–m relations become close to linear. We will make use of these facts in what follows to estimate the position of the shock adiabat for $m>m_{\exp}$.

All the experimental results which we had at our disposal are shown in Fig. 3. This includes results obtained in the present and earlier[2] work. It can be seen from the figure that the shock adiabats occupy practically the whole D–U plane, starting with the "solid" adiabat (i.e., corresponding to an initial crystallographic density $\rho_{00}=8.87$ g/cm^3), $m=1$ and finishing with the limiting line $D=U$ which is the boundary of possible states (in fact, the condition for the existence of a shock wave is the relation $D>U$).

A fairly detailed analysis of the features of the shock adiabats of porous metals in D–U coordinates was given earlier.[2] Here we only note those characteristic features which are produced by or are directly related to the new experimental results.

SHOCK ADIABAT OF NICKEL WITH $m=1.11$

The reason for its 'appearance' is connected with the following facts: as Fig. 3 shows, the first portions of the diagrams of the adiabats of porous nickel tend to (a linear extrapolation) the point with coordinates $U=0$, $D_0\simeq 130$ m/s. In addition, the magnitude of C_0 (also an extrapo-

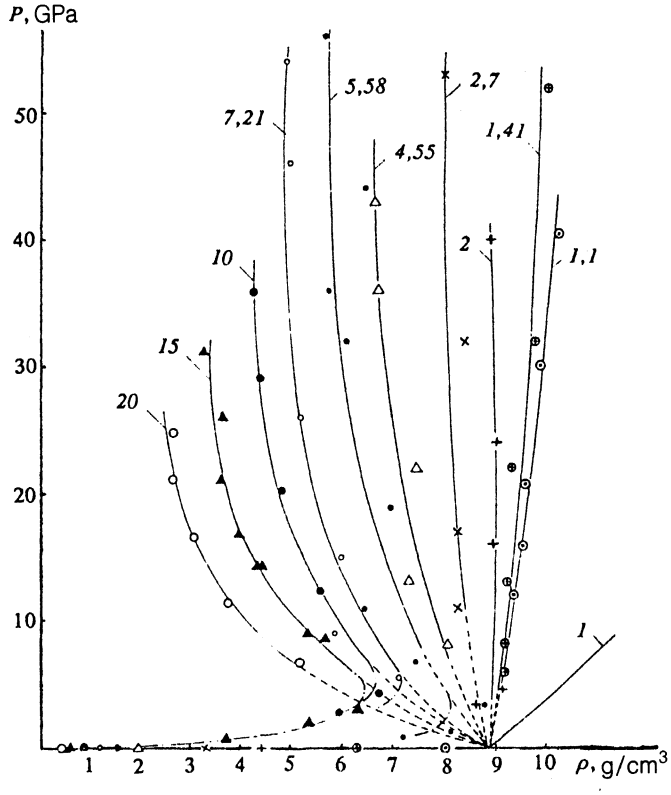

FIG. 4. $P(\rho)$ relation for nickel of different porosities.

lated value) for the adiabat with $m=1$ ($\rho_0=8.87$ g/cm^3) concides with the bulk velocity of sound and is 4.5 km/s. In Trunin *et al.*[2] the adiabat with $m=1.41$ ($\rho_0=6.29$ g/cm^3) was closest to the adiabat with $m=1$ and extrapolating it to the ordinate ($U=0$) did not contradict the value $C_0\simeq 130$ m/s. A question arose as to which value of C_0 adiabats with intermediate values $1<m<1.41$ would approach. Would a situation be possible such that lowering the initial density by even a few percent (compared with the crystallographic density) would yield C_0 close to characteristic values for all other porosities, i.e. in the present case to $C_0\approx 130$ km/s? This was the reason for studying the adiabat with $m=1.11$ ($\rho_{00}=8.01$ g/cm^3). As is seen from Fig. 3, the positions of the experimental points of this adiabat do not contradict the concept of centering the adiabats on a universal point (or a small region ΔD), at which the initial parts of the adiabats for others with $m>1$ come together. Of course, this confirmation is not strict, since it is based on extrapolating adiabats; at the same time it is also not contradicted by the experimental results.

ADIABATS OF ULTRA-LOW DENSITY

In the initial section of the D–U relations adiabats with $m>10$ have a slope dD/dU close to unity (1.03–1.05). When m is decreased the slope of the first sections of the adiabats increases and for $m=1.11$ reaches $dD/dU\simeq 3$.

Thus the first section of the D–U relations for porous nickel are divergent fans of straight lines centered roughly

TABLE II.

m	C_0, km/s	λ
1,0	4,5	1,63
1,1	3,13	1,71
1,41	1,44	1,85
1,72	0,8	1,80
2,0	0,36	1,82
2,7	−0,22	1,54
4,55	−0,46	1,55
5,58	−0,37	1,43
7,21	−0,55	1,41
10,0	−0,68	1,38
15,0	−0,93	1,37
20,0	−1,02	1,36

on a single point (or small interval ΔD). The change of slopes $dD/dU=\lambda(m)$ of the second sections of the adiabats are shown in Table II. The $\lambda(m)$ dependence is characterized by three ranges: in the first of them ($1<m<2$) we have $\lambda(m)\simeq 1.8$, in the second ($2<m<4.5$) we have $\lambda\simeq 1.55$ and finally for $m>5.6$, $\lambda(m)\approx 1.4$ is characterized by a small reduction.

The limiting value of dD/dU for large m is 1. We note that within the limits of the errors in the experiment this interpretation of the $\lambda(m)$ dependence is not entirely strict, since in several cases, e.g., in the interpretation of results for $m=4.55$, 5.58 and others, a somewhat different representation of the experiment is possible. We will give a preferred, more logical, suggestion for a description.

We notice that the transition from the region of constant and relatively large slope λ to a decreasing one ($m>2.7$) corresponds roughly to a change in sign of the extrapolated value of D_0 ($U=0$) from positive to negative.

The slopes of the second sections of the adiabats differ from the limiting value ($\lambda\simeq 1.2$) characteristic of the region of ultra-high pressures, where the conclusions from theoretical models[6] are applicable. The adiabats of porous nickel thus appear to change their slope once more, for higher compression parameters (which, in fact, are also observed for metals studied by Trunin *et al.*[7]).

Finally, we note the following fact: the section of the shock adiabat for $m=20$ near the region of the change of slope dD/dU ($D\simeq 3.6$ km/s) passes to the immediate vicinity ($\Delta D\simeq 250$ m/s) of the D–U line. All the adiabats corresponding to $m>20$ should lie in this interval ΔD!

The special region near the point with parameters $D\simeq 3.6$ km/s, $U\simeq 3.5$ km/s is essentially the start, in its own way, in "reference coordinates" of a new fan of adiabats for nickel with $m>20$.

One such adiabat ($m=30$, $\rho_{00}=0.296$ g/cm^3) is shown in Fig. 3. by the dotted line (its position is estimated from linear extrapolation of the $D(m)$ dependence of Fig. 2, into the region of parameters for $m=30$). It is separated from the limiting line D–U by $\Delta D\approx 150$ m/s. Adiabats with still larger m will be "compressed" into this remaining interval ΔD.

In concluding the consideration of the D–U dependence we draw attention to the fact that the transition from the first to the second sections takes place for most

adiabats ($m > 1.4$) at roughly the same velocity parameters $D \simeq 3.3$–3.7 km/s.

The results are shown in P–ρ coordinates in Fig. 4. The features of adiabats in these variables were essentially noted by Trunin *et al.*[2] We only stress the following facts here.

Adiabats with $m = 10$, 15, and 20 have appreciably enlarged the region of states studied and have also enabled estimates to be made of the parameters of so-called "packing pressures", i.e., those minimum values of pressures on the adiabat of porous metal corresponding to the "P_{pp} point" through which interpolation of the adiabats is carried out to the initial state $P = 0$, $\rho = \rho_{0cr}$.

Figure 4 illustrates a typical picture of the arrangement of experimental points in the P–ρ plane, the characteristic features of which are the start of the gently sloping first section, where the energy is expended on overcoming the elastic interaction of particles and the frictional forces between them, and the appreciably steeper second section. The transition from the first section to the second indicates that in the specimen the pores are completely "taken up" and it is strongly heated (for large m) and compressed to densities of the system not much different from the normal (crystallographic).

The adiabats obtained are shown in Fig. 1. It can be seen that their upper sections are situated in the region of states sought.

We will estimate the temperatures of shock compression on the extreme adiabats with $m = 15$ and 20. These estimates, carried out at the authors' request by A. B. Medvedev using to his model[8] showed that at shock compression pressures $P_G = 35$ GPa the temperature on a nickel adiabat with $m = 20$ is $\sim 60\,000$ K and on an adiabat with $m = 15$ is $\sim 50\,000$ K. Both these values correspond to the required heatings in the region studied. It is interesting that the equivalent temperature of 60 000 K on the adiabat with $m = 1$ is reached for pressures of ~ 1200 GPa.

Finally we give values of the Grüneisen coefficient near the maximum compression parameters for adiabats with $m = 15$ and 20. Since one can neglect elastic ("cold") components of pressure and energy in the states considered, we can write for mean values of the Grüneisen parameter

$$\bar{\Gamma} = \frac{2(D-U)}{U}.$$

For $P = 30$–35 GPa we have $\bar{\Gamma} \simeq 0.45$ which, judging by Fig. 1, is a perfectly feasible value. (Taking into account the contribution of cold components changes these estimates to values ~ 0.65).

The thermodynamic parameters of ultraporous nickel with initial densities of 0.44, 0.59 and 0.89 g/cm^3 thus show that under conditions of shock wave compression by pressures $P_G = 35$ GPa states are realized corresponding to an unexplored region of the phase diagram. We can therefore consider the problem of reaching this region (in the first stage) as achieved.

In our subsequent work we intend to broaden both the variety of materials and also the range of their parameters studied.

[1)]The powder was kindly supplied to us by V. G. Kuropatkin.

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