X-ray diffraction investigation of the structure of shock-compressed aluminum

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Results are presented of an x-ray-structure measurements of the compression of monoblocks of polycrystalline aluminum along the [111] and [100] crystallographic directions. A dependence of the compression of the single-crystal blocks of the materials on their orientation relative to the direction of the shock-wave front was observed in the indicated range of pressures (up to 23 GPa). This points to a strain inhomogeneity of the produced dynamic states.

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1. INTRODUCTION

The behavior of elastoplastic materials under shock compression has been the subject of recent intensive study. The state of the deformed body is described by two tensors, the strain tensor and the stress tensor. The present opinion[1-4] is that the state of a shock-compressed solid is described by a stress tensor with principal stresses that differ by an amount equal to the dynamic yield point. According to available experimental data[5-6] metals at dynamic pressures higher than 10 GPa, while retaining their elastoplastic properties, a relaxed quasi-hydrostatic state have behind the shock-wave front and the tensor stress field turns into a scalar one.

To our knowledge there are no published experimental data that describe the degree of homogeneity of the strained state of a shock-compressed solid. An x-ray structure procedure modified to permit registration of the Debye-Scherer diagrams of shock-compressed materials, makes it possible to measure the compression of single-crystal blocks of the investigated substance along various crystallographic directions and describe by the same token the resultant strain stress.

We present below the results of x-ray structure investigation of an aluminum sample (alloy AD-1), which provide an example of measurements of this kind.

2. EXPERIMENTAL SETUP AND RESULTS

A detailed description of the procedure used to register the Debye-Scherer patterns is given in Refs. 7 and 8. Figure 1 shows a schematic diagram of the experimental setup. It is based on the Seeman-Bohlin focusing photography.[9] To produce dynamic states in the sample, an aluminum striker was used, accelerated by explosion products and stopped by a layer of the investigated material. The opposite side of the layer was in contact with a lithium plate. The lithium plate permits the x rays to reach the compressed sample (the x-ray beam passes through the weakly absorbing lithium layer) and maintained constant the dynamic compression of the central part of the investigated sample surface during the time of the x-ray exposure. The exposure was turned on after the arrival of the shock wave at the sample–lithium interface. The time interval during which the dynamic state of the central part of the investigated sample surface (30 mm diameter) remained unchanged (the mass velocity of the substance stayed constant) was $\sim 1.5 \times 10^{-6}$ sec and was limited by the arrival of the relaxation (unoading) wave. The x-ray exposure did not exceed $\sim 0.3 \times 10^{-6}$ sec. The Debye-Scherrer pattern of the aluminum was registered using the characteristic radiation of molybdenum ($\lambda_{K\alpha} = 0.710$ Å).

The parameters of the registration system were refined in each experiment in accord with a preliminary Debye-Scherrer pattern obtained after all the units were assembled.

Figure 2 shows the P–u diagram (P is the pressure and u is the mass velocity of the substance) of the dynamic compression of the sample. Figure 3 shows photographs of typical Debye-Scherer patterns of the sample. Figure 4 shows examples of the photographic density profiles of the diffraction lines of the sample.

3. DISCUSSION OF EXPERIMENTAL RESULTS

The (111) and (200) diffraction lines of the aluminum samples, which were recorded on the x-ray patterns, made it possible to determine the interplanar distances for these crystallographic-plane systems, as well as the lattice periods of the compressed single-crystal blocks, with definite orientations relative to the shock-

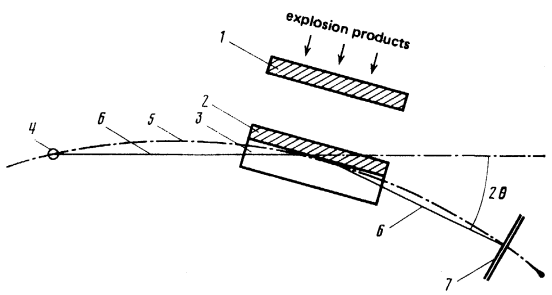

FIG. 1. Schematic diagram of the setup for the registration of Debye-Scherrer diagrams of shock-compressed aluminum: a) striker, 2) sample, 3) lithium layer, 4) anode of pulsed x-ray tube, 5) focusing circle, 6) path of x-ray beam, 7) x-ray film with amplifying screen, θ) Bragg x-ray reflection angle. The sample, the lithium layer, and the strikers are disks of 70 mm diameter and 6, 15, and 6 mm thick, respectively.

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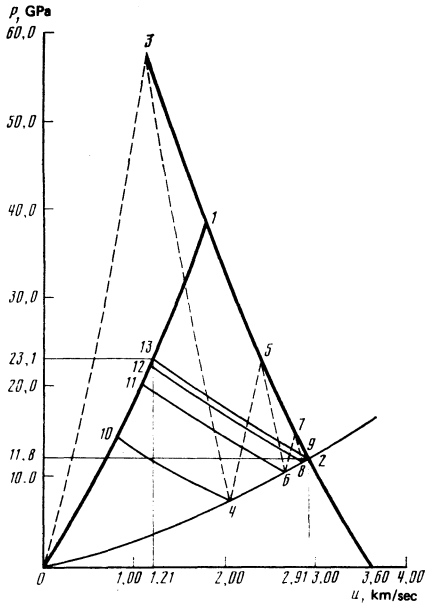

FIG. 2. P–u diagram of the dynamic compression of the sample. Initial coordinates of the striker are $P=0$ and $u=3.6$ km/sec. The coordinates of the striker and sample upon collision (in state 1) are $P=38.6$ GPa and $u=1.80$ km/sec. The coordinates of the recorded state of the sample, produced after the arrival of the shock wave at the sample–lithium interface (state 2) are $P=11.8$ GPa and $u=2.91$ km/sec. Second variant of the experiment. State of striker and copper screen upon their collision (state 3). The circulation of the shock waves in the copper layer and of the relaxation wave gives rise to states 4, 6, 8, and 2 on the copper-lithium interface and to states 5, 7, 9, and 2 on the copper–striker interface. The recorded state of the sample (state 13) with $P=23.1$ GPa and $u=1.21$ km/sec was produced by compression of a sequence of shock waves propagating through the lithium layer (the investigated layer of the material went through the states 10, 11, 12, and 13). The multiple compression (relaxation) adiabats of the materials were obtained by mirror reflection of their first adiabats.[2] The data on the dynamic compressibility of the aluminum, copper, and lithium were taken from Ref. 10. Thin line—adiabat of lithium, dashed—adiabat of copper, thick—adiabat of aluminum.

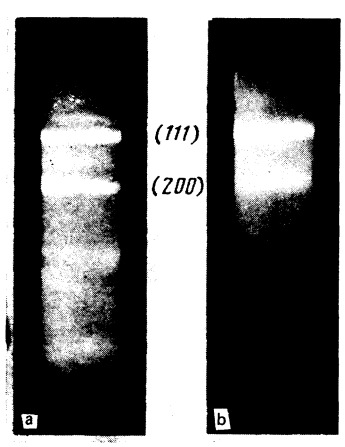

FIG. 3. Typical Debye-Scherrer diagram of aluminum sample with reflections from the (111) and (200) crystallographic planes: a) preliminary photograph (unstressed sample), b) sample compressed by shock wave.

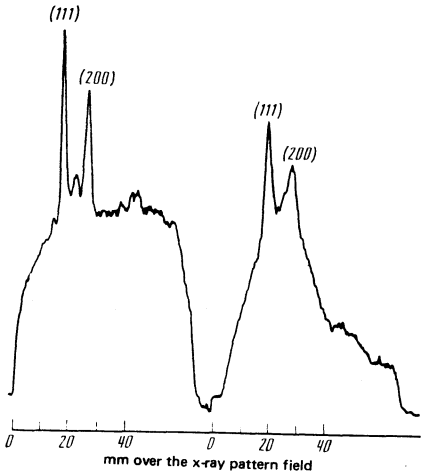

FIG. 4. Typical densitometer record of the profiles of the (111) and (200) diffraction lines of the sample; left—density pattern of preliminary photograph, right—density pattern of shock-compressed pattern. The photographs were obtained with the aluminum sample compressed at a dynamic pressure $P=23.1$ GPa.

wave front. It can be approximately assumed that the crystallographic planes that produce the (111) and (200) diffraction lines are parallel to the front of the shock wave that compresses the sample, since the angle between the x-ray beam and the investigated sample surface was 8–10° in all cases.

The results of the reduction of the obtained experimental data are summarized in Table I.

We used in the calculations the aluminum crystallographic data taken from Ref. 11. The third column of the table gives the results of an experiment in a setup different from that shown in Fig. 1, wherein the lithium plate was placed between the sample and a copper layer 2.7 mm thick, and the striker was stopped in the copper layer. The registered state (state 13 in Fig. 2) was reached through compression of the sample by a sequence of shock waves resulting from the differences between the dynamic impedances of the copper, aluminum, and lithium.[2] The x-ray exposure was turned on approximately one microsecond after the arrival of the first shock wave at the sample–lithium interferface in the constant flow region, as verified by magnetoelectric measurements of the mass velocity[2] in paraffin, which replaced the sample in the assembly.

The values in the first two columns of the table (the pressure P and the compression ρ/ρ_0, where ρ is the density of the compressed sample and ρ_0 is the density of the sample in the initial state) were determined in the hydrodynamic approximation by a standard method.[2]

TABLE I. X-ray diffraction study of the structure of shock-compressed aluminum.

P_{hyd} GPa	ρ_{hyd}/ρ_0	$a(111)$, Å	$a(200)$, Å	$[a(200)/a(111)]^3$	$\rho(200)/\rho_0$
11.8±0.4	1.124±0.006	3.85±0.04	3.89±0.04	1.030±0.003	1.12±0.04
23.1±0.8	1.210±0.006	3.75±0.04	3.80±0.04	1.040±0.003	1.21±0.04

The third and fourth columns of the table give the shock-compressed-aluminum lattice periods calculated from the measurements of the Bragg angles θ of the (111) and (200) diffraction lines. The lattice periods were determined by a method similar to that used in photography with a standard.[12] The comparison diffraction line (whose Bragg angle θ can be regarded as known) can be assumed to be any line on the preliminary x-ray pattern. The coordinate of the maximum of the diffraction line (which was usually symmetrical) was taken to be of the intersection point of the x-ray film plane with the line joining the centers of the chords drawn at different heights of the diffraction profile. This procedure was carried out on density patterns with 10-fold magnification of the linear scale in the direction of the variation of the angle θ, and made it possible to determine the coordinate of the maximum accurate to ±0.05 mm.

The error in the measurement of the lattice period is influenced, besides the standard error sources,[11,13] also by a factor peculiar to experiments in which shock waves are used, namely the motion of the sample in the laboratory frame. The displacement of the diffraction line on an x-ray pattern of a shock-compressed sample is the algebraic sum (with allowance for the sign) of the displacements due to the change of the lattice period and the kinematic change of the position of the investigated layer of matter moving with the mass velocity.

Estimates have shown that the error $|\Delta a/a|$ in the measurement of the lattice period did not exceed 1% and consisted of the errors due to the low order of the reflection of the investigated diffraction lines, and of the errors in the measurement of the time interval between the arrival of the shock wave at the sample-lithium interface and the turning on of the x rays. (The error in the measurement of the time interval was not less than 0.2×10^{-6} sec).

The fifth column of the table shows the ratio of the x-ray diffraction densities of the shock-compressed-material single-crystal blocks for which the lattice periods were determined.

The density ratio as a function of the parameters determined from the x-ray patterns can be represented in the form

$$\frac{\rho(111)}{\rho(200)}=\left[\frac{a(200)}{a(111)}\right]^3=\left\{\frac{2}{\sqrt{3}}\frac{\sin\theta(111)}{\sin[\theta(111)+\varphi]}\right\}^3,$$

where $\theta(111)$ is the Bragg reflection angle of the x-ray beam upon diffraction by the (111) planes of the shock-compressed aluminum sample, and 2φ is the angle between the x-ray beams reflected by the atomic planes (111) and (200) of the shock-compressed sample. This relation is a direct consequence of the Bragg equation.[9]

An analysis of the experimental results has shown that in the ranges of $\theta(111)$ and φ of the experiments considered in the present article the main error of a (200)/$a(111)$ is determined by the errors in the measurement of the angle φ, i.e., by the errors in the measurement of the distance between the diffraction lines on the x-ray pattern and the errors in the measurement of the distance from the sample to the x-ray film at the instant when the x-rays are turned on; the errors in the measurement of the angle $\theta(111)$ can be neglected. Compared with the lattice-period errors, the error in their ratio is decreased by one order, to 0.1% and the error in $\rho(111)/\rho(200)$ is decreased to 0.3%.

The sixth column of the table shows the compression of the single-crystal blocks that produce the (200) diffraction line, taken to be the ratio of the x-ray diffraction density $\rho(200)$ (Ref. 13) of the shock-compressed sample to its initial density $\rho_0=2.71$ g/cm^3.

The results of the reduction of the experimentally recorded Debye-Scherrer diagrams of the shock-compressed aluminum sample point to a strain inhomogeneity of the dynamic states, which do not relax to the state of the uniformly compressed material, at any rate within a lifetime up to $\sim1.5\times10^{-6}$ sec and in the pressure range up to 23 GPa.

The single-crystal blocks of the investigated material, with the crystallographic direction [111] perpendicular to the shock-wave front, are characterized by a compression that exceeds the bulk compression of the sample. The compression of the single-crystal blocks in the [200] direction agrees, within the limits of the measurement errors, with the bulk compression of the sample.

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