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# Propagation and interaction of dodecahedral converging shock waves in steel balls*

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Physical metallurgical and computer simulation methods were used to study the propagation and interaction of shock waves in steel balls subjected to convergent dodecahedrally symmetric shock waves. Conditions for energy cumulation and the realization of regular and irregular types of shock wave interactions were studied. Based on microstructural investigations of intact samples, the parameters of the shock-wave loading, namely pressure, residual temperature, and the density of the material were calculated.

Key words: *shock waves; microstructure; explosive loading; cumulating*

## 1. Introduction

As is known, the application of high dynamic pressures ensures that plastic deformation, fracture, polymorphic and phase transformations, chemical reactions and many other physical and chemical phenomena occur at extremely high rates. Therefore, the shock wave loading of condensed media permits fundamental properties of substances to be studied under extremal conditions.

The development of new technologies based on explosive methods permits one to increase the complexity of experiments conducted with the purpose of obtaining unusual dynamic loading conditions. The increasing complexity of experiments in turn imposes new requirements on the understanding of processes that occur upon the propagation of shock waves with a complex wave front configuration in the material. It is for this reason that studying effects of shock waves with a complex shock-wave-

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front geometry on metallic materials is not only of pure scientific, but also of practical interest from the standpoint of several branches of science.

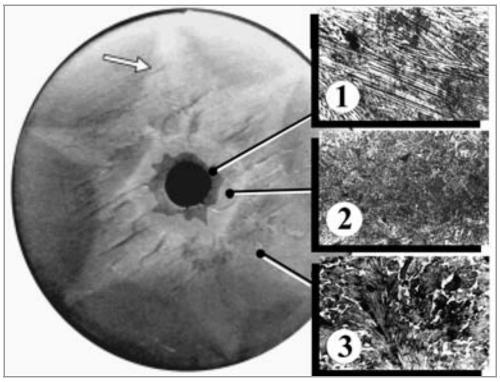
Under the action of a powerful pulse impact, structural changes can arise in a metal that prove to be unattainable under usual (static) conditions. On the other hand, an analysis of the results of shock-wave impacts on a sample permits one to draw conclusions about the character of shock-wave motion and about the processes of shock wave interaction and energy cumulation, i.e., to solve nonlinear problems of the physics of shock waves. With such an approach, the loaded sample is considered to be not only an object of investigation, but also a probe for obtaining information on complex shock-wave processes.

The properties of metals and alloys are closely related to their structure. It is therefore very important to establish a reliable correlation between microstructural changes and the parameters of shock-wave impact (pressure, degree of compression, residual temperature). In this work, we show how residual microstructural changes can help in answering some questions that arise when studying shock-wave motion in terms of hydrodynamics and gas dynamics.

## 2. Methods

Solid steel balls 60 or 40 mm in diameter were shock-loaded by exploding a spherical layer of explosive 10 or 20 mm thick (the ratio $R_{sp}/R_{\mathrm{exp}}$ of the ball radius to the outer radius of the explosive layer was 3/4 and 1/2, respectively). The explosion was initiated (with an asynchronism not exceeding $10^{-7}$ s) at the surface of the charge at twelve points uniformly located over the sphere surface. The explosive-covered sample was placed in a massive metallic casing, which ensured that the ball remained intact after it had been subjected to a convergent quasi-spherical shock wave. The pressure in such a wave grows from the sample surface toward the focusing centre as the amount of the substance encircled by the wave progressively decreases. The growth of pressure results in a temperature rise. The shape of the shock-wave front changes in the course of motion. At the centre of the ball, the shock wave is focused, after which a divergent compression shock wave propagates from the centre to the surface. The interaction of the wave with the rarefaction wave that propagates from the sample surface leads to the appearance of tensile stresses and related spalling phenomena in the material. Since the magnitude of tensile stresses is determined by the rate of unloading, the sample usually fails if unloading occurs too rapidly. Therefore, a massive metallic casing was used in order to retain the sample intact, which allowed a lower rate of unloading and decreased the tensile stresses occurring in the sample [1].

*Shock-wave loading of a 40 mm steel ball.* The formation of a quasi-spherical shock-wave front was studied using a ball made of steel containing 0.37 wt. % C and 1.1 wt. % Cr ($R_{sp}/R_{\mathrm{exp}}$ = 1/2). Various techniques of chemically etching diametrical cross sections reveal radial changes in microstructure near the centre of the sample, indicating the effect of cumulation and show the "nonsphericity" of the loading method. The diametric cross section of a ball is shown in Fig. 1.



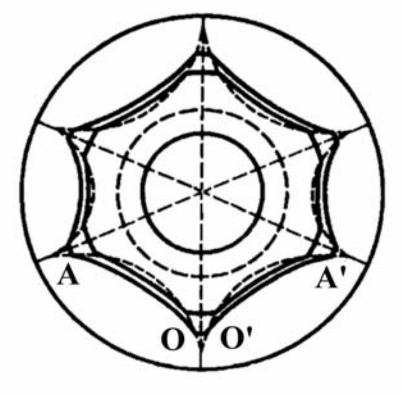




Fig. 1. Diametric section of a 40-mm ball: 1 – dendritic structure, 2 – bainite 3 – ferritic-pearlitic structure

Fig. 2. Scheme of shock-wave propagation in a 40 mm ball

The patterns of various etchabilities were first observed by Al'tshuller et al. [2] on samples loaded with cylindrical shock waves from six and four points. Therefore, the patterns obtained by etching are called Al'tshuller patterns. Measurements of microhardness indicate that a significant reduction in strain hardening is observed in the light regions of Al'tshuller patterns [3]. All the experimental data obtained for this sample can be explained with the help of the sketch shown in Fig. 2 illustrating temporal changes in the initially three-dimensional front. The leading waves of three-wave Mach configurations (segment *OO'* in the scheme), which arise at the collision sites of divergent shock waves moving from neighbouring initiation points (lines *AO* and *A'O'*), have higher velocities, resulting in a smoothing of the front. According to [4], the traces of the points *O* and *O'* represent the boundaries of the contact discontinuity. In Fig. 1, these boundaries separate the Al'tshuller regions, which are light and dark on etching. The boundaries are indicated by arrows in Fig. 1. According to [4], the final magnitude of the pulse pressure is the same on both sides of a boundary of contact discontinuity (with allowance for an additional pressure on the substance due to the waves reflected from the surface of interaction, not shown in the scheme). However, the final state in dark Al'tshuller regions (Fig. 1) is a result of repeated (twofold) compression; i.e., the loading regime is in this case closer to static, which leads to a greater degree of strain hardening in the material.

The shock-wave motion acquires a quasi-spherical character beginning from a certain radius ($r$ ~ 9 mm), and therefore can be considered to be one-dimensional. Figure 1 shows an almost spherical cavity of about 5mm in diameter in the centre of the quasi-dodecahedron. Around this cavity, there is a narrow (0.5–1.0 mm wide) region of columnar crystals that have a pronounced dendritic structure (Fig. 1). The presence of this structure indicates that near the centre, where the focusing occurs, the steel melts (and it may, at the very centre, even evaporate) and then solidifies on cooling. Around the zone of columnar crystals there is a circular zone (about 2 mm thick), in which γ-iron is formed. Microstructural studies show that, in the outer portion of this zone, the formation of the γ phase occurs in place of the pearlitic one found in the initial microstructure of the steel. The inner portion of this zone is completely transformed into austenite. During cooling, after the explosive loading, the austenite transforms into an acicular structure (bainite) whose hardness is greater than that of pearlite and smaller than that of martensite. The outermost zone (about 14 mm thick) retains the initial ferritic-pearlitic structure, although a localized deformation was observed in some regions (Fig. 1).

As previously stated, near a certain critical radius $r$ ~ 9 mm, a quasi-spherical convergent shock wave is formed as a result of the interaction of shock waves moving from different initiation points. According to [5], the pressure in a convergent spherical shock wave grows as $P \approx P_0(r_0/r)$. Based on this and on the fact that a clearly pronounced zone of melting exists in the sample (the distance from the centre of the sample to the outer boundary of the melting region is $r$ = 3.2 mm), the pressure in the melting zone can be estimated considering the melting point of the steel and that solidification occurs after unloading. Results of such calculations are given in Table 1.

Table 1. Dependence of pressure $P$ and residual temperature $T$ on the distance to the ball centre $r$ in the field of one-dimensional shock-wave motion

| $r$, mm | $P$, GPa | $T$, K |
|---|---|---|
| 9 | 52 | 520 |
| 8 | 60 | 590 |
| 7 | 68 | 680 |
| 6 | 81 | 830 |
| 5 | 102 | 910 |
| 4.5 | 115 | 990 |
| 4.0 | 134 | 1150 |
| 3.5 | 161 | 1450 |
| 3.0 | 224 | 2100 |

The residual temperature, pressure and specific volume were calculated in the three-dimensional (non-spherical motion) field of the ball by means of computer modelling of shock-wave motion on the basis of the form of the boundaries of contact discontinuity (indicated by arrows in Fig. 1). The results of these calculations for three-dimensional fields of the ball are given in Table 2.

*Shock-wave loading of a 60-mm steel ball.* Figures 3a, b display macro- and micrographs of the surface of a diametrical cross section of a 60-mm steel ball with $R_{sp}/R_{exp}$ = 3/4. The changes observed in the microstructure (Fig. 3b) and the results of microhardness measurements indicate that in matted Al'tshuller regions (which look brighter in Fig. 3a) cycles of α→ε→α polymorphic transformations took place. Since the ε phase is formed in steel at pressures exceeding 13 GPa, the absence of traces of the α→ε→α transformations in certain regions of the surface means that the pressure in these regions did not exceed this value.

Table 2. Dependence of pressure *P*, density $\rho$, and residual temperature *T* on the distance *r* to the ball centre in the field of three-dimensional shock-wave motion*

| *r*, mm | *P*, GPa | $\rho_1$, g/cm$^3$ | $\rho_2$,g/cm$^3$ | $T_1$, K | $T_2$, K | $\Delta T$, K |
|---|---|---|---|---|---|---|
| 16.58 | 49.0 | 9.86 | 9.83 | 333 | 485 | 152 |
| 16.09 | 53.1 | 9.97 | 9.94 | 345 | 527 | 182 |
| 15.61 | 57.6 | 10.08 | 10.05 | 537 | 575 | 218 |
| 15.20 | 62.1 | 10.19 | 10.16 | 370 | 625 | 255 |
| 14.87 | 66.2 | 10.29 | 10.26 | 381 | 672 | 291 |
| 14.53 | 71.0 | 10.40 | 10.37 | 395 | 729 | 334 |
| 14.27 | 75.0 | 10.49 | 10.45 | 406 | 778 | 371 |
| 14.00 | 79.2 | 10.58 | 10.54 | 419 | 831 | 412 |
| 13.83 | 82.1 | 10.64 | 10.60 | 429 | 869 | 440 |

$\rho_1$ and $T_1$ , $\rho_2$ and $T_2$ are densities and temperatures in dark (1) and light (2) A'tshuller's patterns. $\Delta T$ is temperature on the boundary.

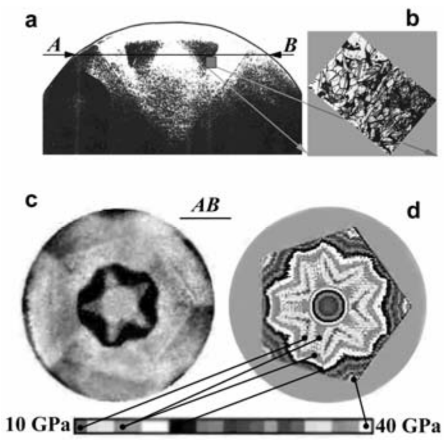



Fig.3. Shock-wave loading of a 60-mm steel ball: a) diametric section of the ball, b) traces of α→ε→α transformations in light regions and absent of the traces in dark regions, c) macrostructure in the section *AB*, d) result of modelling (map of pressure)

The observed shock wave effects suggest that the interaction of shock waves moving from different explosion-initiation points obeys the laws of regular reflection. As a consequence, no energy cumulation or related significant increase in pressure occurs with the approach of the shock waves to the focusing centre. Three observations led to this conclusion.

1. No microstructural changes, such as traces of the α→γ→α transformation cycles or melting, that could indicate a marked growth of pressure as shock waves approach the ball centre are seen.

2. The initial shock-wave loading symmetry is retained throughout the entire propagation of shock waves to the focusing centre (Fig. 3a). As stated above, the shock-wave motion acquires a spherical symmetry for irregular interactions, with the pressure growing according to the l/*r* law, where *r* is the distance to the ball centre.

3. No traces of contact discontinuities are present upon the motion of a three-wave Mach configuration.

A regular character of the interaction of shock waves leads to a situation where the nonsphericity of the shock-wave front is retained in the course of wave motion toward the focusing centre. This substantially complicates the theoretical description of shock-wave motion. The solution of the nonlinear problem of the propagation and interaction of shock waves in the general case with such complex initial and boundary conditions proved impossible. However, the allowance for specific features in the geometry of the experiment permitted us to numerically simulate shock-wave motion from the results of metallographic investigations. Te cross section *AB* (Figs. 3a, c) of the ball was used for modelling. A number of assumptions were made concerning the allowance for nonlinear effects. The agreement achieved between the experimental and theoretical results can be considered as an evidence of the validity of these assumptions. Figure 3d shows the results of the simulation, along with the experimental pattern of microstructural changes observed in the ball cross section given in Fig. 3c. A virtually complete agreement of the calculated results with experimental data is observed.

## 3. Conclusions

Two types of shock-wave motions in metallic balls upon quasi-spherical shock-wave loading were considered. In the first case, the initial conditions become "forgotten" at the stage of convergence, after which the motion acquires a spherical one-dimensional character. In the other case, the initial conditions are not "forgotten" during convergence. It has been established that for the first type of shock-wave motion there is a corresponding Mach (irregular) regime of interaction of shock waves. This occurred in the 40-mm steel balls. The experimental investigations allowed a scheme to be developed for the transformation of dodecahedral shock-wave front into a spherical one. Based on the experimental data, the thermodynamic parameters of shock-wave loading for a steel ball 40 mm in diameter ($R_{sp}/R_{\text{exp}} = 1/2$) were calculated in both the region of one-dimensional and three-dimensional shock-wave motion. When simulating the shock-wave motion, we used a real geometry of the boundaries of contact discontinuity. The second regime of the shock-wave motion is associated with a regular interaction of primary shock waves, as realized in the 60-mm steel balls ($R_{sp}/R_{\text{exp}} = 3/4$). A computer simulation of shock-wave motion based on the metallographic investigations of microstructural changes in the steel permitted us to reconstruct a picture of the shock-wave motion and to describe the spatial distribution of pressures in the ball.

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