STEEL HARDENING BY SHAPED EXPLOSION

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There is extensive experimental evidence for improvement in hardness parameters by impulsive deformation of metals. Thus, according to [1], the impact of metal plates on a stationary target at a velocity of 200–300 m/sec results in the hardening of the metal. Still further improvement is achieved when the velocity is increased to 3300 m/sec [2]. Analysis of the shock waves produced as a result of impact can be used to deduce values of the parameters of the metal at ultrahigh pressures [3]. According to these calculations, high-speed impact gives rise to a rapid rise in the pressure in the metal impacter, which probably leads to the hardening effect. Hydrodynamic analysis of converging cylindrical waves shows that by using such waves it is possible to improve the hardness parameters in the compressed metal still further. For example, when a high-speed (3250 m/sec) plate compressed by an explosion collides with a thin-walled tube, this results in a cylindrical shock wave which converges on the axis of the tube and leads to a further hardening of the material [4] as compared with the effects described in [2]. Shaping is a method of producing very high pressures. A shaped explosion gives rise to a high-speed shaped jet [5]. This jet determines the rupture of the barrier and the "plug" which contains most of the mass of the liner and is compressed on all sides by the explosion.

In this paper we report an investigation of the structural changes in the metal liner as a result of shaped compression.

The experiments were carried out with the high explosive TG50/50. The diameter of the charges was 76 mm, the height 240 mm, and the angle of taper of the shaped recess was 30°. A steel liner (mark-10 steel), 2.5 mm thick, was employed. The charge was fired from the end opposite to the shaped recess.

The explosion results in the formation of a shaped jet and a "plug." We have investigated the "plug" caught after the explosion in a sand damper, which prevented any additional interaction between the "plug" traveling at 300 m/sec and a barrier, which could result in additional hardening. The "plug" was cut along the diameter down its axis. The section was then polished, and a grid was drawn on it. The Vickers-hardness distribution was measured on this grid, and, at the same time, the surface of the "plug" was photographed under different magnifications. Figure 1 shows one such photograph of a specially etched surface, showing the characteristic break-off point of the shaped jet, and the structural changes along the axis.

Lines of equal hardness were then constructed, and these were used to plot out outlines of regions with hardness lying in a given range. Figure 2 shows the approximate shape of these regions when all the results of hardness tests were divided into three intervals. It is clear from the figure that, in addition to region 1, in which the hardness does not exceed 250 kg/mm^2, there is also region 2 with hardness up to 350 kg/mm^2, and region 3 with hardness up to 400 kg/mm^2. For comparison, we note that the maximum hardness of the same steel produced as a result of the impact of plates at a relative velocity of 3300 m/sec did not exceed 250 kg/mm^2, while with the additional formation of the converging cylindrical wave the hardness reached 350 kg/mm^2 [4]. Metallographic studies showed that, under low magnification (X70) all the regions in the "plug" had the same structure. This consisted of elongated grains which are characteristic for very high plastic deformations and flow of the material, and are associated with the mixing of different layers (Fig. 3). Under high magnification (X450) it is clear that in regions with increased hardness (region 3 in Fig. 2) the ferrite grains contain many twins (Fig. 4), while in regions of lower hardness (region 1 in Fig. 2) there are large elongated ferrite grains consisting of small equiaxial grains (Fig. 5).

Analysis of the reasons responsible for the observed hardening must start with the processes occurring during the formation of the "plug." Let us consider the hydrodynamic processes of jet formation. In the usual shaping theory [5, 6] it is assumed that, under the action of the explosion (pressure ~10^5 atm), the liner material assumes a state which can be regarded as that of an incompressible fluid. Next, by considering the geometry of jets formed during the compression of the liner we can determine the velocities and masses of the "plug" and the jet. The formation of the shaped jet is illustrated in Fig. 6, where ere AN is the "plug," NL is the shaped jet, ABEK is the active mass of s of the explosive, AMK is the initial position of the liner, and 2 is the graph of the distribution of the active mass of the explosive per unit area of the liner. However, it is possible to adopt a different approach, put forward in [7] in connection with high-speed shaped jets, in which physical processes occurring during shaping can be seen more clearly. The formation of shaped jets in this case can be regarded as the outflow of the liner metal, which is highly compressed by the explosion, into the atmosphere. If we know the state of the metal in the compressed liner we can determine the velocity of the jet and the state of the material in it.

The state of the material in the compressed liner is determined, on the one hand, by the energy expended in compressing a given part of the liner and, on the other, by the interaction between compression and rarefaction waves produced by the explosion. Calculations of the active mass of the charge (m_A) (indicated by ABEK in Fig. 6) by the method given in [5] shows that the amount of this charge per unit area of the liner is as shown by the graph of Fig. 6. It decreases from the apex of the cone to the base, i.e., the liner compression energy also decreases.

Analysis of the collapse of the liner shows that the compression of the liner by the explosion is followed by a rarefaction wave which reduces the pressure of the explosion by-products acting on the liner. A rarefaction wave also travels along the metal liner itself, and leads to a reduction of the pressure in the liner material. Using the velocity of the liner and the velocity of sound in the explosion by-products [5], we have determined the position of the cross section where the rarefaction waves catch up with the liner and the above effects take place (in Figs. 6 and 2 this point is indicated by G). Therefore, the reduction in the active mass of the charge, and the interaction between rarefaction waves, leads to a reduction in both the effect of the explosion and in the pressure within the compressed metal in the direction of the base of the cumulative recess.

After the collapse of the liner, further changes in its state are determined by cylindrical compression, as a result of which the pressure and temperature in the metal increase radially toward the axis [8]. It may be assumed that the metal in the compressed liner behaves as a liquid in the axial region. The highly compressed metal flows out into the atmosphere (the shaped jet), the pressure on the axis falls, and a rarefaction wave propagates radially toward the periphery. If we know the degree of compression, we can use the method put forward in [7] to estimate the state of the metal in the fully compressed liner, and consider in greater detail the release process. We confine our attention here to a qualitative description of the process.

The above qualitative description of the hydrodynamic processes is confirmed by metallographic examination. Microstructural analysis of the metal suggests that it experiences high pressures and temperatures. The photograph of the elongated grains (Fig. 3) shows that the entire material of the "plug" has undergone "turbulent" flow in the heated state, i.e., the grains have not been uniformly elongated in a particular direction, which is characteristic, for example, for flow during die compression, but there have been complex mixing and deformation processes in the material in different directions. At the same time, the distribution (or the time of operation) of different temperatures in the "plug" is very nonuniform. In the high-hardness regions, high-rate deformation has evidently taken place, and was not accompanied by a substantial increase in temperature. The twinning

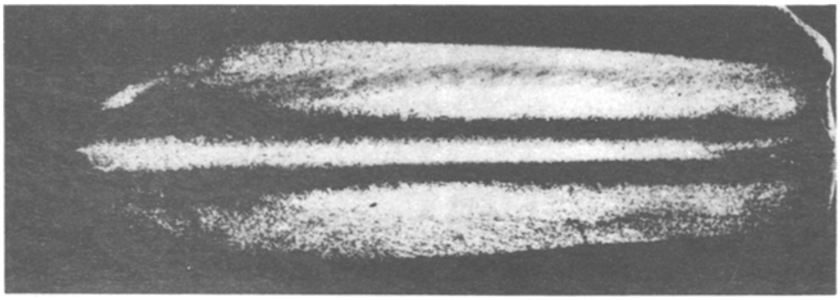

Fig. 1

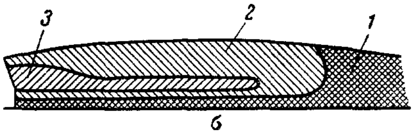

Fig. 2

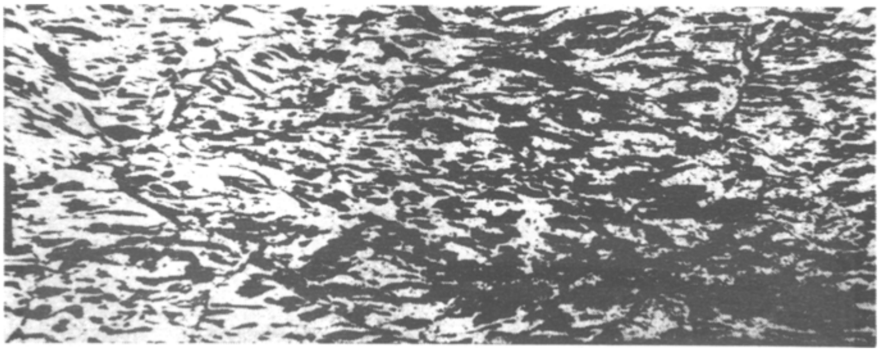

Fig. 3

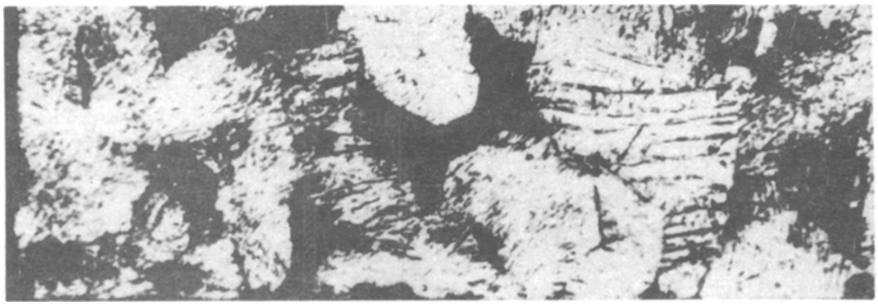

Fig. 4

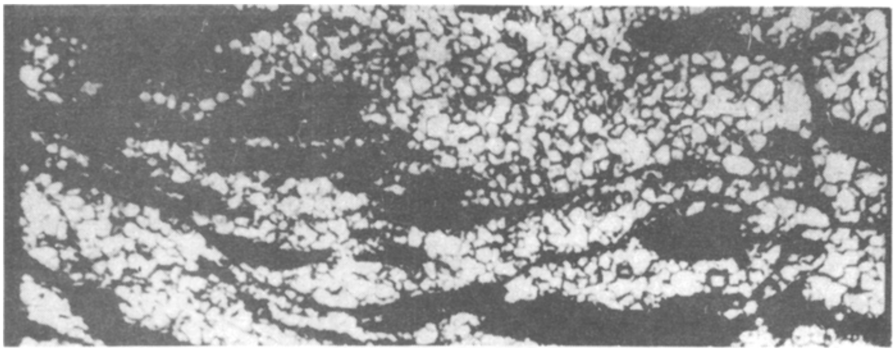

Fig. 5

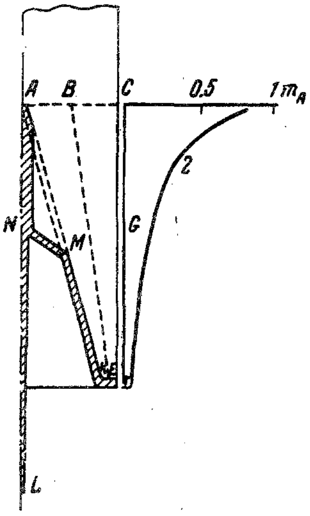

Fig. 6

structure of the ferrite observed in this region is characteristic for high-rate deformation. In regions with lower hardness there appear to be two successive processes: intensive deformation and rapid heating. The presence of the second process is indicated by the fact that each large ferrite grain is split into finer equiaxial grains, which are characteristic for recrystallization structure (see Fig. 5). We note in conclusion that similar structures have been observed at higher impact speeds, up to 4000 m/sec, on the surface of the crater formed by the impact. It is also important to note that the absolute hardness of steel obtained in the present work is higher than the values obtained earlier under impulsive loading, which is probably connected with the more complete fulfillment of the conditions necessary for multilateral compression. Dislocations forming during plastic deformations evidently cannot reach the separation surface, and an increased dislocation density is produced in the metal, leading to considerable hardening with residual phase transitions.

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REFERENCES

1. J. S. Rinehart and J. Pearson, Behavior of Metals Under Impulsive Loads [Russian translation], Izd. inostr. lit., 1958.

2. L. I. Mirkin, "X-ray studies of impulsive deformation of low-carbon steel," Fizika metallov i metallovedenie, 1966.

3. L. V. Al'tschuler, "Application of shock waves to high-pressure physics," Usp. Fiz. nauk, **85**, no. 2, 197, 1965.

4. K. I. Kozorezov and L. I. Mirkin, "Hardening of metals during shock-wave cumulation," Dokl. AN SSSR, 1966.

5. F. A. Baum, K. P. Stanyukovich, and B. I. Shekhter, Physics of Explosions [in Russian], Fizmatgiz, 1959.

6. M. A. Lavrent'ev, "The shaped loading and principles of its operation," Uspekhi matem. nauk, **12**, no. 4, 41, 1957.

7. N. P. Novikov, "High-speed shaped jets," PMTF, no. 6, 22, 1962.

8. K. P. Stanyukovich, Nonsteady Motion of a Continuous Medium [in Russian], Gos. izd. tekh. teor. lit., Moscow, 1955.

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