FLOW OF METALS WITH A HEMISPHERICAL INDENTATION UNDER THE ACTION OF SHOCK WAVES

V. I. Mali

UDC 532.593

The impact on plates of an explosion during welding, with viscosity taken into account, has been examined in [1, 2], and the viscosity coefficients of the most widely used metals were determined experimentally. It was shown that the kinematic viscosity coefficient ν depends on the displacement z of points in the direction of the velocity U_c of the contact point in the following fashion:

$$\nu = \frac{U_c}{z}\,\frac{\delta_1\delta_2(y-\delta_1)^2}{(\delta_1+\delta_2)^2}\cdot\sin\frac{\gamma}{2},$$

where δ_1, δ_2 are the thicknesses of the welded plates; γ is the impact angle; and y is the coordinate vertical to the direction of the velocity of the contact point.

Regarding the expression for the radius of curvature of the free surface in the neighborhood of the contact point

$$R = \frac{2}{\pi}\sqrt{1-\frac{U_c^2}{c_0^2}}\cdot\frac{2\delta_1\delta_2}{\delta_1+\delta_2}\sin^2\frac{\gamma}{2},$$

obtained in [3], as the characteristic dimension, we can estimate the Reynolds number $Re = U_cR/\nu$ at which the flow of the metals, observed in the experiments of [1, 2], occurred. Calculations show that, under the

TABLE 1

Materials	R, cm	δ_c, cm	$U\cdot10^{-5}$, cm/sec	$\nu\cdot10^{-4}$, cm²/sec	H, cm	l_m, cm	l_c, cm	$\frac{U\delta_c}{\nu}$	$\frac{l_c}{R}$
Copper $\rho=8{,}9\frac{g}{cm^3}$	0,4	0,16	2,5	2,5	4	1,5	1,4	1,6	3,5
	1,0	0,4	2,5	2,5	10	5	4,7	4,3	4,7
	1,2	0,5	2,7	2,5	10	6,5	6,1	5,2	5,1
	1,5	0,6	2,7	2,5	15	7,2	6,7	6,5	4,5
D16 $\rho=2{,}7\frac{g}{cm^3}$	0,4	0,2	4,3	2,5	4	1,25	2,1	3,8	4,2
	1,5	0,8	4,0	2,5	15	6,2	10,5	12,8	7,0
Lead $\rho=11{,}3\frac{g}{cm^3}$	0,4	0,2	2,7	0,5	4	2	1,4	10	4,2
	0,95	0,4	2,8	0,5	10	9,2	7,6	23	8,0
	1,5	0,65	2,8	0,5	15	14	11,6	36	7,8
Steel $\rho=7{,}8\frac{g}{cm^3}$	0,4	0,2	1,1	5,5	4	0,4	0,4	0,44	1,0
	1,0	0,5	1,8	5,5	10	1,6	1,6	1,8	1,6
	1,5	0,8	1,7	5,5	6	2,4	2,4	2,5	1,6
Paraffin $\rho=0{,}9\frac{g}{cm^3}$	1,5	0,94	3,5	—	10	2	—	—	—
Wood's alloy $\rho=10\frac{g}{cm^3}$	1,5	0,8	2,8	—	10	7,1	—	—	—

Novosibirsk. Translated from Fizika Goreniya i Vzryva, Vol. 9, No. 2, pp. 282-286, March-April, 1973. Original article submitted August 14, 1972.

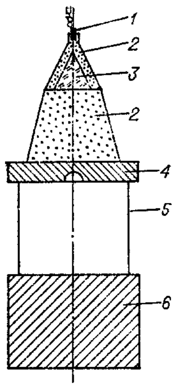


Fig. 1. Schematic drawing of the assembly.

conditions we are considering, values of the Reynolds number do not exceed 10. It is of interest to continue an investigation of such differences among metals as the extent to which they are deformable under explosion loading and characteristics of their internal interaction forces.

In the present paper we give experimental results of an investigation of flows of various metals when a plane shock wave exists from a free surface having hemispherical indentation. The presence of a hemispherical indentation, like the wedge-shaped indentation of [4], makes it possible to isolate and focus the flow of metal. However, the change from a wedge-shaped to a hemispherical indentation provides a significant advantage: a characteristic parameter appears in the problem.

As the thickness of the metal from the charge to the apex of the indentation was maintained constant and the dimensions of the explosive material were so large that further enlargement had practically no influence on the jet emerging from the hemisphere, the radius of the hemisphere can be considered to be the sole characteristic dimension in the problem at hand.

In this work we obtain the experimental dependence of the dimensionless length of the jet on the Reynolds number, which makes it possible to predict the depth of penetration of targets by jets of materials with known viscosity.

Because jets with velocities of the order of several kilometers per second are formed when the shock wave in the metal exists at the hemispherical indentation, high-speed apparatus such as the SFR-2M streak camera and the pulsed x-ray unit PIR-4 were used.

Intermittent shadow photographs of the process of jet motion beyond the boundary of the hemispherical indentation were made by the streak camera. Illumination was accomplished by an "IFK-500" pulse lamp, whose mirror had a rotation rate that was ordinarily 60,000 rpm. The experimental assembly is shown in Fig. 1. The detonator 1 triggers the charge 2, 3, causing the generation of a plane detonation wave. As the basic explosive material a 50/50 cast alloy of trinitrotoluene with hexogene was used. The plane portion of the detonation front was 20 mm in diameter. We used samples 4 that were 40 mm in diameter with hemispherical indentations of 1 to 7 mm in radius. The samples were mounted on supports 5, keeping them a distance H from the target 6, which did not exceed 40 mm in the experiments with the streak camera. The thickness of the metal from the charge to the indentation was maintained at 14 mm. By means of an optical procedure we succeeded in registering the disintegration of the jets from indentations of small radius and their conversion to a focused stream of particles. For example, for the aluminum alloy D16 this critical radius is 1 mm, while for steel it is large by an order of magnitude. The increase in the mean diameter of the jet with increase in the radius of the hemispherical indentation was also ascertained. Typical photographs of jet flow, obtained by the streak camera, are shown in Fig. 2. A study of the zone where the target was hit was also carried out. A photograph of a microsection of one of the targets is shown in Fig. 3.

We succeeded in obtaining more detailed information on the formation, motion, and disintegration of jets by using x-ray photography, which was accomplished with the use of four pieces of pulse equipment, making it possible to obtain four photographs of the process over specified time intervals. Besides samples with the same dimensions as those used with the SRF, we also used samples of 75 mm diameter with indentations up to 20 mm in radius. The thickness of the layer of metal from the charge of explosive material to the apex of the indentation was 14 mm. To maintain geometrical similarity in the experiments the

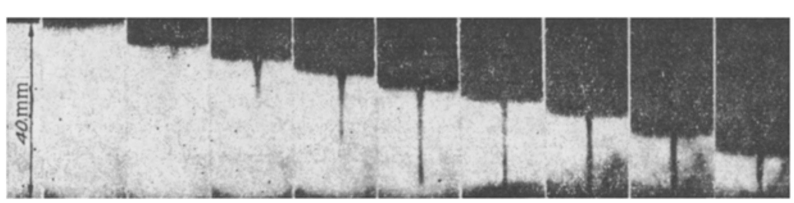


Fig. 2. Intermittent photographs of the motion of a jet out of a hemispherical indentation of 4 mm radius in copper. The time between frames is 4 μsec.

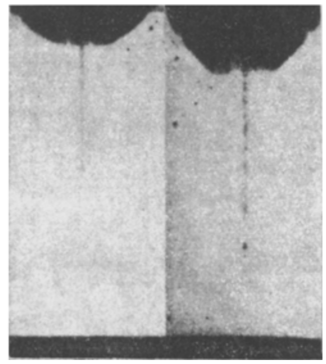
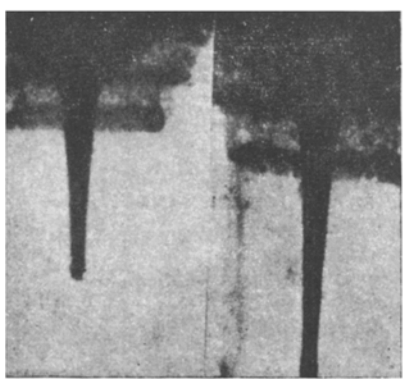


Fig. 3 Fig. 4

Fig. 3. Microsection of a steel target, pierced by a jet from a copper indentation of 4 mm radius. Enlarged eight times.

Fig. 4. X-ray pulse photographs of a jet from a copper indentation of 4 mm radius. Time between frames 10 μsec; jet velocity (of the first element) 2.5 km/sec.



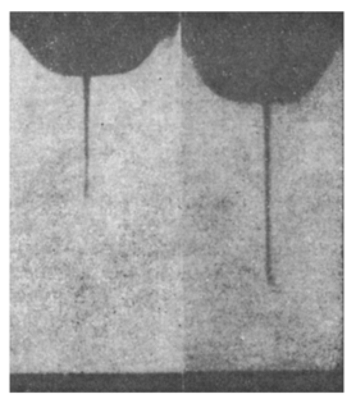


Fig. 5 Fig. 6

Fig. 5. X-ray pulse photographs of a jet from a copper indentation of 15 mm radius. Time between frames 10 μsec; jet velocity 2.7 km/sec.

Fig. 6. X-ray photographs of a jet from a lead indentation of 4 mm radius. Time between frames 10 μsec; jet velocity 2.7 km/sec.

charge of explosive material was increased. The diameter of the basic charge of 50/50 trinitrotoluene-hexogene was 80 mm, the diameter of the plane portion of the detonation front was 40 mm, and the height of the charge was 100 mm. The distance from the sample to the target varied from 50 to 300 mm.

X-ray investigations made it possible to establish the fact that the jet diameter increases linearly with increasing radius of the hemispherical indentation, and confirmed results of optical experiments on the disintegration of jets from indentations having very small radii (Fig. 4). It was possible to determine

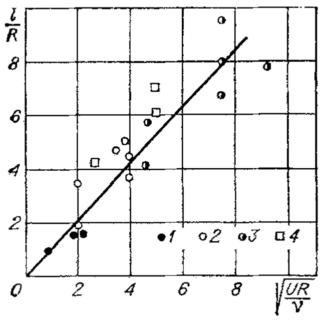


Fig. 7. Dependence of the dimensionless jet length l_c/R on $\sqrt{\frac{UR}{\nu}}$. 1) Steel; 2) copper; 3) lead; 4) D16.

with greater accuracy than with the streak camera the jet velocity for such materials as copper, steel, D16, lead, Wood's alloy, and paraffin. Some characteristic x-ray photographs are shown in Figs. 5, 6. Results of experiments with steel targets are collected in Table 1.

The system of determining parameters for the problem on the motion of a jet of viscous incompressible liquid out of a hemispherical cavity is

$$U,\ \rho_c,\ \mu,\ R,\ \delta_0,\ l_c,$$

from which the following dimensionless combinations can be obtained

$$\frac{\delta_c}{R};\ \frac{l_c}{R};\ \frac{U\delta_c\rho_c}{\mu}=\frac{U\delta_c}{\nu}.$$

Here U is the jet velocity, δ_c, μ are the density and the dynamic coefficient of viscosity, and l_c, δ_c are the length of the continuous portion of the jet and the mean jet diameter, respectively.

Results of direct measurements of the widths of the jets on the x-ray photographs indicate that for all the experiments performed the relationship

$$\frac{\delta_c}{R}=k_1, \tag{1}$$

holds, where k_1 is some constant with values between 0.4 and 0.6 for the various materials. Using the values of the viscosity coefficients of metals obtained in [1], one can construct the experimental dependency of the dimensionless jet length l_c/R on the Reynolds number $U\delta_0/\nu$. Experimental points for various metals and different radii of the hemispherical indentations are plotted in Fig. 7. The dependency we seek can be written as the relationship

$$\frac{l_c}{R}=k_2\sqrt{\frac{U\delta_c}{\nu}}. \tag{2}$$

For the various materials the value of k_2 varied from 1.4 to 2. If we insert k_1 from (1) into (2), we obtain

$$\frac{l_c}{R}=k_2\sqrt{k_1}\sqrt{\frac{UR}{\nu}}. \tag{3}$$

From the quantities k_1 and k_2, defined above, it follows that the quantity $k_2\sqrt{k_1}$ is close to unity.

As the direct recording of the parameter l_c presented considerable difficulty, owing to synchronization troubles, we used in its place the depth of penetration l_m of a target of the same material as that of the jet. When the materials in the jet and the target were different, the calculation of l_c was carried out according to the equation

$$l_c=l_m\sqrt{\frac{\rho_m}{\rho_c}},$$

that was obtained in [5]. Here ρ_m, ρ_c are the densities of the target and the jet, respectively.

From Eq. (3) we can obtain an expression for the kinematic coefficient of viscosity

$$\nu=\frac{UR^3}{l_c^2}.$$

According to this equation one can, with a knowledge of the velocity and the length of the continuous portion of the jet, estimate the viscosity of various metals approximately. Such an estimate was made for Wood's alloy:

$$\nu\approx 10^4\ \mathrm{cm^2/sec}.$$

Results of our studies of the exit of a plane shock wave at a hemispherical indentation in metals enable one to make the following conclusions concerning the dimensions and the velocities of the jets that emerge:

1. The transverse dimension of the jet increases linearly with an increase in the radius of the hemispherical indentation.

2. The length of the jet is proportional to the square root of the Reynolds number.

3. The jet velocity depends weakly on the radius of the hemispherical indentation and in our experiments it depends solely on the material of the sample under investigation.

LITERATURE CITED

1. A. A. Deribas, S. K. Godunov, et al., Fiz. Goreniya i Vzryva, 8, No. 1 (1972).
2. I. D. Zakharenko and V. I. Mali, Heating and Explosion [in Russian], Nauka, Moscow (1971).
3. S. K. Godunow, A. A. Deribas, et al., Journ. Comp. Phys., 5, No. 3 (1970).
4. V. A. Simonov, Fiz. Goreniya i Vzryva, 7, No. 2 (1971).
5. M. A. Lavrent'ev, UMN, 12, No. 4 (1957).