Journal of Applied Mechanics and Technical Physics, Vol. 43, No. 1, pp. 18–21, 2002

ON DEFORMATION OF BERYLLIUM UNDER HIGH-VELOCITY OBLIQUE COLLISION

O. B. Drennov and A. L. Mikhailov

UDC 534.222.2

The high-velocity oblique collision of samples of beryllium (beryllium and stainless steel) was studied experimentally. The disturbance amplitudes of beryllium, magnesium, aluminum, copper, and steel were compared. It is established that for the same Mach numbers, the disturbance amplitude for beryllium is maximal. The low plasticity and high brittleness of beryllium determine the nature of formation of a welded joint. Fusion and mixing of the metals occur in a very narrow zone, which practically cannot be seen in microsections. Under oblique collision of beryllium and steel, a solid solution layer of elevated hardness is attached to the interface.

One method of dynamic loading of metals is loading by blast waves (normal or oblique). Loading by oblique blast waves occurs under oblique collision of a liner and a target.

Oblique collision of metals leads to the occurrence of plastic intense shear strains and strong heating zones in the vicinity of the contact point. Within a short time, a shear flow develops, whose velocity gradient depends on the angle and velocity of plate collision. The local heating due to intense deformation results in considerable weakening of the material. In this region, the shear modulus and the yield point are considerably lower than those under normal conditions [1].

The indicated effects lead to distortion of the interface between the metal after collision. Regular waves, asymmetric waves, and layers of melted mixed components are formed. In some cases, the development of such disturbances leads to strong joining of samples — explosion welding [2–4].

At present, the deformation of a large number of metals under high-velocity oblique collision has been extensively investigated. However, insufficient attention has been given to beryllium, which shows unique physicomechanical properties: a combination of low density and low heat capacity with abnormally high Young's modulus, velocity of sound, and hardness, which can lead to abnormal development of shear instability for this metal. This can be due to the fact that beryllium exhibits the high brittleness and hardness and low plasticity [5].

To study the deformation of beryllium under high-velocity oblique collision, we performed a series of experiments. A diagram of these experiments is given in Fig. 1. A fixed plate (a beryllium disk 4 mm thick and 80 mm in diameter; in some experiments, a disk of 12Kh18N10T stainless steel) and a projectile plate (a beryllium disk 2 mm thick and 80 mm in diameter) were placed in a massive steel casing. A charge of a high explosive (HE) based on plasticized HMX (detonation rate $D \approx 8.75$ mm/μsec and density $\rho \approx 1.85$ g/cm^3) or RDX ($D \approx 8.15$ mm/μsec and $\rho \approx 1.72$ g/cm^3) 20–30 mm thick was placed at the site of contact with the projectile plate on the surface of the casing. A plane gliding detonation wave was initiated in the HE charge. The surface area of the HE charge was 1.75 times larger than the surface area of the casing and 9 times larger than the surface area of the projectile sample. This provided for loading by a steady-state gliding detonation wave with front almost perpendicular to the surface of the beryllium plate.

Institute of Experimental Physics, Sarov 607190. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 43, No. 1, pp. 22–26, January–February, 2002. Original article submitted May 28, 2001; revision submitted August 6, 2001.

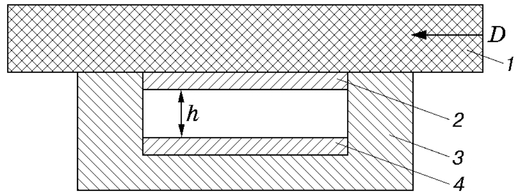

Fig. 1. Diagram of experiment: 1) high-explosive charge; 2) projectile plate; 3) steel casing; 4) fixed plate.

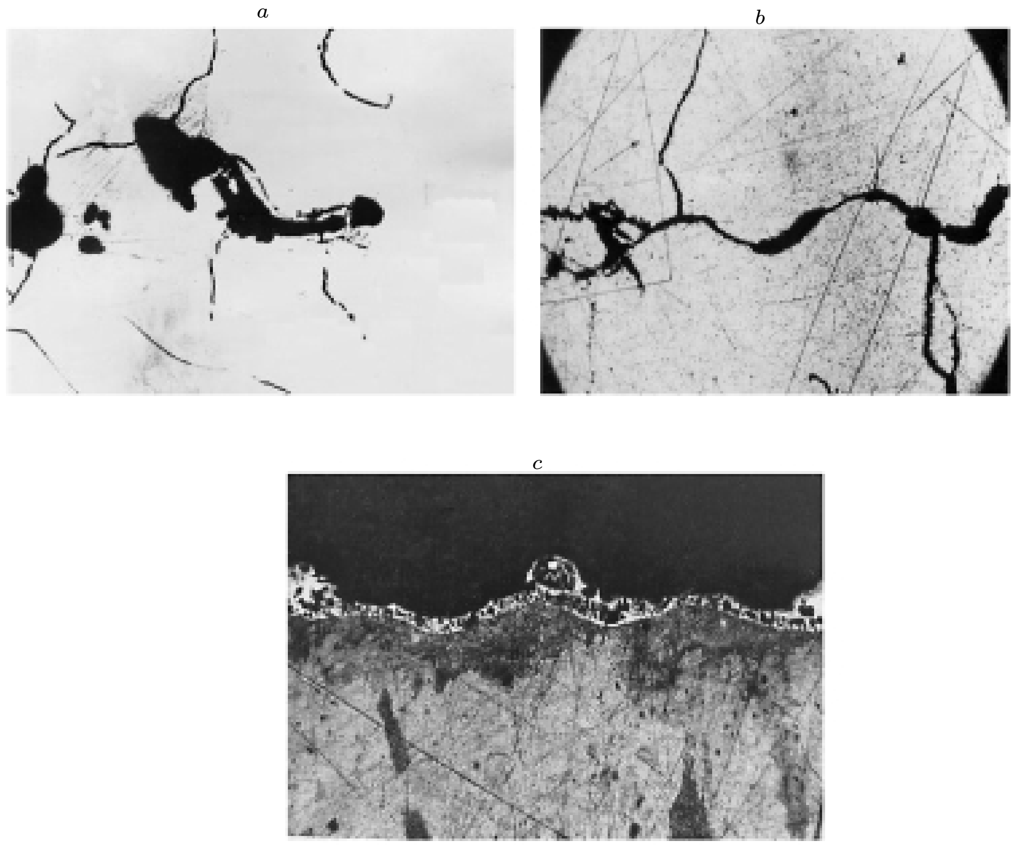

Fig. 2. Photographs of typical microsections (×50): (a) collision of beryllium plates for M ≈ 1.07, $\bar{a} \approx 0.52$ mm, and $\bar{\lambda} \approx 1$ mm; (b) collision of beryllium plates for M ≈ 0.96, $\bar{a} \approx 0.45$ mm, and $\bar{\lambda} \approx 0.85$ mm; (c) collision of a beryllium plate with a plate from stainless steel for M ≈ 1.07, $\bar{a} \approx 0.2$ mm, and $\bar{\lambda} \approx 0.8$ mm.

The acceleration distance of the liner is $h = 10$ mm. Collision of the plates occurs under steady-state conditions [6, 7]. The plate collision angle is estimated from the relations [2, 8]

$$\sin\gamma = \frac{W}{v_{\rm cont}}, \quad W = 1.2D\,\frac{\sqrt{1+(32/27)R}-1}{\sqrt{1+(32/27)R}+1}, \quad R = \frac{m_{\rm HE}}{m_{\rm liner}} = \frac{\rho_{\rm HE}h_{\rm HE}}{\rho_{\rm liner}h_{\rm liner}}, \tag{1}$$

where W is the liner velocity, $v_{\rm cont}$ is the velocity of the contact point, $m_{\rm HE}$ and $m_{\rm liner}$ are the masses of the HE layer and the liner, $\rho_{\rm HE}$ and $\rho_{\rm liner}$ are the density of the HE layer and the liner, and $h_{\rm HE}$ and $h_{\rm liner}$ are the thicknesses of the HE and the liner.

Under the indicated experimental conditions, $v_{\rm cont} = D$. The parameters D, $\rho_{\rm HE}$, $\rho_{\rm liner}$, $h_{\rm HE}$, and $h_{\rm liner}$ are known with high accuracy (to the third decimal place). The possible error in determining the collision angle γ is systematic and depends on the accuracy of describing plate acceleration under gliding detonation of the HE layer by the second relation in (1), which is proved by numerous experiments.

Depending on the value of the ratio R, the plate collision angle changes from $\gamma \approx 26.5°$ to $\gamma \approx 29.5°$, i.e., $\bar{\gamma} \approx 28°$.

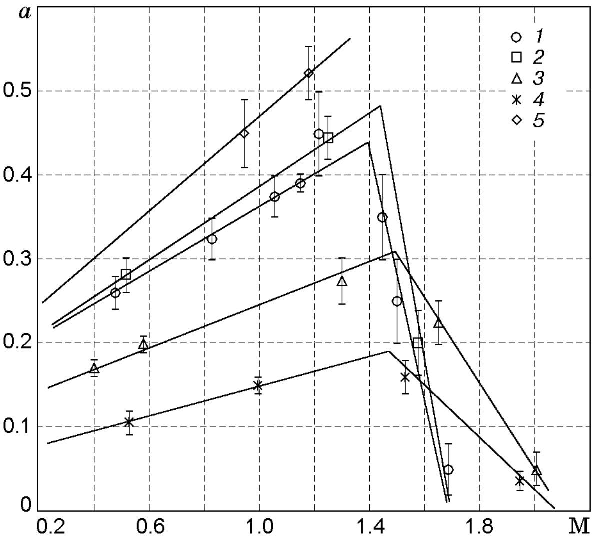

Fig. 3. Disturbance amplitude at the interface of the same metals a versus Mach number: points 1–5 refer to collisions of aluminum, magnesium, copper, steel, and beryllium plates, respectively.

After dynamic loading (in the vicinity of the contact point the pressure in the beryllium samples did not exceed 9 GPa) the casing and the plate packet were trapped by a porous material layer. Then, beryllium samples (projectile and fixed plates) were cut along the central axis in the direction of detonation-wave propagation. The resulting fragments were used to produce microsections for metallographic analysis.

The initial roughness (amplitude of the initial disturbance) of beryllium workpieces was 10 μm $\leqslant a \leqslant$ 20 μm.

Photographs of typical microsections are given in Fig. 2.

It follows from the results of the experiments and metallographic analysis that despite low plasticity, beryllium shows a strong tendency for wave formation without noticeable plastic flow of along the slip line and jet formation.

Figure 2a and b shows photographs of the interface between beryllium samples after high-velocity oblique collision ($\mathrm{M} = v_{\mathrm{cont}}/c$ is the Mach number, where c is the velocity of sound, and $\bar{a}$ and $\bar{\lambda}$ are the averaged amplitude and wavelength of the disturbance, respectively).

Dependences $a(\mathrm{M})$ for some metals based on experimental data are given in [9]. It is noted that for equal values of M, the disturbance amplitude is higher for metals of lower dynamic strength. We compared our experimental results (see Fig. 2a and b) with the data of [9] (Fig. 3). It can be seen that for equal Mach numbers, the maximum amplitude is obtained in oblique collision of beryllium samples. This is apparently explained by the considerable difference in the strength properties of the materials. For beryllium, aluminum, and copper, the static yield points are $2.55 \cdot 10^{-7}$, $5.63 \cdot 10^{-7}$, and $6.88 \cdot 10^{-7}$ N/m^2, respectively, and the static shear moduli are $1.30 \cdot 10^{-10}$, $2.45 \cdot 10^{-10}$, and $4.15 \cdot 10^{-10}$ N/m^2 [5, 10], respectively.

The high brittleness and low plasticity of beryllium have a significant effect on the state of the interface after oblique collision. In the microsections (see Fig. 2a and b), one can see intense cracking and layering along the boundary of ridges and troughs. Apparently, the zone of local fusion near the contact point is rather narrow (less than 1 μm) and cannot be seen in the photographs of sections; the mixing zone is also almost absent. This zone is easily broken by a rarefaction wave. The microsection in Fig. 2a corresponds to the welded joint of the beryllium samples. On the right of Fig. 2a, the interface is not evident. Although layering does not occur, there is no mixing of the metals. Neither are there significant changes in the structure of beryllium at the interface.

The interface "beryllium–12Kh18N10T stainless steel" after high-velocity oblique collision is shown in Fig. 2b. Joining of beryllium and steel is recorded. The thickness of the layer welded to stainless steel does not exceed 125 μm (clad layer). The rarefaction wave which follows the blast wave does not change the structure of the clad layer (voids appear). Spall fracture occurs along coarse voids.

The layer adjacent to the interface of steel is a solid solution of beryllium and iron of elevated strength and hardness (5.9 GPa $< H <$ 9.8 GPa) capable of resisting to spall fracture. Apparently, spallation occurs along the interface between the solid solution and beryllium.

The results of the investigation performed lead to the following conclusions.

Among the metals studied (beryllium, magnesium, copper, and steel), beryllium shows a greatest tendency for wave formation under high-velocity oblique collision (for equal Mach numbers, the disturbance amplitude at the interface is maximal for beryllium).

The low plasticity and high fragility of beryllium determine the nature of formation of the welded joint. Mixing of melted layers occurs in a very narrow zone, which was not revealed in the present experiments. In this zone there is layering in the rarefaction wave. No significant changes of the structure of beryllium are observed in the collision zone.

A beryllium–iron solid solution of elevated strength is formed at the interface under oblique collision of beryllium and steel. This layer remains attached to the steel surface (clad layer) and has a typical porous structure.

Since intense wave formation occurs along the line of collision of beryllium samples and a noticeable zone of plastic flow, melting, and mixing is absent, it is necessary to further study the mechanism of buckling of the interface under the oblique collision (explosion welding of metals).

REFERENCES

1. O. B. Drennov, A. L. Mikhailov, P. N. Nizovtsev, and V. A. Raevskii, "Development of disturbances at the interface between metals under oblique collision with the contact point moving at supersonic velocity," *Vopr. Atom. Nauki Tekh., Ser. Teor. Prikl. Fiz.*, No. 1, 4–12 (2001).
2. A. A. Deribas, *The Physics of Hardening and Explosion Welding* [in Russian], Nauka, Novosibirsk (1980).
3. A. S. Bahrani, T. J. Black, and B. Crosslaud, "The mechanics of wave formation in explosive welding," *Proc. Roy. Soc. London, Ser. A*, **296**, No. 1445, 123–136 (1966).
4. G. Cowan and A. Holtzman, "Flow configurations in colliding plates explosive bonding," *J. Appl. Phys.*, **34**, No. 4, 928–939 (1963).
5. D. White and D. Burke (eds.), *The Metal Beryllium*, Cleveland (1955).
6. G. E. Kuz'min, V. A. Simonov, and I. V. Yakovlev, "Wave parameters in explosive welding and coating-plate acceleration," *Fiz. Goreniya Vzryva*, **12**, No. 3, 458–461 (1976).
7. O. B. Drennov and A. L. Mikhailov, "Initial stage in the acceleration of thin plates in the grazing detonation regime of a high explosive charge," *Fiz. Goreniya Vzryva*, **15**, No. 4, 143–146 (1979).
8. A. A. Deribas, "Acceleration of metal plates by a tangential detonation wave," *Prikl. Mekh. Tekh. Fiz.*, **41**, No. 5, 68–74 (2000).
9. O. B. Drennov, "State of the contact boundary separating layers of metal over a broad range of changes in the velocity of oblique collision," *Fiz. Goreniya Vzryva*, **27**, No. 2, 118–124 (1991).
10. I. K. Kikoin (ed.), *Tables of Physical Quantities: Handbook* [in Russian], Atomizdat, Moscow (1976).