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Crater Formation in Metallic Targets*

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Spheres of copper, lead, tin, iron, aluminum, zinc, silver, and lead-tin alloys were accelerated to velocities of 0.75 to 2.25 km/sec and impacted normally upon targets of the same material as the pellets. Conditions were maintained so that pellets lost no mass before striking the target. The target mass was large compared to the mass of the pellet, so the targets could be considered semi-infinite.

The volume of the crater produced was found to be directly proportional to the kinetic energy of the pellet in the energy range investigated.

The penetration varied linearly with the velocity or momentum of the pellet. The area of the crater as measured in the plane of the original surface of the target was found to be directly proportional to the momentum of the pellet at the time of the impact.

In the case of the lead-tin alloy series, a correlation was observed between the crater parameters, the phase diagram of the alloys, and various functions of the pellet mass and velocity for the following series of alloys: 100% lead; 90% lead, 10% tin; ⋯ ; 10% lead, 90% tin; 100% tin.

INTRODUCTION

RECENTLY there has been an increased interest in the field of high velocity impact.[1–5] Several workers have proposed theories to explain the observed phenomena,[6–9] but to date it has not been possible to determine which ones fit the facts most reliably because of a lack of data in which all pertinent parameters have been accurately controlled.

This paper reports the data obtained when spheres of copper, lead, tin, iron, aluminum, zinc, silver, and a series of lead-tin alloys were fired into semi-infinite targets of the same material as the pellets. The projectile struck the target normally in all cases and conditions were maintained so that the mass of the impacting pellets was known accurately.

Experimental Method

The spherical pellets were fabricated by pressing a small piece of the metal being used in a die with a spherical cavity at the face of the two opposing pieces.

The alloys for the targets and for the projectiles used were prepared in the laboratory and were of the following composition: 100% lead; 90% lead, 10% tin; ⋯; 10% lead, 90% tin; 100% tin. Two sets of targets were prepared. The first was cast in a steel mold and hence cooled quite rapidly, whereas the second set was cast in sand and allowed to cool relatively slowly. The results between the two sets of targets varied slightly, but it is believed that the variation may be at least in part on account of the rate of cooling when they were cast. The cooling rate may alter the composition of the finished target and hence the crater characteristics also, and one would expect the targets cast in steel molds to cool much more rapidly than those cast in sand molds.

The spheres were accelerated by firing them in a special .220-caliber smooth-bore gun. Before firing they were placed in a hollow cup in the forward end of a split plastic sabot, which was then loaded into the cartridge case for the gun. When the gun was fired, the sabot and pellet were accelerated down the barrel, but as they left the gun muzzle, since the plastic sabot was split, the air pressure caused the two parts to separate and allowed the spherical pellet to travel unaccompanied to the target.

Lead spheres were fired in this manner into a long trough of shaving foam with a density of 0.05 g/cm³. Upon recovery it was found that they had lost less than 2% of their mass in every case. Since lead could be expected to ablate at a greater rate than any of the other materials used in the investigation, it was assumed that the other pellets would lose even less mass. Thus, the pellet was assumed to have its original mass when it struck the target.

The pellet velocity was determined by allowing it to pass through two rotating disks of paper located 1 m apart on a rigid shaft.[10] Since the velocity of rotation was known, it was possible to determine the time required for the pellet to pass from one disk to the other by measuring the angle of rotation of the second disk between the time when the pellet perforated the first

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[9] M. A. Cook, "Mechanism of cratering in ultra-high velocity impact," U. S. Air Force Office of Scientific Research Contract No. AF-18(603)100; ASTIA No. AD 136 479.

[10] Technical Report No. OSR-9, United States Air Force Office of Scientific Research, Contract No. AF-18(600)1217.

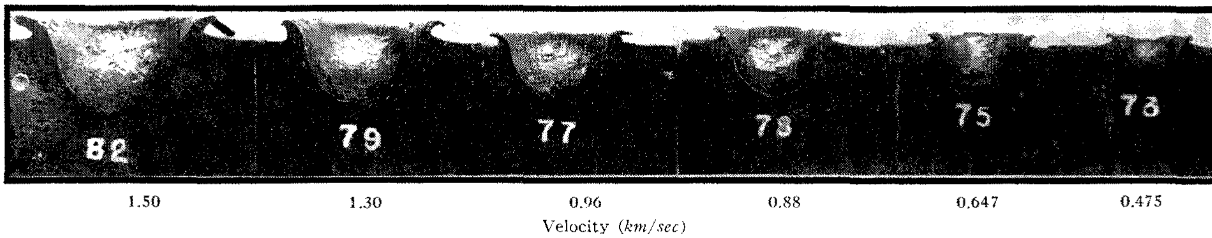

FIG. 1. Photograph of a series of sectioned craters formed in a lead target by 0.483-cm diameter lead spheres. Impact velocities are indicated for each crater.

disk and when it perforated the second one. If two disks were placed 1 m apart on a shaft rotating at 200 revolutions per sec, the shaft and disks would rotate through an angle of 72° between the time when a pellet traveling at 1 km/sec struck the first and the second disks.

Three physical characteristics of the craters were measured. These were the depth of penetration, cross-sectional area, and the volume, and are defined as follows:

1. Depth of penetration: The distance from the original surface of the target to the deepest point in the crater. The measurements were obtained with a spherometer.

2. Cross-sectional area: The area of the crater at the original target surface. In all cases this area was circular and was calculated using the measured diameter.

3. Crater volume: This was taken as the amount of material removed from the target below the original surface. The volume was measured by coating the surface of the crater with a light film of oil and filling it with melted paraffin. This waxy plug was then allowed to cool and solidify, at which time it was carefully shaved down to the plane of the original surface of the target. (This was possible since the petalling or projected material was previously machined off the target.) The wax plug was removed from the crater, weighed, and the volume calculated using the density of the wax which had been previously determined to be 0.943 g/cc at the temperature existing when the calculations were made.

RESULTS

A. Pure Metals

Figure 1 shows a series of lead craters which have been cross-sectioned. Particular attention should be paid to the petalling or projecting of the material above the original surface. The velocities are marked below the craters, with the numbers on the craters referring to shot numbers. The spherical pellets used were the same diameter as the one in the photograph (0.483 cm).

TABLE I.

Material	k_1 (m^3/j)
Zinc	0.586×10^{-9}
Tin	1.104×10^{-9}
Copper	0.588×10^{-9}
Iron	0.282×10^{-9}
Lead	5.000×10^{-9}
Silver	0.800×10^{-9}
Aluminum	0.776×10^{-9}

All of the metals, except Sn, were characterized by the petalling of the material around the rim of the crater. Tin had a tendency to crack and break off rather than petal, but still retained the circular cross section.

When the crater volume, V, as measured experimentally, was plotted against the energy, E, of the impacting projectile, it was found to follow the relationship,

$$V=k_1E=k_1(Mu^2/2), \tag{1}$$

where k_1 is a constant; E, energy of the pellet; M, mass of the pellet; and u = impact velocity of the pellet. Table I gives the experimentally obtained values of the constant k_1 in Eq. 1. Typical plots showing the relationship between crater volume and pellet energy for zinc and iron are shown in Figs. 2 and 3. The data in Table I were obtained from these and similar graphs for the other materials listed.

Only one size pellet (0.483 cm diam) was used in this series of tests, except in the case of copper and iron where smaller pellets (0.38 cm diam) were also used. In Fig. 3, the data from smaller iron pellets are indicated by the black circles. There was a noticeable difference in the shape of the craters in iron formed by the two different-size pellets. Upon closer examination it was found that in the case of the craters formed by the larger pellets, the pellet was still in the crater. Some of the pellets were removed and it was found that they had

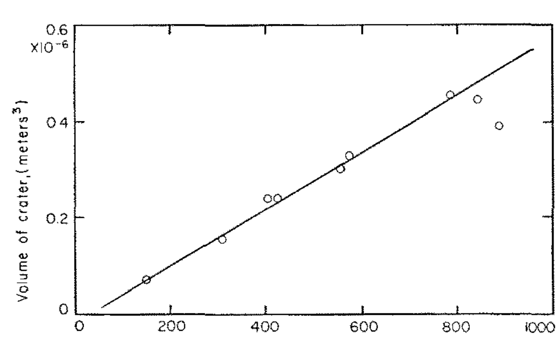

FIG. 2. Relationship between crater volume and pellet energy when zinc spheres are fired into semi-infinite zinc targets.

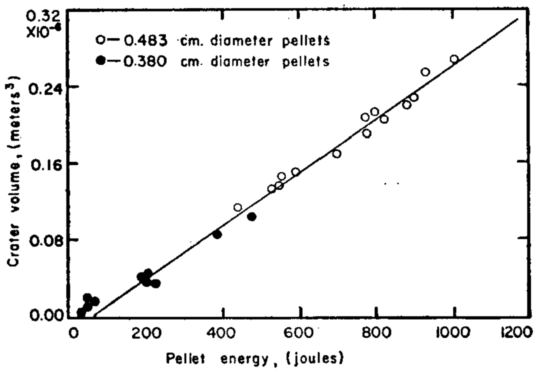

FIG. 3. Relationship between crater volume and pellet energy when mild steel (1040) spheres are fired into semi-infinite targets of the same composition.

deformed into a hemispherical shape and completely covered the inside of the crater. The outside and the inside of the deformed pellets were very nearly the shape of the crater itself and the weight of the fragment was nearly the same as it had been before firing (see Fig. 4). The small iron pellets did not remain in the craters. Penetration and volume data presented in this paper are given with the pellet removed in all cases.

Copper craters formed by the large and small pellets seemed to be identical, with no indication that any of the fragments from the pellet were left in the crater.

Van Valkenburg, Clay, and Huth,[3] in reporting work previously done at this laboratory, have suggested the following relationship,

$$V/E = k_2/c^2\rho, \tag{2}$$

where c = the sound velocity in the target as defined by $(E'/\rho)^{\frac{1}{2}}$, where E' is Young's modulus and ρ is the density of the target. They used the extensional wave velocity to calculate the value of $c^2\rho$. This product is proportional to the bulk modulus since Poisson's ratio is essentially constant. Data they used were obtained by firing $\frac{1}{8}$ in.-diam spheres accelerated by means of a high explosive charge.[11] In more recent work, the value for c^2 was obtained by using the shear wave velocity instead of the extensional wave velocity of the targets, since this seemed to give a better fit. Figure 5 is a plot of their data, together with that reported in this paper. The circles indicate values determined by Van Valkenburg, Clay, and Huth, while the triangles represent data reported in this paper. It should be noted that

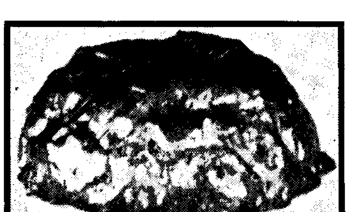

FIG. 4. Photograph of a steel pellet which was removed from the crater after firing.

[11] M. E. Van Valkenburg and C. D. Hendricks, J. Appl. Phys. **26**, 776 (1955).

there is a different slope for each set of data. This may be due to the fact that in earlier experiments the exact mass of the pellet may have been less than was supposed, since in those tests the pellets were accelerated to higher velocities by the explosives and may have abated before striking the target. As mentioned in the introduction, conditions were carefully controlled here so that ablation was minimized and the mass of the pellet striking the target was known accurately. In the previous data, if the energy of the pellet on impact was less than had been calculated, the value of V/E should be larger than indicated. The difference in the slope of

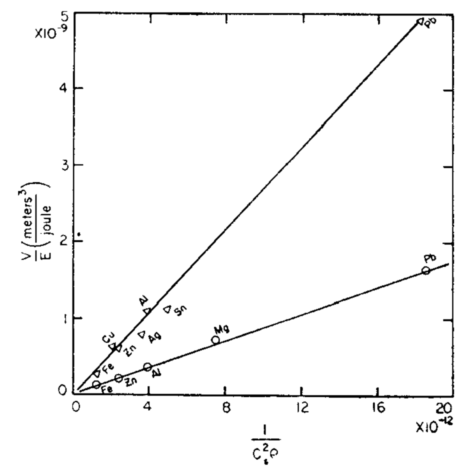

FIG. 5. Volume per unit energy plotted against the parameter, $1/c^2\rho$, for several pure metals.

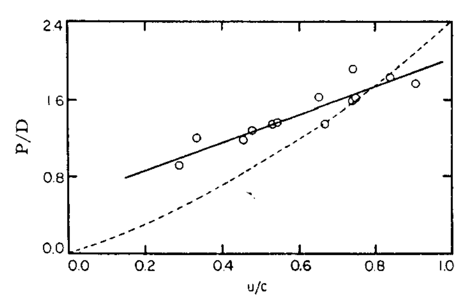

FIG. 6. Penetration in units of the pellet diameter plotted against u/c (Mach number) for tin spheres and targets.

the two lines in Fig. 5 is in the right direction to agree with this assumption. It may also be true that at the higher pellet velocities used in the previous set of experiments, the volume per unit energy is smaller.

In a recent paper by Huth, Thompson, and Van Valkenburg,[5] it has been proposed that penetration and pellet velocity are related in the following manner:

$$P/D = 2.5(u/c)^{1.4} \tag{3}$$

where P = penetration and D = the diameter of the pellet. However, the data from this investigation more closely followed the relationship,

$$P/D = k_2\, u/c + k_3. \tag{4}$$

Table II contains the list of the values of k_2 for the different materials used in this investigation.

Figures 6 and 7 show the relationship between P/D *vs* u/c for tin and lead. The dotted line represents Eq. 3 and the solid line, Eq. 4.

The cross-sectional areas of the craters investigated all seemed to be linear functions of the momentum of the pellet when it struck the target.

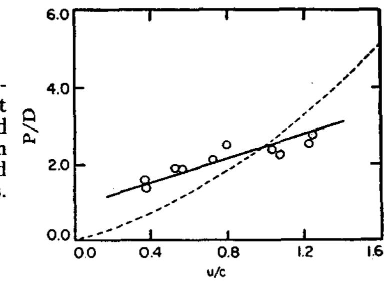

FIG. 7. Penetration in units of pellet diameter plotted against u/c (Mach number) for lead spheres and targets.

B. Lead-Tin Alloys

The appearance of the craters and the surrounding surface varied quite radically as the alloys varied from pure lead to pure tin. The lead craters showed the typical petalling around the crater rim which is characteristic of many metals. The surface of the target surrounding the crater and also the interior of the crater were generally smooth, as though the metal had flowed plastically into the final condition. On the other hand, the pure tin craters had no petalling around the crater rim and the interior surface of the crater was very rough and had a crystalline appearance, while the surface surrounding the craters had a rough and bumpy appearance. As the percentage of lead increased from pure tin to a 50-50 mixture, the crater appearance gradually changed from rough to smooth.

TABLE II.

Material	k_2 (dimensionless)
Zinc	2.14
Tin	1.45
A1 (24ST)	3.50
Cu	2.44
Fe	2.63
Pb	2.00
Al (pure)	3.11

TABLE III.

Composition	V/E (sand cast) m^3/j	V/E (steel mold) m^3/j
100% Pb		5.04×10^{-9}
90% Pb−10% Sn	2.7×10^{-9}	3.51×10^{-9}
80% Pb−20% Sn	2.45×10^{-9}	2.11×10^{-9}
70% Pb−30% Sn	2.00×10^{-9}	2.20×10^{-9}
64.5% Pb−35.5% Sn	...	2.15×10^{-9}
60% Pb−40% Sn	1.83×10^{-9}	...
50% Pb−50% Sn	1.70×10^{-9}	1.96×10^{-9}
40% Pb−60% Sn	1.65×10^{-9}	1.86×10^{-9}
30% Pb−70% Sn	1.62×10^{-9}	1.93×10^{-9}
20% Pb−80% Sn	1.61×10^{-9}	...
10% Pb−90% Sn	1.53×10^{-9}	...
100% Sn	1.18×10^{-9}	1.18×10^{-9}

The results of the data, as shown in Table III, for both the sand mold and the iron mold targets show that the volume per unit energy, V/E, is a constant throughout the range investigated. Figures 8 and 9 show sample plots of the volume *vs* energy for the alloy with 80% lead and 20% tin and also for 30% lead and 70% tin, respectively. These two plots indicate the reproducibility of the data from which the values in Table III were obtained.

Although the data for the two sets of targets varied slightly, it should be observed that the volume-per-unit energy for each case remained constant. It was also observed that for every alloy composition, except one, between pure tin and pure lead, V/E, was less for the sand-cast targets, suggesting that the method of preparation affected physical composition of the targets and hence the cratering characteristics.

In an attempt to find the correlation between the V/E values for the various alloy compositions, the mean volume-per-unit energy for each alloy was plotted against the percentage of lead in the sample. This plot is shown in Fig. 10. Figure 11 is a phase diagram for the lead-tin alloy system plotted in the same manner. It can be seen as one compares the two curves that V/E increases very rapidly in the alpha region and remains almost constant throughout the central region where the eutectic microconstituent is present. Although more data are needed for the beta region, there appears to be an abrupt decrease in V/E in that neighborhood. In observing the data in Fig. 10, one can say that in the neighborhood of pure eutectic mixture there seems to

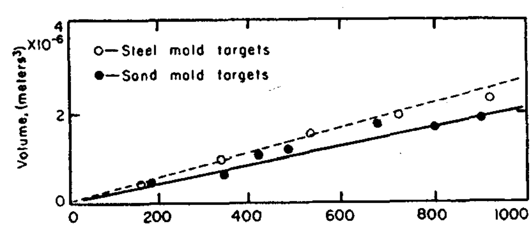

FIG. 8. Crater volume *vs* pellet energy plotted for the alloy of 80% lead and 20% tin.

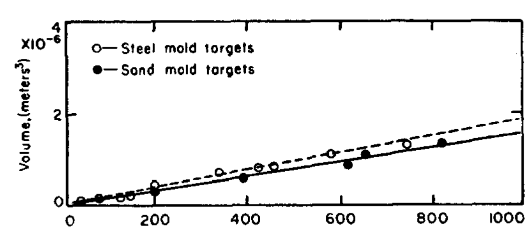

FIG. 9. Crater volume *vs* pellet energy for the alloy of 30% lead and 70% tin.

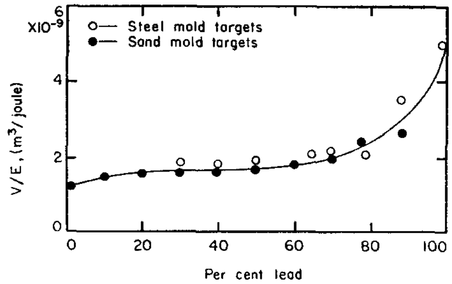

FIG. 10. Crater volume per unit energy, V/E, for different alloys plotted against composition.

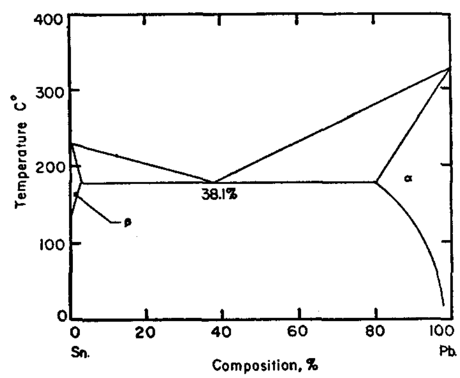

FIG. 11. Phase diagram for the lead-tin alloy system.

be very little change in the volume-per-unit energy. This seems to indicate that the cratering characteristics of the alloy are independent of the percentage of microconstituent present, but highly dependent on whether the microconstituent is present or not. Also, the temperature at which the alloy completely melts seems to have little effect on the cratering characteristics.

In attempting to find a relationship between crater area A and some function of the pellet mass and velocity, pellet energy and momentum were investigated. When crater area was plotted against pellet energy, the curves were not linear. Figures 12 and 13 show the results of plotting the crater area *vs* the momentum of the pellet for two of the alloys investigated. In the interest of space, the curves for the other alloys of the system will be omitted, but can be obtained elsewhere.[12] It can be seen that the curves are approximately linear through the interval investigated. A linear extrapolation of the area *vs* momentum curves predicts that for the $\frac{3}{16}$ in.-diameter pellets used, a momentum greater than 0.12 kg m/sec is necessary to produce any crater area. In order to check this, a series of lead pellets were shot into a lead target with a momentum less than 0.12 kg m/sec. In each case when the pellet energy was sufficient to deform the pellet, it merely flattened out to about twice its original diameter and stuck in the target with no real crater being formed. On the other hand, very tiny craters characteristic of those shown in Fig. 1, whose pellet momenta are much less than 0.12 kg m/sec, are often observed when very small particles are fired at higher velocities. It therefore seems reasonable to expect that this threshold momentum is a function of either the pellet size and shape or presentation area. It can be expected that in the limit as the pellet volume uniformly approaches zero, the threshold momentum will also approach zero.

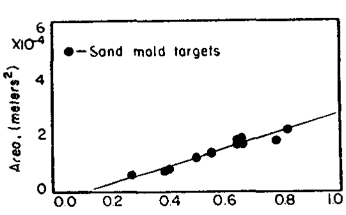

FIG. 12. Crater area *vs* pellet momentum for 10% lead and 90% tin.

[12] ASTIA Document No. AD 148 067.

The depths of the craters were plotted against momentum and it was found that the resulting plot was approximately linear. It appears, however, that the depth is some function of v^a where $0<a<1$.

It should be remembered that the relationships presented here were observed over a limited energy range, and extrapolation to higher pellet energies may lead to erroneous predictions. However, for the range of energies investigated, the data are very reliable.

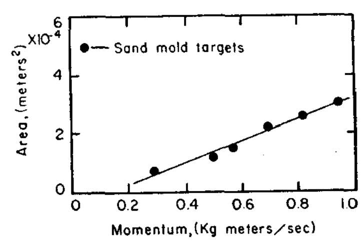

FIG. 13. Crater area *vs* pellet momentum for 50% lead and 50% tin.

SUMMARY

In the energy range investigated, the volume of a crater produced by a high velocity pellet of the same material as the target is directly proportional to the kinetic energy of the pellet for lead, tin, zinc, copper, aluminum, silver, iron, and eleven different compositions of lead-tin alloys.

Penetration was found to vary linearly with velocity for values of u/c from 0.2 to 0.6 for zinc, copper, aluminum, tin, silver, and iron, and 0.2 to 1.25 for lead.

A close correlation was found between the cratering characteristics and the phase diagram for the lead-tin alloy system. Specifically, throughout the alpha and beta solid solution region there occur abrupt changes in the cratering characteristics, whereas throughout the region containing the eutectic microconstituent, very little change in the cratering phenomena was observed. The crater depth was found to be a linear function of momentum (or velocity since the pellets were of equal mass for each sample) for pellet velocities below the sonic velocity of the target material.