Holes Formed in Thin Aluminum Sheets by Spheres with Impact Velocities Ranging from 2 to 10 Km/S

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Abstract

The dimensions of 96 holes produced by the impact of 2017-T4 aluminum spheres with various thicknesses of 6061-T6 aluminum sheets are presented and analyzed. The sphere diameters ranged from 1.40 mm to 19.05 mm and the sheet-thickness-to-projectile-diameter ratio, \( t/D \), ranged from 0.008 to 0.618 with the majority of the tests having \( t/D \) ratios of less than 0.234. Impact velocities ranged from 1.98 km/s to 9.89 km/s. The measured hole diameters were normalized by dividing them by the diameter of the sphere that produced the hole. The normalized diameters of the holes are shown to scale when compared on the basis of \( t/D \) ratio. When the impact velocity was held constant, a relationship between the \( t/D \) ratio and the morphology of the lip structure surrounding the hole was noted. As the \( t/D \) ratio increased, the holes tended to be less circular and the lip morphology became more complex. The results of the analysis of all hole data was used to develop a description of the hole-formation sequence.

Keywords: aluminum-sheet hole diameters, normalized hole diameters, \( t/D \) ratio, hole-formation sequence, 6061-T6 aluminum sheets, 2017-T4 aluminum spheres

1. Introduction

Holes produced in thin sheets by the impact of hypervelocity projectiles have been the subject of study for more than 50 years. Extensive sets of measurements were taken of holes produced by many of the impact experiments performed during the 1960’s and 1970’s (e.g., Maiden and McMillan [1], Nysmith and Denardo [2], and Carson and Swift [3]). Hörz et al. [4, 5] have performed detailed studies of the holes produced in 1100 aluminum and Teflon sheets. The study of holes produced in thin sheets and their description as a function of sheet thickness, projectile diameter, and impact velocity is of interest because the hole produced in a shield or some other component of a spacecraft represents damage that may or may not affect the

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of an optical comparator. Four diameter measurements were made for each of the holes in the sheets. Two of them were verified using orthogonal, flash radiography of the projectile in flight just before impact with the sheet. Sphere diameters were measured with an accuracy of ± 0.0001 inch. The atmosphere in the target chamber was air at a pressure of 5 to 12 mm Hg for the two-stage gun and 6 mm Hg for the three-stage gun.

The diameters of the holes left in the sheets were carefully measured and compared on the basis of t/D ratio and impact velocity. Hole diameters increased as the t/D ratio and/or impact velocity increased. Micrographic cross sections were made of the edge of the hole and material adjacent to the hole for selected target sheets and compared. The micrographic cross sections illustrated that a clear relationship existed between the t/D ratio and the morphology of features evident in the cross sections.

2. Experimental procedures

The impact tests were performed in the UDRI Impact Physics Laboratory using a 50/20 mm, two-stage, light-gas gun and a 75/30/7.62 mm, three-stage, light-gas gun. All target sheets were installed and impacted normal to the range center line. Impact velocity determinations were made with use of four laser-photodetector stations for the two-stage gun and three laser-photodetector stations for the three-stage gun. These laser-photodetector systems were installed at various locations along the flight path of the projectile. Projectile velocities were computed by dividing the distance between pairs of stations by the corresponding measured time of flight of the projectile between those stations. Accuracy of the velocity measurements for the two-stage gun tests (Shot No. prefix “4”) was better than ± 0.11 percent; accuracy of the velocity measurements for the three-stage gun tests (Shot No. prefix “8”) was better than ± 0.16 percent. Projectile integrity was verified using orthogonal, flash radiography of the projectile in flight just before impact with the sheet. Sphere diameters and sheet thicknesses were measured with an accuracy of ± 0.0001 inch. The atmosphere in the target chamber was air at a pressure of 5 to 12 mm Hg for the two-stage gun and 6 mm Hg for the three-stage gun.

The diameters of the holes in the target sheets were carefully measured by projecting a shadow of the hole on the screen of an optical comparator. Four diameter measurements were made for each of the holes in the sheets. Two of them were made in the direction parallel to the rolling direction of the sheets and two were made in the direction perpendicular to the rolling direction. The four measured hole diameters were averaged and the hole diameter, dh, represented the average diameter of the opening in the sheet.

After the hole measurements were complete, small sections of the sheets were removed from the region adjacent to the hole for selected sheets. These small sections were mounted, polished, and the details of the lip morphology were examined using a microscope.

3. Results and discussion

Results of the normalized hole-diameter measurements, dh/D, are presented in Table 1. Hole diameters for 83 of the sheets were obtained with the use of the four optical comparator measurements. Hole diameters for eleven of the sheets (Shots 4-1987, 4-1988, 4-1990, 8-3180, 8-3201, 8-3202, 8-3217, 8-3220, 8-3224, 8-3225, and 8-3260) were provided as a single value by various sponsors. Pieces of the piston used in the operation of the two-stage, light-gas gun struck the sheet for Shot 4-1281 and stretched the hole in one direction, allowing only one measurement of the hole diameter. The hole for Shot 4-1353 was very irregular and contained a loose ring which fell out during removal of the sheet from the range. The inner diameter of the ring was measured with a scale prior to removal of the sheet from the range and is presented in addition to the measurements of the hole after the ring fell out. Finally, one of the tests (Shot 4-1910) used a piece of aluminum shim stock, of unknown alloy, as a target sheet.

For the 83 holes with four diameter measurements, 45 of the holes, or 54 percent, were larger in the direction parallel to the rolling direction of the sheet. The hole diameter perpendicular to the rolling direction of the sheet was larger for 28 (34 percent) of the tests, and the hole diameter was the same in both directions for 10 (12 percent) of the tests. Sensitivity of the hole diameter to very small variations in sheet thickness was obvious during the measurement of the sheet thicknesses and the hole diameters. In a number of instances, two or more tests were performed using the same impact conditions (i.e., sphere diameter, sheet thickness, and impact velocity). The diameters of the holes produced in these tests were nearly identical. Use of the normalized hole diameter, dh/D, permitted the comparison, on the basis of t/D ratio and impact velocity, of the hole diameters produced by the impact of spheres of different diameters.
Table 1. Impact conditions, $t/D$ ratios, and normalized target-sheet hole diameters

| Shot No. | Impact Velocity, km/s | Sphere Dia., mm | $t/D$ | $d/D$ |
|----------|----------------------|-----------------|-------|-------|
| 4-1722   | 2.54                 | 9.53            | 0.132 | 1.624 |
| 4-1718   | 1.98                 | 9.53            | 0.233 | 1.349 |
| 4-1720   | 2.44                 | 9.53            | 0.233 | 1.467 |
| 4-1719   | 2.83                 | 9.53            | 0.233 | 1.547 |
| 4-1721   | 2.23                 | 9.53            | 0.504 | 1.696 |
| 4-1822   | 3.77                 | 9.53            | 0.049 | 1.101 |
| 4-1833   | 3.65                 | 9.53            | 0.062 | 1.155 |
| 4-1837   | 3.47                 | 9.53            | 0.084 | 1.232 |
| 4-1841   | 3.64                 | 9.53            | 0.084 | 1.237 |
| 4-1842   | 3.84                 | 9.53            | 0.084 | 1.253 |
| 4-1843   | 4.67                 | 9.53            | 0.026 | 1.053 |
| 4-1844   | 5.45                 | 9.53            | 0.049 | 1.139 |
| 4-1845   | 4.71                 | 9.53            | 0.049 | 1.136 |
| 4-1846   | 4.62                 | 9.53            | 0.084 | 1.288 |
| 4-1847   | 4.71                 | 9.53            | 0.135 | 1.493 |
| 4-1848   | 4.96                 | 9.53            | 0.168 | 1.632 |
| 4-1392   | 6.54                 | 9.53            | 0.026 | 1.053 |
| 4-1395   | 6.70                 | 9.53            | 0.026 | 1.053 |
| 4-1383   | 6.26                 | 12.00           | 0.047 | 1.138 |
| 4-1789   | 6.40                 | 6.35            | 0.048 | 1.144 |
| 4-1762   | 6.15                 | 15.88           | 0.049 | 1.163 |
| 4-1788   | 6.49                 | 9.53            | 0.049 | 1.147 |
| 4-1360   | 6.62                 | 9.53            | 0.049 | 1.152 |
| 4-1807   | 6.06                 | 6.35            | 0.050 | 1.152 |
| 4-1359   | 6.78                 | 9.53            | 0.062 | 1.221 |
| 4-8125   | 6.11                 | 19.05           | 0.084 | 1.315 |
| 4-1289   | 6.68                 | 9.53            | 0.084 | 1.365 |
| 4-1287   | 6.74                 | 9.53            | 0.084 | 1.371 |
| 4-1763   | 6.17                 | 15.88           | 0.097 | 1.392 |
| 4-1766   | 6.12                 | 15.88           | 0.098 | 1.396 |
| 4-1767   | 6.18                 | 15.88           | 0.098 | 1.392 |
| 4-1768   | 6.18                 | 15.88           | 0.098 | 1.406 |

The normalized target-sheet-hole diameter, $d/D$, is shown as a function of $t/D$ ratio in Fig. 1. The data plotted in Fig. 1 appear to indicate that the use of this simple geometric scaling technique was a very effective procedure for comparing the dimensions of holes produced by spheres whose diameters ranged from 1.40 mm to 19.05 mm. As shown in Table 1, the data set was loosely sorted into eight velocity range subsets. Although the data in the subsets are limited in their range and the numbers of points, they do indicate that the hole diameter increased as $t/D$ ratio and/or impact velocity increased. Impact velocities below 5 km/s failed to produce the lip-region morphological features observed in tests with impact velocities greater than 6 km/s. Hole data for tests with impact velocities between 5 and 6 km/s were not available.

Sufficient data were available in Fig. 1 to provide a reasonable indication of the magnitude of the change in hole diameter that would occur as impact velocity and $t/D$ ratio are varied. Also, the trend in all of the “curves” indicates they would converge on the point $d/D = 1$ and $t/D = 0$ when the impact velocity is low (i.e., the diameter of the hole should approach the diameter of the projectile at low impact velocities). The hole produced in the thinnest sheet ($t/D = 0.008$) was about 1.6 percent larger than the projectile.

Holes produced by the normal impact of 9.53-mm-diameter, aluminum spheres traveling at velocities near 6.70 km/s are shown in Fig. 2 for four $t/D$ ratios. An arrow in each hole identifies the location of the portion of the target sheet that was...
Fig. 1. Normalized hole diameter as a function of $t/D$ ratio for holes formed by the impacts of 2017-T4 aluminum spheres with 6061-T6 aluminum sheets at impact velocities ranging from 2 to 9.9 km/s.

Fig. 2. Photographs and cross sections of holes formed by the impact of 9.53-mm-diameter, 2017-T4 aluminum spheres with various thicknesses of 6061-T6 aluminum sheets at impact velocities near 6.7 km/s. Holes are shown from the impacted side of the sheet. Cross sections are shown with the impacted side toward the top of the page. Arrow in hole indicates where material in micrograph was obtained.

removed and used to provide the micrographic cross section shown to the left of the hole photograph. The holes are shown from the front or impacted side of the sheet and the cross sections are shown with their impacted side toward the top of the figure. In addition to the micrographs presented in Fig. 2, cross sections of target sheets from other tests shown in Table 1 were examined. As the $t/D$ ratio increased, the hole diameter, $d_h$, increased, the holes tended to be less circular, and the structure of the region surrounding the hole became more complex.

The hole photographs and cross sections shown in Fig. 2 illustrate a relationship between $t/D$ ratio (or at least sheet thickness) and the morphology of the region surrounding the hole. Flaps or lips developed on both sides of the sheets. The flap on the impacted side of the sheet was larger than the flap on the rear side of the sheet for all of the holes shown in Fig. 2. Grain structure visible in the micrographs indicated that the flaps were formed from portions of the sheet that overturned...
during the hole-formation process. As target-sheet thickness increased, the width of the overturned flaps increased. At a $t/D$ ratio of 0.102, large cracks were evident in the flaps. As the cracks grew and joined together, pieces of the flap separated from the sheet and reduced the width of the flaps. The cross sections for the tests with $t/D$ ratios of 0.163 or greater merely exhibited a small lip on the front and rear surfaces of the sheet. These small lips appeared to be all that remained of the overturned flaps. As the material in the flap overturned, it was strained excessively, cracked, and was separated from the target sheet. The newly formed fragments became a part of the ejecta veil and/or the external bubble of debris in the debris cloud produced by the impact.

The cross sections for the sheets from the larger $t/D$ ratio tests also exhibited a large ring of material that was attached to the sheet by a thin web of material at the center of the sheet (see cross section for Shot 4-1352 in Fig. 2). The surfaces of the ring that faced away from the impact site were concave and appeared to be smooth or polished, in contrast to the more irregular surfaces evident on target material facing the impact site. The smooth appearance of the ring in these regions may indicate that the ring had been in contact with material in the overturned flap during the flap formation process. The cross section for the $t/D = 0.424$ test clearly showed a detached ring with a wedge-shaped cross section, a split in the sheet, and a section of overturned flap that was smooth on the surface which had been in contact with the ring. The split in the sheet extended all around the inside of the hole. The mating surface irregularities in the split section of the sheet and the position of the wedge-shaped ring suggest that the outward motion of the ring may be responsible for the separation of the sheet. It is probable that the wedge-shaped ring was a continuous structure during the hole-formation process. As shown in Fig. 2, however, only a portion of the ring remained in the hole after the impact. Additional pieces of the ring were recovered from the target-chamber floor after the test.

The changes in the morphology of the lip region may be related to the $t/D$ ratio or they may simply be a result of the change in sheet thickness. The sequence of target-sheet cross sections presented in Fig. 2 demonstrated that the hole-formation process could produce a variety of morphological features in the region adjacent to the holes. An examination of the data presented in Table 1 shows that there are several subsets of data available for use in determining possible relationships between the lip-region morphology and the various test parameters. In one subset (Shots 4-1358, 4-1789, 4-1762, and 4-1788), four different sphere diameters, ranging from 6.35 mm to 15.88 mm, were used while the $t/D$ ratio and impact velocity were held constant at 0.049 and ~6.25 km/s, respectively. The micrographs of the lip regions for these four tests exhibited a structure that was similar to the one shown for Shot 4-1360 in Fig. 2. This similarity of structure may indicate that the morphology of the lip region surrounding the hole is determined solely by the $t/D$ ratio. However, it is possible that the target sheets used in the tests were too thin to show sufficient detail for drawing a meaningful conclusion.

Micrographs from three tests (Shots 8-0125, 4-1291, and 4-1851) employing thicker, 6061-T6 aluminum target sheets (1.55 mm, same thickness as for Shot 4-1291) were compared [6] to verify that the hole morphology was determined by the $t/D$ ratio. Impact velocity for these three tests was nominally 6.1 km/s. The diameters of the spheres used for the tests were 19.05, 9.53, and 3.18 mm and the $t/D$ ratios of the tests were 0.084, 0.163, and 0.488, respectively. Except for the loss of the overturned flaps, the cross section of the lip for Shot 8-0125 was very similar to the cross section of the lip for Shot 4-1287, even though the sheet thicknesses for these two tests varied by a factor of two [6].

Impact velocities below 5 km/s failed to produce the lip-region morphological features observed in tests with impact velocities greater than 6 km/s. Data for tests with impact velocities between 5 and 6 km/s were not available.

4. Hole-formation sequence

The change in the morphological features of the lip regions of the holes suggests a sequence of events for the formation of holes in the thin sheets. When a sphere impacts a thin sheet at hypervelocity, a shock forms and propagates into the sheet and the sphere. The intensity of the shock and the extent of its influence on the sheet are a function of the $t/D$ ratio and the impact velocity of the sphere [7]. After a short period of quasi one-dimensional loading, the lens-shaped region shown in Fig. 3 is formed. In Fig. 3, the instantaneous collision point velocities, $V_{CP,P}$ and $V_{CP,T}$, are shown as functions of time after impact of a 2.60-mm-diameter aluminum sphere with an aluminum target at a velocity of 9.20 km/s. Also shown are horizontal lines representing the velocity of the sphere, $V_{in}$, and the computed velocity, $U$, of the shock in the sphere and the target after impact.

From Fig. 3, it is evident that the shock front in the target will outrun the surface of the advancing sphere for all but the initial, brief period of quasi one-dimensional loading. An implication of this circumstance is that, during most of its encounter with the target sheet, the advancing sphere will contact material that has been shocked and disturbed. The extent of the shock-induced disturbance in the sheet during the impact of a 9.53-mm-diameter sphere is shown in the radiograph presented in Fig. 4. The rear of the sphere was struck by a chip of steel from the sabot-stripper plate and debris from this extraneous impact caused the flash x-ray sources to pretrigger by several microseconds, “catching” the sphere when it was half way through the sheet, about 0.7 µs after impact. In the radiograph, the center of the 9.53-mm-diameter sphere was
shown very close to the front or impacted surface of the sheet. The location, on both sides of the sheet, of the points where an increase in the thickness of the sheet was first evident (shown by arrows) indicated that the shock in the sheet was nearly normal (horizontal dashed line below sphere) to the surface of the sheet at the time the radiograph was made. In addition, the front of the sphere and the target sheet were highly compressed and a well-developed ejecta veil had formed on the front side of the sheet. Clearly, a strong shock had propagated in the sheet and the hole-formation process was well underway. The sequence of target-sheet cross sections presented in Fig. 2 demonstrated that the hole-formation process could produce a variety of morphological features in the region adjacent to the holes. The prominence of one feature over another was a function of $t/D$ ratio. Processes that were latent for tests with low $t/D$ ratios appeared to dominate the formation of lip-region features for tests with high $t/D$ ratios.

Study of the grain structure exposed in the micrograph shown in Fig. 5 (Shot 4-1283, at left) provides insight into the processes that led to the development of the distorted stratigraphy exhibited in the micrograph and the effects of shock propagation in the sheet. The general flow of the severely distorted material closest to the hole opening (i.e., the right side of the figure) indicated that significant, outwardly-directed, radial forces were applied to this material from the inside of the hole. Essentially, all of the voids in this material were closed, indicating that the voids were formed before the radial loads were applied. The voids in the material away from the edge of the hole remained circular. The flow of the grain structure in the left half of the figure indicated the tendency of the material in this region to separate, or at least establish a flow field that
promoted additional separation of this material. Of interest were several large voids near the center of the sheet. These large voids appeared to form when several small voids coalesced, apparently as a result of excessive tensile loads in this region of the sheet. The “flow” pattern of material in the central part of the micrograph, as well as the location of the larger voids, tended to indicate the impending formation of the ring and thin web of material seen in the target-sheet cross sections shown in Fig. 2 for Shot 4-1352.

An enlarged view of the cross section of the target sheet for the $t/D = 0.424$ test (Shot 4-1353) shown earlier in Fig. 2 is presented on the right side of Fig. 5 to illustrate the detached, wedge-shaped ring and overturned flap that were formed in the sheet used for this test. The smooth appearance of the surfaces of the wedge facing the split in the sheet (arrows) indicated that these surfaces were probably smoothed by a sliding contact with the undersides of the overturned flaps of material on either side of the split in the target sheet. The large split in the sheet was formed when release waves generated at both free surfaces of the sheet met and produced the significant tensile stresses that led to a tensile failure along the center of the sheet. Additional growth of the crack could have occurred when the momentum of particles in the wedge-shaped ring drove the wedge into the crack and applied additional tensile loads to the region at the tip of the crack. However, the hole-growth processes deteriorated quickly when the outwardly moving shock was transformed into a weaker elastic wave as a result of geometric dispersion of the shock and the interaction of the release waves with the stressed region of the sheet.

The hole shown in Fig. 6 exhibited features that were observed for a number of tests in which 12.70-mm-diameter, 2017-T4 aluminum spheres were fired at 1.976-mm-thick, 6061-T6 aluminum sheets with an impact velocity of about 6.4 km/s. For most of these tests, the major opening in the sheet was defined by a fragile ring of aluminum surrounded by a series of small holes. The interior rings were weakly attached to the surrounding target sheet and, in some instances, pieces of the ring simply fell from the hole after hole growth ceased. The transition from an attached ring to a detached ring undoubtedly occurred as a result of the loss of material from the thin web that joined the ring structure to the center of the sheet. Features of the sheet cross section presented in Fig. 6 are very similar to the cross section presented for Shot 4-1352 in Fig. 2. Several small holes were occasionally observed around the holes in sheets from tests using a variety of diameters of 2017-T4 aluminum spheres and 6061-T6 aluminum sheets when the $t/D$ ratio was greater than 0.15. The difference between the measured diameter of the inner ring and the measured diameter of the hole defined by the irregular opening outside the ring is significant. The normalized diameter of the inner ring fits the data shown in Fig. 1; the normalized diameter of the outer opening does not.

When the $t/D$ ratio was low, a small lip formed on both sides of the sheet and surrounded the hole. At intermediate $t/D$ ratios, the lip grew and formed an overturned flap which developed localized voids and cracks that led to the separation of
flap material from the sheet. As material separated from the target sheet, a thin web of material at the center of the sheet served to retain a wedge-shaped ring of material that was originally closer to the impact site. At large \( t/D \) ratios, the wedge-shaped ring detached from the sheet and appeared to force the sheet to split apart.

Except for a relatively small central plug of material directly below the sphere, the bulk of the target-sheet material that is in the path of the impacting sphere is shocked and disturbed before being contacted by the sphere. As the sphere advanced through the disturbed material, a secondary disturbance was driven into the void-filled target material. Momentum acquired by particles behind the shock in the virgin material and the secondary disturbance in the “porous” material caused the portion of the sheet nearest the sphere to apply a radial load to the evolving hole, and promoted severe compression, fracture, fragmentation, and ejection of material as fragments in the ejecta veil and external bubble of debris in the debris cloud produced by the impact. The grain structure, voids, and cracks displayed in the micrographs of the sheets were the last features formed as the shock-related activities ceased.

5. Conclusions

Normalization of the hole-diameter data using the sphere diameter, \( D \), permitted the diameters of holes formed in sheets by spheres ranging from 1.40 to 19.05 mm in diameter (and impact velocities ranging from 1.98 to 9.89 km/s) to be compared on the basis of \( t/D \) ratio. The comparisons indicated that the use of this simple geometric scaling technique was extremely effective for the range of data that was examined.

Observations made during the measurement of target-sheet thicknesses and hole diameters emphasized the sensitivity of the hole diameter to very small variations in sheet thickness.

As the \( t/D \) ratio increased, the holes tended to be less circular and the structure of the region surrounding the hole became more complex. Micrographs of cross sections of the sheets showed that a clear relationship existed between the \( t/D \) ratio and the morphology of features evident in the cross sections. The features observed in these cross section were used to develop a description of the hole-formation sequence.

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