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Impact Testing of 410 Stainless Steel for Material Impact Model Development

Duane M. Revilock, Charles R. Ruggeri, and J. Michael Pereira
Glenn Research Center, Cleveland, Ohio

March 2026

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Summary

A project is underway to develop a consistent set of material properties, impact test data, and failure analysis for a variety of metallic aircraft materials that can be used to develop improved impact failure and deformation models. This project is jointly funded by the NASA Glenn Research Center and the Federal Aviation Administration William J. Hughes Technical Center. Particular features of this set of data are that all material property and impact test data are obtained using traceable material, the test methods and procedures are extensively documented, and all the raw data are available. Four parallel efforts are currently underway: measurement of material deformation and failure response over a wide range of strain rates and temperatures, failure analysis of material property specimens and impact test articles, development of improved numerical modeling techniques for deformation and failure, and impact testing of flat panels and substructures for model validation.

This report describes impact testing performed on 410 stainless steel sheet and plate samples of different thicknesses with two different types of projectiles, one a regular cylinder and one with a more complex geometry incorporating features representative of a jet engine fan blade. Data from this testing will be used in validating material models developed under this program. The material tests and the material models developed in this program will be published in separate reports.

Nomenclature

DIC	digital image correlation
FAA	Federal Aviation Administration
HRC	hardness Rockwell C
NGFBF	NASA Generic Fan Blade Fragment
V_{50}	velocity at which the probability of penetration is 50%

Introduction

Numerical simulation of dynamic impact events has reached a level of maturity where it is commonly used as a design tool for a wide variety of aerospace structures, such as jet engine containment systems, fan blades, radomes, cowlings, wings, and empennages. However, current efforts require extensive testing in parallel with modeling, and it is often necessary to adjust model parameters somewhat arbitrarily to ensure the model fits the test results. Explicit transient finite element modeling of even the simplest of problems, such as a regularly shaped projectile impacting a flat plate, can result in widely varying results depending on the material and failure models, available material properties, contact models, mesh density, and a number of different numerical parameters that must be specified in the computer codes.

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*Currently retired.

One of the difficulties with developing and validating accurate impact models is that parameters such as high strain-rate material properties, failure modes, static properties, and impact test measurements are often obtained from a variety of different sources using different materials, with little control over consistency among the various sources. In addition, there is often a lack of quantitative measurements from impact tests to which the models can be compared.

To alleviate some of these problems, a project is underway to develop a consistent set of material property and impact test data and failure analysis for a variety of materials that can be used to develop improved impact failure and deformation models. This project is jointly funded by the NASA Glenn Research Center and the Federal Aviation Administration (FAA) William J. Hughes Technical Center. Unique features of this set of data are that all material property and impact test data are obtained using traceable material, the test methods and procedures are extensively documented, and all of the raw data are available. Four parallel efforts are currently underway: measurement of material deformation and failure response over a wide range of strain rates and temperatures; development of improved numerical modeling techniques for deformation and failure; ballistic impact testing of flat panels and substructures; and failure analysis of material property specimens and impact test articles.

This report describes impact testing conducted on 410 stainless steel sheet and plate samples of different thicknesses and with two types of projectiles. One projectile was a regular cylinder; the second, the NASA Generic Fan Blade Fragment (NGFBF), has a more complex geometry incorporating features representative of a generic jet engine fan blade fragment. The test program described in this report is similar to testing conducted on Al 2024, Ti-6Al-4V, and Inconel® 718 (Huntington Alloys Corp.) sheet and plate samples as described in References 1 and 2. Procedures and results are reported in detail, and information about obtaining raw data is provided. The material properties of this material, measured over a range of temperatures and strain rates, will be provided in a separate report.

Methods

Impact tests were conducted on 410 stainless steel panels with two different areal dimensions: large square panels measuring 24- by 24-in. and small square panels measuring 15- by 15-in. The material was obtained in the annealed state and then heat-treated. The smaller panels were impacted in the normal direction by cylindrical projectiles with diameters of 0.5 and 0.75 in. The larger panels were impacted by the NGFBF as a simplified simulation of a blade impacting a containment structure or aircraft fuselage in an oblique orientation. Different test setups were used for the two sets of impact tests, as described in the following sections. Strains and displacements were measured on the backside of the panels using digital image correlation (DIC) techniques, providing data useful for validating numerical impact models.

Materials

Impact tests for both the small and large panels were conducted on heat-treated 410 stainless steel. The material certification sheets for the 0.25- and 0.5-in.-thick material are shown in Appendix A. The 0.125-in.-thick material was obtained from the same manufacturer, but certification sheets are not available. The material was purchased tempered at 1,150 °F and then heat-treated by vacuum hardening according to the following schedule:

1. Preheat at 1,550 °F for 30 min.
2. Austenitize at 1,800 °F for 30 min.
3. Vacuum temper at 1,150 °F for 2 h.
4. Cool to room temperature.

The heat treatment resulted in a hardness of HRC 42 (certification sheet, Appendix B).

Impact tests on the small and large panels were conducted on panels with the thicknesses shown in Table I. The nominal thickness in the table is the thickness stated on the certification sheet, and the actual thickness is based on averages of multiple measurements of the as-received material. For consistency, future references to target thickness in this report refer to the nominal thickness of the material.

Small Panel Tests

Twelve impact tests were conducted on each of the different-thickness target panels shown in Table I, except for the 0.125-inch small panels, where eleven tests were conducted. The test specimens were cut in squares, 15 in. on a side, with through holes for mounting bolts, as shown in Figure 1. The through holes were 9/16-in. in diameter on a 13-in.-diameter bolt hole circle. The specimens were held in massive steel fixtures with a 10-in. circular aperture, as shown in Figure 2(a). The two parts of the fixture were 1.5-in.-thick steel (Figure 2(b)). The test panels were mounted in the fixture with the rolling direction in the horizontal direction.

TABLE I.—TEST SPECIMEN NOMINAL AND MEASURED THICKNESSES

Thickness	Panels			
	Small			Large
Nominal, in.	0.125	0.250	0.500	0.125
Actual, in.	0.132	0.294	0.554	0.132

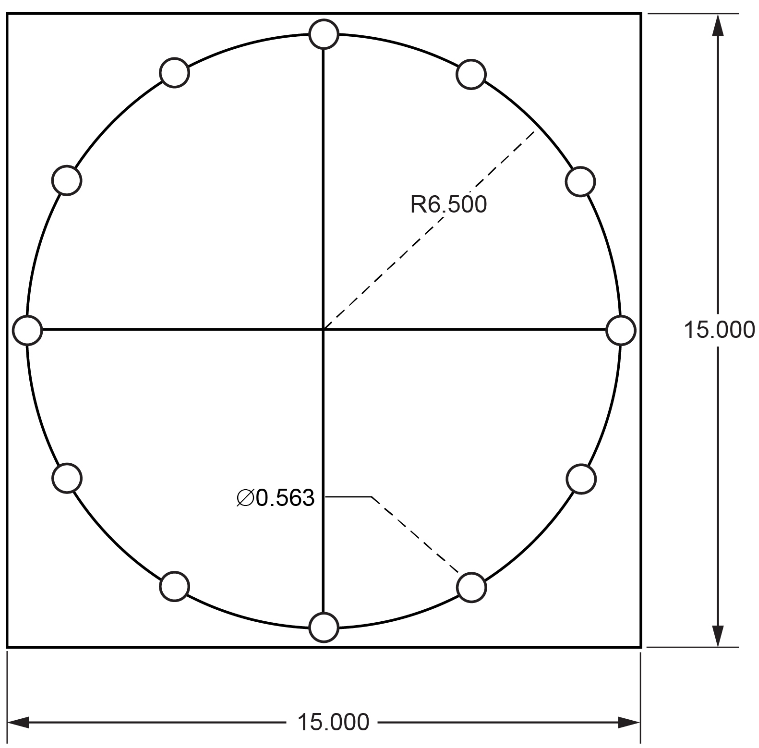


Figure 1.—Small panel test specimen. Dimensions in inches.

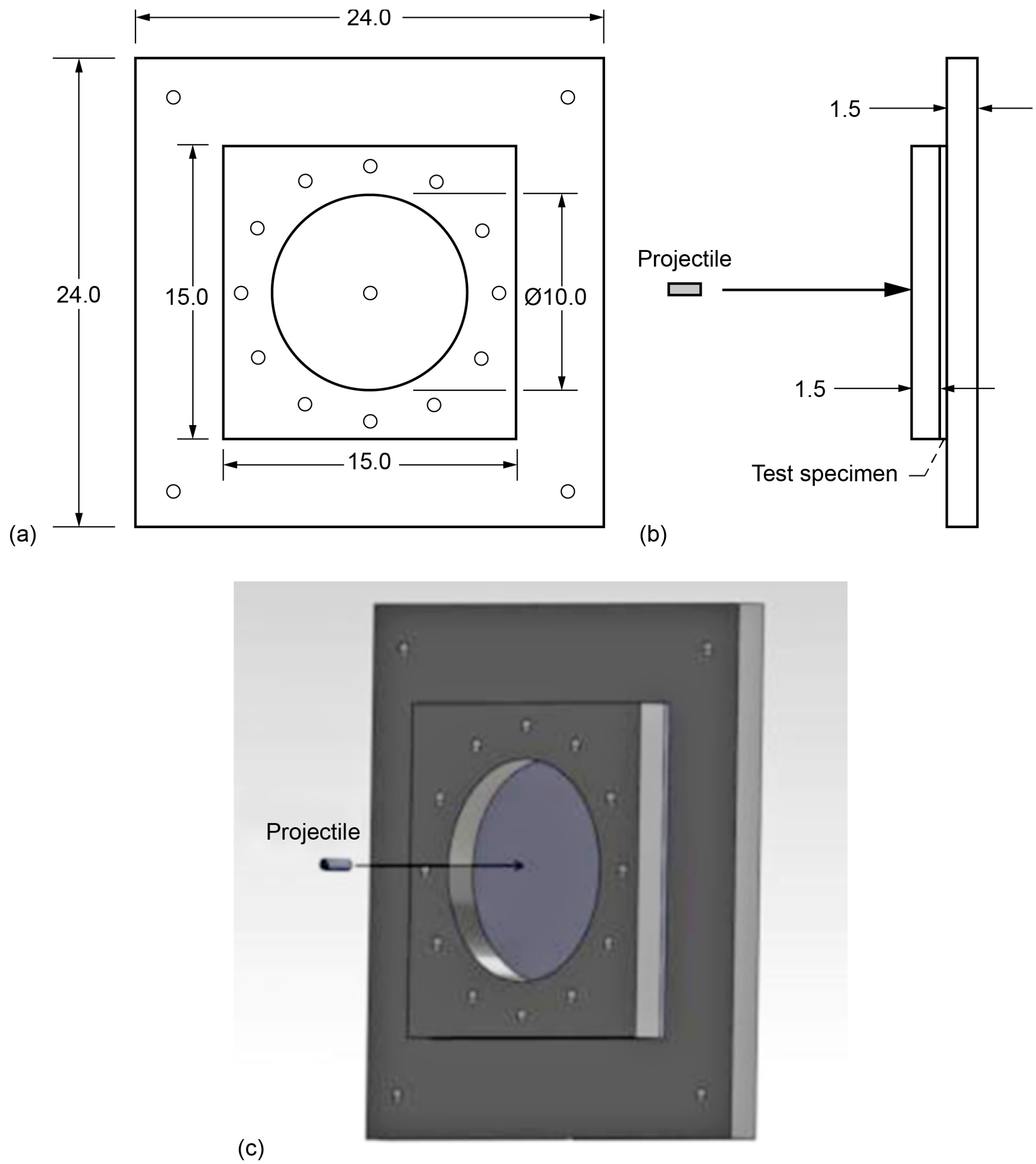


Figure 2.—Test fixture assembly; dimensions in inches. (a) Front view. (b) Side view. (c) Clamp fixture assembly.

The projectiles were cylindrical with a large radius front face and impacted the plates in the normal orientation at the center of the plate, as shown in Figure 2(c). The tests were designed such that the penetration threshold velocity for the various combinations of projectiles and panel thicknesses was in the range of 600 to 900 ft/s. This corresponds to the high-speed range of the center of mass of a typical uncontained engine fan blade fragment. The impact tests were conducted at speeds above and below the penetration threshold so that some projectiles penetrated and some did not.

Projectiles

The projectiles used for the small panel testing were hardened A2 tool steel cylinders with varying length, diameter, and material, as shown in Table II. They had a relatively large nose radius of 2.75 in., which allowed a slight deviation in the normal orientation of the projectile without a front edge impact (Figure 3). The edge of the front face was "broken" with a 1/32-in. radius. The projectiles were hardened to a minimum of Rockwell 55C.

TABLE II.—PROJECTILE MATERIAL AND DIMENSIONS FOR VARIOUS SPECIMEN THICKNESSES

Nominal panel thickness, in.	Projectile material	Projectile length, in.	Projectile diameter, in.	Average mass, g
0.125	A2 tool steel	0.870	0.5	20.91
0.25	A2 tool steel	1.000	0.5	24.69
0.5	A2 tool steel	2.255	0.75	124.21

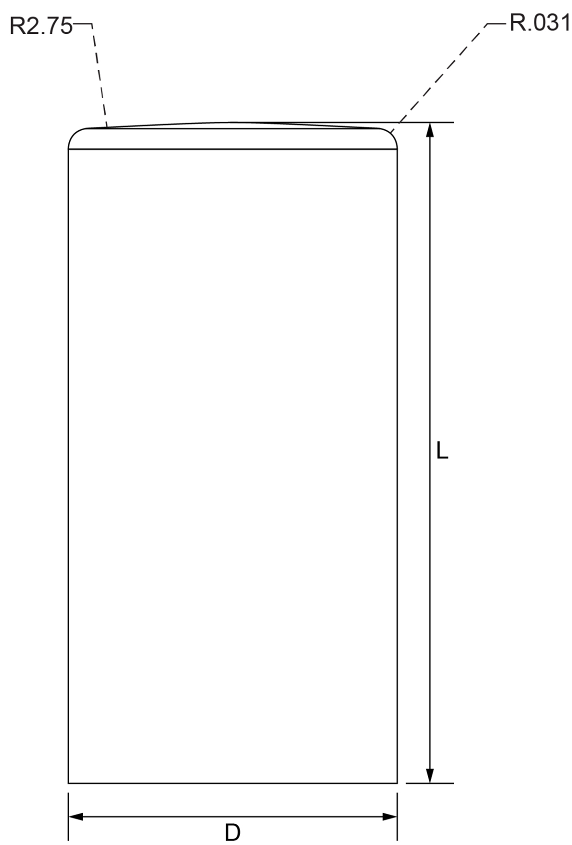


Figure 3.—Sample small panel projectile. Length, L, and diameter, D, vary depending on test specimen thickness and material. Dimensions in inches; radius, R.

Gas Gun

The cylindrical projectiles were accelerated with a gas gun connected to a vacuum chamber, shown in Figure 4, using nitrogen as the propellant. The gun barrel had a length of 23 ft and a bore of 2.0 in. The pressure vessel had a volume of 1.06 ft^3 (Figure 5). The projectile was carried down the gun barrel supported by rigid foam in a cylindrical polycarbonate sabot, shown in Figure 6. The gun barrel protruded into the vacuum chamber, which held the fixture for the specimens. The sabot was stopped at the end of the gun barrel by a stopper plate with a through hole large enough to allow the projectile to pass through.

Instrumentation

Data acquired from the impact tests included measurements of the impact velocity, post-impact penetration or rebound velocity, projectile orientation at the time of impact, and full-field backside strain and displacement measurements using a DIC system. In addition, high-speed cameras provided qualitative observations of each test.

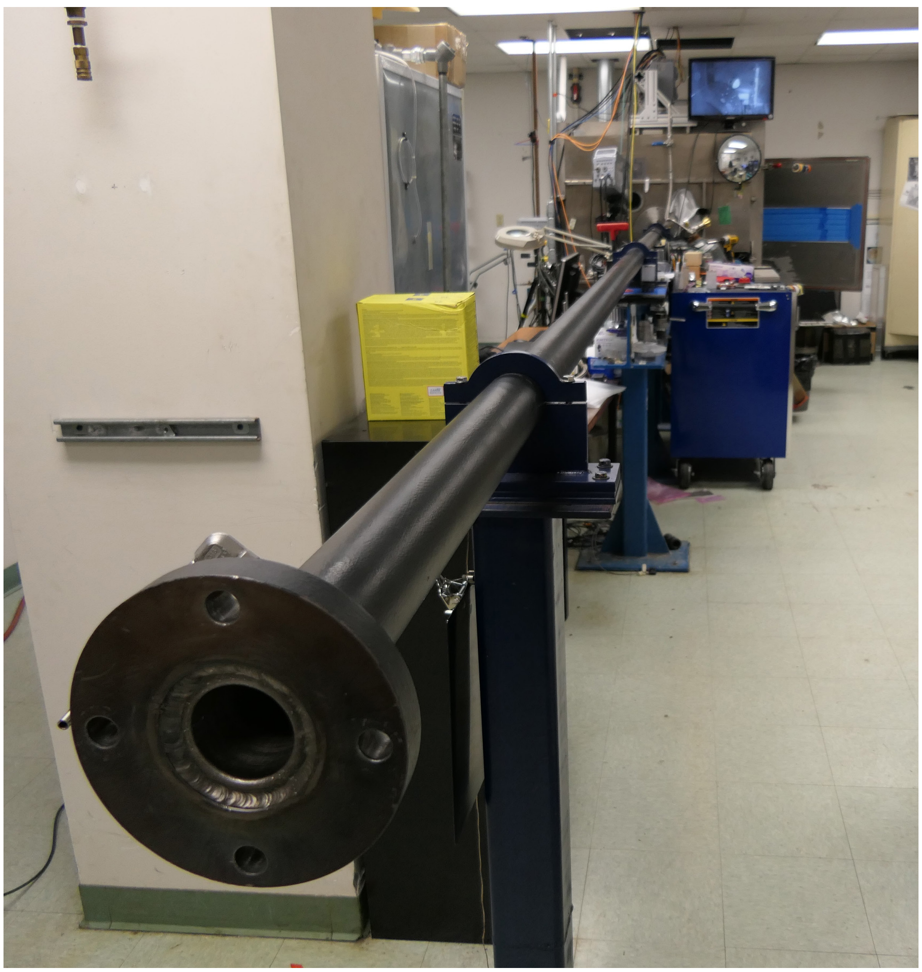


Figure 4.—Large vacuum gas gun; shown with 2-in.-diameter gun barrel.

Figure 5.—Pressure vessel.

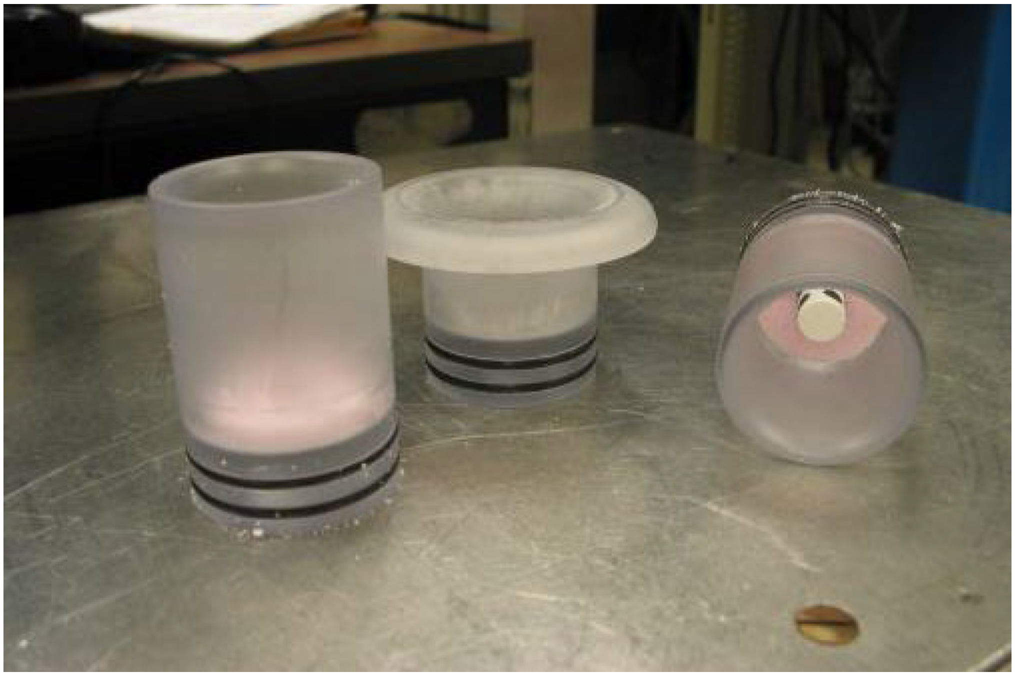


Figure 6.—Sabots used to transport projectile down gun barrel; posttest sabot shown in center.

Eight high-speed digital cameras were used for each test. A calibrated pair of cameras were located above and in front of the panel to quantitatively measure the velocity and orientation of the projectile prior to impact, as well as the post-impact velocity if the projectile did not penetrate the panel. A second calibrated pair of cameras was located above and behind the panel to measure the post-impact velocity and orientation of the projectile if penetration occurred. A third calibrated pair of cameras viewed the backside of the panel to obtain video for DIC. A calibrated single camera viewed the projectile path from the side as a redundant measurement of impact velocity. Finally, an uncalibrated camera viewed the impact from the front to obtain a general view of the impact. Camera locations are shown in Figure 7.

The speed and orientation of the projectile were measured by tracking the position of markers on the projectile relative to the position of fixed points, which defined the fixed laboratory coordinate system. The point tracking was accomplished with the use of a calibrated pair of high-speed cameras (Photron® SA-Z, Photron USA, Inc.) and the PONTOS (ZEISS®, www.zeiss.com) point tracking software system. The fixed points were located on a metal plate mounted to the specimen fixture in a horizontal plane directly below the path of the projectile, as shown in Figure 8. The points defined a coordinate system with the-x axis pointing in the direction of the gun barrel, the z-axis vertically downward, and the y-axis to the right when facing the front of the test panel.

To report the orientation of the projectile, a vector was defined along the projectile centerline. The pitch angle was calculated as the angle between the laboratory x-axis and the projection of the projectile axis in the laboratory x-z plane. The yaw angle was calculated as the angle between the laboratory x-axis and the projection of the projectile axis on the laboratory x-y plane.

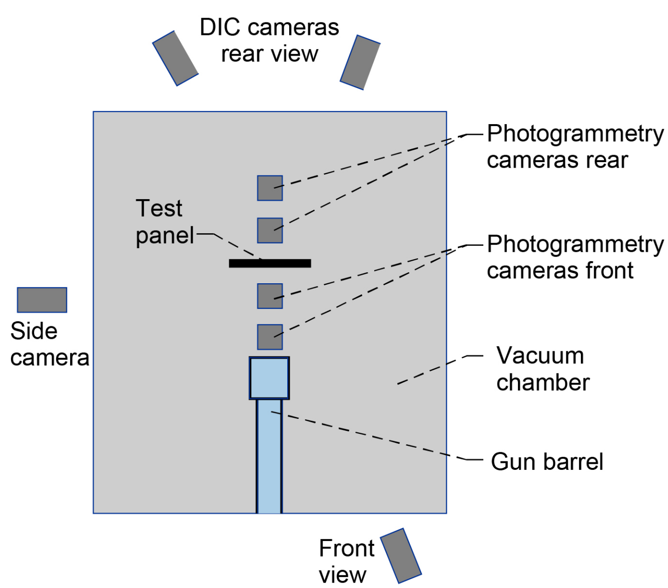


Figure 7.—Top view of vacuum chamber showing high-speed camera locations.

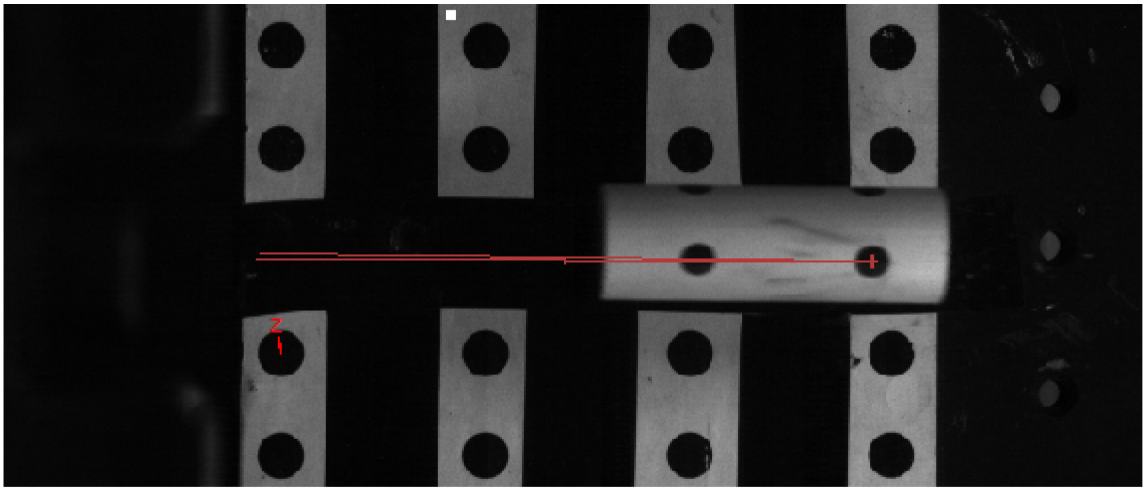


Figure 8.—Points used to define laboratory coordinate system (view from top).

Full-field displacement and strain measurements were obtained using a calibrated pair of high-speed digital cameras (Photron® model SA-Z) and a DIC software package (ARAMIS, www.zeiss.com). The cameras were located on the outside of the vacuum chamber and viewed the backside of the panel through two viewports. The distance from the cameras to the panel was approximately 36 in., and the distance between the cameras was approximately 16 in. The cameras were set with a resolution of 256 × 544 pixels, an exposure of 4 μs, and a frame rate of 100,000 frames per second. The backside of each panel was painted with a random set of black dots on a white background, as required by the ARAMIS software. From the images, the software computed the displacements in three directions at any point in the view for every recorded frame. In-plane strains on the back surface of the panel were computed from the displacements.

Large Panel Tests

Impact tests were conducted on large panels with a thickness of 0.132 in. These tests were designed to utilize a more realistic projectile and non-normal impact orientation to provide data for validation of numerical models under conditions more complex than the small panel tests. It also is a better representative laboratory test for a turbine-engine blade release event. The release of an engine blade is tangential, so as the blade is released, the tip makes contact in such a way that it tends to bend, as opposed to a blade exiting in a purely radial direction. This creates a moment, and the blade rotates after initial contact, with the heavier root section often being the part of the blade that penetrates the engine case. This test is a simple laboratory test to try to represent this type of impact more accurately than a normal impact with a cylindrical projectile would.

Test Specimens

The test specimens were 24- by 24-in. hardened 410 stainless steel with a thicknesses of 0.132 in. These specimens were cut from the same sheet material as the small panel test specimens. The panels were held at a 45° angle in a square fixture with a 20- by 20-in. aperture, as shown in Figure 9. The panels were through-bolted with 24 0.5-in. bolts equally spaced around the sides, 1 in. from the edges, and they were mounted such that the rolling direction of the sheet was in the vertical direction.

Figure 9.—Large panel test setup showing orientation of projectile and test specimen.

Projectile

The NGFBF projectile used for the large panel tests is shown in Figure 10. The projectiles were Ti-6Al-4V, AMS 4911, with a nominal mass of 430 g. The desired orientation of the projectile at impact was at a 45° angle from vertical such that the flat plane of the projectile was at a 90° angle to the plane of the test specimen. A still image from a high-speed video of an impact test, taken directly before impact, is shown in Figure 11.

Instrumentation

Full field displacement data on the backside of the impacted panels were obtained using a pair of calibrated Phantom® V7.3 (Vision Research) high-speed cameras and a DIC system, similar to the small panel tests.

To measure the projectile linear and angular position and velocity, a pair of calibrated Photron® SA-X2 cameras and the PONTOS point tracking software were used to track the position of individual markers on the projectile. These were used to establish the projectile coordinate system and calculate velocity and orientation relative to the fixed laboratory coordinate system.

A Phantom® V7.3 camera oriented normal to the path of the projectile from the side was used for a redundant velocity measurement, and a Phantom® V7.3 camera viewing from above was used to measure the velocity of the projectile if it penetrated the panel.

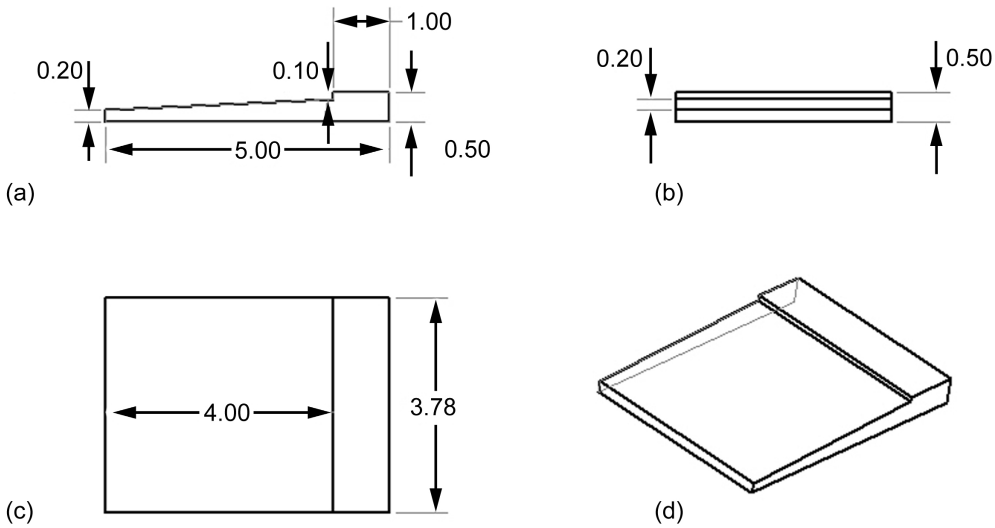


Figure 10.—Generic fan blade fragment; dimensions in inches. (a) Side view. (b) Front view. (c) Top view. (d) View of model.

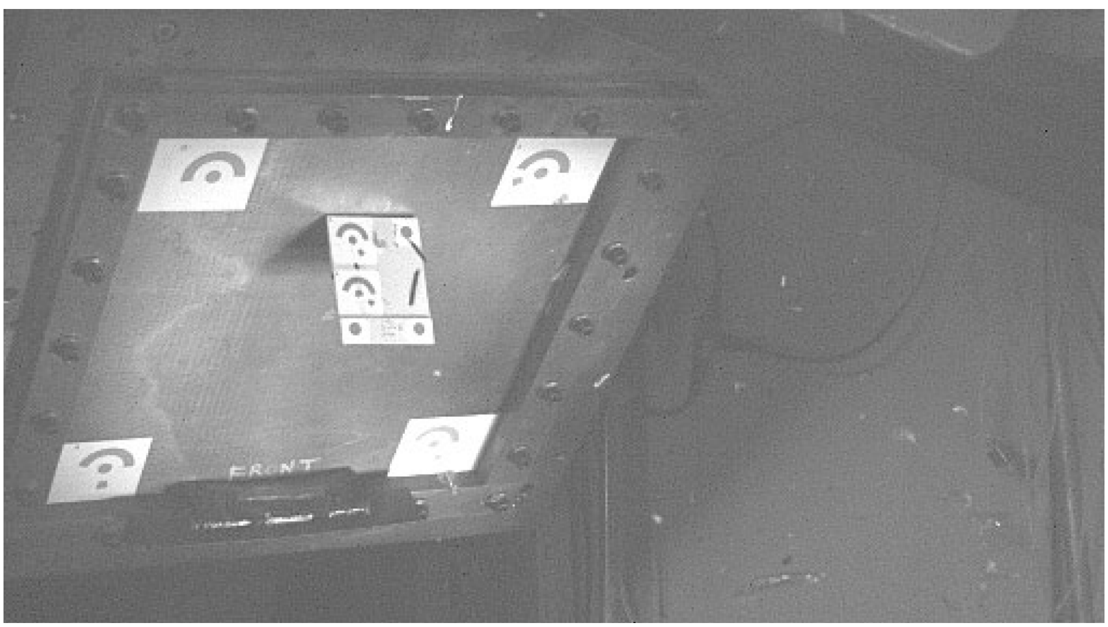


Figure 11.—Still image from high-speed movie of impact test taken directly before impact.

The backside DIC cameras operated at a frame rate of 20,000 frames per second, an exposure of 4 µs, and a resolution of 384 × 344 pixels. The front-side photogrammetry cameras operated at 40,000 frames per second with an exposure of 2.5 µs and a resolution of 768 × 392 pixels.

The side camera operated at a rate of 32,000 frames per second, an exposure of 10 µs, and a resolution of 608 × 96 pixels. The top camera operated at a rate of 10,000 frames per second, an exposure of 25 µs, and a resolution of 400 × 600 pixels.

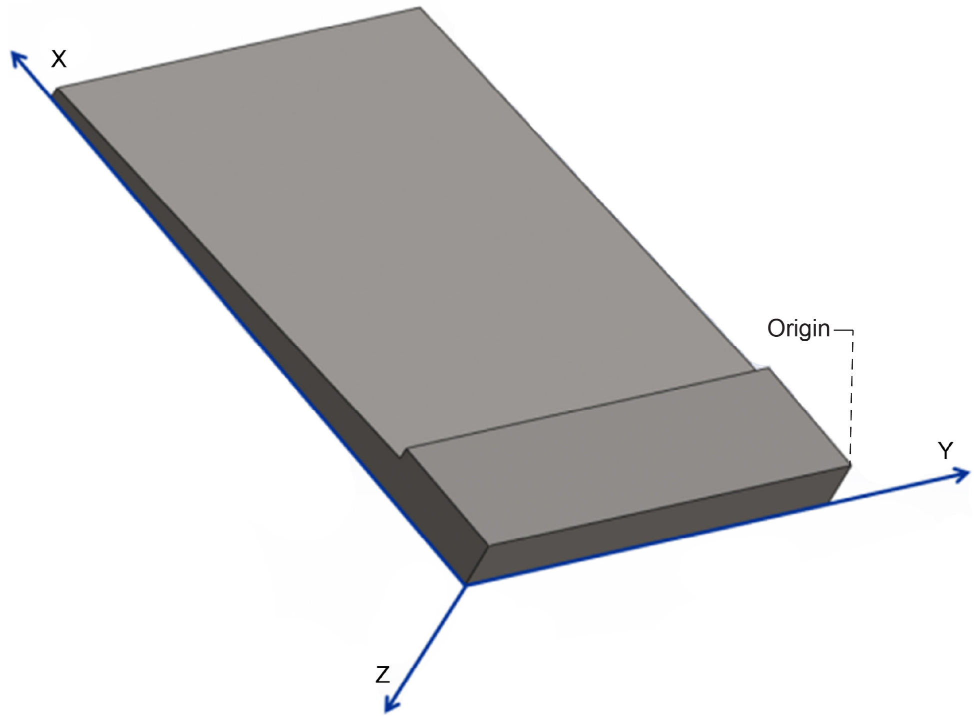


Figure 12.—Projectile local coordinate system.

Coordinate Systems

The fixed laboratory coordinate system was specified with the origin at the center of the impact face of the test panel with the x-direction in the direction of the axis of the gun barrel. The y-direction was to the right when looking toward the test specimen from the gun barrel, and the z-direction was vertically downward.

The projectile coordinate system is shown in Figure 12. The x-y plane was parallel to the inclined plane of the projectile top surface. The x-axis was parallel to the left plane of the projectile and pointed toward the projectile tip, and the y-axis was parallel to the top and bottom edges of the projectile. The point labeled "origin" in Figure 12 was the point at which the linear position and velocity of the projectile are reported.

To report the position, velocity, and orientation of the projectile, the position and velocity of the origin of the projectile local coordinate system are given with respect to the fixed laboratory coordinate system. The angular position and velocity are given as a set of Euler angles and angular velocities with respect to the moving coordinate system. The Euler angles are defined as a rotation about the fixed laboratory x-axis (roll), followed by a rotation about the once-rotated local y-axis (pitch), followed by a rotation about the twice-rotated local z-axis (yaw).

Test Configuration

The desired orientation of the projectile at impact was 0° about the x-axis (roll), 45° about the projectile y-axis (pitch), and 0° about the (rotated) projectile z-axis (yaw). In this orientation, the angle between the projectile and the test panel was 90°. This orientation was not achieved exactly in all tests, but the actual orientations (Euler angles) were measured and recorded.

Results and Discussion

Forty-three instrumented impact tests were conducted in total for the two different size test specimens. The following sections describe and discuss the test results.

Small Panel Impact Tests

A total of 35 small panel impact tests were conducted on three different specimen thicknesses. The tests were conducted at velocities that bracketed the penetration threshold velocity of the panel. The projectile size and mass were different for each panel thickness to maintain a penetration threshold in the range of 600 to 900 ft/s. The results of the tests are summarized in Table III, (0.125-in. panels), Table IV (0.25-in. panels), and Table V (0.5-in. panels).

Figure 13 through Figure 15 plot the penetration (0 or 1) against the projectile impact velocity as well as the exit velocity as a function of impact velocity. For tests on the 0.125-in. specimens, there is no overlap in the results, meaning that the lowest velocity where penetration occurred was higher than the highest nonpenetrating test velocity. For the 0.25- and 0.5-in. specimens, there is some overlap. For cases in which there is an overlap, a logistic regression analysis was used to compute the probability of penetration and the velocity at which the probability of penetration is 50%, termed V_{50}. For the 0.125-in. panels, where there is no overlap, it is not possible to compute the probability, so V_{50} is assumed to be the average of the highest nonpenetrating velocity and the lowest penetrating velocity. Table VI shows V_{50} values for panels of three different thicknesses.

Photographs and deformation responses from the small panel tests are given in Appendix C.

TABLE III.—IMPACT TEST RESULTS FOR 0.125-in. SMALL PANELS

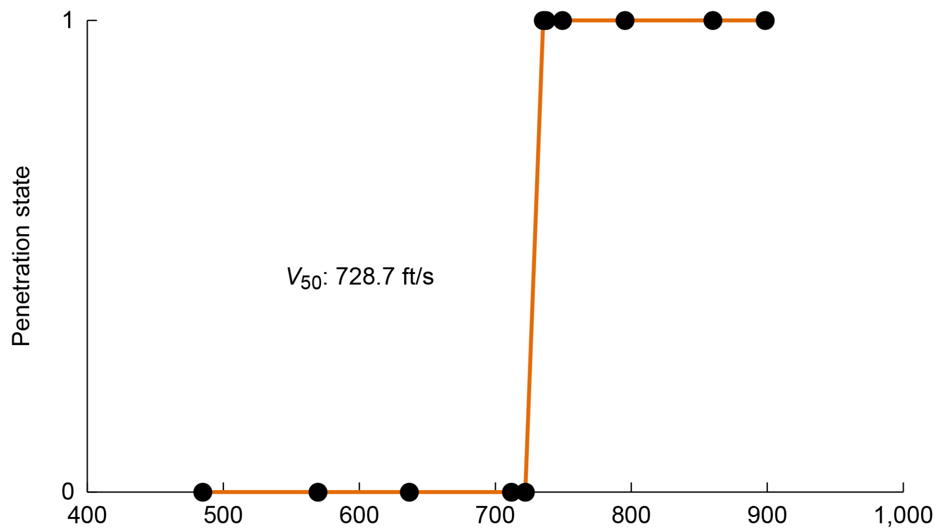
Test no.	Panel thickness, in.	Impact velocity, ft/s	Yaw, deg	Pitch, deg	Projectile mass, g	Plug mass, g	Impact energy, J	Projectile exit velocity, ft/s	Rebound velocity, ft/s	Plug exit velocity, ft/s	Penetration, Yes/No	Comment
DB275	0.1329	898.4	–0.8	–3.9	20.87	3.07	782.5	495.6	----	526.9	Yes	
DB276	0.1324	711.8	–0.6	–3.1	20.90	0.00	491.9	0.0	26.2	----------	No	
DB277	0.1326	749.4	0.5	1.5	20.88	NA	544.7	147.8	----	Attached	Yes	
DB278	0.1327	722.1	0.4	1.3	20.97	0.00	507.9	0.0	23.9	----------	No	
DB279	0.1336	737.2	–0.6	0.4	20.93	NA	528.4	121.5	----	NA	Yes	
DB280	0.1337	636.8	–0.3	–0.8	20.93	NA	394.3	0.0	31.4	----------	No	
DB281	0.1327	569.6	1.7	–0.8	20.88	NA	314.7	0.0	58.8	----------	No	
DB282	0.1318	484.8	–1.4	–3.1	20.97	NA	228.9	0.0	20.8	----------	No	
DB283	0.1315	735.2	–1.1	–1.6	20.94	NA	525.8	175.1	----	NA	Yes	Could not track plug
DB284	0.1322	794.3	–1.7	–2.0	20.87	NA	611.6	469.0	----	571.6	Yes	
DB285	0.1322	849.3	–1.4	–1.5	20.92	NA	700.9	NA	----	NA	Yes	No exit video

TABLE IV.—IMPACT TEST RESULTS FOR 0.25-in. SMALL PANELS

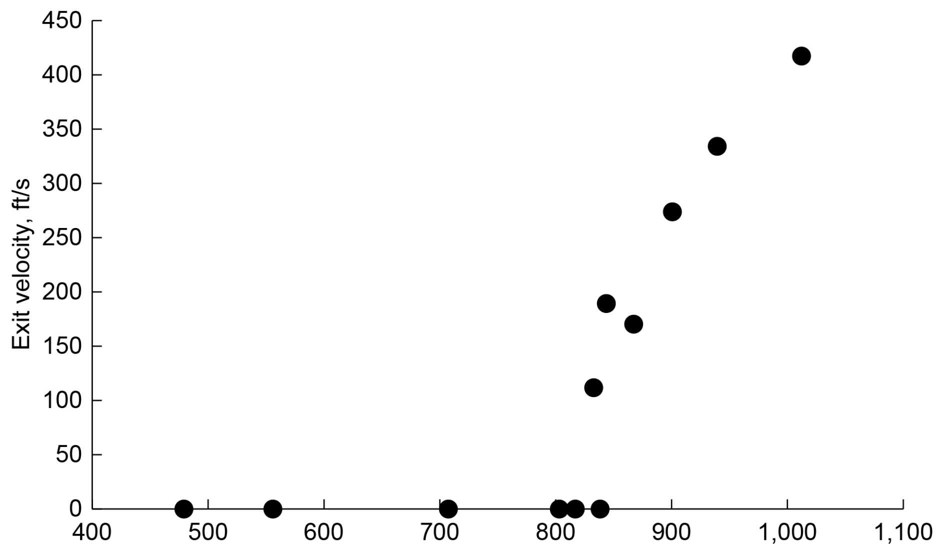
Test no.	Panel thickness, in.	Impact velocity, ft/s	Yaw, deg	Pitch, deg	Projectile mass, g	Plug mass, g	Impact energy, J	Projectile exit velocity, ft/s	Rebound velocity, ft/s	Plug exit velocity, ft/s	Penetration, Yes/No	Comment
DB286	0.2936	939.4	–0.7	–0.5	24.71	6.97	1,012.8	334.2	-----	309.8	Yes	
DB287	0.2925	838.2	–0.1	1.1	24.71	6.79	806.6	0.0	-----	-------	No	Perforated panel
DB288	0.2935	843.7	–0.3	0.3	24.71	6.96	817.1	189.3	-----	168.1	Yes	
DB289	0.2923	707.3	–0.8	0.3	24.71	-----	574.2	0.0	24.2	-------	No	
DB290	0.2913	555.8	–1.3	4.1	24.71	-----	354.6	0.0	24.9	-------	No	
DB291	0.2925	479.1	–2.4	–3.9	24.71	-----	263.4	0.0	30.2	-------	No	
DB292	0.2899	832.7	0.3	–0.7	24.71	6.67	795.9	111.8	-----	217.5	Yes	
DB293	0.2909	803.0	0.2	–1.3	24.71	-----	740.1	0.0	29.5	-------	No	
DB294	0.2911	816.9	0.6	–0.7	24.71	-----	766.0	0.0	29.6	-------	No	
DB295	0.2889	1,012.1	0.0	–1.6	24.71	6.67	1,175.8	417.4	-----	357.8	Yes	
DB296	0.2899	900.6	0.8	–0.8	24.55	6.65	925.0	273.9	-----	357.8	Yes	
DB297	0.2900	867.2	1.8	–0.8	24.68	6.60	862.2	170.3	-----	270.2	Yes	

TABLE V.—IMPACT TEST RESULTS FOR 0.5-IN. SMALL PANELS

Test no.	Panel thickness, in.	Impact velocity, ft/s	Yaw, deg	Pitch, deg	Projectile mass, g	Plug mass, g	Impact energy, J	Projectile exit velocity, ft/s	Rebound velocity, ft/s	Plug exit velocity, ft/s	Penetration, Yes/No	Comment
DB298	0.5530	719.5	0.6	–1.7	123.91	-------	2,979.7	0	32.8	-------	No	
DB299	0.5522	734.5	2.3	–0.4	124.03	29.4	3,108.2	0	0	212.3	No	Perforated panel
DB300	0.5539	681.3	0.6	–0.6	124.13	-------	2,676.4	0	67.1	-------	No	
DB301	0.5515	601.3	0.6	–0.5	124.24	-------	2,086.6	0	58.4	-------	No	
DB302	0.5587	746.0	0.7	–0.5	124.23	-------	3,211.5	0	0	-------	No	Perforated panel
DB303	0.5568	779.9	1.2	–0.2	124.40	28.16	3,514.8	0	-----	182.8	No	Perforated panel
DB304	0.5597	868.5	1.0	–0.3	124.63	27.23	4,366.8	236.3	-----	360.2	Yes	
DB305	0.5562	831.8	0.6	–0.5	123.97	28.21	3,984.3	196.3	-----	308.9	Yes	
DB306	0.5590	809.9	1.1	–0.3	124.63	28.51	3,797.4	177.7	-----	263.5	Yes	
DB307	0.5511	793.2	1.2	–1.5	124.29	27.89	3,632.5	128.3	-----	198.5	Yes	
DB308	0.5560	770.5	0.9	–0.3	123.94	28.33	3,417.9	52.4	-----	169.6	Yes	
DB309	0.5576	908.2	0.6	–0.6	124.15	26.76	4,756.7	220.5	-----	387.2	Yes	



(a)



(b)

Figure 13.—Penetration results for 0.125-in. (nominal) small panels. (a) Penetration (1 = yes, 0 = no). (b) Exit velocity versus impact velocity.

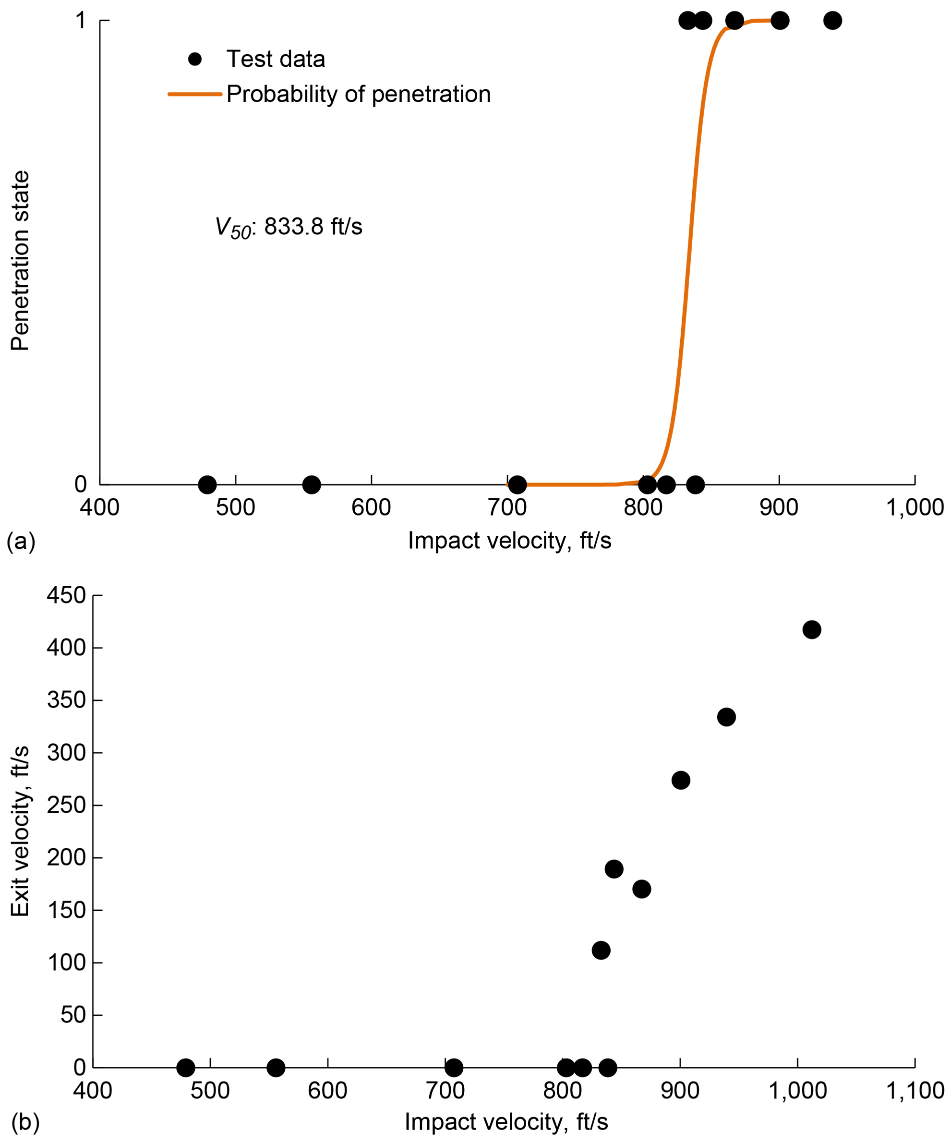


Figure 14.—Penetration results for 0.25-in. (nominal) small panels. (a) Penetration (1 = yes, 0 = no));. (b) Exit velocity versus impact velocity.

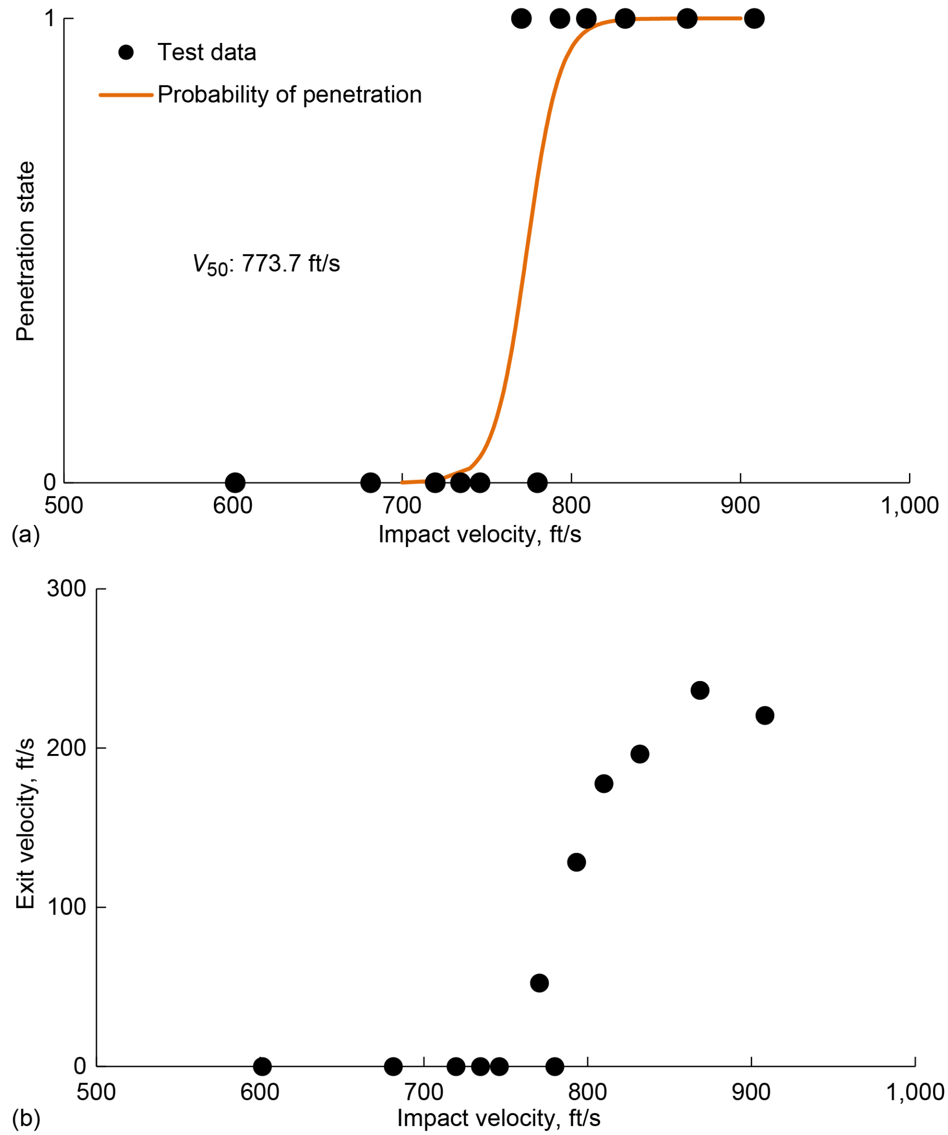


Figure 15.—Penetration results for 0.5-in. (nominal) small panels. (a) Penetration (1 = yes, 0 = no)); (b) Exit velocity versus impact velocity.

TABLE VI.—PENETRATION VELOCITY THRESHOLD (V_{50})

Panel thickness, in.	V_{50}, ft/s
0.125	728.7
0.250	833.8
0.500	773.7

Large Panel Impact Tests

Eight tests were conducted on the 0.125-in.-thick large heat-treated panels. Test conditions and results are shown in Appendix D. At least a portion of the blade penetrated in four of the tests, with perforation or tearing of the panel occurring in another three. Projectile position and orientation are provided in Table VIII, and linear and angular velocities are provided in Table I. No photogrammetry data was available in the first test due to improper synching of the two cameras. Photographs and deformation responses from the large panel tests are presented in Appendix D.

TABLE VII.—LARGE PANEL IMPACT TEST RESULTS

Test ID	Projectile mass, g	Penetration, Yes/No	Comment
LG1117	445.7	Yes	Photogrammetry camera data not available
LG1118	445.4	No	
LG1119	445.4	No	Blade root perforated panel
LG1120	449.2	No	Partial perforation of blade root
LG1121	447.6	Yes	Large hole in panel; blade fractured in two pieces, with one piece penetrating
LG1122	445.5	Yes	Large hole in panel; blade fractured in two pieces, with one piece penetrating
LG1123	448.9	No	
LG1124	446.5	Yes	Perforation initiated at root; large section of blade penetrated

TABLE VIII.—PROJECTILE POSITION AND ORIENTATION FROM LARGE PANEL TESTS

Test ID	X position in.	Y position, in.	Z position, in.	Roll, deg	Pitch, deg	Yaw, deg
LG1117	NA	NA	NA	NA	NA	NA
LG1118	–4.6	2.0	1.9	–2.2	62.9	2.7
LG1119	–5.0	1.9	1.7	–4.4	59.8	1.6
LG1120	5.0	2.0	1.9	0.2	61.6	0.4
LG1121	–5.1	1.9	1.6	–5.0	57.1	–0.6
LG1122	–5.2	1.9	2.1	1.0	58.4	4.6
LG1123	–4.8	1.8	2.1	–0.1	61.6	–0.3
LG1124	–4.7	1.8	2.1	3.1	64.5	2.5

TABLE IX.—PROJECTILE LINEAR AND ANGULAR VELOCITY FROM LARGE PANEL TESTS

Test ID	X velocity, ft/s	Y velocity, ft/s	Z velocity, ft/s	Roll velocity, deg/s	Pitch velocity, deg/s	Yaw velocity, deg/s
LG1117	1,080.0	NA	NA	NA	NA	NA
LG1118	802.0	10.3	–24.0	–4,488.5	9,806.6	3,203.4
LG1119	901.8	16.1	–30.8	–5,147.3	3,901.7	8,805.7
LG1120	877.1	10.3	–19.0	–8,12.7	10,276.6	–8,414.3
LG1121	998.8	9.4	–30.6	–6,572.1	2,171.5	6,639.3
LG1122	900.9	4.3	21.9	6,191.6	–2,488.7	6,950.5
LG1123	745.6	–1.4	–4.9	–3,688.5	7,402.5	7,012.4
LG1124	924.6	17.3	–32.8	–1,390.6	16,387.0	146.2

Concluding Remarks

This report provides results of instrumented impact tests on 15-in. square 410 stainless steel panels of various thicknesses impacted in a normal direction by a cylindrical projectile, and 24-in. square panels of the same materials impacted at a 45° angle by a more complex projectile having bladelike features. In the small panel tests, the 0.125-in.-thick panels had a well-defined ballistic threshold velocity, whereas there was some overlap in the thicker panels (0.25- and 0.5-in.). These results are similar to those obtained in previous studies on Al 2024, Ti-6Al-4V, and Inconel® 718 materials. As in the previous studies, it is postulated that irregular results obtained for the thicker materials may be due to a high sensitivity to frictional effects. The data provided in this report are useful for validation of numerical and empirical impact models for metals. Unique features of the data provided include extensive documentation of test procedures and results, traceable materials used for both material characterization and impact testing, and extensive instrumentation results. This report provides a set of data that can be used for developing and validating computational and empirical high strain rate and impact deformation and failure models. Although it is impossible to report all data in a single report, the data are archived and available from the NASA Glenn Ballistic Impact Laboratory.

Appendix A.—Material Certification Sheets

Material certification sheets for the 0.25 and 0.50 410 sheet thicknesses are shown in Figure A.1 and Figure A.2. The 0.125-in.-thick material was obtained from the same manufacturer, but certification sheets are not available.

ATI Flat Rolled Products

500 Green Street
Washington, PA 15301

Certificate of Test

Stephen Wolff - Director, Corporate Quality Assurance

Mill Information		Customer Information	
Cert Number	0139536-00	Name	ROLLED ALLOYS INC
Sales Order	50-124-489	PO	0120385-HOU
Cert Date	Mar-06-2015	PO Date	Dec-19-2014

Sold to: ROLLED ALLOYS INC
PO BOX 310
TEMPERANCE, MI 48182

Ship to: ROLLED ALLOYS INC.
9818 E. HARDY ROAD
HOUSTON, TX 77093

Material Information

"ATI 410"STAINLESS STEEL
PMP HOT ROLLED PLATE ANNEALED PICKLED COMMERCIAL CUT EDGE

ASTM-A-240-14 ASME-SA-240 ED 2013
AMS 5504M UNS S41000

Piece Information

Pcs	Gauge (in)	Width (in)	Length (in)	Heat #	Piece ID	Section Id	Lot #	Total Wt (lbs)
Item: 001	Cust-Id: 0015885 Cust-Job:			Govt-Contract-#: ScheduleB:		Govt-DO-Rating:		
1	.2500	96.0000	276.0000	954498	CC95736	---	444135	1974

Chemistry Testing

Element (wt %)	Requirements Min	Max	Final Heat Analysis 954498	Loc
C	.08	.15	.13	MI
MN	---	1.00	.47	MI
P	---	.040	.025	MI
S	---	.030	< .001	MI
SI	---	1.00	.47	MI
CR	11.50	13.50	12.10	MI
NI	---	.75	.25	MI
AL	---	.05	< .01	MI
MO	---	.50	.07	MI
CU	---	.50	.16	MI
N	---	.08	.01	MI
SN	---	.05	.01	MI

Rolled Alloys Quality Assurance
Approved
Date 03/17/2015

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TRACER # 0447328US

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Figure A.1.—Material certification for 0.25-in.-thick panels, certificate 0139536-00, 3/6/2015.

ATI Flat Rolled Products	**Certificate of Test**	Stephen Wolff - Director, Corporate Quality Assurance

	Mill Information	Customer Information
500 Green Street Washington, PA 15301	Cert Number 0139536-00	Name ROLLED ALLOYS INC
	Sales Order 50-124-489	PO 0120385-HOU
	Cert Date Mar-06-2015	PO Date Dec-19-2014

Chemistry Testing

ATI Flat Rolled Products performs chemical analysis by following techniques for testing locations TC,BN,MI, & LO:
C, S by combustion/infrared; N, O, H by inert fusion/thermal conductivity;
Mn, P, Si, Cr, Ni, Mo, Cu, Cb, Co, V, by WDXRF; Pb, Bi, Ag by GFAA;
B by OES; Al and Ti (>=0.10%) by WDXRF, otherwise by OES.

954498 - Material was produced by EF melting with AOD refining.

Mechanical Testing

		LOT 444135		LOT 444135	
Condition:		ANNEALED		AMS 5504 HT	
Direction:		TRANSVERSE		TRANSVERSE	
Temperature:		ROOM TEMP		ROOM TEMP	
Spec:					
Test Limit	Units	Result	Loc	Result	Loc
YIELD 0.2%	psi	49300.	TC	---	--
TENSILE	psi	83600.	TC	---	--
ELONGATION	%	28.	TC	---	--
RED OF AREA	%	68.	TC	---	--
HARDNESS	---	174. HBW	TC	43. HRC	TC
BEND	P/F	PASS	TC	---	--

When hardness is measured using the Brinell scale, the indentation measuring device is Type A.

Harenability -Lab heat treatment on test samples - 1750F (954C), holding at heat for 15 -30 minutes.

Mechanical Property Requirements

Condition:		ANNEALED		AMS 5504 HT	
Direction:		TRANSVERSE		TRANSVERSE	
Temperature:		ROOM TEMP		ROOM TEMP	
Spec:					
Test Limit	Units	Min	Max	Min	Max
YIELD 0.2%	psi	30000.	---	---	---
TENSILE	psi	65000.	95000.	---	---
ELONGATION	%	20.	---	---	---

HEAT # 954498
TRACER # 0447328US

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Figure A.1.—Continued.

ATI Flat Rolled Products	**Certificate of Test**	Stephen Wolff - Director, Corporate Quality Assurance
500 Green Street Washington, PA 15301	**Mill Information** Cert Number 0139536-00 Sales Order 50-124-489 Cert Date Mar-06-2015	**Customer Information** Name ROLLED ALLOYS INC PO 0120385-HOU PO Date Dec-19-2014

Mechanical Property Requirements

Condition:		ANNEALED		AMS 5504 HT	
Direction:		TRANSVERSE		TRANSVERSE	
Temperature:		ROOM TEMP		ROOM TEMP	
Spec:					
Test Limit	**Units**	**Min**	**Max**	**Min**	**Max**
RED OF AREA	%	---	---	---	---
HARDNESS	---	---	217. HBW	35. HRC	45. HRC
BEND	P/F	---	---	---	---

Metallography - General

Test ID	Result Name	Condition	Test Result	Loc	Requirements
444135	GRAIN SIZE	ANNEALED	9.	TC	---

Metallographic magnification: 100X; Etchant used HCL/PICRIC ACID

Certification Statements

Material was annealed at 1550F (843C) minimum for a time commensurate with thickness and furnace cooled.

ATI Flat Rolled Products does not use mercury in the testing or production of its products.

Material is of USA melt and manufacture.

No welds/weld repairs performed.

Knowingly and willfully recording any false, fictitious or fraudulent statement or entry on this document may be punished as a felony under Federal Statutes, including Federal Law, Title 18, Chapter 47.

EN 10204:2005 3.1 Certificate.

General Statements

TESTING WAS PERFORMED AT THE FOLLOWING LOCATIONS
MI = ATI FLAT ROLLED PRODUCTS; 950 Tenth Street; Midland, PA 15059
TC = ATI FLAT ROLLED PRODUCTS; 1300 Pacific Avenue; Natrona Heights, PA 15065
WARNING: Processing that makes fumes, dust, or solutions may cause lung disease. Please see Safety Data Sheet for further information which has been supplied to your Purchasing Department. For an additional copy, please refer to our website at:
www.atimetals.com/business/ATIFlatRolledProducts/Tools/Pages/Safety-and-MSDS.aspx

For access to online Certifications of Test, please register at MyATI.ATIMetals.com

This Certified Material Test Report is a true representation of the data on file. The reported results conform to the sales contract and specification(s) as set forth in ATI Flat Rolled Products order acknowledgement. This Certificate of Test may not be reproduced except in full without the written authorization of the company.

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Figure A.1.—Continued.

ATI Flat Rolled Products	**Certificate of Test**		Stephen Wolff - Director, Corporate Quality Assurance
	Mill Information		**Customer Information**
	Cert Number	0139536-00	Name ROLLED ALLOYS INC
500 Green Street Washington, PA 15301	Sales Order	50-124-489	PO 0120385-HOU
	Cert Date	Mar-06-2015	PO Date Dec-19-2014

General Statements

ATI Flat Rolled Products website contains listing of material produced, general technical and contact information, and current quality and company accreditations including but not limited to ISO-9001, AS-9100, Nadcap, and ISO/IEC 17025. Please visit us at www.atimetals.com

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Figure A.1.—Concluded.

ATI
Flat Rolled Products

500 Green Street
Washington, PA 15301

Certificate of Test

Stephen Wolff - Director, Corporate Quality Assurance

Mill Information		Customer Information	
Cert Number	0140146-00	Name	ROLLED ALLOYS INC
Sales Order	50-015-031	PO	0120709-HOU
Cert Date	Mar-24-2015	PO Date	Jan-02-2015

Sold to: ROLLED ALLOYS INC
PO BOX 310
TEMPERANCE, MI 48182

Ship to: ROLLED ALLOYS INC.
9818 E. HARDY ROAD
HOUSTON, TX 77093

Material Information

"ATI 410" STAINLESS STEEL
PMP HOT ROLLED PLATE ANNEALED PICKLED COMMERCIAL CUT EDGE

ASTM-A-240-14 ASME-SA-240 ED 2013
AMS 5504M UNS S41000

Piece Information

Pcs	Gauge (in)	Width (in)	Length (in)	Heat #	Piece ID	Section Id	Lot #	Total Wt (lbs)
Item: 004	Cust-Id: 0015891 Cust-Job:			Govt-Contract-#: ScheduleB:			Govt-DO-Rating:	
1	.5000	96.0000	270.0000	983372	CD01986	---	444929	3749

Chemistry Testing

Element (wt %)	Requirements Min	Max	Final Heat Analysis 983372	Loc
C	.08	.15	.13	MI
MN	---	1.00	.51	MI
P	---	.040	.025	MI
S	---	.030	< .001	MI
SI	---	1.00	.61	MI
CR	11.50	13.50	11.95	MI
NI	---	.75	.24	MI
AL	---	.05	< .01	MI
MO	---	.50	.05	MI
CU	---	.50	.15	MI
N	---	.08	.01	MI
SN	---	.05	.01	MI

Rolled Alloys Quality Assurance
Approved ______
Date 04/01/15

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Figure A.2.—Material certification for 0.50-in.-thick panels, certificate 0140146-00, 1/2/2015.

ATI
Flat Rolled Products

500 Green Street
Washington, PA 15301

Certificate of Test

Stephen Wolff - Director, Corporate Quality Assurance

Mill Information		Customer Information	
Cert Number	0140146-00	Name	ROLLED ALLOYS INC
Sales Order	50-015-031	PO	0120709-HOU
Cert Date	Mar-24-2015	PO Date	Jan-02-2015

Chemistry Testing

ATI Flat Rolled Products performs chemical analysis by following techniques
for testing locations TC,BN,MI, & LO:
C, S by combustion/infrared; N, O, H by inert fusion/thermal conductivity;
Mn, P, Si, Cr, Ni, Mo, Cu, Cb, Co, V, by WDXRF; Pb, Bi, Ag by GFAA;
B by OES; Al and Ti (>=0.10%) by WDXRF, otherwise by OES.

983372 - Material was produced by EF melting with AOD refining.

Mechanical Testing

		LOT 444929		LOT 444929	
Condition:		ANNEALED		AMS 5504 HT	
Direction:		TRANSVERSE		TRANSVERSE	
Temperature:		ROOM TEMP		ROOM TEMP	
Spec:					
Test Limit	Units	Result	Loc	Result	Loc
YIELD 0.2%	psi	47400.	TC	---	--
TENSILE	psi	78400.	TC	---	--
ELONGATION	%	38.	TC	---	--
RED OF AREA	%	76.	TC	---	--
HARDNESS	---	163. HBW	TC	38. HRC	TC
BEND	P/F	PASS	TC	---	--

When hardness is measured using the Brinell scale, the indentation measuring device is Type A.

Harenability -Lab heat treatment on test samples - 1750F (954C), holding at heat for 15 -30 minutes.

Mechanical Property Requirements

Condition:		ANNEALED		AMS 5504 HT	
Direction:		TRANSVERSE		TRANSVERSE	
Temperature:		ROOM TEMP		ROOM TEMP	
Spec:					
Test Limit	Units	Min	Max	Min	Max
YIELD 0.2%	psi	30000.	---	---	---
TENSILE	psi	65000.	95000.	---	---
ELONGATION	%	20.	---	---	---

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Figure A.2.—Continued.

ATI Flat Rolled Products	**Certificate of Test**	Stephen Wolff - Director, Corporate Quality Assurance
500 Green Street Washington, PA 15301	**Mill Information**	**Customer Information**
	Cert Number 0139536-00	Name ROLLED ALLOYS INC
	Sales Order 50-124-489	PO 0120385-HOU
	Cert Date Mar-06-2015	PO Date Dec-19-2014

Mechanical Property Requirements

Condition:		ANNEALED		AMS 5504 HT	
Direction:		TRANSVERSE		TRANSVERSE	
Temperature:		ROOM TEMP		ROOM TEMP	
Spec:					
Test Limit	**Units**	**Min**	**Max**	**Min**	**Max**
RED OF AREA	%	---	---	---	---
HARDNESS	---	---	217. HBW	35. HRC	45. HRC
BEND	P/F	---	---	---	---

Metallography - General

Test ID	Result Name	Condition	Test Result	Loc	Requirements
444135	GRAIN SIZE	ANNEALED	9.	TC	---
Metallographic magnification: 100X; Etchant used HCL/PICRIC ACID					

Certification Statements

Material was annealed at 1550F (843C) minimum for a time commensurate with thickness and furnace cooled.

ATI Flat Rolled Products does not use mercury in the testing or production of its products.

Material is of USA melt and manufacture.

No welds/weld repairs performed.

Knowingly and willfully recording any false, fictitious or fraudulent statement or entry on this document may be punished as a felony under Federal Statutes, including Federal Law, Title 18, Chapter 47.

EN 10204:2005 3.1 Certificate.

General Statements

TESTING WAS PERFORMED AT THE FOLLOWING LOCATIONS
MI = ATI FLAT ROLLED PRODUCTS; 950 Tenth Street; Midland, PA 15059
TC = ATI FLAT ROLLED PRODUCTS; 1300 Pacific Avenue; Natrona Heights, PA 15065
WARNING: Processing that makes fumes, dust, or solutions may cause lung disease. Please see Safety Data Sheet for further information which has been supplied to your Purchasing Department. For an additional copy, please refer to our website at:
www.atimetals.com/business/ATIFlatRolledProducts/Tools/Pages/Safety-and-MSDS.aspx

For access to online Certifications of Test, please register at MyATI.ATIMetals.com

This Certified Material Test Report is a true representation of the data on file. The reported results conform to the sales contract and specification(s) as set forth in ATI Flat Rolled Products order acknowledgement. This Certificate of Test may not be reproduced except in full without the written authorization of the company.

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Figure A.2.—Continued.

ATI Flat Rolled Products	Certificate of Test		Stephen Wolff - Director, Corporate Quality Assurance
	Mill Information		**Customer Information**
	Cert Number	0139536-00	Name: ROLLED ALLOYS INC
500 Green Street Washington, PA 15301	Sales Order	50-124-489	PO: 0120385-HOU
	Cert Date	Mar-06-2015	PO Date: Dec-19-2014

General Statements

ATI Flat Rolled Products website contains listing of material produced, general technical and contact information, and current quality and company accreditations including but not limited to ISO-9001, AS-9100, Nadcap, and ISO/IEC 17025. Please visit us at www.atimetals.com

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Figure A.2.—Concluded.

Appendix B.—Heat Treatment Results

The following sheet (Figure B.1) certifies the material hardness after heat treatment.

Order ID 375650 | Load 1 | Code 4

P:(614) 247-2155
F:

Ohio State University COD
Columbus OH 43210
PO:0214058SUS
PL: In by:Pitt Ohio

Req:04/06/15 Mon

Entered: 03/30/15 05:17 PM
Printed: 04/01/15 10:21 AM

Type: Standard Pg:1

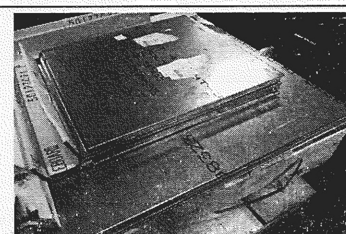
#	Qty	Part Number / Part Name / Part Description	Ea Wt.	Line Wt.
1	12	RF013936233244880-TEM/12 410 SS Mat'l Plates Harden and temper per customer instructions.	0	343
2	8	RF013936233244880-TEM/15	0	0
3	2	RF013936233244880-TEM/13	0	0
4	2	RF013936233244880-TEM/14	0	0
	24	Order Qty: 24 Order Net: 343 — Load Qty: 24 Load Net: 343		343

Serial/Lot # — **Serial Number**

Heat # 983233

CONTAINERS	#	Qty	Gross Wt.	Tare	Net	ID
Skid	12	24	363	20	343	7350

INSPECTION	Scale	Min	Max
none	RA	.	.



PROCESS ID 410 flat 280/320 BHN

PROCESS STEPS

1 — 1 **Comments** — Gr: 000
COMMENT: Rewrite all instructions that were written on parts by customer in high temperature paint marker.
PROCESS: A.H
See comments above.

2 — 1 **Fixture** — Gr: 000
PROCESS: Fixture on edge in baskets.

3 — 1 **Vac Variable** — Gr: 000
PROCESS: 2-BAR PRESSURE QUENCH

4 **Track In** — 1 **V/H - air** — Gr: Vac Air
PROCESS: Vacuum harden as follows:
a) Pre-heat at 1550 F for 30 minutes to 1 hour.
b) Austenitize at 1800 F to 1850 F for 30 minutes to 1 hour.
Operator: [illegible] Equipment 910 Time ½ x ½ Temp 1550/1800
TrackOut
Operator CN

5 — 1 **In-proc Insp** — Gr: 000
PROCESS: Inspect "as quenched" Rockwell "C" hardness and record below:
42 RC Inspected by: [illegible] Date: 4/6

6 **Track In** — 1 **Vac temper** — Gr: Vactemp
COMMENT: 904 only.
PROCESS: Vacuum temper at 1150 F for 2 hours and cool to room temperature.
Operator: [illegible] Equipment 904 Time 2 Temp 1150
TrackOut
Operator CN

EHT Form-001 08/23/02

Figure B.1.—Heat treatment certification.

Order ID	Load	Code
375650	**1**	**4**

P:(614) 247-2155
F:

Ohio State University COD
Columbus OH 43210
PO:0214058SUS
PL: In by:Pitt Ohio

Req:04/06/15 Mon

PAGE #:2

PROCESS STEPS

7 **Track In** 1 **Final Inspec** Gr: 001

PROCESS: Final Inspection Results:

TrackOut-Final Inspe

Final - Approval:____________ Date:___4/7/15___

Additional Operations:

Operation / Temp / Time / Equip / Operator / Date

EHT Form-001 08/23/02

Figure B.1.—Concluded.

Appendix C.—Small Panel Deformations

Photographs and deformation responses from the small panel tests are given in Figure C.1 to Figure C.104.

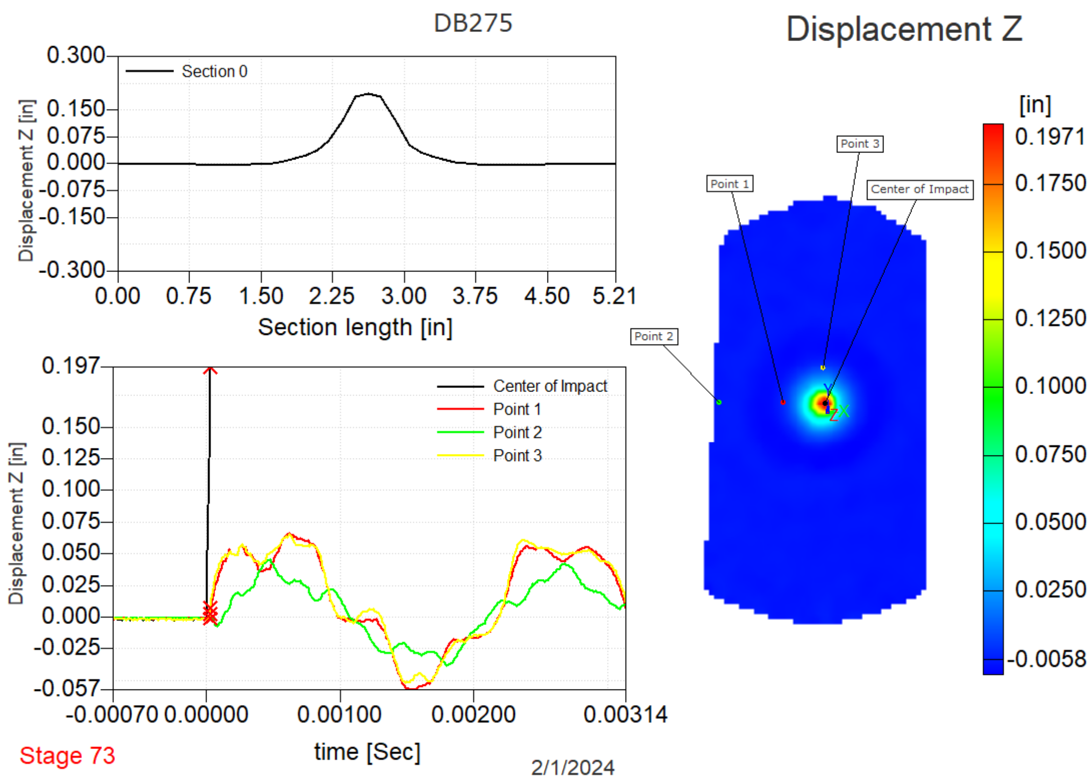


Figure C.1.—DB275: Out-of-plane displacement at time of maximum displacement.

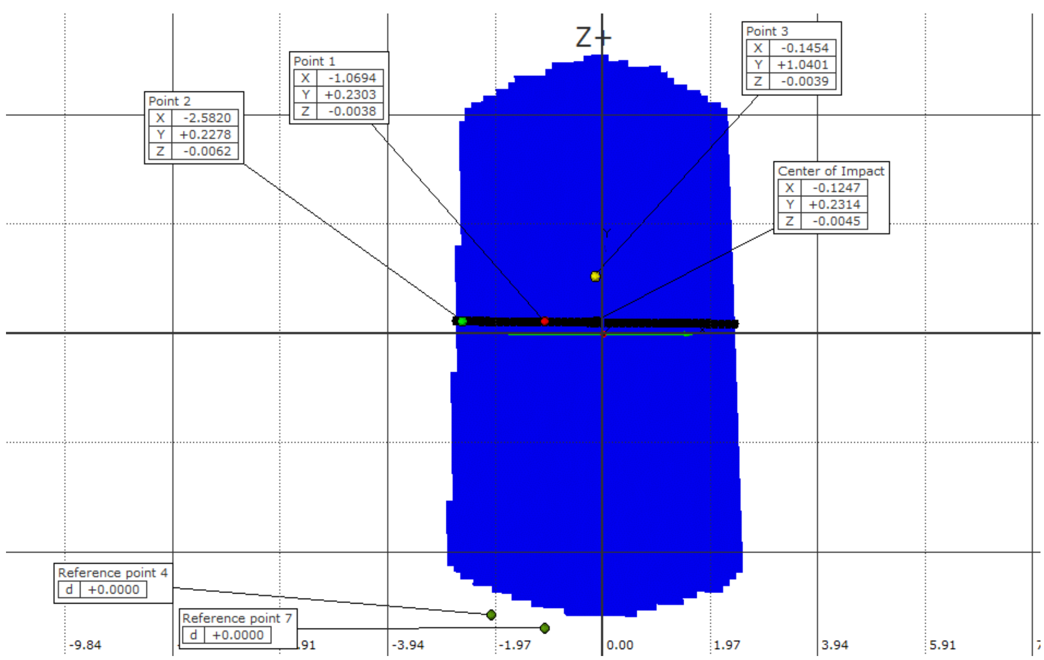


Figure C.2.—DB275: Point locations.

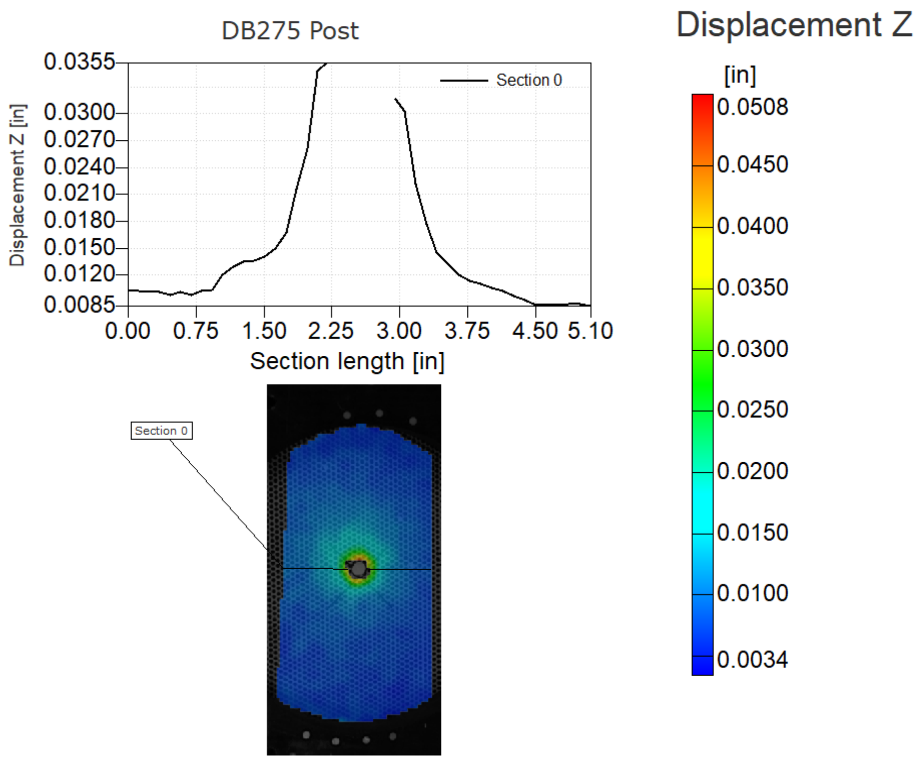


Figure C.3.—DB275: Posttest panel deformations.

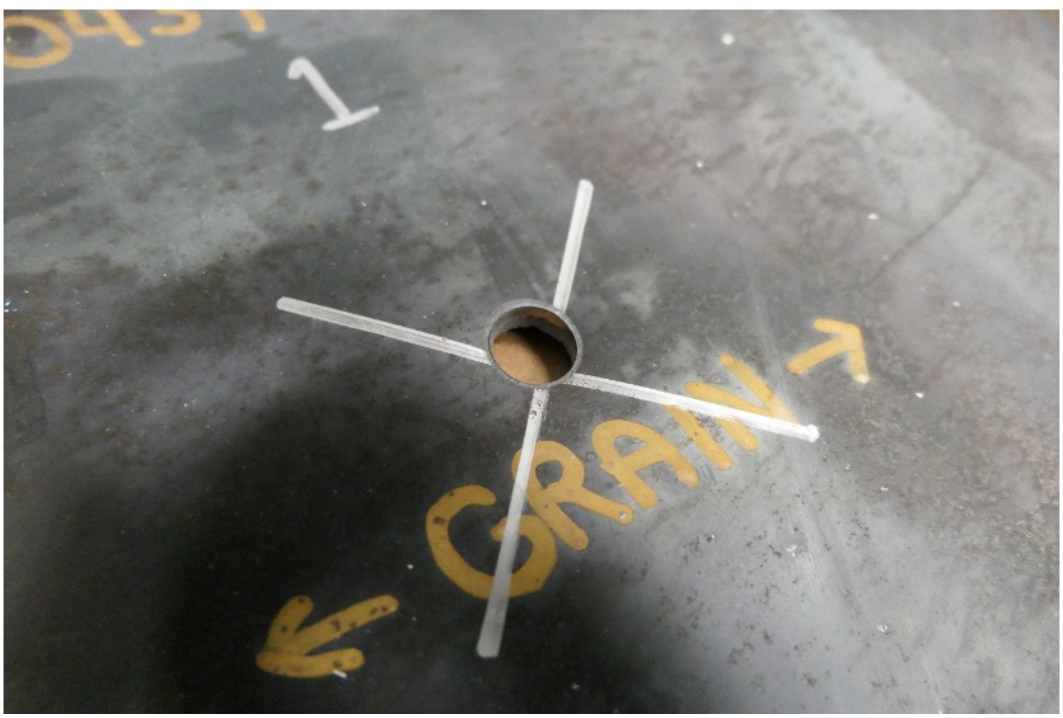


Figure C.4.—DB275: Posttest front view.

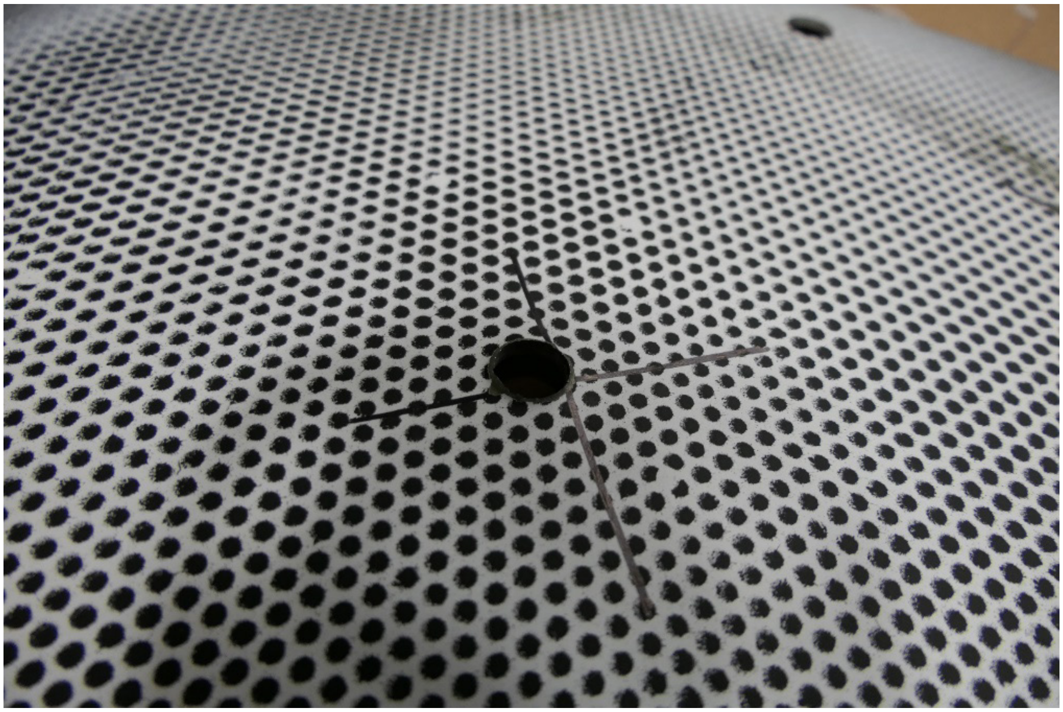


Figure C.5.—DB275: Posttest rear view.

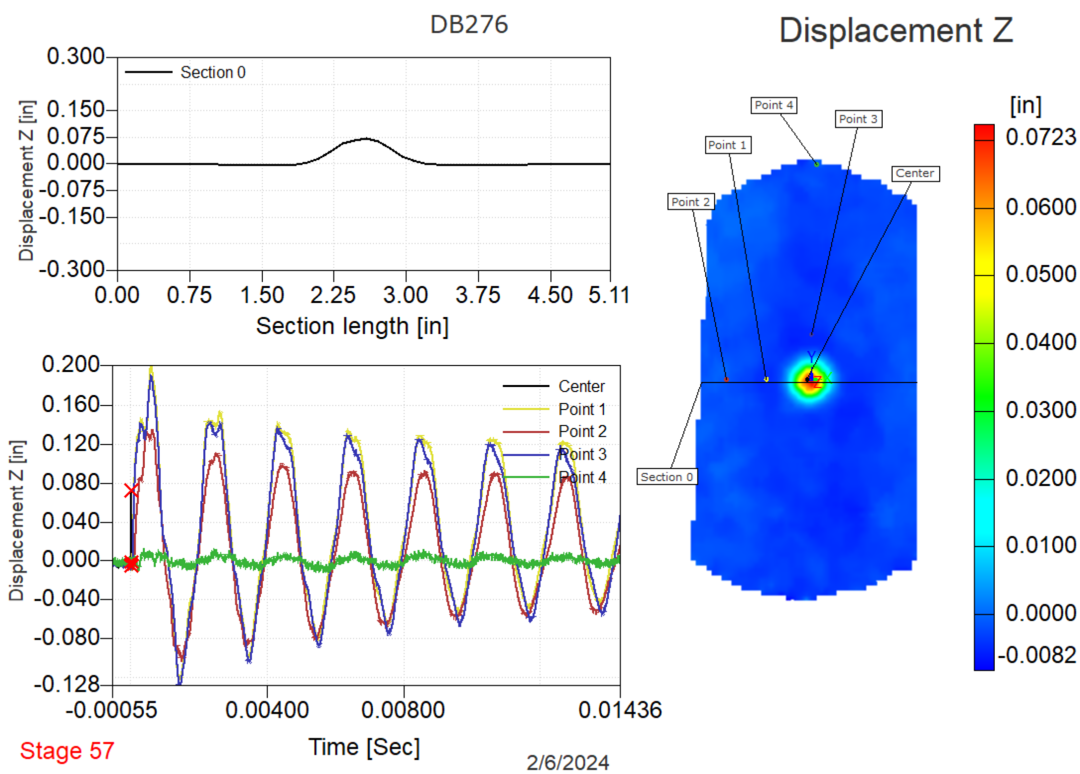


Figure C.6.—DB276: Out-of-plane displacement at time of maximum displacement.

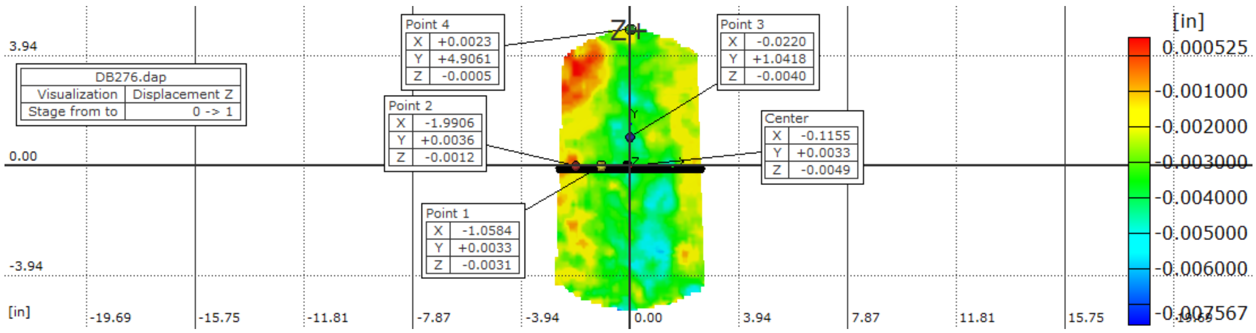


Figure C.7.—DB275: Point locations.

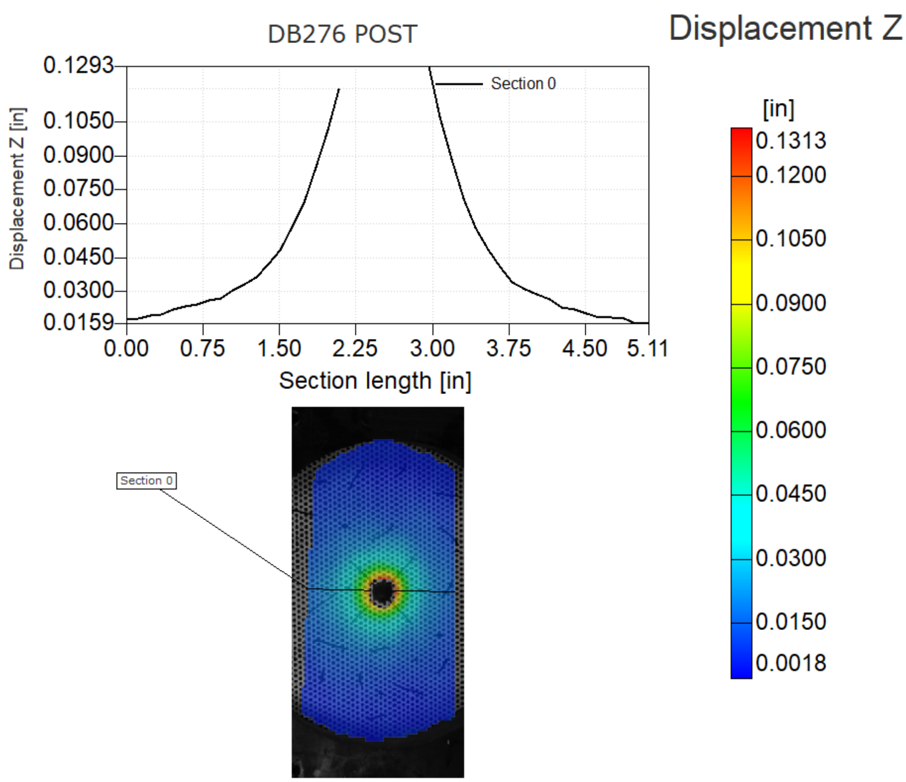


Figure C.8.—DB276: Posttest panel deformations.

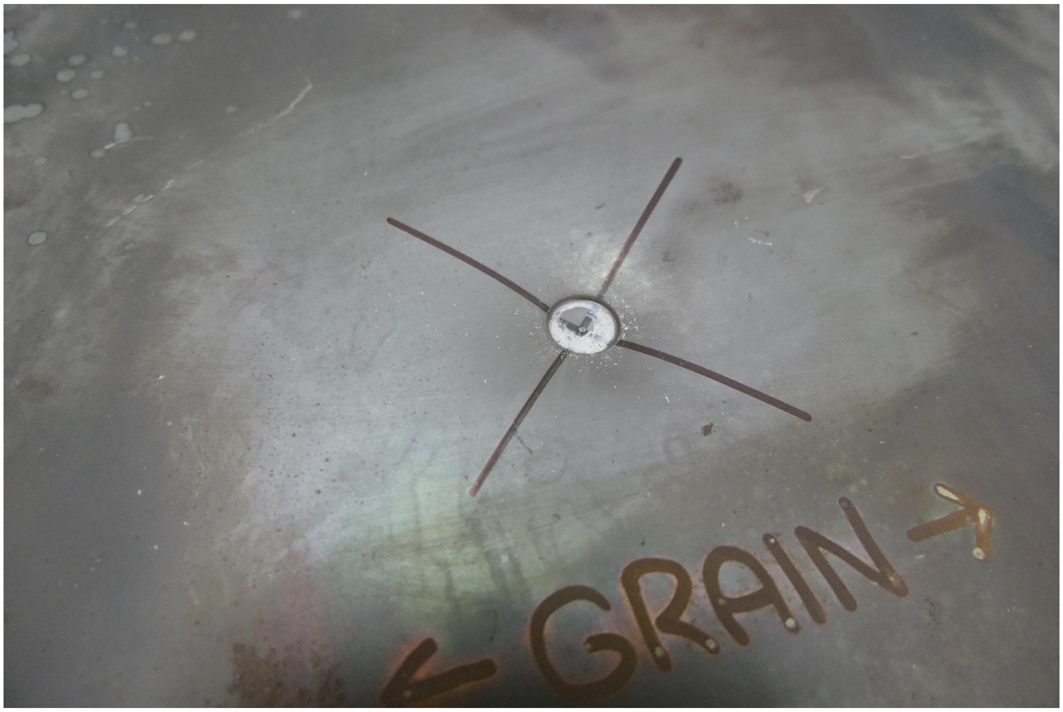


Figure C.9.—DB276: Posttest front view.

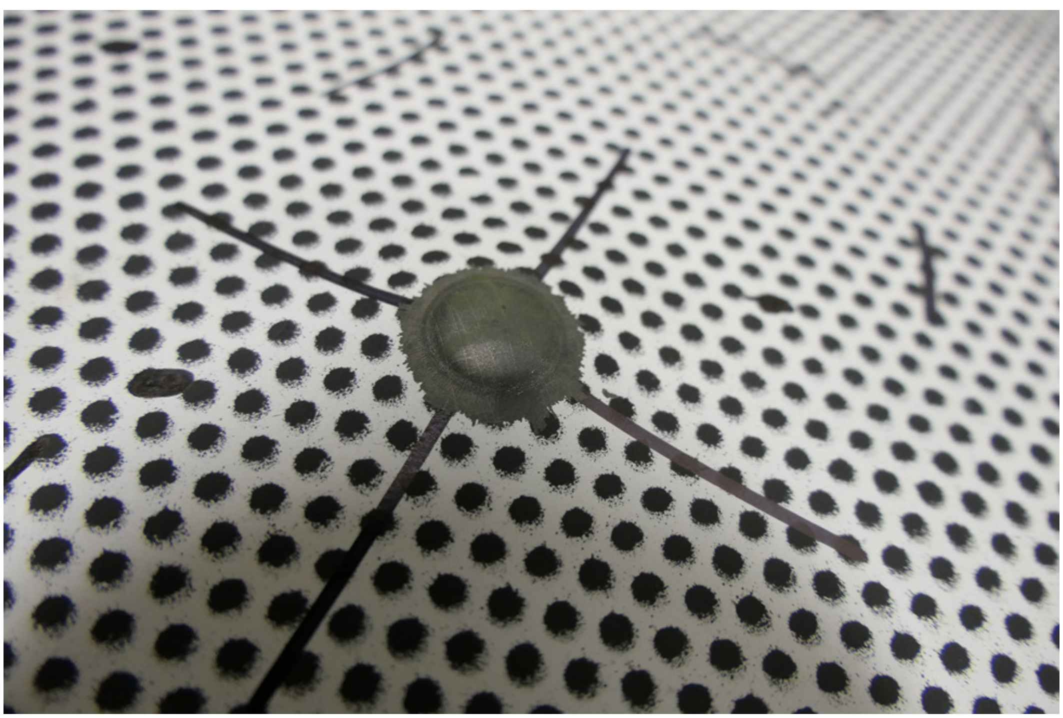


Figure C.10.—DB276: Posttest rear view.

Figure C.11.—DB277: Posttest front view.

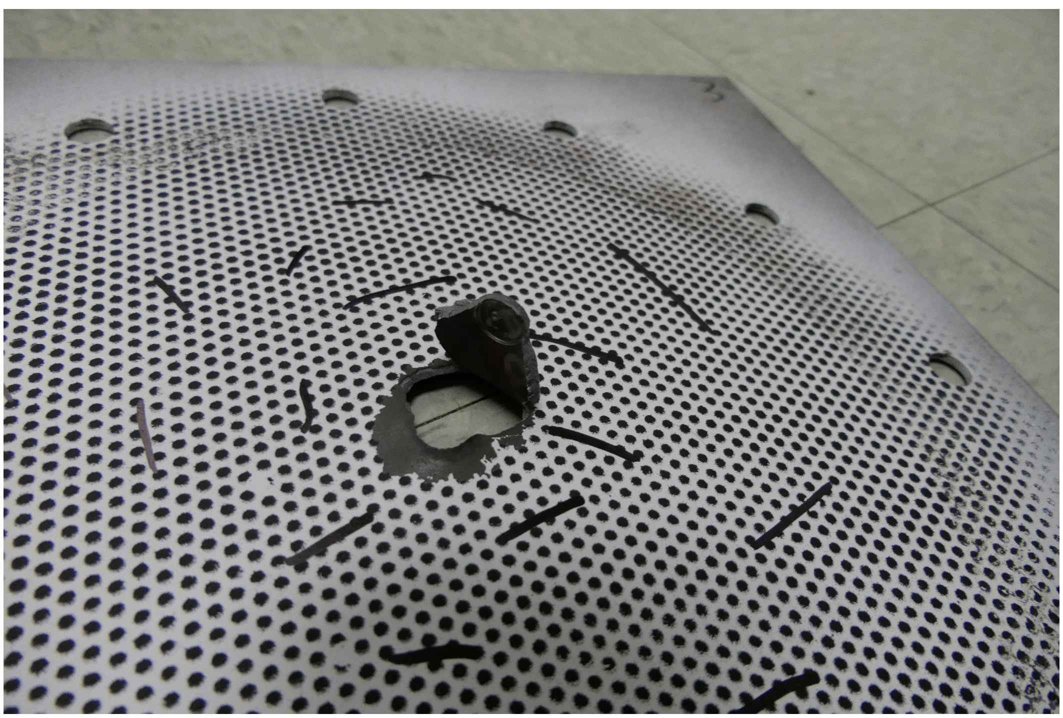


Figure C.12.—DB277: Posttest rear view.

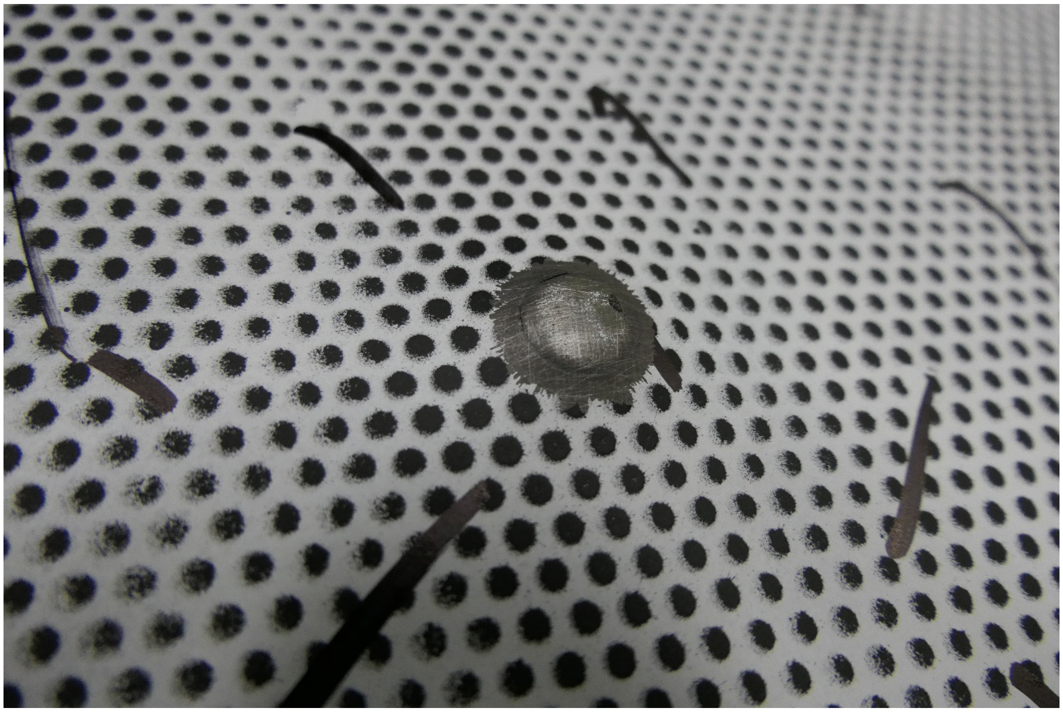


Figure C.13.—DB278: Posttest rear view.

Figure C.14.—DB278: Posttest front view.

Figure C.15.—DB279: Posttest front view.

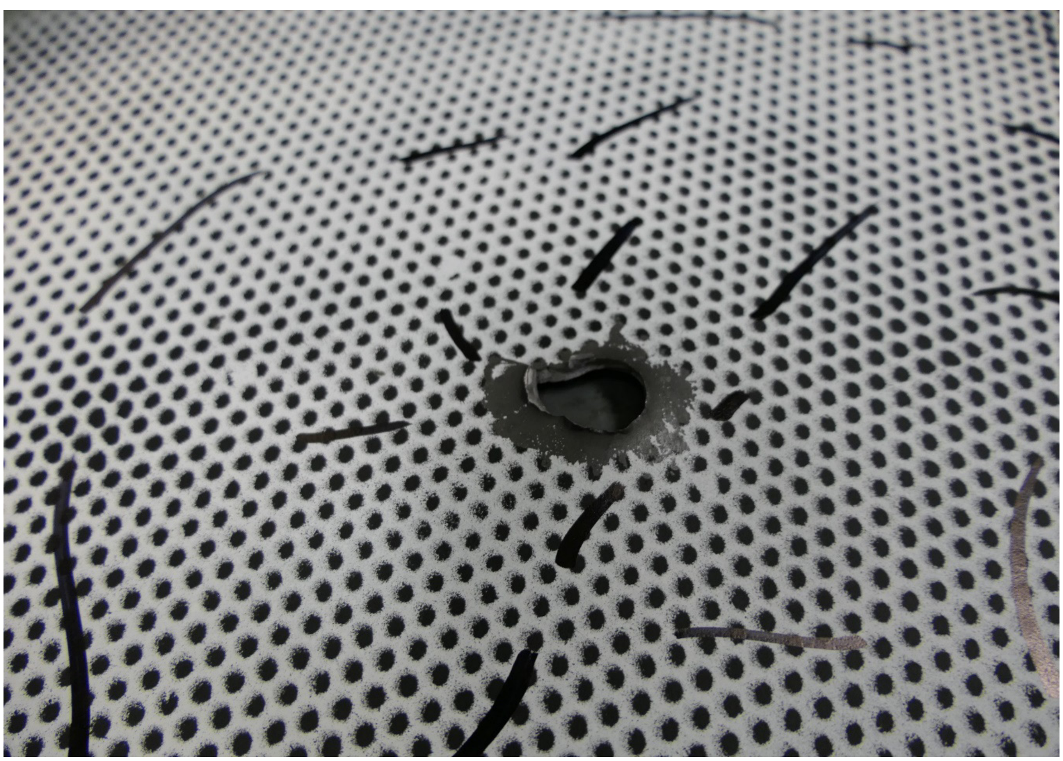


Figure C.16.—DB279: Posttest rear view.

Figure C.17.—DB280: Posttest front view.

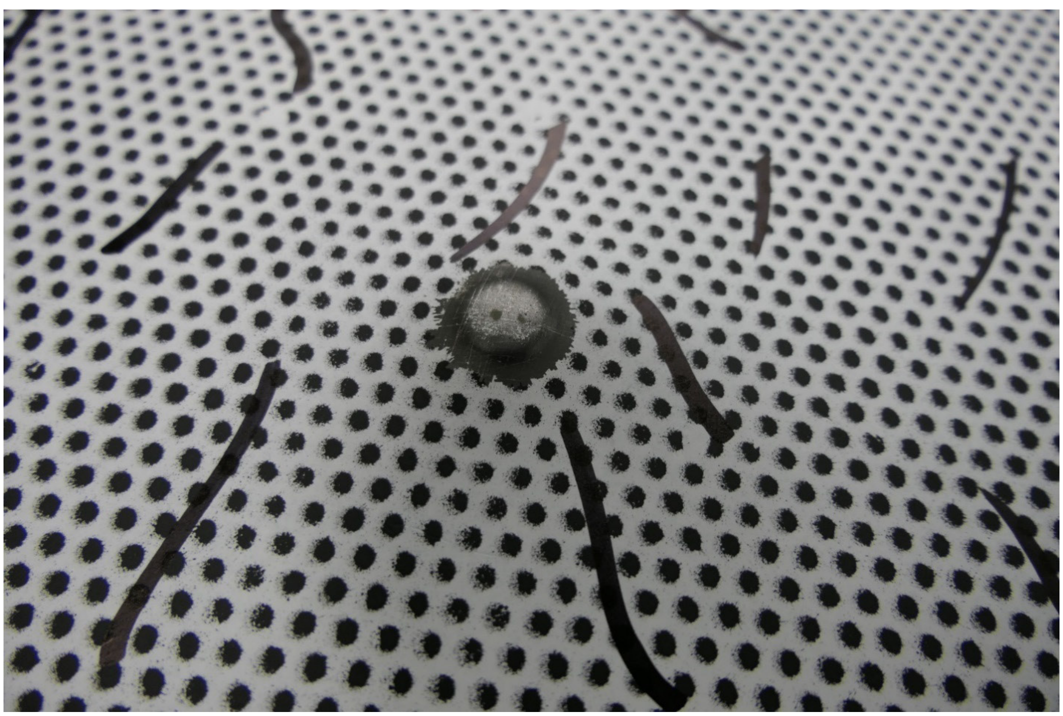


Figure C.18.—DB280: Posttest rear view.

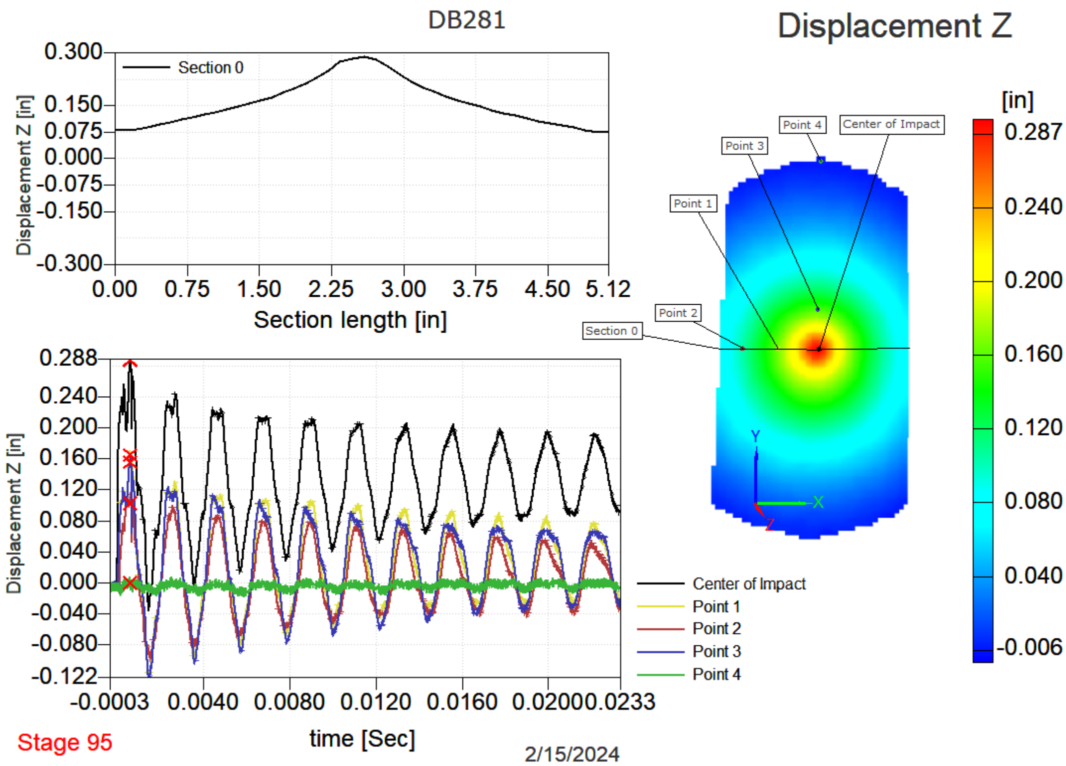


Figure C.19.—DB281: Out-of-plane displacement at time of maximum displacement.

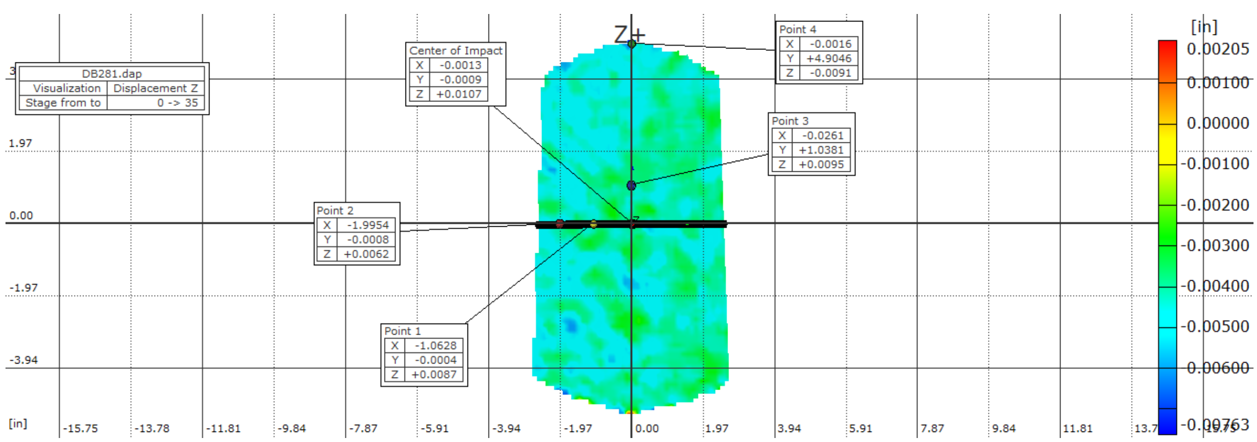


Figure C.20.—DB281: Point locations.

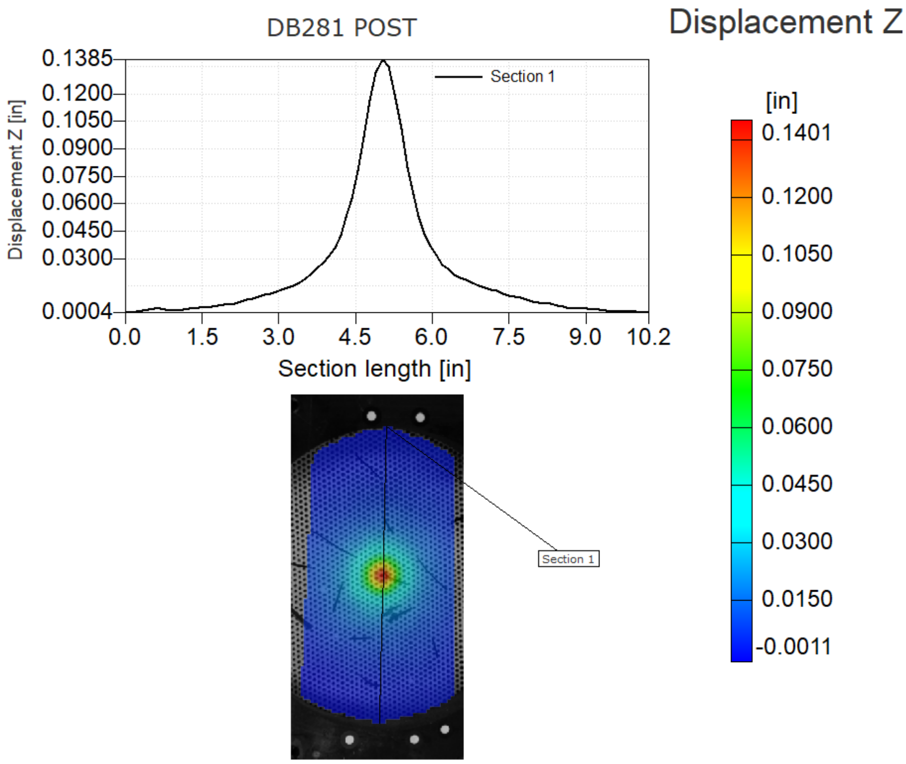


Figure C.21.—DB281: Posttest panel deformation.

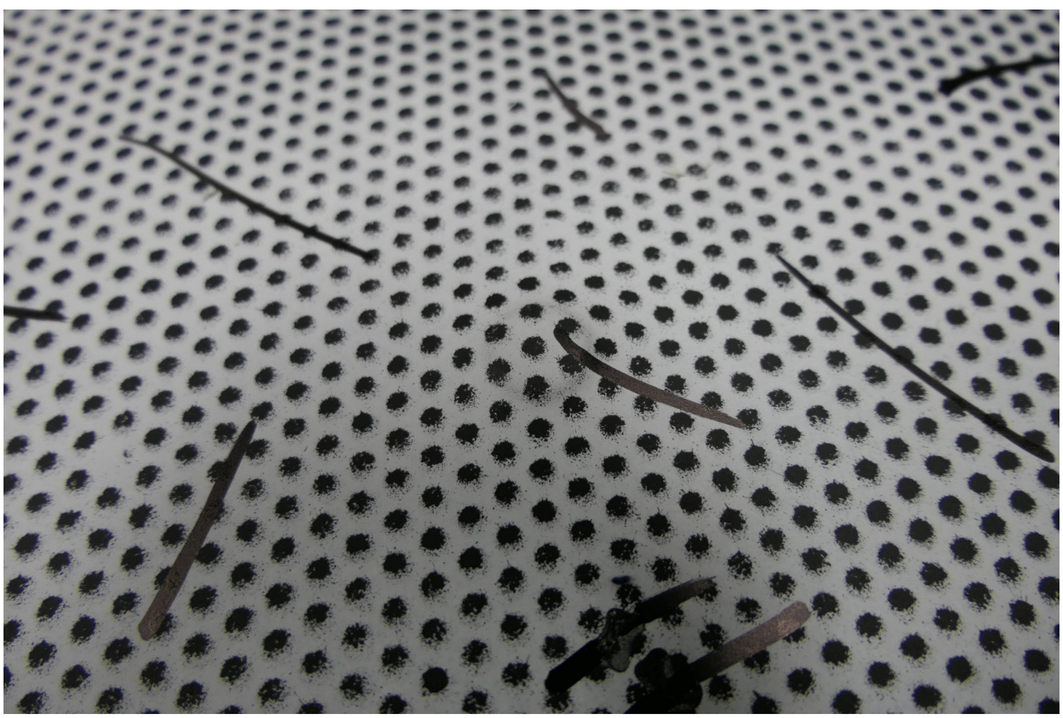


Figure C.22.—DB281: Posttest rear view.

Figure C.23.—DB281: Posttest front view.

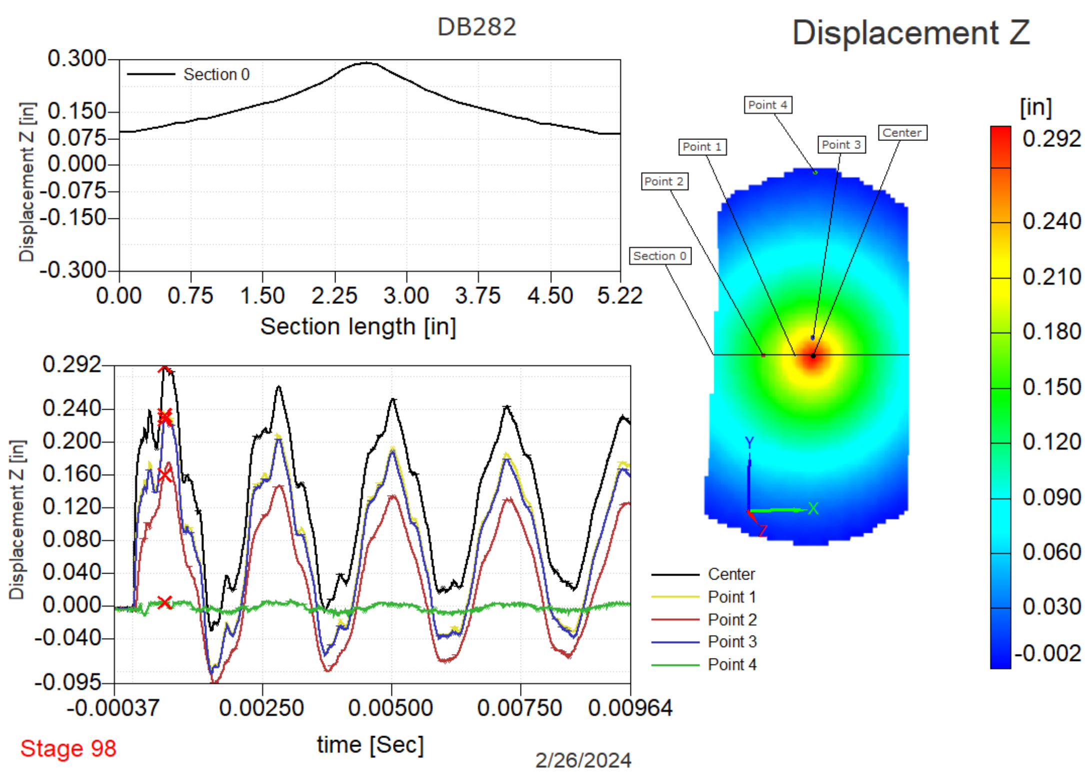


Figure C.24.—DB282: Out-of-plane displacement at time of maximum displacement.

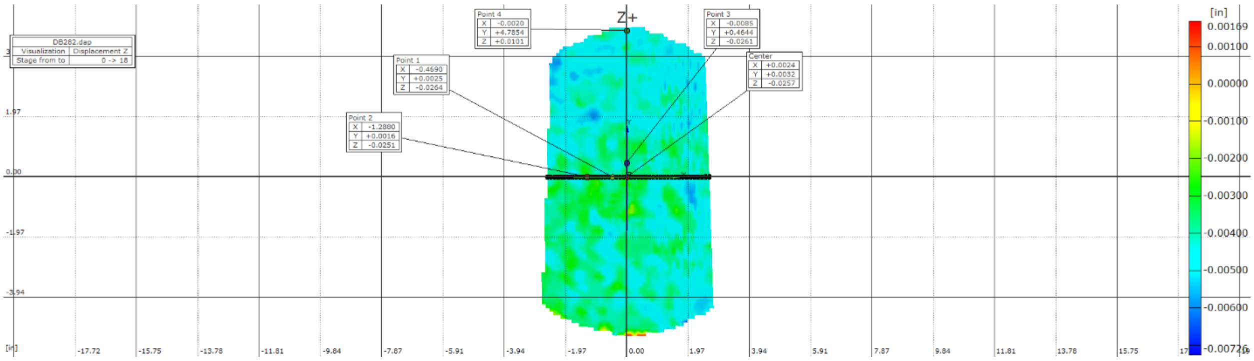


Figure C.25.—DB282: Point locations.

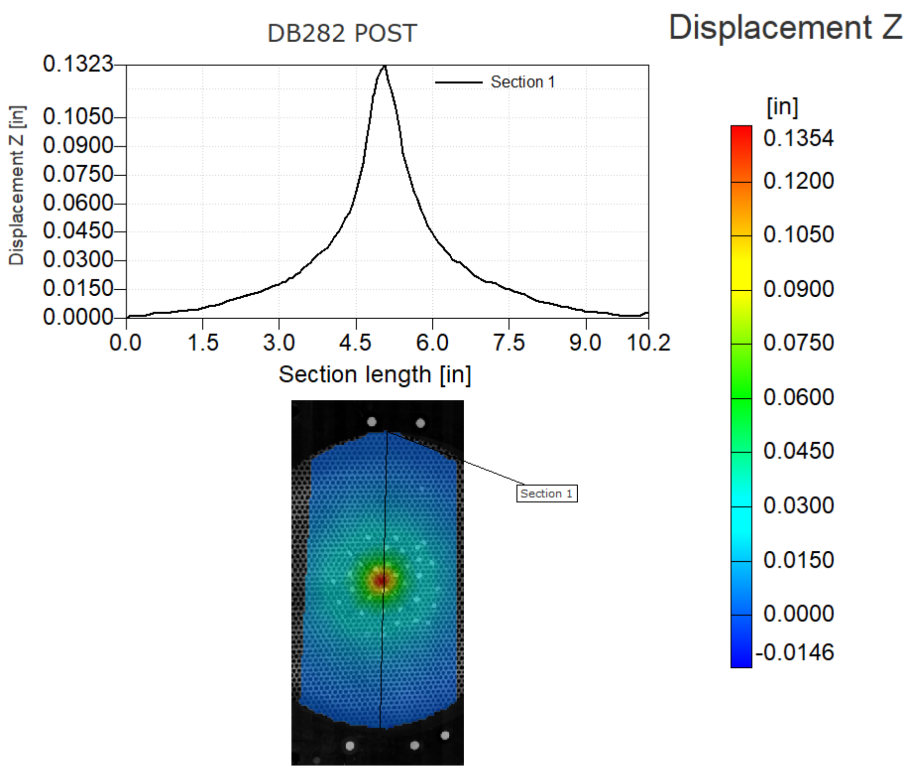


Figure C.26.—DB282: Posttest panel deformation.

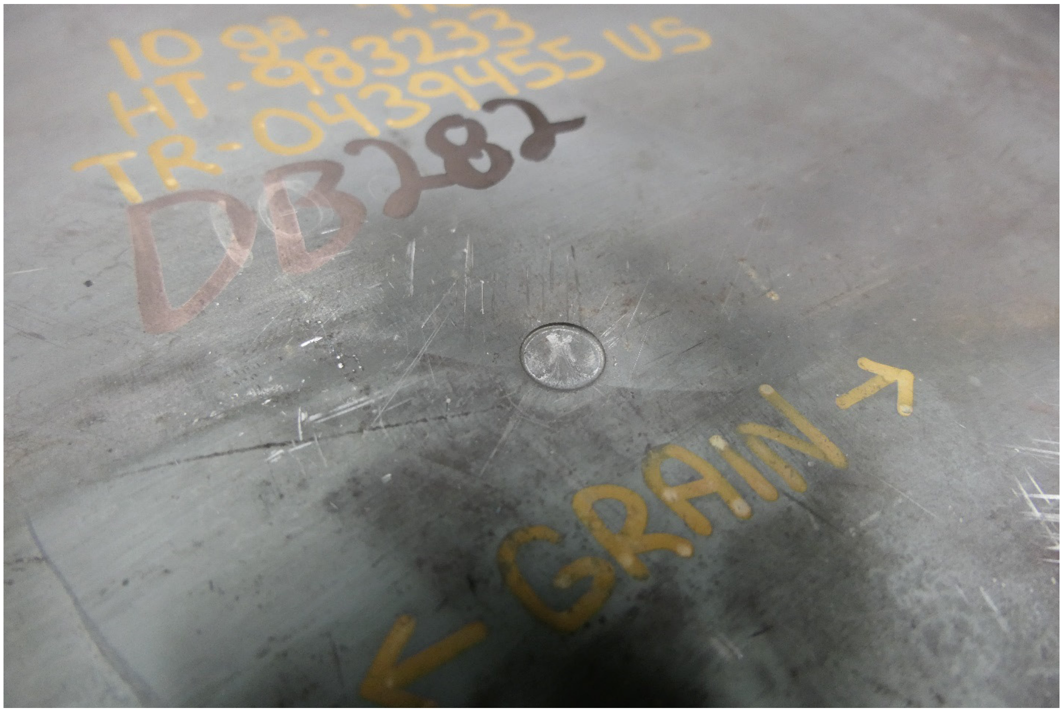


Figure C.27.—DB282: Posttest rear view.

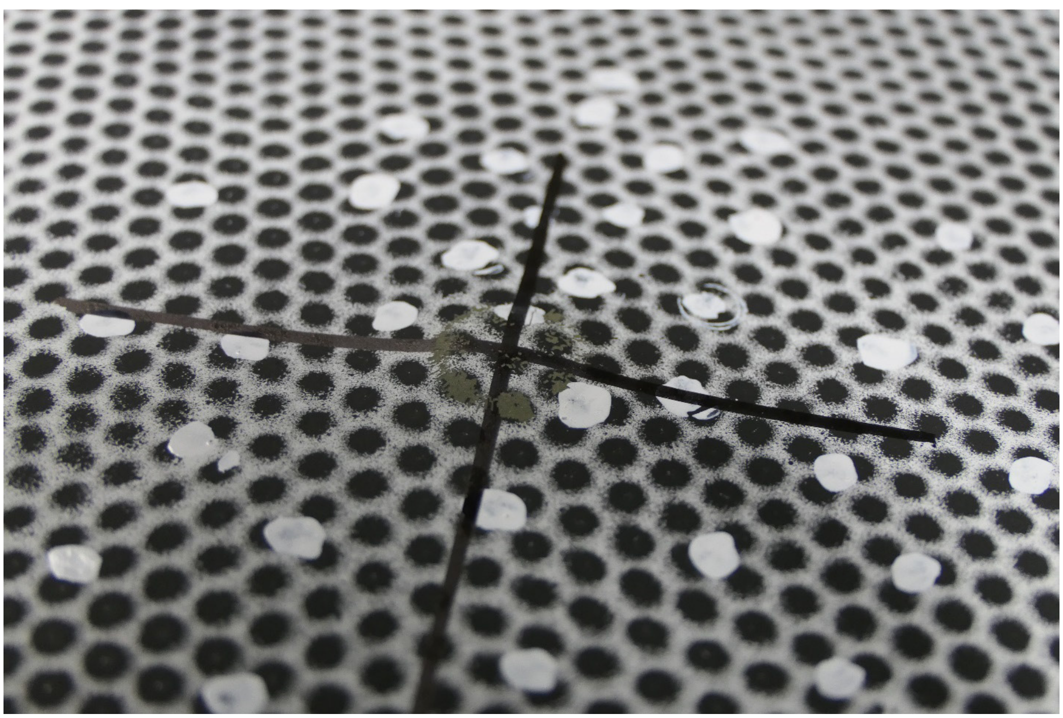


Figure C.28.—DB282: Posttest rear view.

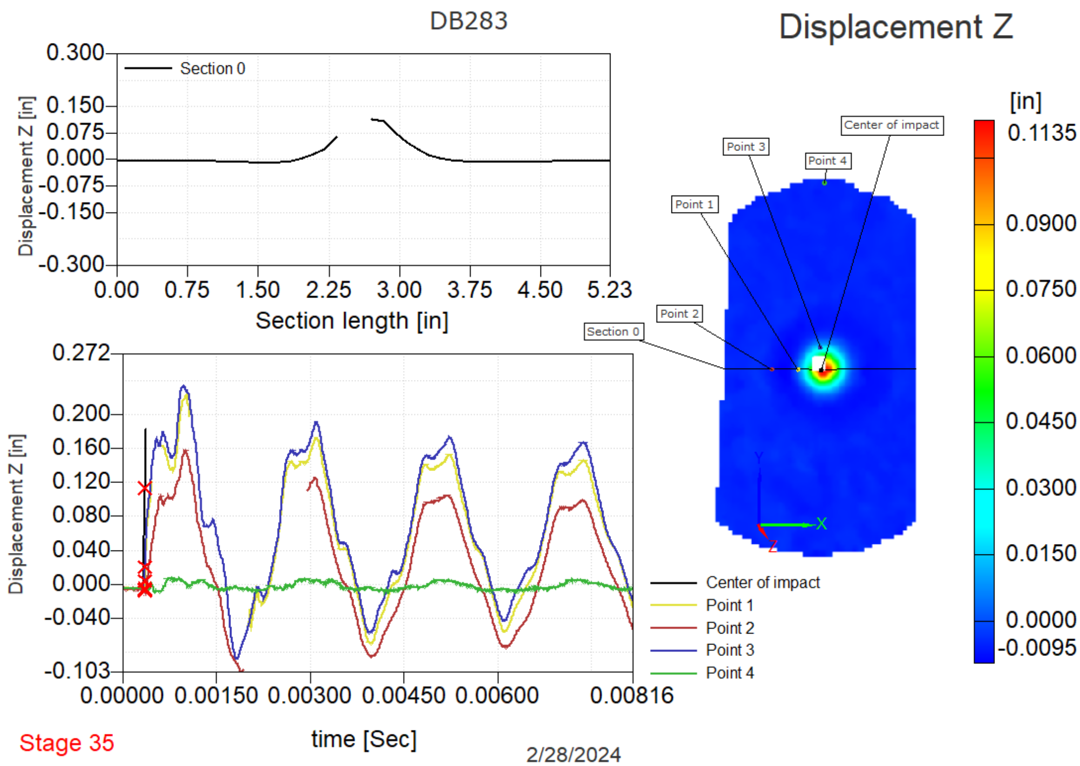


Figure C.29.—DB283: Out-of-plane displacement at time of maximum displacement.

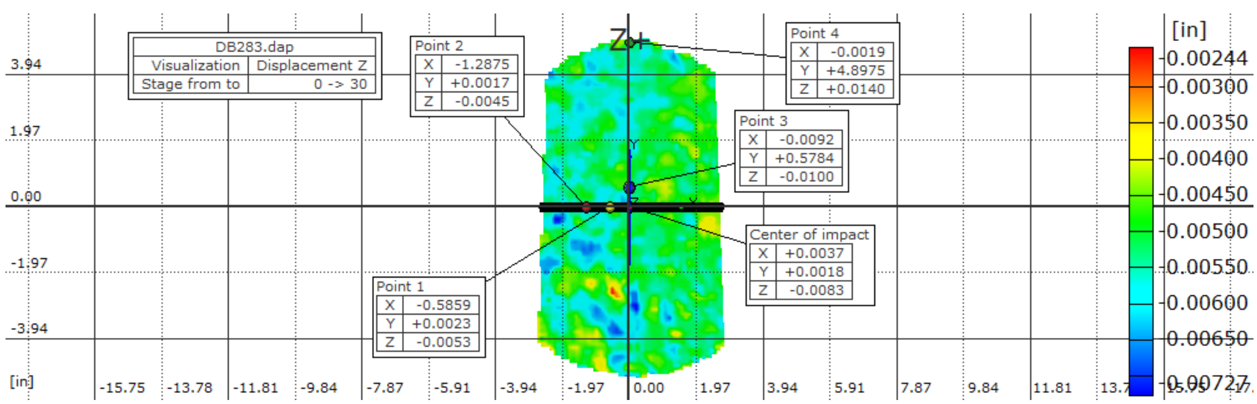


Figure C.30.—DB283: Point locations.

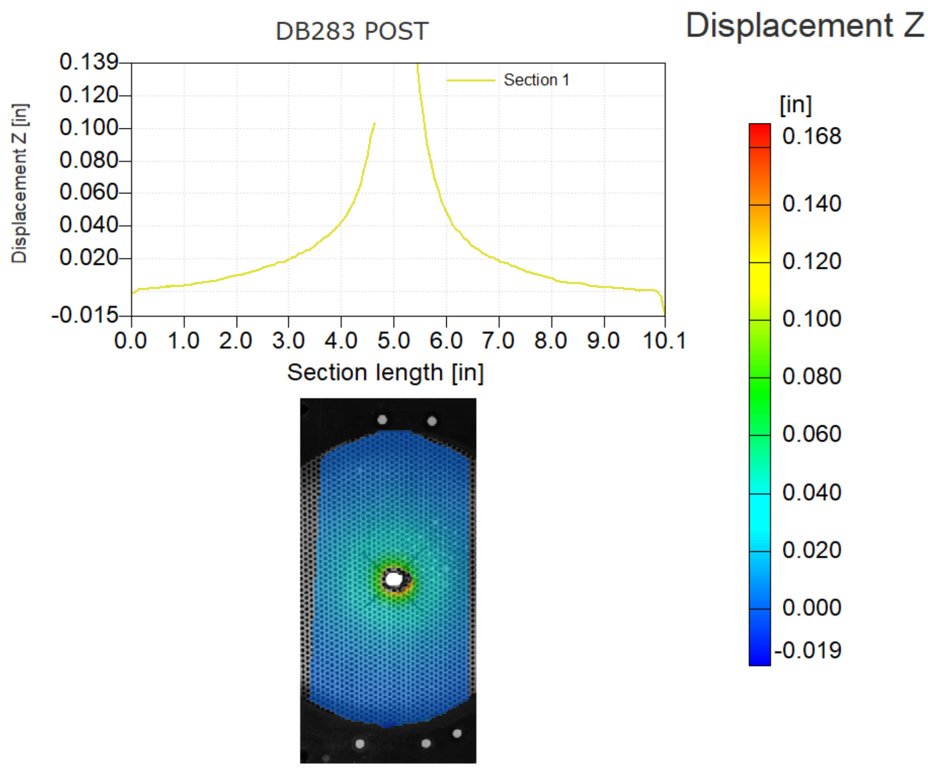


Figure C.31.—DB283: Posttest panel deformation.

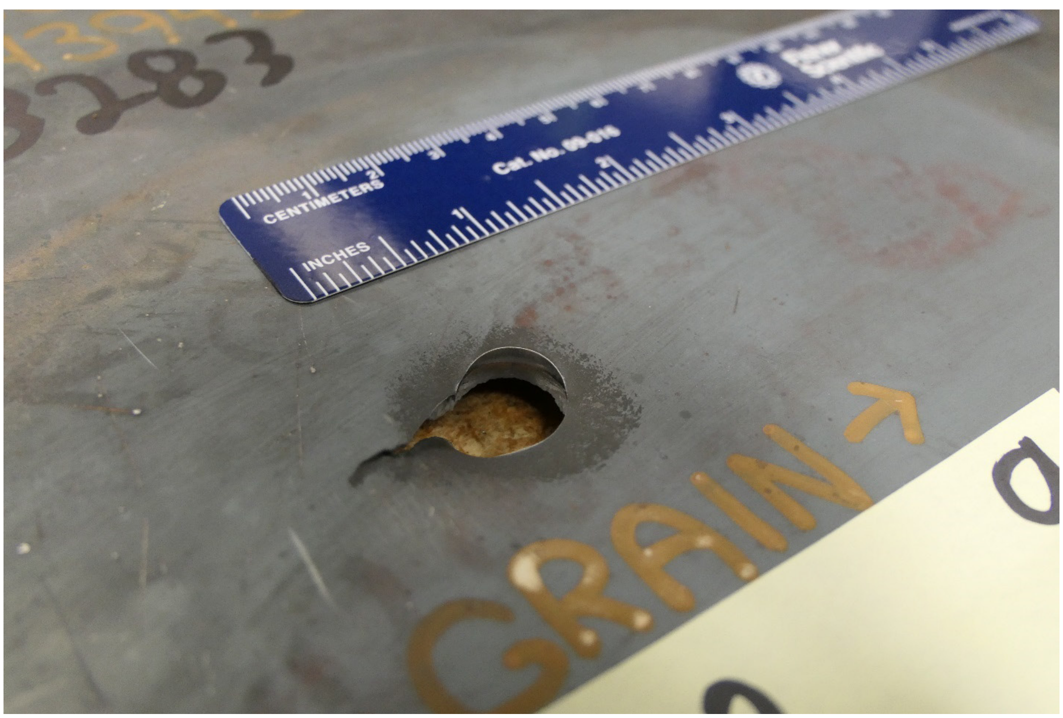


Figure C.32.—DB283: Posttest front view.

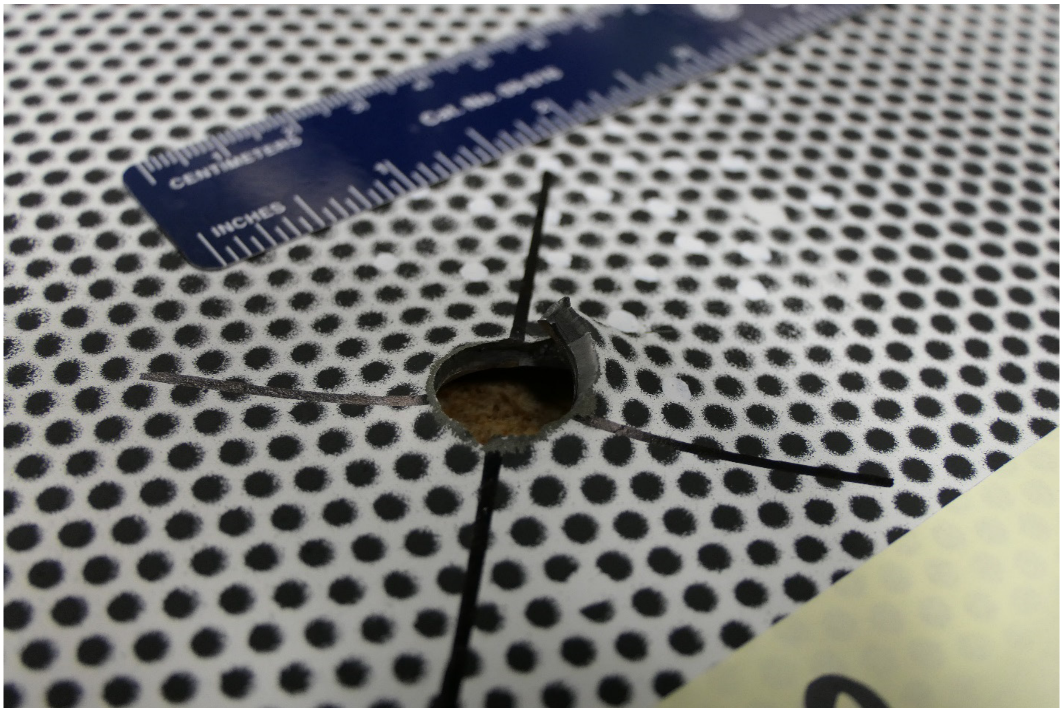


Figure C.33.—DB283: Posttest rear view.

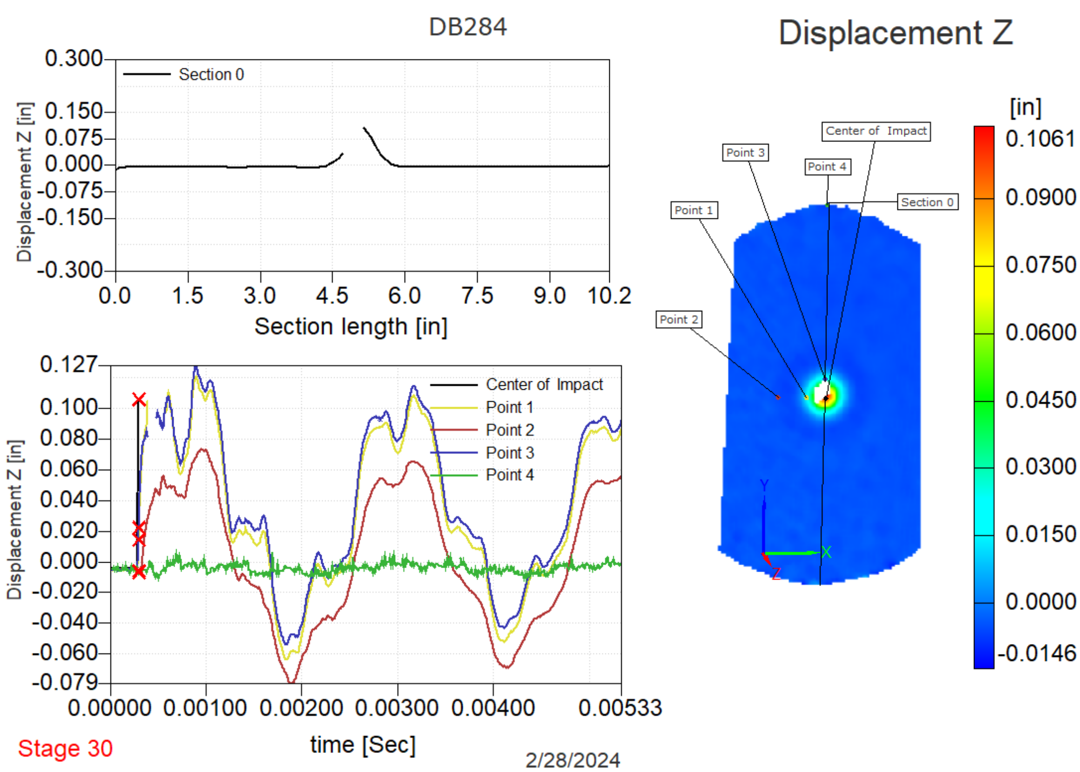


Figure C.34.—DB284: Out-of-plane displacement at time of maximum displacement before failure.

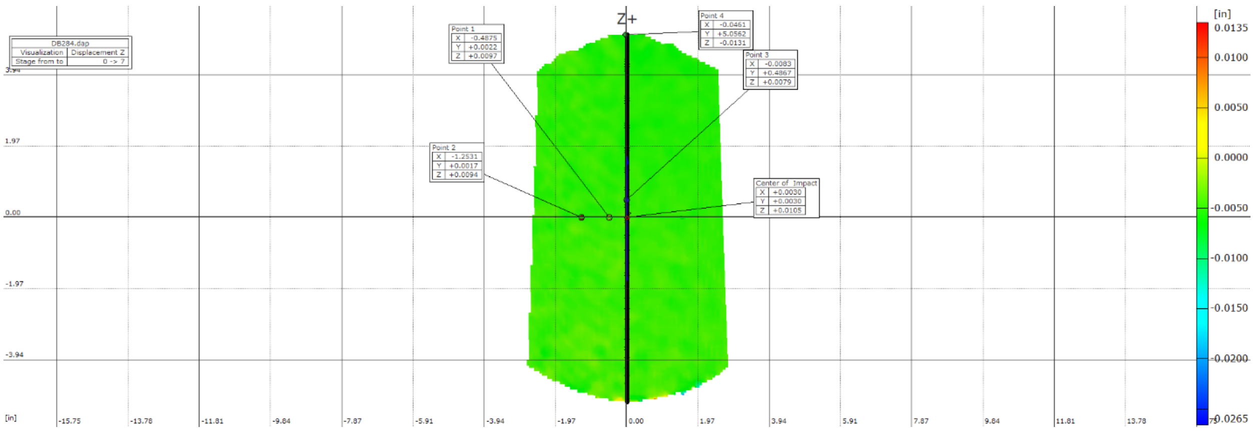


Figure C.35.—DB284: Point locations.

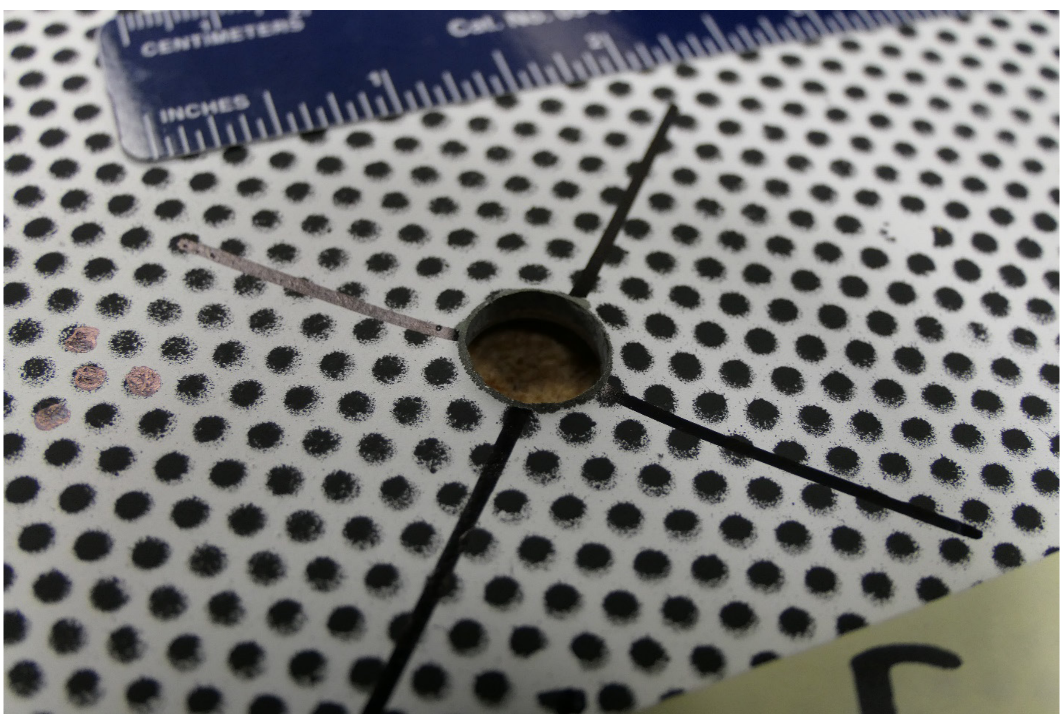


Figure C.36.—DB284: Posttest rear view.

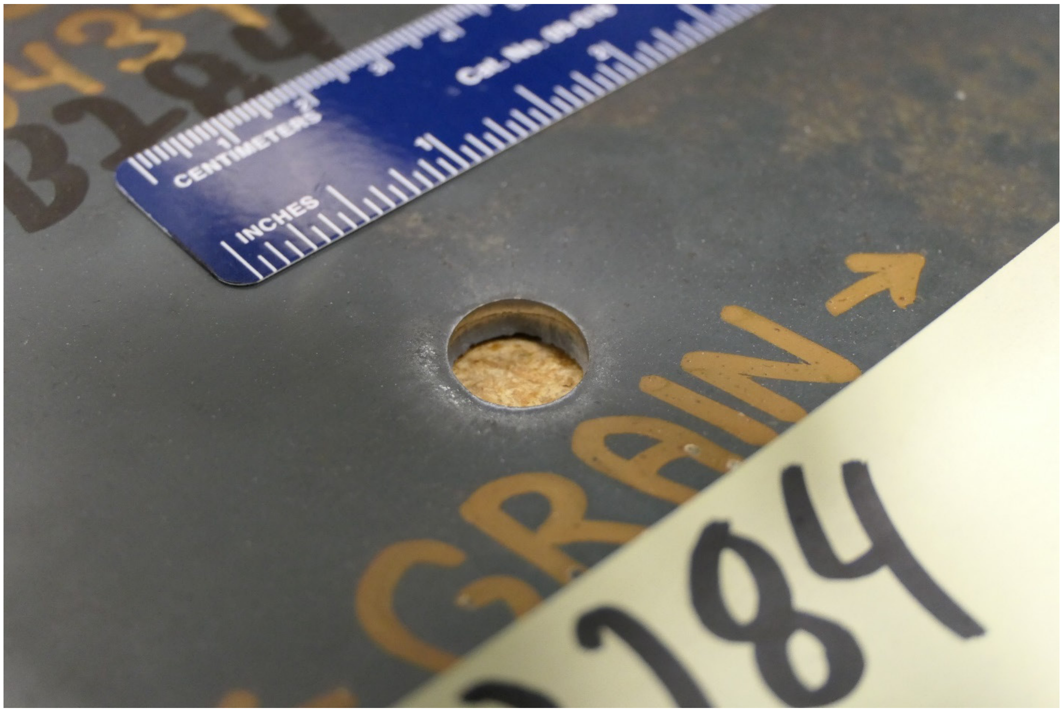


Figure C.37.—DB284: Posttest front view.

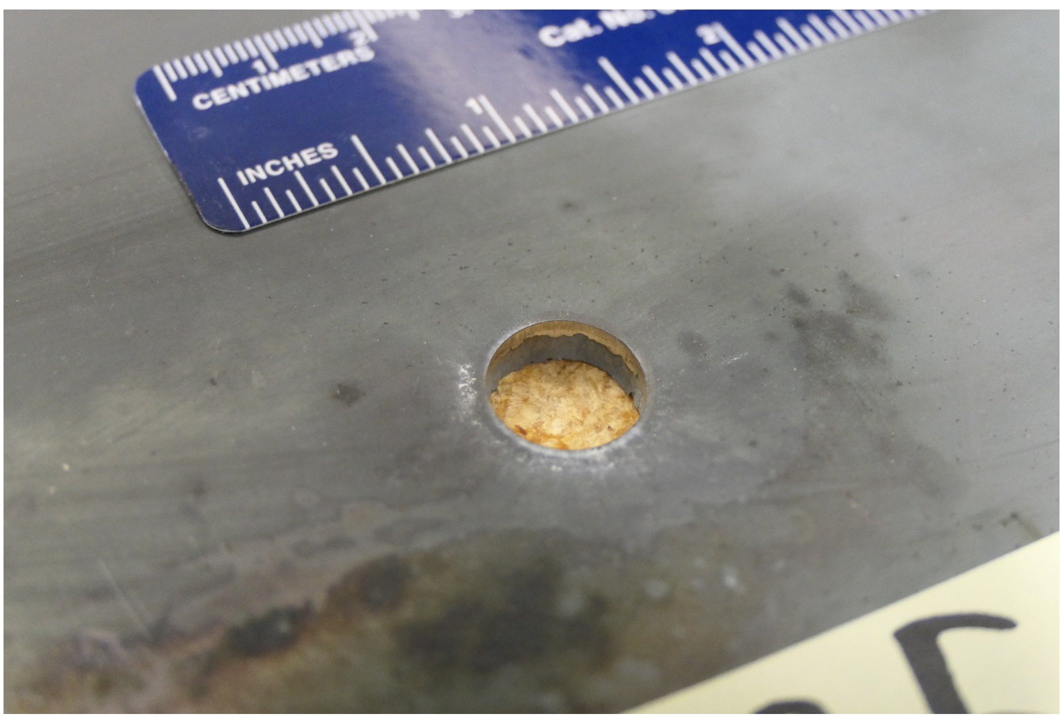


Figure C.38.—DB285: Posttest front view.

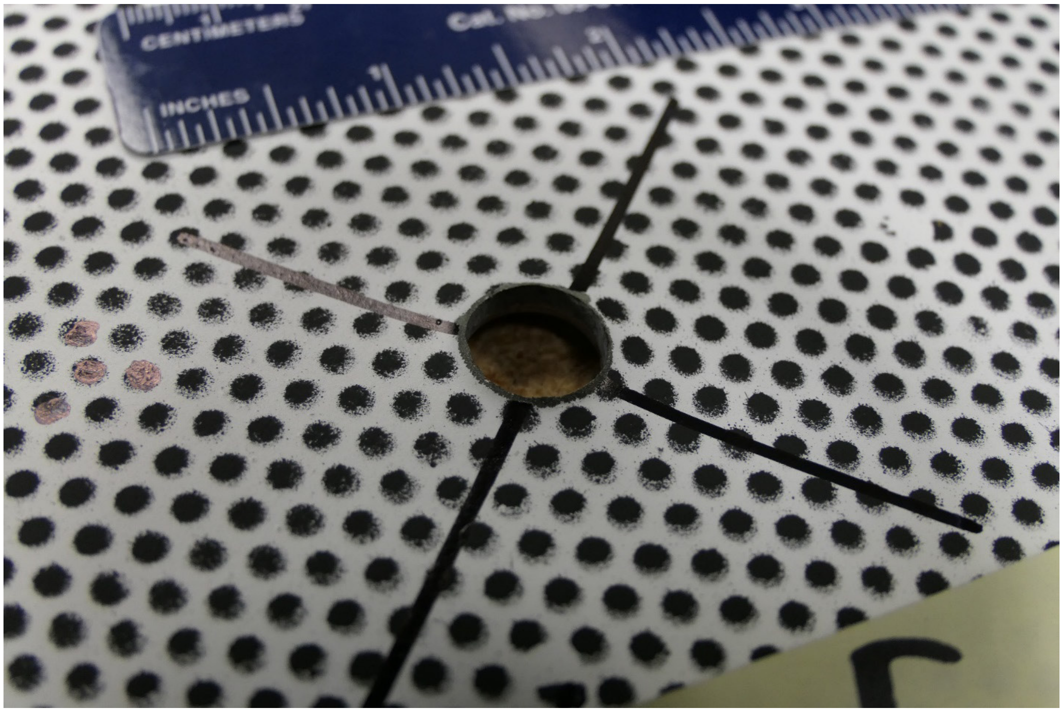


Figure C.39.—DB285: Posttest rear view.

Figure C.40.—DB286: Posttest front view.

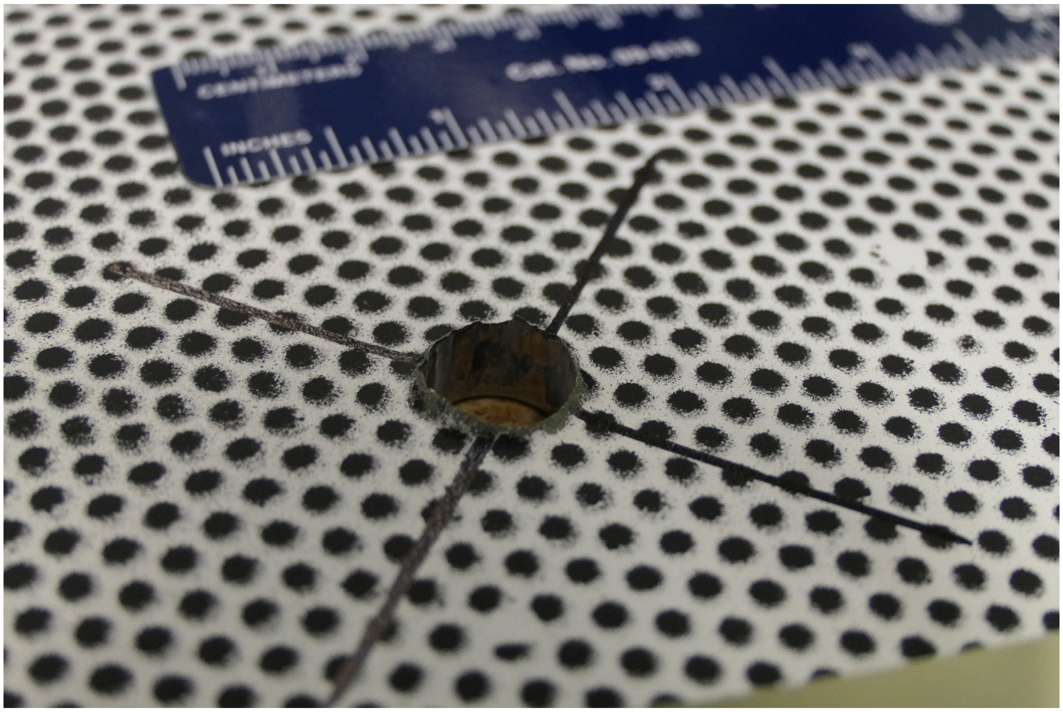


Figure C.41.—DB286: Posttest rear view.

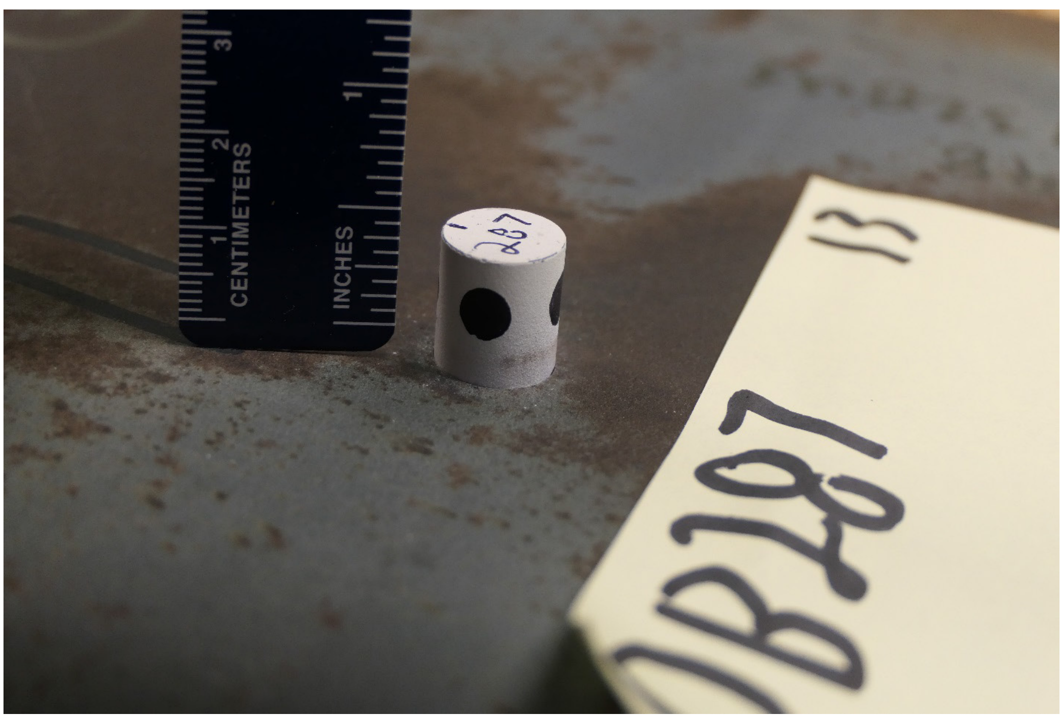


Figure C.42.—DB287: Posttest front view.

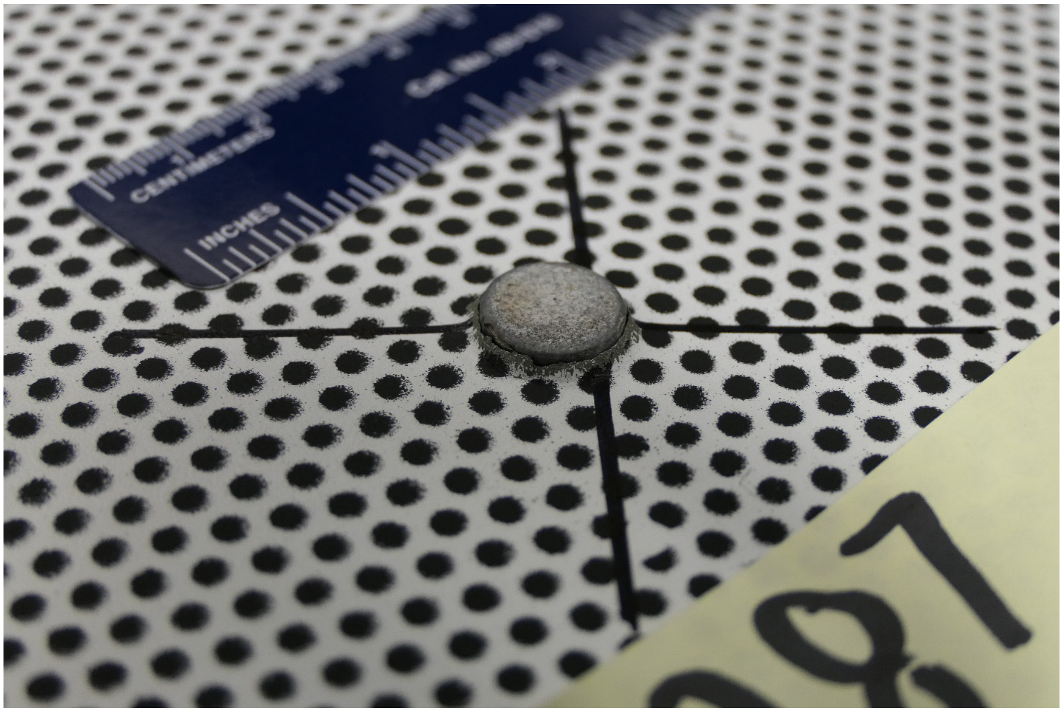


Figure C.43.—DB287: Posttest rear view.

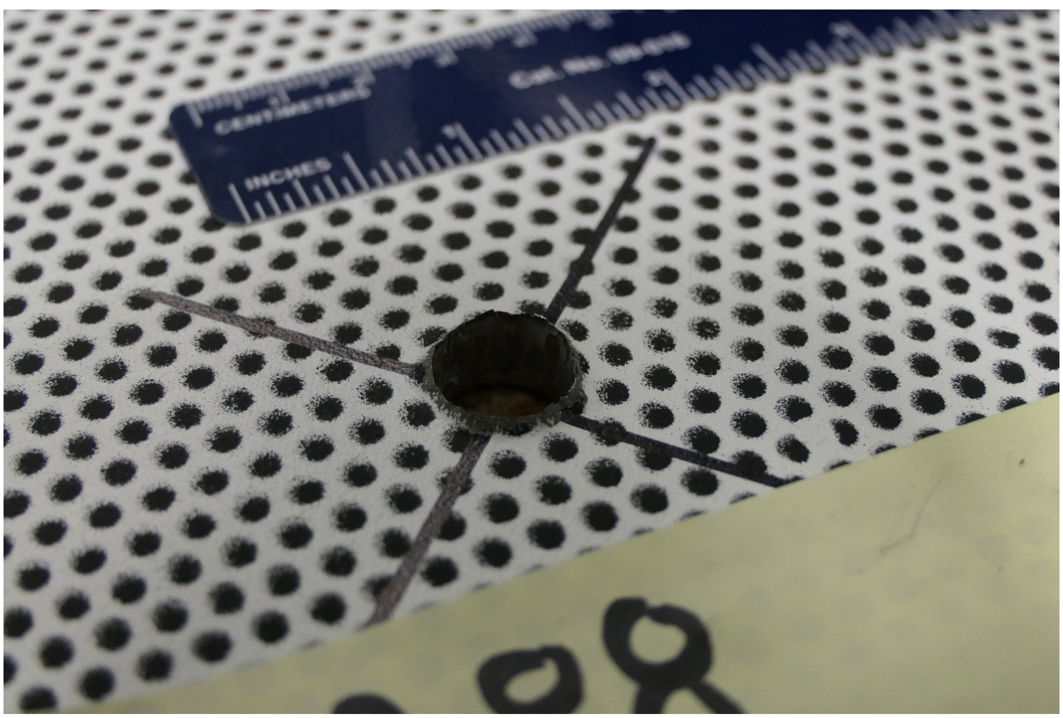


Figure C.44.—DB288: Posttest rear view.

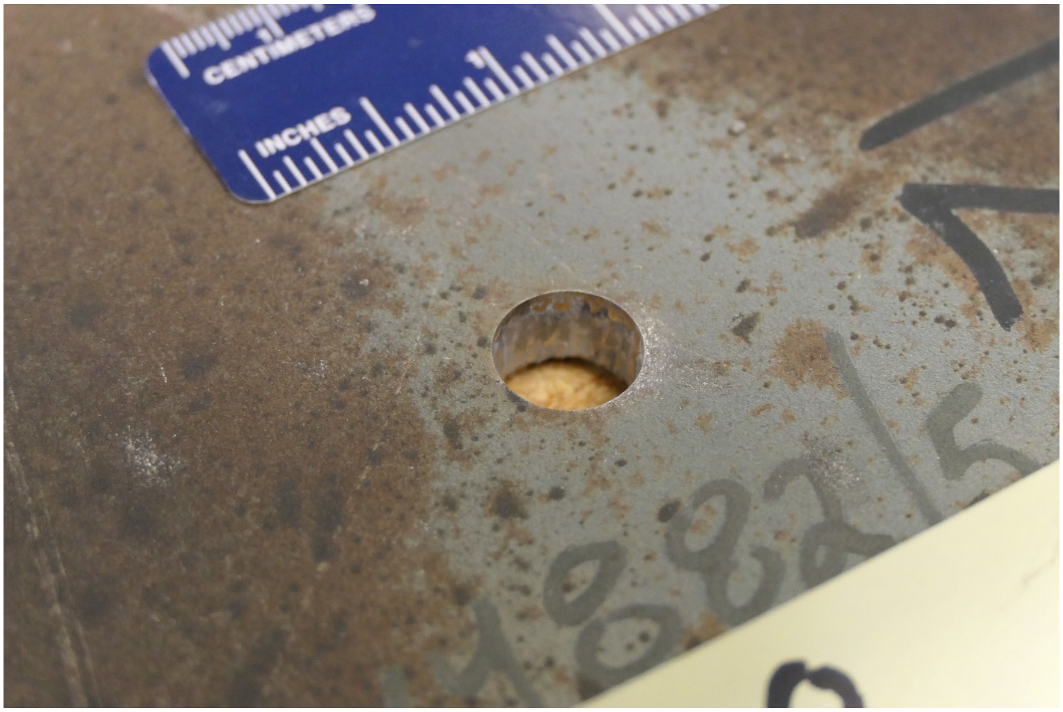


Figure C.45.—DB288: Posttest front view.

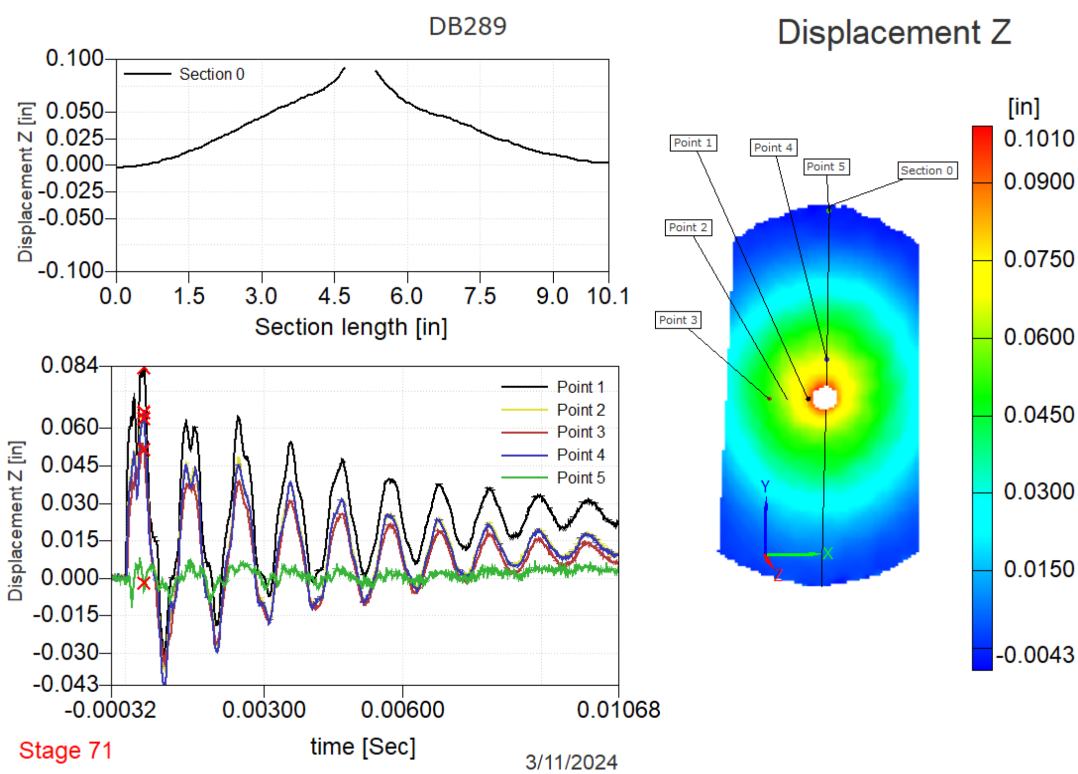


Figure C.46.—DB289: Out-of-plane displacement at time of maximum displacement.

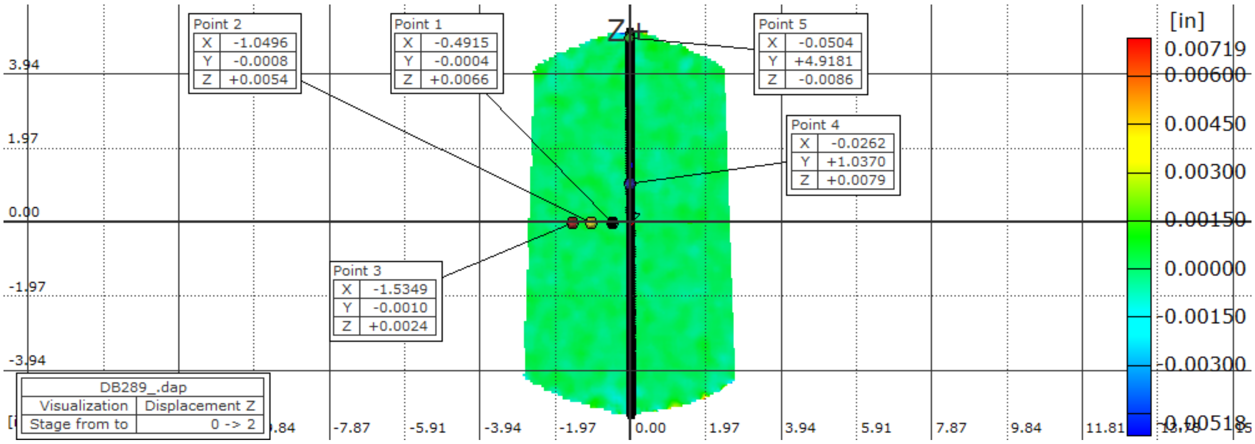


Figure C.47.—DB289: Point locations.

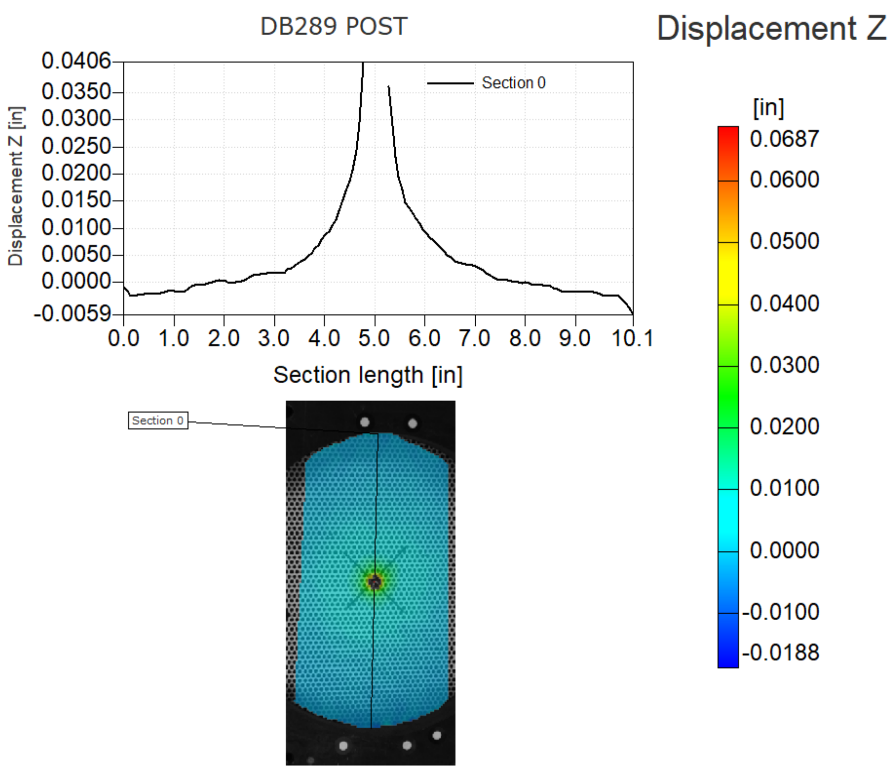


Figure C.48.—DB289: Posttest panel deformation.

Figure C.49.—DB289: Posttest front view.

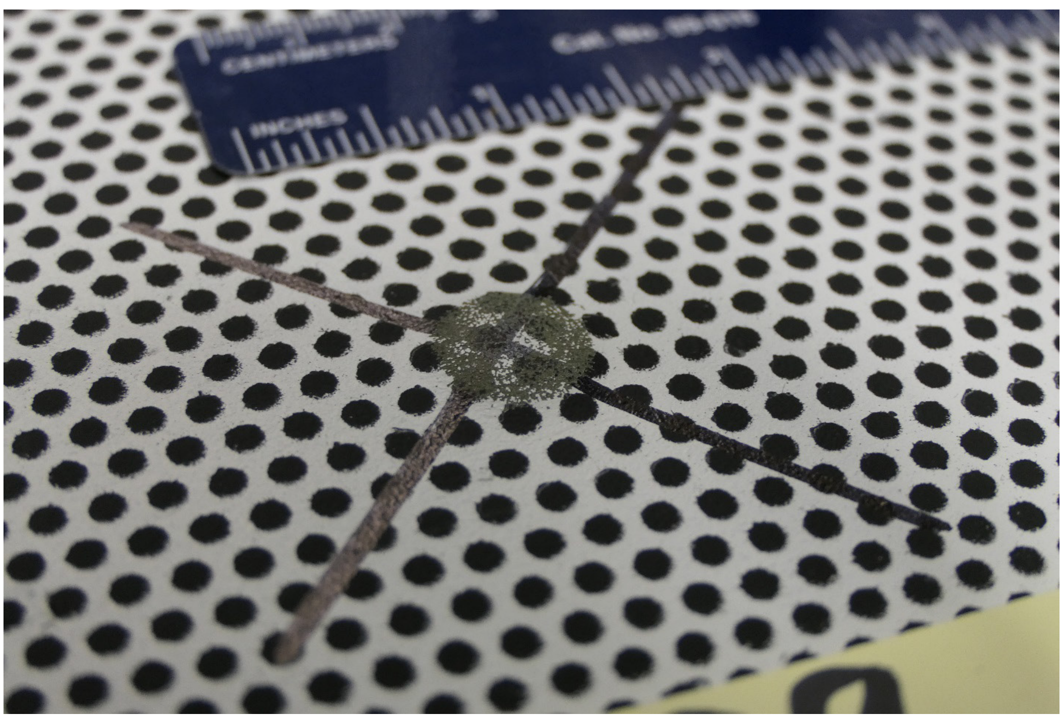


Figure C.50.—DB289: Posttest rear view.

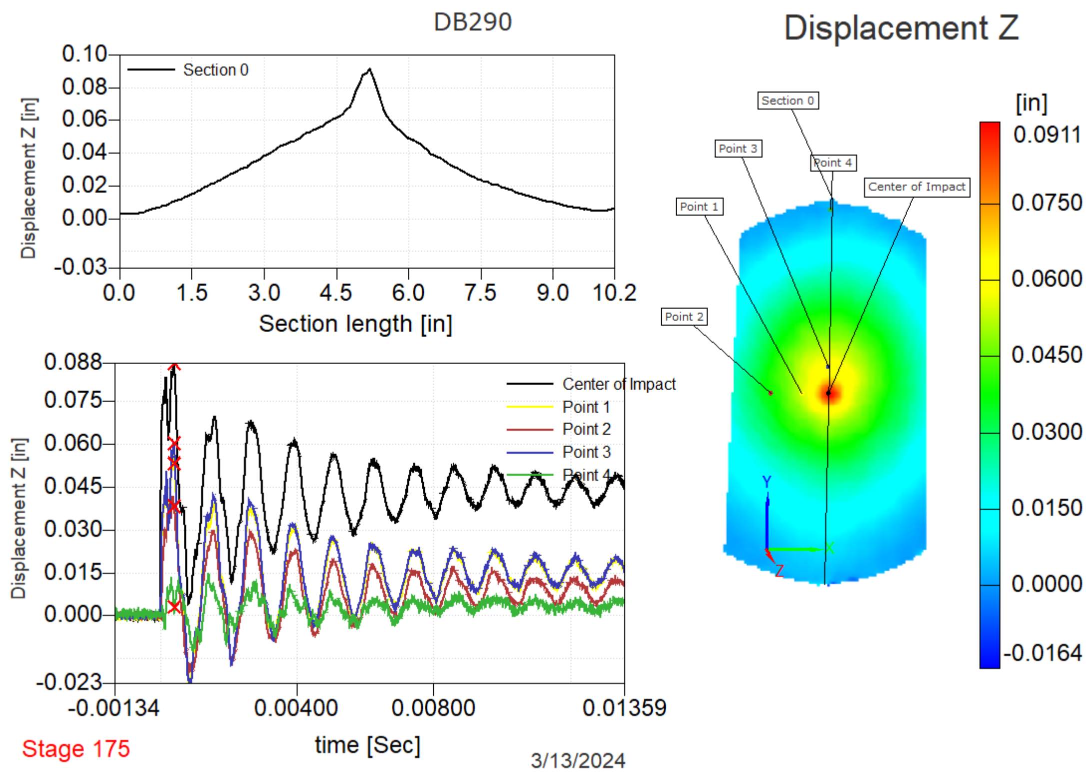


Figure C.51.—DB290: Out-of-plane displacement at time of maximum displacement.

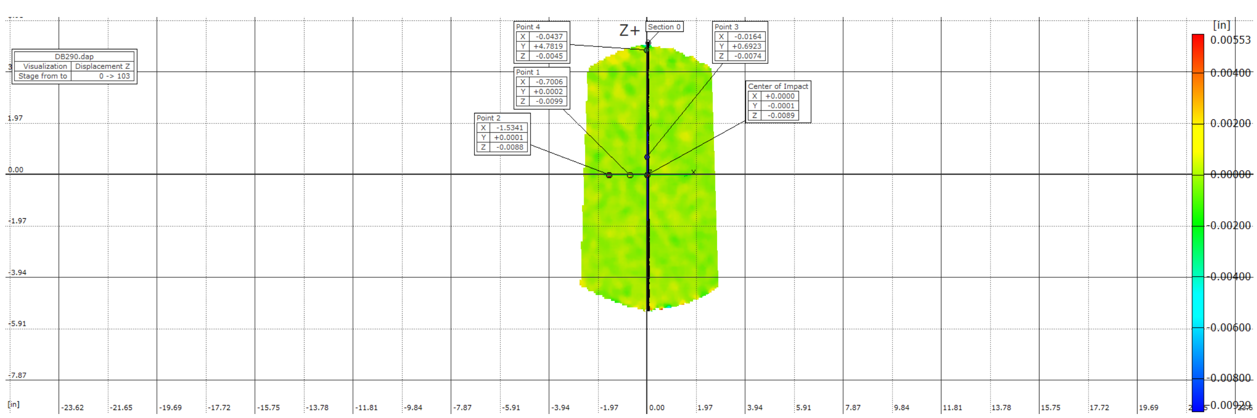


Figure C.52.—DB290: Point locations.

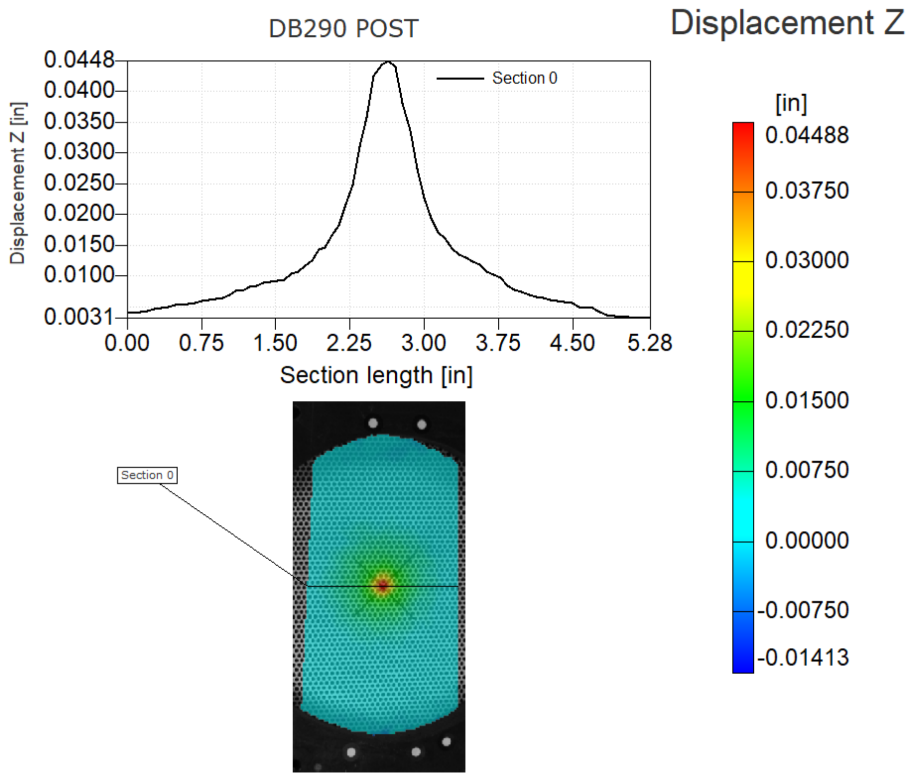


Figure C.53.—DB290: Posttest panel deformation.

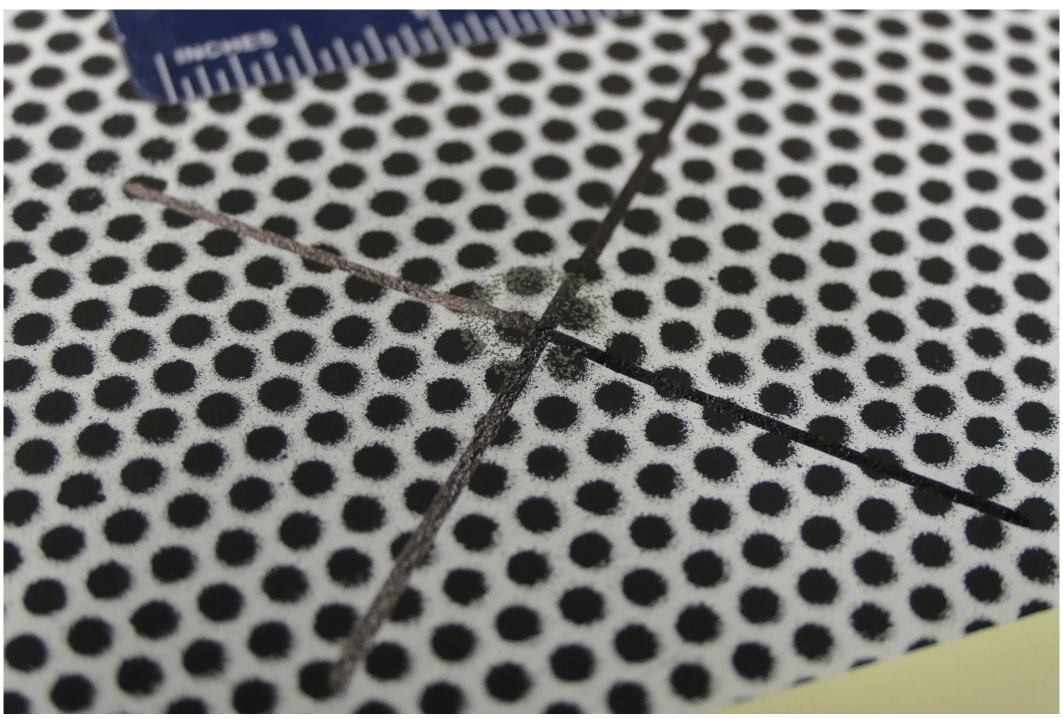


Figure C.54.—DB290: Posttest rear view.

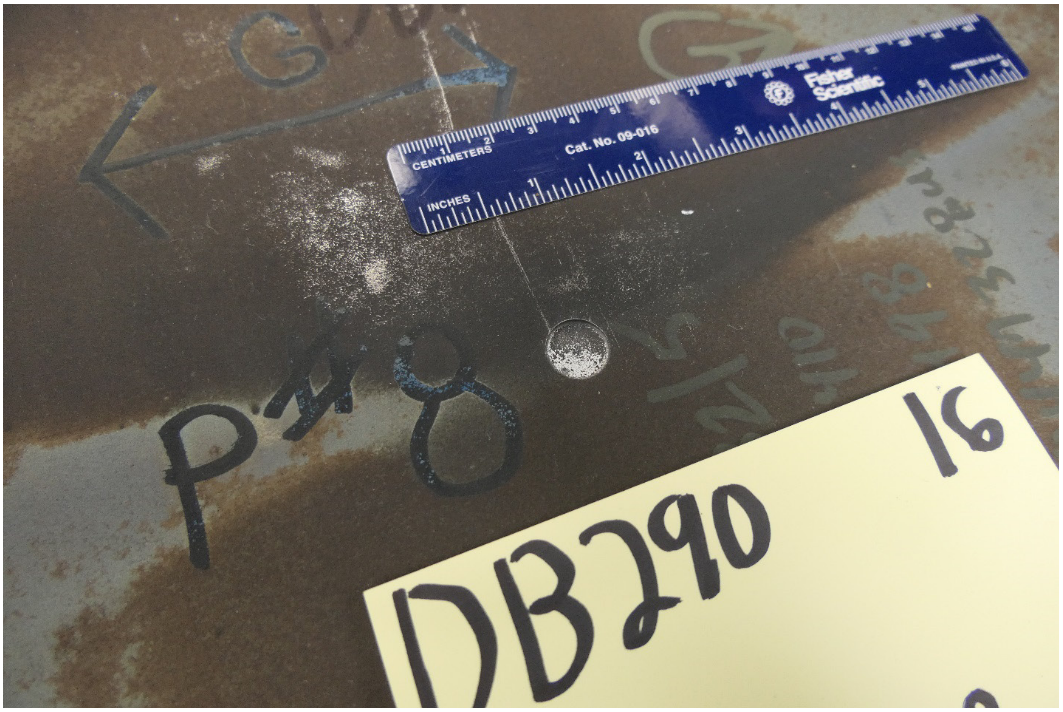


Figure C.55.—DB290: Posttest front view.

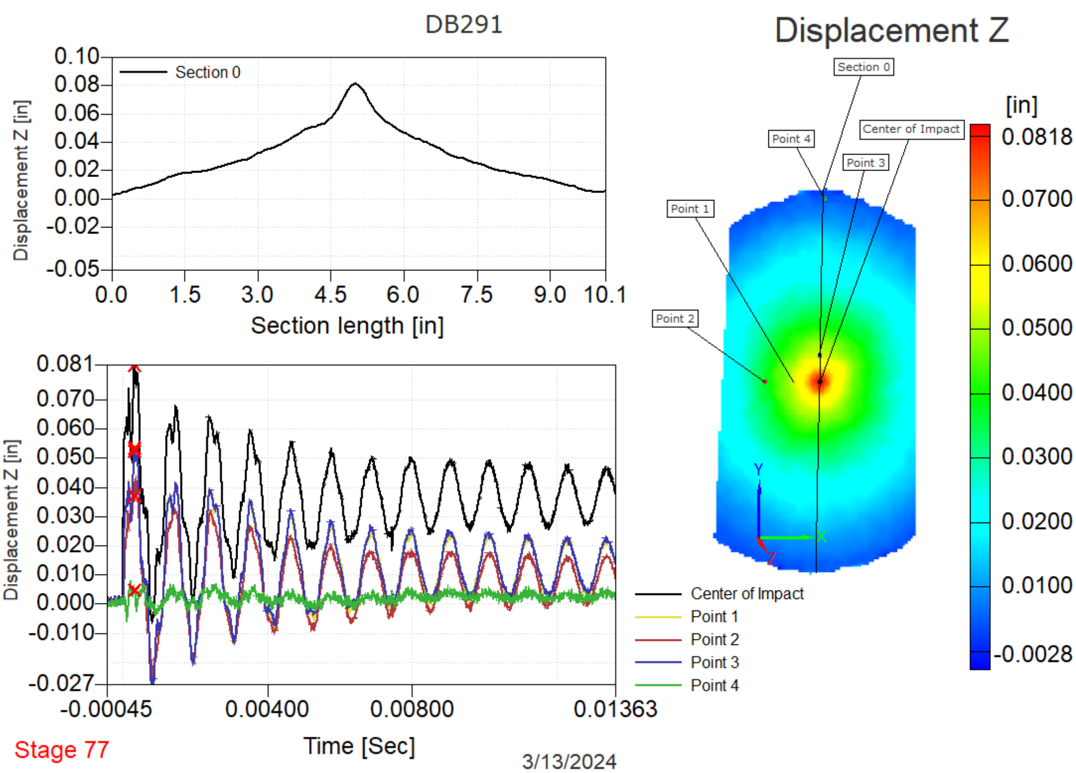


Figure C.56.—DB291 Out-of-plane displacement at time of maximum displacement.

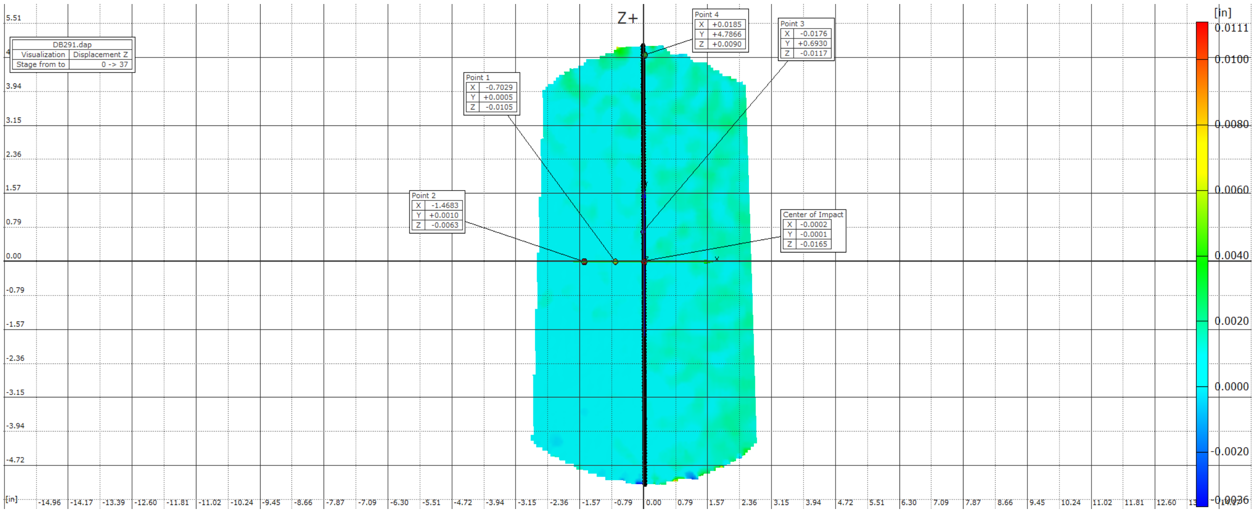


Figure C.57.—DB291: Point locations.

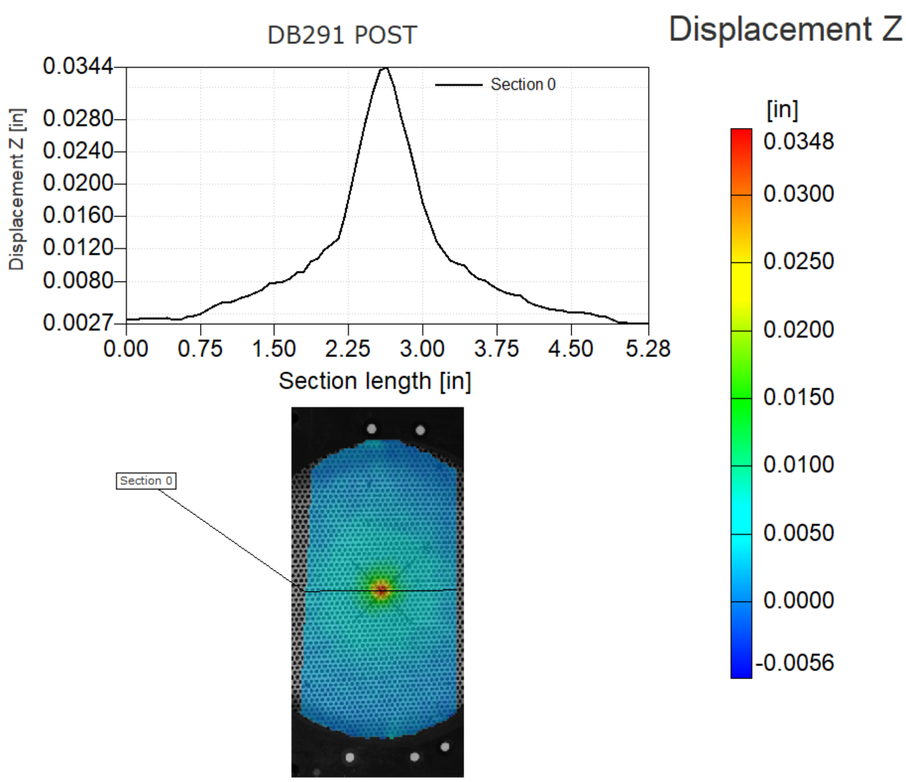


Figure C.58.—DB291: Posttest panel deformation.

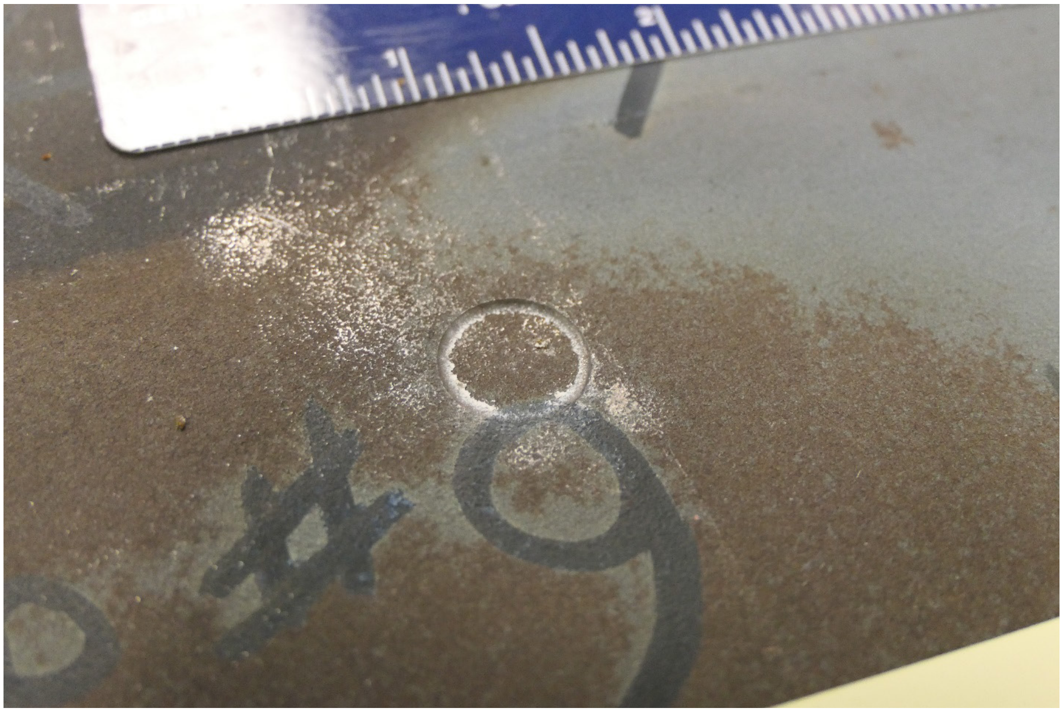


Figure C.59.—DB291: Posttest front view.

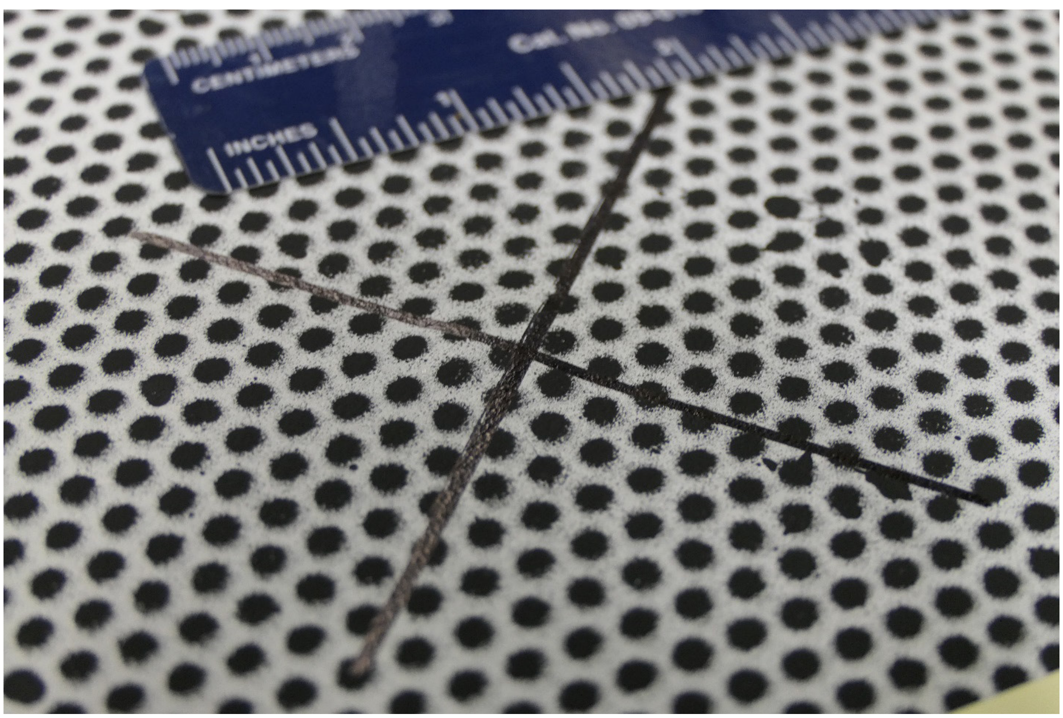


Figure C.60.—DB291: Posttest rear view.

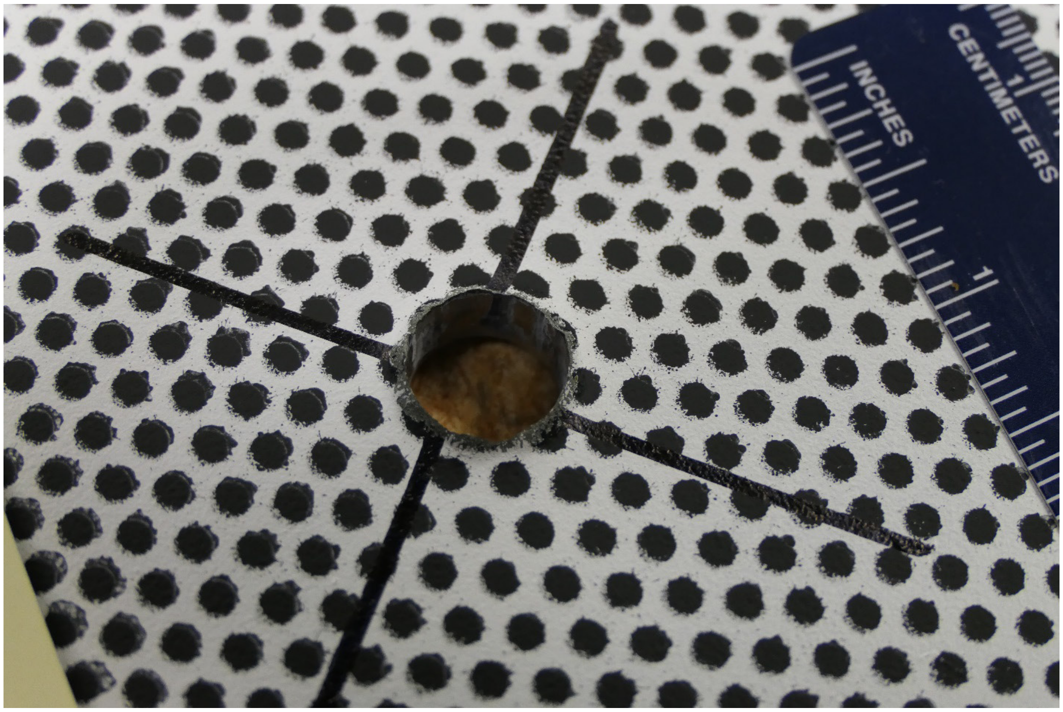


Figure C.61.—DB292: Posttest rear view.

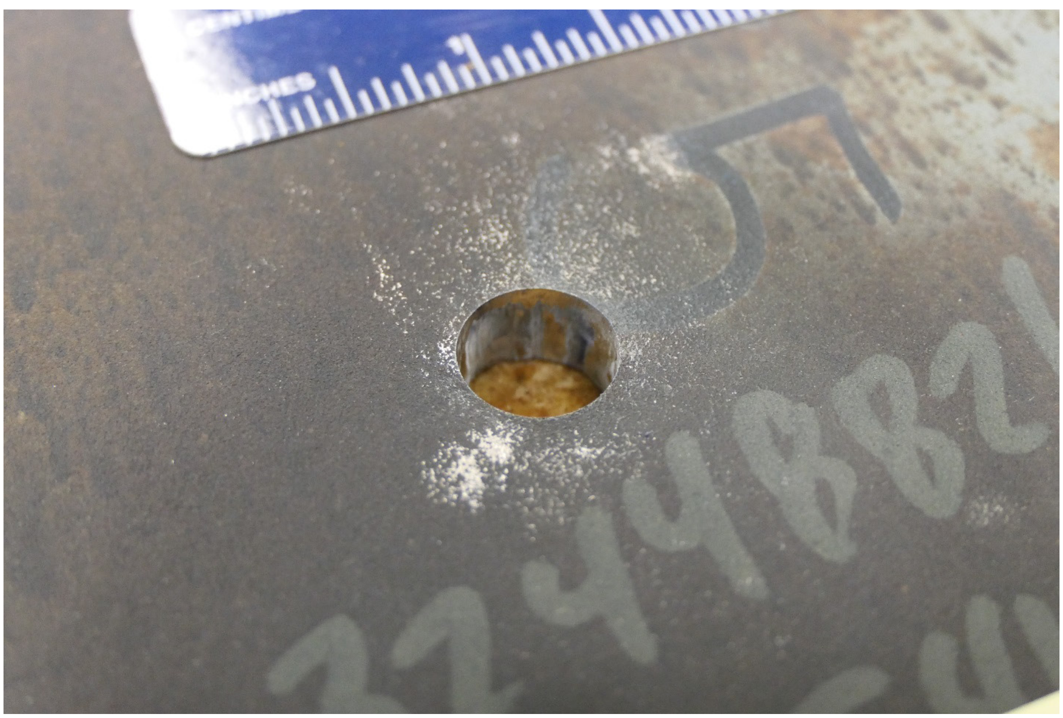


Figure C.62.—DB292: Posttest front view.

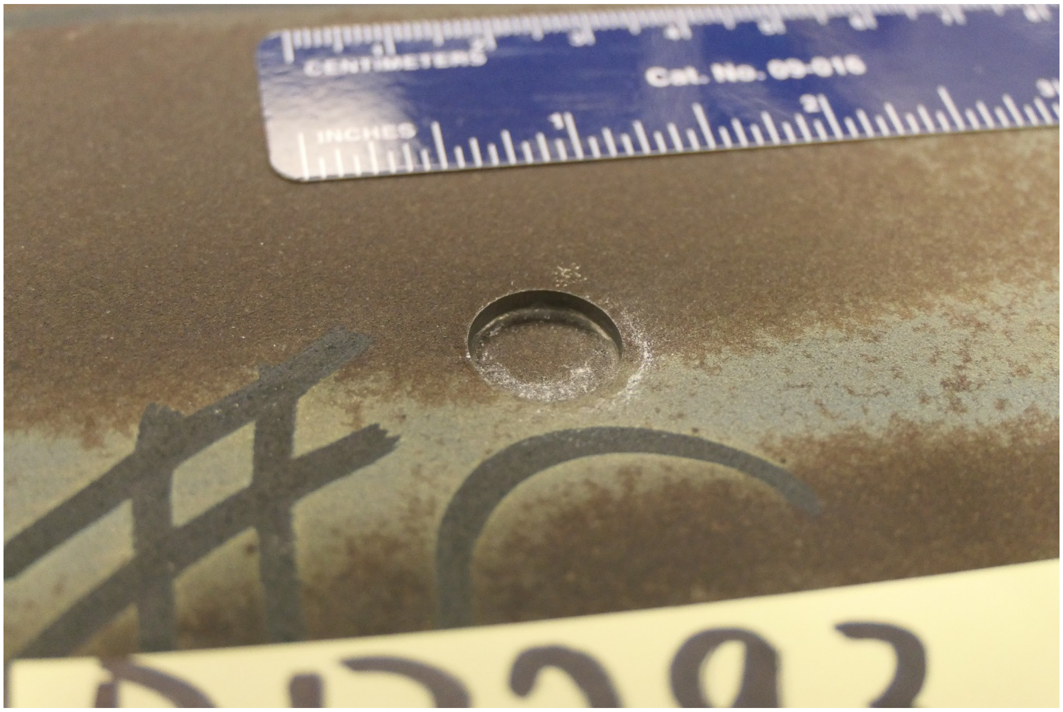


Figure C.63.—DB293: Posttest front view.

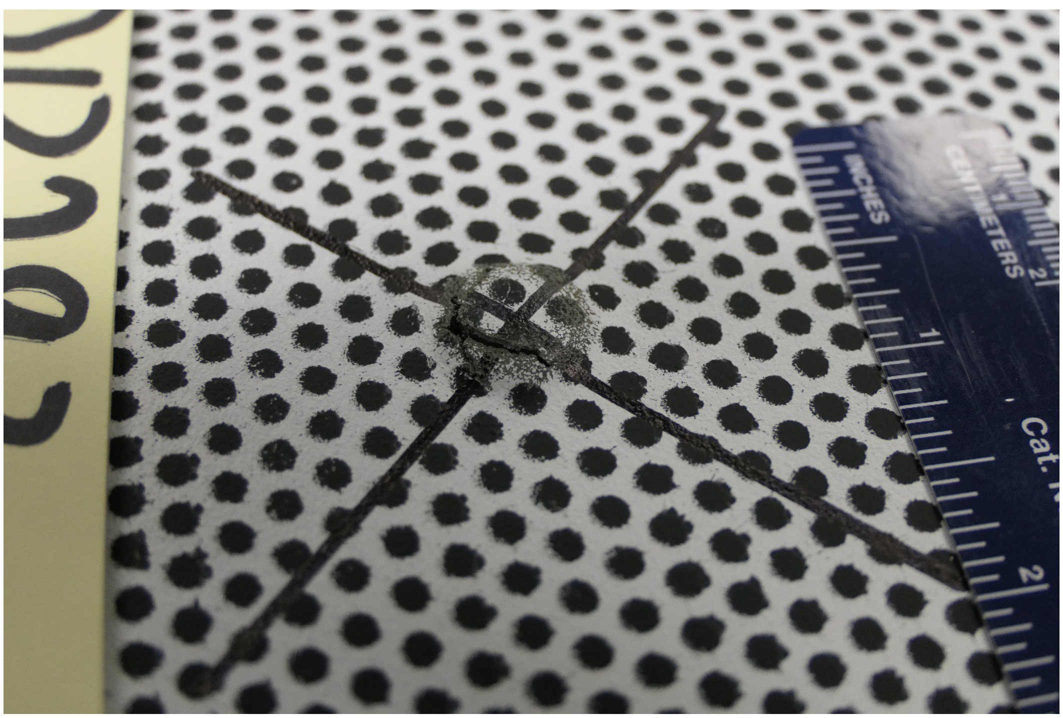


Figure C.64.—DB293: Posttest rear view.

Figure C.65.—DB294: Posttest front view.

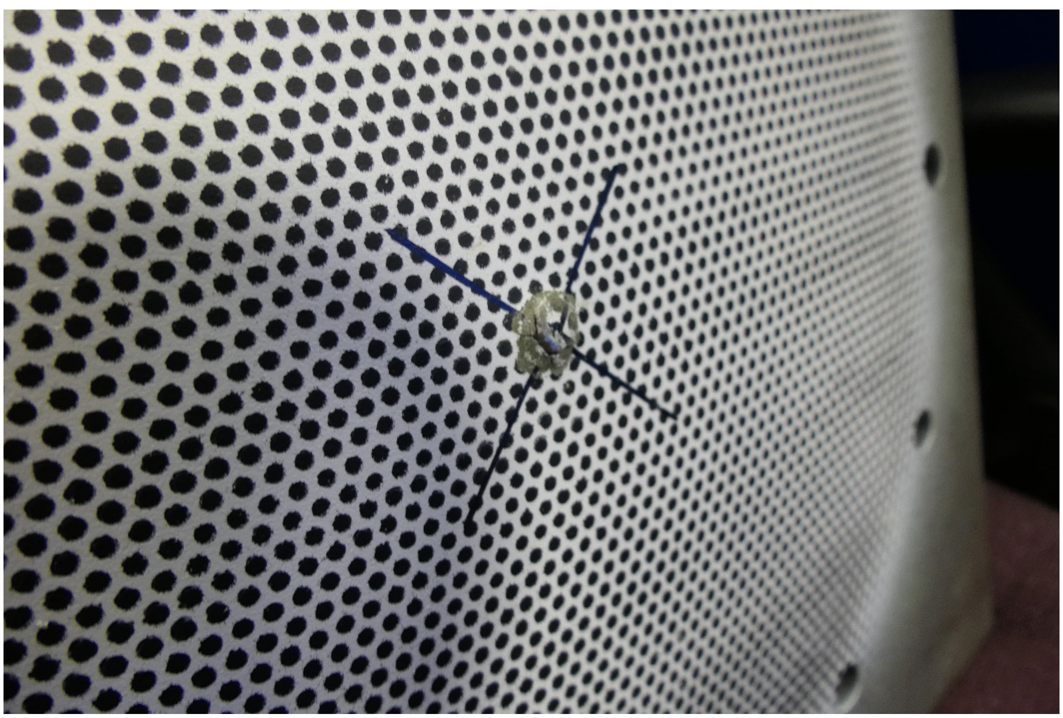


Figure C.66.—DB294: Posttest rear view.

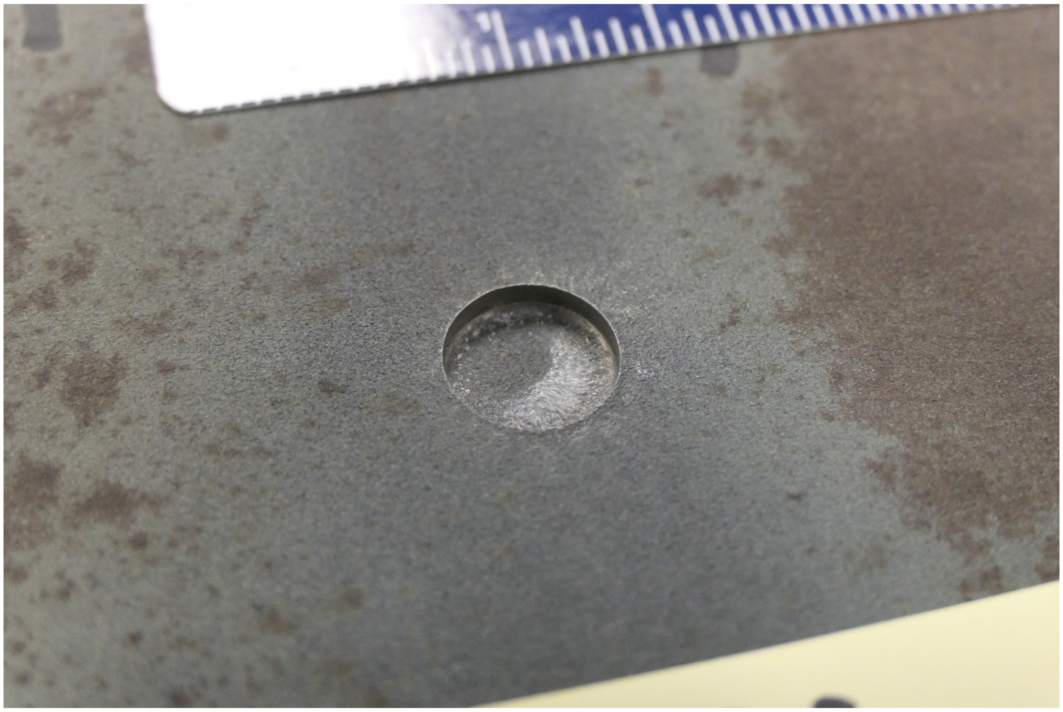


Figure C.67.—DB295: Posttest front view.

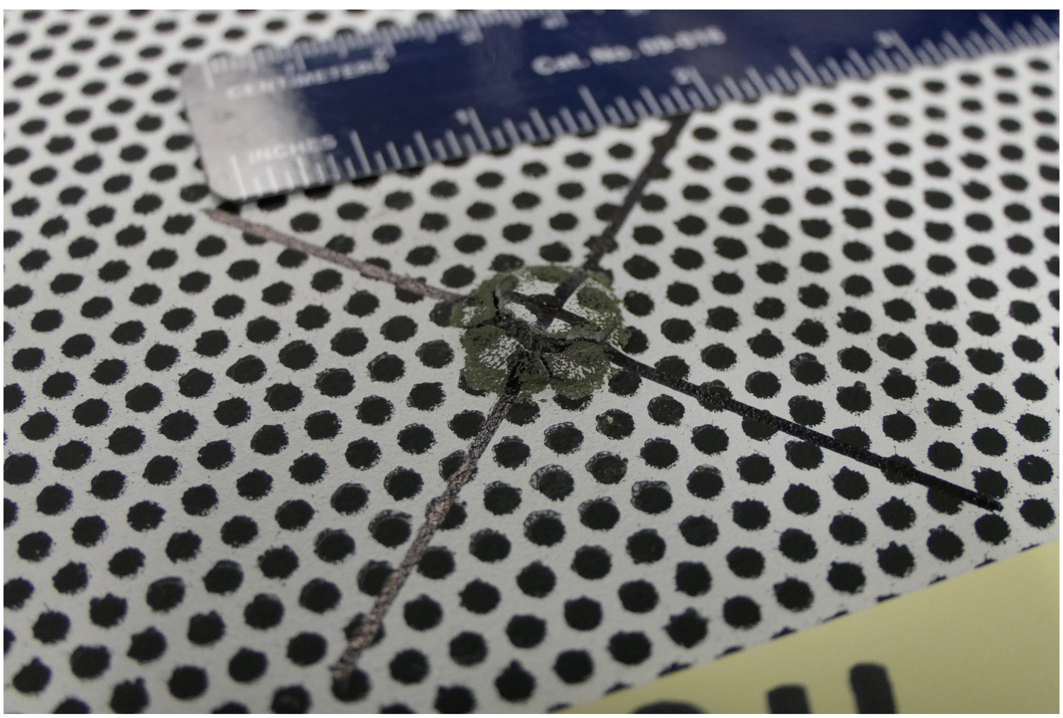


Figure C.68.—DB295: Posttest rear view.

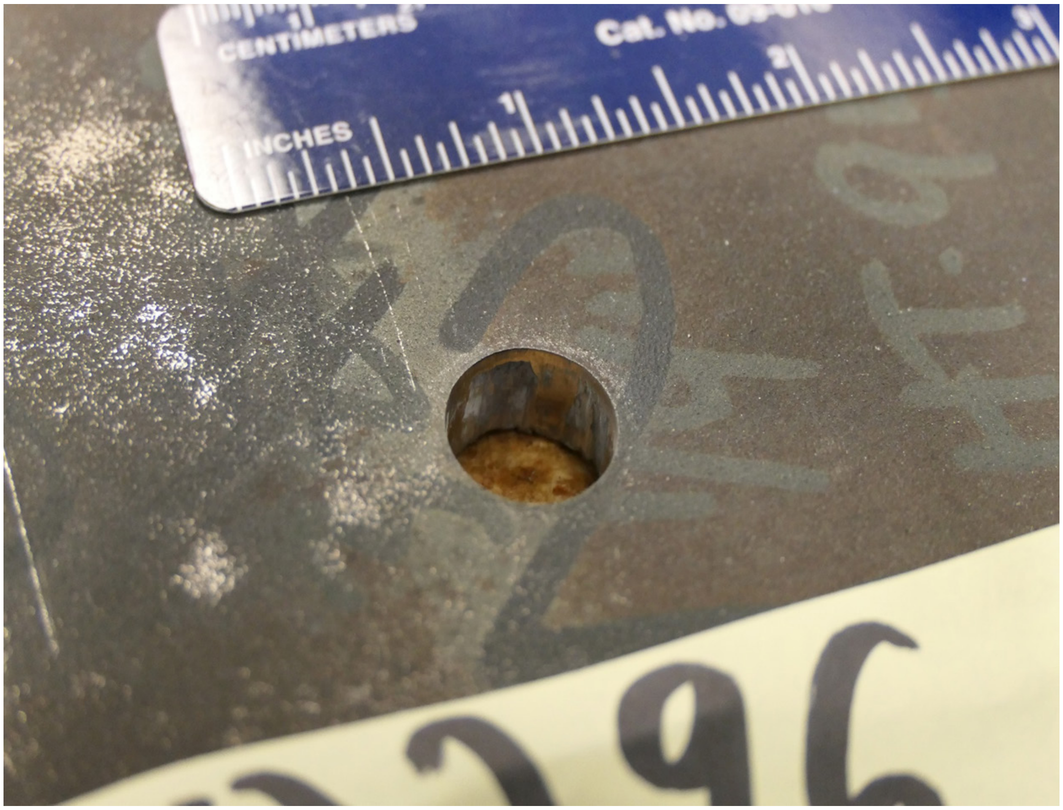


Figure C.69.—DB296: Posttest front view.

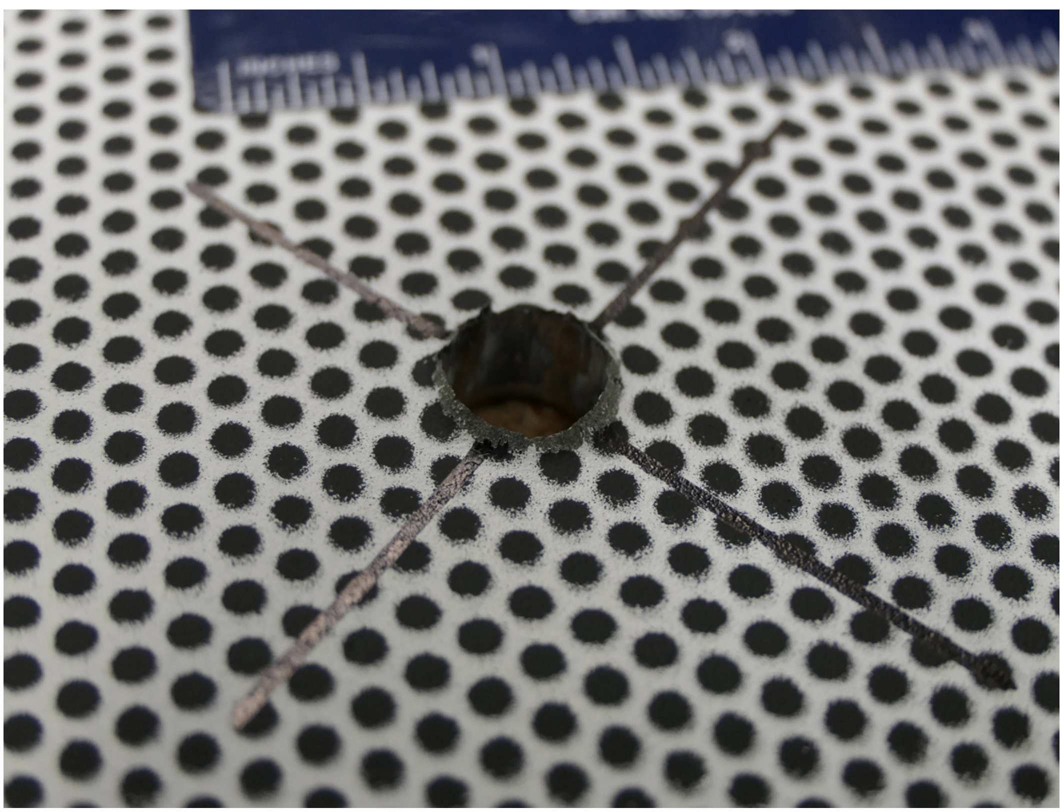


Figure C.70.—DB296: Posttest rear view.

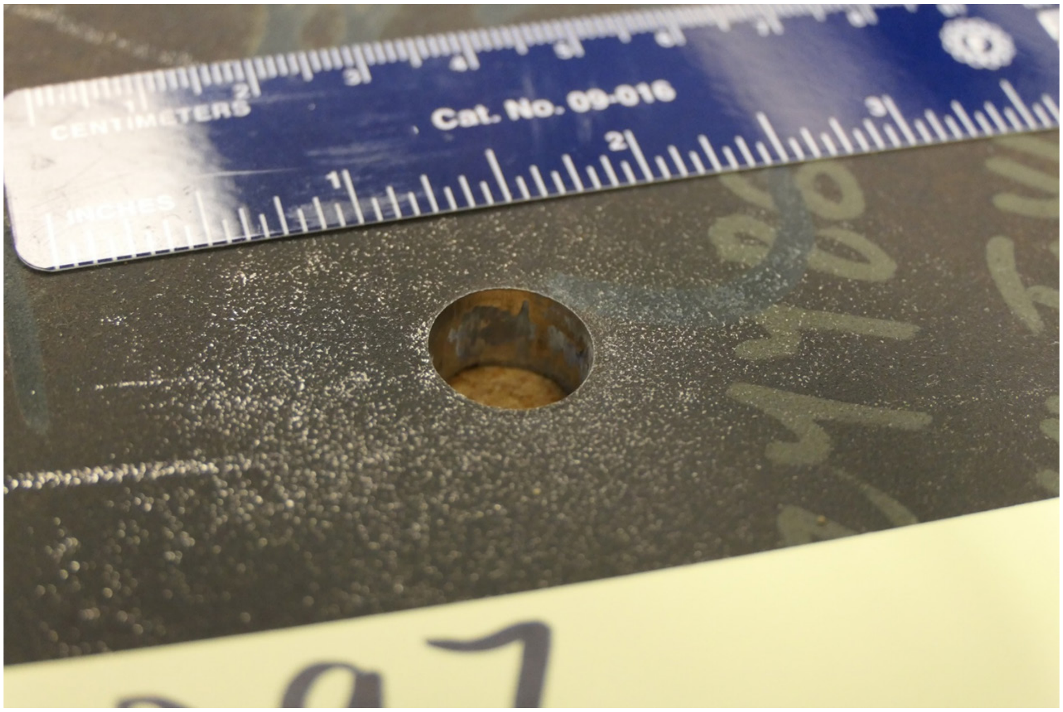


Figure C.71.—DB297: Posttest front view.

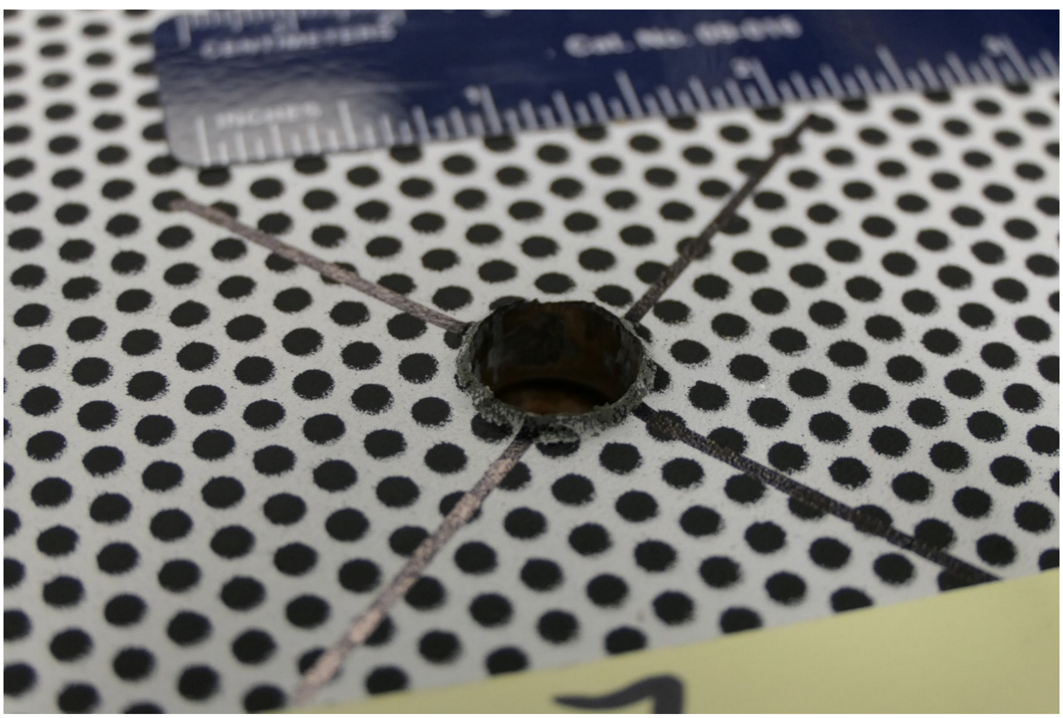


Figure C.72.—DB297: Posttest rear view.

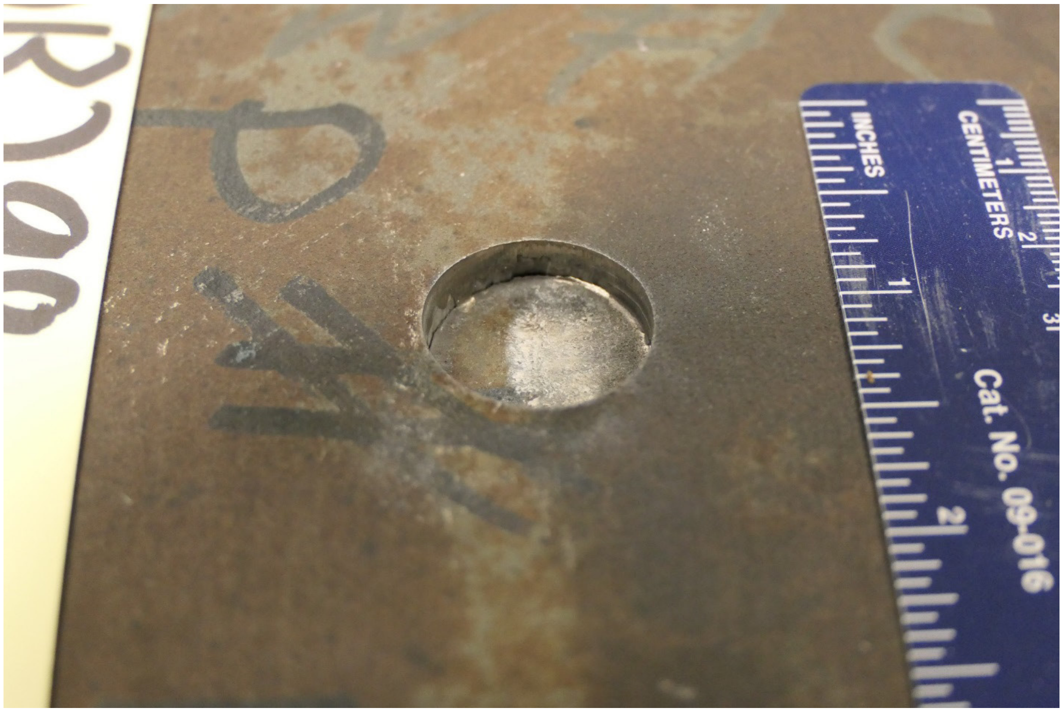


Figure C.73.—DB298: Posttest front view.

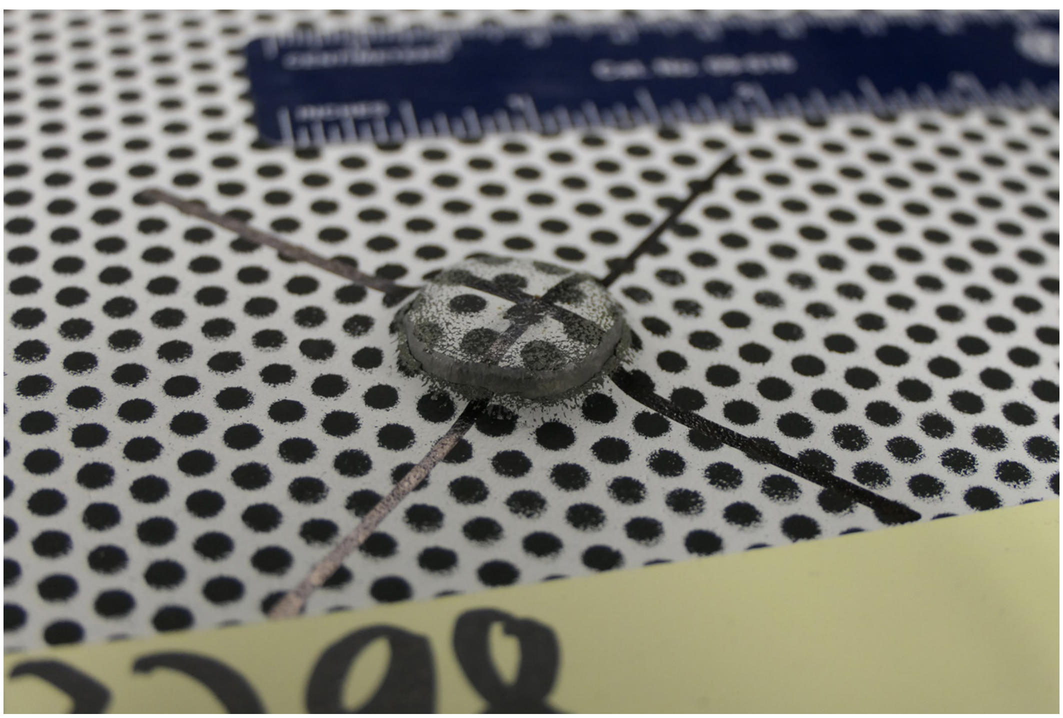


Figure C.74.—DB298: Posttest rear view.

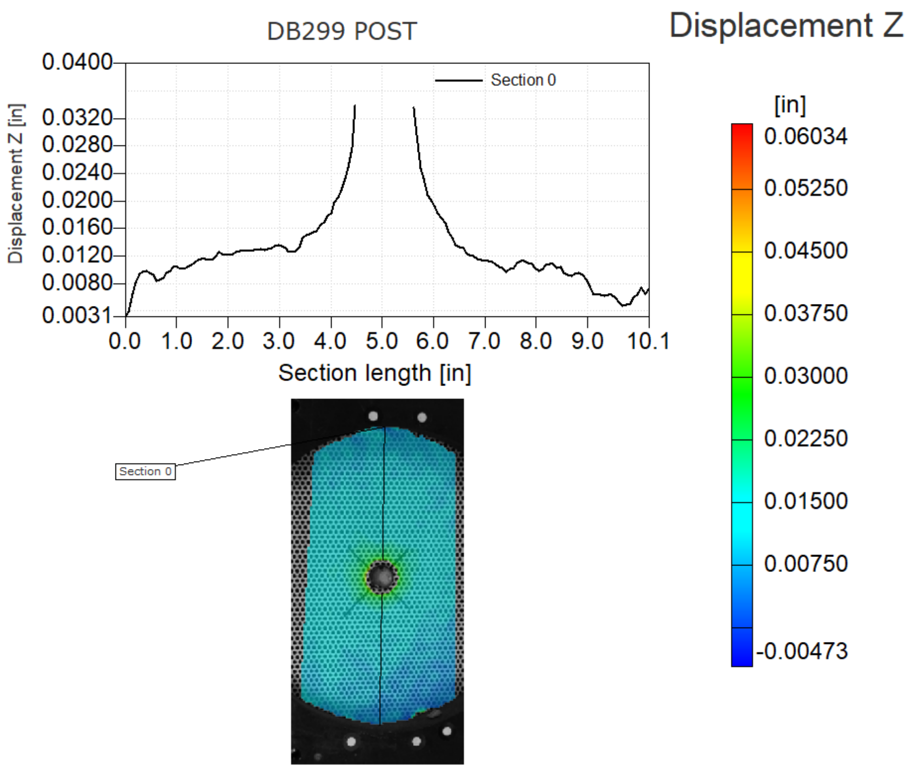


Figure C.75.—DB299: Out-of-plane displacement at time of maximum displacement.

Figure C.76.—DB299: Posttest front view.

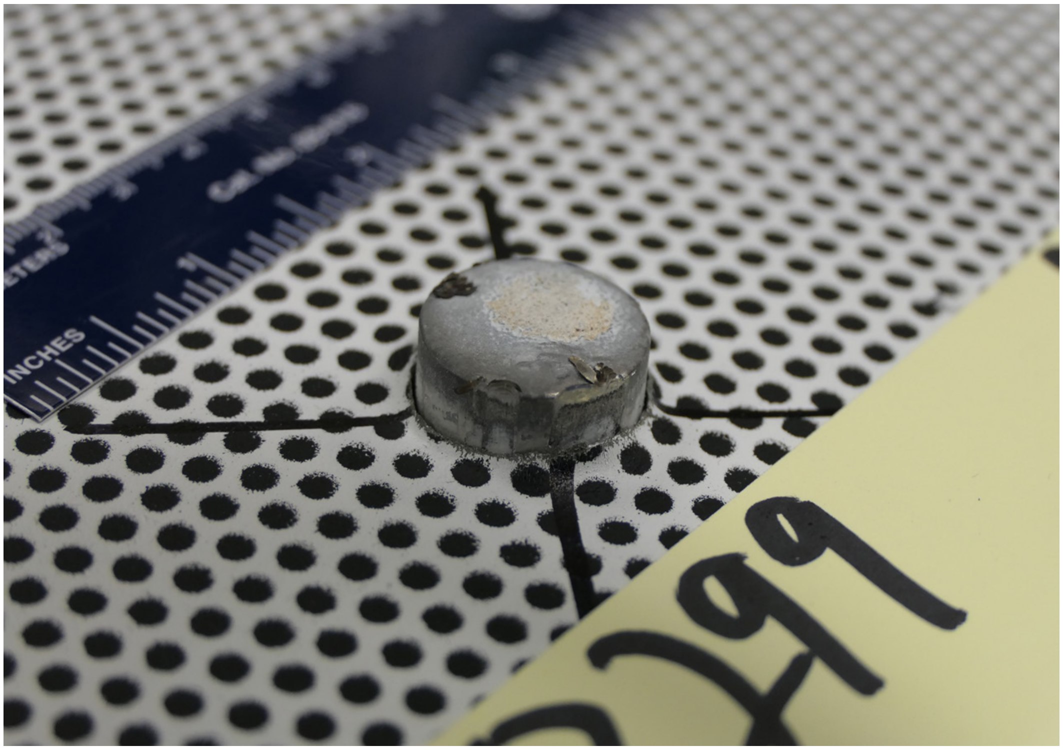


Figure C.77.—DB299: Posttest rear view.

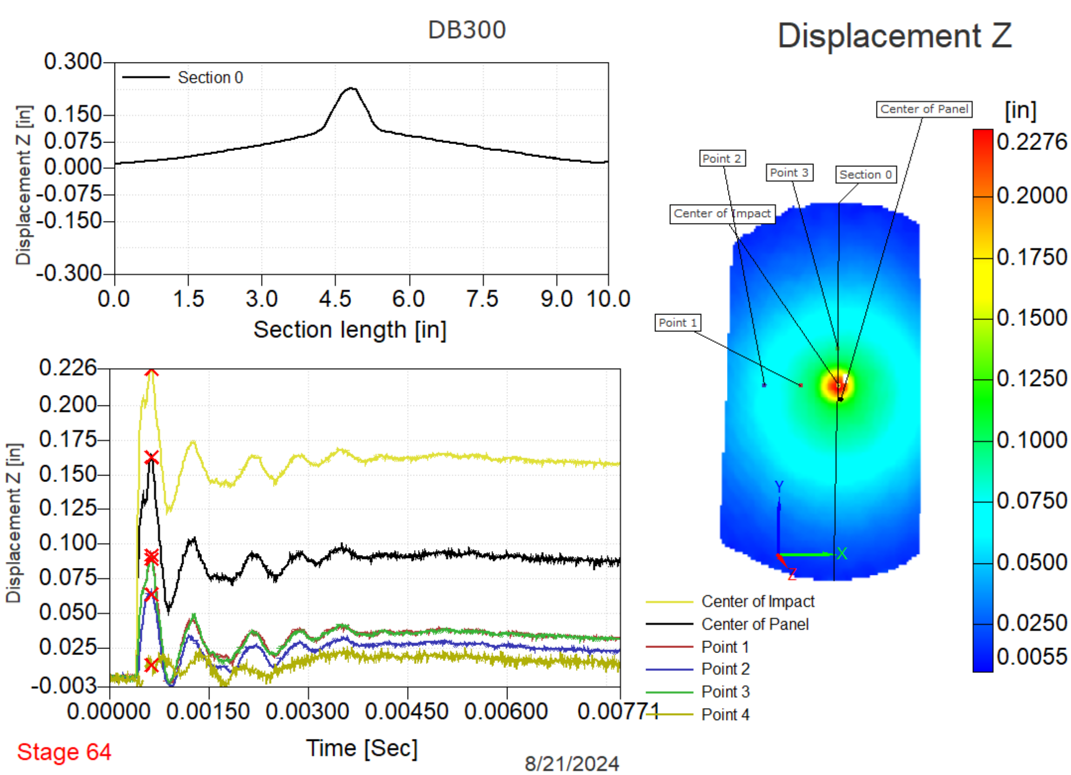


Figure C.78.—DB300: Out-of-plane displacement at time of maximum displacement.

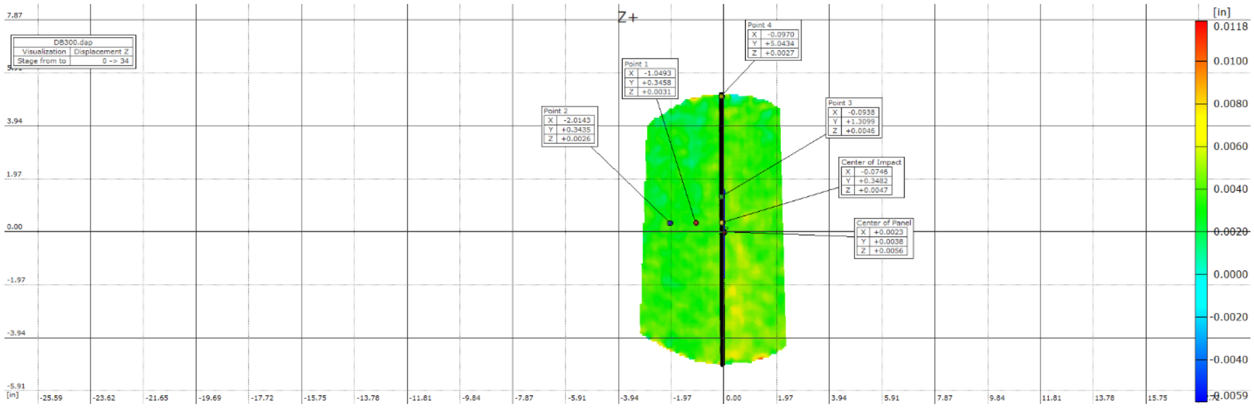


Figure C.79.—DB300: Point locations.

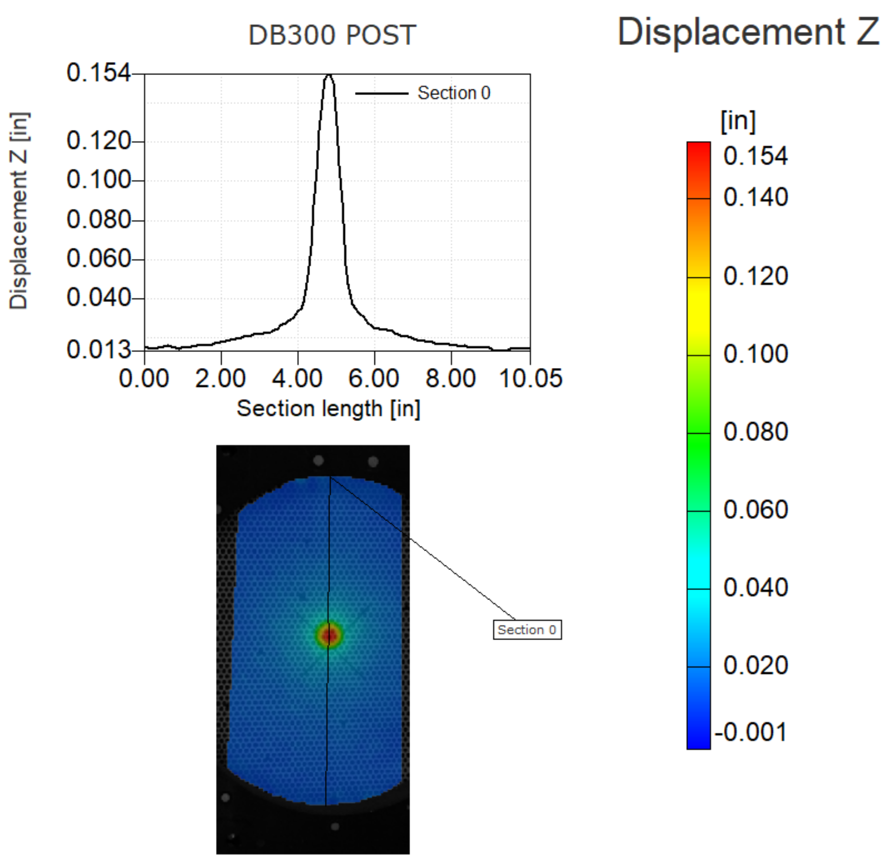


Figure C.80.—DB300: Posttest panel deformation.

Figure C.81.—DB300: Posttest front view.

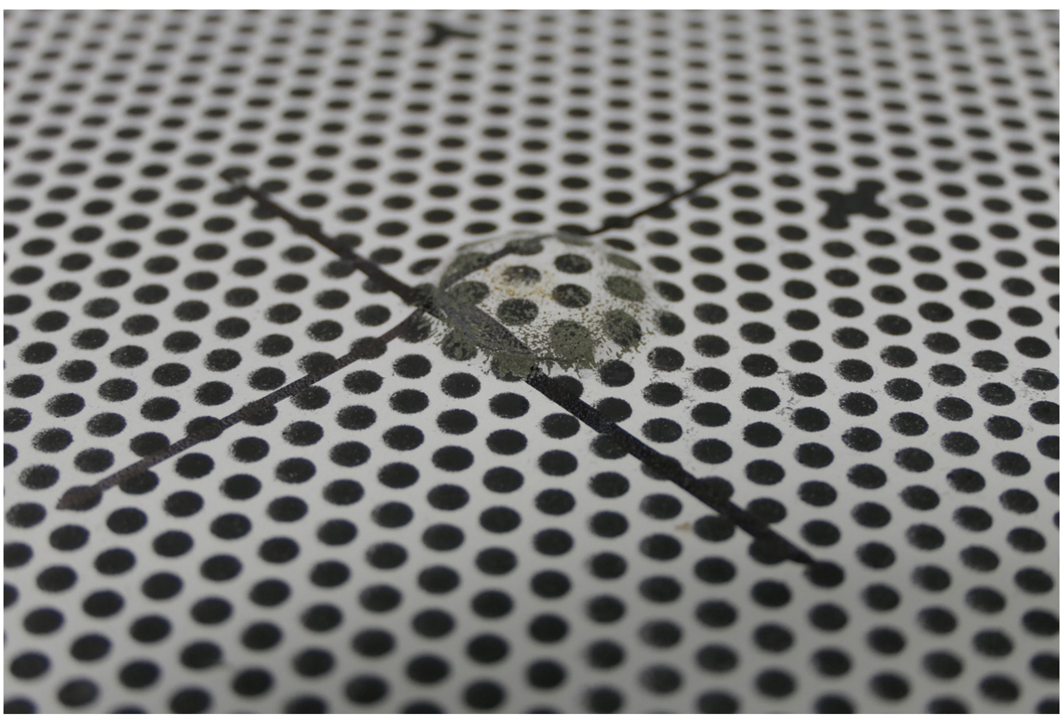


Figure C.82.—DB300: Posttest rear view.

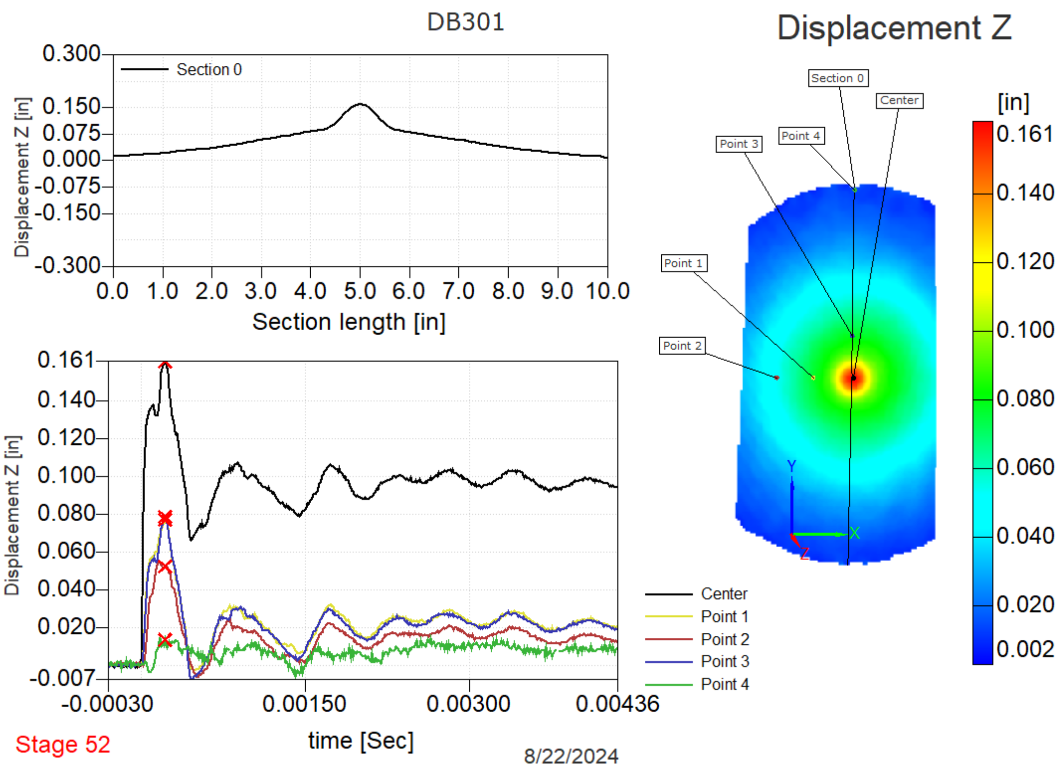


Figure C.83.—DB301: Out-of-plane displacement at time of maximum displacement.

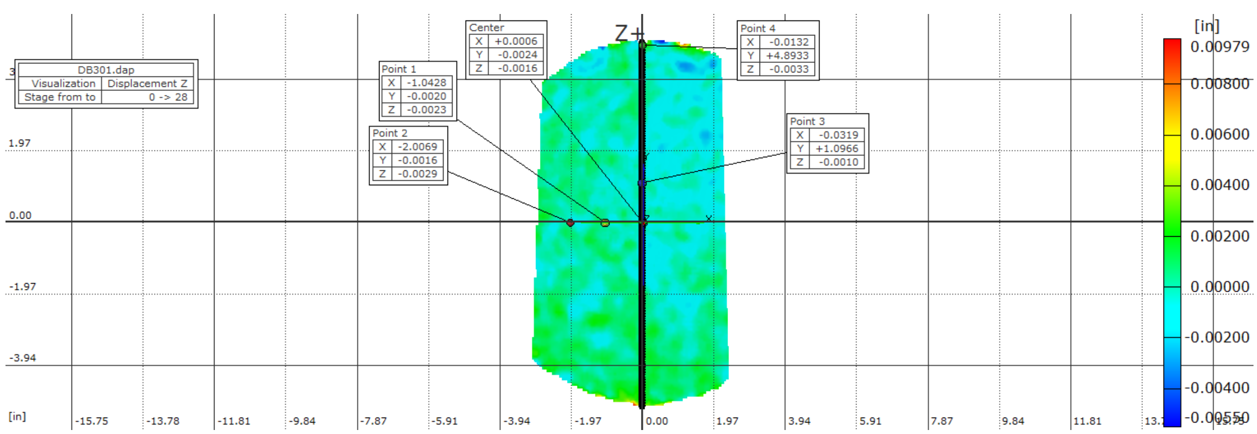


Figure C.84.—DB301: Point locations.

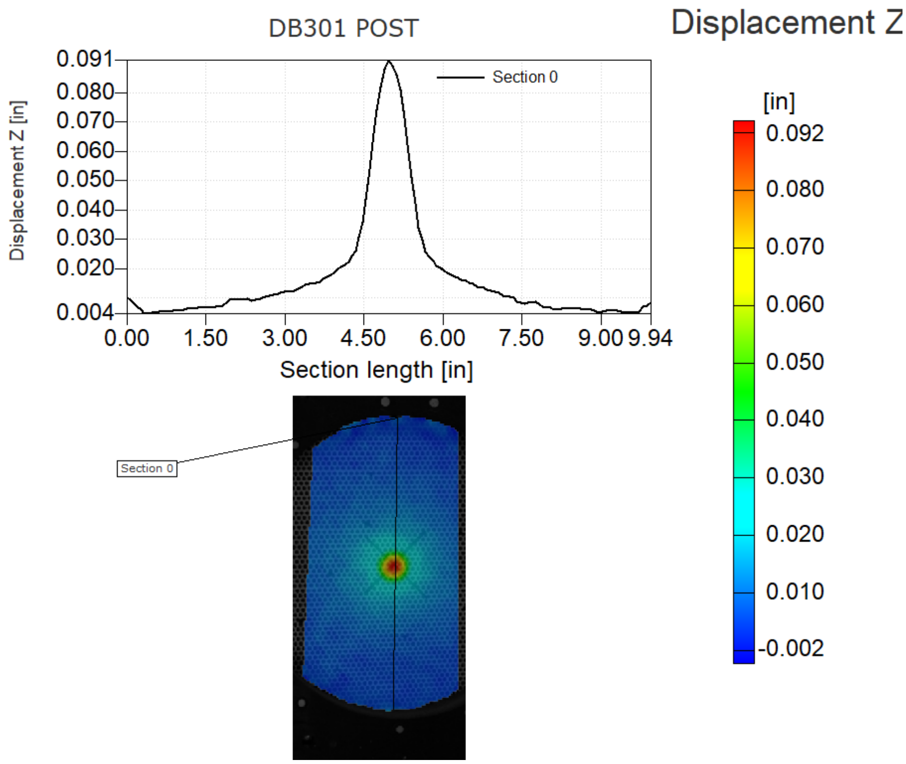


Figure C.85.—DB301: Posttest panel deformation.

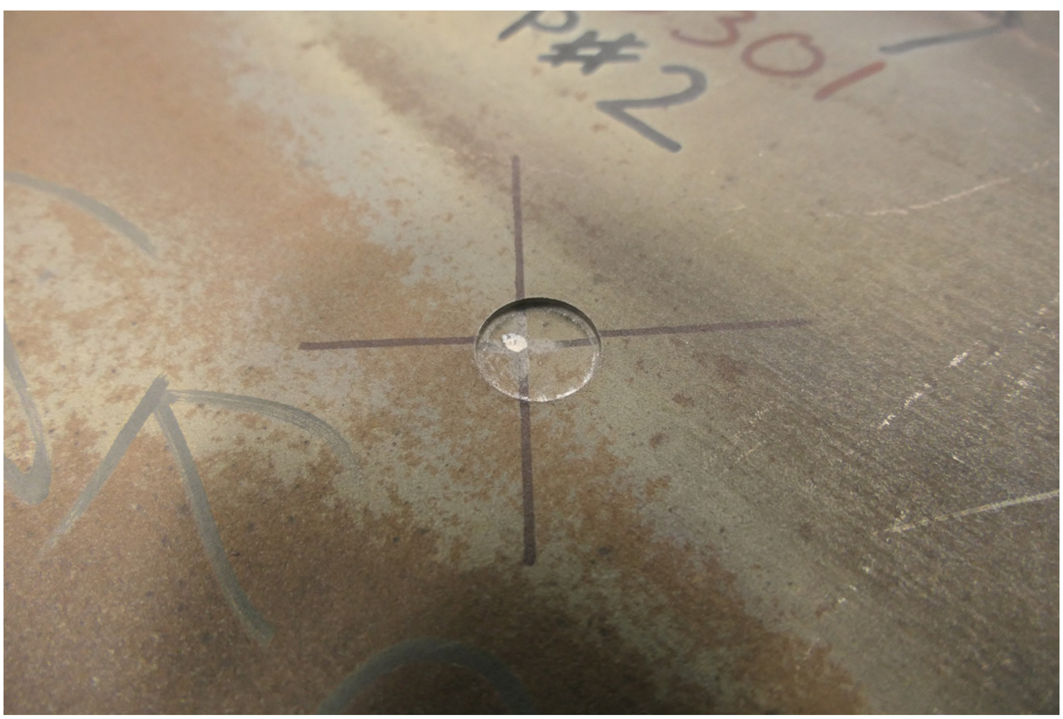


Figure C.86.—DB301: Posttest front view.

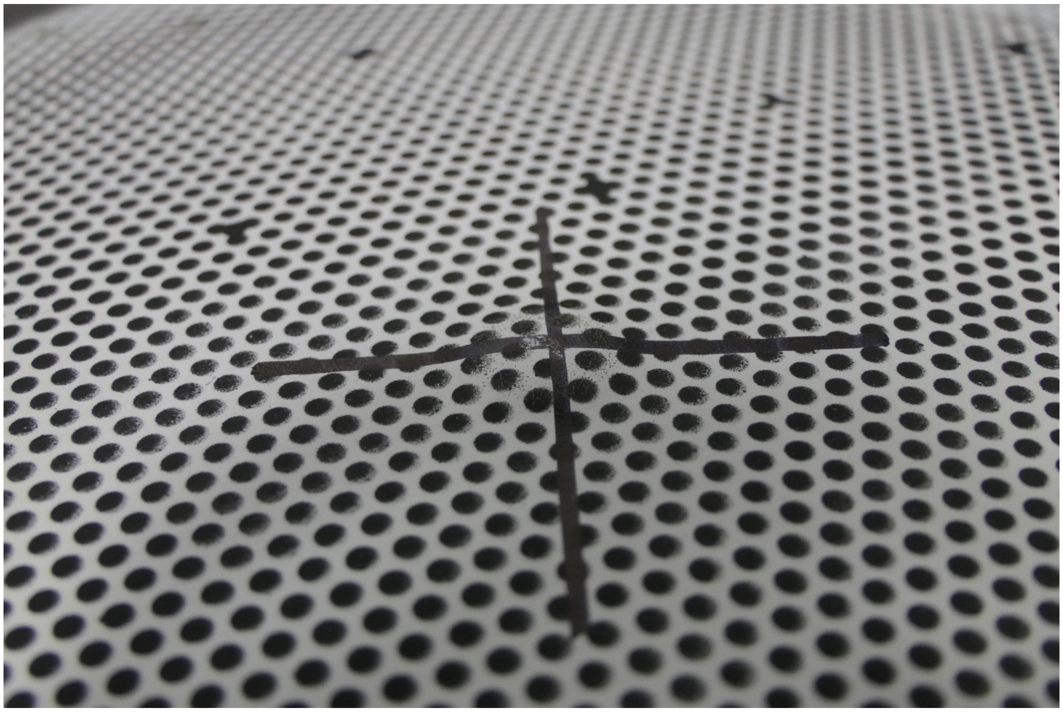


Figure C.87.—DB301: Posttest rear view.

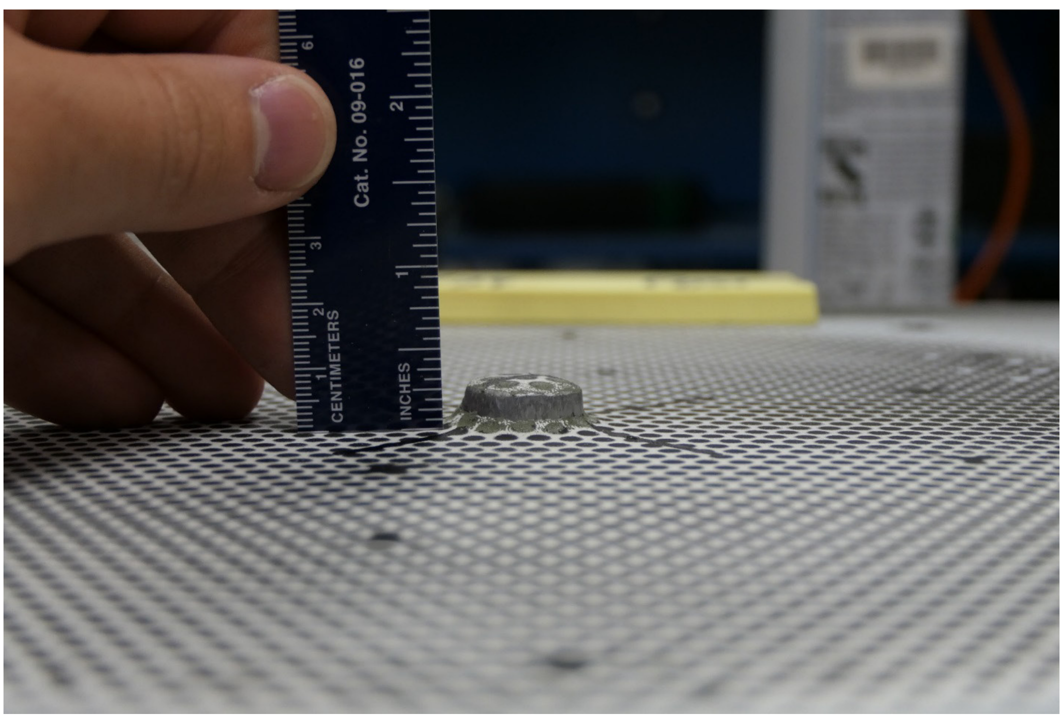


Figure C.88.—DB302: Posttest rear view.

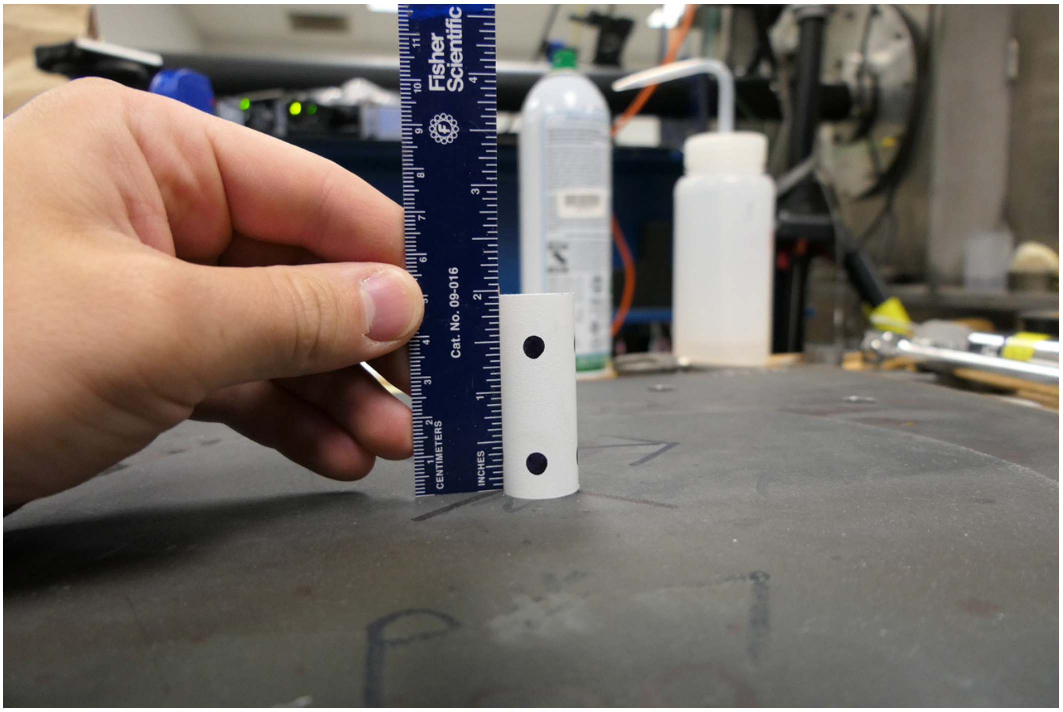


Figure C.89.—DB302: Posttest front view.

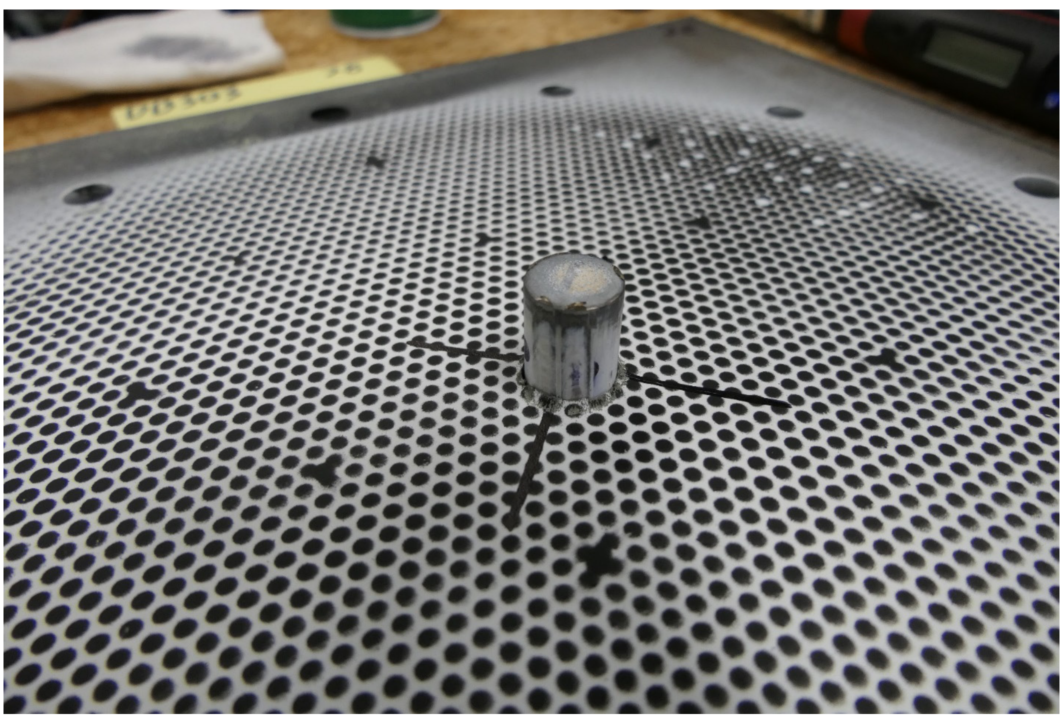


Figure C.90.—DB303: Posttest rear view.

Figure C.91.—DB303: Posttest front view.

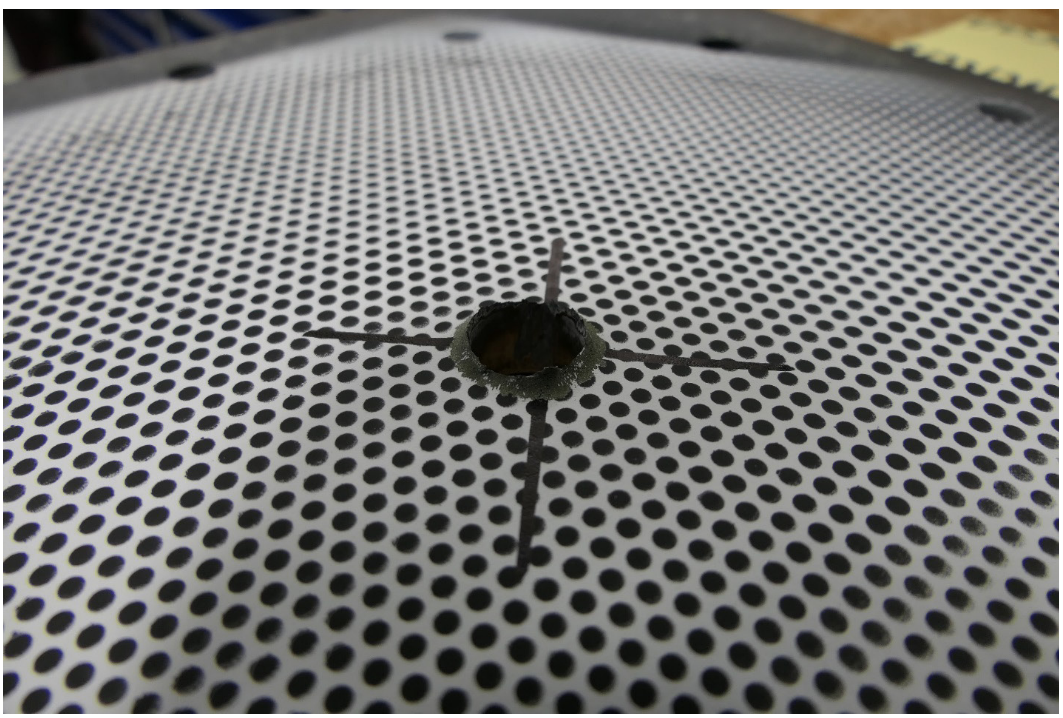


Figure C.92.—DB304: Posttest rear view.

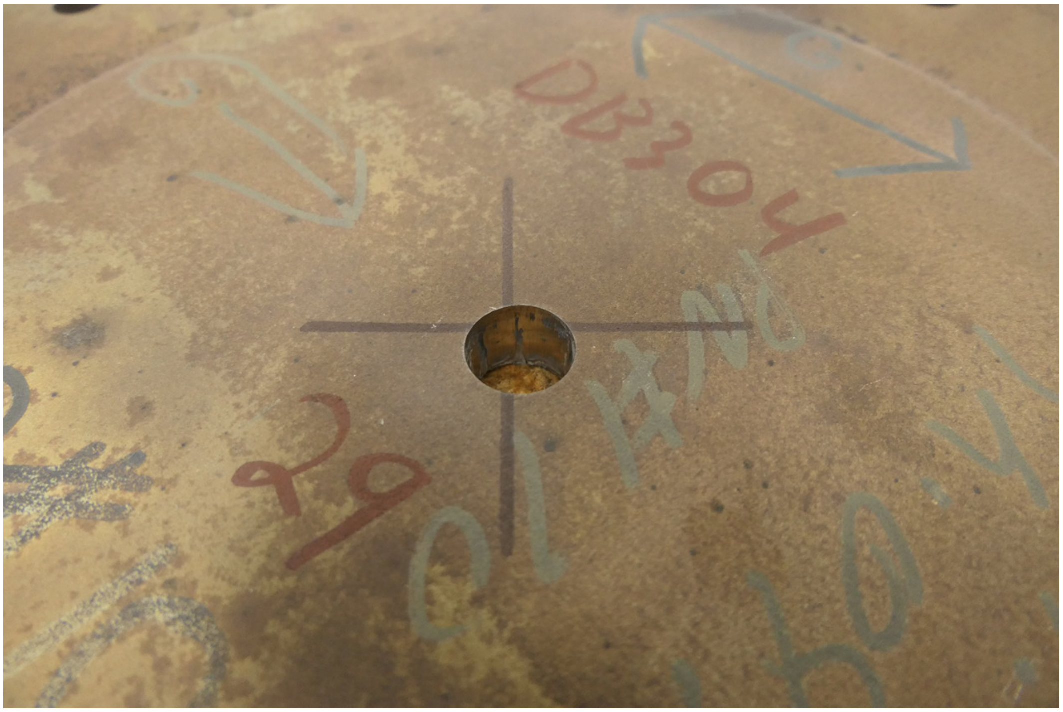


Figure C.93.—DB304: Posttest front view.

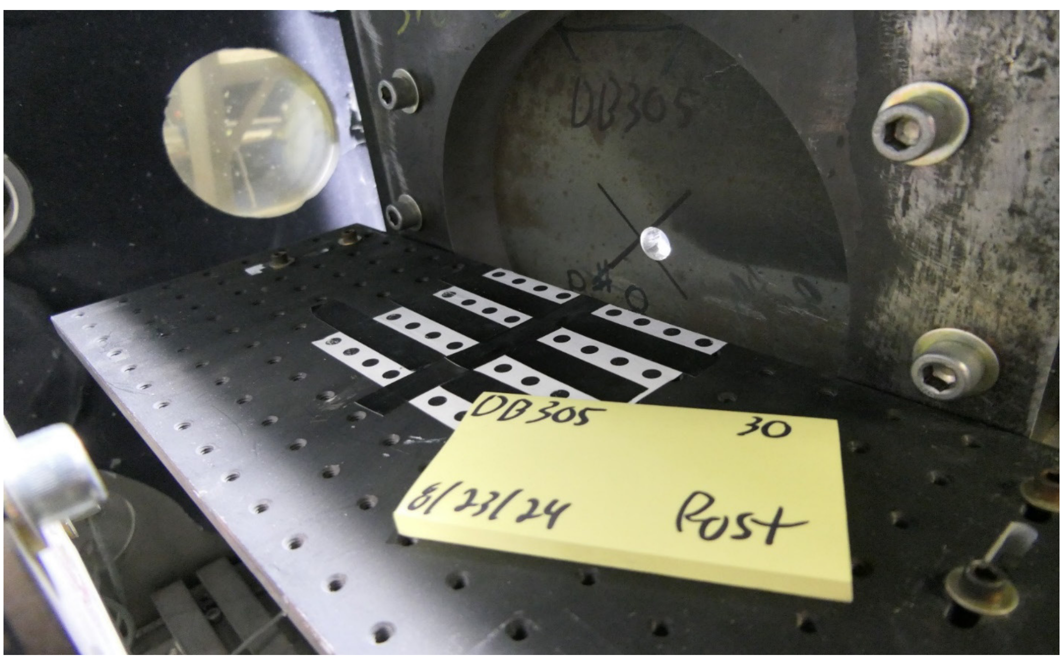


Figure C.94.—DB305: Posttest front view.

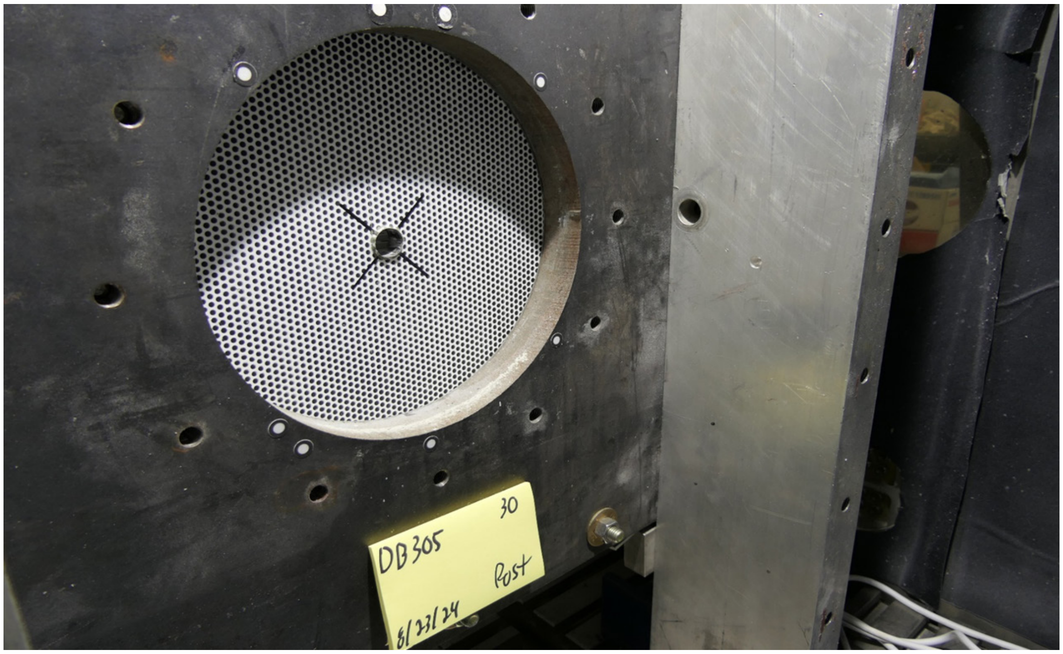


Figure C.95.—DB305: Posttest rear view.


Figure C.96.—DB306: Posttest front view.

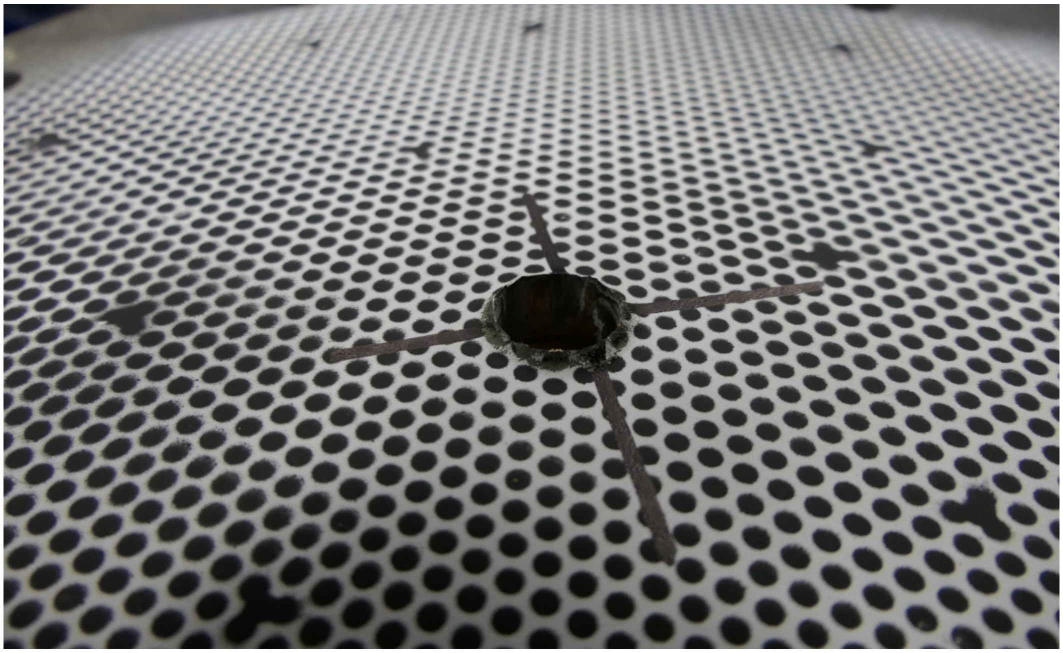


Figure C.97.—DB306: Posttest rear view.

Figure C.98.—DB307: Posttest front view.

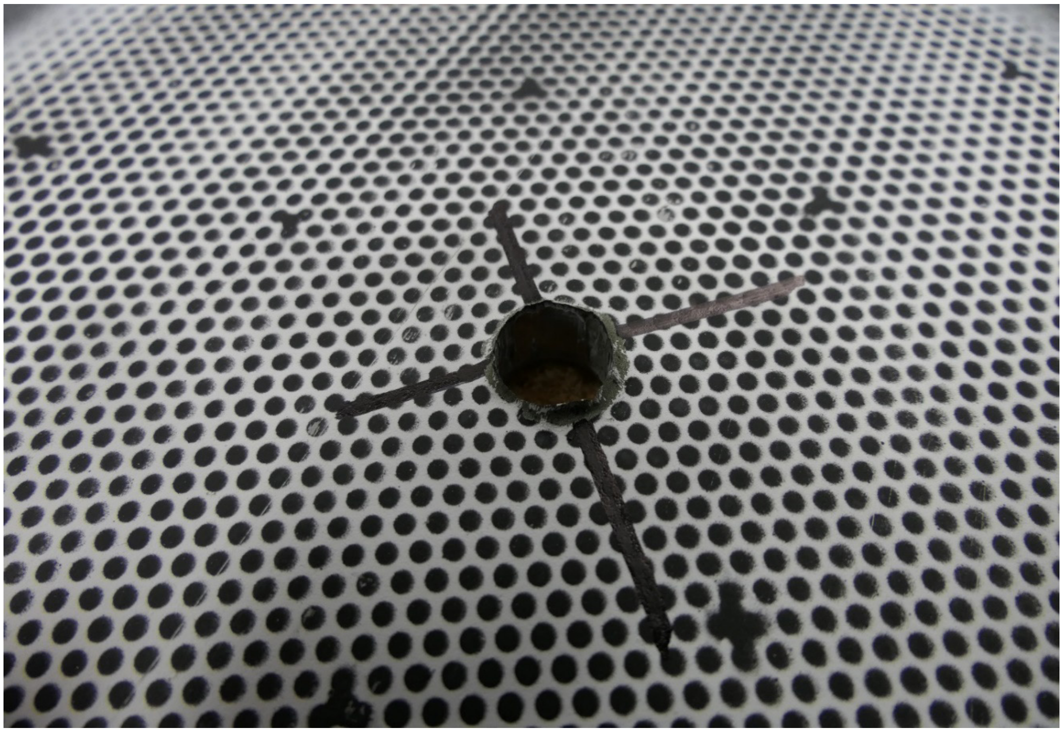


Figure C.99.—DB307: Posttest rear view.

Figure C.100.—DB308: Posttest front view.

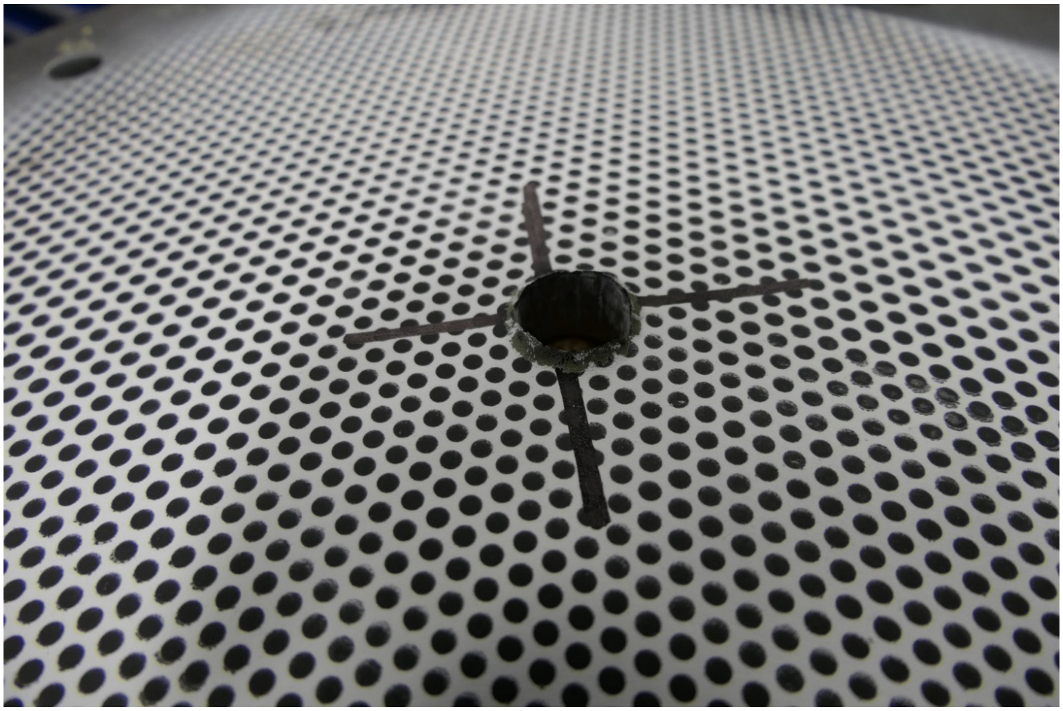


Figure C.101.—DB308: Posttest rear view.

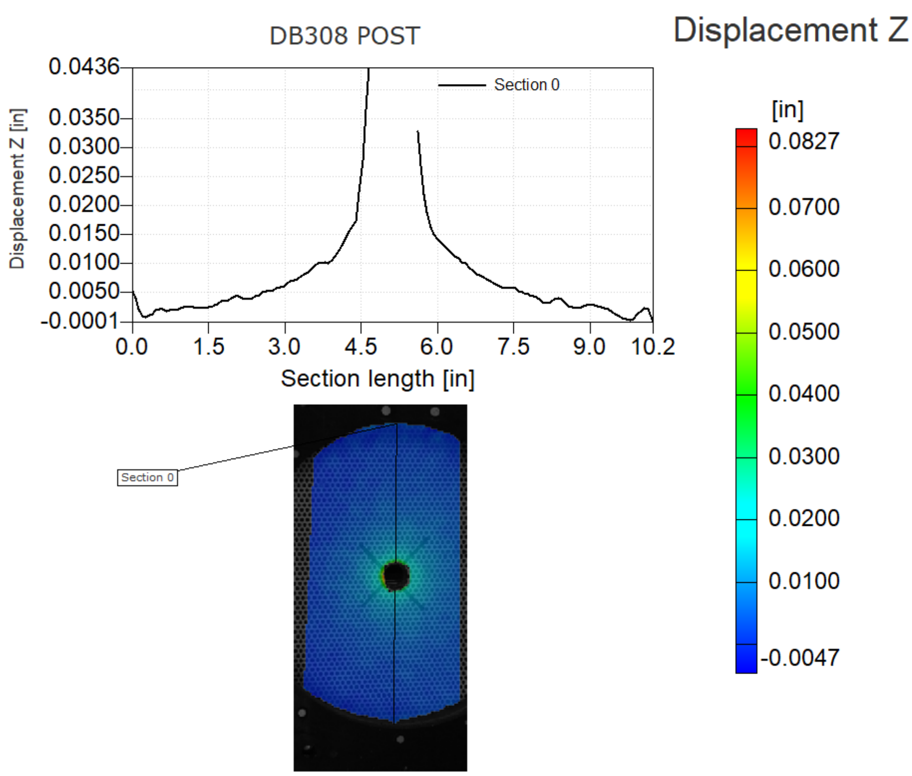


Figure C.102.—DB308: Posttest panel deformation.

Figure C.103.—DB309: Posttest front view.

Figure C.104.—DB309: Posttest rear view.

Appendix D.—Large Panel Deformation Responses and Photographs

Large panel deformation responses and posttest photographs are shown in Figure D.1 to Figure D.30.

Figure D.1.—LG1117: Posttest front view.

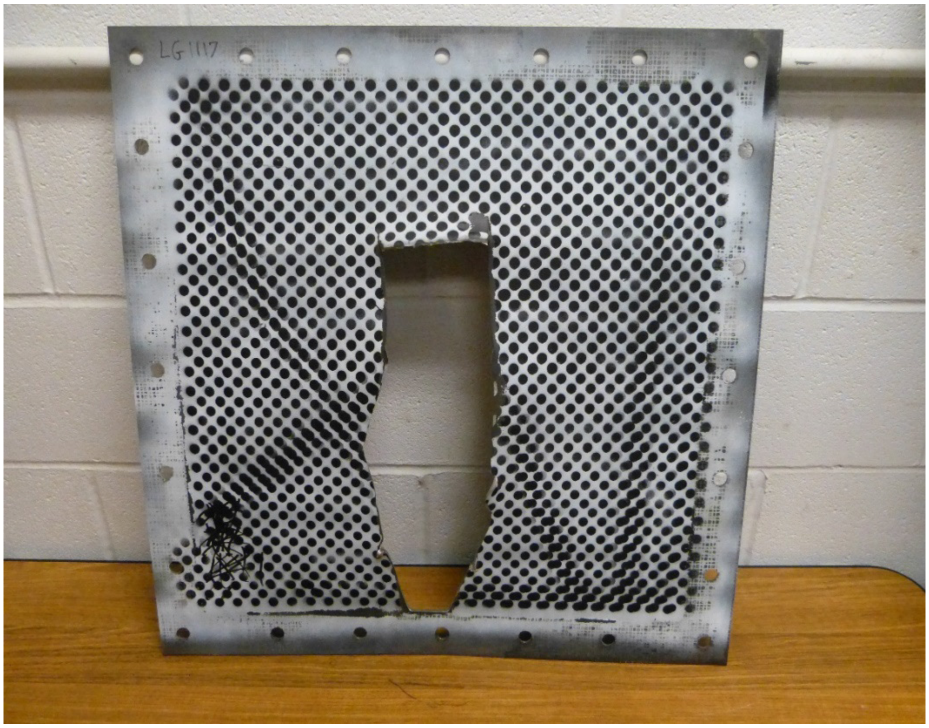


Figure D.2.—LG1117: Posttest rear view.

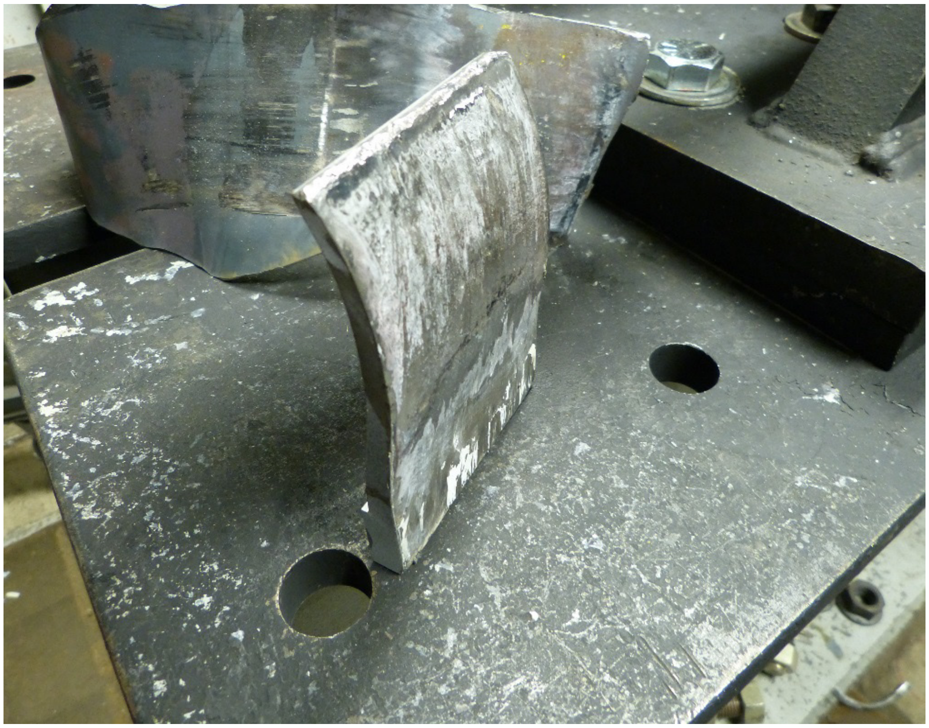


Figure D.3.—LG1117: Posttest projectile.

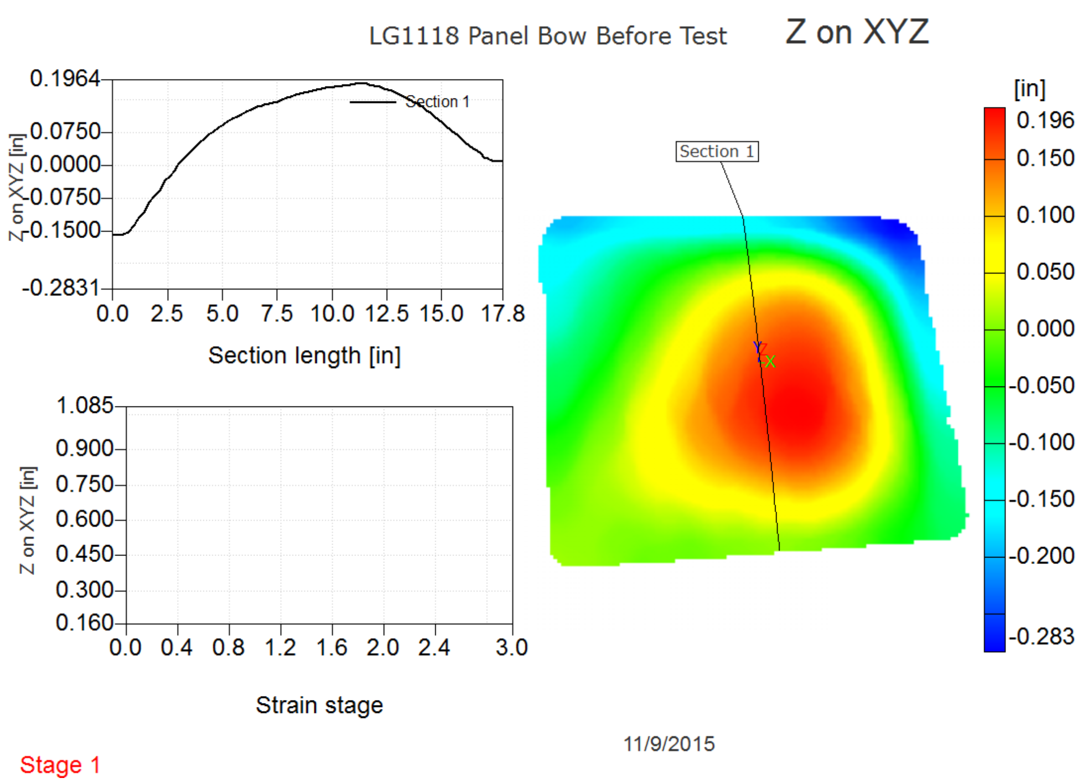


Figure D.4.—LG1118: Panel deformation from heat treatment before test.

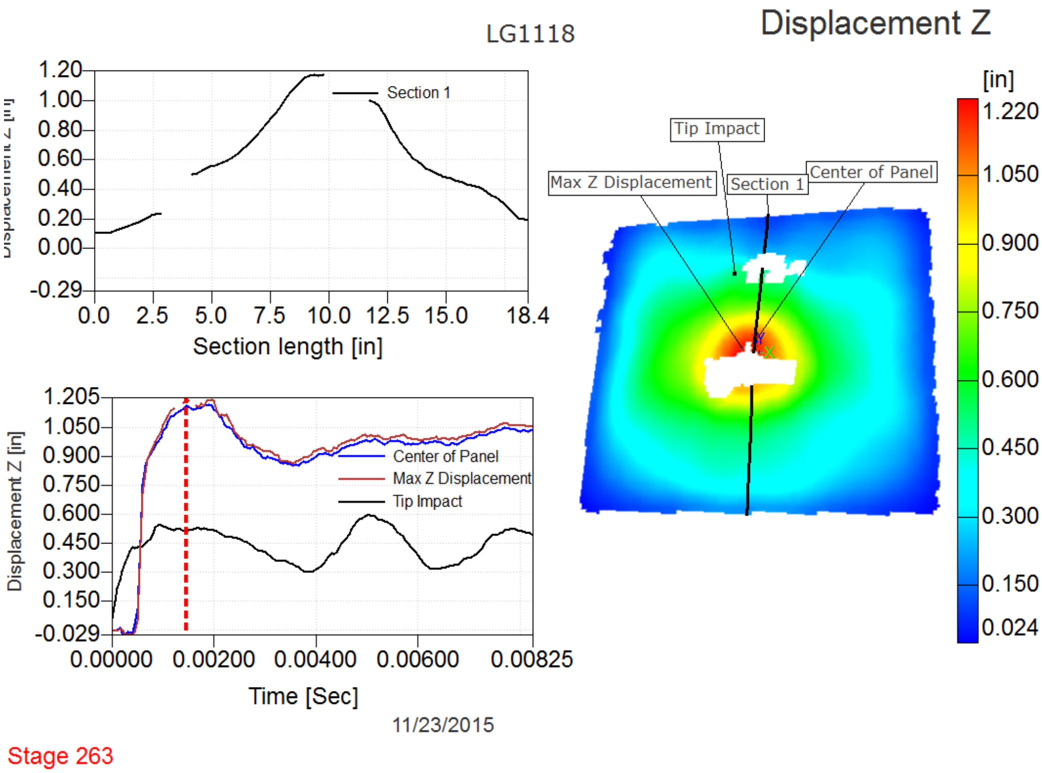


Figure D.5.—LG1118: Out-of-plane displacement at time of maximum displacement.

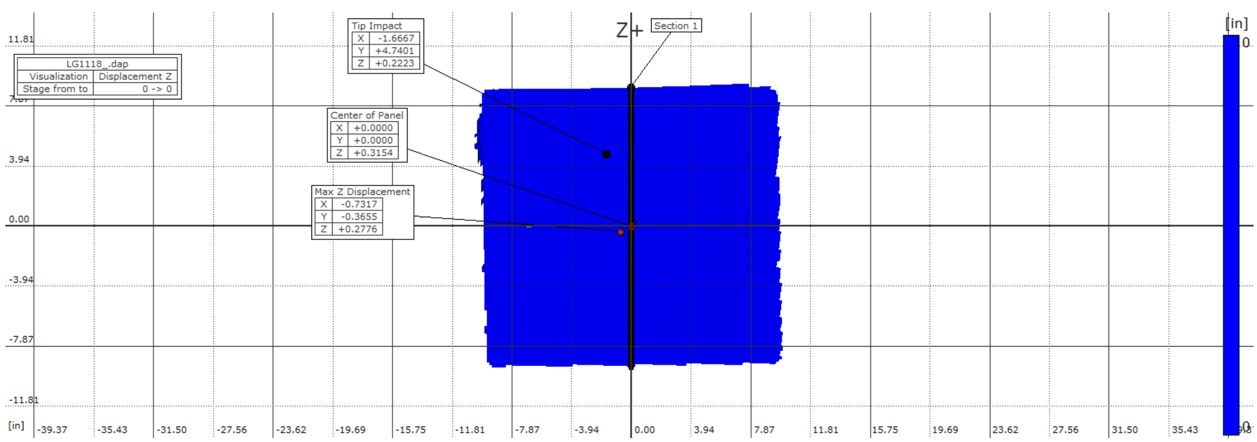


Figure D.6.—LG1118: Point locations.

Figure D.7.—LG1118: Posttest front view.

Figure D.8.—LG1118: Posttest rear view.

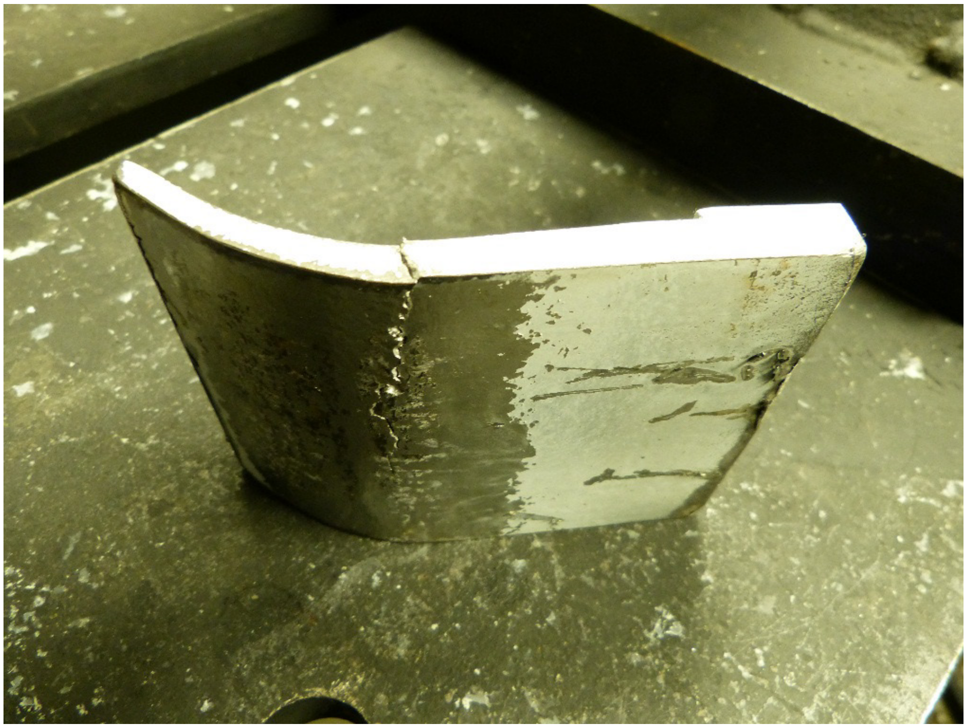


Figure D.9.—LG1118: Posttest projectile.

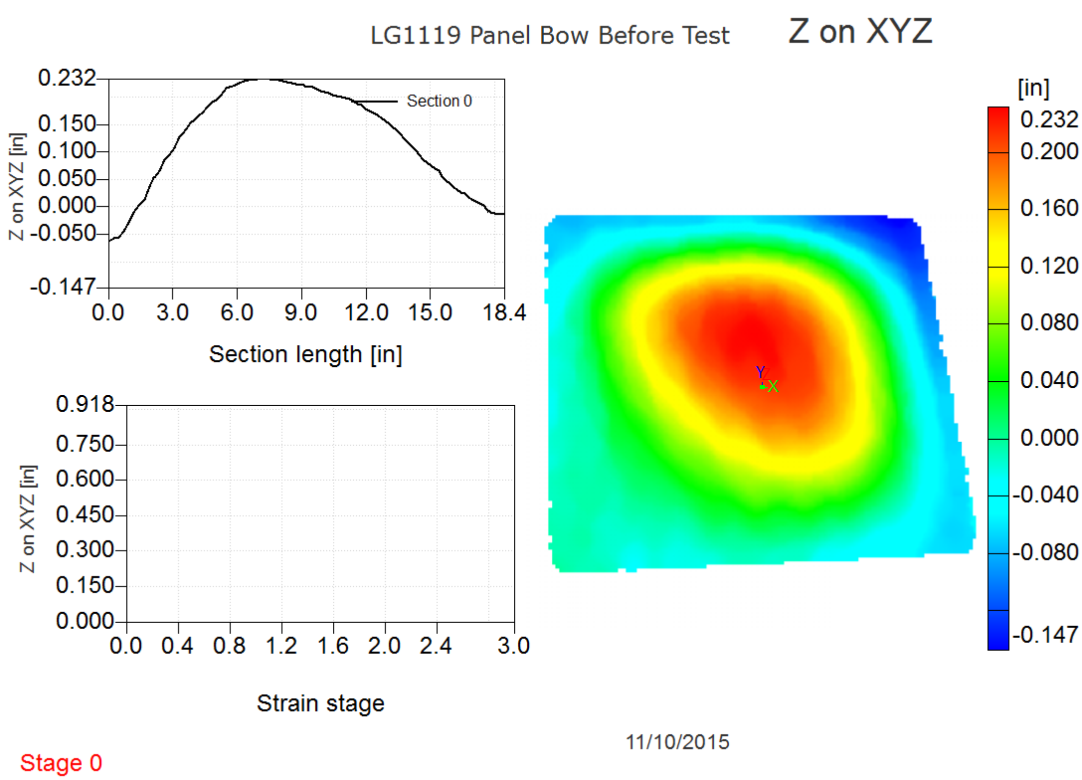


Figure D.10.—LG1119: Panel deformation from heat treatment before test.

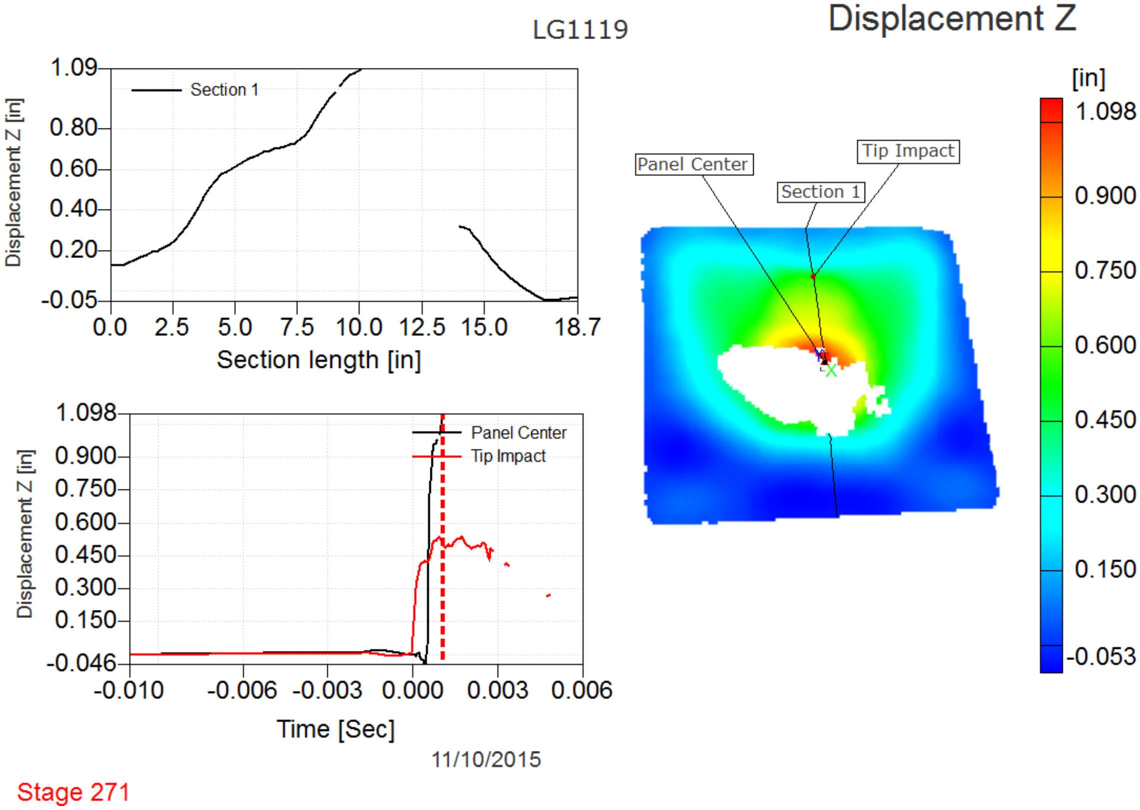


Figure D.11.—LG1119: Out-of-plane displacement at time of maximum displacement.

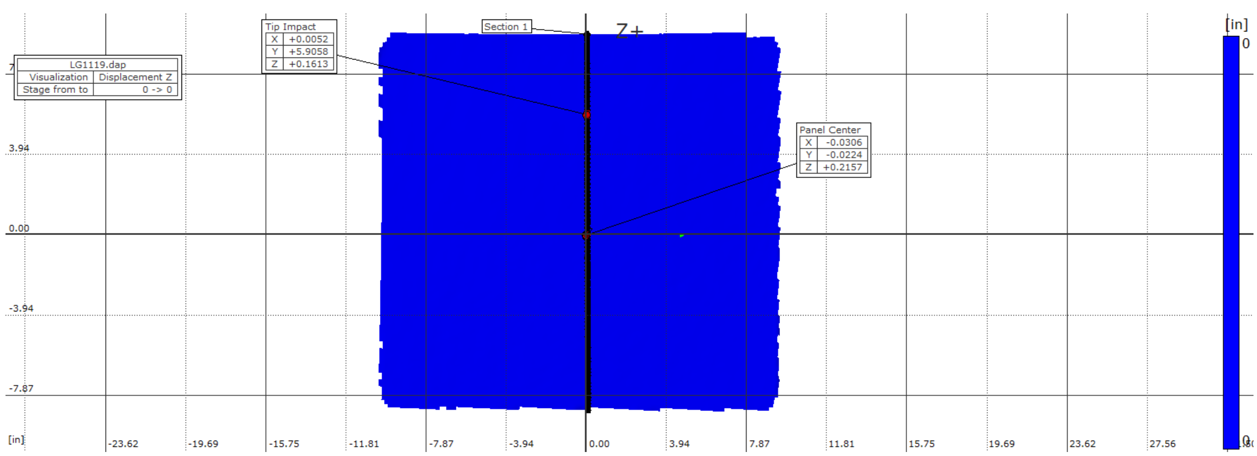


Figure D.12.—LG1119: Point locations.

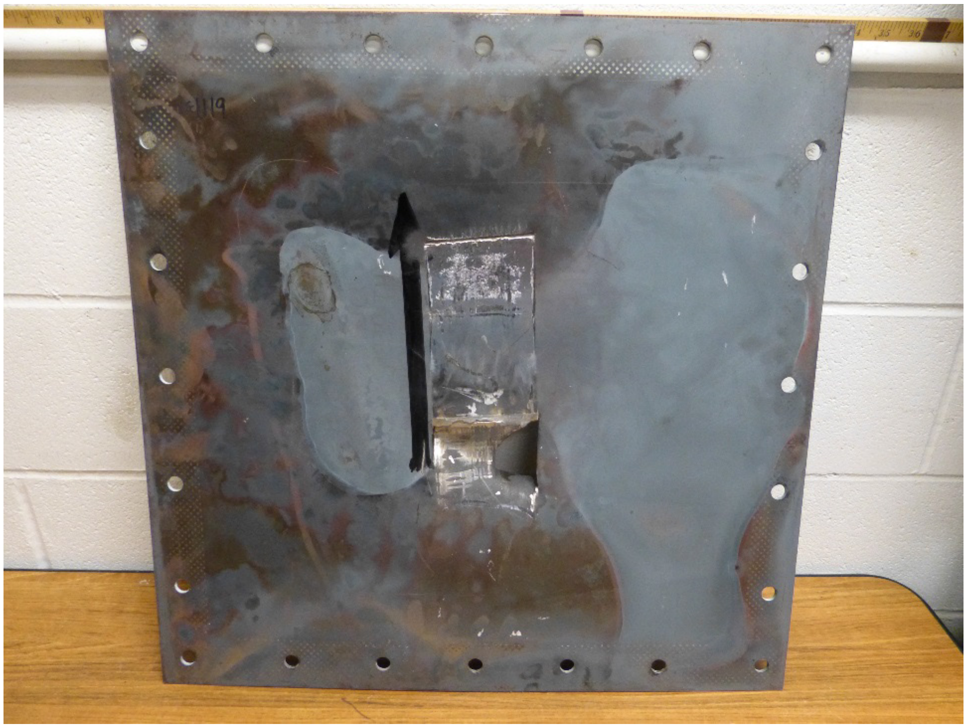


Figure D.13.—LG1119: Posttest front view.

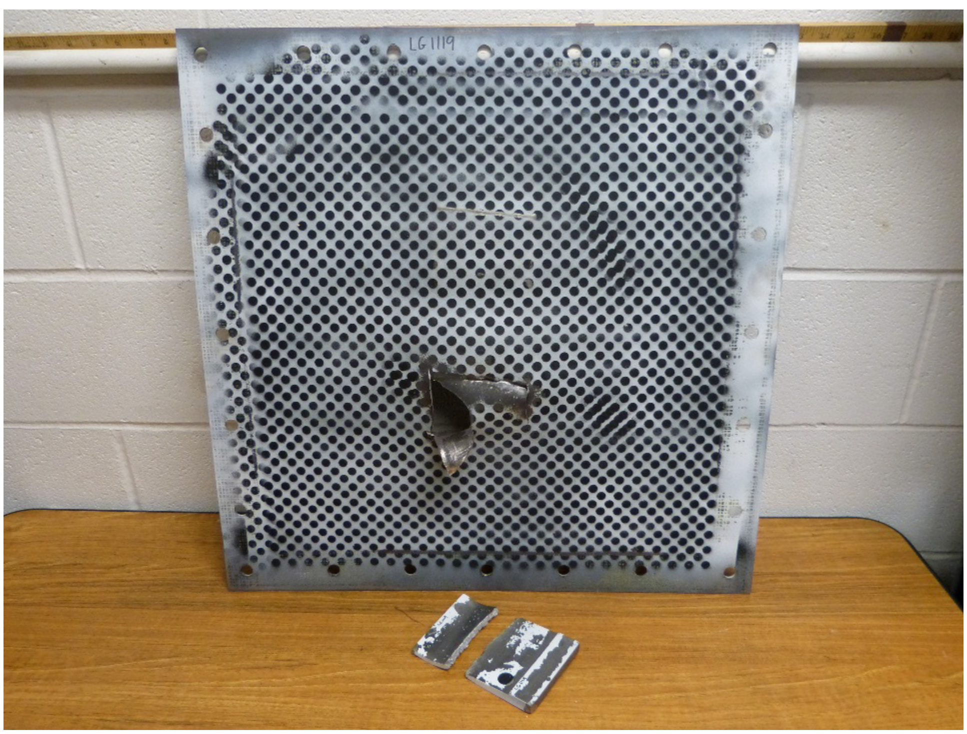


Figure D.14.—LG1119: Posttest rear view.

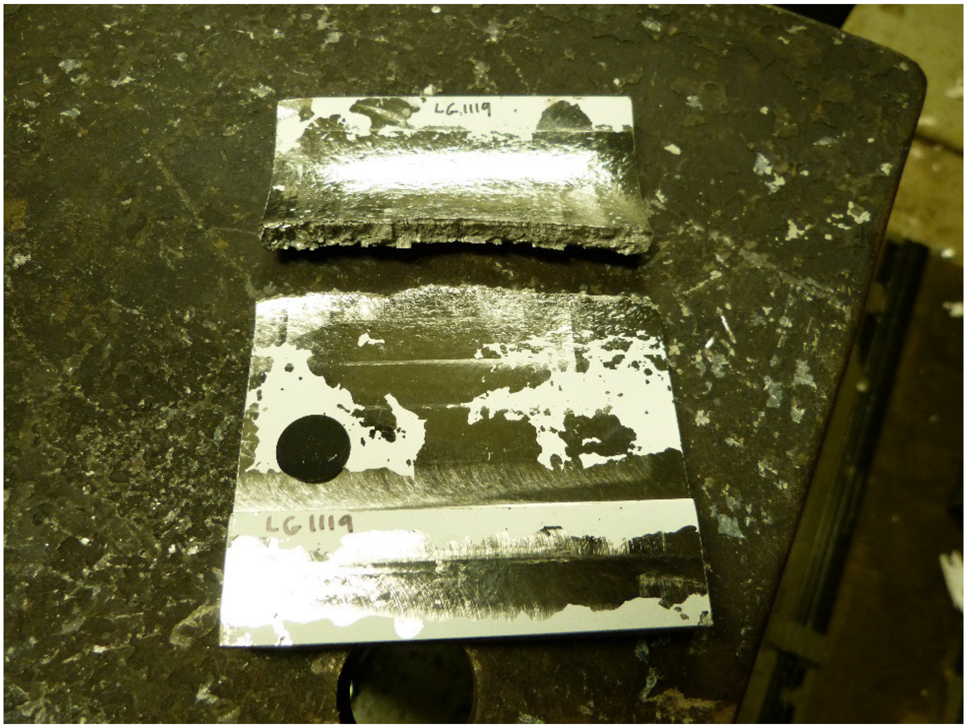


Figure D.15.—LG1119: Posttest projectile.

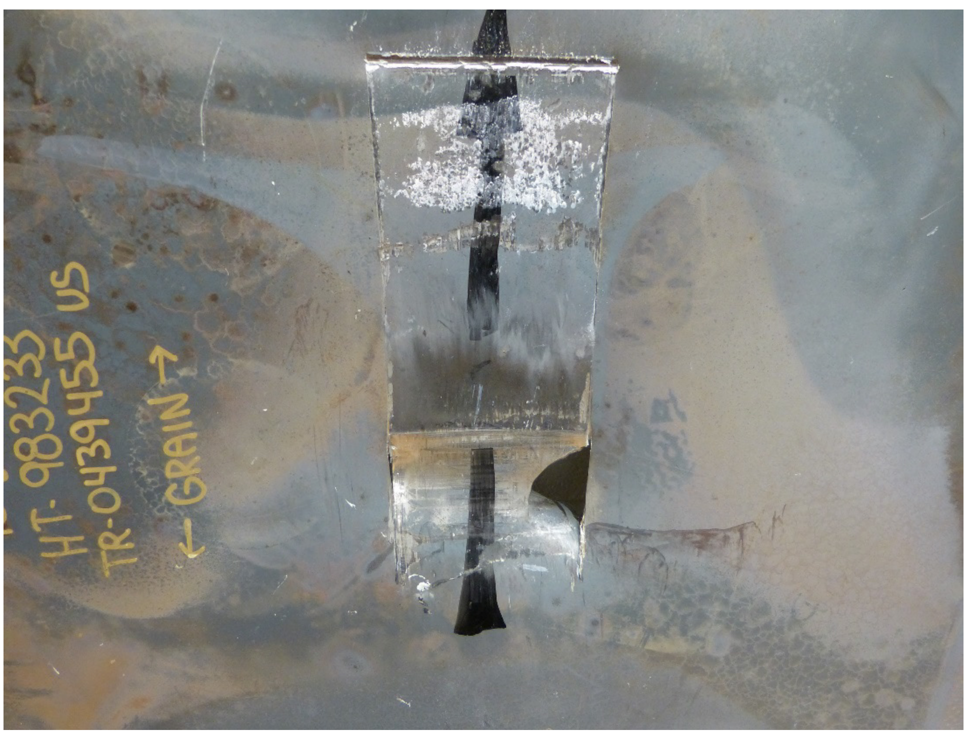


Figure D.16.—LG1120: Posttest front view.

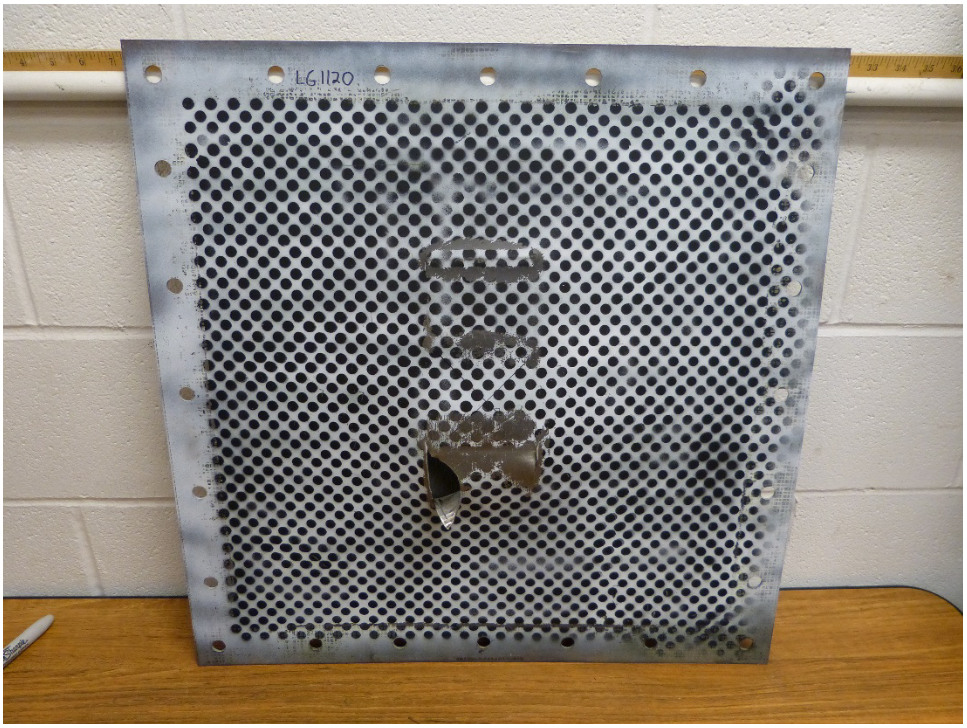


Figure D.17.—LG1120: Posttest rear view.

Figure D.18.—LG1120: Posttest projectile.

Figure D.19.—LG1121: Posttest front view.

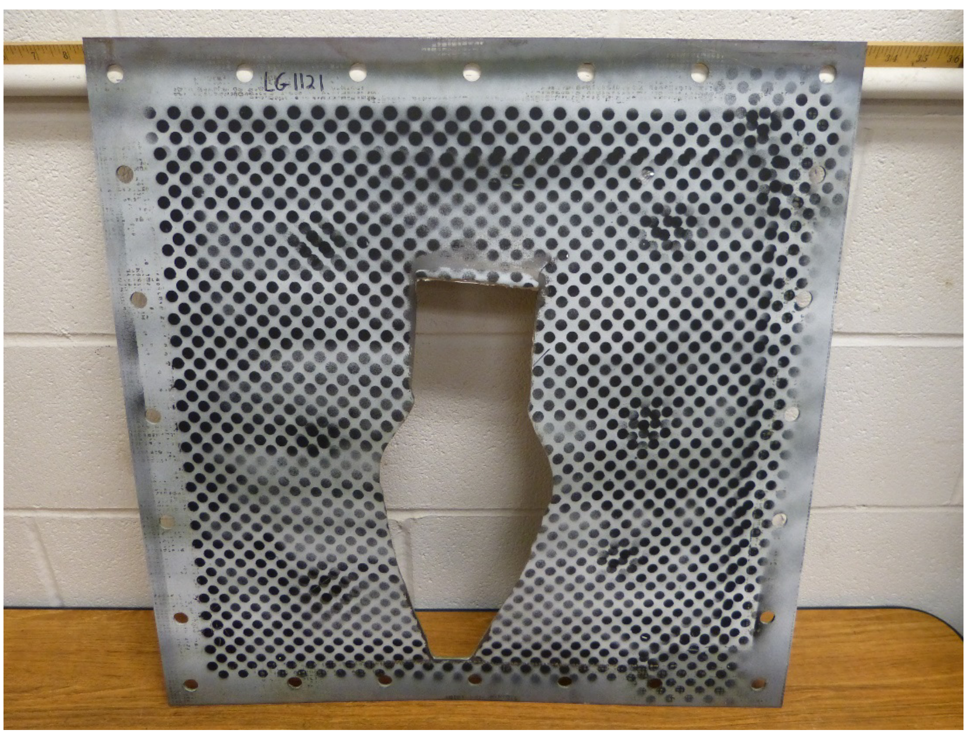


Figure D.20.—LG1121: Posttest rear view.

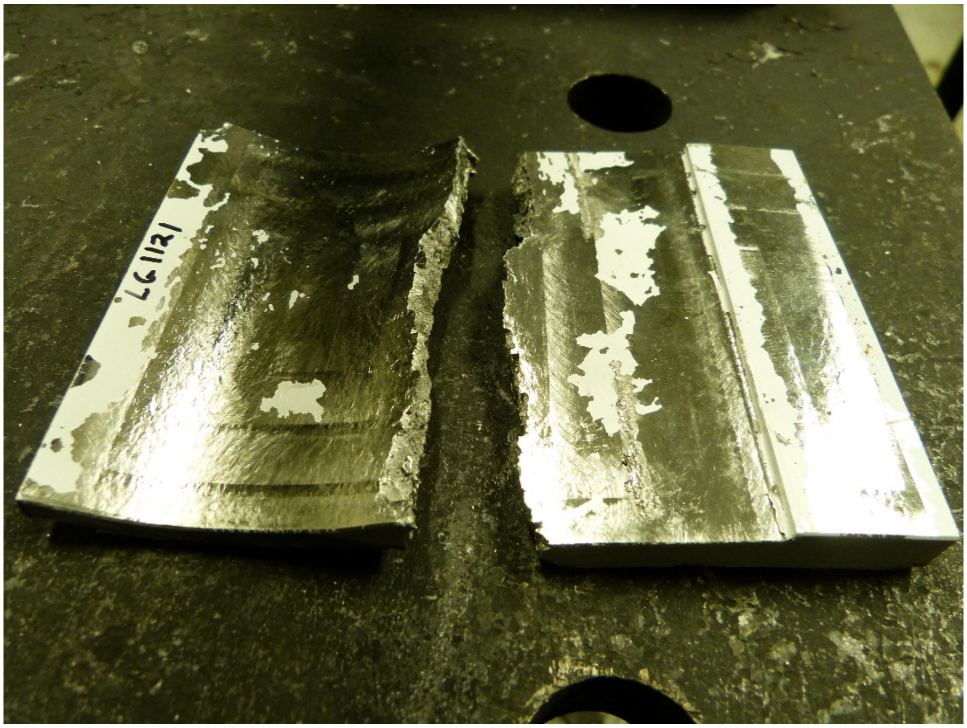


Figure D.21.—LG1121: Posttest projectile.

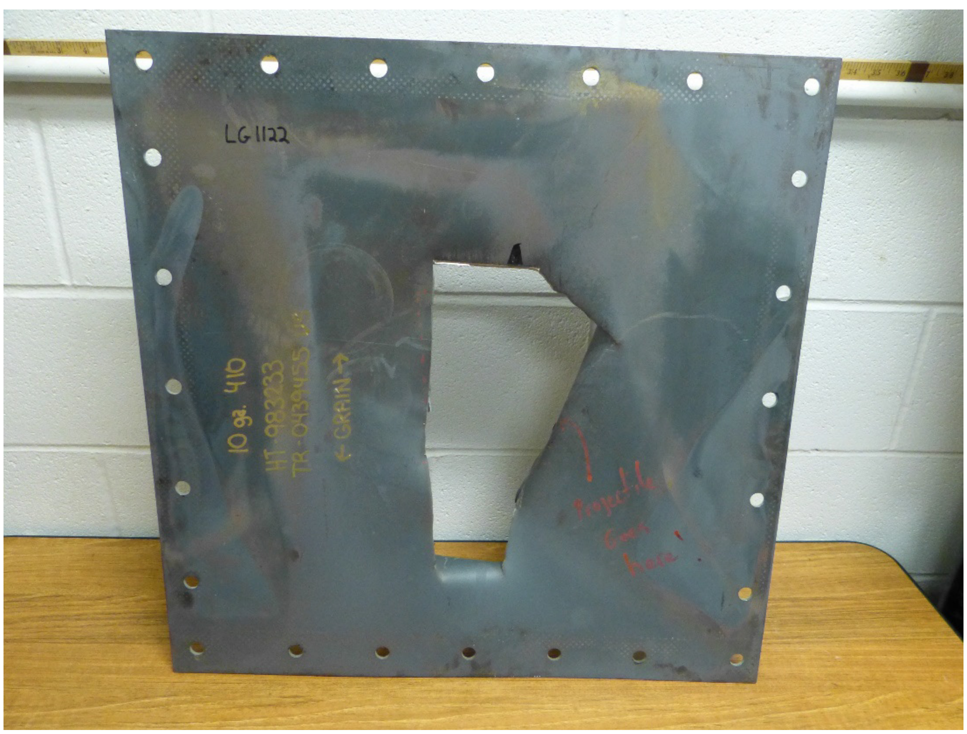


Figure D.22.—LG1122: Posttest front view.

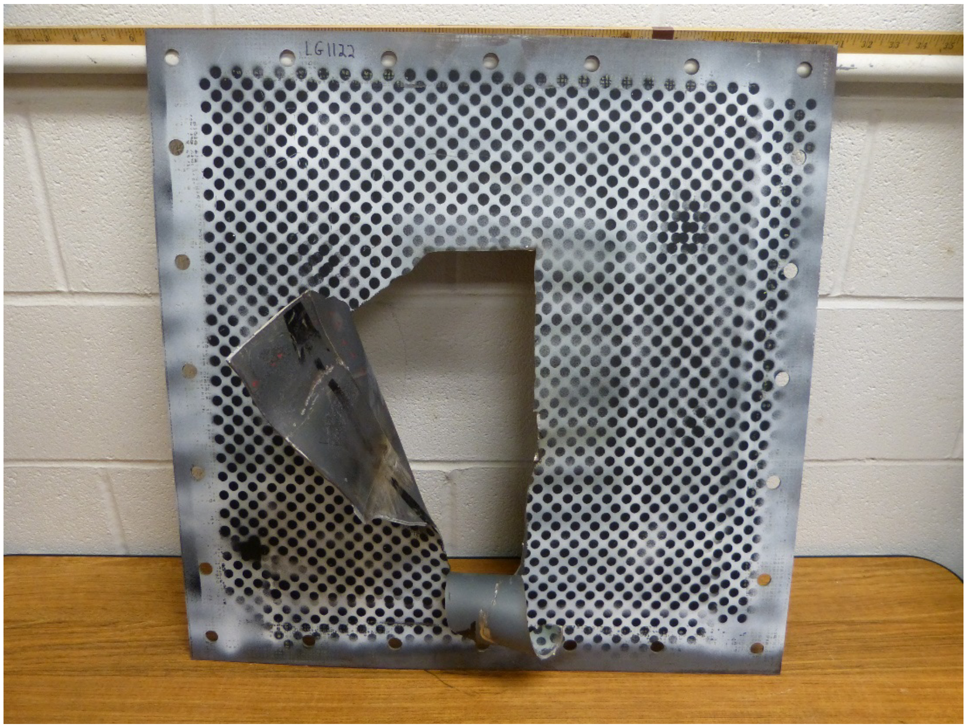


Figure D.23.—LG1122: Posttest rear view.

Figure D.24.—LG1122: Posttest projectile.

Figure D.25.—LG1123: Posttest front view.

Figure D.26.—LG1123: Posttest rear view.

Figure D.27.—LG1123: Posttest projectile.

Figure D.28.—LG1124: Posttest front view.

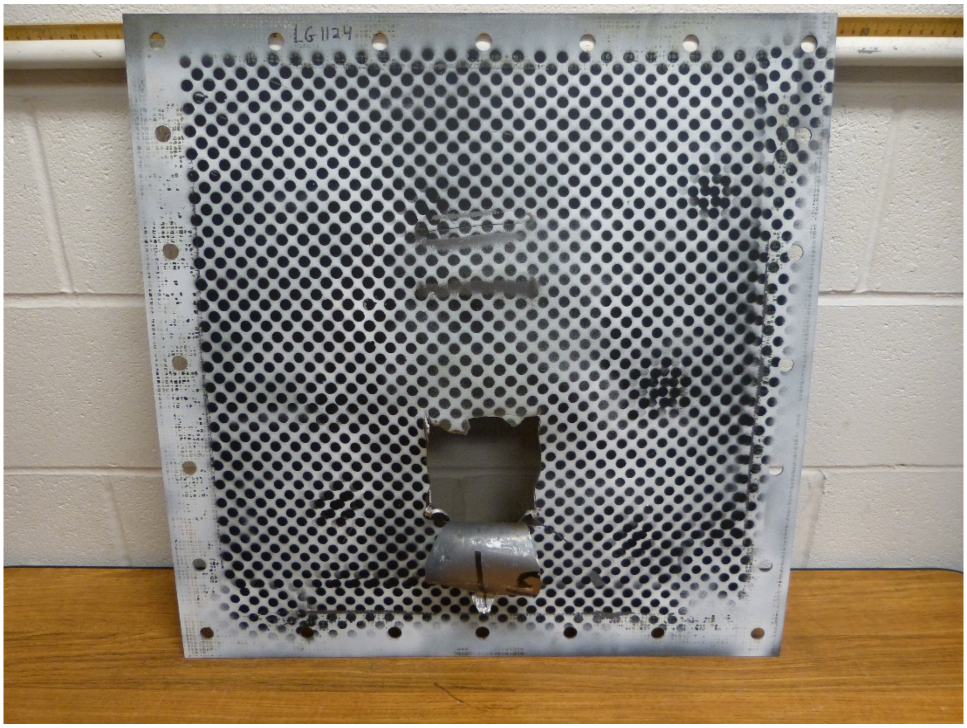


Figure D.29.—LG1124: Posttest rear view.

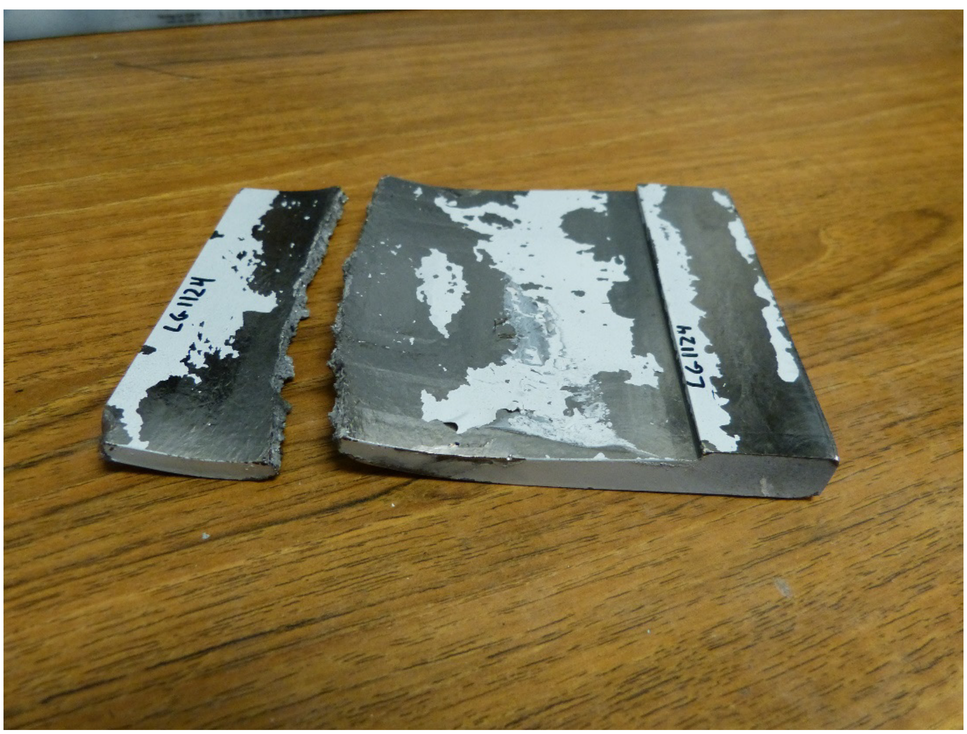


Figure D.30.—LG1124: Posttest projectile.

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1. Pereira, J.M., Revilock, D.M., Lerch, B.A. and Ruggeri, C.R., “Impact Testing of Aluminum 2024 and Titanium 6Al-4V for Material Model Development,” NASA/TM—2013-217869 (DOT/FAA/TC–12/58), Oct. 2014.
2. Pereira, J.M., Revilock, D.M. and Ruggeri, C.R., “Impact Testing of Inconel 718 for Material Impact Model Development,” NASA/TM-2020220451 (DOT/FAA/TC-19/40), June 2020.