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Impact Testing of Aluminum 2024 and Titanium 6Al-4V for Material Model Development

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

An Erratum was added to this report October 2014.

May 2013

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National Aeronautics and
Space Administration

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Acknowledgments

The authors recognize the work of Dr. Richard Rogers in performing the texture analyses.

Erratum

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Table 6(e), column 5: Header has been changed to read as follows:

(e) Impact Results for 0.5 in. Thick Ti-6Al-4V

Test	Projectile mass, gram	Projectile impact velocity, ft/sec	Projectile exit velocity, ft/sec	Plug exit velocity, ft/sec	Plug depth, in.	Comments
DB177	126.3	896	475	620	Full	Penetrated
DB178	126.4	865	424	522	Full	Penetrated
DB179	126.2	713	241	360	Full	Penetrated
DB180	126.2	646	152	310	Full	Penetrated
DB182	126.4	527	0	0	.053	Contained
DB184	126.3	581	0	0	.237	Contained
DB185	126.2	597	0	0	.308	Contained
DB186	126.4	578	0	0	.187	Contained
DB192	126.3	630	0	153	Full	Contained/plug released
DB193	126.3	629	104	226	Full	Penetrated
DB195	126.3	616	0	132	Full	Contained/plug released

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Executive Summary

One of the difficulties with developing and verifying 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 different sources. In addition there is often a lack of quantitative measurements in 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, impact test data and failure analysis for a variety of 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 FAA William J. Hughes Technical Center. Unique features of this set of data are that all material property data and impact test data are obtained using identical material, the test methods and procedures are extensively documented and all of the raw data is available. Four parallel efforts are currently underway: Measurement of material deformation and failure response over a wide range of strain rates and temperatures and failure analysis of material property specimens and impact test articles conducted by The Ohio State University; development of improved numerical modeling techniques for deformation and failure conducted by The George Washington University; impact testing of flat panels and substructures conducted by NASA Glenn Research Center.

This report describes impact testing which has been done on aluminum (Al) 2024 and titanium (Ti) 6Al-4vanadium (V) sheet and plate samples of different thicknesses and with 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.

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Glenn Research Center
Cleveland, Ohio 44135

1.0 Introduction

Numerical simulation of dynamic impact events has reached a level of maturity at which it is commonly used as a design tool for a wide variety of aerospace structures such as jet engine containment systems, fan blades, radomes and cowlings. However, current efforts require extensive testing in parallel with modeling and it is often necessary to adjust model parameters somewhat arbitrarily in order that the model fit 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, the contact models, the mesh density, and a number of different numerical parameters that must be specified in the computer codes.

One of the difficulties with developing and verifying 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 different sources. In addition there is often a lack of quantitative measurements in 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 (GRC) and the FAA William J. Hughes Technical Center. Unique features of this set of data are that all material property data and impact test data are obtained using identical material, the test methods and procedures are extensively documented and all of the raw data is 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 which has been done on aluminum (Al) 2024 and titanium (Ti)-6aluminum (AL)-4vanadium (V) sheet and plate samples of different thicknesses and with different types of projectiles, one a regular cylinder and one with a more complex geometry incorporating features representative of a generic jet engine fan blade fragment—called the NASA Generic Fan Blade Fragment (NGFBF). Procedures and results are reported in detail, and information on 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.

2.0 Methods

Impact tests were conducted on flat Al-2024T3/T351 and Ti-6AL-4V panels with two different areal dimensions, 24- by 24-in. large panel and 15- by 15-in. small panel. The smaller panels were impacted in a normal direction with a cylindrical projectiles ranging in diameter from 0.5 to 0.75 in. The larger panels were impacted by the NGFBF as a simplified simulation of a blade impacting containment structure 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 back side of the panels and post-test metallography was selectively performed to characterize the material microstructure and damage and failure in the test specimens.

2.1 Materials

Impact tests were conducted on Al-2024 T3/T351 (AMS 4037) and Ti-6Al-4V (AMS 4911) sheet and plate material of the thicknesses shown in Table 1. The nominal thickness is the thickness stated on the certification sheet and the actual thickness is based on averages of multiple measurements of the as-received material. The material certification sheets are given in Appendix A. For consistency, future reference to target thickness in this report refers to the nominal thickness of the material.

TABLE 1.—TEST SPECIMEN NOMINAL AND MEASURED THICKNESSES (in.)

		Small panel				Large panel
Al-2024	Nominal		0.125	0.25	0.5	0.5
	Actual		0.126	0.255	0.503	0.503
Ti-6Al-4V	Nominal	0.09	0.14	0.25	0.5	0.09
	Actual	0.092	0.135	0.254	0.515	0.092

2.1.1 Material Chemistry

Chemistry was checked by spectroscopy at GRC for all of the plates tested in this study. The results for Al-2024T3/T351 are shown in Table 2 and are within the ranges given in AMS 4037.

TABLE 2.—Al-2024 CHEMISTRY (wt %)

Element	Panel thickness (in.)			AMS 4037N	
	0.125	0.25	0.5	Min	Max
Cr	0.003	0.032	0.01		0.1
Cu	4.41	4.32	4.21	3.8	4.9
Fe	0.12	0.25	0.19		0.5
Mg	1.43	1.26	1.27	1.2	1.8
Mn	0.60	0.55	0.55	0.3	0.9
Si	0.06	0.10	0.1		0.5
Ti	0.032	0.017	0.019		0.15
Zn	0.09	0.12	0.17		0.25
Al	Balance	Balance	Balance		Balance

The chemical results for Ti-6Al-4V from NASA spectroscopy analysis are shown in Table 3. The columns in Table 3 labeled “Cert” refer to the values given in the material certification sheets in Appendix A. The chemical composition of the Ti-6-4 materials is consistent with the ranges specified in AMS 4911.

TABLE 3.—Ti-6Al-4V CHEMISTRY (wt %)

Element	Panel thickness, in.								AMS 4911J	
	0.09	Cert	0.135	Cert	0.25	Cert	0.5	Cert	Min	Max
Al	6.74	6.16	6.56	6.27, 6.32	6.13	5.91, 6.03	6.64	6.27	5.50	6.75
V	4.07	3.82	3.99	3.94, 4.03	3.97	4.00, 4.02	4.04	4.08	3.50	4.50
Fe	0.16	0.17	0.15	0.13, 0.16	0.18	0.19, 0.20	0.13	0.16		0.30
O	0.151	0.150	0.146	0.162, 0.145	0.173	0.185, 0.200	0.190	0.170		0.20
C	0.003	0.009	0.017	0.023, 0.027	0.016	0.020, 0.020	0.011	0.016		0.08
N	0.006	0.005	0.006	0.004, 0.005	0.006	0.006, 0.007	0.006	0.006		0.05
Ti	Balance	Balance	Balance	Balance	Balance	Balance	Balance	Balance	Balance	Balance

2.1.2 Material Texture and Microstructure

The texture and microstructure of all materials used in this study were examined. Techniques and results are given for texture in Appendix B. The aluminum plates were found to have cube textures typical of annealing textures observed in face center cubic (FCC) structure materials. The Ti-6Al-4V plates had either basal or transverse textures typical of hexagonal close packed structure (HCP) materials. For both materials the sharpness of the texture (degree of anisotropy) in each plate varied from plate to plate. This is most likely due to the specific thermal-mechanical processing history rather than a direct consequence of the plate thickness. Therefore, any future plate could have more or less texture than those observed in this study.

Appendix C describes the microstructures for each plate. The aluminum plates exhibit pancake-shape grains typical of aluminum alloys with their longest dimension in the rolling direction. The 1/8 in. thick aluminum has the most equiaxed and the smallest grains. The Ti-6Al-4V plates each have their own unique microstructure dependent on their thermal-mechanical history, yet typical of alpha-beta titanium alloys.

Appendix D is a description of material pedigree for separate purchases of Ti-6Al-4V plates to permit some comment on the variation in pedigree. The additional plates had normal chemistry and microstructure for annealed Ti-6-4. The textures were typical of rolled plate. The degree of anisotropy as given by the texture index was no greater than 1.54 for all eight plates examined.

2.2 Small Panel Test Setup

Twelve Ti-6Al-4V and fifteen Al-2024 target ballistic impact tests were conducted on each of the different thickness target panels shown in Table 1, with the exception of the 0.5 in. thick Ti-6Al-4V for which limited material was available. The projectiles were cylindrical with a large radius almost flat front face and impacted the plates in a normal orientation at the center of the plate. The only exception to this was with the 0.5 in. thick Ti-6Al-4V specimens, for which there were only eleven impact tests and multiple impacts were conducted on each panel, at least 3 in. away from each other. The 0.5 in. thick Ti-6Al-4V multiple tests on a single panel was considered acceptable as the damage was highly localized. The tests were designed such that the ballistic limit velocity for the particular combinations of projectiles and panels was in the range of 600 to 900 ft/sec. 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 ballistic limit so that some projectiles penetrated and some did not.

2.2.1 Al-2024 Test Specimens

Al-2024 sheet and plate, AMS 4037 of three different thicknesses, nominally 0.125, 0.25 and 0.5 in. were tested. The 0.125 in. material had a temper of T3 and the 0.25 in and 0.5 in. material had a temper of T351. The certified test reports for the material are shown in Appendix A and actual measured thicknesses are reported in Table 1.

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. diameter on a 13 in. diameter bolt-hole circle. They were held in massive steel fixtures with a circular aperture shown in Figure 2(a) and (b). The two parts of the fixture were 1.5 in. thick steel.

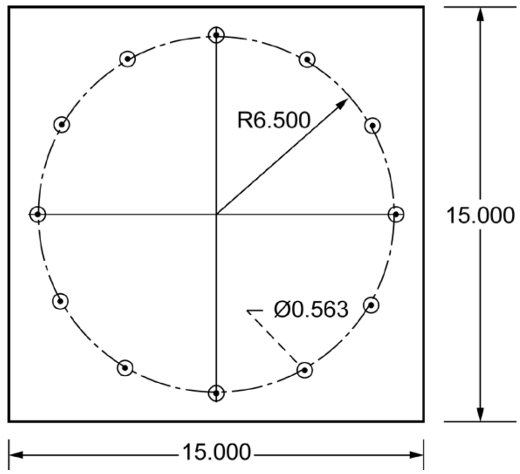

Figure 1.—Small Panel Test Specimen (dimensions in inches).

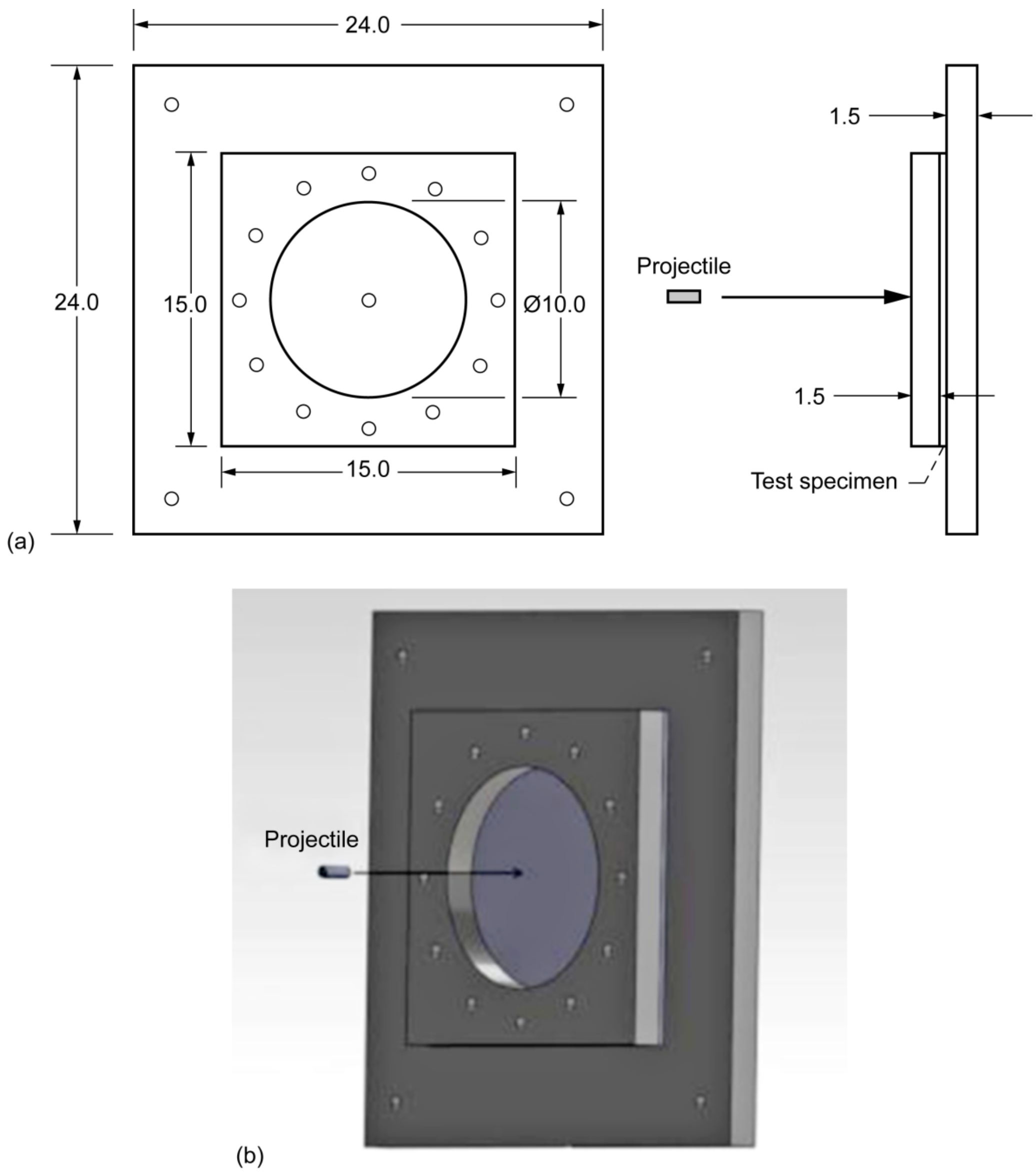

Figure 2.—Test Fixture Assembly, (a) front and side view (dimensions in inches), and (b) Clamp Fixture Assembly.

2.2.2 Ti-6Al-4V Test Specimens

The titanium test specimens were Ti-6Al-4V, AMS 4911, with nominal thicknesses of 0.09, 0.14, 0.25 and 0.5 in., and the same areal dimensions as the aluminum specimens discussed above. The material certification test reports for the material are shown in Appendix A and actual measured thicknesses are reported in Table 1.

2.2.3 Projectiles

The projectiles used for the small panel testing were cylindrical with varying length, diameter and material (Figure 3). They had a relatively large nose radius of 2.75 in., which allowed a slight deviation of 5° in the normal orientation of the projectile without a front edge impact. The edge of the front face was "broken" with a 1/32 in. radius.

2.2.3.1 Projectiles for Aluminum Panels

The projectiles used for the 0.125 and 0.25 in. aluminum plates were Ti-6Al-4V cylinders, AMS 4928, with a hardness of 36-37 HRC and a diameter of 0.5 in. The projectiles used for the 0.125 in. plates were 0.7 in. long with a nominal mass of 9.9 gram. The projectiles used for the 0.25 in. plates were 0.9 in. long with a nominal mass of 12.8 gram. The projectiles used for the 0.5 in Al plate had a similar geometry but were manufactured from A2 tool steel and hardened to Rockwell 59C. The diameter was 0.5 in. and initially had a length of 1.5 in. The length was reduced to 1.125 in. after four tests indicated that the longer projectile resulted in a penetration velocity below that desired by this program.

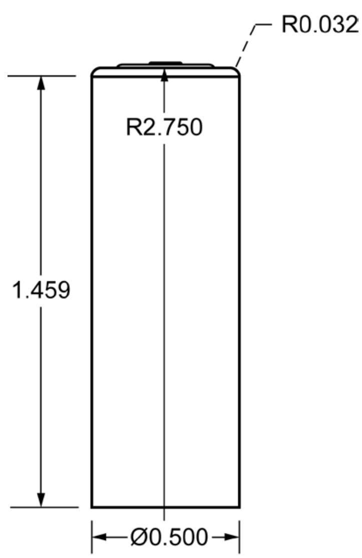

Figure 3.—Sample Small Panel Projectile (length and diameter vary depending on test specimen thickness and material. Dimensions in inches.)

2.2.3.2 Projectiles for Titanium Panels

The projectiles used for the 0.09 in. thick Ti-6Al-4V panels were 0.5 in. diameter, 1 in. long Ti-6Al-4V, AMS 4928, with a hardness of 36-37 HRC, an average mass of 14.05 gram and the same nose profile as described above. For the 0.14 in. thick Ti-6Al-4V panels, two different projectiles were used to investigate the effects of projectile hardness. The first set of tests used a Ti-6Al-4V projectile similar to the 0.09 in. panel tests, but 1.5 in long and with an average mass of 21.28 gram. The second set of tests on the 0.14 in. thick Ti-6Al-4V panels utilized a hardened A2 tool steel projectile with a diameter of 0.5 in., a length of 0.86 in., an average mass of 21.25 gram and a hardness of 59 HRC. For the 0.25 in. thick Ti-6Al-4V panels the projectile was 0.5 in. diameter, 0.875 in. long A2 tool steel with an average mass of 21.56 gram and a hardness of 59 HRC. The projectiles used for the 0.5 in. thick Ti-6Al-4V were considerably larger and heavier than any of the others, as shown in Table 2. A sample small panel projectile is shown in Figure 3.

The panel thickness and projectile information is summarized in Table 4. Actual thickness of panels were slightly different from the nominal, as shown in Table 1.

TABLE 4.—PROJECTILES USED FOR SMALL PANEL IMPACT TESTS

Target material	Nominal thickness, in.	Projectile material	Hardness, HRC	Length, in.	Diameter, in.	Mass, gram
Al2024	0.125	Ti-6Al-4V, AMS 4928	36-37	0.7	0.5	9.0
Al2024	0.25	Ti-6Al-4V, AMS 4928	36-37	.9	.5	12.8
Al2024	0.5	A2 Tool Steel	59	1.125	.5	28.0
Ti-6Al-4V	0.09	Ti-6Al-4V, AMS 4928	36-37	1.0	.5	14.05
Ti-6Al-4V	0.14	Ti-6Al-4V, AMS 4928	36-37	1.5	.5	21.28
Ti-6Al-4V	0.14	A2 Tool Steel*	59	.86	.5	21.25
Ti-6Al-4V	0.25	A2 Tool Steel	59	.875	.5	21.56
Ti-6Al-4V	0.5	A2 Tool Steel	63	2.25	.75	126.3

* Used to study the effect of projectile hardness on penetration speed

2.2.4 Gas Gun

The cylindrical projectiles were accelerated with a helium filled gas gun connected to a vacuum chamber, shown in Figure 4. The gun barrel had a length of 12 ft and a bore of 2.0 in. The pressure vessel was made up of sections as shown in Figure 5, with a total volume of 681 in^3. 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. This stopper system was designed such that the bottom of the sabot, including the o-rings, remained in the gun barrel and formed a seal which prevented the gas pressure behind the sabot from affecting the pressure in the vacuum chamber.

2.2.5 Instrumentation

Data acquired from the impact tests included measurements of the impact velocity, post-impact velocity (if penetration occurred) projectile orientation prior to impact, strain gage measurements and full field backside strain and displacement measurements using a digital image correlation system. In addition, high speed cameras provided qualitative observations of each test.

Figure 4.—Large Vacuum Gas Gun (shown with 3 in. diameter gun barrel).

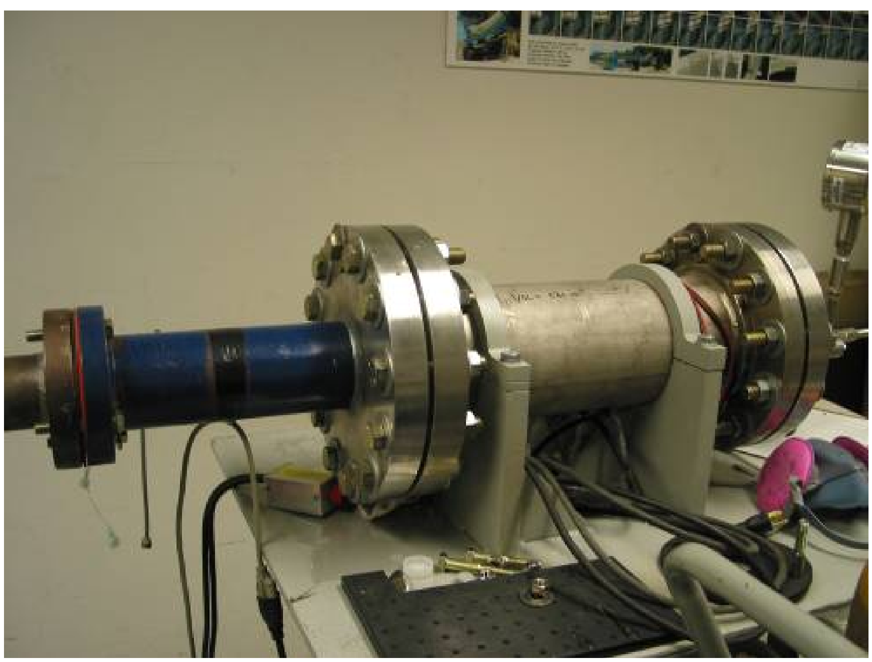

Figure 5.—Pressure vessel.

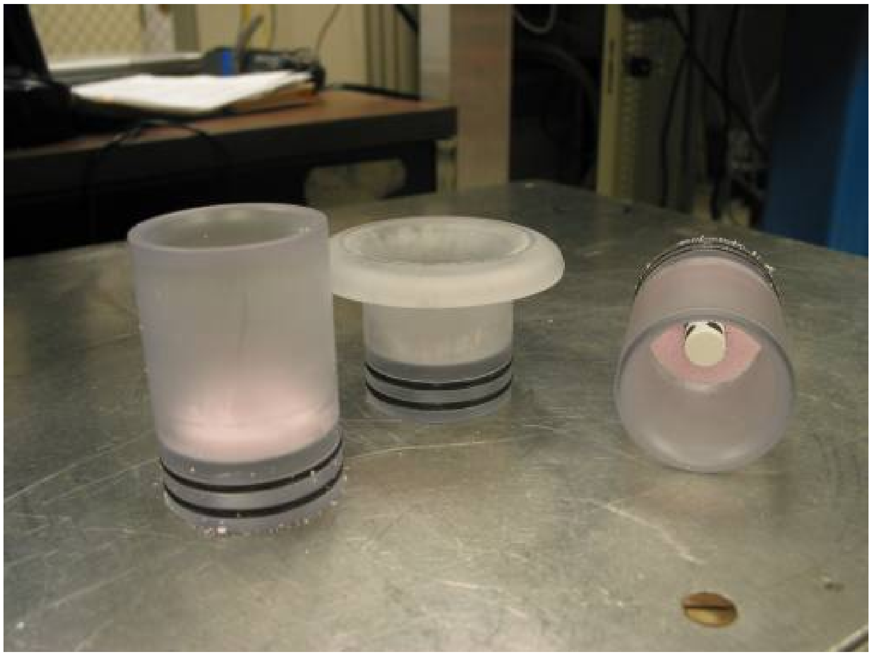

Figure 6.—Sabots used to transport projectile down the gun barrel. (Post-test sabot shown in center.)

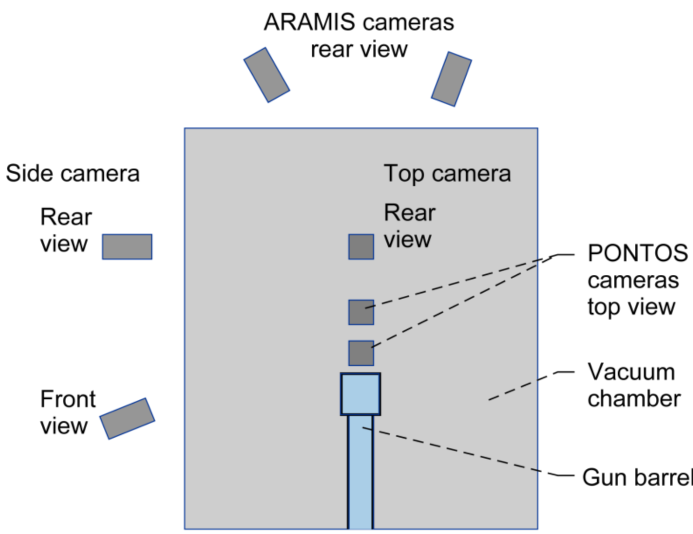

Figure 7.—Schematic of a top view of the vacuum chamber showing the high speed camera locations.

2.2.5.1 General Photo-Instrumentation

Seven high speed digital cameras were used for each test. These cameras provided a side view of the front of the panel and two views of the rear of the panel (side and top) for post-impact velocity measurement. In addition, a calibrated pair of cameras located above and in front of the panel were used to measure impact velocity and projectile orientation, and a calibrated pair of cameras viewing the backside of the panel were used to compute the backside displacement and strain. The locations of these cameras are shown schematically in Figure 7.

2.2.5.2 Point Strain Measurement

Six of the 15 panels from each of the three thicknesses were instrumented with strain gages. Four of these six instrumented panels had five uniaxial strain gages located as shown in Figure 8. The other two of the instrumented panels had triaxial rosettes substituted for two of the uniaxial gages, resulting in nine strain measurements (Figure 9). The uniaxial strain gages were Vishay Micro-Measurements EA-06-125AD-120 (Vishay Micro-Measurements, Malvern, PA), with a gage factor of 2.085. The triaxial rosettes were Vishay Micro-Measurements WA-06-060WR-120 with a gage factor of 2.11. The strain gage bridge completion, signal conditioning and recording were performed with a Spectral Dynamics Impax-SD measurement and control system utilizing SD-VX2805 data acquisition modules (Spectral Dynamics, Inc., San Jose, CA). The acquisition rate for the strain gages was 1.25 Msamples/sec.

2.2.5.3 Projectile Speed and Orientation

The speed and orientation of the projectile were measured by tracking the position of two points on the projectile and the position of three 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 (Phantom V7.3, Vision Research, Inc., Wayne, NJ) and the PONTOS point tracking software system (GOM, Braunschweig, Germany). The three 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 10. The three points defined a coordinate system with the X-axis pointing in the opposite direction of the direction of travel of the projectile, the Z axis vertically upward and the Y-axis in the horizontal plane and in a direction defined by the vector product of unit vectors in the Z and X directions respectively (Figure 10). The origin of the coordinate system was at point 1 shown in Figure 10. All positions reported for the projectile and the impact point were computed with respect to this coordinate system. In this coordinate system, the center of the impact surface of the test specimens is at (-4.24, 0.8125, 1.125) in.

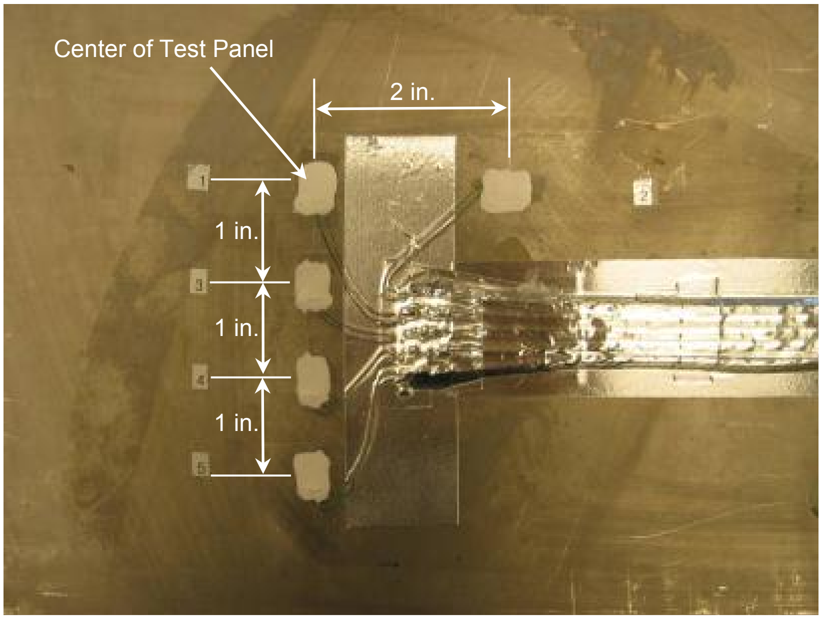

Figure 8.—Strain gage locations on panels with five gages.

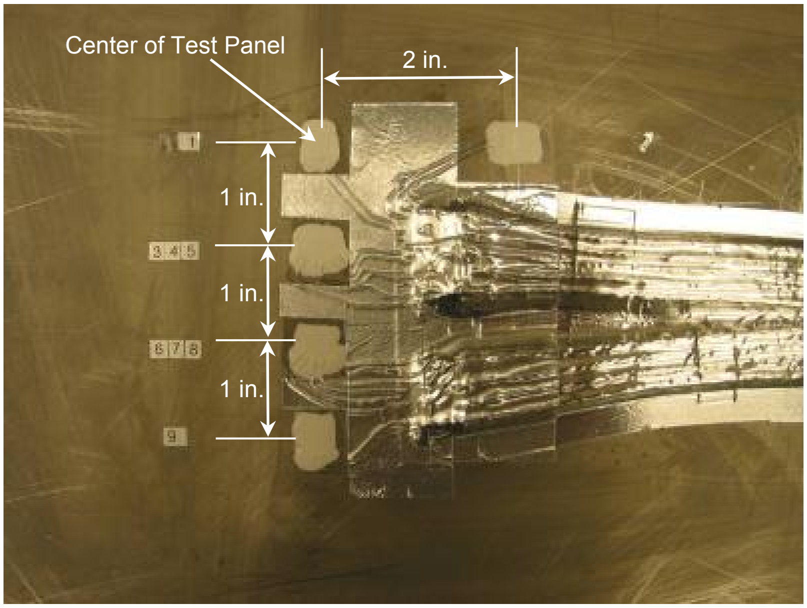

Figure 9.—Strain gage locations on panels with nine gages.

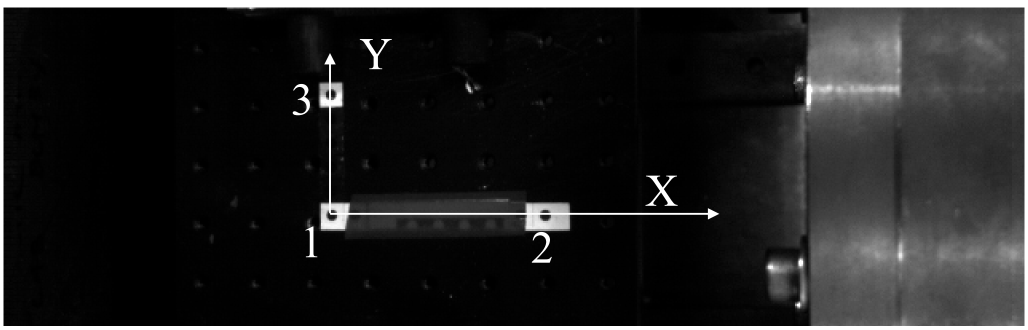

Figure 10.—Points used to define the Laboratory Coordinate System.

The post-impact velocity for the aluminum panel testing was measured with two high speed cameras on the backside of the panel, oriented normal to the path of the projectile, one viewing from above and one viewing from the left side (viewing from the gun barrel). These cameras were calibrated prior to the impact test using an aluminum rod protruding from the gun barrel with calibration marks located at every inch. Calibration tests in which no panel was mounted indicated that the differences in velocity measurements between the two cameras and the PONTOS system were well under 1%.

For the Ti-6Al-4V panel testing, the orthogonal camera system for exit velocity measurement was replaced with a second pair of calibrated cameras and the PONTOS point tracking system.

2.2.5.4 Full Field Displacement and Strain

Full field displacement and strain measurements were obtained using a calibrated pair of high speed digital cameras (Photron model SA1.1, Photron USA, San Diego, CA) and a digital image correlation software package (ARAMIS, GOM, Braunschweig, Germany). 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. For test DB58 and prior tests, the cameras recorded an area of approximately 4- by 4-in. with a resolution of 128 pix in the horizontal direction and 128 pix in the vertical direction and a frame rate of 180,000 frames/sec. Later tests used a resolution of 128 x 160 pixels and a frame rate of 150,000 frames/sec. The back side 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.

2.3 Large Panel Test Setup

Four ballistic impact tests were conducted on larger flat panels of each material. These tests were designed to involve 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. Since the release of an engine blade is tangential, 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 rig test to try to more represent this type of impact.

2.3.1 Test Specimens

The aluminum test specimens were 24- by 24-in. Al 2024-T351 with a nominal thickness of 0.25 in. The titanium test specimens were 24- by 24-in. Ti-6Al-4V, AMS 4911, with a nominal thickness of 0.090 in. The material certification sheets are shown in Appendix A. The panels were held at a 45° angle in a square fixture with a 20- by 20-in. aperture as shown in Figure 11. The panels were through-bolted with 24 0.5 in. bolts equally spaced around the sides, 1 in. in from the edges.

2.3.2 Projectile

The NGFBF projectile used for the large panel test was designed to include some of the features of a real fan blade, such as a thin tip and a heavier shank, while being relatively simple to manufacture and model. It was made from Ti-6Al-4V, AMS 4911 and had a nominal mass of 340 gram. The dimensions are shown in Figure 12 and a still image from a high speed video of an impact test, directly before impact is shown in Figure 13.

Figure 11.—Schematic of the Large Panel Test Setup showing the orientation of the projectile and test specimen.

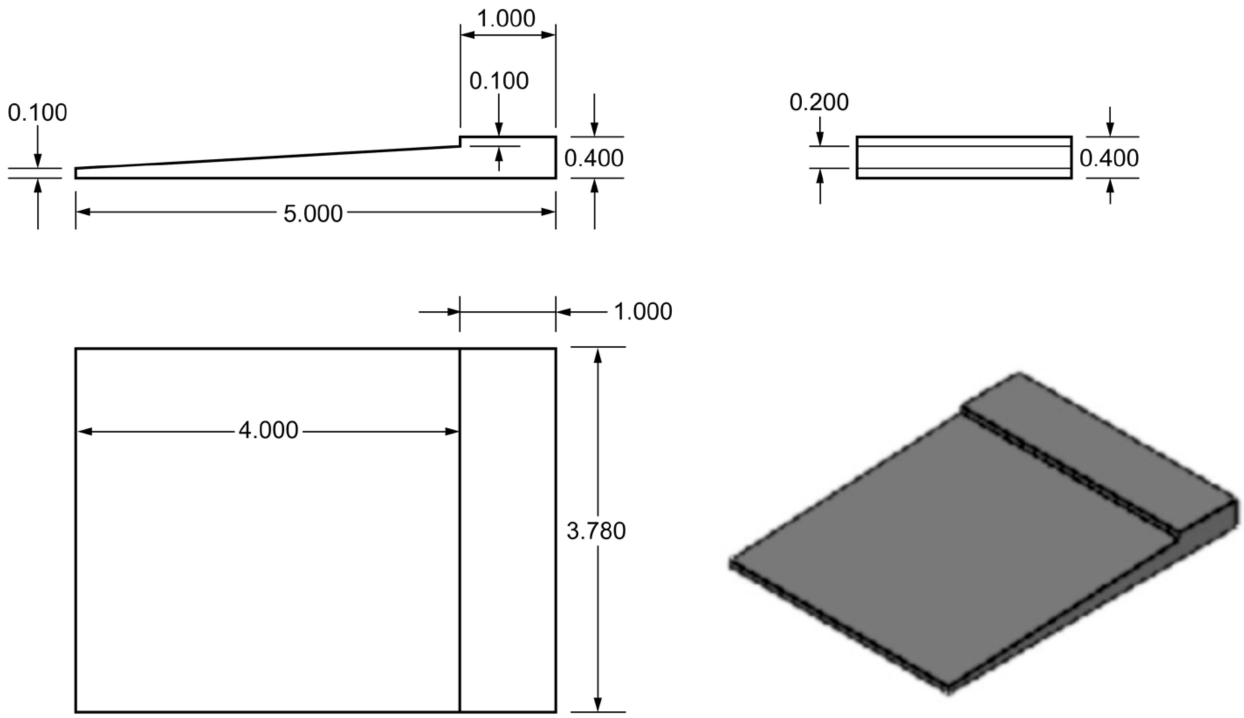

Figure 12.—Projectile used in the Large Panel Impact Tests. (Dimensions in inches.)

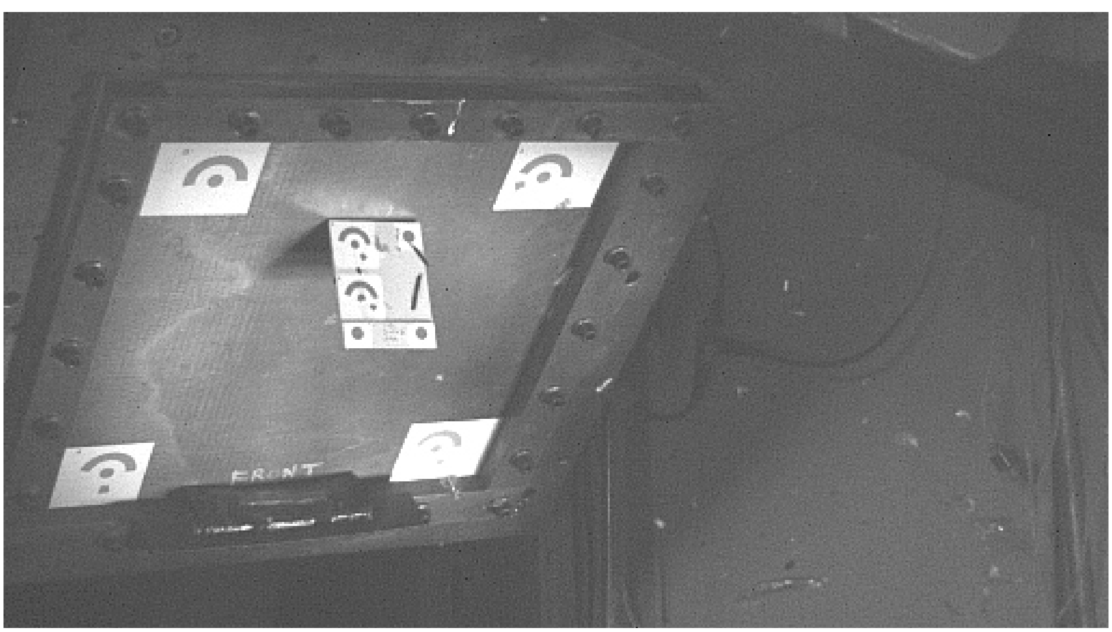

Figure 13.—Still image from a high speed movie of an impact test taken directly before impact.

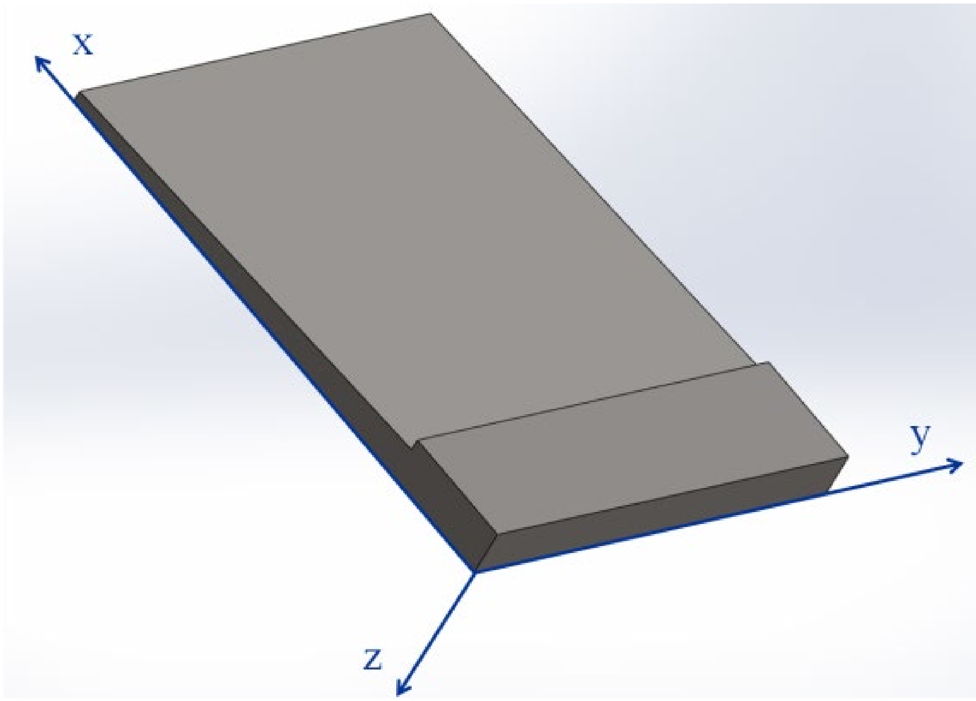

Figure 14.—Projectile Coordinate System.

2.3.3 Instrumentation

Full field displacement data on the back side of the impacted panels were obtained using a pair of calibrated high speed cameras and a digital image correlation (DIC) system, similar to the small panel tests. In these tests the cameras were operating at 32,000 frames per second with a spatial resolution of 256x256 pixels. In addition a second pair of calibrated cameras and DIC system were used to track the position of individual points on the projectile. From these data, the impact velocity and orientation of the projectile were computed. The cameras used for the projectile information were operating at 12,500 frames/sec with a resolution of 512 pixels in the horizontal direction and 288 pixels in the vertical direction.

For measuring the projectile orientation a coordinate system was established on the projectile as shown in Figure 14. The fixed laboratory coordinate system was specified such that the X direction was 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 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.

3.0 Results and Discussion

3.1 Small Panel Impact Tests

A summary of the small panel impact tests for each of the two materials is given in Table 5 and Table 6. In these tables the impact angle is the angle between the axis of the cylindrical projectile and the normal direction to the panel at the moment of impact.

TABLE 5.—SMALL PANEL IMPACT RESULTS FOR Al-2024

(a) Impact Results for 0.125 in. Thick Al-2024

Test	Projectile mass, gram	Projectile impact velocity, ft/sec	Projectile exit velocity, ft/sec	Projectile impact angle, deg	Comments
DB54	9.90	739	41	1.2	Penetrated
DB55	9.88	722	176	2.1	Penetrated
DB56	9.90	707	69	1.7	Penetrated
DB57	9.90	674	0	3.9	Contained
DB66	9.92	782	383	1.9	Penetrated
DB67	9.91	642	0	3.1	Contained
DB68	9.90	626	0	1.0	Contained
DB69	9.90	673	0	1.1	Contained
DB70	9.90	679	0	3.2	Contained
DB71	9.93	920	697	1.7	Penetrated
DB73	9.95	883	644	1.3	Penetrated
DB74	9.95	978	803	6.1	Penetrated
DB75	9.90	858	610	1.7	Penetrated
DB76	9.95	666	0	3.1	Contained
DB77	9.85	663	0	2.4	Contained

(b) Impact Results for 0.25 in. Thick Al-2024

Test	Projectile mass, gram	Projectile impact velocity, ft/sec	Projectile exit velocity, ft/sec	Projectile impact angle, deg	Comments
DB39	12.8	795	386	5.8	Penetrated
DB42	12.8	729	0	3.9	Contained
DB44	12.8	721	0	2.6	Contained
DB45	12.8	752	0	4.0	Hole, projectile rebounded
DB47	12.8	710	17	2.2	Penetrated
DB51	12.7	734	172	5.6	Penetrated
DB52	12.8	763	153	3.2	Penetrated
DB58	12.7	750	0	7.8	Projectile lodged, plug ejected
DB59	12.7	746	145	2.7	Projectile lodged, plug ejected
DB60	12.8	713	0	4.7	Contained
DB61	12.8	733	0	3.3	Contained
DB62	12.8	685	0	3.8	Contained
DB63	12.7	648	0	1.2	Contained
DB64	12.8	861	444	0.6	Penetrated
DB65	12.8	938	494	0.3	Penetrated

(c) Impact Results for 0.5 in. Thick Al-2024

Test	Projectile mass, gram	Projectile impact velocity, ft/sec	Projectile exit velocity, ft/sec	Projectile impact angle, deg	Comments
DB79	37.6	757	232	0.5	Penetrated
DB80	37.5	717	279	1.0	Penetrated
DB81	37.5	690	239	0.8	Penetrated
DB82	37.6	659	155	1.5	Penetrated
DB83	27.9	786	0	1.3	Contained, plug almost ejected
DB84	28.1	832	0	1.0	Projectile lodged, plug ejected
DB85	28.0	876	143	1.7	Penetrated
DB86	28.0	751	0	1.4	Contained
DB87	28.0	819	212	0.4	Penetrated
DB88	28.0	961	400	9.4	Penetrated
DB89	28.0	906	191	2.2	Penetrated
DB90	28.0	851	114	0.8	Penetrated
DB91	28.0	843	244	0.9	Penetrated
DB92	28.0	759	187	1.8	Penetrated
DB93	28.0	717	0	1.6	Projectile lodged, plug ejected

TABLE 6.—SMALL PANEL IMPACT RESULTS FOR Ti-6Al-4V

(a) Impact Results for 0.09 in. Thick Ti-6Al-4V

Test	Projectile mass, gram	Projectile impact velocity, ft/sec	Projectile exit velocity, ft/sec	Projectile impact angle, deg	Comments
DB126	14.01	768	369	3.8	Penetrated
DB127	14.02	720	(116)	4.5	Contained
DB128	14.04	640	(61)	4.4	Contained, no crack
DB129	14.01	716	(64)	10.4	Contained, petal
DB130	14.06	764	385	6.0	Penetrated
DB132	14.10	864	630	2.3	Penetrated
DB133	14.04	706	(75)	4.1	Contained, petal
DB134	14.09	668	(76)	5.1	Contained, petal
DB135	14.07	705	(57)	0.9	Contained
DB136	14.05	669	(29)	3.7	Contained, crack
DB137	14.08	777	377	2.4	Penetrated
DB138	14.08	637	(52)	0.1	Contained

* Rebound velocity given in parentheses where available

(b) Impact Results for 0.14 in. Thick Ti-6Al-4V (Using Ti-6Al-4V Projectile)

Test	Projectile mass, gram	Projectile impact velocity, ft/sec	Projectile exit velocity, ft/sec	Projectile impact angle, deg	Comments
DB144	21.23	725	(116)	2.7	Contained, crack
DB145	21.24	695	(61)	1.5	Contained, no crack
DB146	21.25	743	(106)	2.3	Contained, flap
DB147	21.33	785	298	8.0	Penetrated
DB148	21.26	901	571	3.7	Penetrated
DB149	21.29	743	(70)	0.7	Contained
DB150	21.29	783	262	1.3	Penetrated
DB151	21.30	773	36	2.2	Penetrated
DB152	21.30	904	625	0.7	Penetrated
DB153	21.30	861	580	2.0	Penetrated
DB154	21.27	771	232	1.6	Penetrated
DB155	21.26	757	(15)	1.4	Contained

* Rebound velocity given in parentheses where available

(c) Impact Results for 0.14 in. Thick Ti-6Al-4V (Using Hardened Steel Projectile)

Test	Projectile mass, gram	Projectile impact velocity, ft/sec	Projectile exit velocity, ft/sec	Projectile impact angle, deg	Comments
DB157	21.25	674	Not measurable	3.9	Penetrated
DB160	21.24	614		3.4	Contained
DB161	21.26	650		3.5	Contained
DB162	21.25	651		1.3	Contained

TABLE 6.—CONCLUDED.

(d) Impact Results for 0.25 in. Thick Ti-6Al-4V

Test	Projectile mass, gram	Projectile impact velocity, ft/sec	Projectile exit velocity, ft/sec	Projectile impact angle, deg	Comments
DB114	21.52	752	241	2.2	Penetrated
DB115	21.51	710	(59)	1.7	Penetrated, flap
DB118	21.61	715	(41)	6.8	Contained, plug
DB119	21.62	630	(14)	5.5	Contained, crack
DB121	21.55	696	(16)	3.0	Contained, flap
DB122	21.59	650	(21)	2.1	Contained
DB123	21.54	814	336	1.7	Penetrated
DB124	21.58	852	372	1.5	Penetrated
DB125	21.61	911	396	5.0	Penetrated
DB139	21.54	619	(57)	Not available	Contained
DB140	21.55	762	277	2.0	Penetrated
DB141	21.55	753	281	1.1	Penetrated

* Rebound velocity given in parentheses where available

(e) Impact Results for 0.5 in. Thick Ti-6Al-4V

Test	Projectile mass, gram	Projectile impact velocity, ft/sec	Projectile exit velocity, ft/sec	Projectile impact angle, deg	Plug depth, in.	Comments
DB177	126.3	896	475	620	Full	Penetrated
DB178	126.4	865	424	522	Full	Penetrated
DB179	126.2	713	241	360	Full	Penetrated
DB180	126.2	646	152	310	Full	Penetrated
DB182	126.4	527	0	0	.053	Contained
DB184	126.3	581	0	0	.237	Contained
DB185	126.2	597	0	0	.308	Contained
DB186	126.4	578	0	0	.187	Contained
DB192	126.3	630	0	153	Full	Contained/plug released
DB193	126.3	629	104	226	Full	Penetrated
DB195	126.3	616	0	132	Full	Contained/plug released

3.1.1 Projectile Residual Velocity

The residual velocity of the projectile is plotted against the impact velocity in Figure 15 to Figure 17 for the Al2024 tests. For the 0.125 in. and the 0.25 in. Al2024 plates the results show a fairly well defined transition between penetration and non-penetration, and a generally regular increase in residual velocity as the impact velocity increases. However, for the 0.5 in. thick Al-2024 plates there is a considerable range of impact velocities where in some cases penetration occurred and in others did not. Due to this unexpected result, the data for these tests were carefully reviewed to the satisfaction of the authors that there is no significant anomaly in the data. It is not known why this occurred for the thick aluminum plates. It is clear that friction plays a more important role in the thicker plates. (In some of the tests, the projectile became embedded in the 0.5 in. plate after a plate plug was ejected.) For the heavier and longer projectiles used for the 0.5 in. thick plates the projectile orientation was generally very good, so the impact angle could not be considered an explanation for the irregularities.

The residual velocity of the projectile is plotted against the impact velocity in Figure 18 to Figure 21 for the Ti-6Al-4V tests. Note that there is no residual velocity plot for the 0.14 in. thick Ti-6Al-4V impacted with the hardened steel projectile due to the fact that only one projectile penetrated this limited set of tests. The residual velocity was low, but could not be accurately measured. For all the Ti-6Al-4V tests there was a well-defined transition between tests where penetration occurred and those where there was no penetration as well as a generally regular increase in residual velocity as the impact velocity increased.

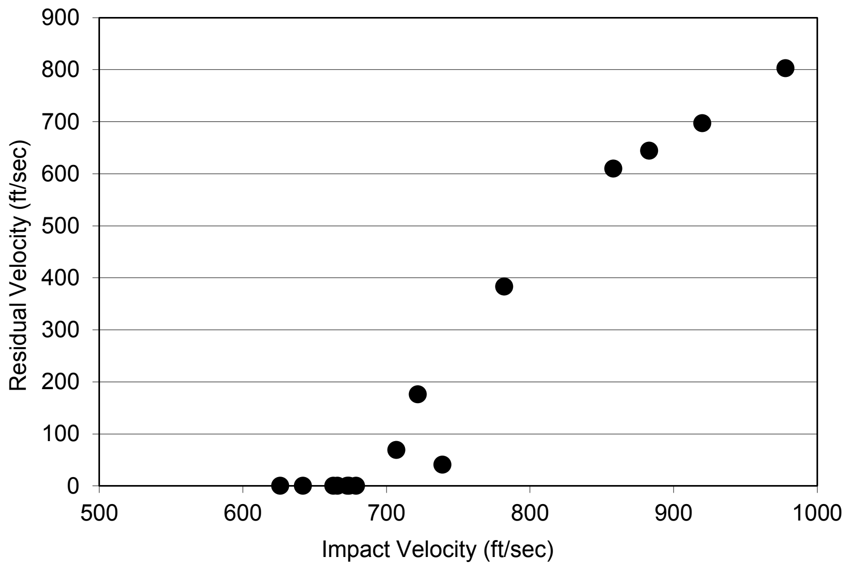

Figure 15.—Exit velocity vs. impact velocity for 0.125 in. thick Al-2024 sheet.

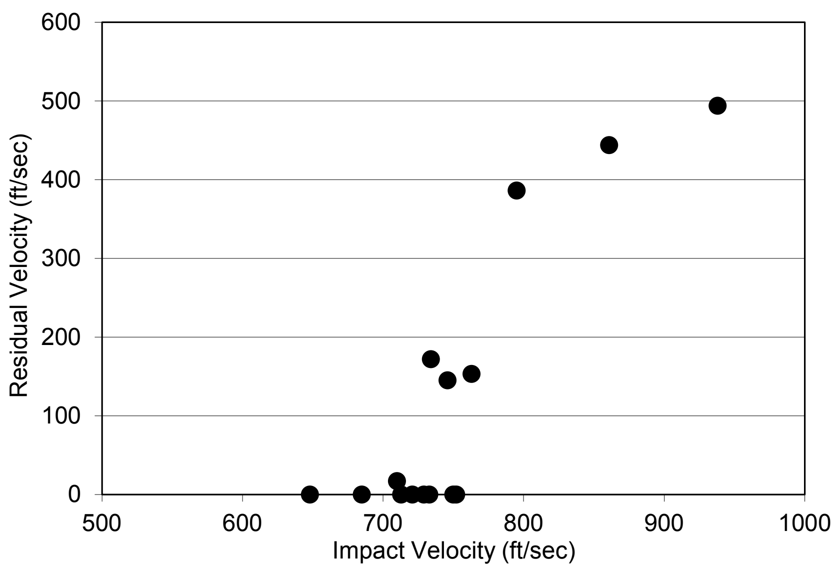

Figure 16.—Exit velocity vs. impact velocity for 0.25 in. thick Al-2024 plate.

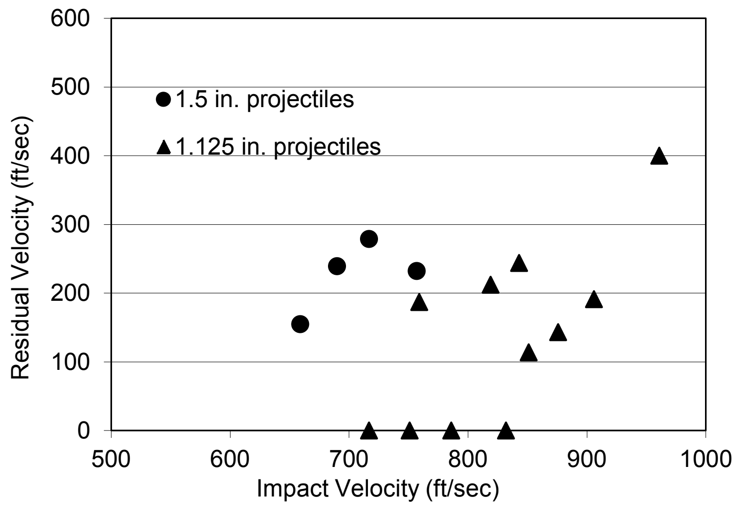

Figure 17.—Exit velocity vs. impact velocity for 0.5 in. thick Al-2024 plate.

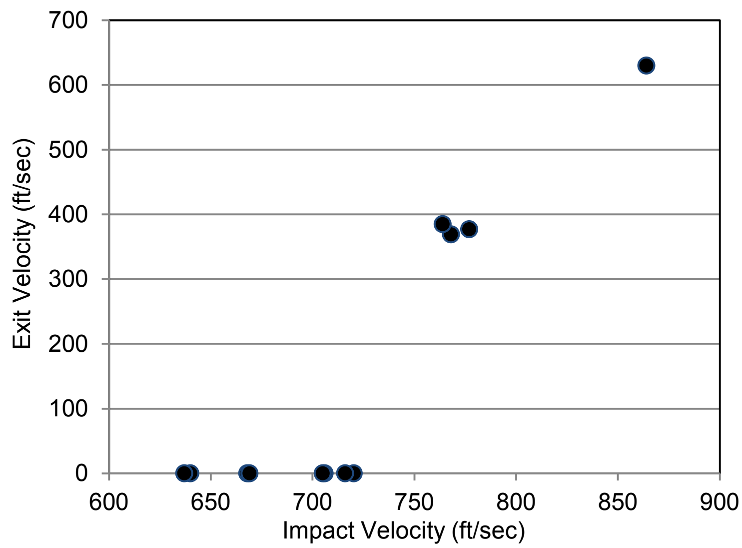

Figure 18.—Exit velocity vs. impact velocity for 0.09 in. thick Ti-6Al-4V sheet.

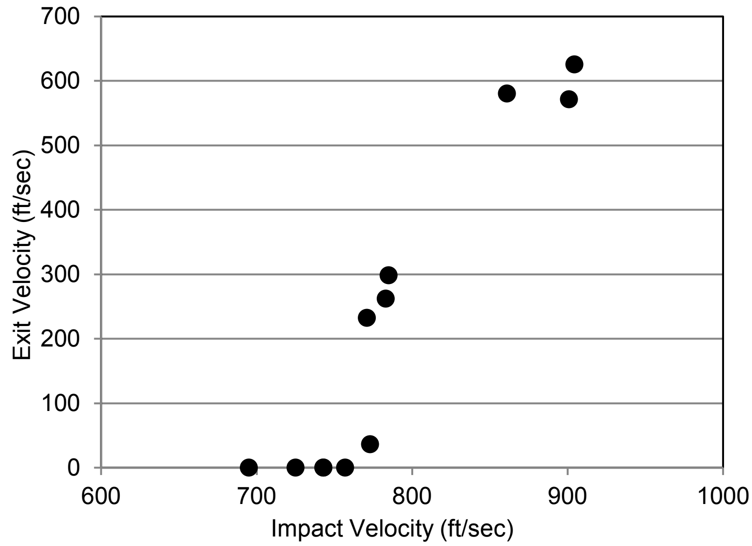

Figure 19.—Exit velocity vs. impact velocity for 0.14 in. thick Ti-6Al-4V sheet with Ti-6-4 projectile.

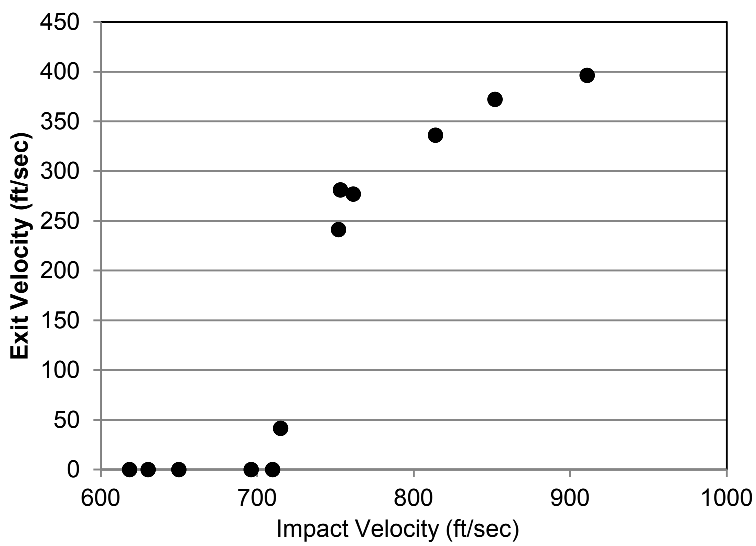

Figure 20.—Exit velocity vs. impact velocity for 0.25 in. thick Ti-6Al-4V plate.

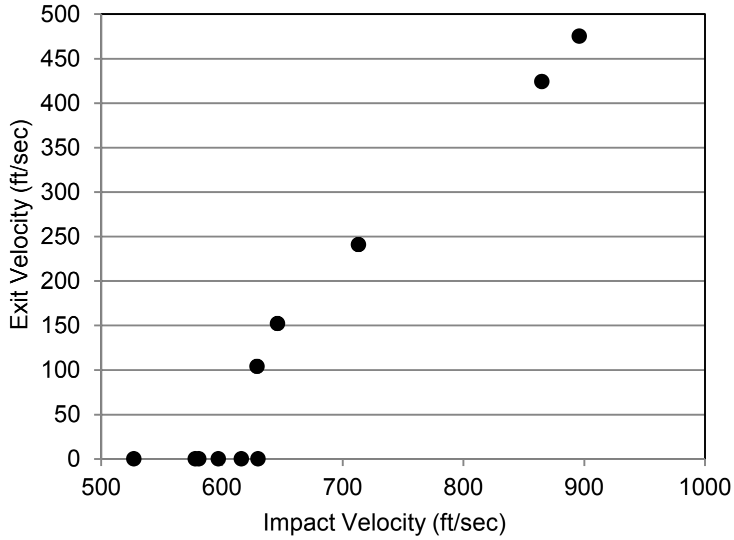

Figure 21.—Exit velocity vs. impact velocity for 0.5 in. thick Ti-6Al-4V plate.

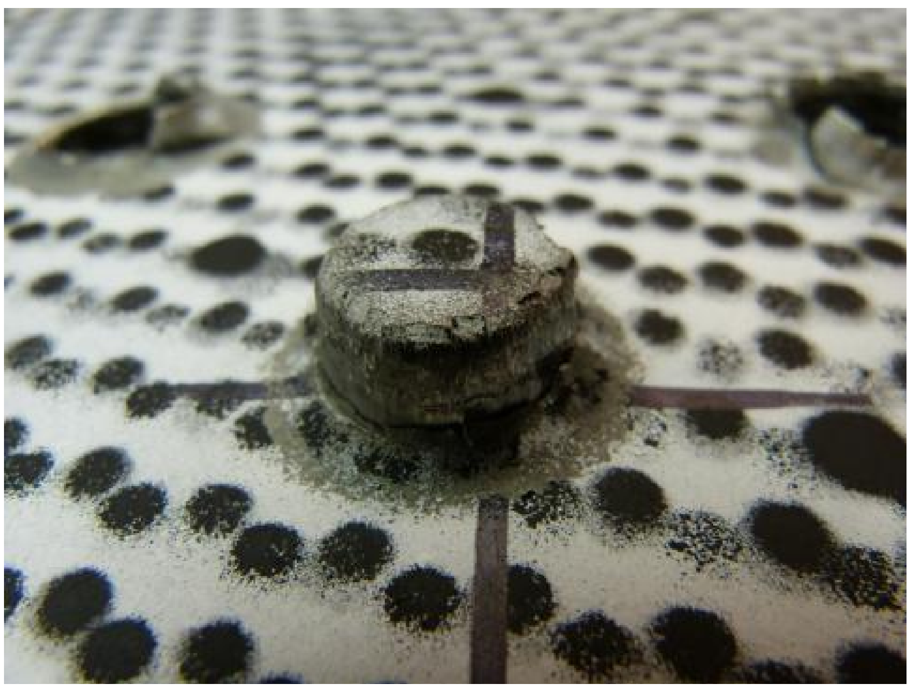
Figure 22.—Example of plug formed in 0.5 in. Ti-6Al-4V plate.

For the 0.5 in. Ti-6Al-4V plates, the damage was highly localized and there was a velocity range over which a plug developed but was not ejected (Figure 22). This occurred in the impact velocity range of 578 to 597 ft/sec. Above this there was a velocity range in which a plug was ejected but the projectile was contained. At velocities above 630 ft/sec both the plug and projectile penetrated the panel. For the tests in which a plug formed but was not ejected, measurements were made of the plug displacement (Table 6(e)). This measurement is the height of the plug face above the back surface of the plate.

The penetration results for the two materials are presented in Figure 23 and Figure 24 which show the impact velocity for each test and whether or not penetration occurred. Based on the results shown in Figure 15 to Figure 21 and Figure 23 and Figure 24 the approximate projectile penetration velocity results are shown in Table 7.

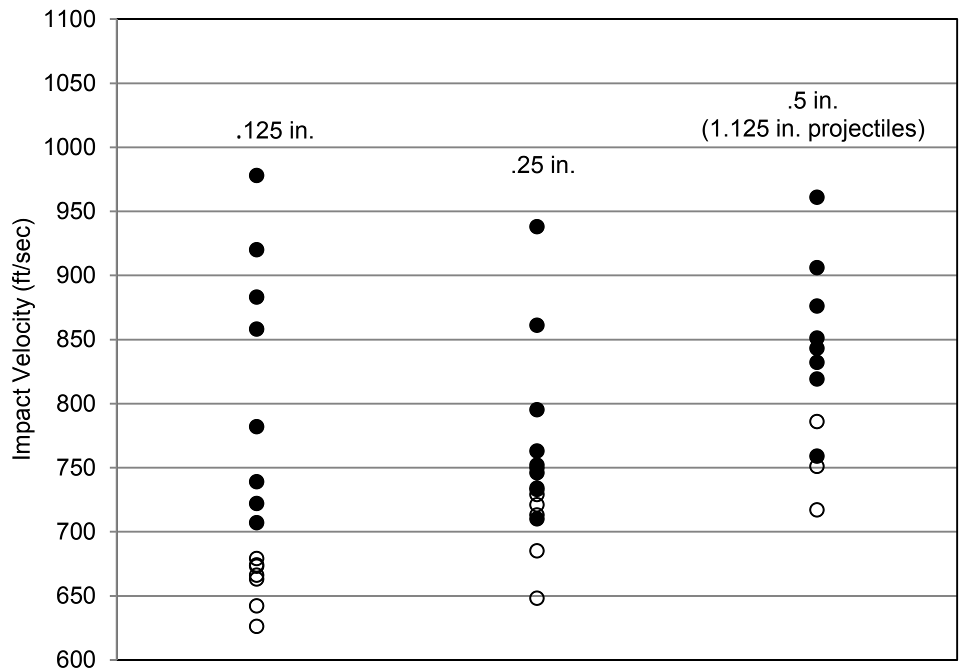

Figure 23.—Penetration Results for Al-2024. (Dark circles indicate tests in which penetration occurred. Open circles indicate tests where there was no penetration.)

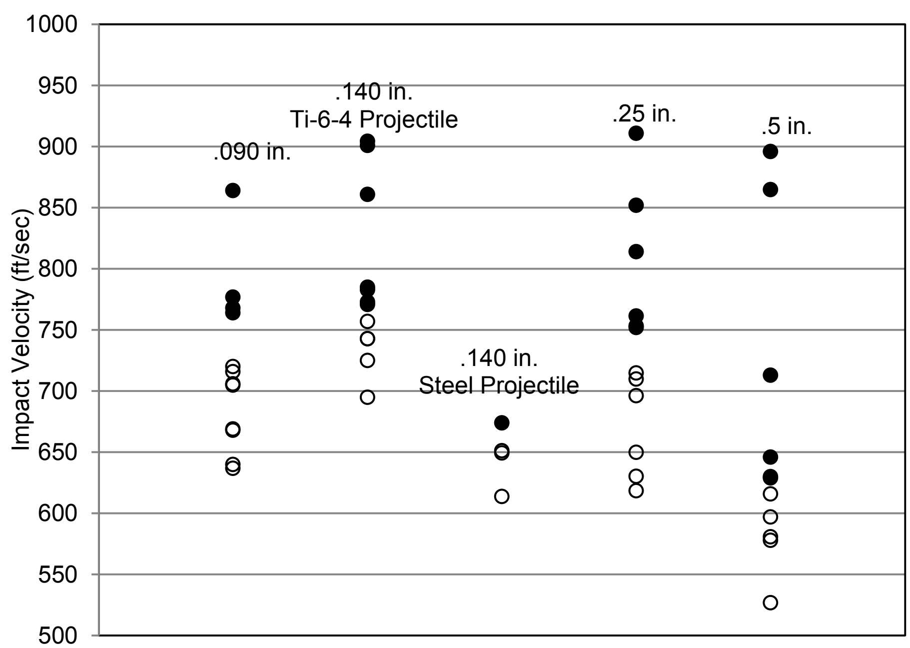

Figure 24.—Penetration results for Ti-6Al-4V. (Dark circles indicate tests in which penetration occurred. Open circles indicate tests where there was no penetration.)

TABLE 7.—APPROXIMATE PROJECTILE PENETRATION VELOCITY FOR THE SMALL PANEL IMPACT TESTS

Target material	Nominal thickness, in.	Projectile material	Hardness, HRC	Length, in.	Mass, gram	Projectile penetration velocity, ft/sec
Al2024	0.125	Ti-6Al-4V	36-37	0.7	9.0	700
Al2024	0.25	Ti-6Al-4V	36-37	.9	12.8	750
Al2024	0.5	A2 Tool Steel	59	1.125	28.0	800
Ti-6Al-4V	0.09	Ti-6Al-4V	36-37	1.0	14.05	740
Ti-6Al-4V	0.14	Ti-6Al-4V	36-37	1.5	21.28	770
Ti-6Al-4V	0.14	A2 Tool Steel*	59	.86	21.25	650
Ti-6Al-4V	0.25	A2 Tool Steel	59	.875	21.56	735
Ti-6Al-4V	0.5	A2 Tool Steel	62-63	2.25	126.2	629

*Used to study the effects of projectile hardness

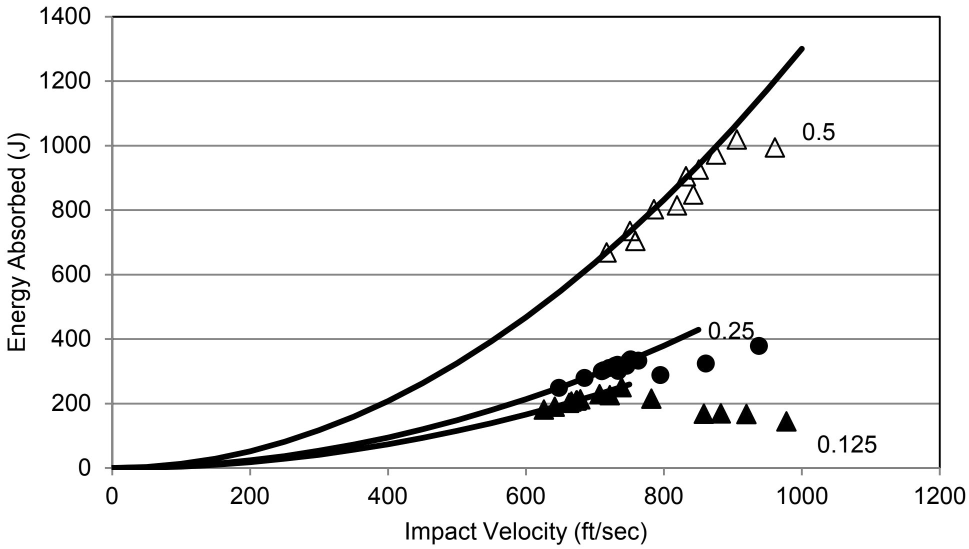

Figure 25.—Kinetic energy lost by projectile in Al-2024 impact tests.

3.1.2 Projectile Kinetic Energy Absorbed

A useful metric for impact model validation is the amount of kinetic energy absorbed by a panel when impacted. Figure 25 shows the kinetic energy absorbed by the Al2024 test panels. This is defined simply as the difference in projectile kinetic energy before and after impact and does not take into account the kinetic energy of the plug if one was ejected. In many cases it was not possible to accurately measure the plug kinetic energy, but in general it was less than 5% of the total energy absorbed. The curved reference lines represent the kinetic energy of the projectile as a function of impact velocity. For cases where all of the kinetic energy was absorbed (no penetration), the data points lie on the curves. For higher velocities where the projectile has residual kinetic energy, the points fall below the curves. Figure 26 to Figure 28 show the same information for the Ti-6Al-4V plates. The data is plotted on separate graphs for clarity. In general, for speeds just above the penetration velocity the amount of energy absorbed is slightly less than that at just below the penetration velocity. However, as speeds increase, there is no general trend. The data shows that for thicker panels (0.25 in. and above) the amount of energy absorbed increases as the speed increases beyond the penetration velocity. For thinner panels (0.14 in. and lower) the energy absorbed tends to decrease with increasing impact velocity. This may be indicative of a role that friction may play in the impact process. Another explanation may be related to the different failure modes in thicker specimens and related strain rate hardening effects. At this point there is not enough data to support a general conclusion.

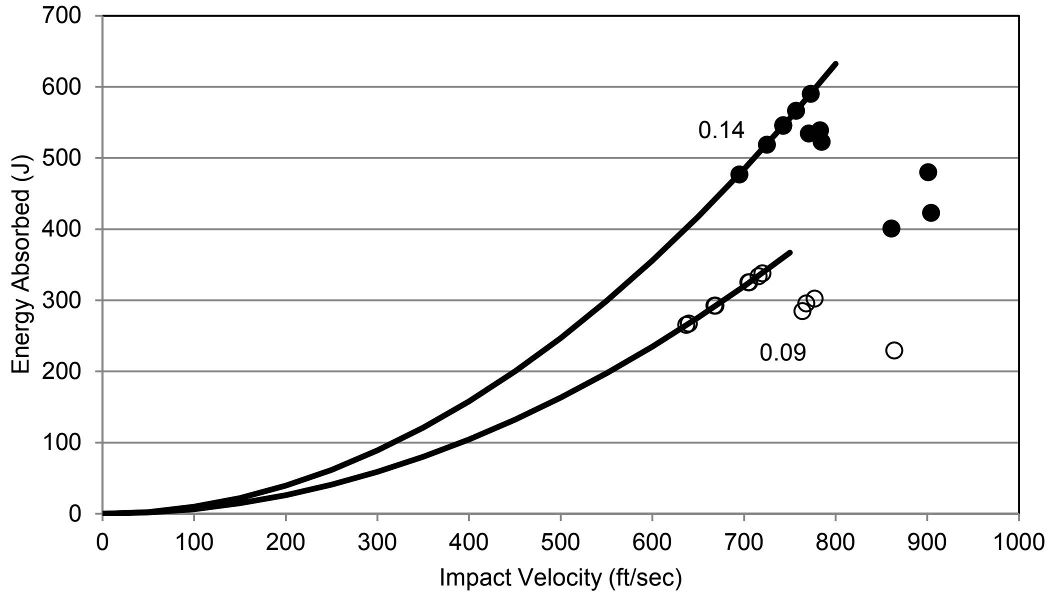

Figure 26.—Kinetic energy lost by projectile in 0.09 and 0.14 in. Ti-6Al-4V impact tests.

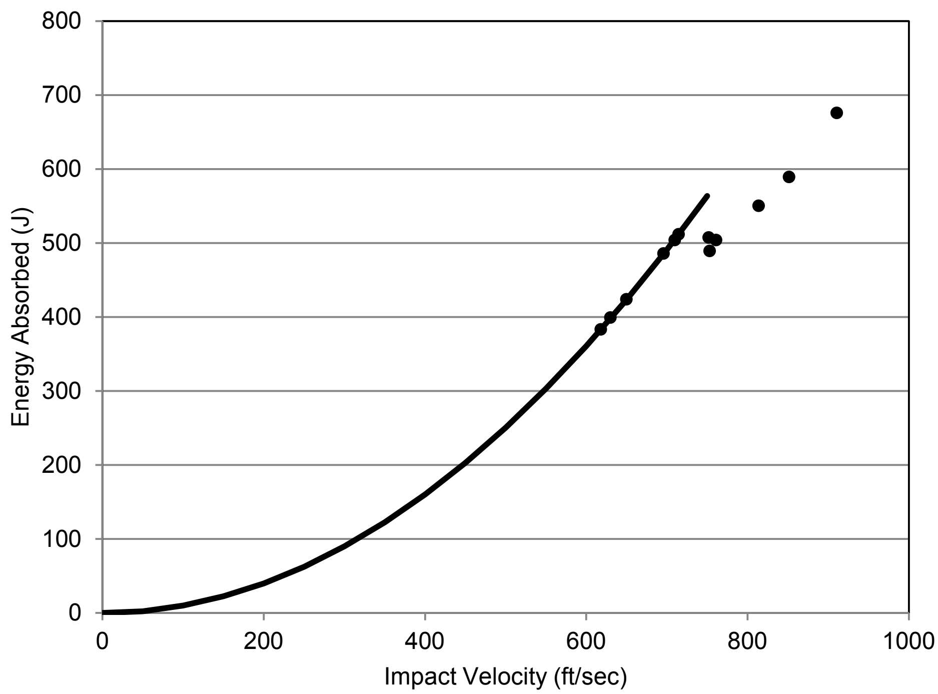

Figure 27.—Kinetic energy lost by projectile in 0.25 in. Ti-6Al-4V impact tests.

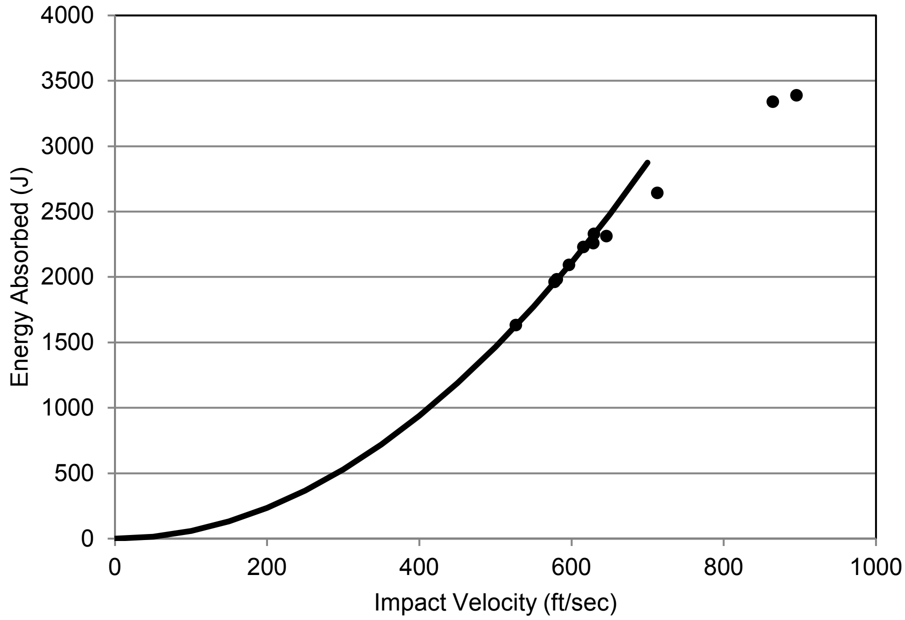

Figure 28.—Kinetic energy lost by projectile in 0.5 in. Ti-6Al-4V impact tests.

3.1.3 Effects of Projectile Hardness

Referring to Table 7, it can be seen that the Ti-6Al-4V projectile used on the 0.14 in. thick Ti-6Al-4V material (row 5) had a similar mass to the hardened steel projectile used with the 0.25 in. thick Ti-6Al-4V. The penetration velocity for the thicker material was lower than that of the thinner material. It was suspected that the cause for this was the difference in material properties of the projectiles. Macroscopic examination of the two types of projectiles demonstrated mushrooming on the front face of the Ti-6-4 projectiles (Figure 29) which was an obvious indication of extensive plastic deformation. However there were no signs of slip bands, shear bands or grain distortion due to the deformation. In addition, a hardness profile was taken from the top radius of the projectile into the core, looking for evidence of work hardening. Hardness readings were independent of location. The only sign of plasticity was the deformation.

No evidence of plasticity or macro deformation was seen in the hardened A2 projectiles. However, micro-hardness profiles indicated that the surface of the projectile was softer than the core. The surface had a hardness of approximately HRC45 and got increasingly harder toward the center of the projectile, until it reached a constant value of HRC64 at a distance of 200 µm from the surface. The projectile core hardness is similar to the values for projectile hardness provided in Table 4, since the values in Table 4 were only taken in the core. The reduced hardness at the projectile surface is believed to be due to decarburization of the surface during heat treatment. In some cases the projectiles were hardened in an air atmosphere, producing some surface scale. However, a hardness value of HRC45 is relatively high compared with the Ti-6Al-4V test panel and probably did not affect the overall behavior significantly.

An additional set of tests was conducted on the 0.14 in. thick Ti-6Al-4V plates using a hardened steel projectile of the same mass as the Ti-6Al-4V projectile (see Table 7, row 6). As shown in the table, there was a considerable reduction (15%) in the penetration speed. Simple elastic-plastic LS-DYNA analyses confirmed a significant increase in plastic strains in the panel with a projectile having a higher yield strength, and therefore hardness, and it can be speculated that the higher impedance of the harder projectile induces higher particle velocities and resulting higher strains. It has been observed elsewhere in Anderson et al. (Ref. 1) that the ballistic limit velocity decreases significantly when the hardness of the projectile exceeds that of the target. In thick targets, it has been shown by Forrestal and Piekutowski (Ref. 2) that penetration depth increases and projectile deformation decreases as the hardness of the projectile increases. Hardness is an indicator of material yield strength.

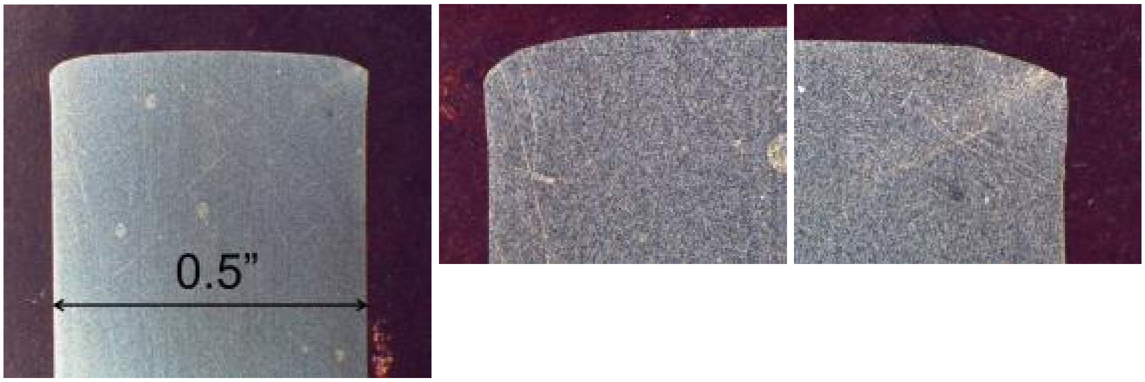

Figure 29.—Evidence of extensive plastic deformation in Ti-6Al-4V projectile.

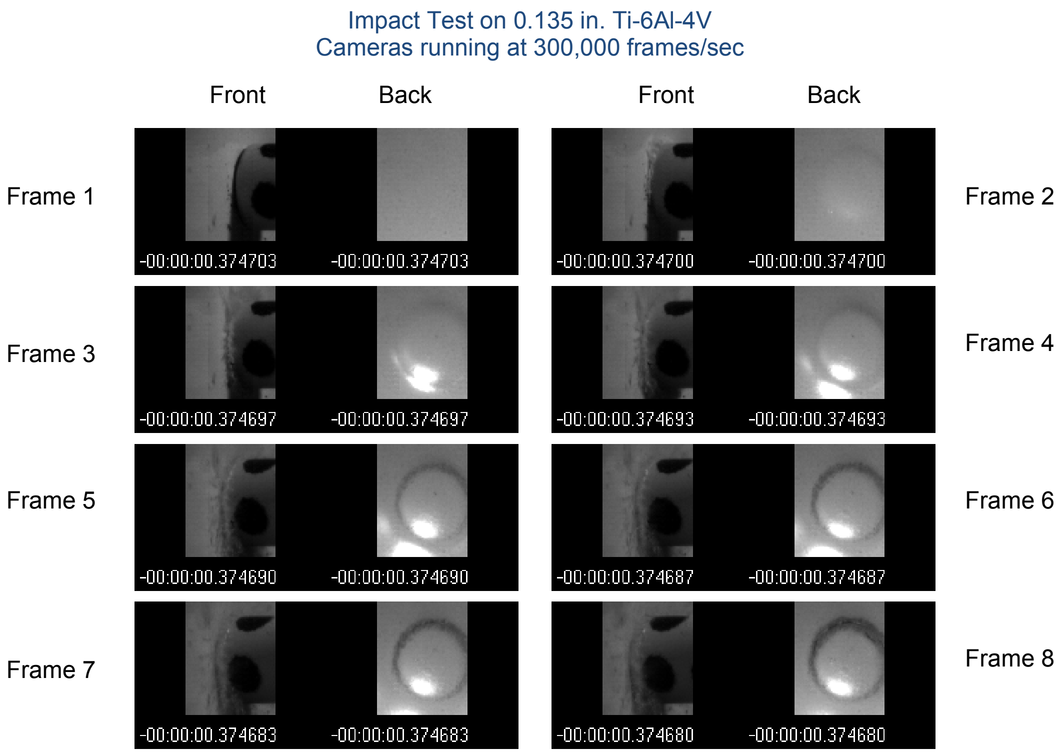

Figure 30.—Sequential frames from front and back cameras viewing an impact on a 0.135 in. thick Ti-6Al-4V specimen.

3.1.4 Boundary Conditions

One impact test was conducted using a higher camera frame rate to determine the time duration for failure to develop in a panel compared with the time required for a stress wave to reach the panel boundaries and back. This test was conducted to determine whether boundary conditions play a role in the penetration process. This test was conducted on a 0.14 in. thick Ti-6Al-4V test panel. Two synchronized cameras, operating at 300,000 frames/sec, showed the time of impact and the time at which damage was fully evident on the back side of the panel. Due to the high frame rate, the spatial resolution was limited. The test was somewhat qualitative as the time at which damage fully developed is a matter of judgment. Sequential frames from the two cameras are shown in Figure 30. Each frame is separated by a time of 3.33 µsec. Based on strain gage measurements at different distances from the impact point, the speed of the fastest recorded strain wave in the panel was 208,000 in./sec. For a 10 in. traverse distance (5 in. to the panel boundary and 5 in. back), the time duration is approximately 48.1 µsec, corresponding to approximately 14 camera frames. It is clear from the images in Figure 29 that damage is fully developed within eight frames for this thickness panel. This leads to the conclusion that the boundary conditions do not play a role in panels of this thickness.

3.1.5 Strain Measurements

Strain measurements on the backside of the panels were recorded using both strain gages and the digital image correlation (DIC) system. Because of the large volume of strain data collected in this study, they are not reported here. However a number of comparisons were conducted to check the correlation between strain measurements using the two measurement methods. It was questionable whether using the DIC system to measure the strain at the actual location of the gage would give accurate results, due to the coating used and the existence of the gage itself. So in addition to comparing the results at the gage location, the strain gage results were also compared with DIC results at the same radial distance from the impact point, but at a location 180° away. Figure 31 shows two strain gage and two DIC strain measurements at four locations on a 0.125 in. thick Al-2024 panel impacted at 679 ft/sec, approaching the penetration velocity (test DB70, Table 6(a)). Strain gage measurements are shown from gages 2 and 7, which, referring to Figure 9, are both 2 in. from the center of the panel and are measuring strain in the radial direction. DIC strain measurements are also shown, one directly on gage 7 and the other 180° away from gage 7 at the same radial distance. It can be seen that strain gages 2 and 7 have a very similar response, indicating that the impact is very symmetric. The DIC strain measurement 180° away from gage 7 also shows very good agreement. The DIC measurement directly on gage 7 has a similar response, although the peak values are somewhat higher. There is more noise in the DIC measurements, due mainly to the limited spatial resolution of the high speed cameras. However, in general the agreement is good, which gives confidence in the full field strain measurements available in both the small panel tests and the large panel tests discussed below, in which no strain gage instrumentation was used.

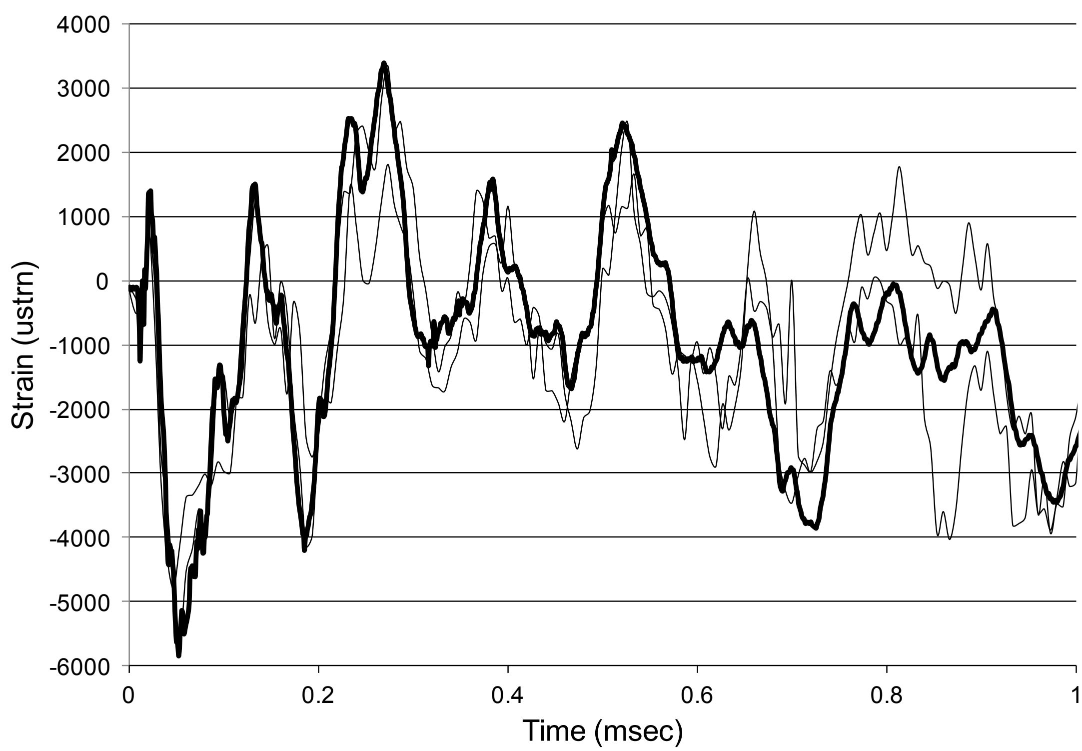

Figure 31.—Comparison of strain gage (bold line) and DIC strain measurements on a 0.125 in. thick AL2024 panel impacted at 679 ft/sec.

3.2 Large Panel Impact Tests

Four impact tests on each of the large Al-2024 and Ti-6Al-4V panels described in Section 2.2, using the NGFBF blade fragment simulating projectile. Results of these tests are shown in Table 8 and Table 9. Photos from the impact tests are shown in Figure 32 to Figure 39. It can be seen from the test photographs that failure initiation and the majority of the damage occurs when the heavier root section of the blade impacts the panel. This is consistent with what occurs in an actual jet engine fan blade out incident.

TABLE 8.—RESULTS OF IMPACT TESTS ON LARGE Al-2024 PANELS

Test ID	Measured thickness, in.	Projectile material	Projectile mass, gram	Impact velocity ft/sec	Result
LG908	0.257	Ti-6Al-4V	330	685	Contained.
LG909	.259	Ti-6Al-4V	338	791	Contained, perforated
LG910	.257	Ti-6Al-4V	329	746	Contained, perforated
LG911	.257	Ti-6Al-4V	338	721	Contained, perforated

TABLE 9.—RESULTS OF IMPACT TESTS ON LARGE Ti-6Al-4V PANELS

Test ID	Measured thickness, in.	Projectile material	Projectile mass, gram	Impact velocity ft/sec	Result
LG912	0.094	Ti-6Al-4V	339	626	Contained. Small crack
LG913	.095	Ti-6Al-4V	344	698	Projectile penetrated
LG915	.094	Ti-6Al-4V	344	653	Projectile penetrated
LG916	.094	Ti-6Al-4V	344	569	Contained. No cracks

The projectile impact orientation and angular velocities for the large panel Al-2024 and Ti-6Al-4V panel tests are shown in Table 10. In this table, the roll angle refers to rotation of the projectile x axis about the fixed laboratory X axis, the pitch angle is the rotation of the projectile about the once rotated (rolled) y axis and the yaw is the rotation of the projectile about the twice rotated (rolled and pitched) z axis (refer to Figure 14). The desired orientation of the projectile at impact was (0, 45, 0). Actual orientations of the projectile were somewhat different due to the difficulty of precisely controlling orientation in the impact tests. The lack of precise control is due to the highly dynamic nature of the event. When the sabot impacts the sabot stopper, significant deformations occur immediately which can change the orientation and introduce angular velocities in the projectile as it exits the gun barrel. In addition, the roll angle of the sabot is not constrained as it travels down the gun barrel.

TABLE 10.—PROJECTILE ORIENTATION AND ANGULAR VELOCITY AT IMPACT

Test number	Orientation angle			Angular velocity		
	Roll, deg	Pitch, deg	Yaw, deg	Roll velocity, deg/sec	Pitch velocity, deg/sec	Yaw velocity, deg/sec
Al-2024						
LG908	–2.82	90.64	0.44	1.24	161.12	–0.14
LG909	2.13	75.04	1.03	–8.97	155.80	66.09
LG910	–5.66	81.02	0.77	–6.95	119.10	–32.84
LG911	10.90	85.47	–1.06	68.52	58.41	311.26
Ti-6Al-4V						
LG912	0.42	63.92	7.15	1.00	3,862.00	–808.00
LG913	0.70	88.59	1.82	–349.00	8,022.00	555.00
LG915	2.74	85.52	11.49	555.00	7,330.00	1221.00
LG916	–4.79	68.52	5.60	–172.00	3,132.00	622.00

Figure 32.—Large Al-2024 Test Panel, front and back, side test LG908.

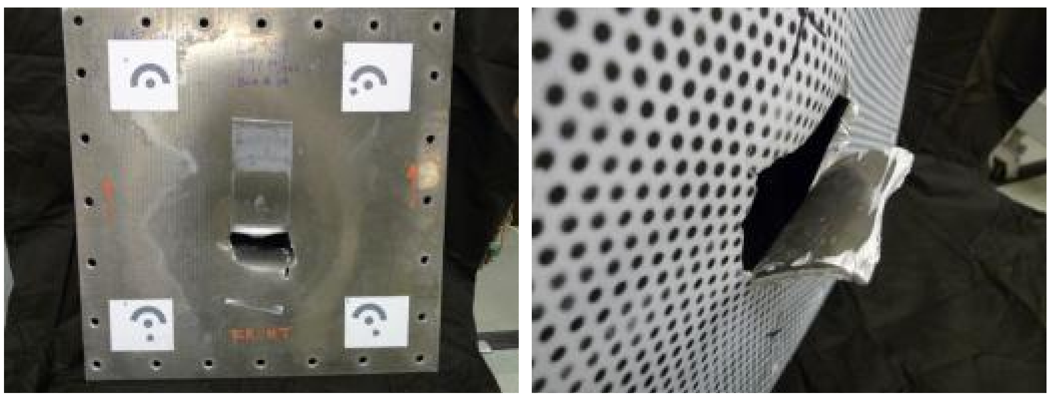

Figure 33.—Large Al-2024 Test Panel, front and back side, test LG909.

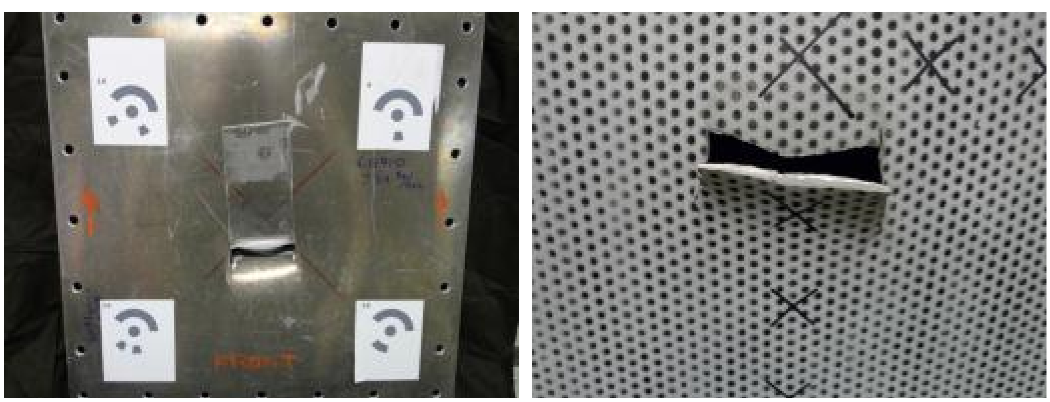

Figure 34.—Large Al-2024 Test Panel, front and back side, test LG910.

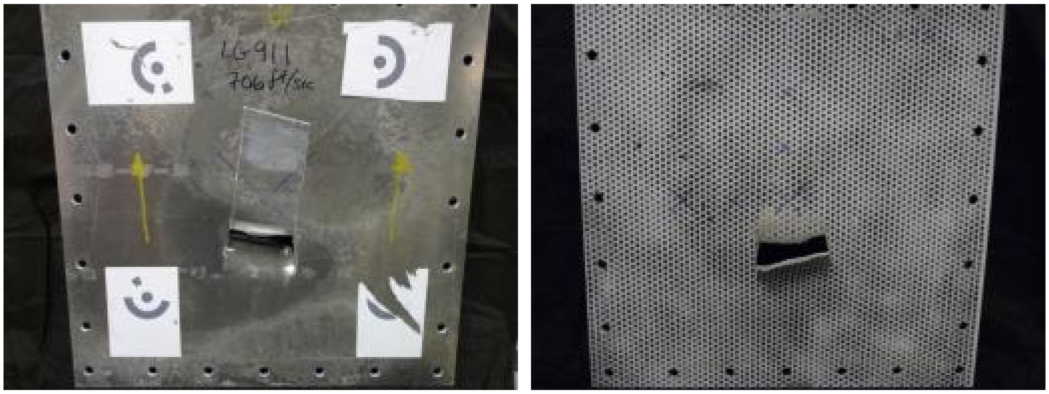

Figure 35.—Large Al-2024 Test Panel, front and back side, test LG911.

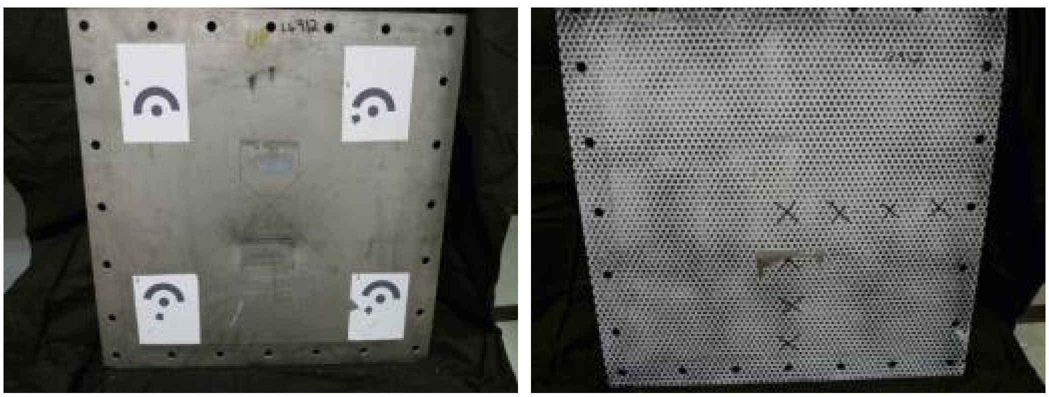

Figure 36.—Large Ti-6Al-4V Test Panel, front and back side, test LG912.

Figure 37.—Large Ti-6Al-4V Test Panel, front and back side, test LG913.

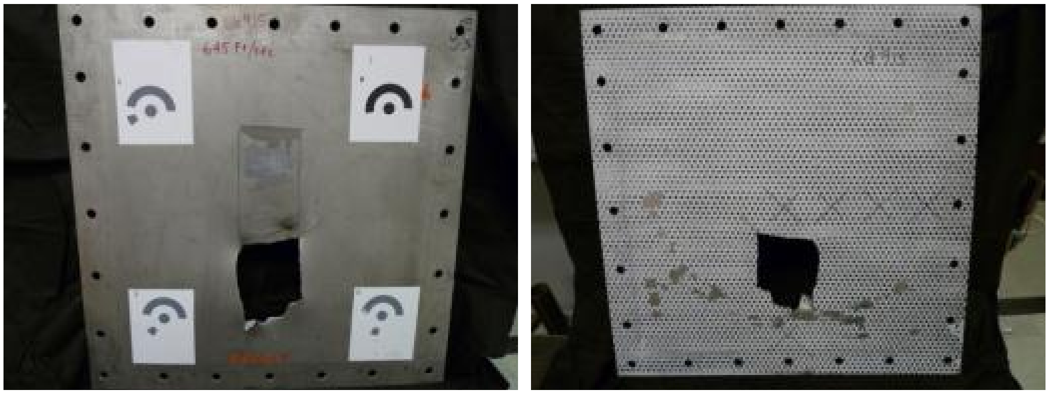

Figure 38.—Large Ti-6Al-4V Test Panel, front and back side, test LG915.

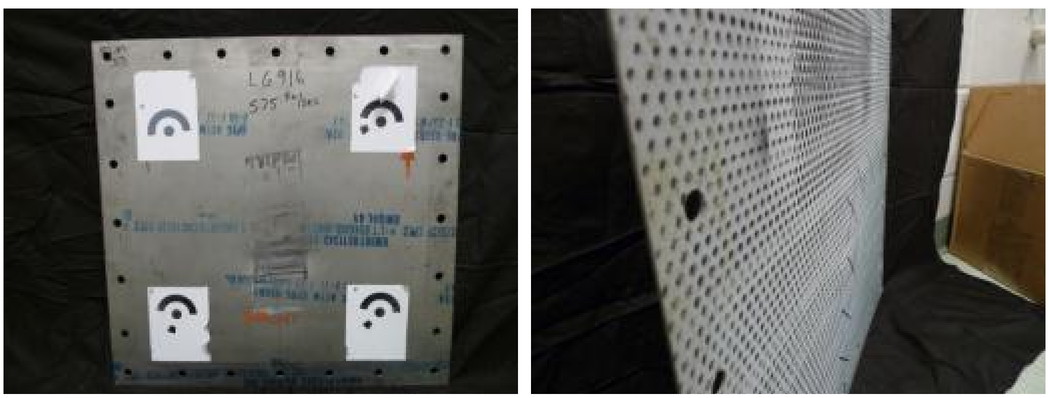

Figure 39.—Large Ti-6Al-4V Test Panel, front and back side, test LG916.

Full field deformation results were obtained using the DIC discussed above. Results for the Al-2024 and Ti-6Al-4V tests in Table 8 and Table 9 are shown in Figure 40 to Figure 47. Perforation occurred in all of the panels except one Al-2024 panel (LG908) and one Ti-6Al-4V panel (LG916). For these panels, the displacement time history of the point of maximum displacement is also shown in Figure 40(c) and Figure 47(c) respectively. It is also noted that each deformation curve is plotted for successive camera frames operating at 32,000 frames per second.

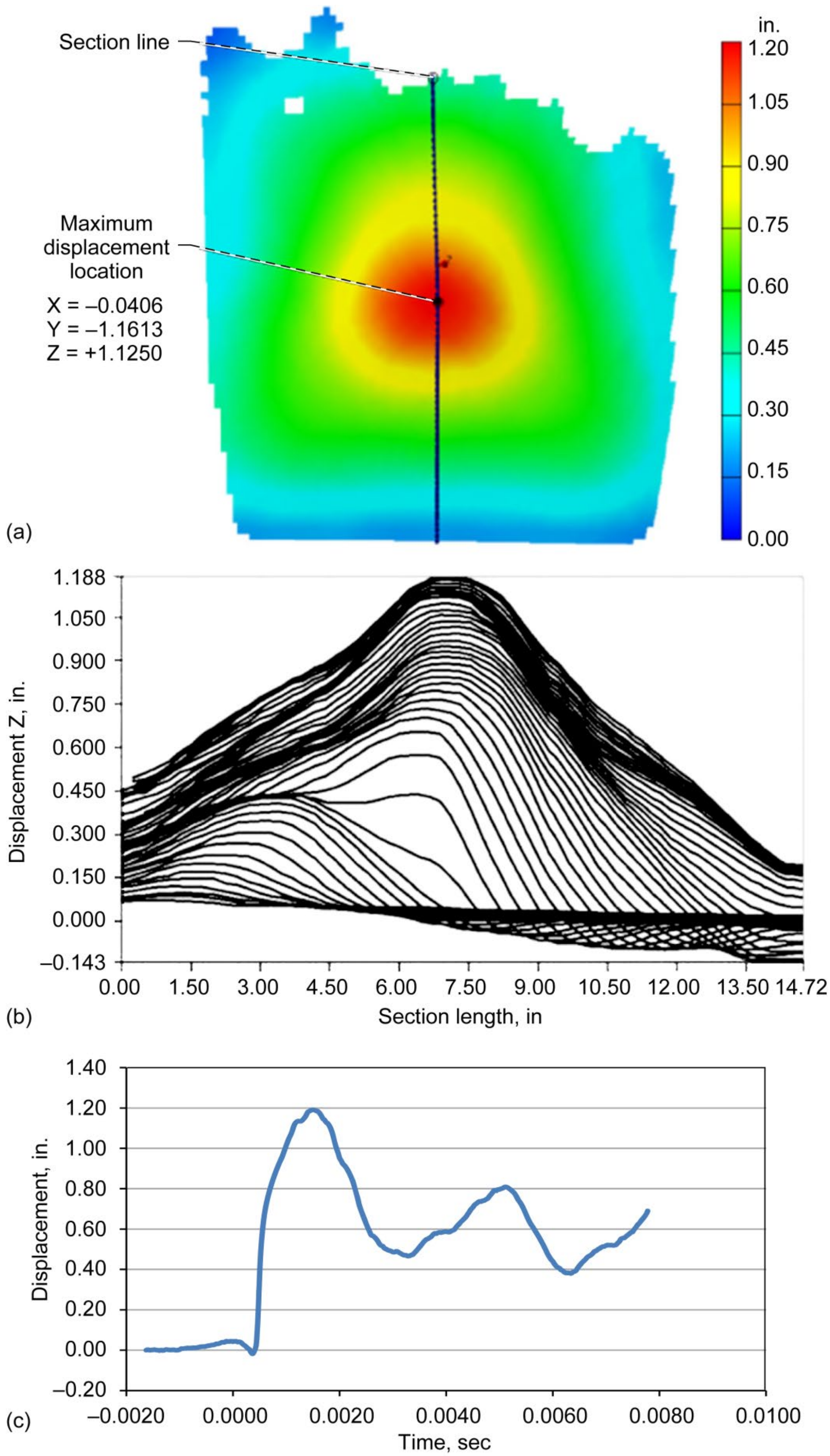

Figure 40.—(a) Deformation profile in Al-2024 test LG908 at the time of maximum deformation. (b). Deformation along section line shown in Figure 40(a) as a function of time (Al-2024 test LG908). (c). Deformation as a function of time for the point of maximum deformation shown in Figure 40(a) (Al-2024 test LG908).

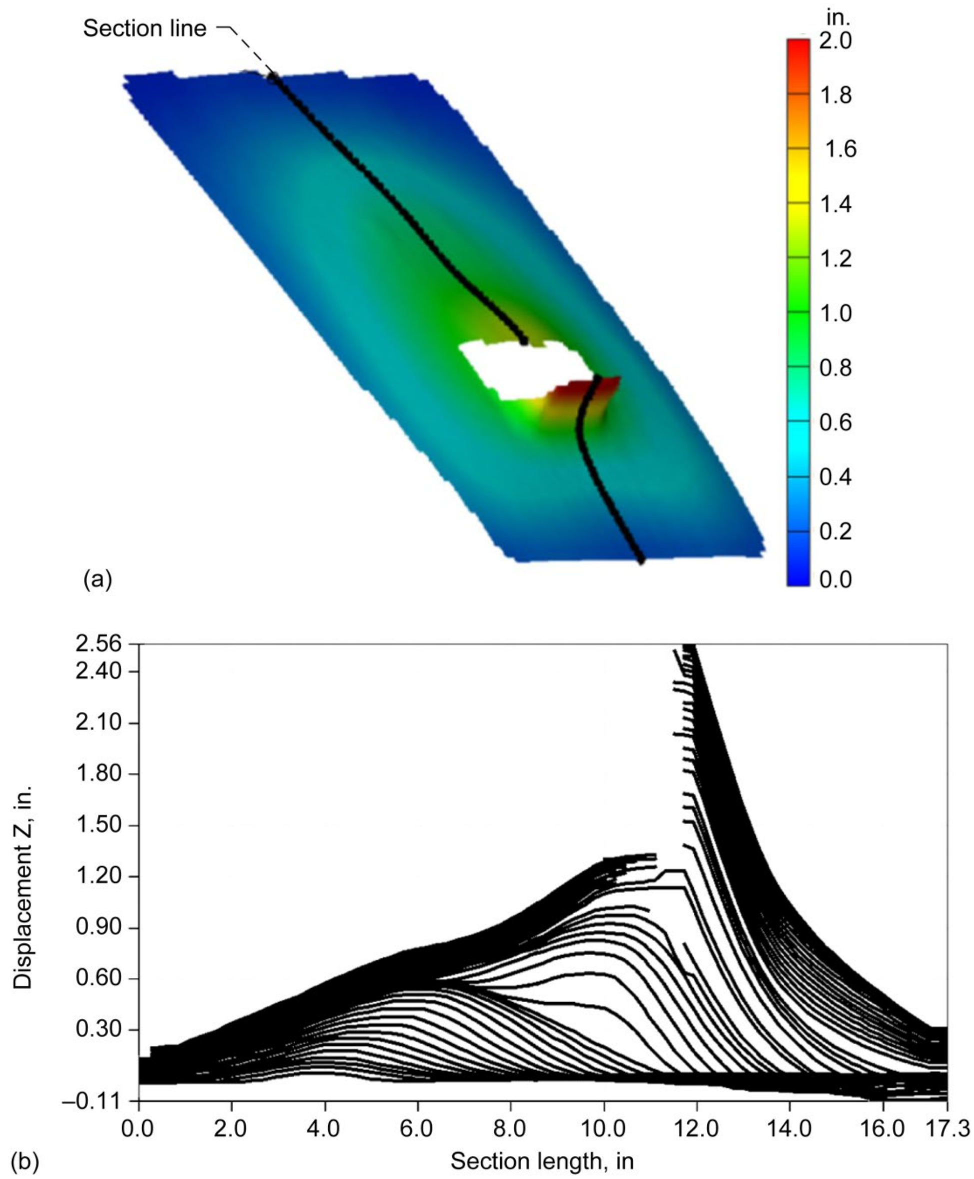

Figure 41.—(a) Deformation profile in Al-2024 Test LG909 after projectile penetration. (b) Deformation along section line shown in Figure 41(a) as a function of time (Al-2024 test LG909).

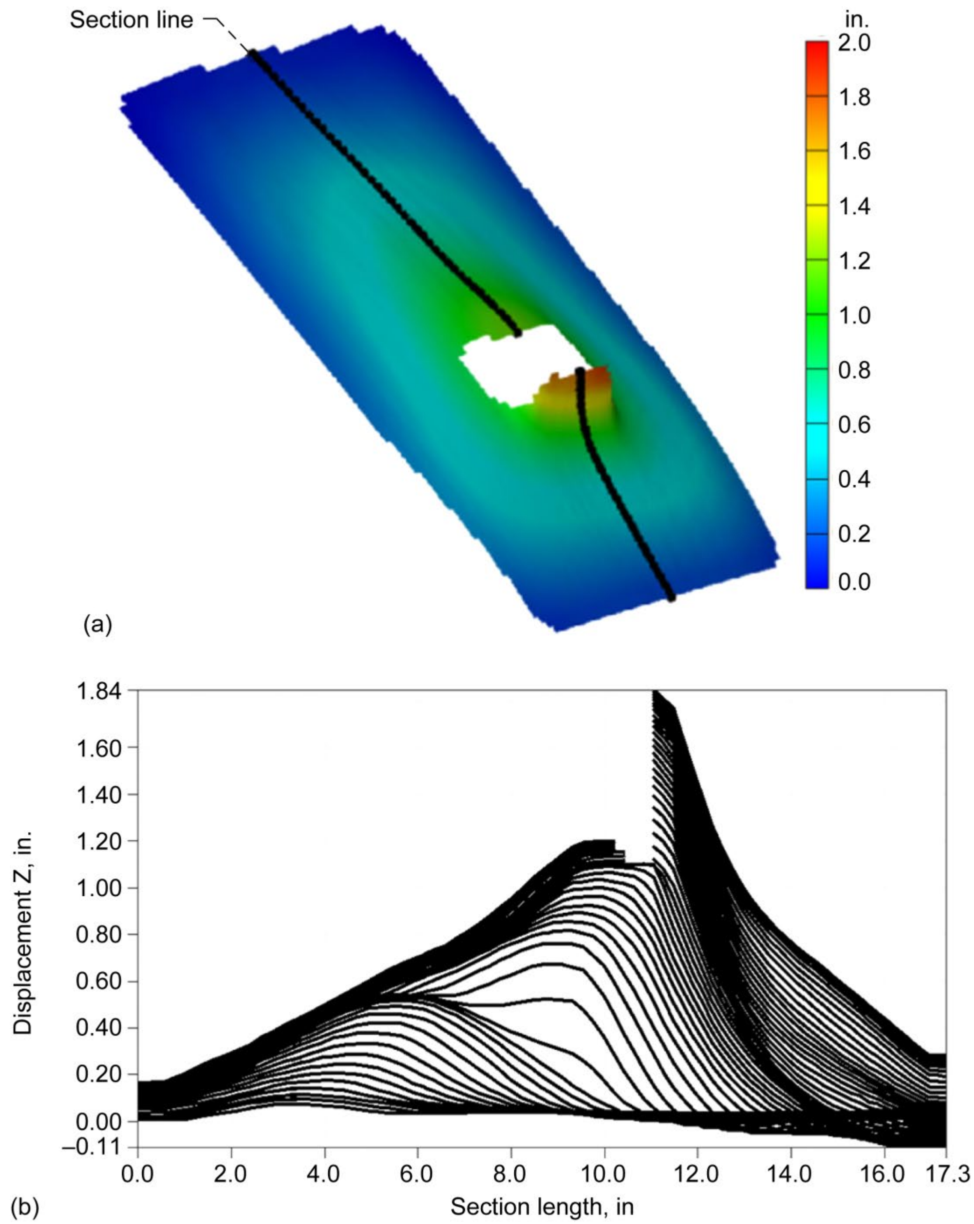

Figure 42.—(a) Deformation profile in Al-2024 Test LG910 after projectile penetration. (b) Deformation along section line shown in Figure 42(a) as a function of time (Al-2024 test LG910).

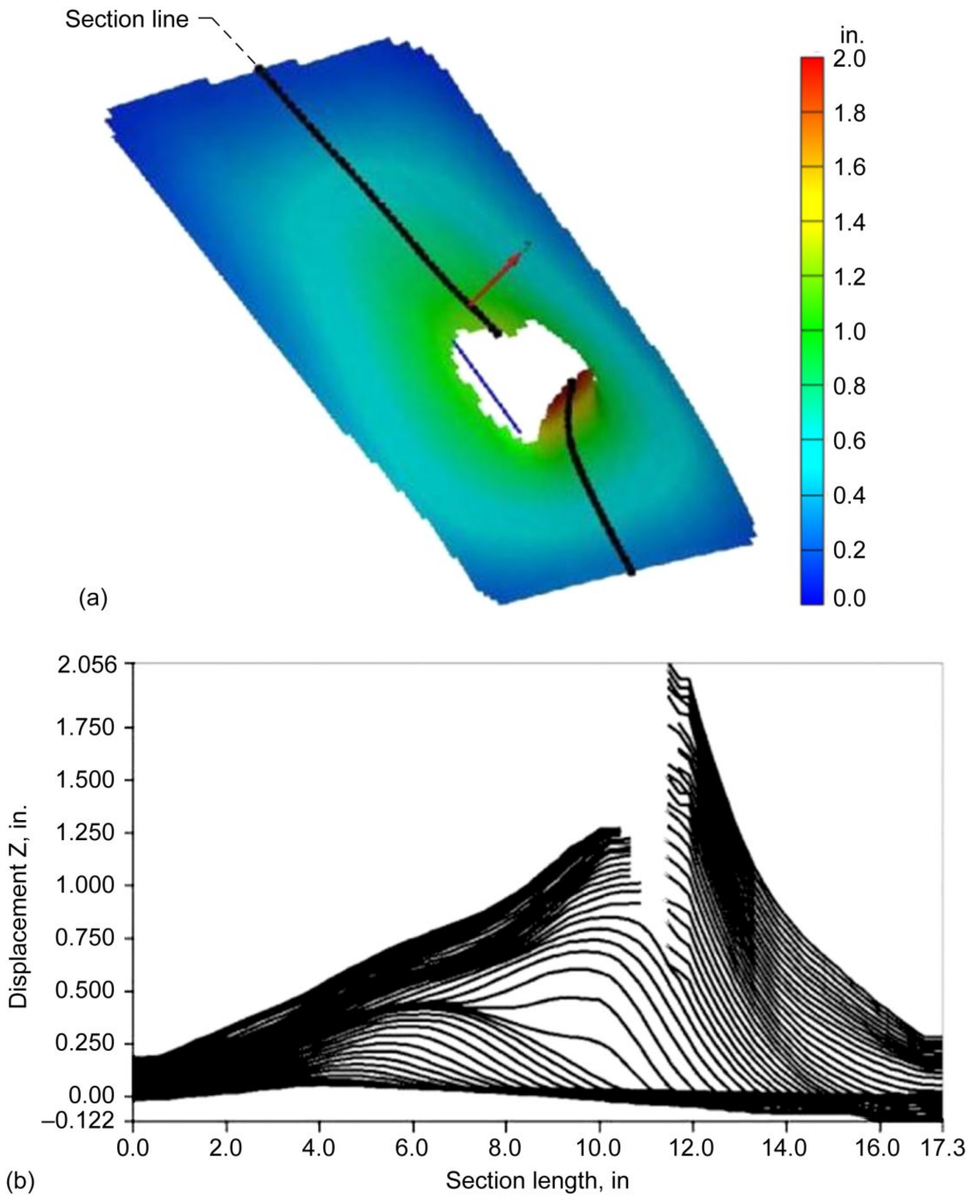

Figure 43.—(a) Deformation profile in Al-2024 Test LG911 after projectile penetration. (b) Deformation along section line shown in figure 43(a) as a function of time (Al-2024 test LG911)

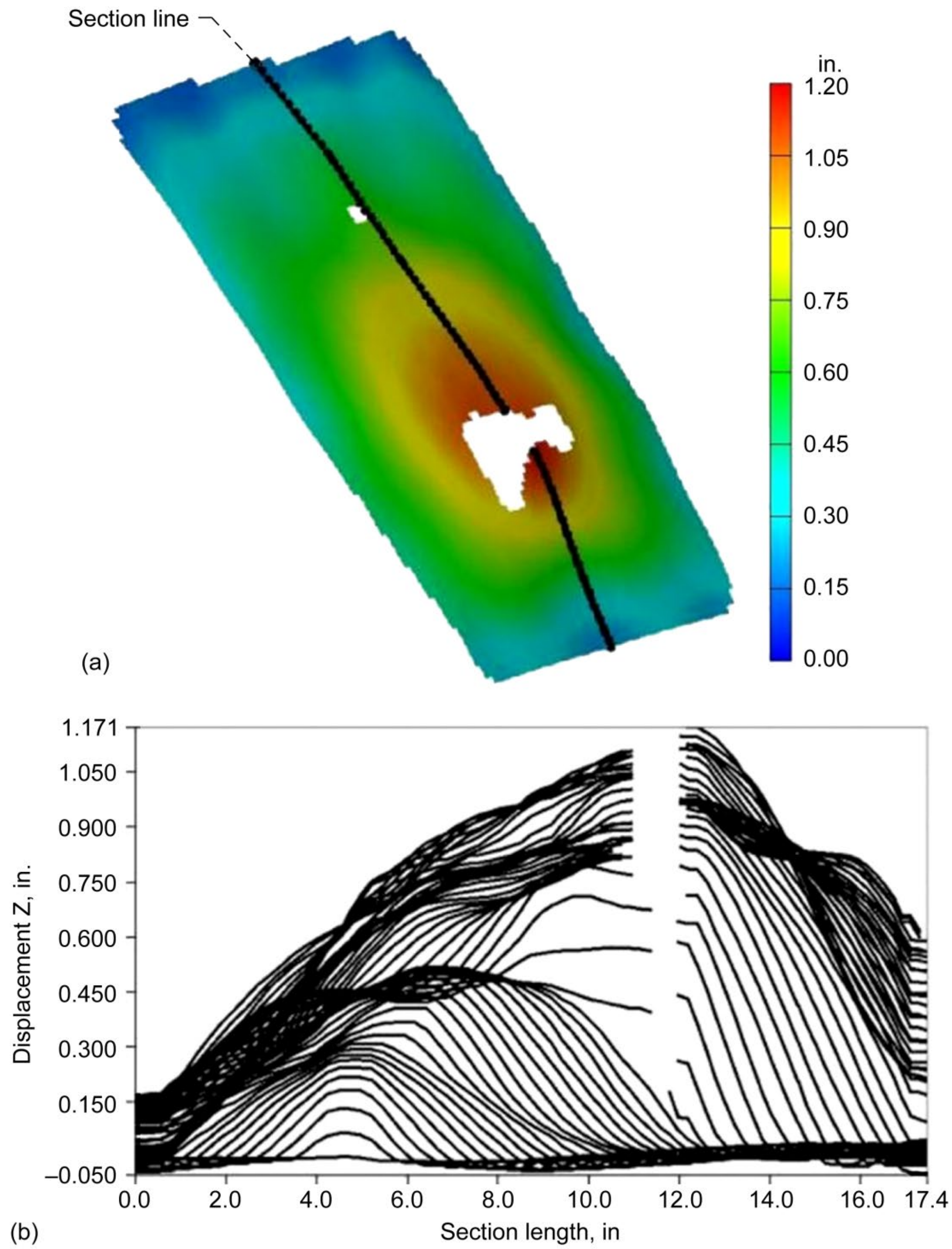

Figure 44.—(a) Deformation profile in Ti-6Al-4V Test LG912 at the time of maximum deformation. (b) Deformation along section line shown in figure 44(a) as a function of time (Ti-6Al-4V test LG912).

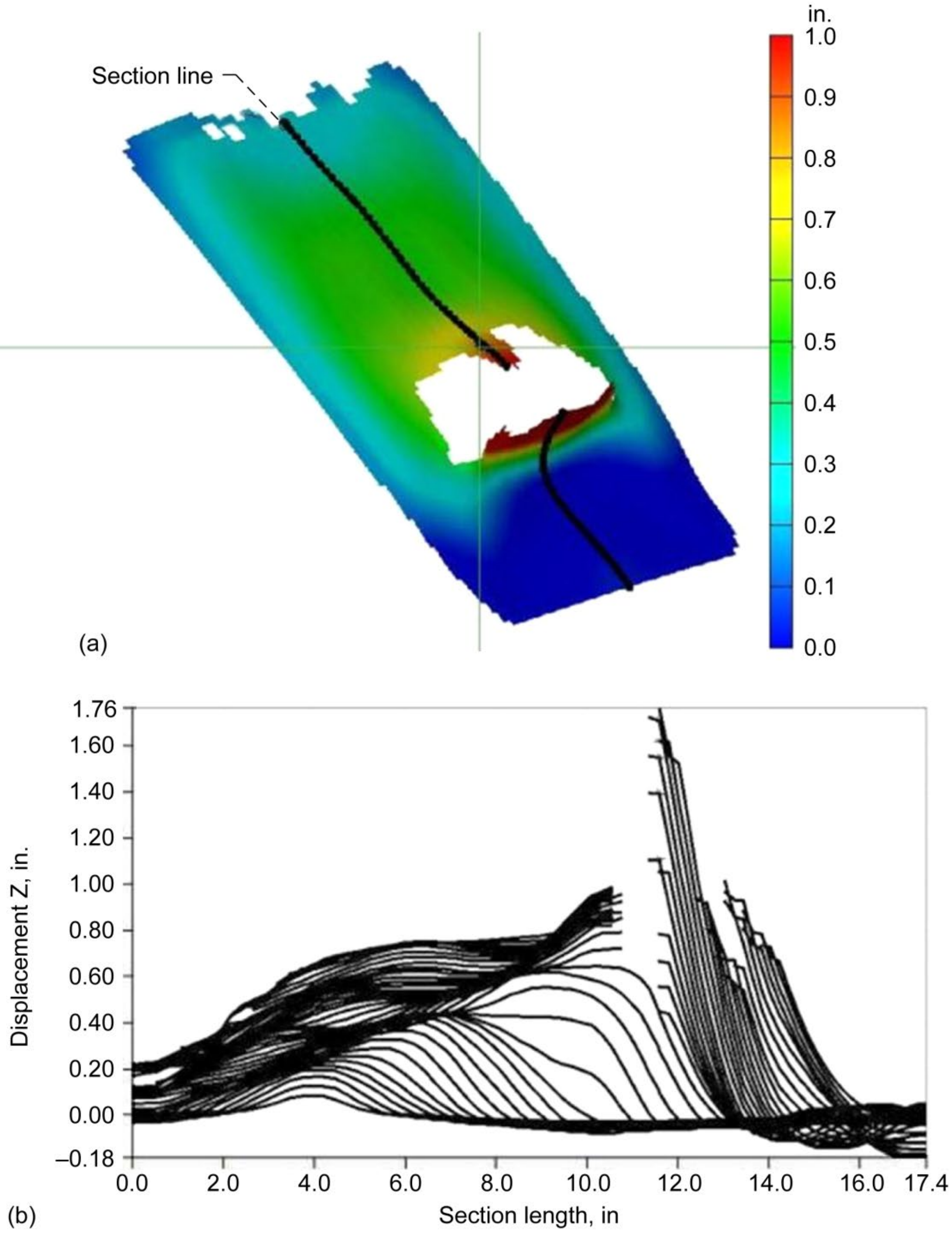

Figure 45.—(a) Deformation profile in Ti-6Al-4V Test LG913 at the time of maximum deformation. (b) Deformation along section line shown in Figure 45(a) as a function of time (Ti-6Al-4V test LG913)

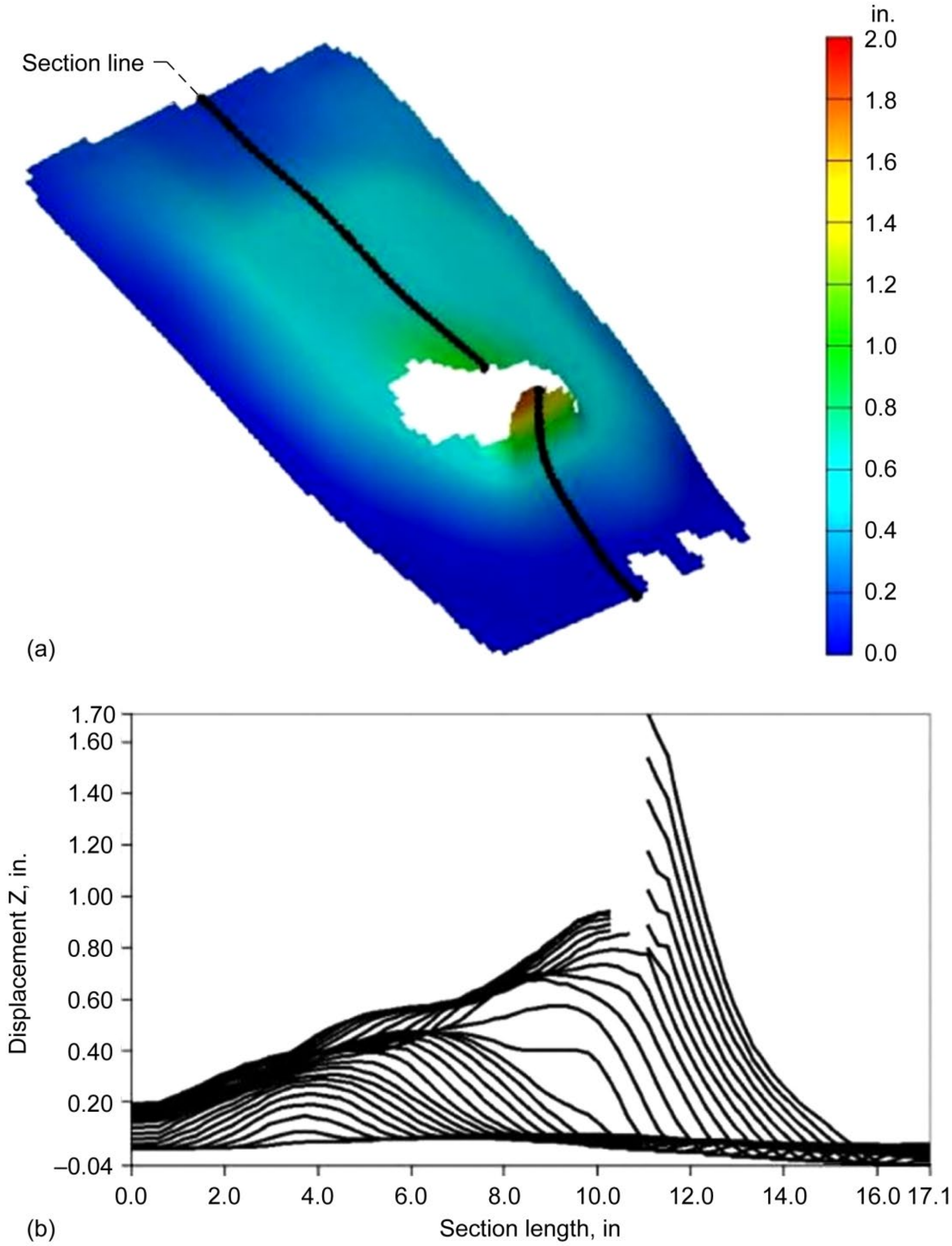

Figure 46.—(a) Deformation profile in Ti-6Al-4V Test LG915 at the time of maximum deformation. (b) Deformation along section line shown in Figure 46(a) as a function of time (Ti-6Al-4V test LG915).

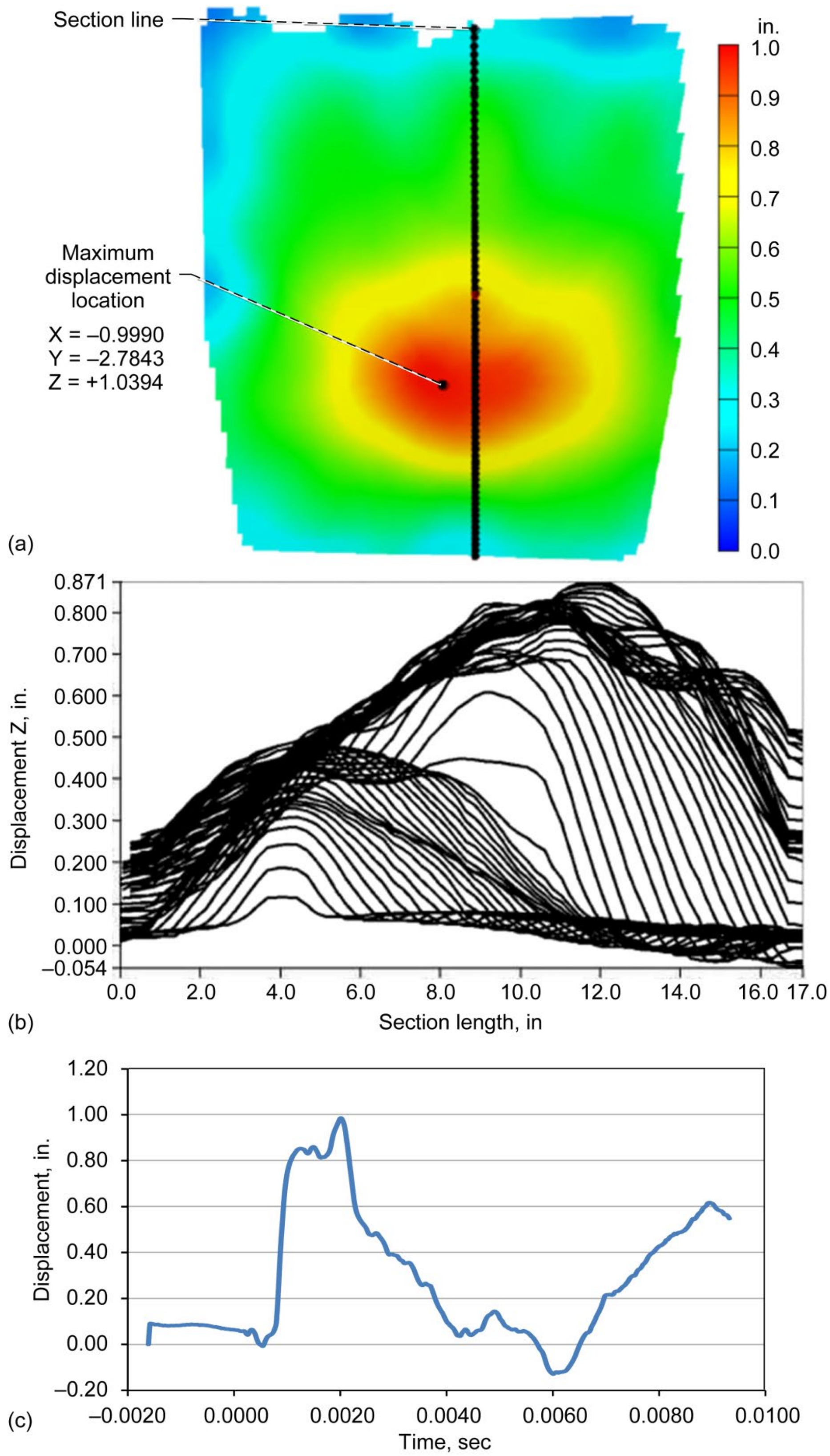

Figure 47.—(a) Deformation profile in Ti-6Al-4V Test LG916 at the time of maximum deformation. (b) Deformation along section line shown in Figure 47(a) as a function of time (Ti-6Al-4V test LG916). (c) Deformation as a function of time for the point of maximum deformation shown in Figure 47(a) (Ti-6Al-4V test LG916).

4.0 Discussion and Summary

In the two materials tested there is generally a well-defined ballistic limit velocity. The one exception to this is the case of the 0.5 in. thick Al-2024. The plugs formed in the thick aluminum and titanium plates were tapered at the front, with significant gouging along the sides. This indicates that fracture occurred while the rear side of the plates were under elastic bending deformation which reduced the size of the hole when the plate returned to a flat orientation, resulting in a hole with a smaller diameter than the projectile. This presumably increased the friction on the projectile as it travelled through the plate, as evidenced by the gouging observed in the plugs. The irregular results obtained for the 0.5 in. thick Al-2024 plates may be due to a high sensitivity to frictional effects. It is not known why the same sensitivity was not observed with the 0.5 in. thick Ti-6Al-4V plates, in which frictional effects were also present, but it should be noted that the impact conditions were significantly different, involving a projectile of different size and material.

At velocities higher than the ballistic limit, the energy absorption could either increase or decrease with impact velocity. For thicker panels (0.25 in. and above) the amount of energy absorbed increased as the speed increased beyond the penetration velocity. For thinner panels (0.14 in. and lower) the energy absorbed generally decreased with increasing impact velocity.

The projectile properties had a significant effect on the ballistic limit. The harder steel projectile resulted in a 15% decrease in penetration velocity in the 0.14 in. thick Ti-6-4 plate. It is not clear whether this is a result of just the hardness difference in the projectile or if the overall mechanical impedance is the primary driver, but results in the literature indicate that projectile hardness has an effect on both penetration velocity and penetration depth in thick test specimens.

Digital image correlation (DIC) yields good results for strain, even at the relatively low image resolution used in this study. However, it is useful to have a limited number of strain gages to verify results at discrete points.

In the large panel tests the major damage occurred where the heavier root section of the projectile impacted the test panel. This may be counter-intuitive since the tip of the projectile is relatively sharp, but is consistent with the damage that results from a fan blade-out in a jet engine.

This report provides results of instrumented impact tests on 15 in. square Al-2024 and Ti-6Al-4V panels of three different 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 blade-like features. The data provided in this report is 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, material characterization of the very same materials used for impact testing, and extensive instrumentation results. These reports provide a valuable set of data which 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, they are archived and available through the authors.

Appendix A.—Material Certification Sheets

A.1 Material Certification Sheet for 0.125 in. Al-2024

Date: 5/8/2006 Time: 5:31...

From: To: Sharon

MAY-05-2006 16:49 EMO TRANS BALTO EXPORT

AMAG rolling

AMAG rolling GmbH

Abnahmeprüfzeugnis 3.1 (EN 10204)
Inspection certificate – mill certificate
AMAG rolling GmbH
Zertifiziert nach / certified to ISO/TS 16949, EN 9100, ISO 14001

Nr.: 85521763 1 / 1
Rev. 0
Seite / page: 1 von / of 2
Datum / date: 2006 04 06

Auftraggeber / orderer: TW METALS, INC 760 CONSTITUTION DR USA-19341 Exton,PA **Warenempfänger / consignee:** TW Metals - Wichita **Endkunde, Bestell Nr. / Your cust., ord. no.:**	Bestell Nr. / order no.: M 49143690 Datum / date: 2005 12 20 Auftragsbest. Nr. / order confirmation no.: 558068 Datum / date: 2006 01 11 Lieferschein Nr. / delivery note.: 85521763 Datum / date: 2006 04 11 Akkreditiv Nr. / letter of credit no.:

Produkt/product	**Bedingungen/terms**
Form / form: sheet Werkstoff / material: 2024 Zustand / temper: T3 Dim. / dim: [inch]: 0,125x48,00x144,00 Kundenartikel-Nr / customer item no.: 05309	Techn. Lieferbedingungen / techn. spec.: AMS-QQA-250/4A, ASTM B209-04, AMS 4037 N Sondervorschrift / special terms:

AB-Pos. ord.-Pos.	BNr/Los/Teillos Lot/No./Part	Guss Nr. cast no.	Werkstoff material	Kollo packno.	Gewicht netto weight net	Stk. pcs.
01	70675/01/00	01/0013994/5	2024.4	5580680001	1227	31
01	70675/01/00	01/0013994/5	2024.4	5580680002	1234	31
01	70675/01/00	01/0013994/5	2024.4	5580680004	1231	31
01	70675/01/00	01/0013994/5	2024.4	5580680003	1232	31

Chemische Zusammensetzung / chemical composition: [%] Gewichtsanteile / weight proportion

cast no.	AMAG		Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	
01/0013994/5	2024.4	Min.			3,8	0,30	1,2					
		Max.	0,50	0,50	4,9	0,9	1,8	0,10	0,05	0,25	0,15	
			0,06	0,13	4,6	0,64	1,5	<0,01	<0,01	0,09	0,03	

Zugversuch / tensile test

BNr/Los/Tl. Lot/No./Part	Zustand temper	Richtung direction		Rm [ksi]	Rp0,2 [ksi]	A2" [%]				
			Min.	63,0	42,0	15				
			Max.							
70675/01	T3	LT		66,0	47,9	18				
70675/01	T3	LT		66,3	48,3	16				
70675/01	T3	LT		66,4	48,3	16				
70675/01	T3	LT		66,3	48,3	17				
70675/01	T3	LT		66,4	48,3	16				
70675/01	T3	LT		66,8	48,9	17				

pg 19

AMAG rolling GmbH, Postfach 32, A-5282 Ranshofen, Österreich – www.amag.at
AMAG rolling GmbH, P.O. Box 32, A-5282 Ranshofen, Austria – www.amag.at

TW METALS
TEST
Austin
MAY 1 1 2006
Burchard
ACCEPTED BY

AMAG rolling GmbH

AMAG rolling

Abnahmeprüfzeugnis 3.1 (EN 10204)
Inspection certificate – mill certificate
AMAG rolling GmbH
Zertifiziert nach / certified to ISO/TS 16949, EN 9100, ISO 14001

Nr.: **85521763** 1 / 1
Rev. 0
Seite / page: 2 von / of 2
Datum / date: 2006 04 06

Elektr. Leitfähigkeit / electr. conductivity

BNr/Los/TL Lot/No./Part	Zustand temper		dL_B [MS/m]			
		Min.				
		Max.	1,5			
70675/01	T3		0,2			

Sonstige Prüfungen / other Tests

Biegeversuch / Transverse bend test: OK.
Maßkontrolle / Dimensional Check: OK.
Oberfläche / Surface Inspection: OK.

Es wird bestätigt, dass die Lieferung geprüft wurde und den Vereinbarungen bei der Bestellung entspricht.
We hereby certify that the material described above has been tested and complies with the terms of the order contract.

Werkssachverständiger / factory specialist	Telefon / telephone	Fax / fax	E-Mail / e-mail
Rendl	+43 (7722) 801-2746	+43 (7722) 809-442	h.rendl@amag.at

Maschinell erstellt - Gültig ohne Unterschrift / Automated - valid without being signed

PS20

AMAG rolling GmbH, Postfach 32, A-5282 Ranshofen, Österreich – www.amag.at
AMAG rolling GmbH, P.O. Box 32, A-5282 Ranshofen, Austria – www.amag.at

TW METALS
TEST REPORTS
Austin
MAY 11 2006
Burchard
ACCEPTED BY

A.2 Material Certification Sheet for 0.25 in. Al2024

49133447

KAISER ALUMINUM

Trentwood Works - Spokane, WA 99215
Phone: (800) 367-2586

CERTIFIED TEST REPORT

Serial Number
4046144

SHIP TO:
TW METALS
1200 BLAKE DRIVE
WICHITA, KS 67219

SOLD TO:
TW METALS INC
THE ARBORETUM
760 CONSTITUTION DRIVE
EXTON, PA 19341

CUSTOMER PO NUMBER:	CUSTOMER PART NUMBER:	SHIPPING RUN #/LOAD ID:	GOV'T CONTRACT NUMBER:
M49133447	06232	100444/8	

KAISER ORDER NO:	LINE ITEM:	SHIP DATE:	ALLOY:	CLAD:	TEMPER:
1025400	1	16-AUG-2005	2024	BARE	T351
WEIGHT SHIPPED:	**QUANTITY:**	**B/L NUMBER:**	**GAUGE:**	**WIDTH:**	**LENGTH:**
3984 LB	22 PCS EST.	205660	0.2500 IN	48.500 IN	144.500 IN

Certified Specifications

AMS 4037/RevN   AMS-QQ-A-250/4/RevA   ASTM B 209/Rev04

Test Code: 1504

Test Results

Lot: 337156A4   Cast 282   Drop 11   Ingot 1

Tensile:	Temper	Dir / # Tests	Ultimate KSI (MPA)	Yield KSI (MPA)	Elongation %
	T351	LT / 2 (Min:Max)	69.4 : 70.1 (479 : 483)	48.8 : 50.5 (336 : 348)	16.6 : 17.0

Chemistry:	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR		OTHER
Actual	0.10	0.24	4.43	0.56	1.33	0.01	0.11	0.02	0.01	0.00	TOT	0.05

Lot: 337187A9   Cast 282   Drop 16   Ingot 4

Tensile:	Temper	Dir / # Tests	Ultimate KSI (MPA)	Yield KSI (MPA)	Elongation %
	T351	LT / 2 (Min:Max)	70.1 : 70.3 (483 : 485)	49.5 : 50.4 (341 : 348)	16.6 : 16.7

Chemistry:	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR		OTHER
Actual	0.10	0.28	4.65	0.59	1.38	0.03	0.12	0.02	0.01	0.00	TOT	0.04

ALLOY LIMITS

Chemistry:	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR	OTHER	MAX
2024 MIN	0.00	0.00	3.80	0.30	1.20	0.00	0.00	0.00	0.00	0.00	EACH	0.05
MAX	0.50	0.50	4.90	0.90	1.80	0.10	0.25	0.15	0.05	0.05	TOT	0.15

Aluminum Remainder

TW METALS
TEST REPORTS
AUG 22 2005
ACCEPTED BY

Page 1 of 2

49143561

KAISER ALUMINUM

Trentwood Works - Spokane, WA 99215
Phone: (800) 367-2586

CERTIFIED TEST REPORT

Serial Number
4060640

SHIP TO:
TW METALS
1200 BLAKE DRIVE
WICHITA, KS 67219

SOLD TO:
TW METALS INC
THE ARBORETUM
760 CONSTITUTION DRIVE
EXTON, PA 19341

CUSTOMER PO NUMBER:	WORK PACKAGE:	CUSTOMER PART NUMBER:	SHIP RUN/LOAD ID:	GOV'T CONTRACT NUMBER:
M49143561		06232	100602/3	

KAISER ORDER NO:	LINE ITEM:	SHIP DATE:	ALLOY:	CLAD:	TEMPER:
1031631	1	22-FEB-2006	2024	BARE	T351
WEIGHT SHIPPED:	**QUANTITY:**	**B/L NUMBER:**	**GAUGE:**	**WIDTH:**	**LENGTH:**
3806 LB	21 PCS EST.	207522	0.2500 IN	48.500 IN	144.500 IN

Certified Specifications

AMS 4037/RevN
CMMP 025/RevQ

AMS-QQ-A-250/4/RevA

ASTM B 209/Rev04

TW METALS
TEST REPORT
FEB 24 2006
ACCEPTED

Test Code: 1504

Test Results

Lot: 340929A9 **Cast 313** **Drop 09** **Ingot 4**

Tensile:	Temper	Dir / # Tests	Ultimate KSI (MPA)	Yield KSI (MPA)	Elongation %
	T351	LT / 2 (Min:Max)	68.8 : 69.3 (474 : 478)	49.1 : 49.2 (339 : 339)	16.5 : 17.1

Chemistry:	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR		OTHER
Actual	0.10	0.27	4.53	0.56	1.41	0.01	0.19	0.02	0.01	0.00	TOT	0.05

Chemistry:	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR	OTHER	MAX
2024 MIN	0.00	0.00	3.80	0.30	1.20	0.00	0.00	0.00	0.00	0.00	EACH	0.05
MAX	0.50	0.50	4.90	0.90	1.80	0.10	0.25	0.15	0.05	0.05	TOT	0.15

CERTIFICATION

KAISER ALUMINUM & CHEMICAL CORPORATION (KAISER) HEREBY CERTIFIES THAT METAL SHIPPED UNDER THIS ORDER WAS MELTED AND MANUFACTURED IN THE U.S.A. AND HAS BEEN INSPECTED, TESTED, AND FOUND IN CONFORMANCE WITH THE REQUIREMENTS OF THE APPLICABLE SPECIFICATIONS AS INDICATED HEREIN. ALL METAL WHICH IS SOLUTION HEAT-TREATED COMPLIES WITH AMS 2772. ANY WARRANTY IS LIMITED TO THAT SHOWN ON KAISER'S STANDARD GENERAL TERMS AND CONDITIONS OF SALE. TEST REPORTS ARE ON FILE, SUBJECT TO EXAMINATION. TEST REPORTS SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT THE WRITTEN APPROVAL OF KAISER ALUMINUM & CHEMICAL CORPORATION LABORATORY. THE RECORDING OF FALSE, FICTITIOUS, OR FRAUDULANT STATEMENTS OR ENTRIES ON THE CERTIFICATE MAY BE PUNISHED AS A FELONY UNDER FEDERAL LAW. ISO-9001:2000 CERTIFIED

BILL POYNOR, LABORATORIES SUPERVISOR

Page 1 of 1

A.3 Material Certification Sheet for 0.5 in. Al2024

SHIP TO:	
TW METALS 1200 BLAKE DRIVE WICHITA, KS 67219	**KAISER ALUMINUM** Trentwood Works - Spokane, WA 99215 Phone: (800) 367-2586
SOLD TO: TW METALS INC THE ARBORETUM 760 CONSTITUTION DRIVE EXTON, PA 19341	**CERTIFIED TEST REPORT** Serial Number 4062667

CUSTOMER PO NUMBER:	WORK PACKAGE:	CUSTOMER PART NUMBER:	SHIP RUN/LOAD ID:	GOV'T CONTRACT NUMBER:
M49144942		06251	100627/7	

KAISER ORDER NO:	LINE ITEM:	SHIP DATE:	ALLOY:	CLAD:	TEMPER:
1032601	1	21-MAR-2006	2024	BARE	T351
WEIGHT SHIPPED:	**QUANTITY:**	**B/L NUMBER:**	**GAUGE:**	**WIDTH:**	**LENGTH:**
2856 LB	8 PCS EST.	207817	0.5000 IN	48.500 IN	144.500 IN

TW METALS
TEST
MAR 27 2006
ACCEPTED BY

Certified Specifications

AMS 4037/RevN
CMMP 025/RevQ
AMS-QQ-A-250/4/RevA
ASTM B 209/Rev04

Test Code: 1504

Test Results

Lot: 352560A7 Cast 318 Drop 30 Ingot 3

Tensile:	Temper	Dir / # Tests	Ultimate KSI (MPA)	Yield KSI (MPA)	Elongation %
	T351	LT / 2 (Min:Max)	68.5 : 69.6 (472 : 480)	50.0 : 50.6 (345 : 349)	16.9 : 17.4

Chemistry:	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR		OTHER
Actual	0.08	0.22	4.47	0.59	1.37	0.01	0.18	0.02	0.01	0.01	TOT	0.04

ALLOY LIMITS

Chemistry:	SI	FE	CU	MN	MG	CR	ZN	TI	V	ZR	OTHER	MAX
2024 MIN	0.00	0.00	3.80	0.30	1.20	0.00	0.00	0.00	0.00	0.00	EACH	0.05
MAX	0.50	0.50	4.90	0.90	1.80	0.10	0.25	0.15	0.05	0.05	TOT	0.15

Aluminum Remainder

CERTIFICATION

KAISER ALUMINUM & CHEMICAL CORPORATION (KAISER) HEREBY CERTIFIES THAT METAL SHIPPED UNDER THIS ORDER WAS MELTED AND MANUFACTURED IN THE U.S.A AND HAS BEEN INSPECTED, TESTED, AND FOUND IN CONFORMANCE WITH THE REQUIREMENTS OF THE APPLICABLE SPECIFICATIONS AS INDICATED HEREIN. ALL METAL WHICH IS SOLUTION HEAT-TREATED COMPLIES WITH AMS 2772. ANY WARRANTY IS LIMITED TO THAT SHOWN ON KAISER'S STANDARD GENERAL TERMS AND CONDITIONS OF SALE. TEST REPORTS ARE ON FILE, SUBJECT TO EXAMINATION. TEST REPORTS SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT THE WRITTEN APPROVAL OF KAISER ALUMINUM & CHEMICAL CORPORATION LABORATORY. THE RECORDING OF FALSE, FICTITIOUS, OR FRAUDULANT STATEMENTS OR ENTRIES ON THE CERTIFICATE MAY BE PUNISHED AS A FELONY UNDER FEDERAL LAW. ISO-9001:2000 CERTIFIED

BILL POYNOR, LABORATORIES SUPERVISOR

Bill Poynor

Page 1 of 1

A.4 Material Certification Sheet for 0.09 in. Ti-6Al-4V

FORM 44A REV 6/7/04 — TEST REPORT — PAGE 1 of 1

RTI International Metals, Inc.

[ ] RMI TITANIUM COMPANY, 1000 WARREN AVE., NILES, OHIO 44446	DATE: 1/24/2006	SALES ORDER NO.: 61420	GRADE: 6AL-4V	PACKING LIST NO.: 80125439
[X] TRADCO, INC., 1701 WEST MAIN ST., WASHINGTON, MO 63090	CUSTOMER NAME: RTI ST. LOUIS			CUSTOMER ORDER NO.: 1064988
	MATERIAL: H.R ANN. & CLD. TI SHEET			

IDENTIFICATION & REFER MATERIAL NUMBER	INGOT NO	LOT	S-R	SPECIFICATION
	8511343	06	00	AMS 4911J MIL-T-9046J AB-1 AM.2 DMS 1592F; AMS-T-9046A AB-1 ASTM B 265-05 GR.5; ASTM F 1472-02A F-14-17-22-23 PWA 300BH; PWA 310AY
PRODUCTION ORDER	30086131			

CHEMISTRY: HEAT CODE PBCER [ ] INGOT (AVERAGE of TOP-CENTER-BOTTOM) [X] INGOT (AVERAGE of TOP-BOTTOM) [ ] FINAL PRODUCT

ELEMENT		TEST	LAB
C	.009	INGOT CHEMISTRY	RMI Titanium, Niles, OH
N	.005	BALANCE OF TESTS	Tradco Inc., Washington, MO
FE	.17		
AL	6.16		
V	3.82		
O	.15		
Y	<50 PPM		
TI	BALANCE		
FINAL PRODUCT OXY			
FINAL PRODUCT HYD(PPM)	26		

CHEMISTRY TEST METHODS
ALLOY CHEM: SPARK OES
O2/N2: ASTM E 1409/1937
HYDROGEN: ASTM E 1447
CARBON: ASTM E 1941

FRACTURE TOUGHNESS KSI √IN — Specimen Size: ID | Toughness # | Val. Ck

PROPERTIES					
ULTIMATE KSI	L	145.3 / 145.9	/	/	148.2 /
	T	150.6 / 151.5	/	/	147.7 /
YIELD (2%) OFFSET	L	138.0 / 138.4	/	/	138.8 /
	T	143.0 / 144.9	/	/	143.3 /
% ELONGATION (INCHES)	L	12.1 / 13.0	/	/	13.6 /
	T	12.6 / 13.5	/	/	10.7 /
% REDUCTION IN AREA	L	/	/	/	/
	T	/	/	/	/
BEND 105	L	5.0 TR / 10.0TD	/		/
	T	5.0 TR / 10.0TD	/	BEND 180	/
HARDNESS				STATIC NOTCH	

This certificate shall not be reproduced except in full without written approval of the RTI International Metals, Inc. lab at which it was prepared. The recording of false, fictitious, or fraudulent statements or entries on this documents may be punished as a felony under federal law.

BETA TRANSUS	1810°F ± 25°F (CALCULATED)
CREEP	
ULTRASONIC	
HEAT TREAT/ TEAT FORGE	PROD. ANN. 1450°F 15 MIN. A.C. — LAB ANN. 1325°F 20 MIN. & A.C. TESTED ON IIT. 8511343-04-00
SHIPPING	
NO. OF PIECES	20 PCS.
WEIGHT (LBS)	1003#
SIZE (IN)	0.090 X 36.00 X96.00
TEST PIECES	X X

OTHER DATA:
INGOT WAS MELTED AT RMI TITANIUM COMPANY, NILES, OHIO. PRODUCT CONFORMS TO ALL OTHER TECHNICAL REQUIREMENTS OF THE SPECIFICATION. MATERIAL CHECKED FOR SURFACE CONTAMINATION AND MEETS THE REQUIREMENTS OF THE TEST. MICROSTRUCTURE IS ACCEPTABLE AND MEETS THE REQUIREMENTS OF THE TEST. MATERIAL HAS BEEN TESTED IN ACCORDANCE WITH THE RMI / PWA VENDOR AGREEMENT LABORATORY CONTROL AT SOURCE (LCS). TESTING WAS CONDUCTED IN COMPLIANCE TO MCL MANUAL SECTION F-23. TRADCO INC., WASHINGTON, MO. AEBG NO. T6060 / RMI CO., NILES, OH AEBG NO. 72566. DOMESTICALLY MELTED MATERIALS ONLY. MATERIAL CODE: 464-00090. MATERIAL IS FREE OF MERCURY CONTAMINATION. MATERIAL HAS NO WELD REPAIR.

RTI-SL 2 — JAN 31 2006

THIS IS TO CERTIFY THAT THE ABOVE TEST RESULTS ARE CORRECT AS CONTAINED IN THE RECORDS OF THE COMPANY

NAME/TITLE: SHARON FREDRICK, LAB SUPERVISOR
SIGNED:
DATE: 1-24-06

TRI-TECH METALS INC OVERSTAMP
Ph# 909-948-1401, Order Date:06/26/2006
Cust: FAA/AAC, ACCTG OFC Job#: FS3143
P.O. DTFACT-06-P-00167
Size: .090"x 36"x 96", 3 ea, 1 pc cut to 12 eac@15"x 15"
Item 001 Heat/Lot# 8511343/06

A.5 Material Certification Sheet for 0.140 in. Ti-6Al-4V

TIMET®

Titanium Metals Corporation
100 Titanium Way, Toronto, Ohio 43964
Telephone (740) 537-5694, FAX (740) 537-5759

PAGE 1 OF 2

CERTIFICATE ID	CUSTOMER	PURCHASE ORDER
R8468--G01		4500005213
HEAT	GRADE	PRODUCT DESCRIPTION
R8468	TIMETAL 6-4	.140" SHEET

SPECIFICATIONS

AMS 4911_H; DMS 1592_F; MIL-T-9046_J AM 2 AB-1

CHEMICAL ANALYSIS
(Weight Percent)

	C	Fe	N	Al	V	O
R8468-TOP	0.027	0.160	0.004	6.322	4.030	0.145
R8468-BOT	0.023	0.130	0.005	6.272	3.944	0.162

	H2 (ppm)	LOCATION	METHOD
R8468--G01-S4826-2	30	-	HOT EXT.
R8468--G01-S4826-3	25	-	HOT EXT.

Yttrium less than 10 ppm.
Balance titanium.

MECHANICAL PROPERTIES

VCF 8 HRS. @ 1350°F
Room Temperature Tensile Results (YS @ .2% offset)

IDENTITY	TENSILE DIR	TS KSI	YS KSI	4D, % EL
R8468--G01-S4826-2	L	145	138	14
R8468--G01-S4826-2	T	152	143	13
R8468--G01-S4826-3	L	145	137	16
R8468--G01-S4826-3	T	148	140	16

MACROSTRUCTURE/MICROSTRUCTURE

L-Micro Spec.: AMS 4911_H

IDENTITY	MICRO RATING PRED	MICRO RATING OCC	GRAIN SIZE
R8468--G01-S4826-2	A	--	10.0
R8468--G01-S4826-3	A	--	10.0

COMPLIANCE STATEMENTS

1 Microstructure examined and acceptable.
2 Surface free from contamination.
3 105 degree bend test performed and is acceptable. Bend factor R/T 5.0 examined at 20X.

TRI-TECH METALS INC
TRI-TECH METALS INC OVERSTAMP
Ph# 909-948-1401, Order Date:06/26/2006
Cust: FAA/AAC, ACCTG OFC Job#: FS3143
P.O. DTFACT-06-P-00167
Size: .140"x 36"x 72", 4 ea, 2 pc cut to 12 each@15"x 15"
Item 002 Heat/Lot# R8468

ANSI-RAB ACCREDITED
American Quality Assessors
REGISTERED ISO 9002

NADCAP
NDT & LAB

A.6 Material Certification Sheet for 0.250 in. Ti-6Al-4V

Traveler(s) 21234 B Heat # G05F Ingot#

CERTIFICATE OF TEST

Page 1 of 5

ALLVAC
P.O. Box 5030 2020 Ashcraft Ave.
Monroe, NC 28111-5030
Phone (704) 289-4511

Customer Name

PCS Weight

TRI-TECH METALS INC
TRI-TECH METALS INC OVERSTAMP
Ph# 909-948-1401, Order Date:06/26/2006
Cust: FAA/AAC, ACCTG OFC Job#: FS3143
P.O. DTFACT-06-P-00167
Size: .250"x 36"x 96", 3 ea, 1 pc cut to 12 each@15"x 15"
Item 003 Heat/Lot# G05F

Purchase Order	Size	Alloy
17803 - Item 2	SEE BELOW	ALLVAC 6-4

Proj Rev 0

Date: 06/30/2006 Quality Auditor: Todd Langer

SPECIFICATIONS

**AMS-T-9047	05/03	COMP. 6-4 COND. A	**MIL-T-9047	G AM2	COMP. 6-4 COND. A
AMS 2631	B	CLASS A1	AMS 4911	J	
AMS 4928	Q		AMS-T-9046	A	CODE AB-1 COND. A
ASTM B265	2006	GRADE 5	DMS 1592	F	
DMS 1592F SPEO96-062	01/16/97		DMS 1592FSPEO98-009A	04/19/99	
F-28	03/15/04		MIL-I-45208	A	AM2
MIL-STD-2154	09/30/82	TYPE 1 CLASS A	MIL-T-9046	J AM2	CODE AB-1 COND. A
MMS 1217	G		PWA 300	BH	
S-1000	01/03/2005		S-400	04/29/2004	

**EXCLUDING UT REQUIREMENTS

SIZE: 0.250" X 48.000" X 120"/160" (RANDOM LENGTH)

PLATE IDENTITY: A2C1, A2C2, A2D1, A2D2

We hereby certify that these are correct copies of reports now on file at Western Titanium, Inc.

By: Cheem Ang - Q.A. Manager

Traveler(s)		Heat #	Ingot#		
21234	B	G05F		ALLVAC P.O. Box 5030 2020 Ashcraft Ave. Monroe, NC 28111-5030 Phone (704) 289-4511	Page 2 of 5

HEADER REMARKS

This material was manufactured and tested as rolled plate in accordance with the requirements of the plate product specification(s) called out by the purchase order for said material. The test data reported for this product, or portions cut/sectioned from this product, also demonstrates the products capability of meeting the testing requirements of the bar product specification(s) called out by the purchase order for said material; as they may be applicable to and capable of the product sizes provided. Required test specimen orientations and locations are limited to the dimensions of the parent rolled plate product.

CHEMISTRY

CR EQ = Chromium Equiv Cb = Nb

	C	C Tested At	Si	Mn	Mo	Ti	Al	Ti+Al	V	Fe	Cu	XRF Tested At
TOP	.020	WAH CHANG	.02	<.01	.02	BAL	5.91	-	4.02	.20	<.01	WAH CHANG
BOTTOM	.020	WAH CHANG	.02	<.01	.02	BAL	6.03	-	4.00	.19	<.01	WAH CHANG

	B	B Tested At	Zr	Y	Y Tested At	O	N	O/N Tested At	Sn	Sn Tested At	Cr	Cb	Ta	Ni
TOP	<.000	WAH CHANG	.12	<.0005	WAH CHANG	.2000	.0068	WAH CHANG	<.01	WAH CHANG	.02	-	-	.06
BOTTOM	<.000	WAH CHANG	.12	<.0005	WAH CHANG	.1850	.0062	WAH CHANG	<.01	WAH CHANG	.02	-	-	.06

	H
PLATE A2C1	.0135

CHEMISTRY REMARKS

Chemistry tested at ALLVAC unless otherwise noted.

BETA TRANSUS CALCULATED BY CHEMISTRY:
TOP = 1821F
BOTTOM = 1818F

Wah Chang/GE Aircraft Engine Code 91974 applies.

Traveler(s)		Heat #	Ingot#
21234	B	G05F	

ALLVAC P.O. Box 5030 2020 Ashcraft Ave. Monroe, NC 28111-5030 Phone (704) 289-4511

As Shipped Tensile Test

Operation	Ingot	Heat Treat Code	Test Dir	Temp F	UTS ksi	.2% Yield ksi	.02% Yield ksi	%EL 4D	%EL 5D	%RA	Gage Length 4D	Gage Length 5D	Tensile Diameter	Tested At
SUPER		VCF2	LC	ROOM	143.5	134.0		21.0		45.0	1.0			WESTMORELAND
SUPER		VCF2	LTC	ROOM	149.1	139.1		22.0		47.0	1.0			WESTMORELAND
SUPER		VCF2	LC	ROOM	142.6	131.7		19.0		40.0	1.0			WESTMORELAND
SUPER		VCF2	LTC	ROOM	152.2	139.2		20.0		42.0	1.0			WESTMORELAND
SUPER		VCF2	LTC	ROOM	151.6	138.7		19.0		43.0	1.0			WESTMORELAND
SUPER		VCF2	LTC	ROOM	152.5	139.6		21.0		41.0	1.0			WESTMORELAND

Test Dir: L = Longitudinal, T = Transverse, ST = Short Transverse, LT = Long Transverse,
TC = Transverse Center At Size, TM = Transverse Mid-Radius At Size,
PC = Pancake, DB = Drawbar, PD = Paddle, TT = Top Transverse At Size,
BT = Bottom Transverse At Size, LC = Long Center, TX = Top Transverse Mid-Radius At Size,
LM = Longitudinal Mid Radius, LS = Longitudinal Surface, TS = Transverse Surface
Operation: SUPER = Crosshead Sep Rate of .10 inches/minute

TENSILE/STRESS RUPTURE HEAT TREATMENT

HT Code: VCF2

Location	Temp F	Hours	Mins	Furnace Cool Rate Per Hrs (F)	Cool Code	
PLANT	1450	8			FC	VCF 6 HRS. MIN.

METALLOGRAPHY

Microstructure evaluated in accordance with the referenced specifications and found acceptable.
Material evaluated and determined to be free of alpha case.

SONIC

A.7 Material Certification Sheet for 0.500 in. Ti-6Al-4V

Titanium Industries, Inc.

Certificate of Analysis

Cert Number 1058 4/23/2010
Test Reference 8740

FAA WM. J. HUGHES TECHNICAL CENTER
ATLANTIC CITY INT'L AIRPORT
ATTN: DONALD ALTOBELLI(BLDG 292)
ATLANTIC CITY, NJ 08405

Issued from
Titanium Industries, Inc.
Rockaway Service Center
18 Green Pond Road
Rockaway, NJ 07866

Sold To: FAA WM. J. HUGHES TECHNICAL CENTER, ATLANTIC CITY INT'L AIRPORT, ATTN: DONALD ALTOBELLI(BLDG 292), ATLANTIC CITY, NJ 08405

Ship To: J. MICHAEL PEREIRA, NASA GLENN RESEARCH CENTER, MS 49-8, 2100 BROOKPARK ROAD, CLEVELAND, OH 44135

Reference

Customer	57/0	**Your Order**	credit card (4/20/2010)
Our Order	9811-1-1	**Packing List**	11009-1 (4/23/2010)

Product Information

	Heat	Tag	Pcs	LBS
Titanium Plate 6AL-4V US Titanium Plate 0.500" x 36" x 48"	H13962-E10211	4233AA	2	283

Shipped Heats H13962-E10211
Conform To AMS-4911 8/28/2008

Chemical Composition

N	C	Fe	O	H	Al	V	Y
0.006	0.016	0.16	0.17	0.0085	6.27	4.08	0.0004

Ti
BAL

Physical Tests

Tensile L	Tensile T	Yield L	Yield T
148 KSI	145 KSI	137 KSI	136 KSI

Elongation L	Elongation T
16 %	16 %

CERTIFICATE OF COMPLIANCE

ALL ITEMS FURNISHED ARE IN FULL COMPLIANCE WITH PURCHASE ORDER AND SPECIFICATION REQUIREMENTS LISTED. THE MATERIAL APPLIED DID NOT COME IN CONTACT WITH MERCURY NOR WAS ANY WELD REPAIR PERFORMED DURING PROCESSING BY TITANIUM INDUSTRIES, INC.

THE MATERIAL SUPPLIED MEETS THE VISUAL AND DIMENSIONAL REQUIREMENTS OF THE PURCHASE ORDER AND TEST REPORTS/CERTIFICATIONS REPRESENT THE ACTUAL ATTRIBUTES OF THE ITEMS FURNISHED.

AUTHORIZED SIGNATURE: [illegible] 4/23/10

The contents of this order have been inspected by:

4/23/2010 | 03:58 PM | 1

TIMET

Titanium Metals Corporation

100 Titanium Way, Toronto, OH 43964
Telephone (740) 537-5694, Fax (740) 537-5653

Approved Certificate

Page 1 of 3

CERT ID	*PURCHASE ORDER*	*SOLD TO CUSTOMER*
H13980-A1X *26-FEB-2010 18:28:05 GMT*	20060408	TIMET Service Center St. Louis *109 Interstate Drive, Wentzville, MO 63385*
HEAT NUMBER	***GRADE***	***SHIP TO CUSTOMER***
H13980	TIMETAL®6-4	TIMET Service Center St. Louis *109 Interstate Drive, Wentzville, MO 63385*
TEST NUMBER		
E10225		

PRODUCT DESCRIPTION
.500" SQ Plate

DELIVERY CONDITION
Annealed

Specifications
This material complies with the following specifications:
AMS 4911 L DMS 1592 G

Release Statements
1. TIMET-Toronto has a Quality Management System that is in compliance with ISO 9001:2000, ANSI/ISO/ASQ Q9001-2000 and AS 9100:2001 Revision B, Certificate No. UQA 0113328, through Lloyd's Register Quality Assurance, effective 24-Jul-03.

Melt Method	*Melt/Process Location*
3-VAR	TIMET - Henderson, NV, USA / TIMET - Toronto, OH, USA

Compliance Statements
1. In accordance with AMS-T-9046 B cancellation notice, material is tested and certified to Table 1 superceding specification AMS 4911 Rev L.
2. Surface free from alpha case and product conforms to the other technical requirements of the referenced specification(s).
3. Microstructure examined and acceptable to the order specifications.
4. Immersion ultrasonic tested to a #3 FBH per AMS 2631 C Class A1 and acceptable.
5. Material meets the special flatness requirements of the purchase order.
6. TIMET-Toronto is an approved supplier of this product per DMS QPL 1592 Issue 18. Ingot melted in accordance with DMS 2442; TIMET-Henderson, NV, is an approved ingot source per DMS QPL-2442 Issue 18.

Accredited Nadcap Materials Testing Laboratory ISO/IEC 17025 Nondestructive Testing Heat Treating

REGISTERED ISO 9001/AS9100 FACILITY

First in Titanium Worldwide

TIMET Titanium Metals Corporation — **Approved Certificate**

100 Titanium Way, Toronto, OH 43964
Telephone (740) 537-5694, Fax (740) 537-5653

CERT ID	*PURCHASE ORDER*	*SOLD TO CUSTOMER*
HI3980-A1X	20060408	TIMET Service Center St. Louis
26-FEB-2010 18:28:05 GMT		*109 Interstate Drive, Wentzville, MO 63385*

Ingot Chemical Analysis
(Weight percent)

Unless otherwise noted, Ingot Chemical Analysis performed at Henderson Process Lab, 181 N. Water Street, Henderson, NV, 89015, US

Sample ID	Fe	V	Al	C	O	N	Y
TOP	0.16	4.05	6.28	0.015	0.18	0.008	<0.0004
BOTTOM	0.15	4.00	6.25	0.016	0.19	0.007	<0.0004

Product Analysis
(Weight percent)

Unless otherwise noted, Product Analysis performed at Toronto Laboratory, 100 Titanium Way, Toronto, OH, 43964, US

Sample ID	H
1	46
2	69

Chemistry Statements

1. Hydrogen values reported in PPM. Hydrogen determined by inert gas fusion per ASTM E1447. Carbon determined by combustion per ASTM E1941. Oxygen and Nitrogen determined by inert gas fusion per ASTM E1409. Henderson Melt: Metallics determined by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) per ASTM E2371. Morgantown Melt: Copper and Boron by atomic spectrometry (ingot only) and all other elements by x-ray fluorescence spectrometry.
2. Residual elements each less than 0.10% maximum, 0.40% maximum total.
3. Balance titanium.

Mechanical Properties

Unless otherwise noted, testing performed at Toronto Laboratory, 100 Titanium Way, Toronto, OH, 43964, US

RTT - Longitudinal (ASTM E 8)
Test Condition: Mill VCF 8 Hours Minimum @ 1400°F

Sample ID	0.2YS	U.T.S.	4DEL
	ksi	ksi	%
1	133	144	18
2	133	145	18

RTT - Transverse (ASTM E 8)
Test Condition: Mill VCF 8 Hours Minimum @ 1400°F

Sample ID	0.2YS	U.T.S.	4DEL
	ksi	ksi	%
1	139	150	18
2	139	150	18

Accredited Nadcap — Materials Testing Laboratory, ISO/IEC 17025, Nondestructive Testing, Heat Treating

REGISTERED ISO 9001/AS9100 FACILITY

First in Titanium Worldwide

TIMET **Titanium Metals Corporation** **Approved Certificate**

100 Titanium Way, Toronto, OH 43964
Telephone (740) 537-5694, Fax (740) 537-5653

CERT ID	*PURCHASE ORDER*	*SOLD TO CUSTOMER*
H13980-A1X *26-FEB-2010 18:28:05 GMT*	20060408	TIMET Service Center St. Louis *109 Interstate Drive, Wentzville, MO 63385*

Tests on Other Material

Unless otherwise noted, testing performed at Toronto Laboratory, 100 Titanium Way, Toronto, OH, 43964, US

Batch: H13550-31 (J9833)
RTT - Longitudinal (ASTM E 8)
Test Condition: Periodic Test: Mill Annealed 60 Minutes 1400°F AC + Lab Annealed 20 Minutes @ 1325°F AC

Sample ID	**0.2YS**	**U.T.S.**	**4DEL**	**R.A.**
	ksi	**ksi**	**%**	**%**
1	126	137	15	31

Results are from TIMET Quality Control Records on file
Sales Order # 273575 Item # 10
v.1

Bill Williamson - Certification Specialist

TIMET 150

Accredited Nadcap Materials Testing Laboratory ISO/IEC 17025 Nondestructive Testing Heat Treating
REGISTERED ISO 9001/AS9100 FACILITY

The intentional recording of false, fictitious, or fraudulent statements or entries on the certificate may be punished as a felony under federal law

First in Titanium Worldwide

TIMET

St. Louis Mill Sales
109 Interstate Drive
WENTZVILLE MO 63385
USA
Tel:800-753-1550 Fax:636-887-9098
Shipping Plant: St. Louis Service Center

Attachment to Product Certification

Customer P.O. Number/Date
CRP-20447-KS/Feb 25, 2010
TIMET Sales Order Number/Date
281118/Feb 26, 2010
TIMET Packing List Number/Scheduled Ship Date
80417460/Apr 02, 2010

Sold-to Address
Titanium Industries Inc
18 Green Pond Road
ROCKAWAY NJ 07866
USA

Ship-to Address
Titanium Industries Inc
18 Green Pond Road
ROCKAWAY NJ 07866
USA

TIMET Item # / Customer Item #	Material # / Customer Material #	Material Description	Quantity	Weight
000010	110357	*TIMETAL®* 6-4 Titanium Aero Plate		

Heat Treatment : Mill Annealed
Specifications : 01 AMS 4911 * L
: 02 AMS 2631 * C CL A1
: 03 AMS-STD-2154 TY1 CL A
: 04 AMS-T-9046 * A AB-1 COND A
: 05 ASTM B 265 * -09AE1 GR 5
: 08 DMS 1592 * G
: 09 MIL-STD-2154 ORG TY1 CL A
: 10 MIL-T-9046 J AMD2 AB-1 CD A

Batch Number : H13962-Y16 469.000LB 469.000LB
Batch Dimensions : 0.500" X 48.000" X 120.000"
Batch Number of Pieces : 1.000
Country of Origin : USA
Heat Number : H13962
Test Number : E10211

Batch Number : H13980-Y03 489.000LB 489.000LB
Batch Dimensions : 0.500" X 48.000" X 120.000"
Batch Number of Pieces : 1.000
Country of Origin : USA
Heat Number : H13980
Test Number : E10226

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Appendix B.—Texture Analysis

Texture analyses were performed on samples from all the 2024 aluminum (Al) sheet and plates that were impact tested in this report. The samples were prepared for measurement by ultrasonic cleaning in ethanol followed by immersion etching at ambient temperature. The Al 2024 samples were etched in a 50% sodium hydroxide solution for 7 minutes followed by a rinse in 50% nitric acid. The titanium (Ti) 6Al-4 vanadium (V) samples were etched in a 2%HF + 8%HNO3 + 90%H2O solution for 40min followed by a water rinse. Typical material removal per surface was 125 µm for the Al 2024 samples and 50 µm for the Ti-6Al-4V samples.

Texture data was acquired using a Bruker D8 Discover X-ray Diffractometer equipped with a sealed Cu tube, graphite monochrometer set to Kα radiation, 0.5 mm diameter collimator, and a proportional multiwire 2–D position-sensitive detector (area detector). The sample was mounted in a 2-axis Eulerian cradle equipped with a 3-axis translation stage and aligned using a laser/videomicroscope system.

A data acquisition scheme was designed with 5° resolution for reflection-mode pole figure (PF) coverage up to 75° (nominal) from the surface normal. For the Al 2024 samples, this included the (200), (111), and (220) poles. For the Ti-6Al-4V samples, this included the (10.0), (00.2), (10.1), (10.2), (11.0), and (10.3) poles of the alpha Ti phase and the (110) and (200) poles of the beta Ti phase. Data was taken from the rolled surface of the samples. The rolling direction (RD) was marked on the samples by the requester and preserved during etching by beveling a sample edge parallel to the RD. Sample coverage was maximized by oscillating over a 30- by 30-mm area using a 2-axis raster pattern during each of the data acquisition frames (180s/frame).

The raw 2D data was reduced to experimental (incomplete) pole figures using the Multex3 software package (Bruker AXS, Madison, WI). Data from these pole figures were then used to compute the Orientation Distribution Function (ODF) using the harmonic method (Ref. 3) as implemented in the TexEval software package (Bruker AXS, Madison, WI). Full pole figures were then calculated from the ODF and are shown in this appendix.

A quantitative measure of texture sharpness is the texture index, which is computed from the ODF. Its value lies between 1 for a texture-free sample and infinity for a single crystal. For comparison, the texture index of a sample of commercial aluminum foil (a highly textured material) was measured at 4.14. Texture index values, predominant textures present, and degrees off-center (for the Ti-6-4 basal textures) are summarized in Table B.1. All the texture measurements were taken at the surface of the sheet or plate with the exception of the Ti-6-4 (0.5 in. thick) plate which was measured both at the surface ant at the center of the plate thickness.

TABLE B.1.—SUMMARY TEXTURE RESULTS

Sample	Texture index	Predominant texture type	Degrees off-center
Al 2024 1/8 in.	1.26	Cube	N/A
Al 2024 1/4 in.	1.89	Cube	N/A
Al 2024 1/2 in.	1.34	Cube	N/A
Ti-6-4 0.09 in.	1.40	Transverse	N/A
Ti-6-4 0.135 in.	1.17	Basal	30°
Ti-6-4 0.25 in.	1.48	Basal	18°
Ti-6-4 0.5 in.	1.03	Basal, Transverse	---
Ti-6-4 0.5 in.	1.45	Transverse	(thru-thickness at the center of the plate)

B.1 Al 2024-T3

All of the Al 2024 exhibit a cube texture (Figure B.1) with the textures of the 1/8 in. and 1/2 in. samples being considerably weaker than the 1/4 in. sample. The 1/4 in. thick plate also contained the largest grain sizes. The 1/8 in. plate had the most equiaxed grains. The cube texture is a typical annealing texture seen in Face Center Cubic (FCC) structured metals. The symmetry of the (200) PF from the 1/8 in. sample may indicate cross-rolling (4-fold symmetry with one direction weaker than the perpendicular direction. The apparent 6-fold symmetry of the 1/4 and 1/2 in. samples perhaps indicates clock-rolling.

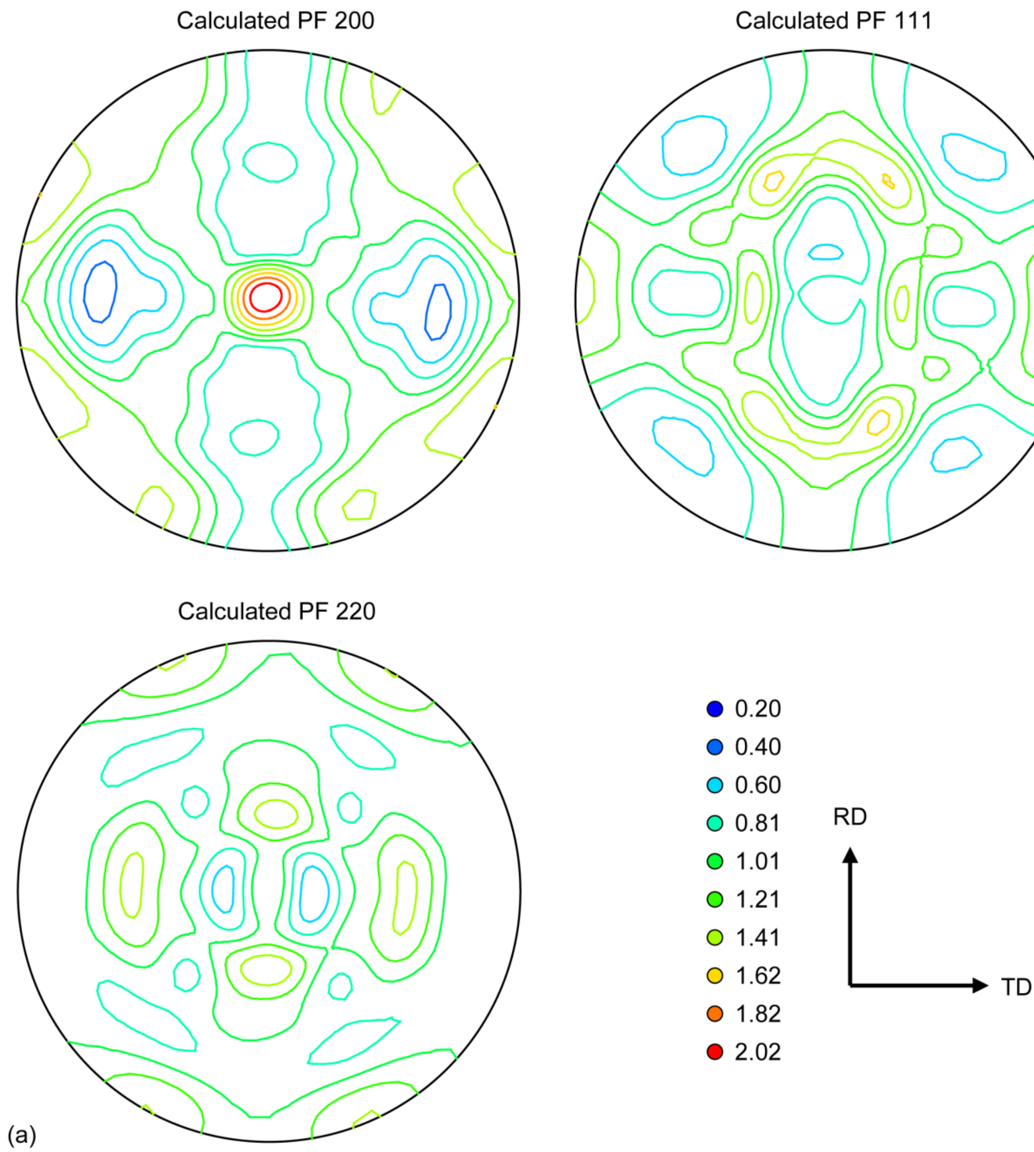


Figure B.1.—Pole figures for Al 2024-T3. (a) Plate thickness: 1/8 in., (b) Plate thickness: 1/4 in., and (c) Plate thickness: 1/2 in.

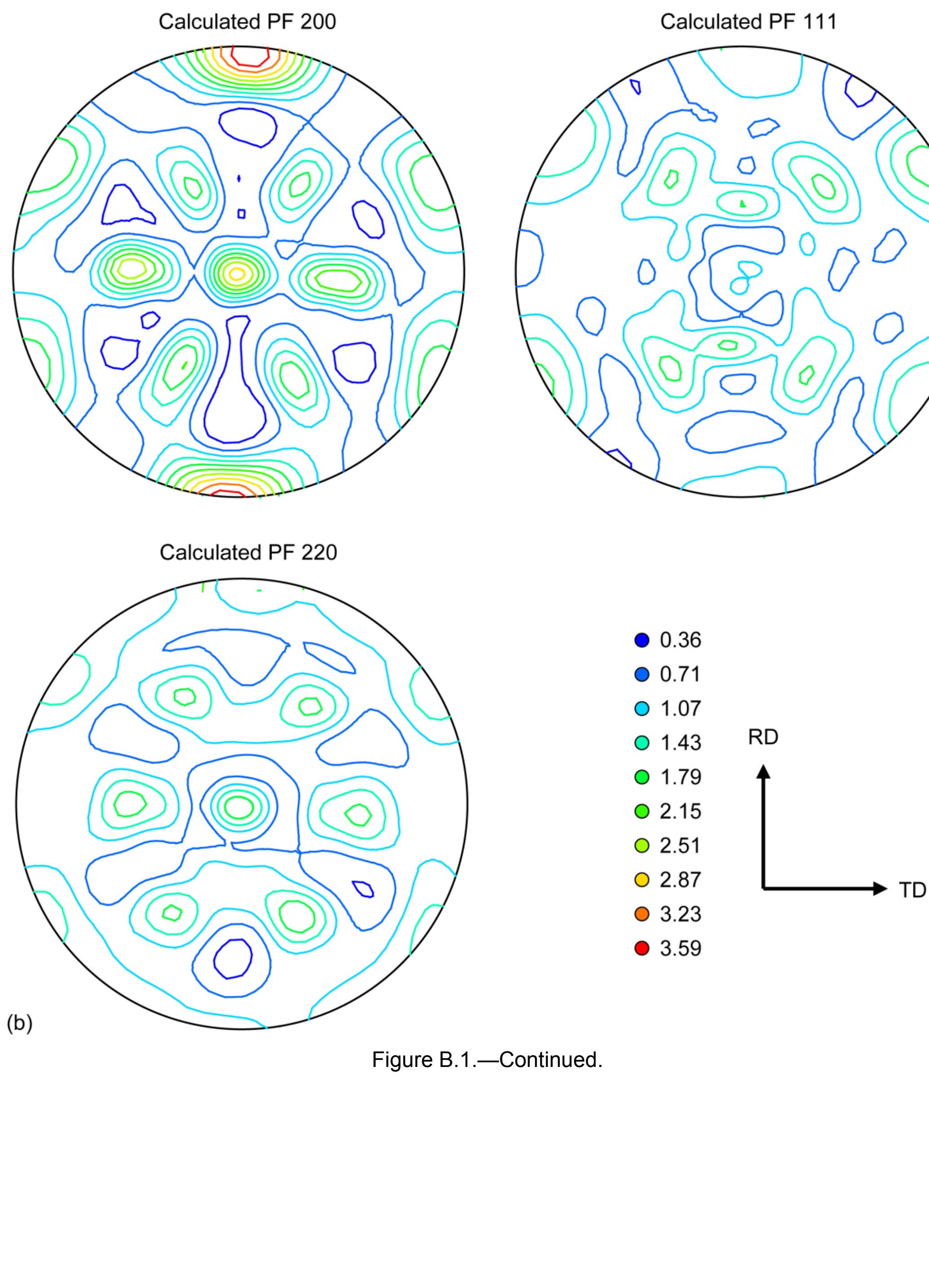


Figure B.1.—Continued.

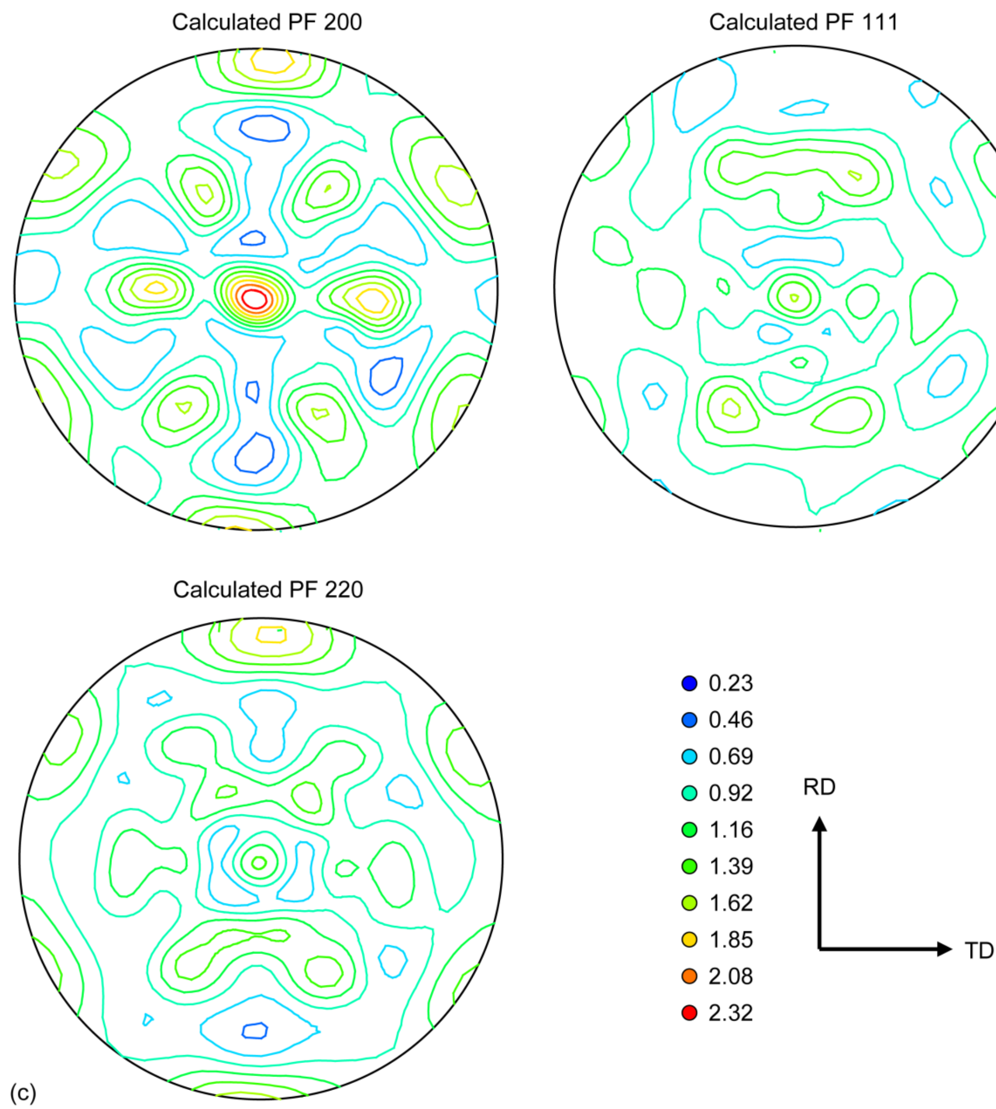


Figure B.1.—Concluded.

B.2 Ti-6-4

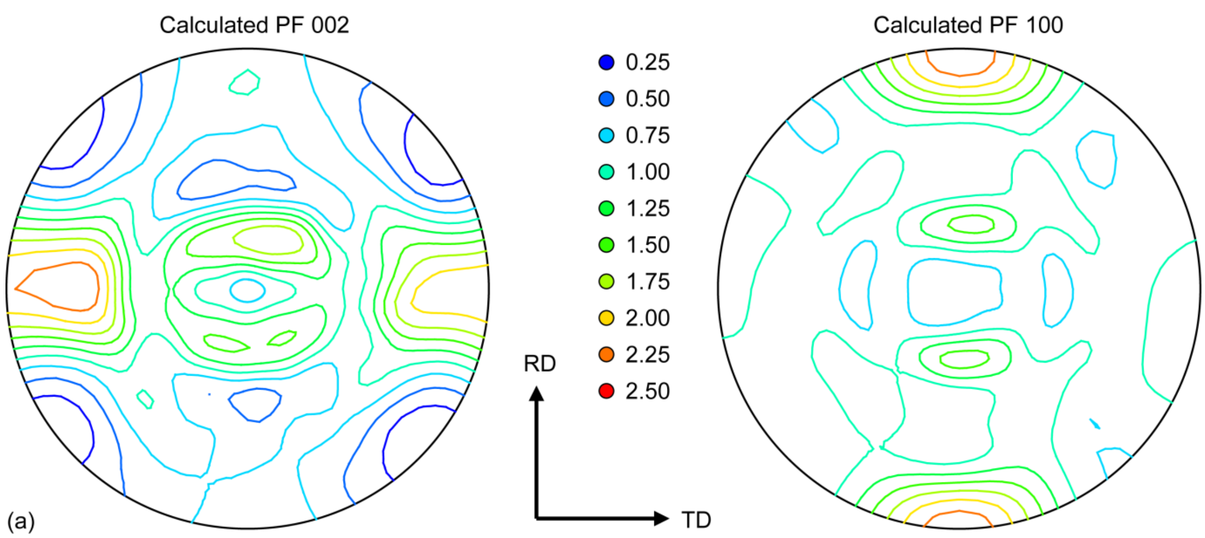
The strong overlap of the beta Ti (110) pole with both of the alpha Ti (00.2) and (10.1) poles prevented successful extraction of beta phase pole. This is a common problem with Ti-6Al-4V samples. Likewise, the beta (110) phase data could not be completely separated from the alpha (00.2) and (10.1) pole figures, especially at high tilt angles. Therefore, texture for only the alpha phase is presented.

The texture index in Table B.1 indicates that the 0.09, 0.25 and the 0.5 in. thick Ti-6-4 plates have the strongest textures. This is consistent with the high degree of anisotropy observed in the mechanical test samples taken out of these plates (Ref. 4). The 0.135 in. plate had a relatively weak texture. The last two rows in Table B.1 gives texture measurements for the same 0.5 in. thick plate. The difference between these rows is that the first row was taken 50 µm below the surface of the plate, whereas the data for the last row was measured 90° with the beam incident to the thickness of the plate. These two measurements indicate that there is inhomogeneity within the 0.5 in. plate with the near surface being isotropic and becoming strongly textured toward the mid-thickness of the plate. It should be noted that samples for mechanical tests were also taken through-the-thickness and exhibit anisotropic results (Ref. 4).

The pole figures are given in Figure B.2. The 0.09 in. sample displays a transverse (T) texture, where the basal planes align perpendicular to the rolling plane with the c-axis parallel to the transverse direction (TD) as illustrated in Figure B.3. This indicates that the sample was rolled at a temperature between ~ °F and the alpha/beta transus temperature (Ref. 5). Note from the (10.0) pole figure that this pole is parallel to the RD. This differs slightly from Figure B.3, which shows the (11.0) pole parallel to the RD.

The 0.13 and 0.25 in. samples display a basal (B) texture, where the basal planes are nearly aligned with the rolling plane (also illustrated in Figure B.3). This indicates that the sample was rolled at a temperature below ~1652 °F (Ref. 5). Table B.1 includes the angle between the maximum intensities of the basal planes and the rolling plane (degrees off center). This angle decreases with increasing degree of deformation (Ref. 6). Therefore, these angles are qualitatively consistent with the respective texture index values for these samples.

The 0.5 in. plate (through-thickness) showed a strong texture. The pole figures in Figure B.2(d) indicate that the basal planes tend to be oriented with their normals parallel to the RD. The prismatic planes tend to align with the original sample rolling surface and ± 60° inclinations to that surface. These orientations are consistent with a transverse texture. A possible explanation for this is that the plate was cross-rolled.



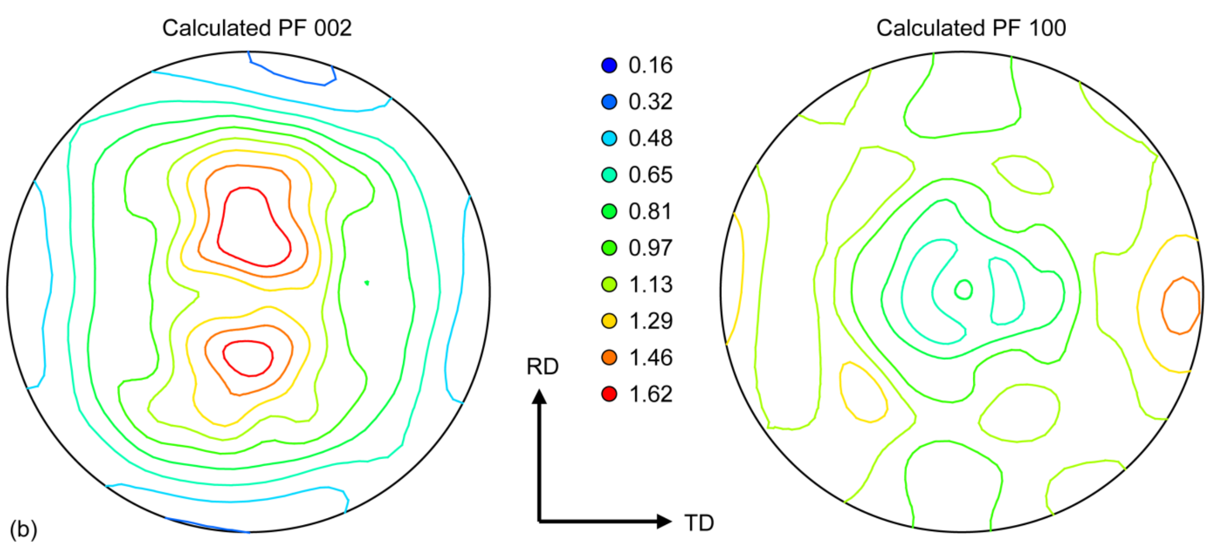


Figure B.2.—Pole figures for Ti-6Al-4V. (a) Plate thickness: 0.09 in., (b) Plate thickness: 0.135 in., (c) Plate thickness: 0.25 in., and (d) Plate thickness: 0. 5 in. (Note: These pole figures are rotated 90° from those of the other plates due to the location of the incident x-ray beam.)

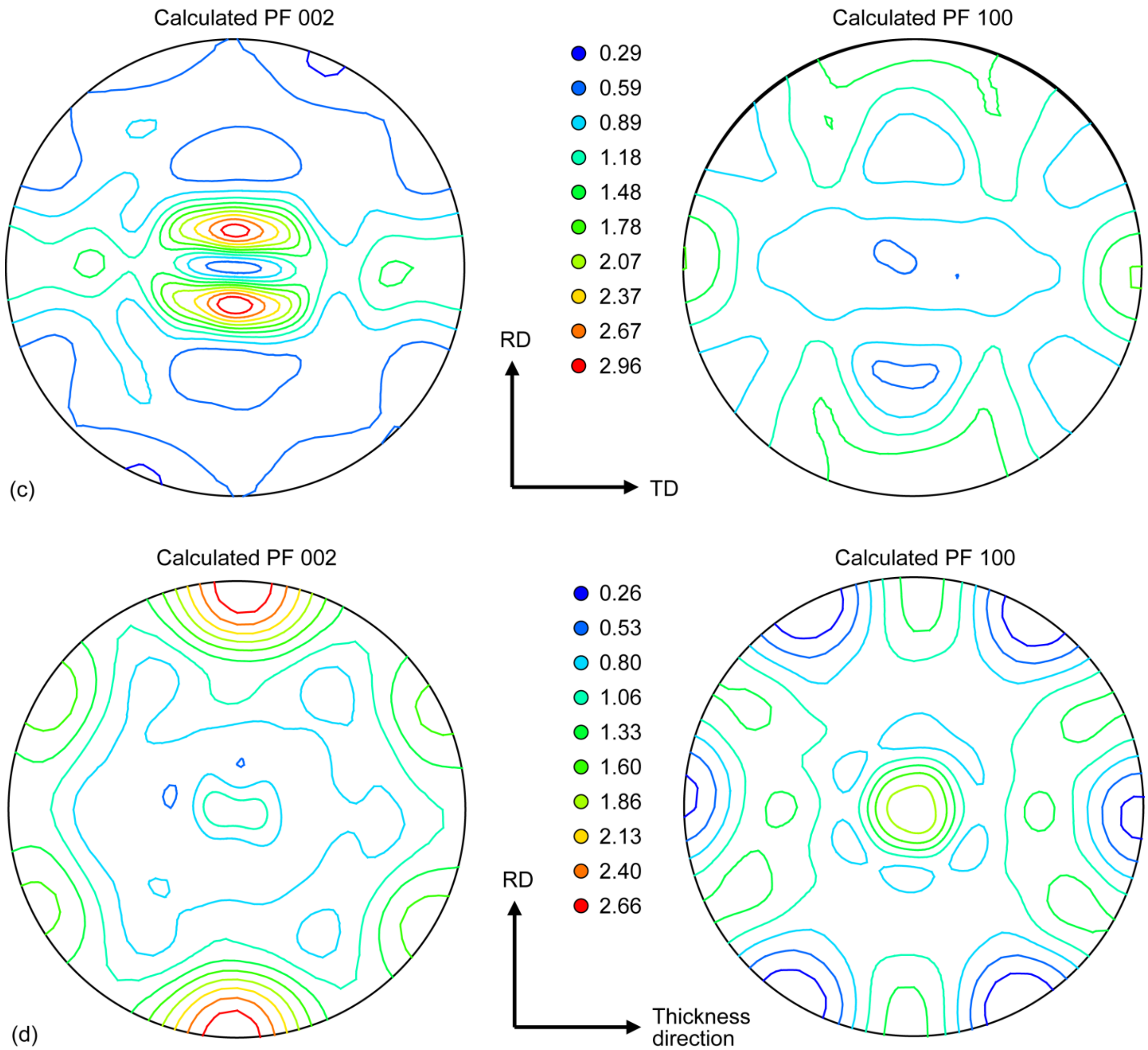


Figure B.2.—Concluded.

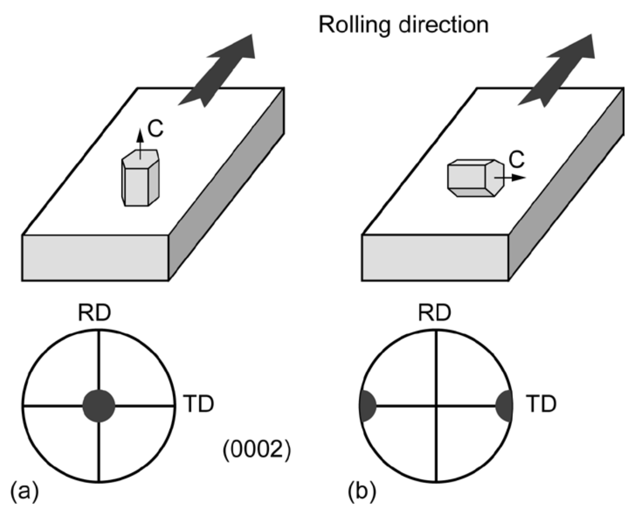


Figure B.3.—Basal (a) and transverse (b) textures of titanium alloys (schematic, (00.2) pole figures) (Ref. 7).

Appendix C.—Grain Structure

Metallographic sections were taken out of all plates to document the general grain structure. All three plate dimensions were polished and examined. The Al 2024 samples were immersion etched in an solution of 2 ml HF, 3 ml HCl, 5 ml HNO_3 and 190 ml H_2O (Keller's etch). The Ti-6-4 samples were etched in 2 mL HF, 8 mL HNO3, and 90 mL distilled water (Kroll's etch).

The 3-D views of the microstructure in each aluminum 2024 plate are shown in Figure C.1.

The three plate directions are indicated in the figure. Table C.1 provides the average grain dimensions for the three plates. The maximum observed grain size is also given in the table and their variables defined in Figure C.2. Finally, the aspect ratio (L/h : W/h : h/h) of each dimension based on the grain thickness is listed.

TABLE C.1.—GRAIN DIMENSIONS (µm) FOR Al 2024 PLATES

Thickness	L_{mean}	L_{max}	W_{mean}	W_{max}	h_{mean}	h_{max}	Aspect ratio
1/2 in.	706	1861	163	492	40	130	18:4:1
1/4 in.	1505	4249	344	1356	111	382	14:3:1
1/8 in.	37	122	31	86	17	58	2:2:1

The ½ and ¼ in. plates have large aspect ratios with the longest grain dimension elongated in the rolling direction. While the ½ in. plate has the largest grain aspect ratio, its grains are noticeably shorter than those in the ¼ in. plate. The other two grain dimensions are also smaller for the ½ in. plate. The 1/8 in. plate contained grains that were more equiaxed and had average grain dimensions less than 50 µm. Of all three plates, the 1/8 in. plate had substantially smaller grains. All of the aluminum plates were peppered with second phase particles aligned in the rolling direction. These were presumably $CuMgAl_2$ particles, but were not specifically investigated.

The 3-D views of the Ti-6Al-4V microstructures are shown in Figure C.3. The ½ in. thick plate has a binomial grain size consisting of many large areas of elongated unrecrystallized grains interspersed with equiaxed grains having diameters of approximately 15 µm. The ¼ in. thick plate has an equiaxed grain structure with an average grain size of 13.5 µm. The microstructure consists of equiaxed alpha grains in a transformed beta matrix containing coarse acicular alpha. The microstructure of the 0.135 in. plate consists of equiaxed alpha grains of an average diameter of 8.2 µm, and particles of beta. The 0.09 in. plate contains flattened alpha grains 30 µm in length, 9 µm in width, and 3 µm thick. Grain boundary and particulate beta are also present.

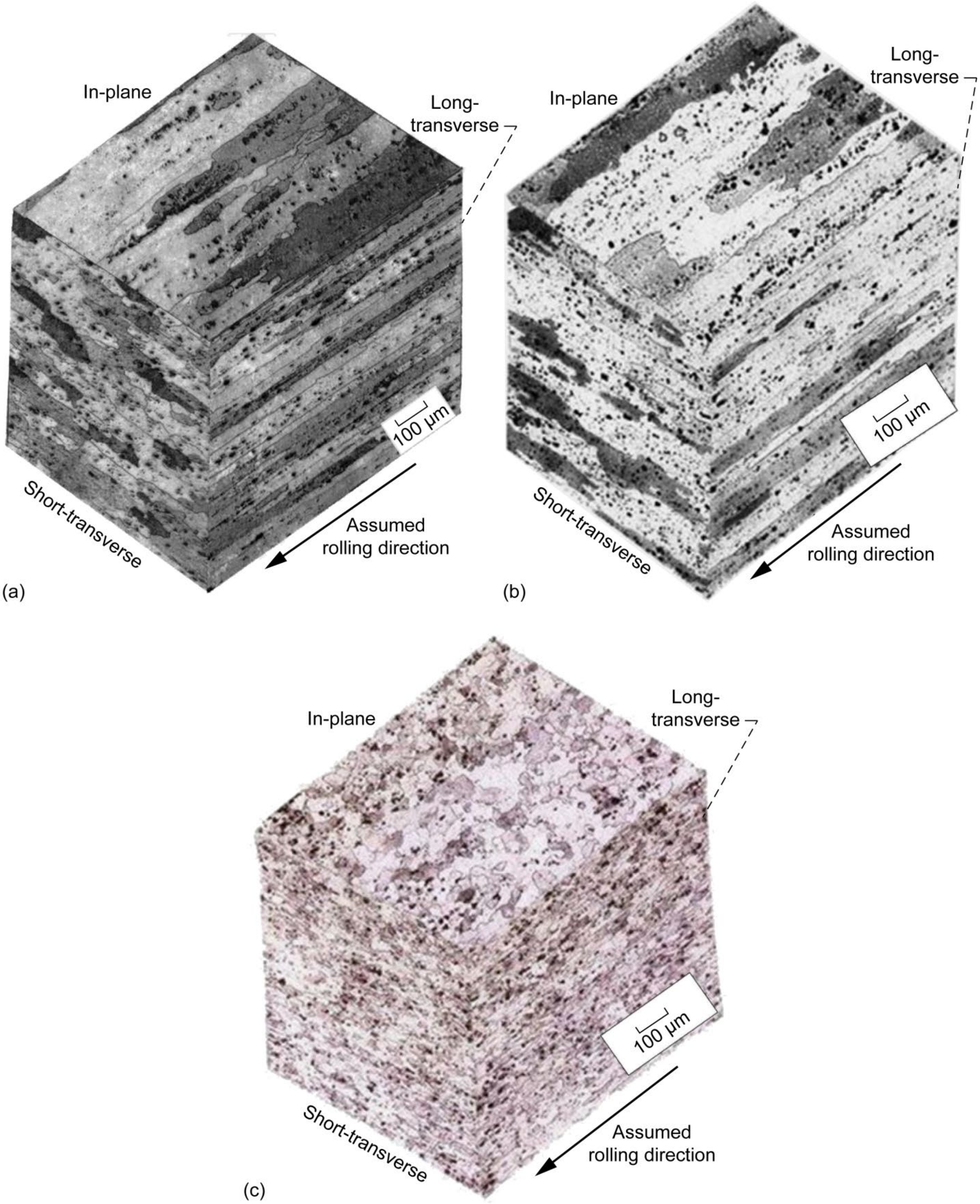


Figure C.1.—Grain structure for the Al 2024 plates: (a) 1/2 in., (b) 1/4 in., and (c) 1/8 in.

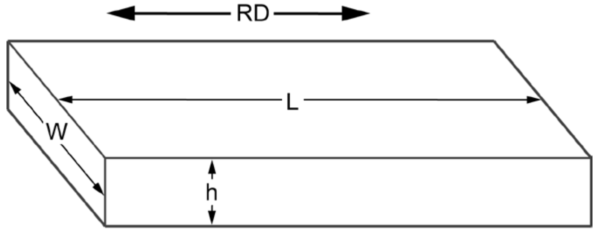


Figure C.2.—Direction of grain dimensions. L is parallel to the rolling direction.

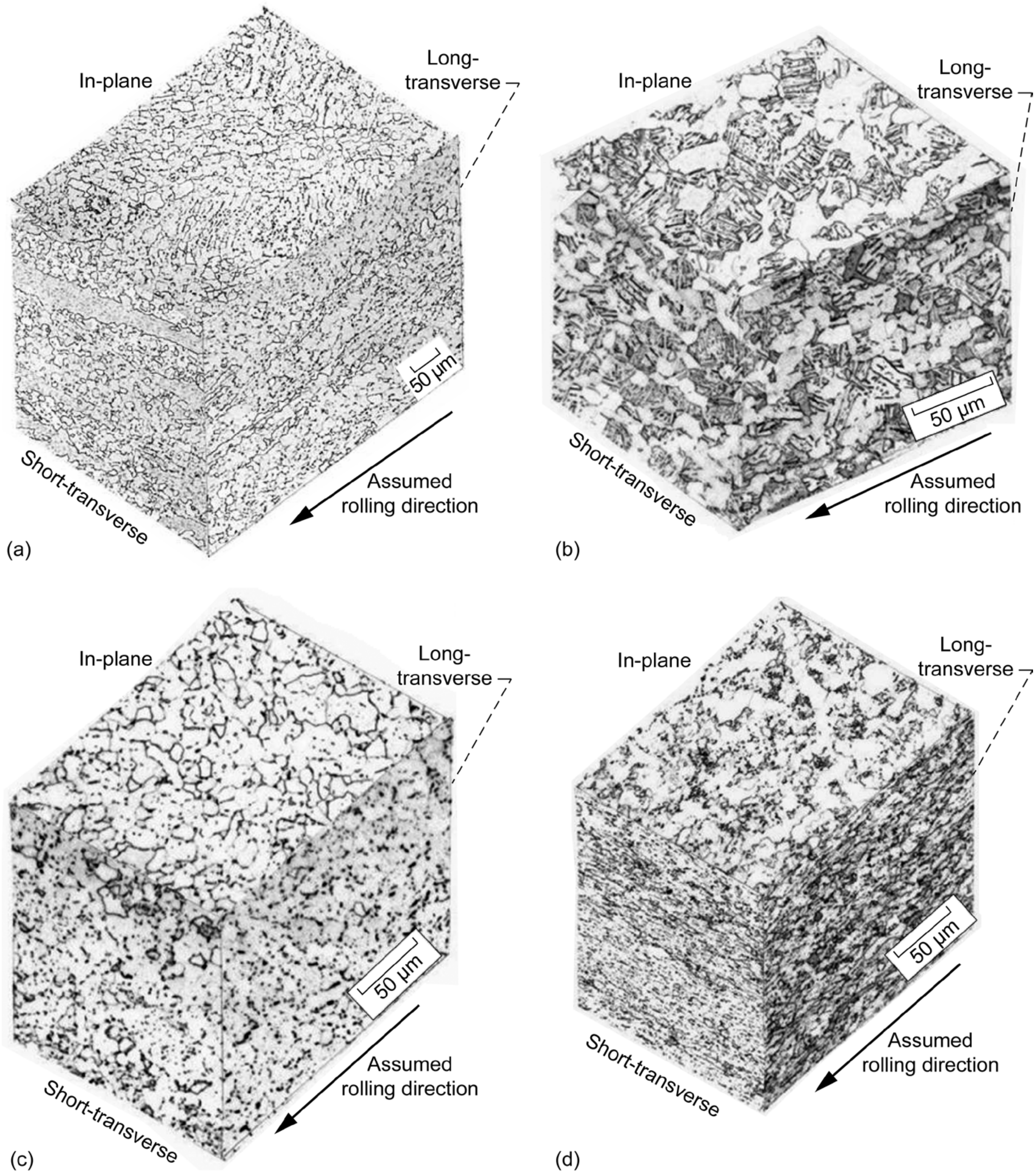


Figure C.3.—Grain structure for the Ti-6-4 plates: (a) 0.5 in., (b) 0.25 in., (c) 0.135 in., and (d) 0.09 in.

Appendix D.—Pedigree of Supplemental Ti-6-4 Plates

Four additional plates of Ti-6-4 were examined to provide some guidance on plate variability in the pedigree. Chemistry, texture and microstructure were documented following the procedures described earlier for Ti-6-4. The chemistry is shown in Table D.1 and documents a normal Ti-6-4 composition.

TABLE D.1.—Ti-6Al-4V CHEMISTRY (wt %)

Element	Panel thickness (in.)								AMS 4911J	
	BLM45 0.27 in.	Cert	BLM45 0.53 in.	Cert	BLM46 0.27 in.	Cert	BLM47 0.425 in.	Cert	Min	Max
Al	6.2	6.35	6.28	6.28	6.29	6.18	6.25	6.25	5.50	6.75
V	3.99	4.00	4.11	3.97	3.99	4.00	3.75	3.9	3.50	4.50
Fe	0.16	0.19	0.16	0.15	0.15	0.16	0.15	0.18	0.30	
O	0.193	0.175	0.177	0.183	0.191	0.170	0.176	0.170	0.20	
C	0.004	0.003	0.027	0.027	0.013	0.017	0.016	0.010	0.08	
N	0.004	0.006	0.004	0.006	0.006	0.006	0.005	0.006	0.05	
Ti	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.

The 3-D microstructures are shown in Figure D.1, displaying common grain structures for alpha-beta titanium alloys. The grain size appears similar to those from the earlier batch of plates.
Texture measurements were taken on the near-surface of the rolling plane for each plate. The texture index is given in Table D.2.

TABLE D.2.—TEXTURE RESULTS FOR THE SECOND BATCH OF Ti-6-4 PLATES

Sample	Texture index	Predominant texture type	Degrees off-center
BLM 45 0.270 in.	1.24	Transverse	31°
BLM 45 0.530 in.	1.13	Basal	27°
BLM 46 0.270 in.	1.33	Transverse	24°
BLM 47 0.425 in.	1.54	Transverse	---

The texture indices are the range of values listed earlier for the first set of plates. BLM 47 (0.425 in. thick) has the strongest texture of all eight plates. Unfortunately no mechanical tests were conducted on the latter set of four plates for comparison.

Pole figures are given in Figure D.2. For plates with a transverse (T) texture, the basal planes align perpendicular to the rolling plane with the c-axis parallel to the transverse direction (TD). This indicates that the sample was rolled at a temperature between ~1706 °F and the alpha/beta transus temperature. For a basal (B) texture, the basal planes are nearly aligned with the rolling plane. This indicates that the sample was rolled at a temperature below ~1652 °F (Ref. 5). Table D.2 includes the angle between the maximum intensities of the basal planes and the rolling plane (degrees off center). This angle decreases with increasing degree of deformation (Ref. 6). However, the angles in Table D.2 do not correlate well with the texture indices. This might be due to the fact that there are also transverse texture components present and that the base texture is dominant only in the BLM 45 0.530 in. sample.

General phase ID data was gathered on each sample prior to the detailed texture measurements. As expected, the alpha phase dominated all samples. Unexpectedly, sample BLM 46 0.270 in. showed a visibly noticeable shift in the beta lattice parameter. Therefore, lattice parameters were calculated from the phase ID scans and summarized in Table D.3 along with composition data (major elements only) as determined by a handheld x-ray fluorescence (XRF) instrument. It can be seen from Table D.3 that the beta lattice parameter for sample BLM 46 0.270 in. is clearly larger than the rest. For this sample, the alpha lattice parameters are also larger than those of the other samples, though the differences are much less than the beta phase difference. The sample composition data show only minor variations between samples and also from the expected composition given in the specification. Therefore, the BLM 46 0.270 in. lattice parameter variations do not appear to be due to sample composition.

TABLE D.3.—LATTICE PARAMETERS FOR EACH PLATE

Sample	Lattice parameters			Alloy composition (wt%)		
	alpha (Å)		beta (Å)	Ti	Al	V
	a	c	a			
BLM 45 0.270 in.	2.924	4.671	3.192	89.59 ± 0.65	5.89 ± 0.60	4.12 ± 0.28
BLM 45 0.530 in.	2.924	4.672	3.198	90.06 ± 0.64	5.03 ± 0.60	4.50 ± 0.28
BLM 46 0.270 in.	2.929	4.673	3.236	89.57 ± 0.71	6.07 ± 0.68	4.09 ± 0.27
BLM 47 0.425 in.	2.923	4.669	3.198	90.00 ± 0.64	5.56 ± 0.60	4.07 ± 0.28

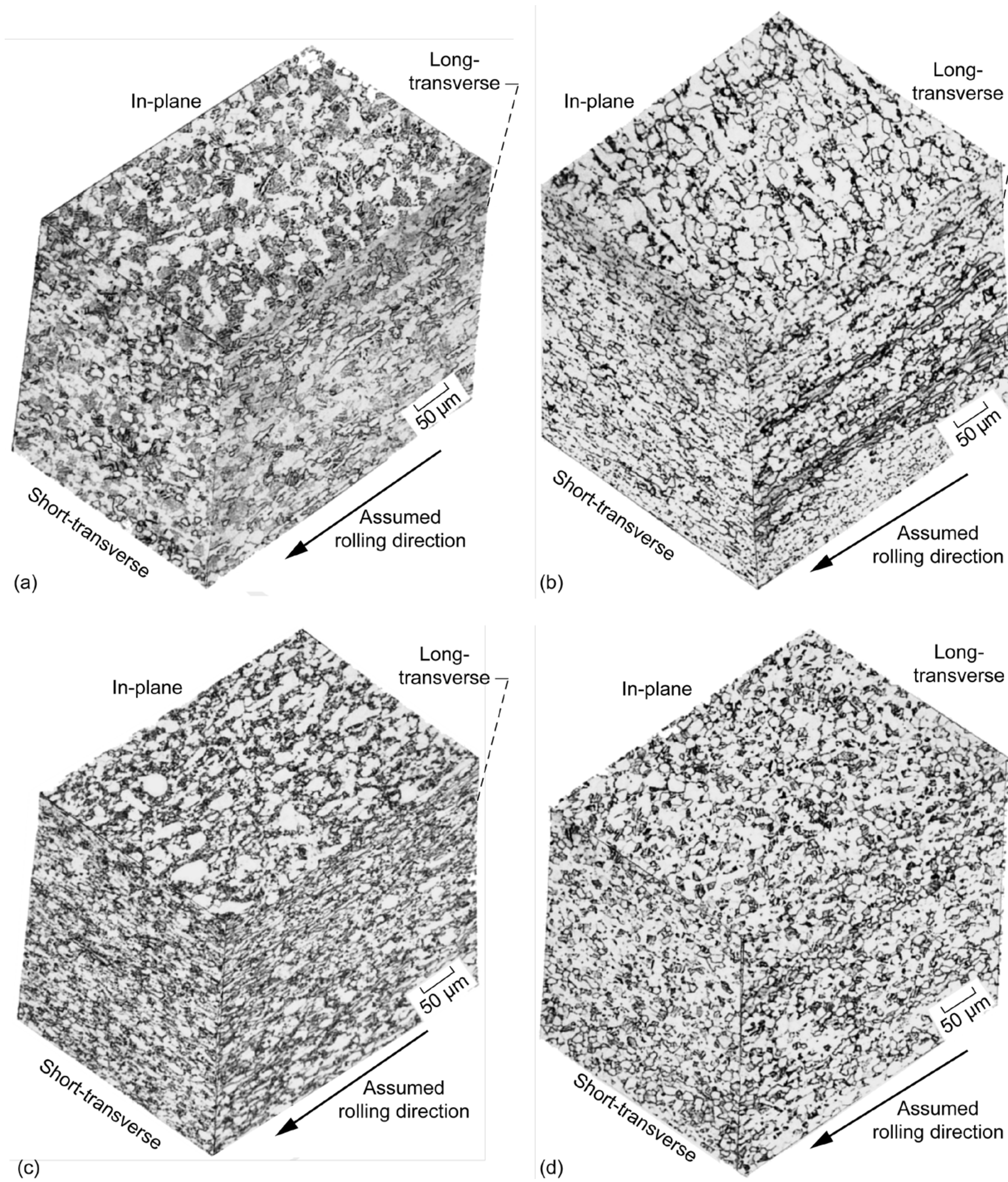


Figure D.1.—Microstructures of supplemental Ti-6-4 Plates: (a) BLM 45, 0.270 in. (b) BLM 45, 0.530 in. (c) BLM 46, 0.270 in. (d) BLM 47, 0.425 in.

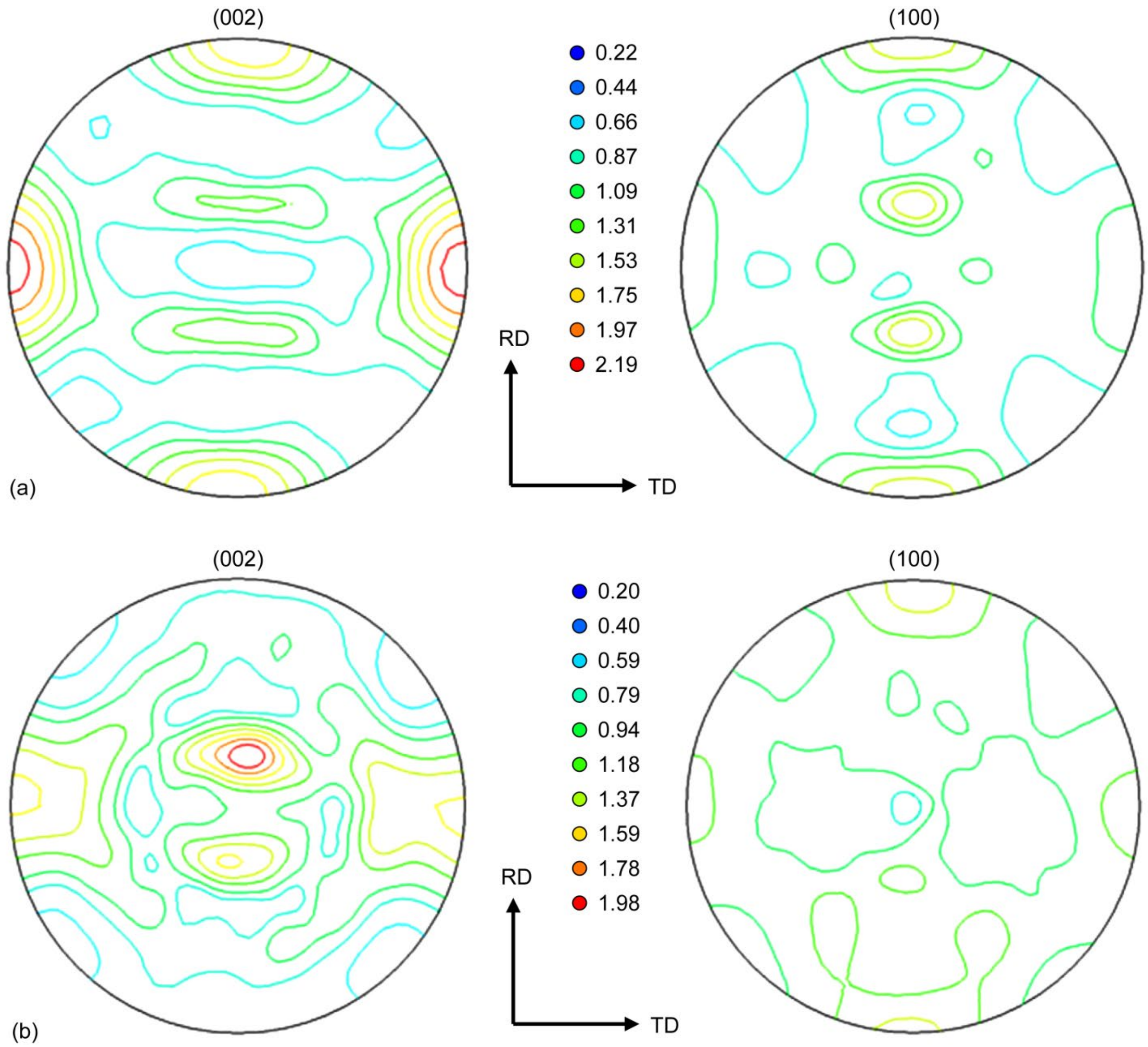


Figure D.2.—Pole figures of the supplemental Ti-6-4- plates: (a) BLM 45, 0.270 in., (b) BLM 45, 0.530 in., (c) BLM 46, 0.270 in., and (d) BLM 47, 0.425 in.

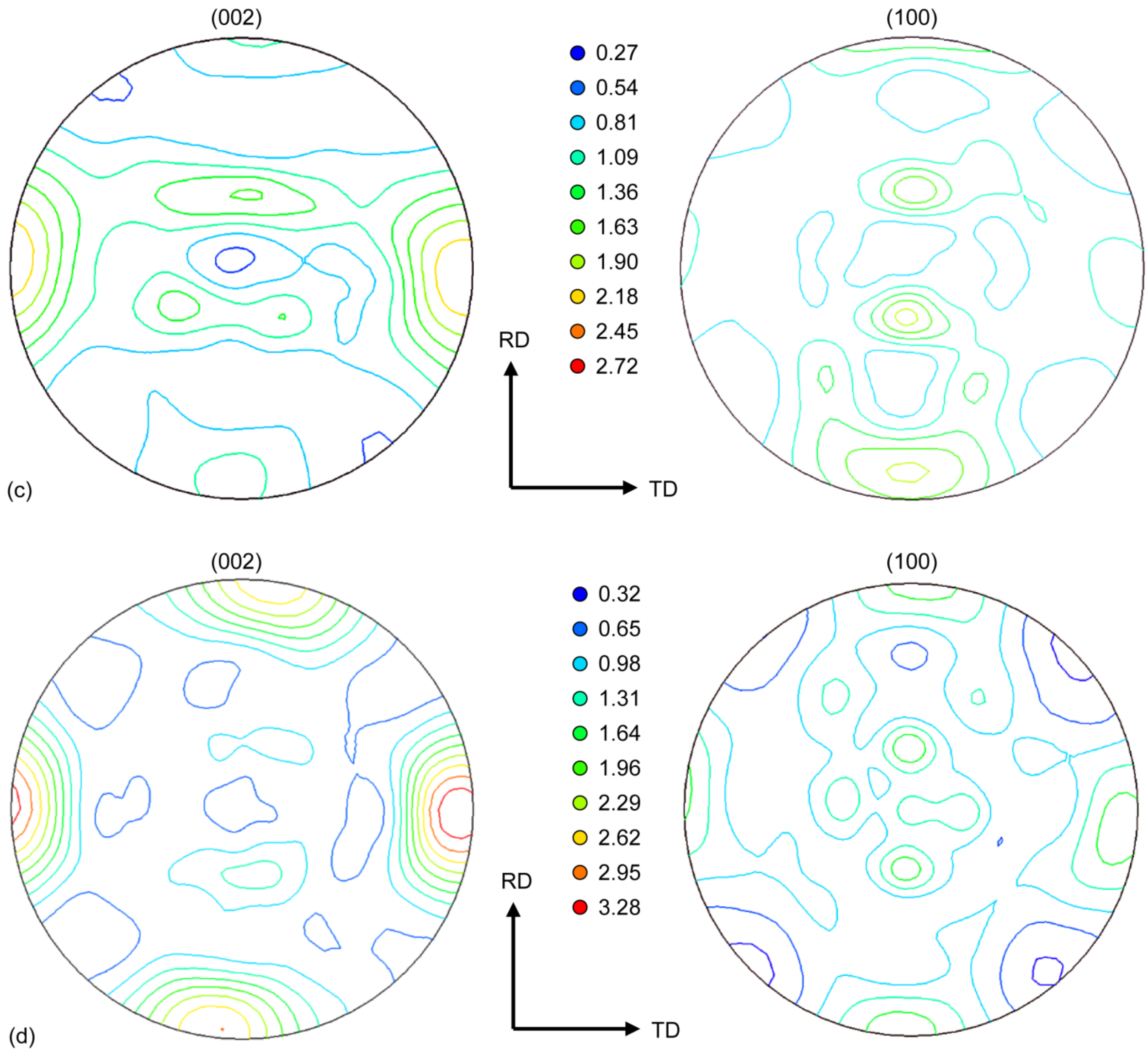


Figure D.2.—Concluded.

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An Erratum was added to this report October 2014.

14. ABSTRACT
One of the difficulties with developing and verifying 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 different sources. In addition there is often a lack of quantitative measurements in 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, impact test data and failure analysis for a variety of 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 FAA William J. Hughes Technical Center. Unique features of this set of data are that all material property data and impact test data are obtained using identical material, the test methods and procedures are extensively documented and all of the raw data is archived Four parallel efforts are currently underway: Measurement of material deformation and failure response over a wide range of strain rates and temperatures and failure analysis of material property specimens and impact test articles conducted by The Ohio State University; development of improved numerical modeling techniques for deformation and failure conducted by The George Washington University; impact testing of flat panels and substructures conducted by NASA Glenn Research Center. This report describes impact testing which has been done on Aluminum (Al) 2024 and Titanium (Ti) 6Al-4Vanadium (V) sheet and plate samples of different thicknesses and with 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.

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