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JSC 66540

DETERMINE ISS SOYUZ ORBITAL MODULE BALLISTIC LIMITS FOR STEEL PROJECTILES HYPERVELOCITY IMPACT TESTING

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July 2013

National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

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Prepared for the

ISS Systems Engineering and Integration Office

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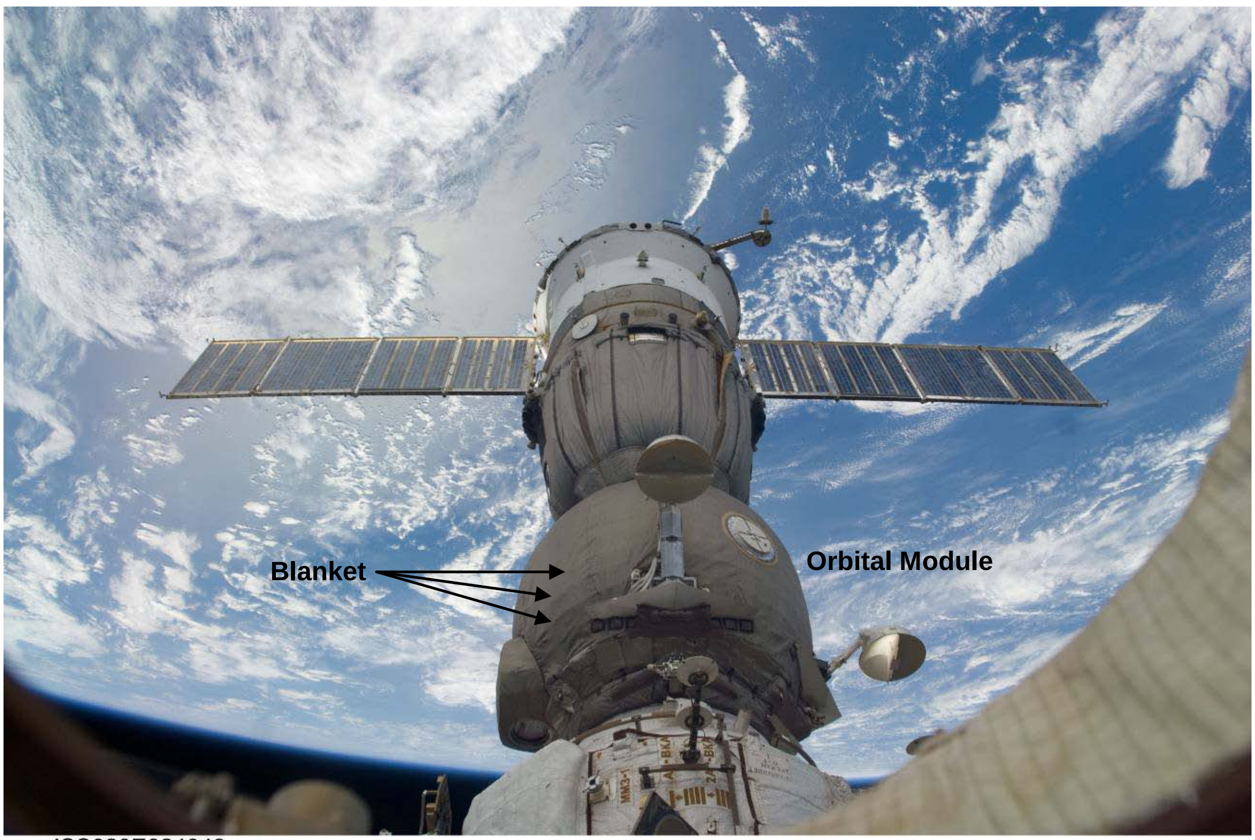
Table of Contents

ACRONYMS AND ABBREVIATIONS

2SLGG	Two Stage Light Gas Gun
Al	aluminum
g/cm	gram per centimeter
HITF	Hypervelocity Impact Technology Facility
HVI	Hypervelocity Impact
HVIT	Hypervelocity Impact Technology Group
in	inch
ISS	International Space Station
JSC	Johnson Space Center
KA	Astromaterials Research and Exploration Science Directorate
km/s	kilometers per second
KX	Human Exploration Science Office
MLI	Multi-layer Insulation
mm	millimeter
MMOD	micrometeoroid orbital debris
NASA	National Aeronautics and Space Administration
NASA-JSC	National Aeronautics Space Administration – Johnson Space Center
NASA-JSC/HVIT	National Aeronautics and Space Administration – Johnson Space Center/Hypervelocity Impact Technology Group
NASA-JSC/WSTF	National Aeronautics and Space Administration – Johnson Space Center/ White Sands Test Facility
NMI	National Measurement Institute
OM	Orbital Module
PNP	Probability of No Penetration
psi	pounds per square inch
QA	Quality Assurance
RHTL	Remote Hypervelocity Test Laboratory
TRR	Test Readiness Review
UTC	United Technologies Corporation
V_n	velocity (normal vector component)
WSTF	White Sands Testing Facility

1. INTRODUCTION

A new orbital debris environment model (ORDEM 3.0) defines the density distribution of the debris environment in terms of the fraction of debris that are low-density (plastic), medium-density (aluminum) or high-density (steel) particles. This hypervelocity impact (HVI) program focused on assessing ballistic limits (BLs) for steel projectiles impacting the enhanced Soyuz Orbital Module (OM) micrometeoroid and orbital debris (MMOD) shield configuration. The ballistic limit was defined as the projectile size on the threshold of failure of the OM pressure shell as a function of impact speeds and angle. The enhanced OM shield configuration was first introduced with Soyuz 30S (launched in May 2012) to improve the MMOD protection of Soyuz vehicles docked to the International Space Station (ISS). This test program provides HVI data on U.S. materials similar in composition and density to the Russian materials for the enhanced Soyuz OM shield configuration of the vehicle. Data from this test program was used to update ballistic limit equations used in Soyuz OM penetration risk assessments.



ISS020E024048

Figure 1: Soyuz docked to ISS

HVI testing was coordinated by the NASA Johnson Space Center (JSC) Hypervelocity Impact Technology Group (HVIT) [1] in Houston, Texas. HVI testing was conducted at the NASA-JSC White Sands Hypervelocity Impact Test Facility (WSTF) at Las Cruces, New Mexico.

2. OBJECTIVES

The objective of this hypervelocity impact test program was to determine the ballistic limit particle size for 440C stainless steel spherical projectiles on the Soyuz OM shielding at several impact conditions (velocity and angle combinations). This test report was prepared by NASA-JSC/ HVIT, upon completion of tests.

3. TEST ARTICLE DESCRIPTION

The Enhanced Soyuz OM MMOD shield for this test series consisted of U.S. materials that match as closely as possible actual Russian materials, mass per unit area and gaps (Figures 3 and 4). The target configuration is shown in Figure 2 and consists of a Soyuz-type thermal blanket that covers a 0.02” (0.5mm) thick aluminum 6061-T6 bumper that stands-off from the rear wall by 15mm. The rear wall was 0.080” (2.0mm) thick aluminum 5456-0 plate that represented the pressure shell. The Soyuz-type thermal blanket consisted of an outer beta cloth layer, an aluminized Mylar layer, a “shield” consisting of a 0.008” thick aluminum plate sandwiched between fiberglass-7781 cloths followed by 20 thin layers of aluminized Mylar with Dacron scrim separators. A 0.040” thick Al 2024-T3 witness plate was included 2.0” behind the rear wall. Figures 5 through 8 show the Russian and U.S. materials side by side. In the “shield” layer, the Russian design uses a perforated aluminum plate with a 10 x 10 matrix of 2mm diameter holes over a 4” x 4” plate area. The U.S. plate was not perforated. The aluminum in the shield layer (both Russian and U.S.) has a 0.125” (3.2mm) wide 90-degree bend on the edges of all 4 sides of the plate, with the bend direction in opposite directions for the orthogonal edges (i.e., 2 sides of the plate were bent upward, while the other two sides were bent downward). This configuration resulted in a miniature gap in the shield layer which was approximately 0.25” (6.4mm) thick (the overall thickness exceeded 0.25” by the thickness of the fiberglass layers and aluminum layer).

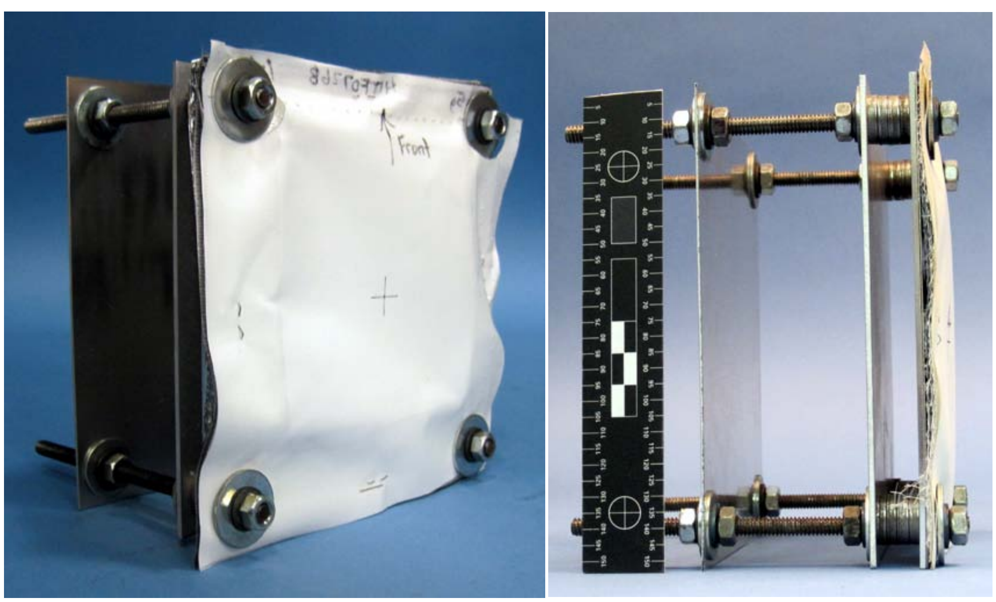


Figure 2: Overall oblique and side view of test article configuration (typical)

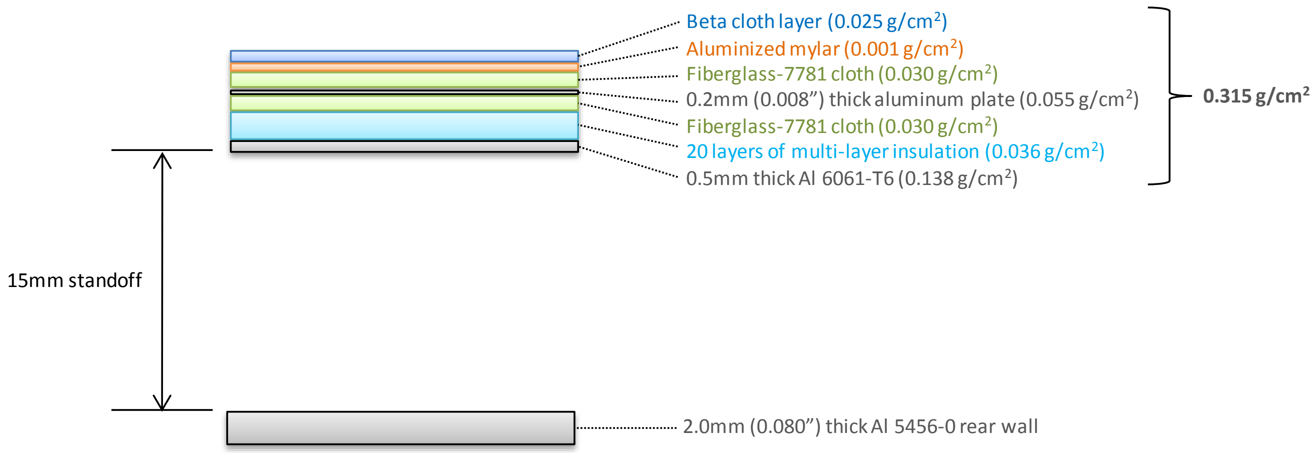


Figure 3: Enhanced Soyuz Orbital Module Shield Configuration (U.S. Version) [2]

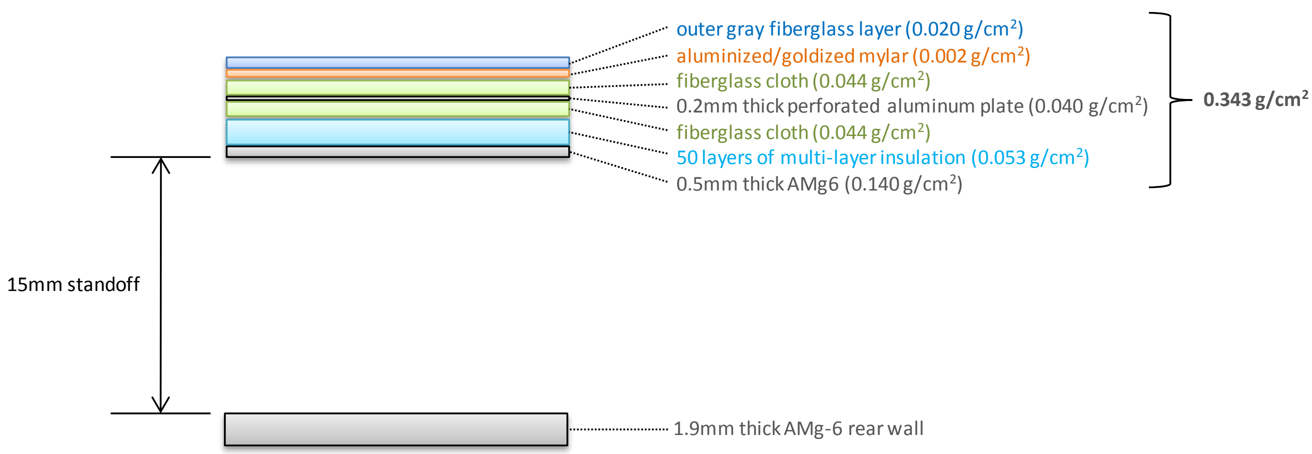


Figure 4: Enhanced Soyuz OM Shield Configuration (Russian Version) [2]

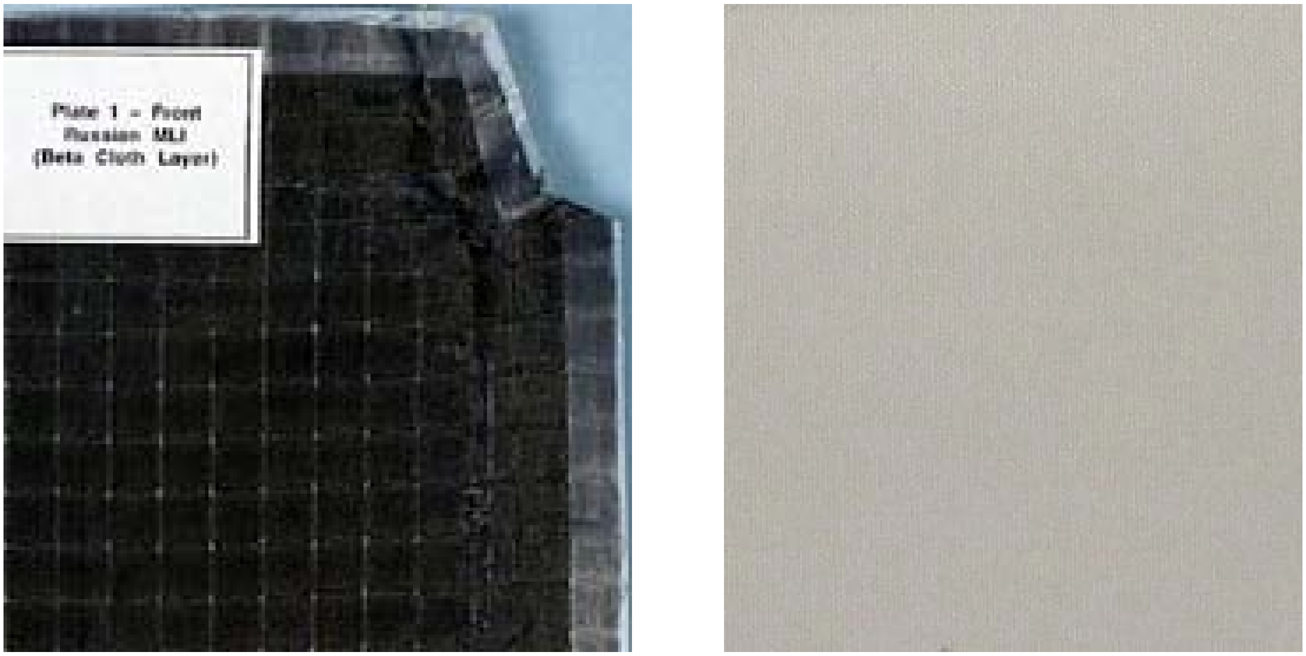


Figure 5: Layer 1 Russian Outer Gray Fiberglass (left) and U.S. Beta Cloth (right)

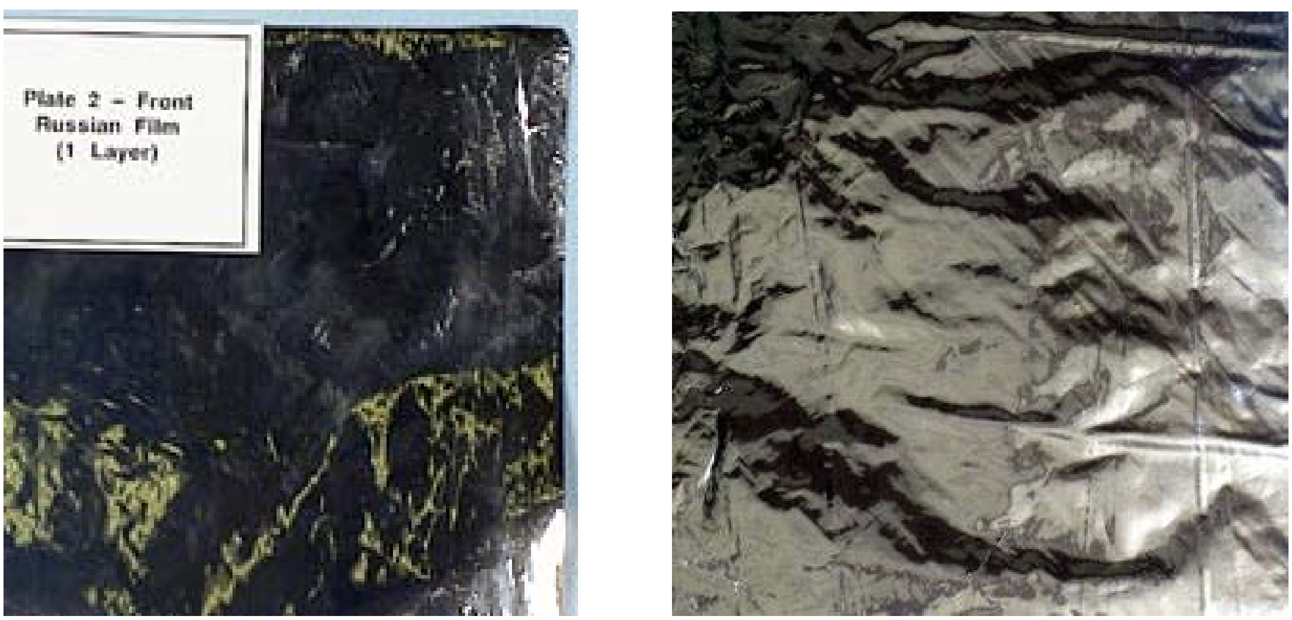


Figure 6: Layer 2 Russian Aluminized/Goldized Mylar (left) and U.S. Mylar (right)

Figure 7: Layer 3 Russian Fiberglass Cloth (left) and U.S. Fiberglass-7781 (right)

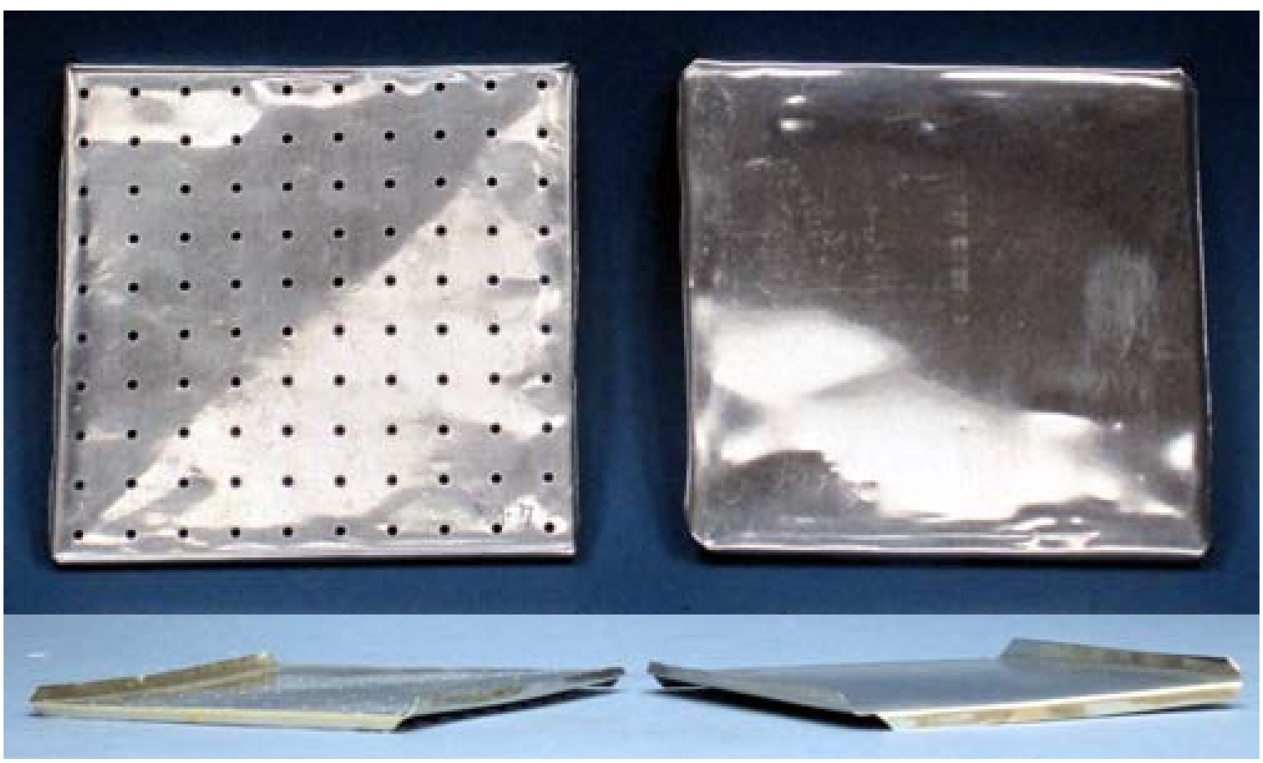


Figure 8: Layer 4 Russian Perforated Al Plate (left) and U.S. Al Plate (right)

4. TEST RANGE DIAGNOSTICS

The 0.17caliber [3] and 0.50 caliber [4] launcher test ranges at WSTF were used for these tests.

0.17-Caliber Projectile Velocity

Projectile velocity was obtained with the following methods:

- Laser station consisting of two multi-beam lasers, LX1 to LX2.
- Muzzle laser is paired with either laser station or with either photo diode to obtain velocity.
- Photo diode impact flash detectors are located at the stripper plate and target impact point

WSTF 17-Caliber Velocity Measurement Uncertainty Analyses Summary

.17-caliber Light Gas Gun					
Measurement System	Laser LX1 to LX2	Muzzle Laser to LX1	Muzzle Laser to LX2	Muzzle Laser to Sabot Stripper	Muzzle Laser to Target
Random Uncertainty, ±	1.1%	0.5%	0.4%	0.8%	0.9%
Upper Bound Uncertainty, ±	1.8%	0.9%	0.6%	1.4%	1.2%

WSTF-IR-1086-001-07

0.17-Caliber Projectile Integrity

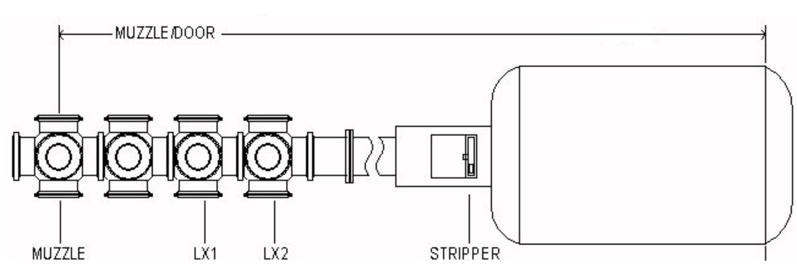
Projectile integrity was obtained on projectiles larger than 0.4mm using ultra high speed imaging system cameras to capture projectiles in flight immediately prior to impact. The typical setup captures a shadowgraph of the projectile. Images of the impact can usually be obtained upon request.

0.17-Caliber Target Tank Pressure

The pressure within the target chamber was maintained below 2.5 torr (~0.05 psi) Nitrogen during impact. Higher pressures were available upon request. Nitrogen was used in order to minimize the effects of oxygen during impact.

Typical Range Diagnostics Configuration Schematic

Note: The door was considered the primary point of reference from which to measure back to the impact face of the installed test article.



0.50-Caliber Projectile Velocity

Projectile velocity was obtained with the following methods:

- Laser station consisting of two multi-beam lasers, LX1 to LX2.
- Muzzle laser, LX0, paired with LX1 and LX2 laser stations or with target photo diode.
- Photo diode impact flash detectors are located at the stripper plate and target impact point.

WSTF .50-Caliber Gun Velocity Measurement Uncertainty Analysis Summary
.50-Caliber Light Gas Gun

LX0 = Muzzle Laser LX1 = Laser 1 LX2 = Laser 2 EP1 = Stripper Diode EP2 = Target Diode	Recommended Uncertainties Between Velocity Stations (µsec)				
	LX0 to LX1	LX0 to LX2	LX1 to LX2	LX0 to EP1	LX0 to EP2
Random Uncertainty, +/-	0.3%	0.3%	0.4%	0.8%	0.4%
Upper Bound Uncertainty, +/-	0.48%	0.43%	0.96%	1.63%	0.85%

WSTF-IR-1103-001-08.C

0.50-Caliber Projectile Integrity

Projectile integrity was obtained using ultra high speed imaging system cameras and/or high speed video cameras to capture projectiles in flight immediately prior to impact. The typical setup captures a shadowgraph of the projectile. Images of the impact can usually be obtained upon request.

0.50-Caliber Target Tank Pressure

The pressure within the target chamber was maintained at 0.3 psia (14 to 16 torr) Nitrogen during impact. Higher pressures were available upon request. Nitrogen was used in order to minimize the effects of oxygen during impact.

5. PROJECTILE VERIFICATION SUMMARY

The table below provides a summary of projectile verification for each test conducted within this test program. There were two different high-speed cameras used to capture the projectile prior to impacting the target, Specialized Imaging SIMX-8 (capable of 200 million frames per second) and Phantom v711 (capable of 1.4 million frames per second). The SIMX-8 camera is primarily used to capture a side view of the projectile approaching the target and the Phantom v711 is oriented to capture the projectile from a front oblique view of the target.

Table 1: Projectile Verification Summary

Test Number HVIT Number	*Projectile Verification		**Secondary Debris		Is Data Usable (yes or no)	Comments
	SIMX-8 (yes or no)	Phantom v711 (yes or no)	SIMX-8 (yes or no)	Phantom v711 (yes or no)		
1 HITF12257	yes	---	yes	---	yes	SIMX-8 video frames are scratchy; No Phantom video. Projectile roundness verified in SIMX-8 frame number 2.
2 HITF12258	no	---	no	---	yes	SIMX-8 video frames are scratchy; No Phantom video. Projectile roundness could not be verified in SIMX-8 video frames.
3 HITF12259	no	---	yes	---	yes	SIMX-8 video frames are scratchy; No Phantom video. Projectile roundness could not be verified in SIMX-8 video frames.
4 HITF12260	yes	---	yes	---	yes	SIMX-8 video frames are scratchy; No Phantom video. Projectile roundness verified in SIMX-8 frame number 3.
5 HITF12261	---	---	---	---	no	No SIMX-8 and No Phantom video.
6 HITF12262	no	---	no	---	no	Projectile was not captured in SIMX-8 video frames; No Phantom video. Projectile roundness could not be verified in SIMX-8 video frames.
6B HITF12262	no	no	no	no	yes	SIMX-8 video frames are scratchy; Projectile roundness could not be verified in SIMX-8 video frames or by Phantom video.
7 HITF12263	no	yes	no	no	yes	SIMX-8 video frames are scratchy; Projectile roundness could not be verified in SIMX-8 video frames. Phantom video verifies projectile.
8 HITF12264	yes	---	no	---	yes	Projectile was captured in SIMX-8 video frames verifying projectile roundness; No Phantom video.
9 HITF12265	no	no	no	no	yes	SIMX-8 video frames are scratchy; Projectile roundness cannot be verified in SIMX-8 video frames or by Phantom video.

*** Projectile verification prior to impact and verify roundness of projectile.**
**** Secondary debris impact observed via camera.**
--- **Video not available.**

Table 1 (Continue): Projectile Verification Summary

Test Number HVIT Number	*Projectile Verification		**Secondary Debris		Is Data Usable (yes or no)	Comments
	SIMX-8 (yes or no)	Phantom v711 (yes or no)	SIMX-8 (yes or no)	Phantom v711 (yes or no)		
10 HITF12266	yes	yes	no	no	yes	Projectile was captured in SIMX-8 video frames and Phantom video verifying projectile roundness.
11 HITF12271	no	no	yes	yes	yes	SIMX-8 video frames are scratchy; Projectile roundness could not be verified in SIMX-8 video frames or by Phantom video. There was a secondary debris hole above the entry damage.
12 HITF12272	yes	no	no	yes	yes	Projectile was captured in SIMX-8 video frames verifying projectile roundness. Phantom video was too blurry to verify projectile roundness. There was a secondary debris hole above the entry damage.
13 HITF12273	no	---	no	---	no	Projectile was not captured in SIMX-8 video frames; No Phantom video. Projectile roundness could not be verified in SIMX-8 video frames.
13B HITF12273	no	yes	no	yes	yes	Projectile was captured in Phantom video verifying projectile roundness; projectile was not captured in SIMX-8 video frames. There is a secondary debris hole above the entry damage.
14 HITF12274	yes	yes	no	no	yes	Projectile was captured in SIMX-8 video frames verifying projectile roundness. Phantom video was too blurry to verify projectile roundness.
15 HITF12275	no	no	yes	yes	no	Projectile was not captured in SIMX-8 video frames. Phantom video was too blurry to verify projectile roundness. There were secondary debris holes below the entry damage.
15B HITF12275	no	---	no	---	no	Projectile was not captured in SIMX-8 video frames; No Phantom video. No impact on target.
15C HITF12275	yes	yes	no	no	yes	Projectile was captured in SIMX-8 video frames and Phantom video verifying projectile roundness.
16 HITF12276	no	no	no	no	yes	SIMX-8 video frames are scratchy; Projectile roundness could not be verified in SIMX-8 video frames or by Phantom video.
17 HITF12277	yes	yes	no	no	yes	Projectile was captured in SIMX-8 video frames verifying projectile roundness. Phantom video was too blurry to verify projectile roundness.

*** Projectile verification prior to impact and verify roundness of projectile.**
**** Secondary debris impact observed via camera.**
--- **Video not available.**

6. ISS Soyuz OM Ballistic Limits using Steel Projectiles Test Results

The following table and images document results from the impact tests on the Soyuz orbital module shield test articles. A brief description is provided of each damaged layer resulting from the impact test. All projectiles are 440C stainless steel spheres, with a projectile density of 7.65 g/cm^3. Actual projectile diameters are calculated from the measured projectile mass.

Table 2: Hypervelocity Impact Test Results for the Evaluation of ISS Soyuz Orbital Module Ballistic Limits using Steel Projectiles

Test No.	Actual Projectile Diameter (mm)	Actual Projectile Mass (g)	Actual Impact Velocity (km/s)	Impact Angle (deg)	Results
1 HITF12257	1.79	0.02310	7.18	30	**Fail** **Beta cloth entry damage** = 1.77mm x 1.96mm hole **Mylar Film damage** = 45.97mm x 33.08mm hole **Fiberglass entry damage** = 10.81mm x 13.44mm hole **Al 6061 Foil damage** = 8.64mm x 8.26mm hole **Fiberglass exit damage** = 12.89mm x 15.04mm hole **MLI exit damage** = 7.71mm x 9.88mm hole **Al 6061-T6 plate damage** = 8.14mm x 10.21mm hole **Al 5456-0 RW damage** = 3 holes largest is 2.45 x 3.09mm **Al 2024-T3 WP damage** = 0.198mm x 0.218mm x 0.051mm deep crater & many smaller
2 HITF12258	1.59	0.01610	4.99	30	**Fail** **Beta cloth entry damage** = 1.54mm x 1.95mm hole **Mylar Film damage** = 13.43mm x 9.34mm hole **Fiberglass damage** = 2.87mm x 3.87mm hole **Al 6061 Foil damage** = 6.04mm x 5.06mm hole **Fiberglass damage** = 8.47mm x 12.48mm hole **MLI exit damage** = 7.01mm x 7.80mm hole **Al 6061-T6 plate damage** = 4.42mm x 6.33mm hole **Al 5456-0 RW damage** = 2 holes largest is 6.57mm x 8.95mm **Al 2024-T3 WP damage** = 0.58mm x 0.97mm x 0.275mm deep crater & many smaller
3 HITF12259	1.72	0.02046	5.78	30	**Fail** **Beta cloth entry damage** = 1.61mm x 2.11mm hole **Mylar Film damage** = 9.83mm x 13.76mm hole **Fiberglass damage** = 5.69mm x 7.78mm hole **Al 6061 Foil damage** = 6.09mm x 5.58mm hole **Fiberglass damage** = 8.24mm x 14.03mm hole **MLI exit damage** = 6.38mm x 10.22mm hole **Al 6061-T6 plate damage** = 7.38mm x 9.42mm hole **Al 5456-0 RW damage** = 4.97 x 4.53mm hole **Al 2024-T3 WP damage** = 0.140mm x 0.187mm x 0.034mm deep crater & several smaller

Table 2 (Continue): Hypervelocity Impact Test Results for the Evaluation of ISS Soyuz Orbital Module Ballistic Limits using Steel Projectiles

Test No.	Actual Projectile Diameter (mm)	Actual Projectile Mass (g)	Actual Impact Velocity (km/s)	Impact Angle (deg)	Results
4 HITF12260	1.99	0.03157	7.06	45	**Fail** **Beta cloth entry damage** = 1.98mm x 2.71mm hole **Mylar Film damage** = 42mm x 41mm hole **Fiberglass damage** = 17.58mm x 23.22mm hole **Al 6061 Foil damage** = 14.40mm x 15.82mm hole **Fiberglass damage** = 15.57mm x 20.44mm hole **MLI exit damage** = 9.36mm x 12.81mm hole **Al 6061-T6 plate damage** = 11.65mm x 15.93mm hole **Al 5456-0 RW damage** = 3.91 x 3.53mm hole **Al 2024-T3 WP damage** = 0.645mm x 0.763mm x 0.667mm deep crater & many smaller
5 HITF12261	1.29	0.00860	no data	30	**Pass** **Beta cloth entry damage** = 5.39mm x 6.09mm hole **Mylar Film damage** = 10.17mm x 10.04mm hole **Fiberglass damage** = 6.82mm x 7.61mm hole **Al 6061 Foil damage** = 9.22mm x 10.83mm hole **Fiberglass damage** = 6.61mm x 7.62mm hole **MLI exit damage** = 7.37mm x 9.95mm hole **Al 6061-T6 plate damage** = 13.31mm x 14.77mm hole **Al 5456-0 RW damage** = 1.31 x 1.66 x 0.61mm deep crater on front 0.22mm high bump on back **Al 2024-T3 WP damage** = no damage
13B HITF12273	1.29	0.00863	2.87	30	**Fail** **Beta cloth entry damage =** 1.39mm x 1.35mm hole **Mylar Film damage** = 6.54mm x 5.89mm hole **Fiberglass damage** = 2.42mm x 2.98mm hole **Al 6061 Foil damage** = 2.53mm x 2.50mm hole **Fiberglass damage** = 2.84mm x 2.95mm hole **MLI exit damage** = 3.03mm x 4.17mm hole **Al 6061-T6 plate damage** = 2.05mm x 2.48mm hole **Al 5456-0 RW damage** = 2.23mm x 2.33mm hole **Al 2024-T3 WP damage** = 0.64mm x 0.74mm x 0.1mm deep crater & several smaller
6B HITF12262	1.49	0.01332	7.14	30	**Pass** **Beta cloth entry damage** = 1.97mm x 1.72mm hole **Mylar Film damage** = 24.76mm x 31.83mm hole **Fiberglass entry damage** = 7.66mm x 11.22mm hole **Al 6061 Foil damage** = 8.67mm x 6.48mm hole **Fiberglass exit damage** = 12.33mm x 11.26mm hole **MLI exit damage** = 8.01mm x 8.64mm hole **Al 6061-T6 plate damage** = 6.66mm x 5.18mm hole **Al 5456-0 RW damage** = 0.97mm x 1.11mm x 1.09mm deep crater of many with a 0.94mm high bump on back **Al 2024-T3 WP damage** = no damage

Table 2 (Continue): Hypervelocity Impact Test Results for the Evaluation of ISS Soyuz Orbital Module Ballistic Limits using Steel Projectiles

Test No.	Actual Projectile Diameter (mm)	Actual Projectile Mass (g)	Actual Impact Velocity (km/s)	Impact Angle (deg)	Results
7 HITF12263	1.49	0.01332	6.23	30	**Fail** **Beta cloth entry damage** = 1.40mm x 2.03mm hole **Mylar Film damage** = 19.09mm x 13.97mm hole **Fiberglass entry damage** = 5.06mm x 7.27mm hole **Al 6061 Foil damage** = 6.26mm x 4.02mm hole **Fiberglass exit damage** = 12.13mm x 12.38mm hole **MLI exit damage** = 6.69mm x 8.17mm hole **Al 6061-T6 plate damage** = 6.93mm x 7.23mm hole **Al 5456-0 RW damage** = 1.10mm x 1.67mm hole **Al 2024-T3 WP damage** = 0.188mm x 0.166mm x 0.07mm deep crater & several smaller
8 HITF12264	1.29	0.00859	4.90	30	**Pass** **Beta cloth entry damage =** 1.29mm x 1.71mm hole **Mylar Film damage** = 19.30mm x 22.42mm hole **Fiberglass damage** = 3.49mm x 5.23mm hole **Al 6061 Foil damage** = 5.51mm x 4.47mm hole **Fiberglass damage** = 7.60mm x 10.60mm hole **MLI exit damage** = 4.73mm x 6.56mm hole **Al 6061-T6 plate damage** = 3.83mm x 4.45mm hole **Al 5456-0 RW damage** = 1.09mm x 1.10mm x 1.14mm deep crater of many with a 0.32mm high bump on back **Al 2024-T3 WP damage** = no damage
9 HITF12265	1.6	0.01615	7.14	45	**Fail** **Beta cloth entry damage** = 5.49mm x 17.51mm hole **Mylar Film damage** = 35.16mm x 19.19mm hole **Fiberglass damage** = 13.55 x 14.32mm hole **Al 6061 Foil damage** = 9.50 x 14.24mm hole **Fiberglass damage** = 14.57 x 16.36mm hole **MLI exit damage** = 8.51mm x 11.30mm hole **Al 6061-T6 plate damage** = 8.93mm x 9.57mm hole **Al 5456-0 RW damage** = 1.50 x 2.39mm hole **Al 2024-T3 WP damage** = 31mm x 30mm area of aluminum specks
10 HITF12266	1.39	0.01075	3.19	30	**Fail** **Beta cloth entry damage** = 1.56mm x 1.50mm hole **Mylar Film damage** = 13.80mm x 15.43mm hole **Fiberglass damage** = 2.67 x 2.27mm hole **Al 6061 Foil damage** = 2.50 x 2.74mm hole **Fiberglass damage** = 2.45 x 2.93mm hole **MLI exit damage** = 3.83mm x 4.66mm hole **Al 6061-T6 plate damage** = 2.53mm x 2.92mm hole **Al 5456-0 RW damage** = 2.84 x 3.09mm hole **Al 2024-T3 WP damage** = 1.48mm x 1.93mm x 0.089mm deep crater & many smaller

Table 2 (Continue): Hypervelocity Impact Test Results for the Evaluation of ISS Soyuz Orbital Module Ballistic Limits using Steel Projectiles

Test No.	Actual Projectile Diameter (mm)	Actual Projectile Mass (g)	Actual Impact Velocity (km/s)	Impact Angle (deg)	Results
11 HITF12271	1.5	0.01331	6.14	45	**Fail** **Beta cloth entry damage** = 1.60mm x 2.05mm hole **Mylar Film damage** = 52.09mm x 24.07mm hole **Fiberglass damage** = 7.83mm x 9.30mm hole **Al 6061 Foil damage** = 6.22 x 7.26mm hole **Fiberglass damage** = 6.31 x 6.85mm hole **MLI exit damage** = 13.47mm x 18.16mm hole **Al 6061-T6 plate damage** = 7.36mm x 10.58mm hole **Al 5456-0 RW damage** = 1.96mm x 2.69mm hole **Al 2024-T3 WP damage** = 0.66mm x 0.78mm x 0.15mm deep crater & several smaller
12 HITF12272	1.4	0.01074	6.17	45	**Pass** **Beta cloth entry damage** = 1.49mm x 1.97mm hole **Mylar Film damage** = 18.24mm x 27.07mm hole **Fiberglass damage** = 3.89 x 6.40mm hole **Al 6061 Foil damage** = 5.09 x 6.25mm hole **Fiberglass damage** = 4.56 x 5.38mm hole **MLI exit damage** = 13.22mm x 19.74mm hole **Al 6061-T6 plate damage** = 6.98mm x 10.45mm hole **Al 5456-0 RW damage** = 0.88mm x 1.17mm x 0.98mm deep crater with a 0.48mm high bump on back **Al 2024-T3 WP damage** = no damage
14 HITF12274	1.3	0.00864	4.18	45	**Fail** **Beta cloth entry damage** = 1.43mm x 1.87mm hole **Mylar Film damage** 33.26 x 22.20mm hole **Fiberglass damage** = 3.10 x 5.92mm hole **Al 6061 Foil damage** = 2.95 x 4.06mm hole **Fiberglass damage** = 3.46 x 4.32mm hole **MLI exit damage** = 5.07mm x 6.72mm hole **Al 6061-T6 plate damage** = 3.05mm x 5.04mm hole **Al 5456-0 RW damage** = 0.87mm x 0.99mm hole **Al 2024-T3 WP damage** = 0.50mm x 0.85mm x 0.056mm deep crater
15C HITF12275	1.0	0.00400	3.93	45	**Pass** **Beta cloth entry damage** = 1.23mm x 1.68mm hole **Mylar Film damage** 24.03 x 20.59mm hole **Fiberglass damage** = 1.72 x 2.52mm hole **Al 6061 Foil damage** = 2.23 x 3.04mm hole **Fiberglass damage** = 2.20 x 3.15mm hole **MLI exit damage** = 4.10mm x 5.64mm hole **Al 6061-T6 plate damage** = 2.70mm x 3.95mm hole **Al 5456-0 RW damage** = 1.10mm x 1.21mm hole **Al 2024-T3 WP damage** = no damage

Table 2 (Continue): Hypervelocity Impact Test Results for the Evaluation of ISS Soyuz Orbital Module Ballistic Limits using Steel Projectiles

Test No.	Actual Projectile Diameter (mm)	Actual Projectile Mass (g)	Actual Impact Velocity (km/s)	Impact Angle (deg)	Results
16 HITF12276	1.6	0.01610	7.00	30	**Fail** **Beta cloth entry damage** = 1.69mm x 1.84mm hole **Mylar Film damage** 23.55 x 18.53mm hole **Fiberglass damage** 10.23 x 10.29mm hole **Al 6061 Foil damage** = 7.72 x 5.93mm hole **Fiberglass damage** 11.36 x 12.23mm hole **MLI exit damage** = 8.75mm x 9.62mm hole **Al 6061-T6 plate damage** = 6.66mm x 7.91mm hole **Al 5456-0 RW damage** = 1.77mm x 1.75mm hole **Al 2024-T3 WP damage** = 52mm x 63mm area of aluminum specks
17 HITF12277	1.5	0.01331	4.83	30	**Fail** **Beta cloth entry damage** = 1.66mm x 1.70mm hole **Mylar Film damage** 15.62 x 12.15mm hole **Fiberglass damage** = 3.63 x 4.03mm hole **Al 6061 Foil damage** = 4.32 x 5.02mm hole **Fiberglass damage** = 4.62 x 5.64mm hole **MLI exit damage** = 6.47mm x 7.43mm hole **Al 6061-T6 plate damage** = 4.63mm x 6.11mm hole **Al 5456-0 RW damage** = 2 holes largest is 1.54mm x 2.20mm **Al 2024-T3 WP damage** = 0.487mm x 0.536mm x 0.372mm deep crater & many smaller

7. ISS Soyuz Vehicle Orbital Module Ballistic Limit Equations

NASA JSC-KX/Eric Christiansen has revised ballistic limit equations (BLEs) for Soyuz Orbital Module (OM) shielding based on hypervelocity impact data obtained by NASA Johnson Space Center Hypervelocity Impact Technology (HVIT) group at White Sands Test Facility (WSTF) (Figure 7) and at the University of Dayton Research Institute (UDRI) (Figure 8). The Soyuz OM shielding consists of an outer multi-layer insulation (MLI) thermal blanket that is attached to a 0.5mm thick aluminum AMg-6 bumper plate, followed by 15mm spacing to a 1.9mm thick aluminum AMg-6 pressure shell. The MLI thermal blanket for Soyuz OM also contains a 0.2mm thick aluminum layer and 2 layers of fiberglass cloth.

Hypervelocity impact tests were performed on US materials that closely match the Russian materials in type, thickness and mass. The WSTF tests were performed with a two-stage light-gas gun at speeds of up to 7.0 km/s. The UDRI tests were performed on a three-stage light-gas gun with speeds of up to 10.1 km/s. Tests were performed with Steel (440C stainless steel) spherical projectiles. All of the testing was with steel projectiles, as previous work [1] concentrated on aluminum projectiles. The steel projectiles were included in the testing because the new orbital debris model (ORDEM 3.0) contains a significant fraction of high-density (steel) impactors.

The ballistic limit equations are used in *Bumper* Code to assess the Probability of No Penetration (PNP) from impacts by micrometeoroids and orbital debris (MMOD).

Nomenclature

d projectile diameter (cm)

m_b areal density of MLI and aluminum bumper (g/cm^2)

ρ density (g/cm^3)

θ impact angle from surface normal (deg)

V projectile velocity (km/s)

V_n normal component of projectile velocity (km/s) = $V \cos\theta$

Subscripts:

- b bumper
- c critical particle diameter
- n normal component (of velocity vector)
- p projectile

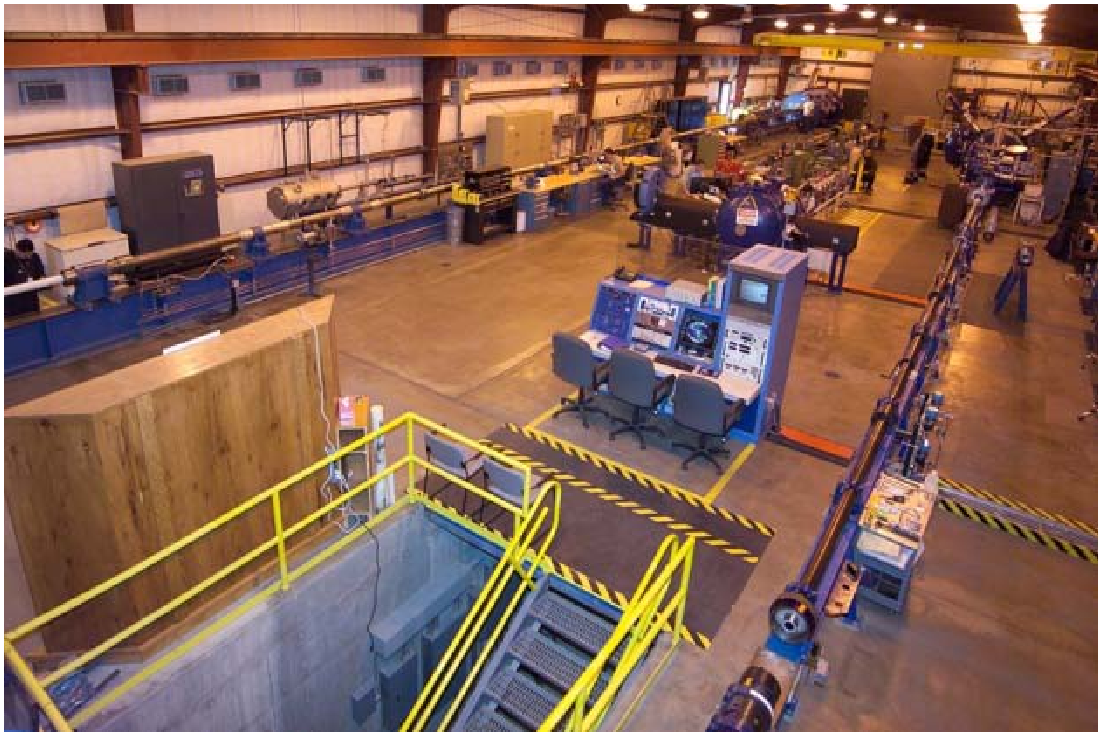


Figure 9: WSTF hypervelocity launchers.

Figure 10: UDRI hypervelocity impact laboratory.

Soyuz OM Ballistic Limit Equations

Ballistic limit equations (BLEs) for the Soyuz OM were updated based on the test data. These equations relate the particle size, d_c (cm), on the failure threshold of the shield as a function of impact and target parameters. Failure is defined as a through-hole or through-crack in the rear wall or pressure shell of the shield. The BLEs are provided for three velocity ranges, as follows.

<u>High-Velocity:</u> when $V \geq V_H/(\cos\theta)^{exph}$,

$$d_c = K_H\, t_w^{eh}\, \rho_p^{-1/3}\, (V \cos\theta)^{-eh} \tag{1}$$

<u>Intermediate-Velocity</u>: when $2.5/(\cos\theta) < V < V_H/(\cos\theta)^{exph}$,

$$d_c = K_{hi}\, t_w^{eh}\, \rho_p^{-1/3}\, (\cos\theta)^{[eh * exph - eh]}\, [V - 2.5\, (\cos\theta)^{-1}] / [V_H(\cos\theta)^{-exph} - 2.5\, (\cos\theta)^{-1}]$$
$$+\ K_{li}\, (t_w + 0.37\, f_l\, m_b)\, \rho_p^{-0.5}\, (\cos\theta)^{-2/3}\, [V_H\, (\cos\theta)^{-exph} - V] / [V_H(\cos\theta)^{-exph} - 2.5\, (\cos\theta)^{-1}] \tag{2}$$

<u>Low-Velocity:</u> when $V \leq 2.5/(\cos\theta)$,

$$d_c = K_L\, (t_w + 0.37\, f_l\, m_b)\, (\cos\theta)^{-4/3}\, \rho_p^{-0.5}\, V^{-2/3} \tag{3}$$

No upper impact angle constraint is defined. Coefficients and variables for Soyuz OM shield BLEs are given in following table.

Table 3: Coefficients and Variables for Soyuz OM BLEs.

	Old Coefficients	**New coefficients for Flight vehicle**		**Test article coefficients**	
Parameter	**Original**	**Update for Aluminum projectile**	**Update for Steel projectile**	**Update for Aluminum projectile**	**Update for Steel projectile**
m_b (g/cm^2)	0.34	0.343	0.343	0.315	0.315
t_w (cm)	0.19	0.19	0.19	0.20	0.20
ρ_p (g/cm^3)	2.8	2.8	7.9	2.796	7.667
V_H (km/s)	6.2	6.2	7.5	6.2	7.5
exph	0.33	0.4	0.4	0.4	0.4
eh	1/3	1/3	1/3	1/3	1/3
f_l	1.0	1.0	1.0	1.0	1.0
K_H	1.180	1.070	1.070	1.070	1.070
K_{hi}	0.642	0.582	0.547	0.582	0.547
K_{li}	0.977	0.841	0.841	0.841	0.841
K_L	1.800	1.550	1.550	1.550	1.550

Figures 11-15 show the comparison between predicted ballistic limits for the test articles and impact test data. Figures 11 and 12 are for steel particles impacting at 30deg and 45deg impact angles. Figures 13, 14 and 15 are for aluminum particles impacting at 0deg, 30deg and 45deg impact angles.

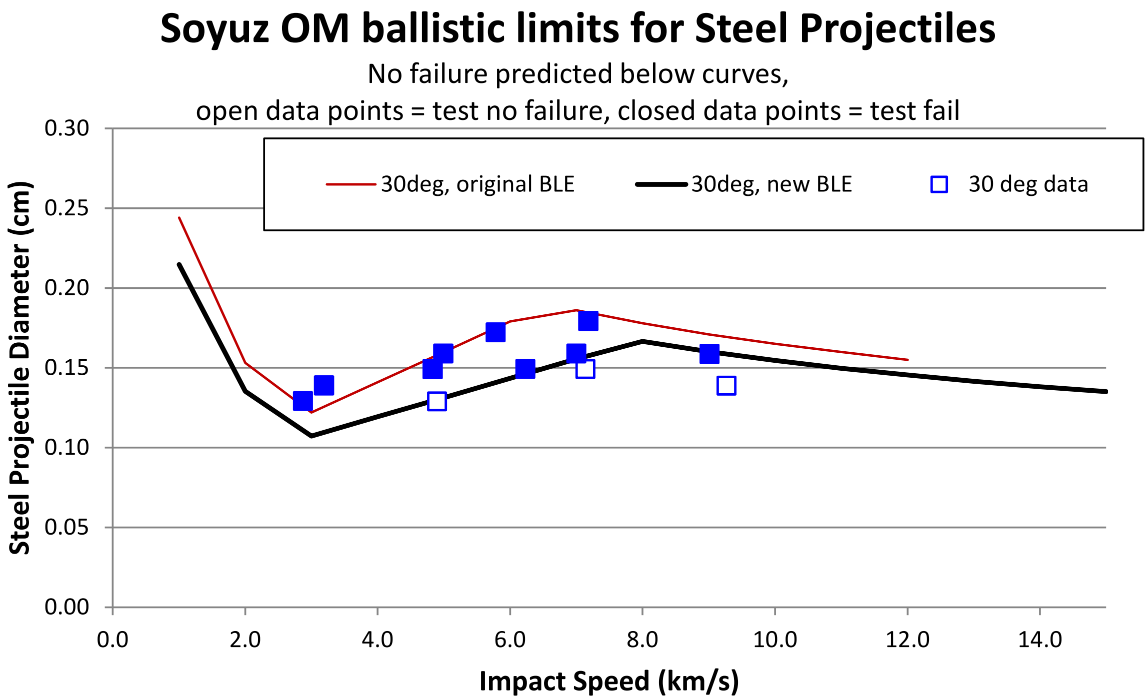


Figure 11: Soyuz OM BLE predictions compared to 30deg impact test data for steel projectiles.

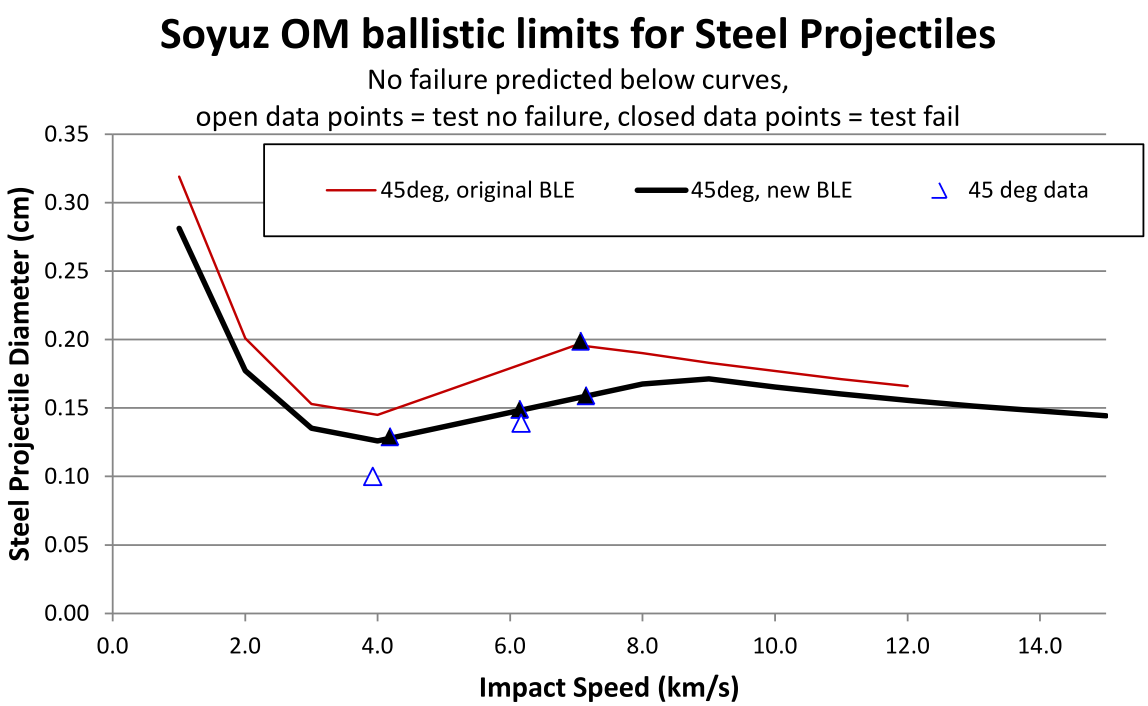


Figure 12: Soyuz OM BLE predictions compared to 45deg impact data for steel projectiles.

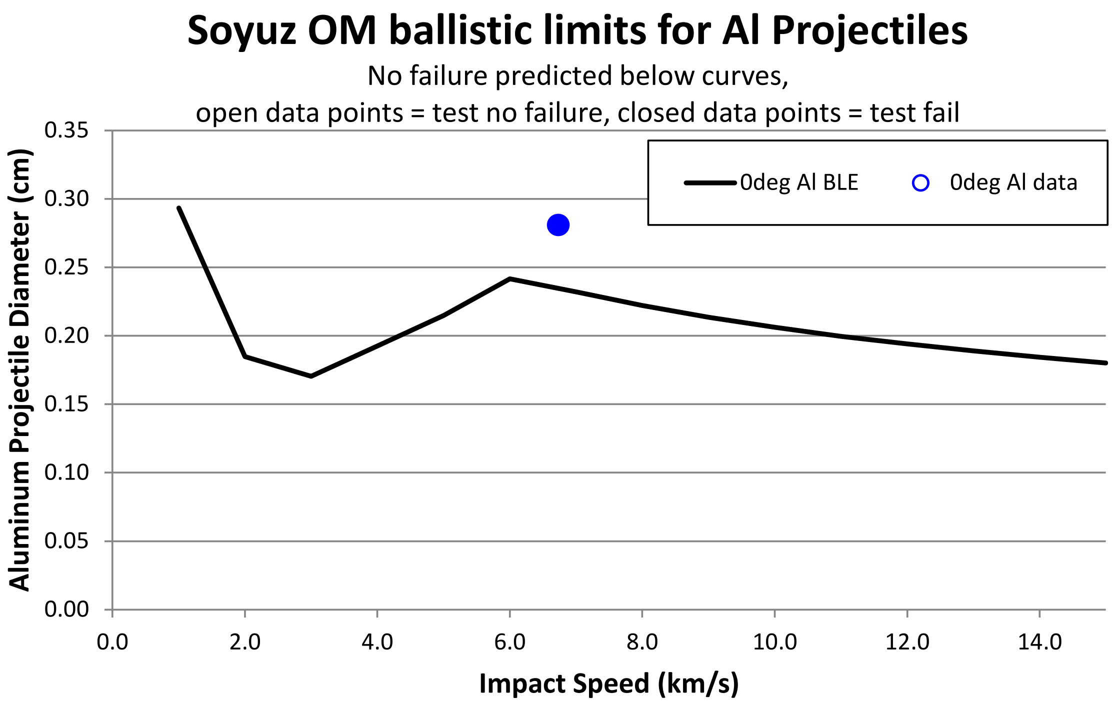


Figure 13: Soyuz OM BLE predictions compared to 0deg impact test data for aluminum projectiles.

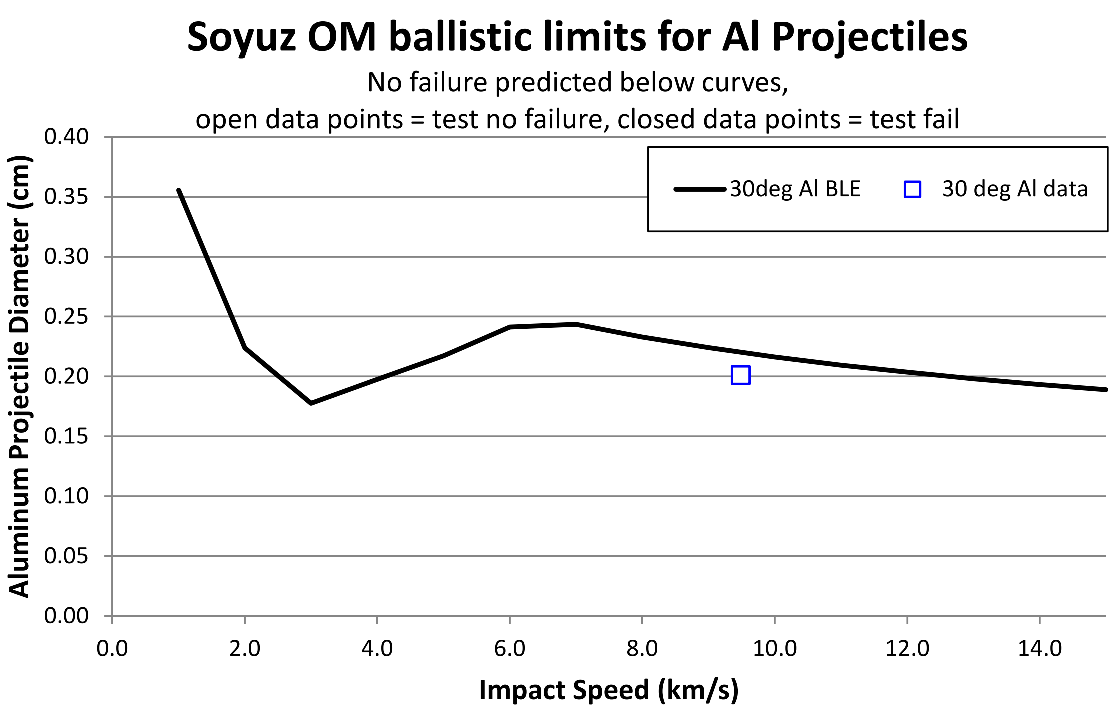


Figure 14: Soyuz OM BLE predictions compared to 30deg impact test data for aluminum projectiles.

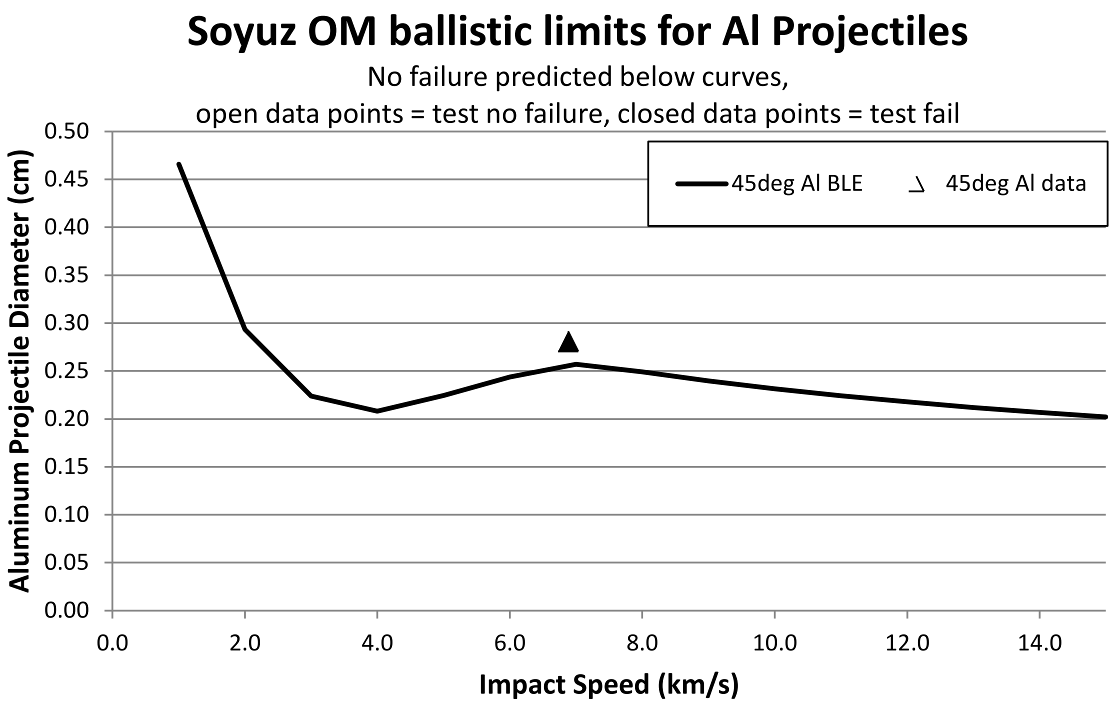


Figure 15: Soyuz OM BLE predictions compared to 45deg impact test data for aluminum projectiles.

Ballistic Limit Critical Diameter Tables

Tables 4 and 5 provide the predicted ballistic limit critical particle diameters for steel and aluminum projectiles for the Progress CM flight configuration shields.

Table 4: Soyuz OM critical particle diameter for Steel projectiles as function of impact angle and velocity.

	Soyuz OM, Steel Projectiles Critical particle diameter (cm) on failure threshold of shield					
Velocity (km/s)	**0 deg**	**15 deg**	**30 deg**	**45 deg**	**60 deg**	**75 deg**
1	0.1748	0.1830	0.2117	0.2774	0.4404	1.0596
2	0.1101	0.1153	0.1334	0.1748	0.2774	0.6675
3	0.1011	0.1021	0.1057	0.1334	0.2117	0.5094
4	0.1137	0.1145	0.1172	0.1240	0.1748	0.4205
5	0.1264	0.1268	0.1287	0.1338	0.1505	0.3624
6	0.1390	0.1392	0.1402	0.1436	0.1568	0.3209
7	0.1516	0.1515	0.1516	0.1534	0.1631	0.2896
8	0.1544	0.1562	0.1620	0.1632	0.1694	0.2649
9	0.1485	0.1502	0.1558	0.1667	0.1757	0.2449
10	0.1434	0.1450	0.1504	0.1609	0.1806	0.2307
11	0.1389	0.1405	0.1457	0.1559	0.1750	0.2224
12	0.1349	0.1365	0.1415	0.1514	0.1700	0.2142
13	0.1314	0.1329	0.1378	0.1474	0.1655	0.2061
14	0.1281	0.1296	0.1344	0.1438	0.1615	0.2011
15	0.1252	0.1267	0.1314	0.1406	0.1578	0.1965

Table 5: Soyuz OM critical particle diameter for aluminum projectiles as function of impact angle and velocity.

	Soyuz OM, Aluminum Projectiles Critical particle diameter (cm) on failure threshold of shield					
Velocity (km/s)	**0 deg**	**15 deg**	**30 deg**	**45 deg**	**60 deg**	**75 deg**
1	0.2936	0.3074	0.3556	0.4660	0.7397	1.7798
2	0.1849	0.1937	0.2240	0.2936	0.4660	1.1212
3	0.1698	0.1715	0.1774	0.2240	0.3556	0.8556
4	0.1909	0.1920	0.1962	0.2076	0.2936	0.7063
5	0.2121	0.2126	0.2149	0.2226	0.2528	0.6087
6	0.2332	0.2331	0.2337	0.2376	0.2591	0.5390
7	0.2281	0.2308	0.2394	0.2526	0.2653	0.4864
8	0.2182	0.2208	0.2289	0.2449	0.2716	0.4449
9	0.2098	0.2123	0.2201	0.2355	0.2643	0.4113
10	0.2026	0.2049	0.2125	0.2274	0.2552	0.3642
11	0.1962	0.1985	0.2059	0.2203	0.2472	0.3079
12	0.1906	0.1928	0.2000	0.2140	0.2402	0.2991
13	0.1856	0.1878	0.1947	0.2083	0.2339	0.2913
14	0.1811	0.1832	0.1900	0.2033	0.2281	0.2841
15	0.1770	0.1790	0.1857	0.1986	0.2230	0.2777

Test #1, HITF12257

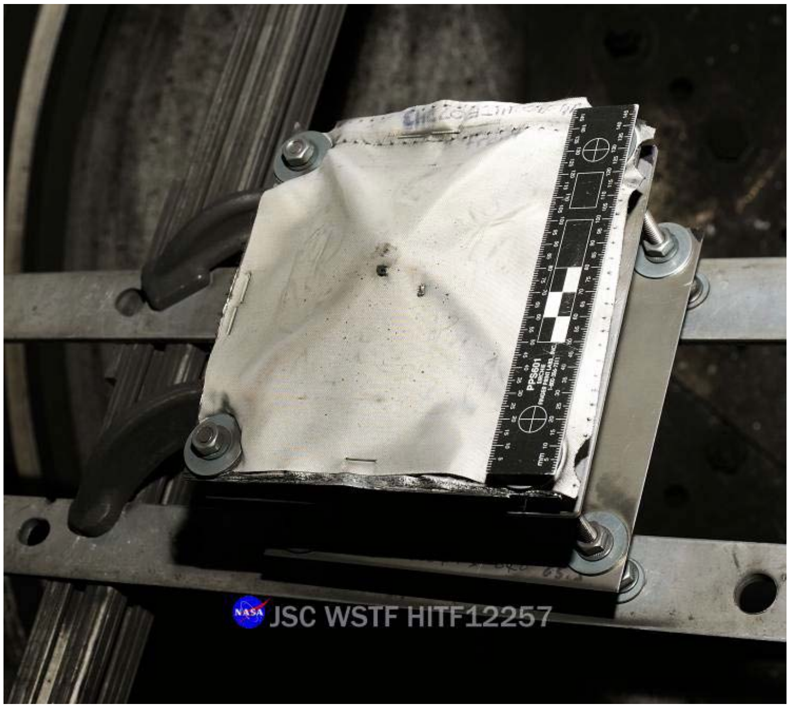


Figure 16: Post-test of ISS Soyuz Orbital Module Test #1 (HITF12257) article mounted in 0.50-caliber target tank.

Figure 17: Side View of ISS Soyuz Orbital Module Test #1

Test #1, HITF12257

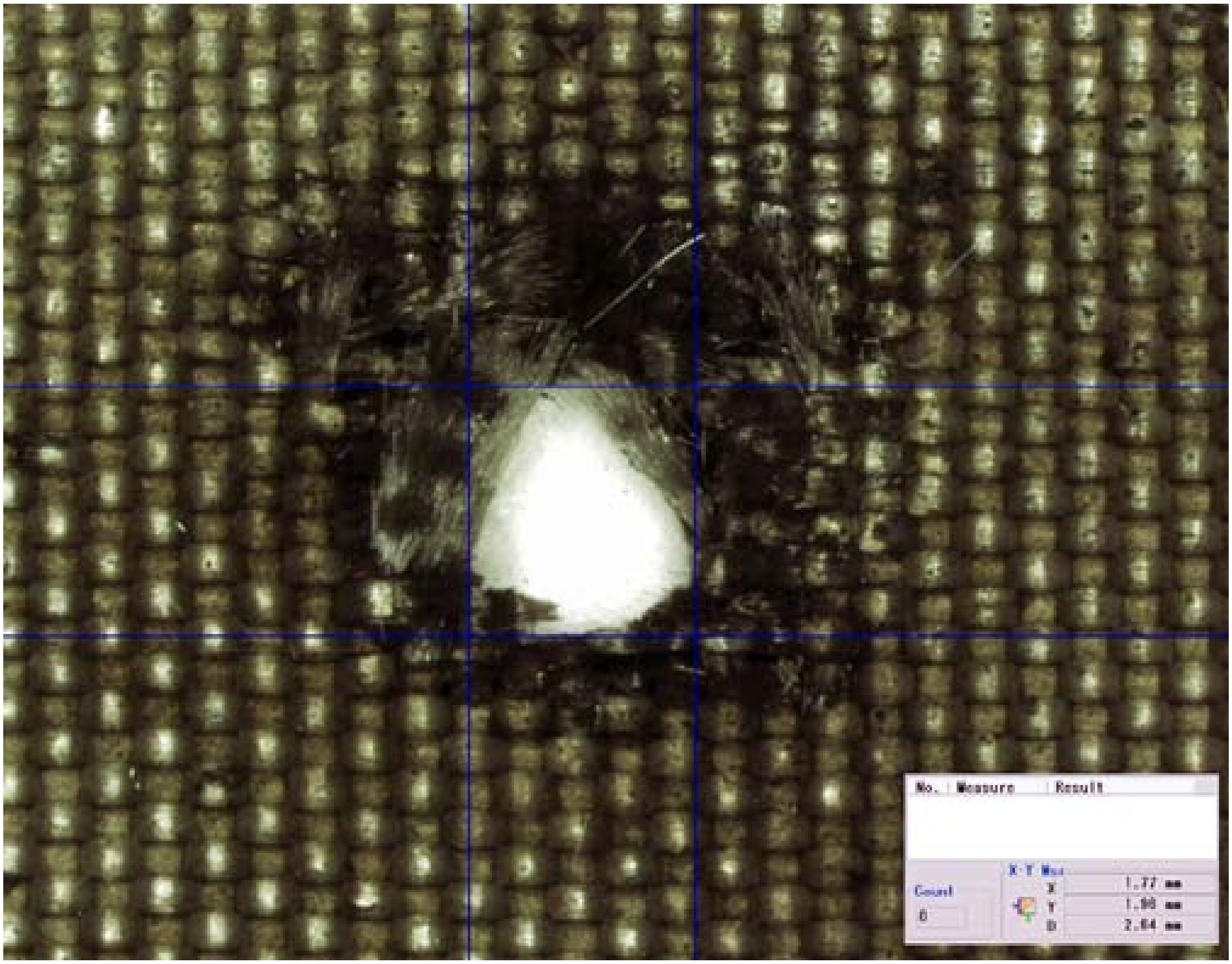


Figure 18: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #1
(Keyence 3D Microscope Image)

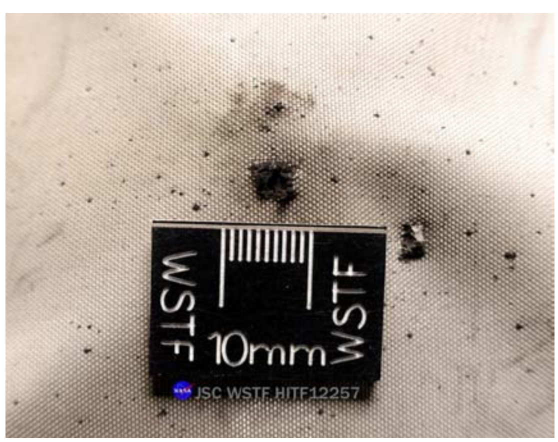


Figure 19: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #1

Test #1, HITF12257

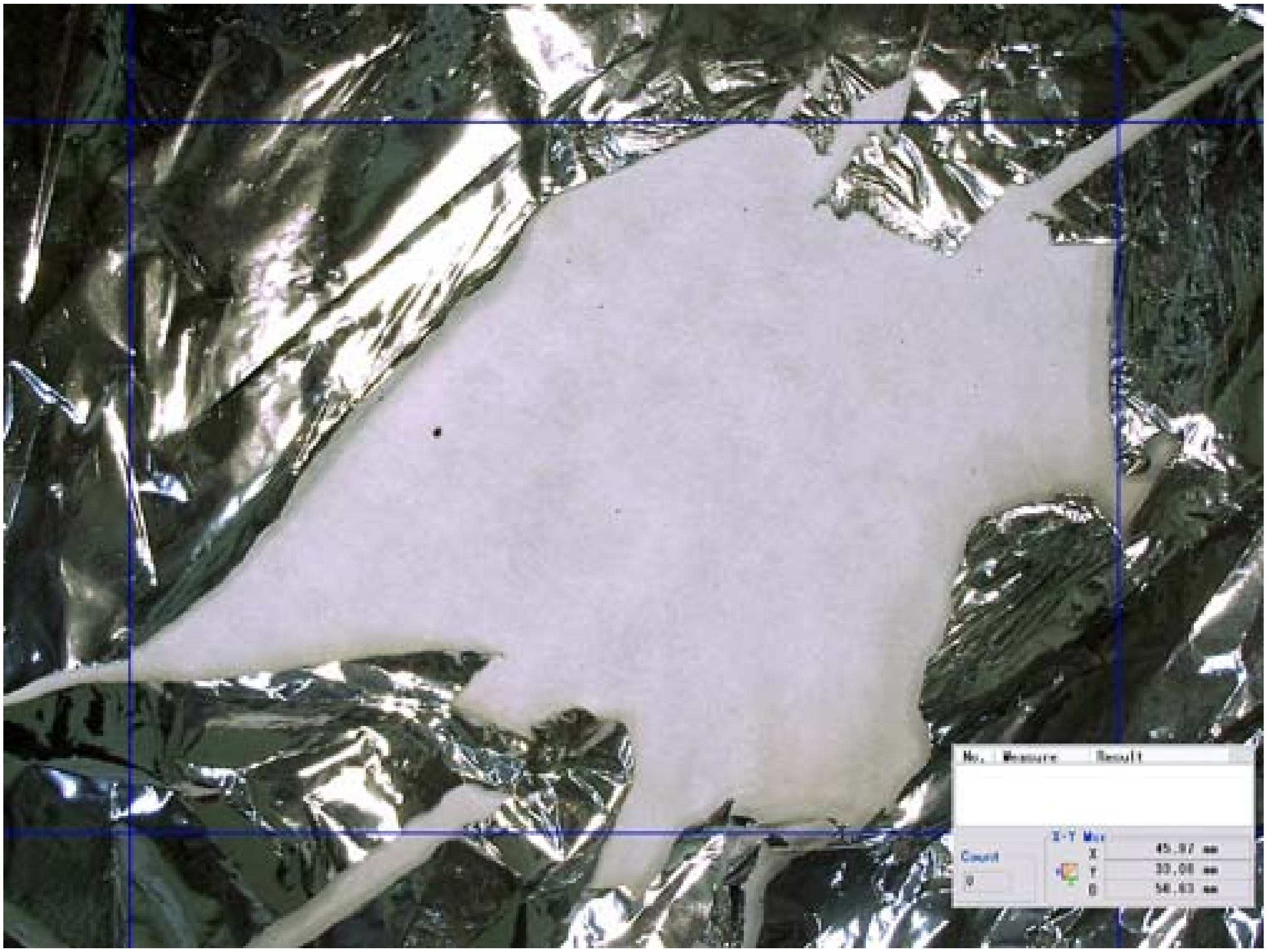


Figure 20: Mylar Film Layer 2 of ISS Soyuz OM Test #1 (Keyence 3D Microscope Image)

Test #1, HITF12257

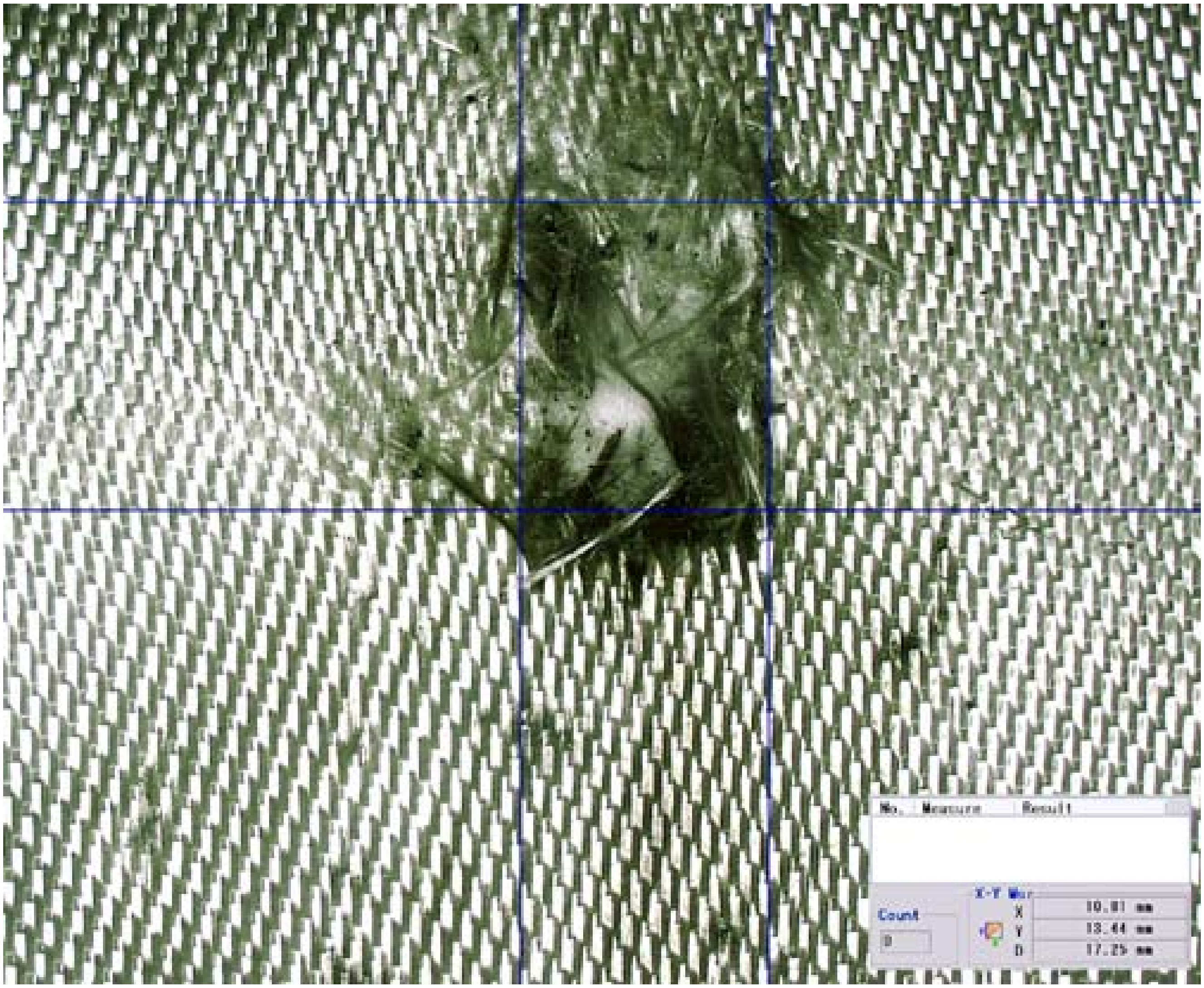


Figure 21: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #1 (Keyence 3D Microscope Image)

Test #1, HITF12257

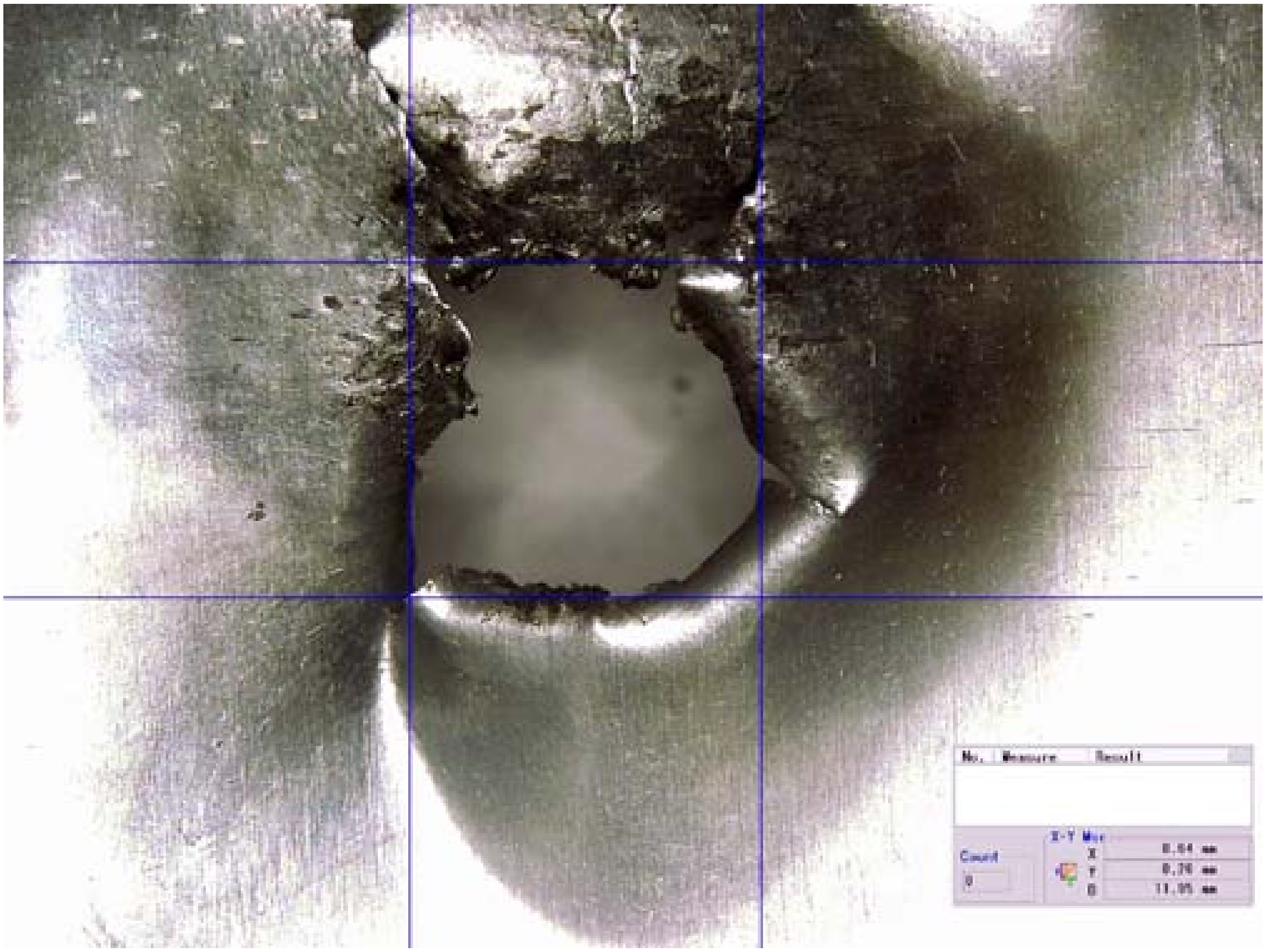


Figure 22: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #1 (Keyence 3D Microscope Image)

Test #1, HITF12257

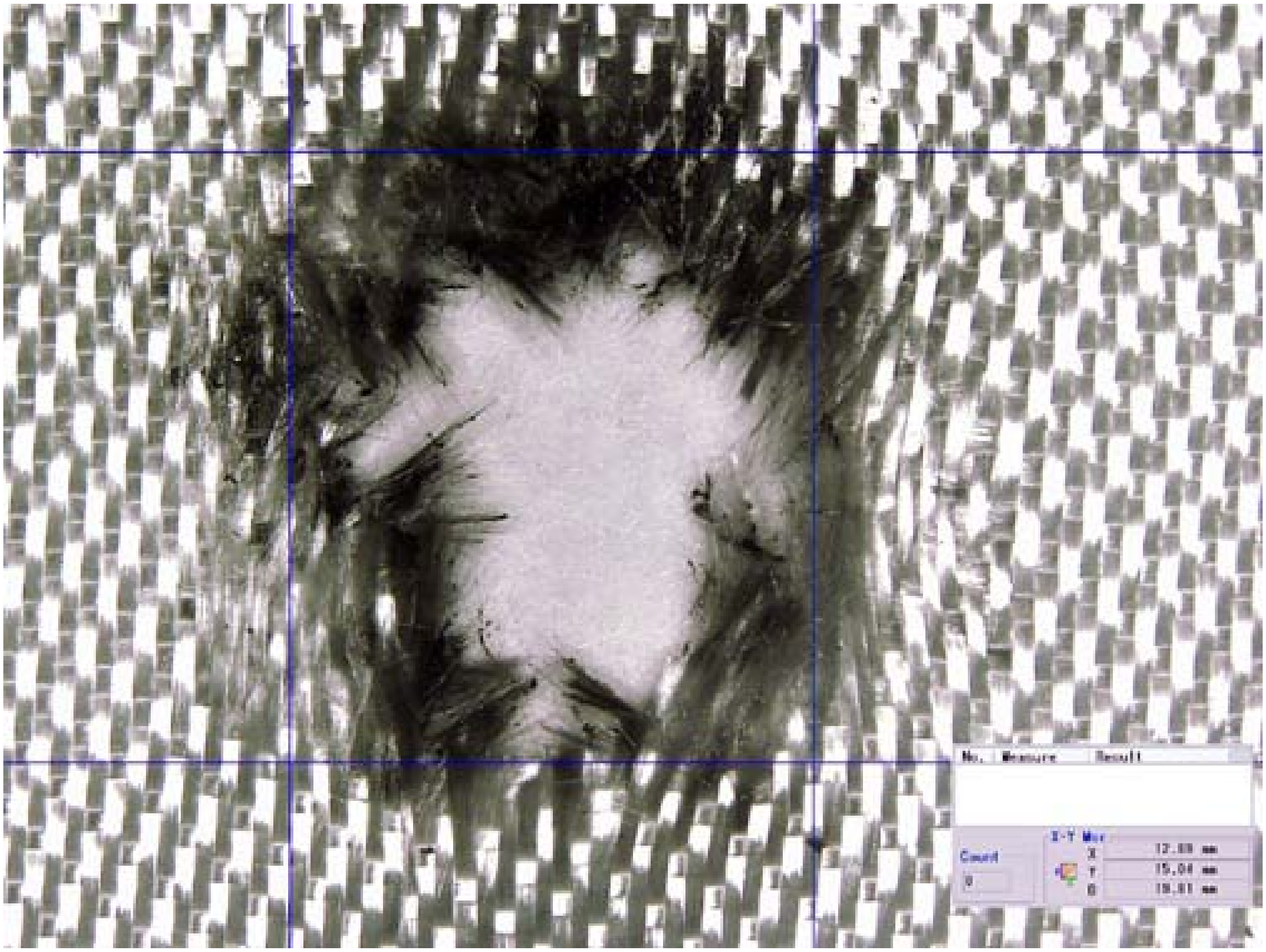


Figure 23: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #1
(Keyence 3D Microscope Image)

Test #1, HITF12257

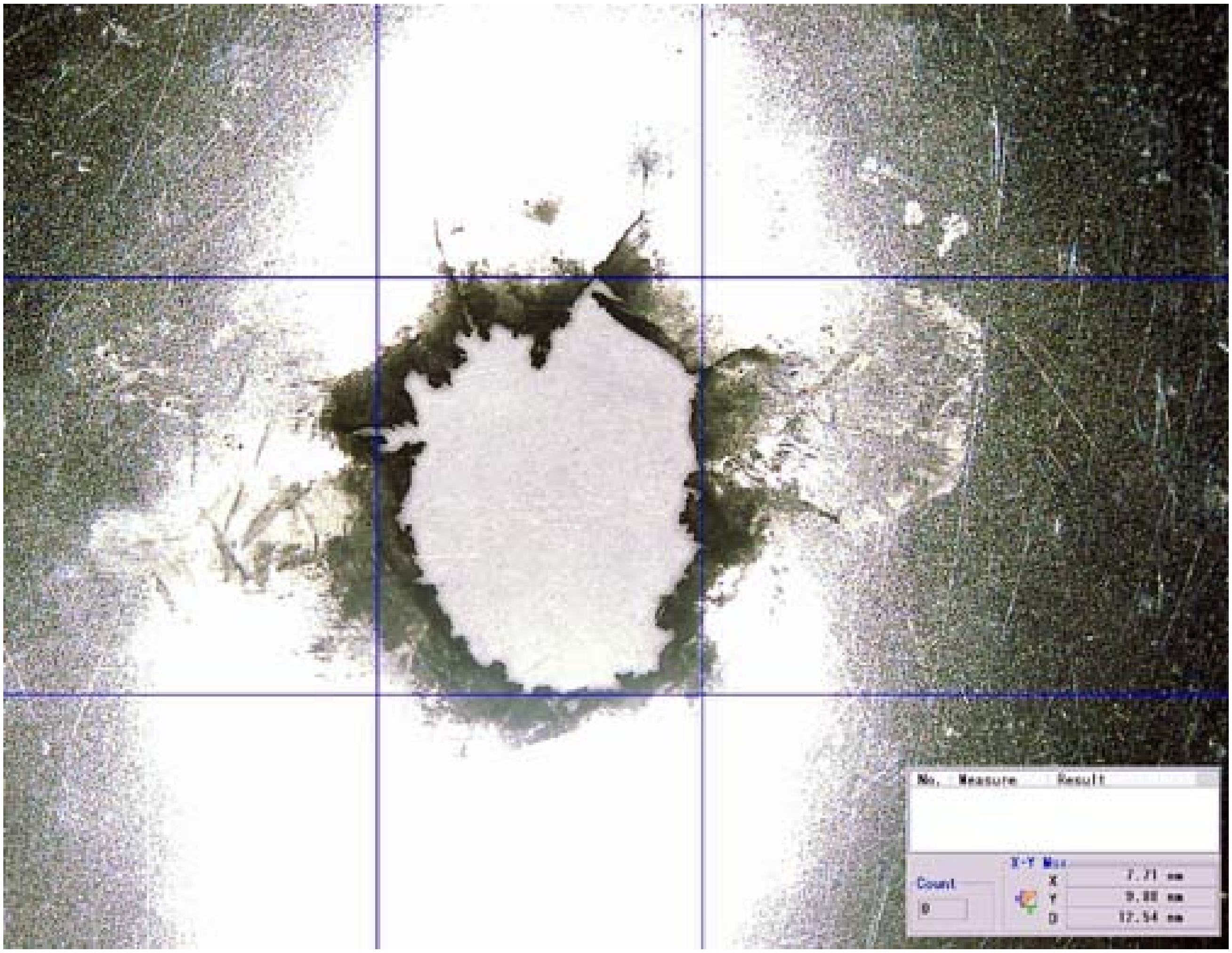


Figure 24: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #1 (Keyence 3D Microscope Image)

Test #1, HITF12257

Figure 25: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #1 (Keyence 3D Microscope Image)

Test #1, HITF12257

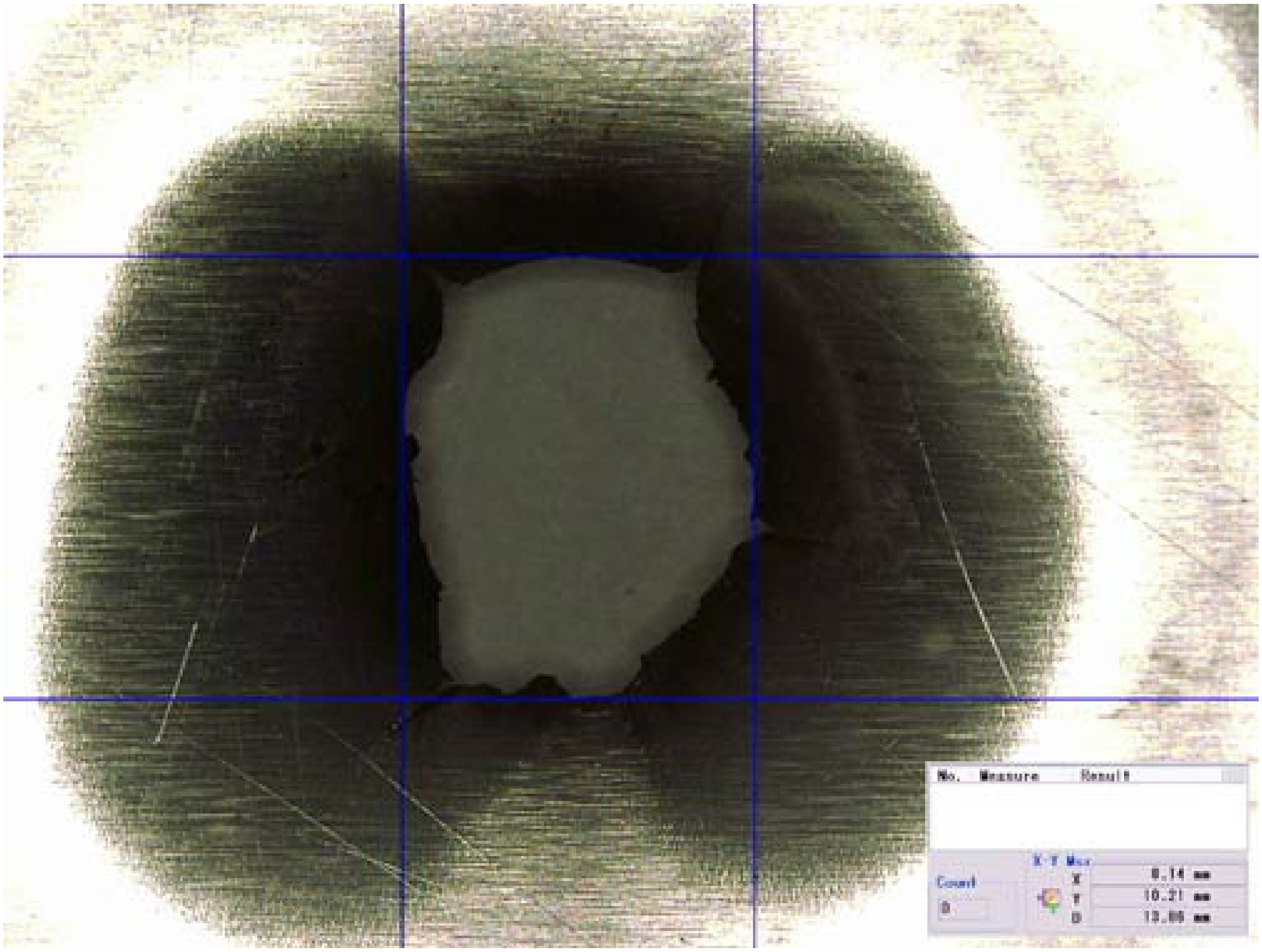


Figure 26: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #1 (Keyence 3D Microscope Image)

Test #1, HITF12257 Rear Wall

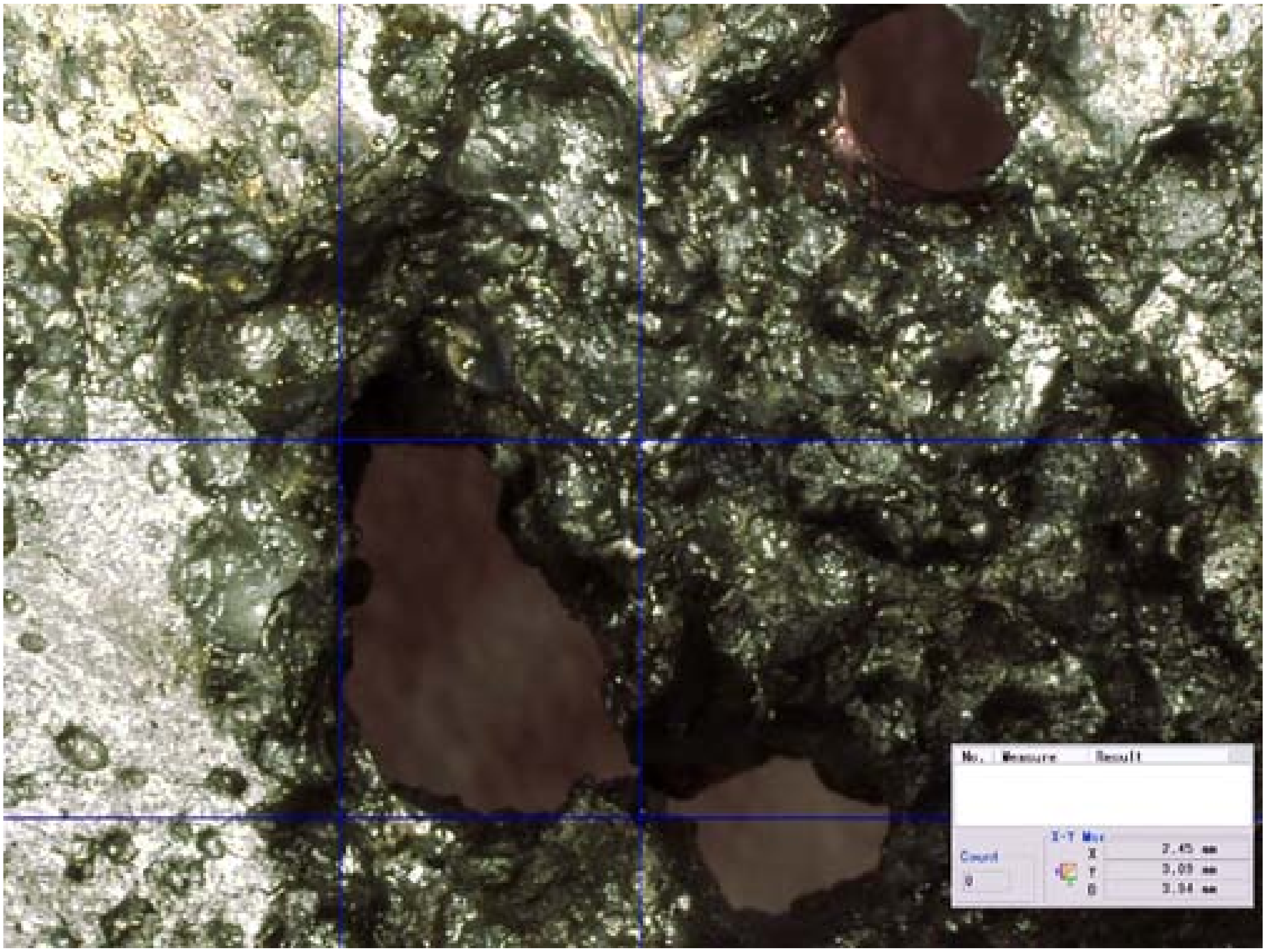


Figure 27: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #1 (Keyence 3D Microscope Image)

Test #1, HITF12257

Figure 28: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #1 (Keyence 3D Microscope Image)

Test #1, HITF12257

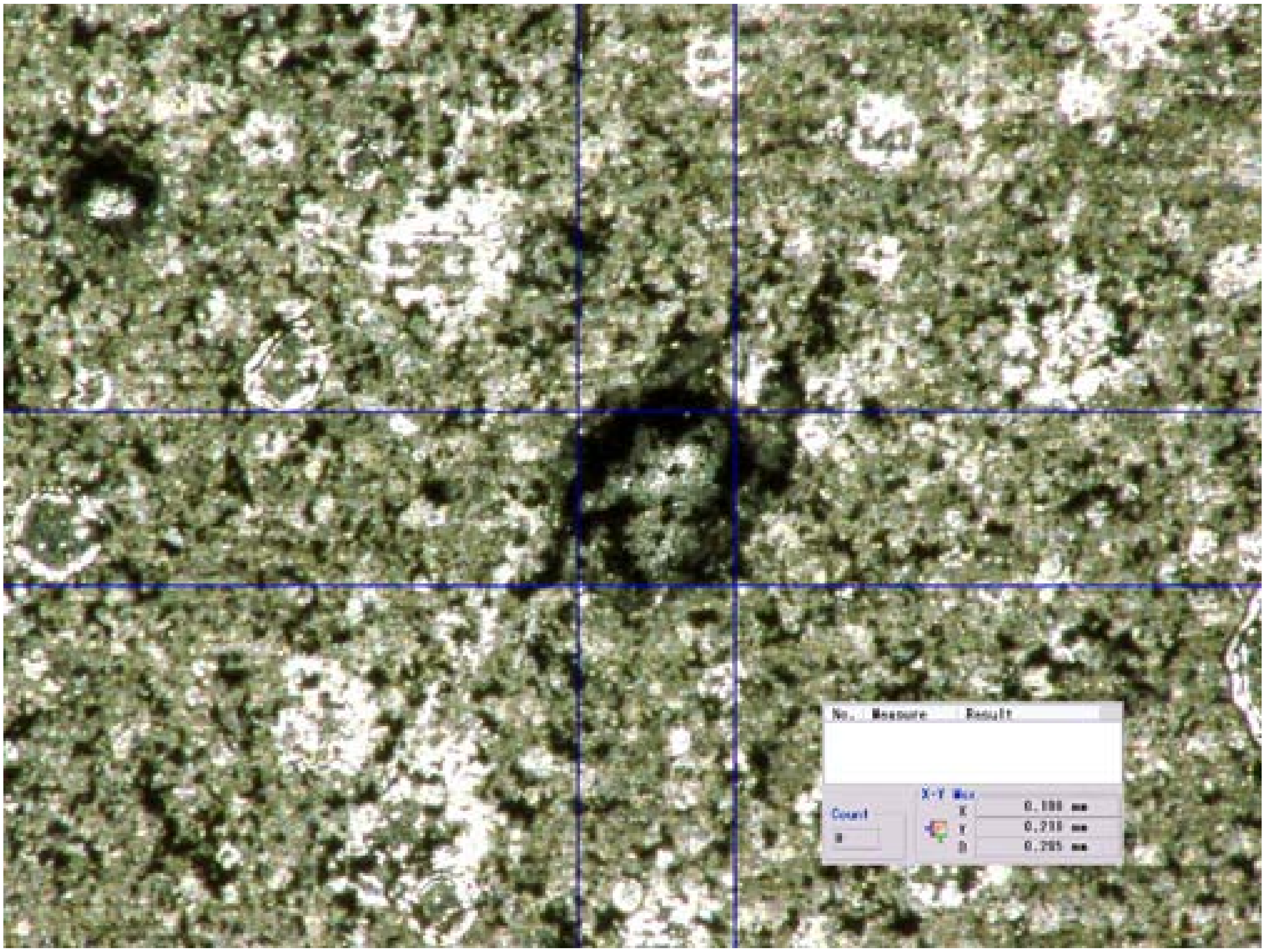


Figure 29: Witness Plate of ISS Soyuz OM Test #1
(Keyence 3D Microscope Image)

Test #1, HITF12257

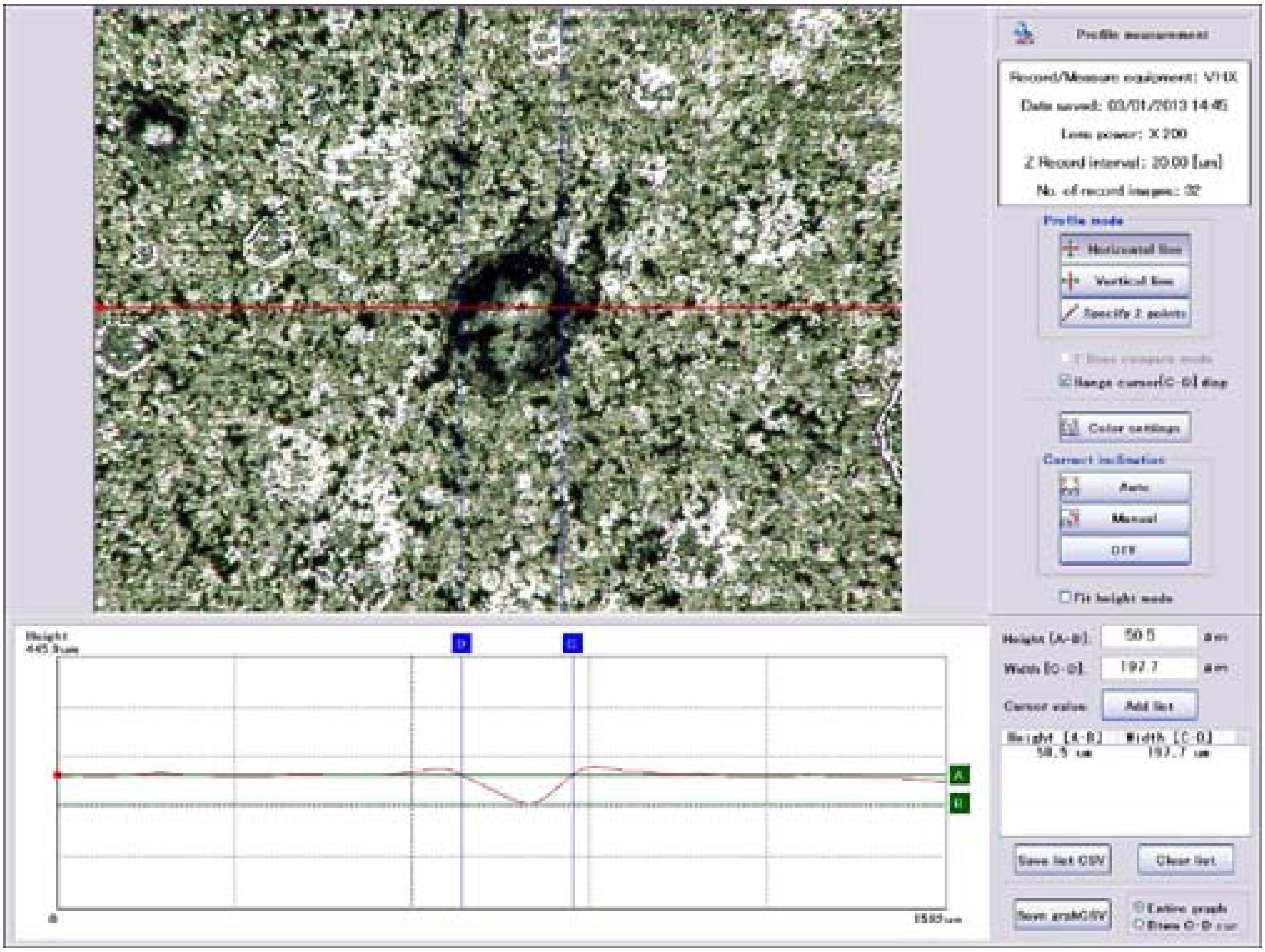


Figure 30: Witness Plate of ISS Soyuz OM Test #1
(Keyence 3D Microscope Image)

Test #1, HITF12257

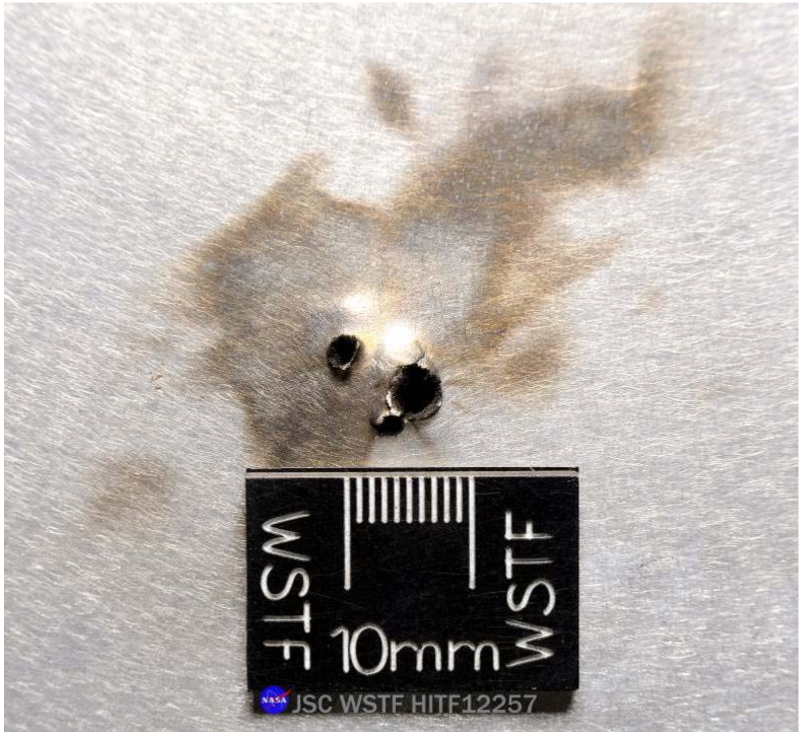


Figure 31: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #1

Figure 32: Front Witness Plate View of ISS Soyuz Orbital Module Test #1

Test #2, HITF12258

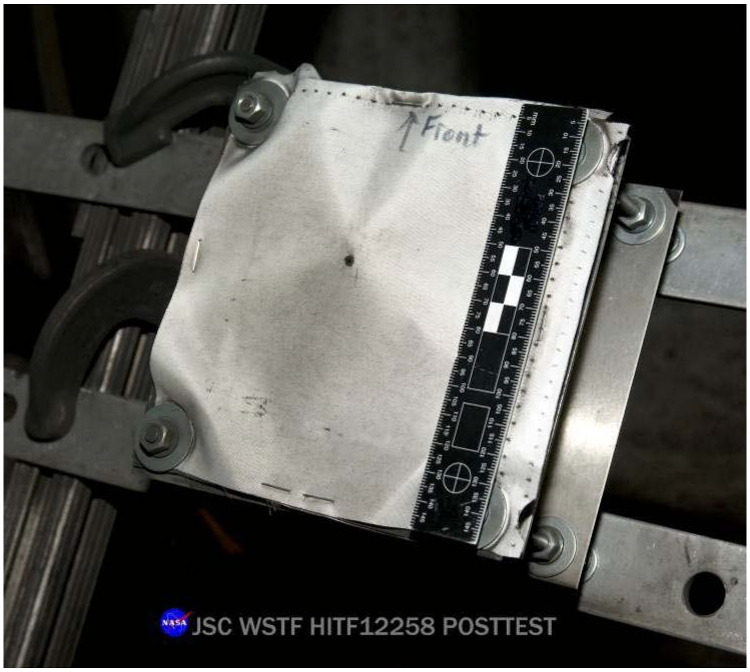


Figure 33: Post-test of ISS Soyuz Orbital Module Test #2 (HITF12258) article mounted in 0.50-caliber target tank.

Figure 34: Side View of ISS Soyuz Orbital Module Test #2

Test #2, HITF12258

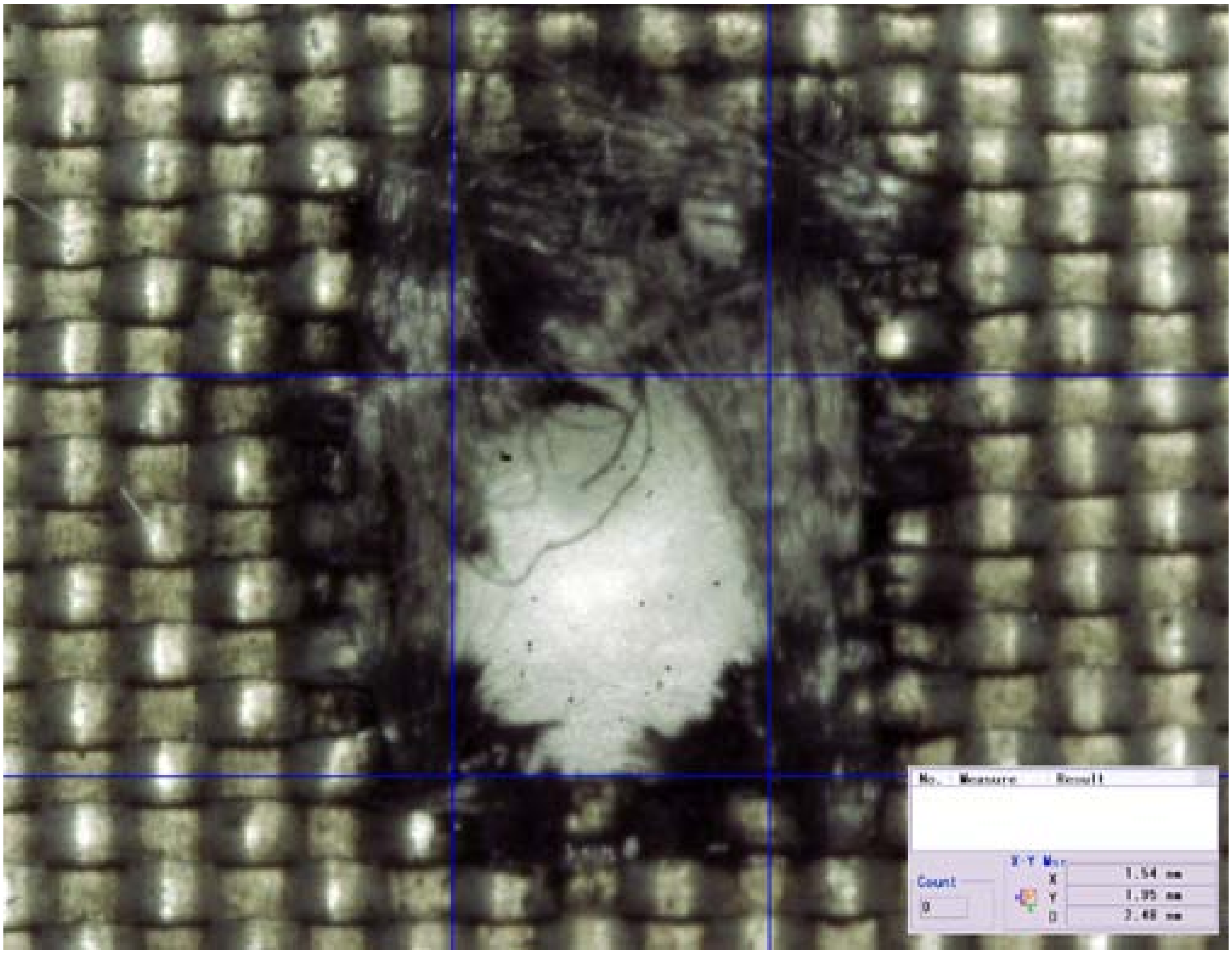


Figure 35: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #2 (Keyence 3D Microscope Image)

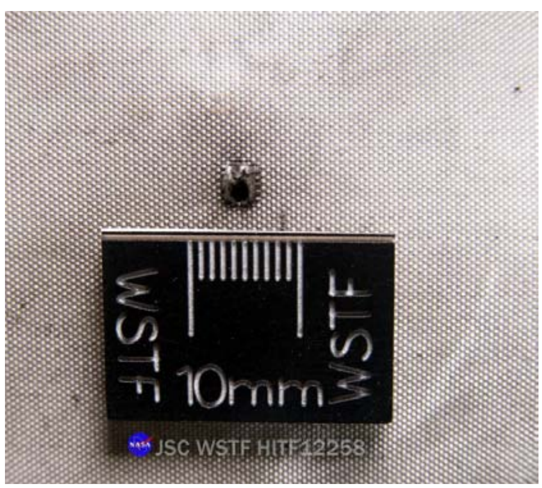


Figure 36: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #2

Test #2, HITF12258

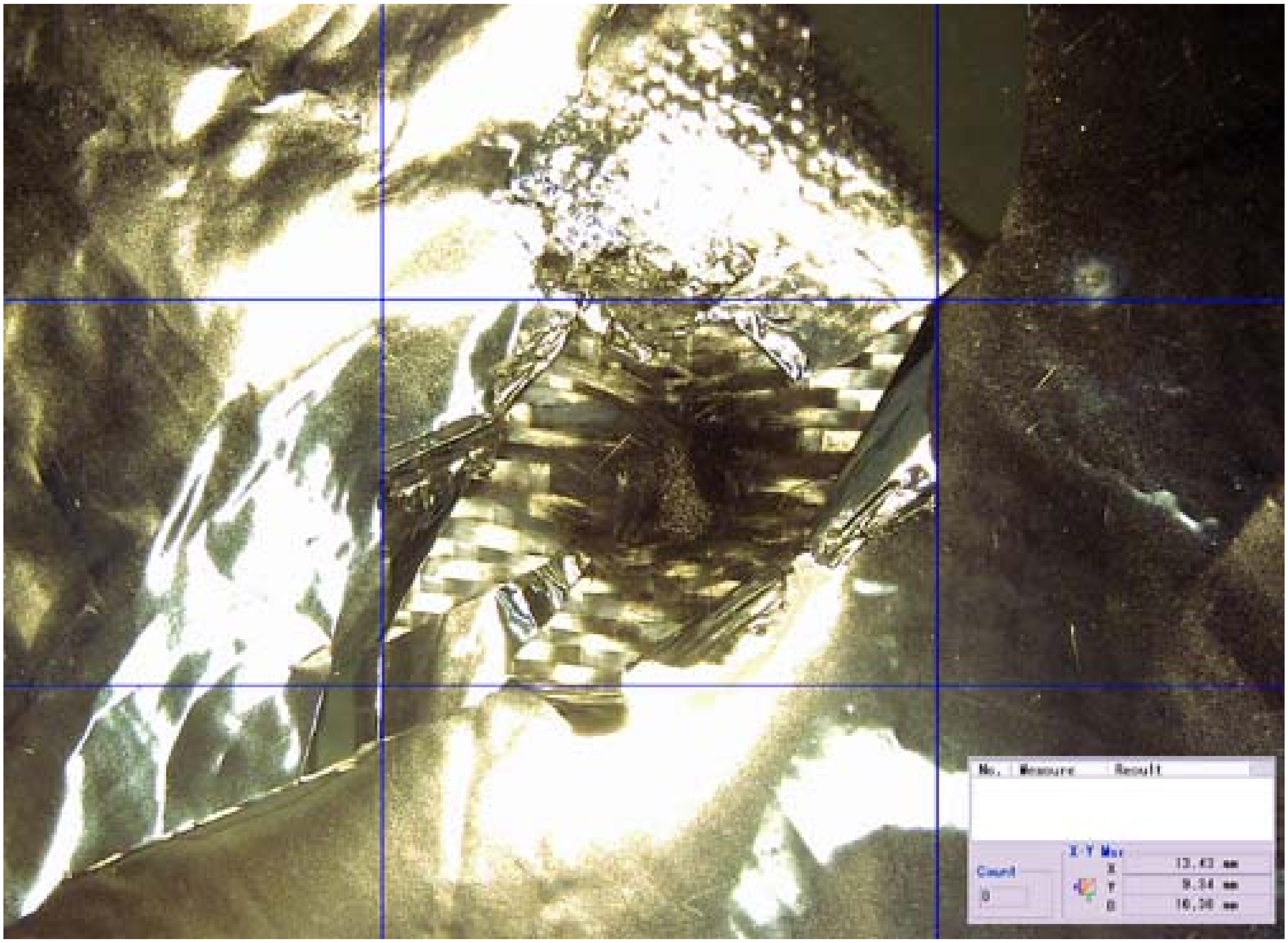


Figure 37: Mylar Film Layer 2 of ISS Soyuz OM Test #2 (Keyence 3D Microscope Image)

Test #2, HITF12258

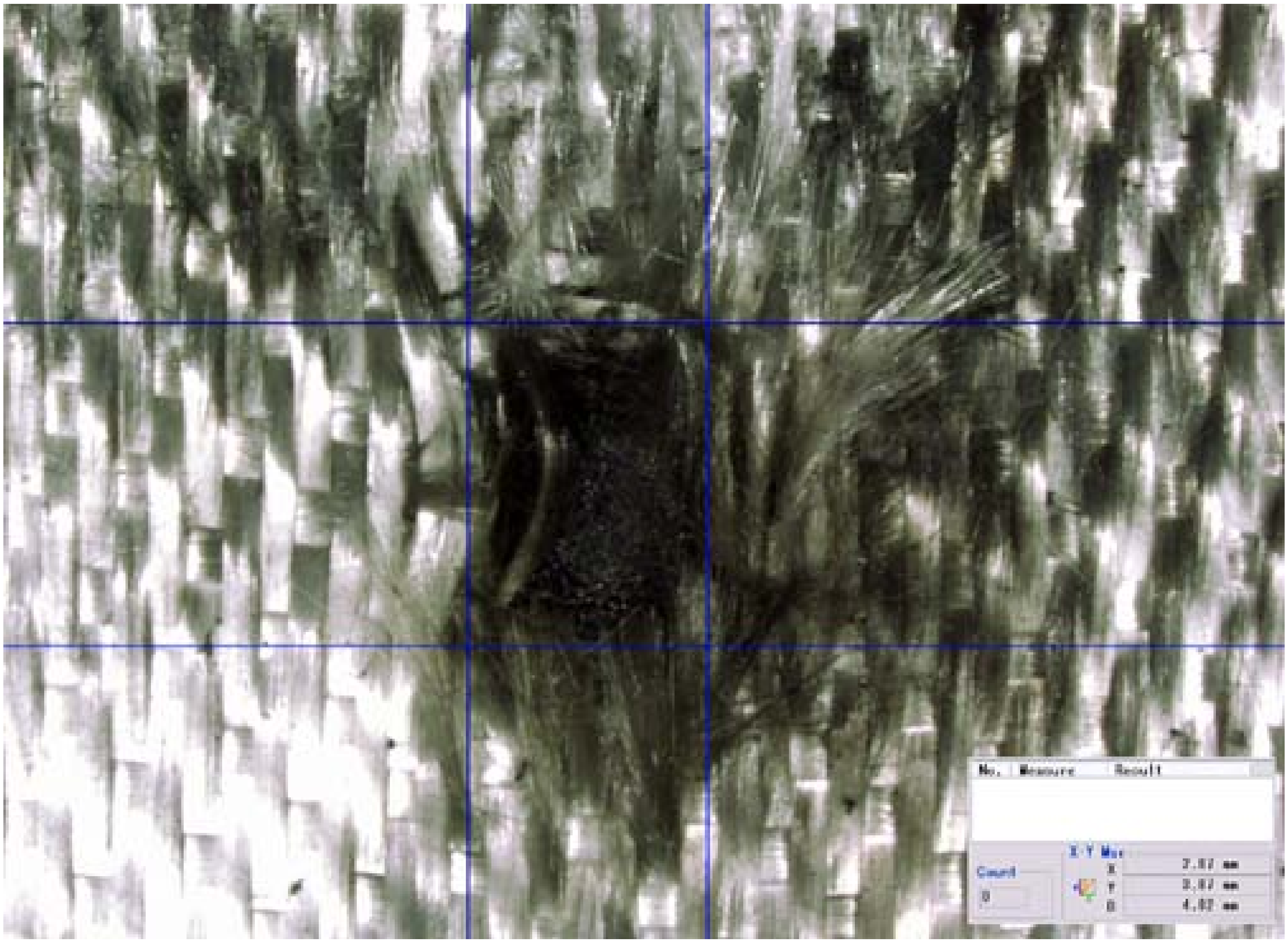


Figure 38: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #2
(Keyence 3D Microscope Image)

Test #2, HITF12258

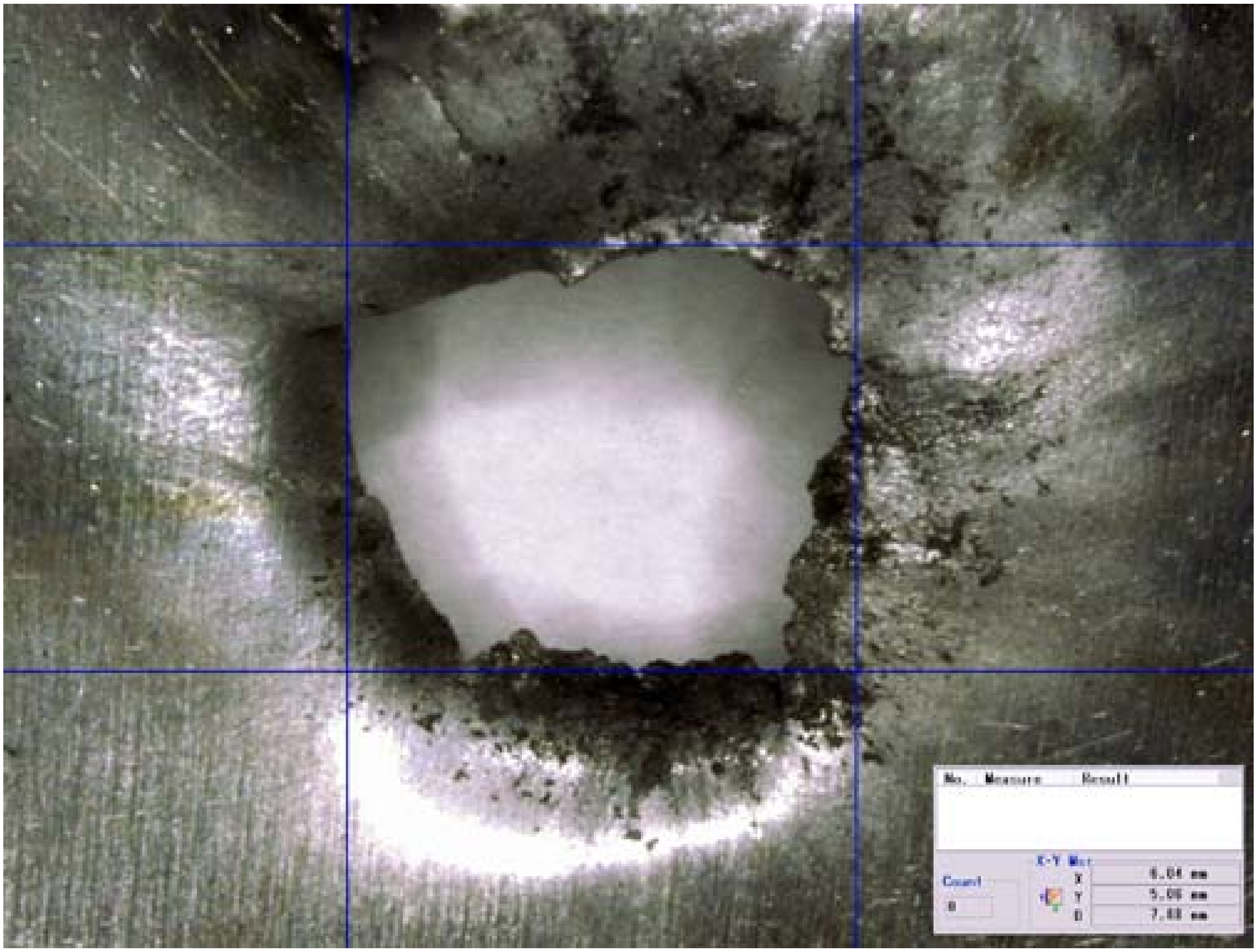


Figure 39: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #2 (Keyence 3D Microscope Image)

Test #2, HITF12258

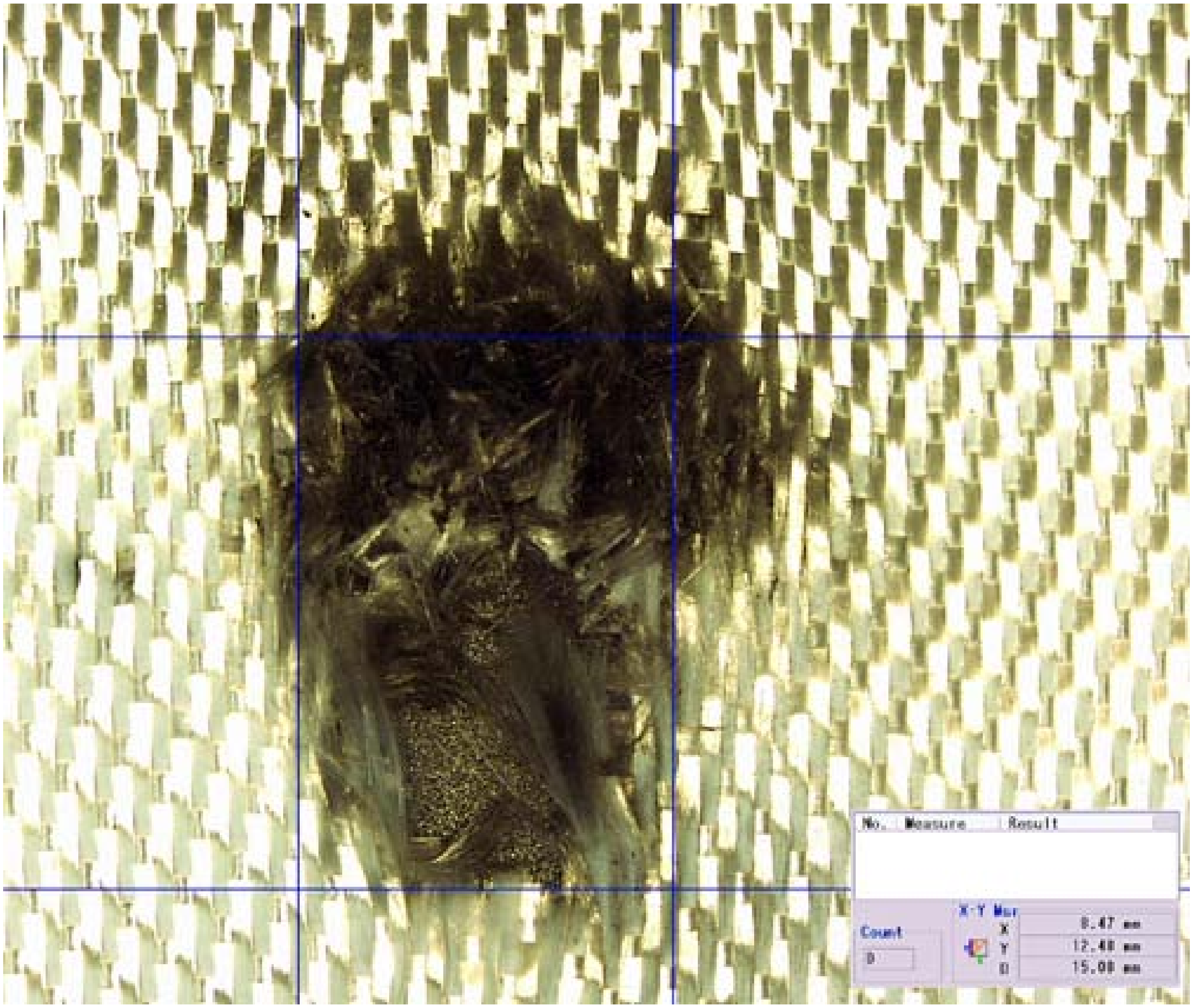


Figure 40: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #2
(Keyence 3D Microscope Image)

Test #2, HITF12258

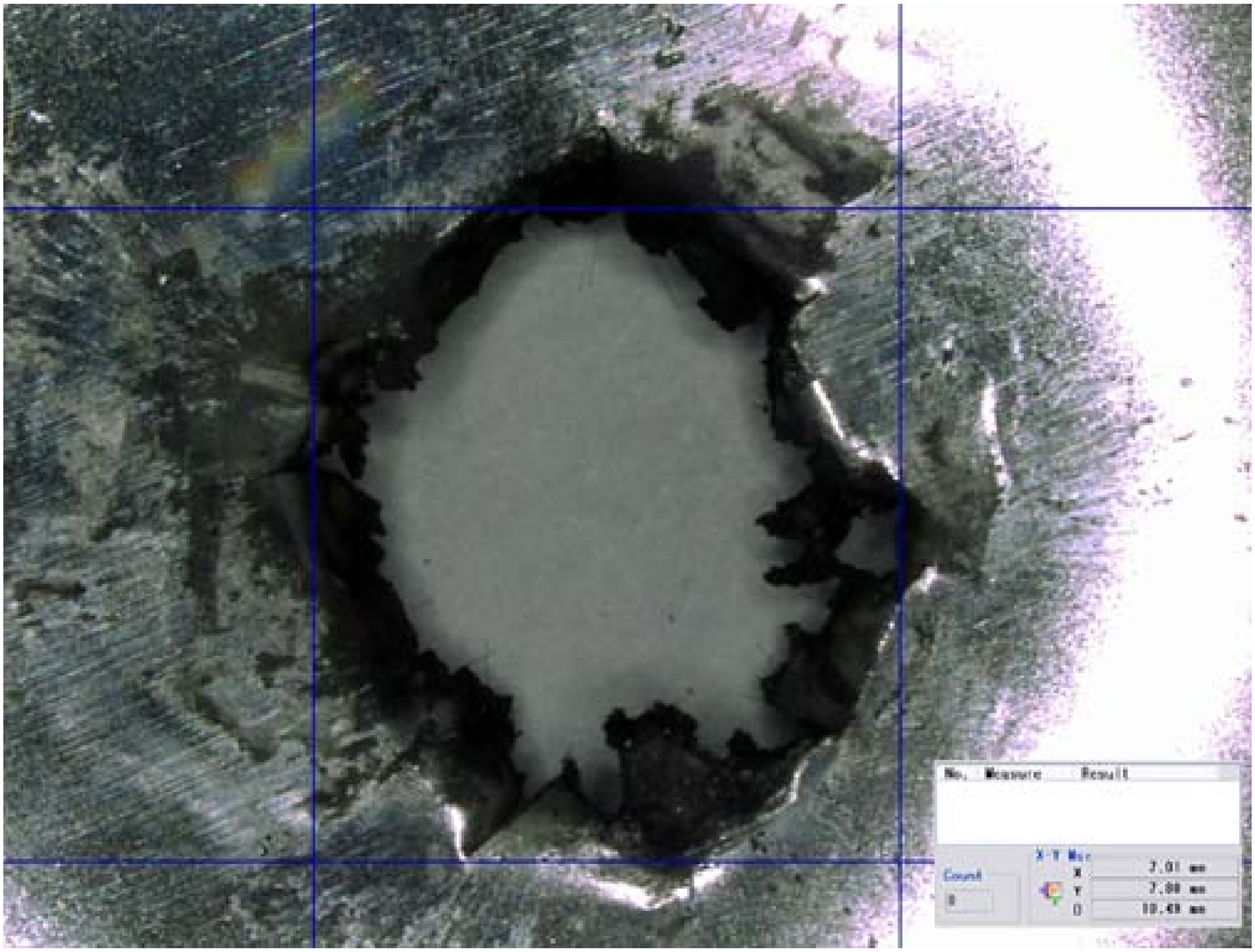


Figure 41: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #2 (Keyence 3D Microscope Image)

Test #2, HITF12258

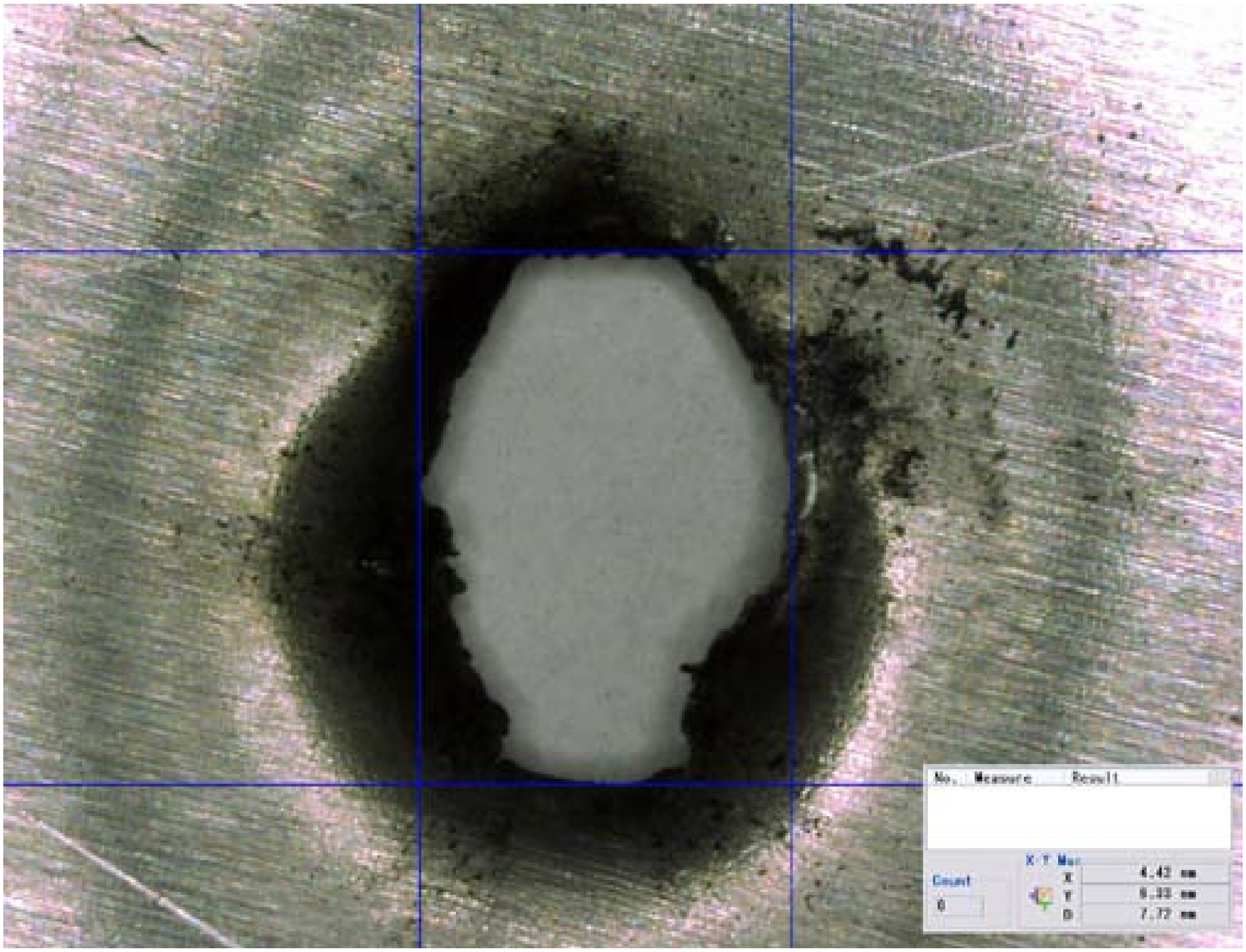


Figure 42: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #2 (Keyence 3D Microscope Image)

Test #2, HITF12258

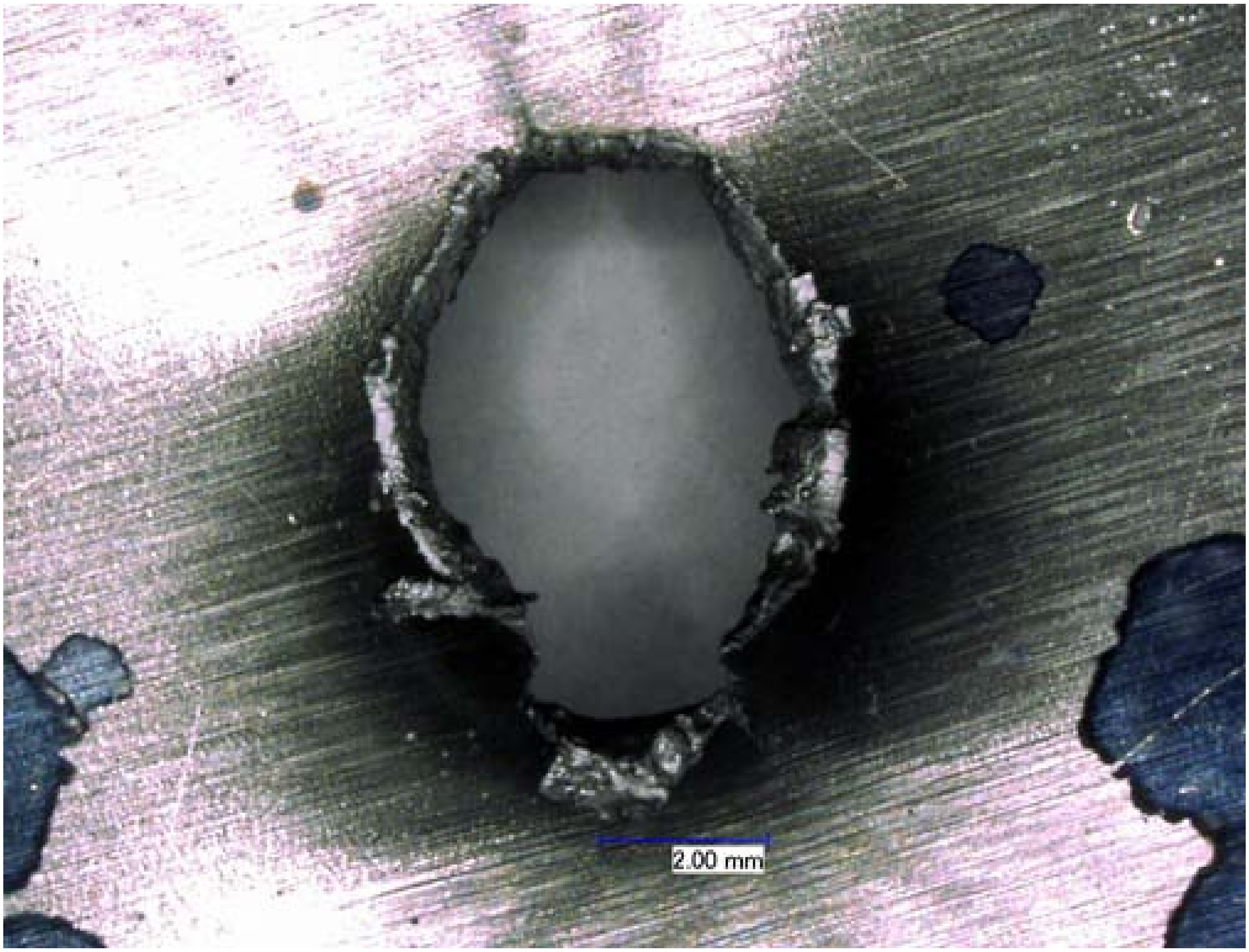


Figure 43: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #2 (Keyence 3D Microscope Image)

Test #2, HITF12258 Rear Wall

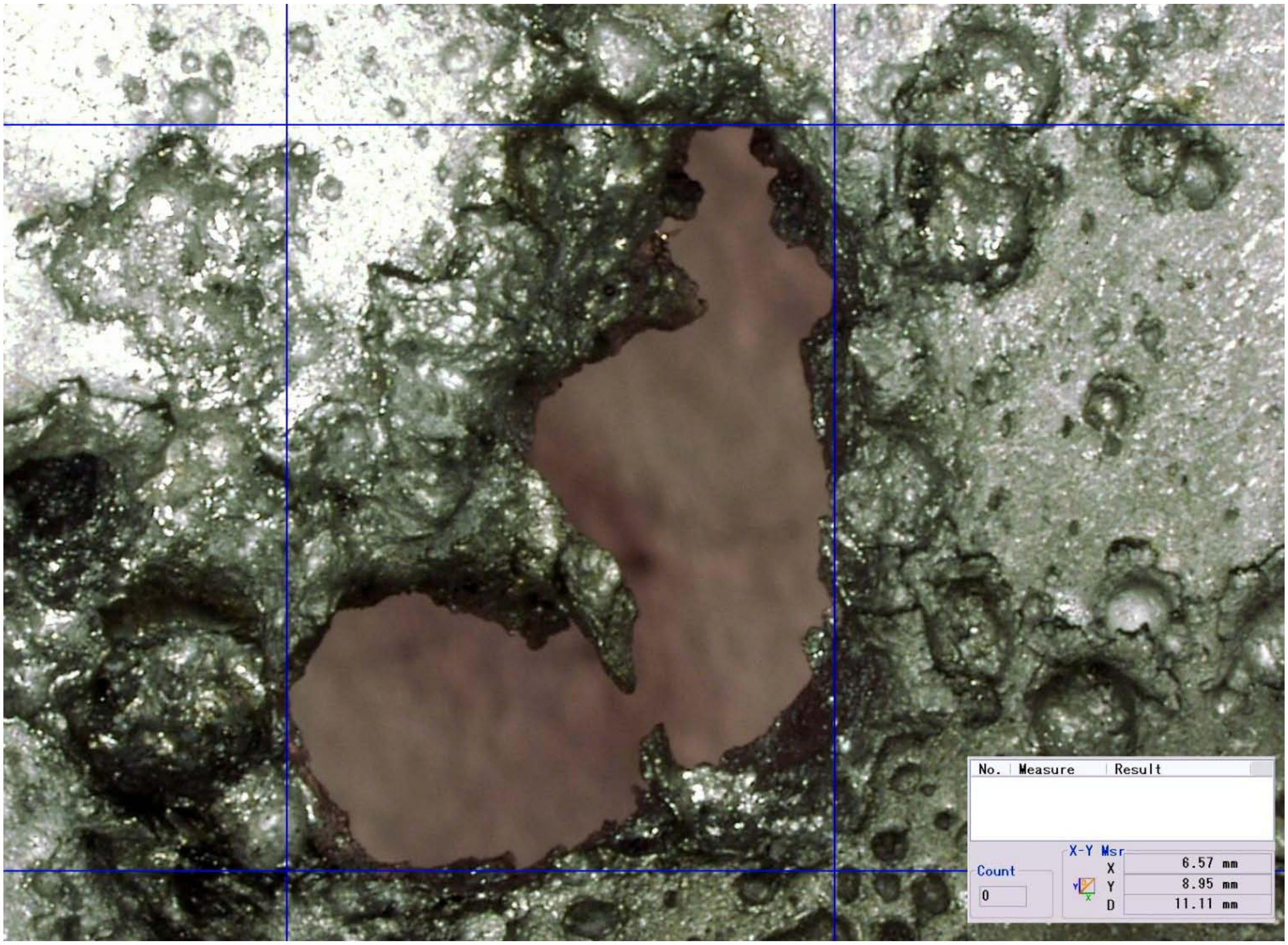


Figure 44: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #2 (Keyence 3D Microscope Image)

Test #2, HITF12258

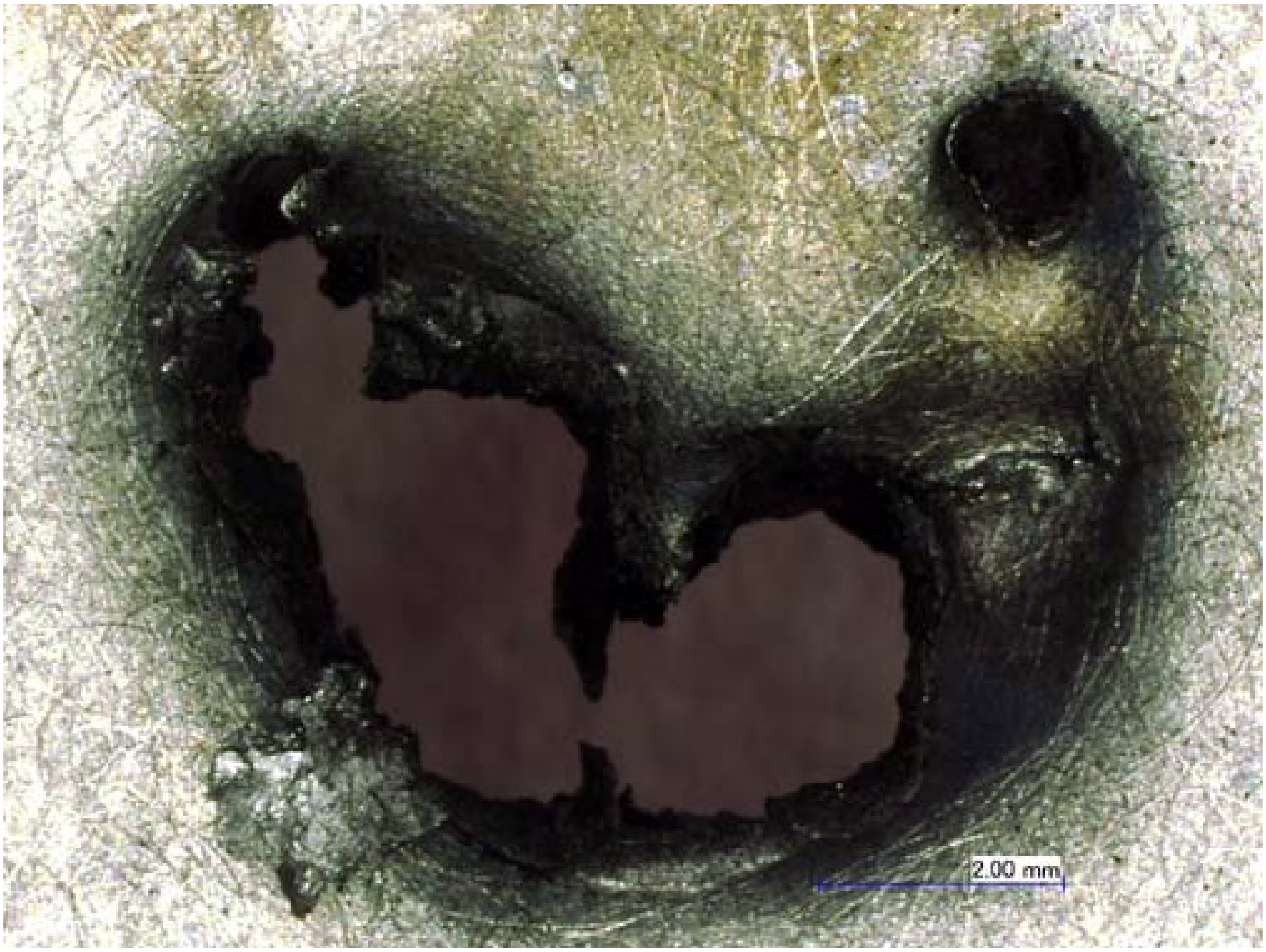


Figure 45: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #2 (Keyence 3D Microscope Image)

Test #2, HITF12258

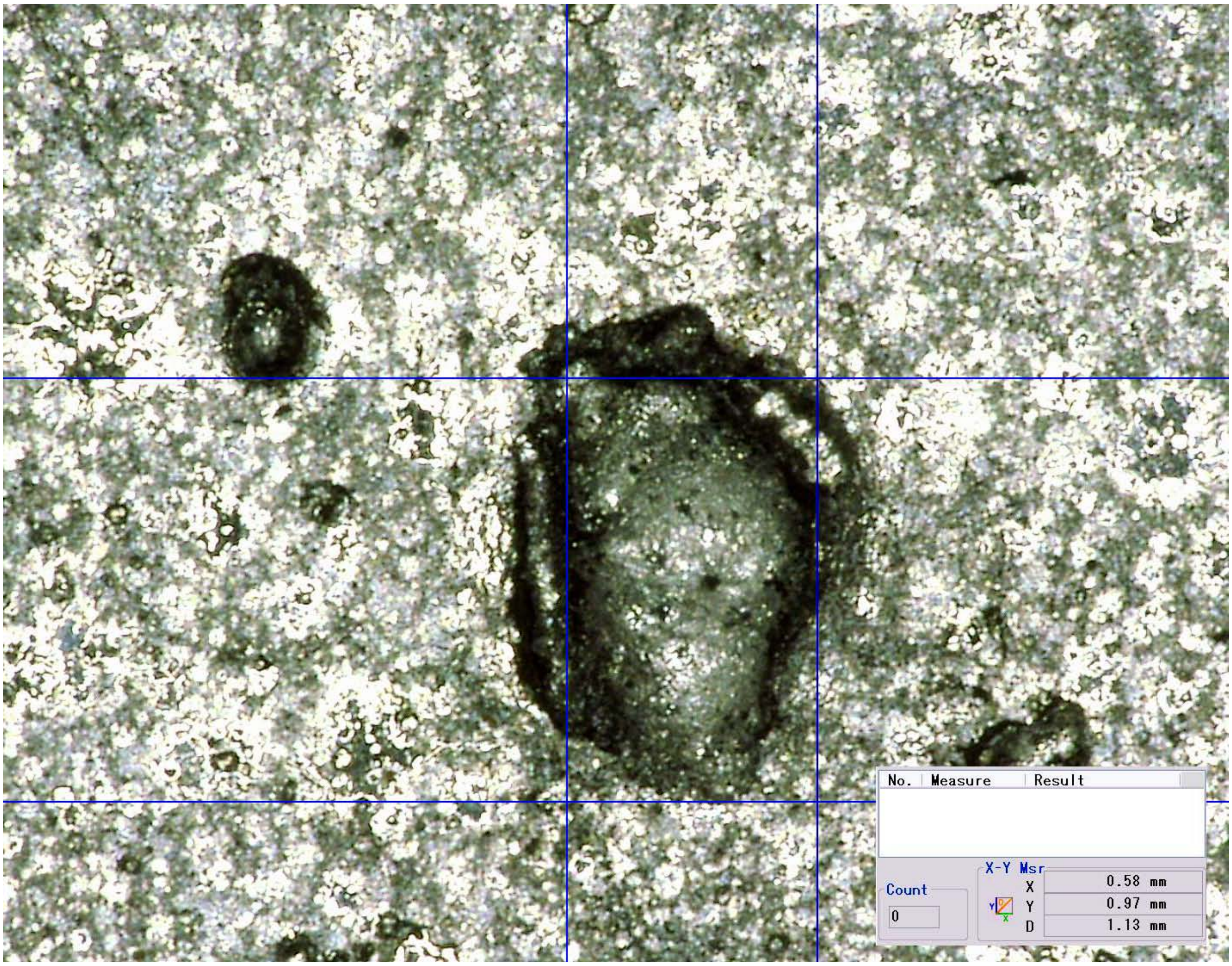


Figure 46: Witness Plate of ISS Soyuz OM Test #2
(Keyence 3D Microscope Image)

Test #2, HITF12258

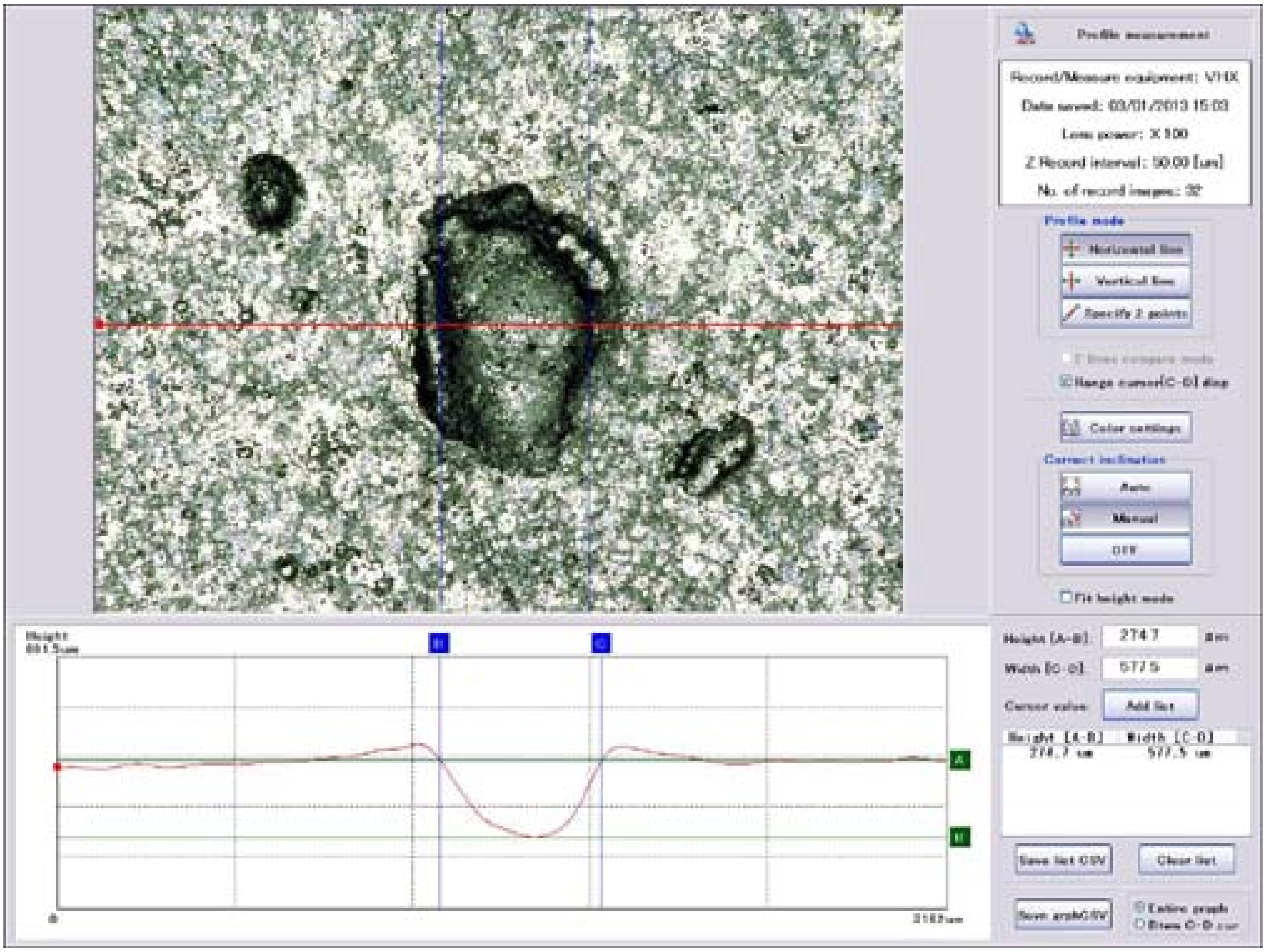


Figure 47: Witness Plate of ISS Soyuz OM Test #2 (Keyence 3D Microscope Image)

Test #2, HITF12258

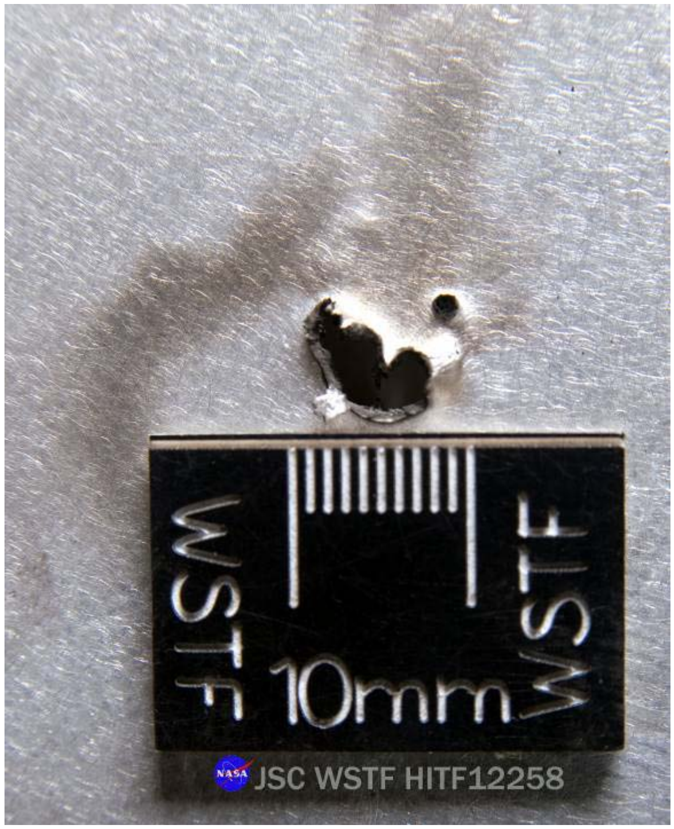


Figure 48: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #2

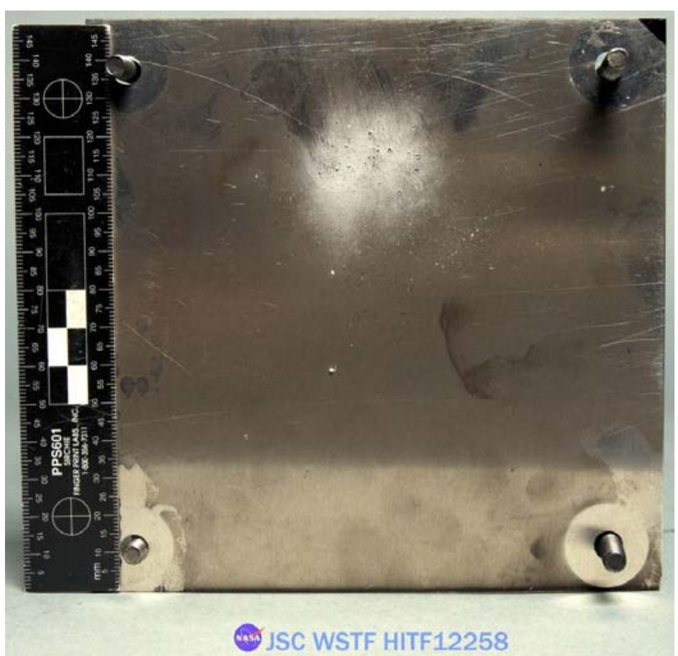


Figure 49: Front Witness Plate View of ISS Soyuz Orbital Module Test #2

Test #3, HITF12259

Figure 50: Post-test of ISS Soyuz Orbital Module Test #3 (HITF12259) article mounted in 0.50-caliber target tank.

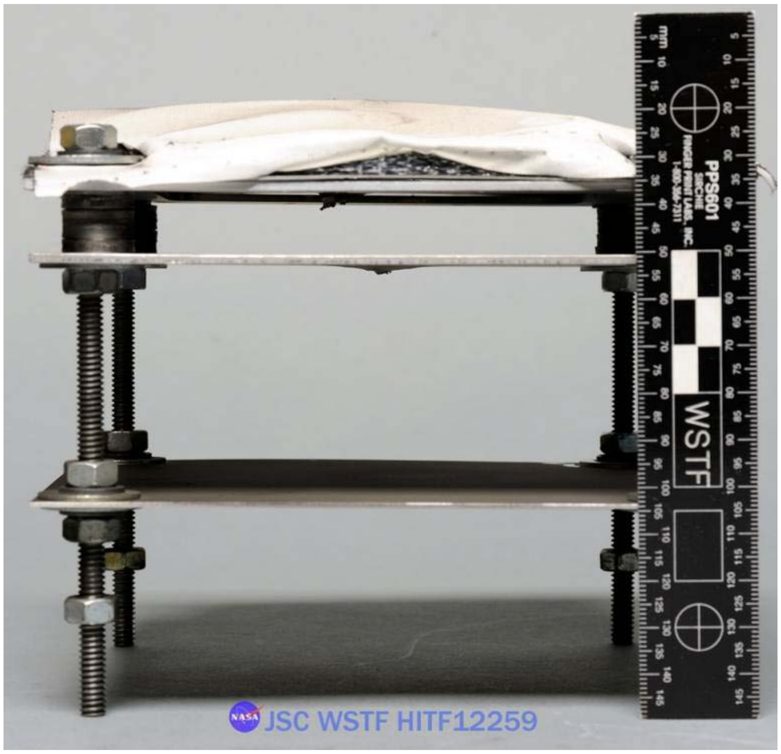


Figure 51: Side View of ISS Soyuz Orbital Module Test #3

Test #3, HITF12259

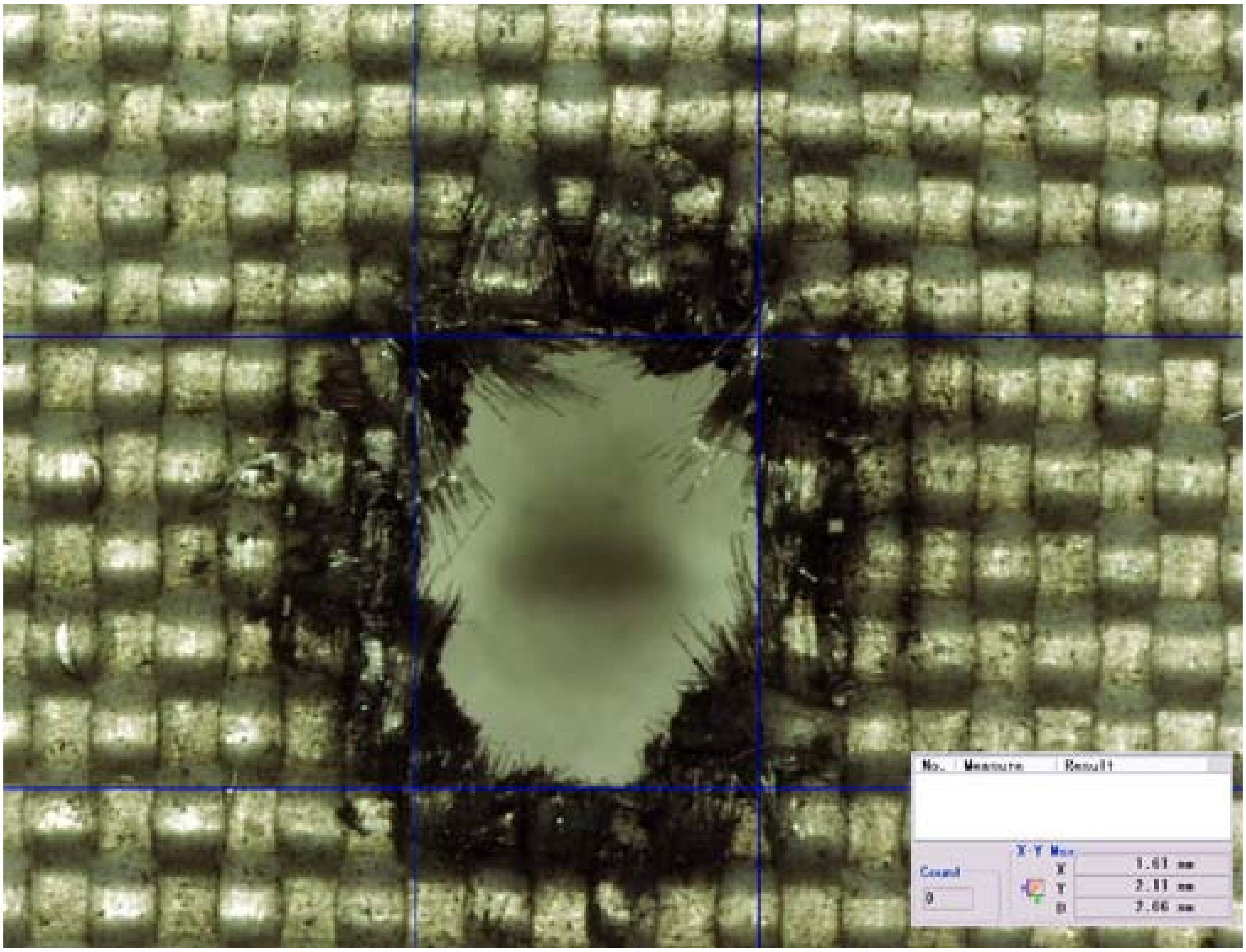


Figure 52: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #3 (Keyence 3D Microscope Image)

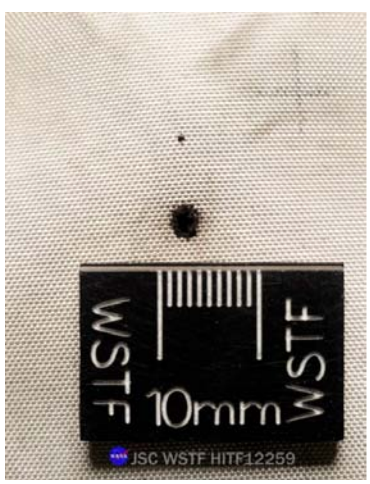


Figure 53: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #3

Test #3, HITF12259

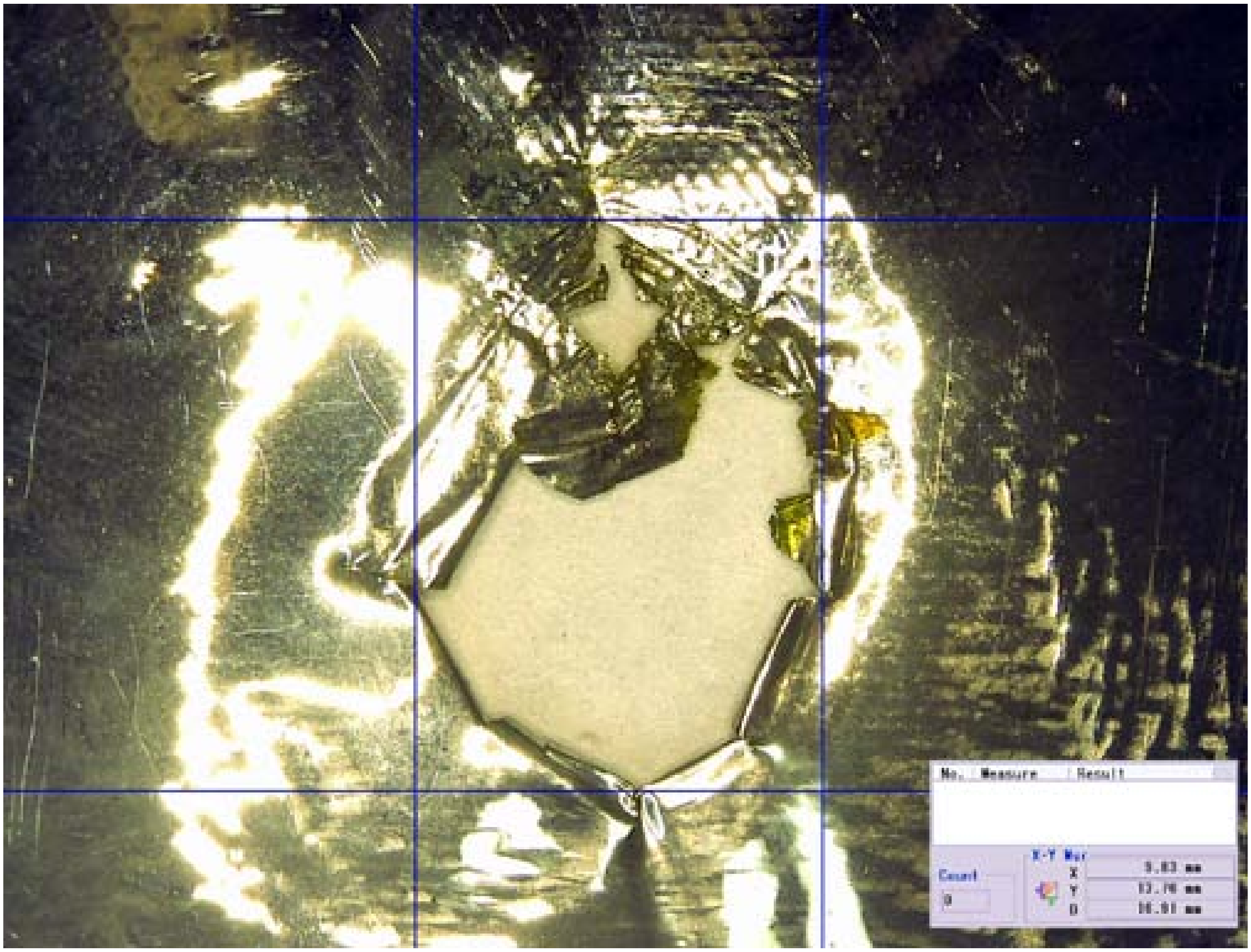


Figure 54: Mylar Film Layer 2 of ISS Soyuz OM Test #3 (Keyence 3D Microscope Image)

Test #3, HITF12259

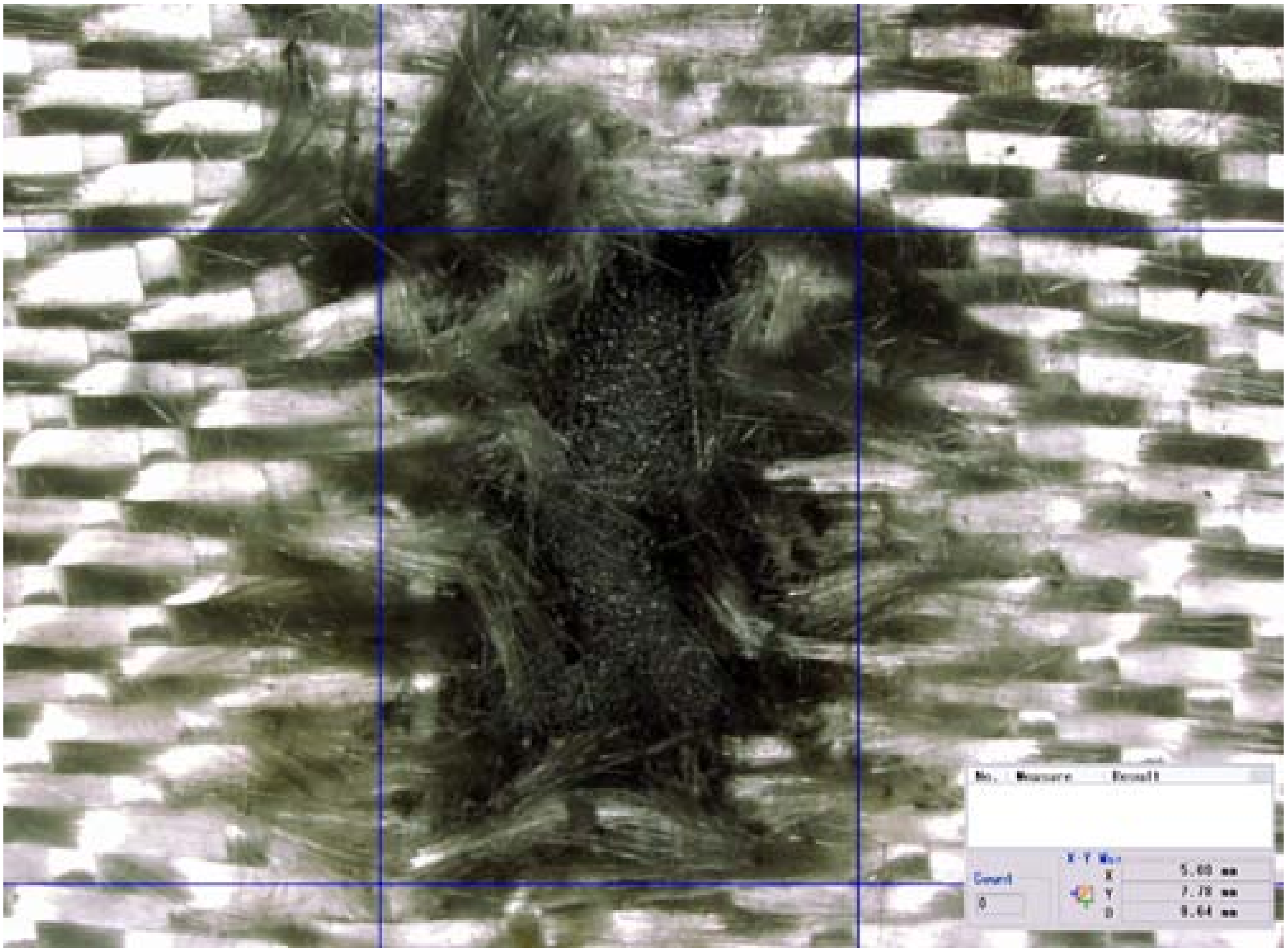


Figure 55: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #3 (Keyence 3D Microscope Image)

Test #3, HITF12259

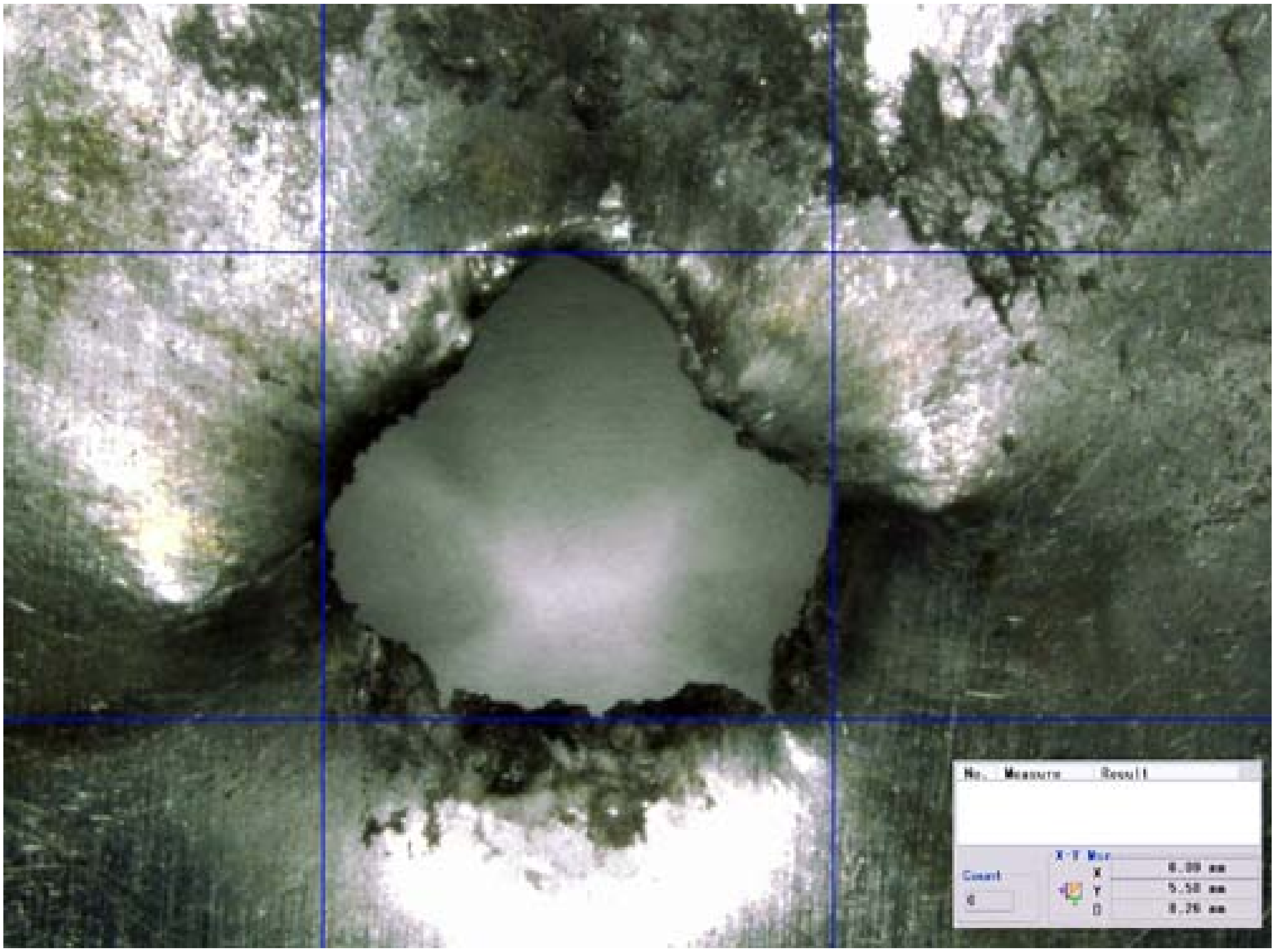


Figure 56: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #3
(Keyence 3D Microscope Image)

Test #3, HITF12259

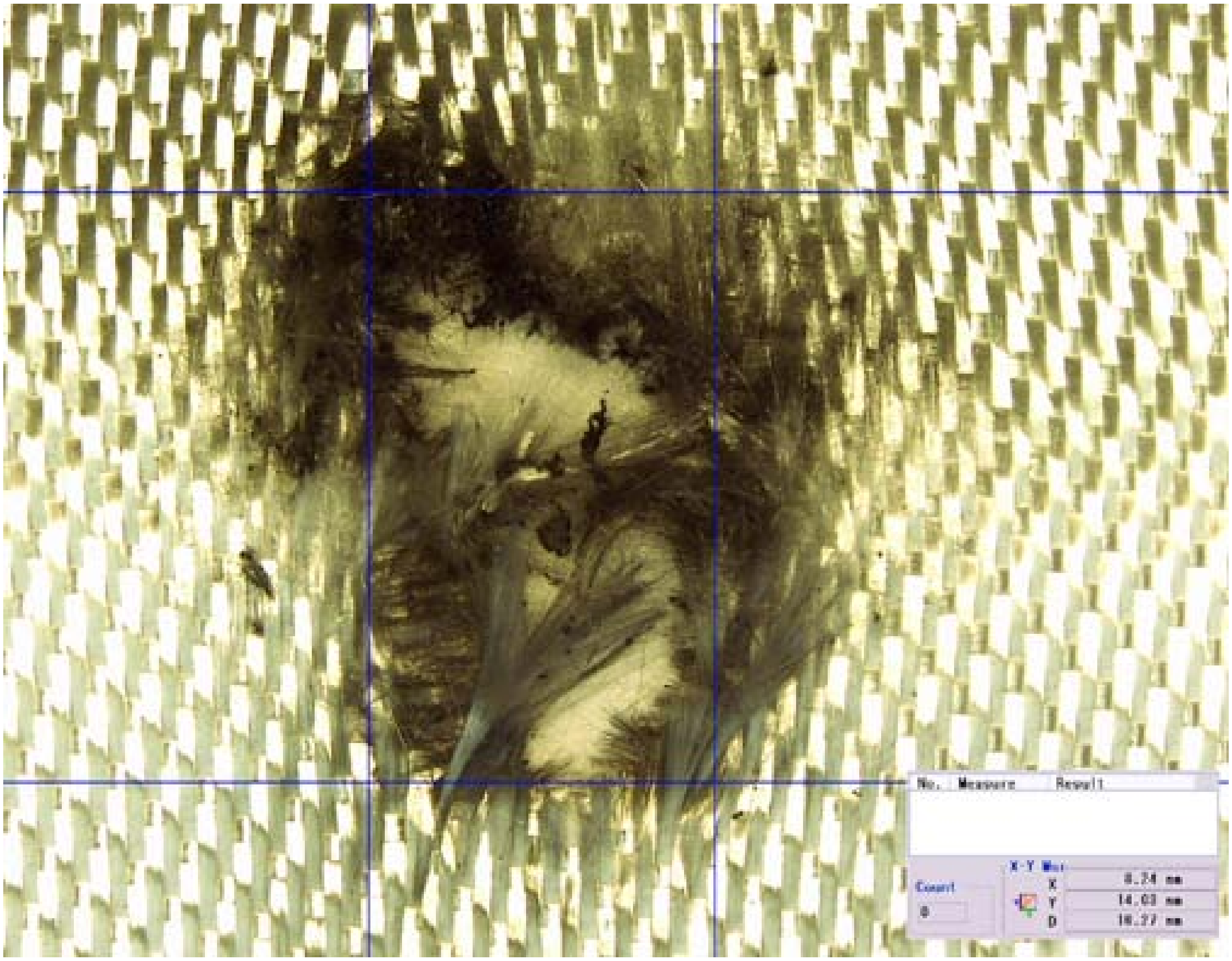


Figure 57: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #3
(Keyence 3D Microscope Image)

Test #3, HITF12259

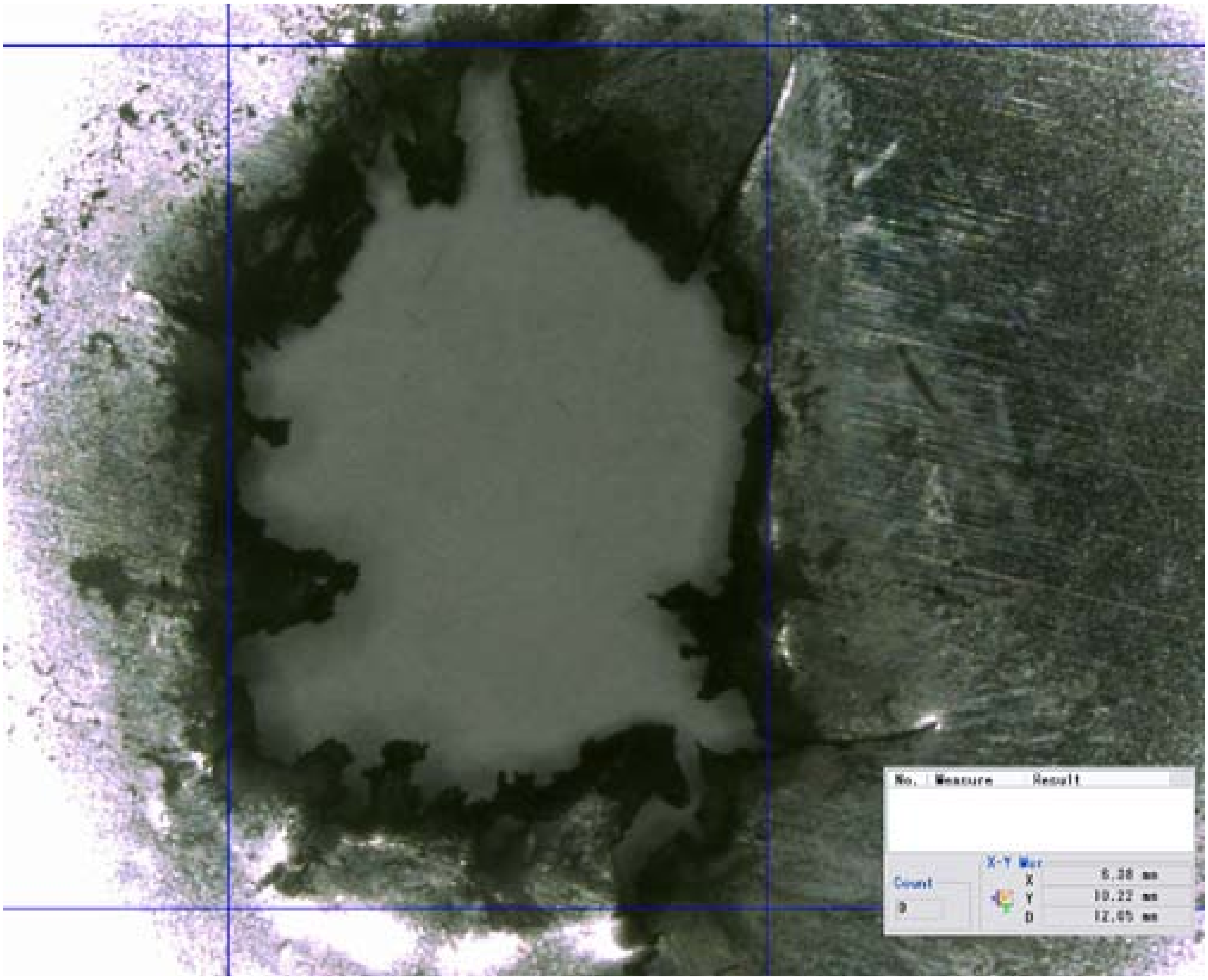


Figure 58: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #3 (Keyence 3D Microscope Image)

Test #3, HITF12259

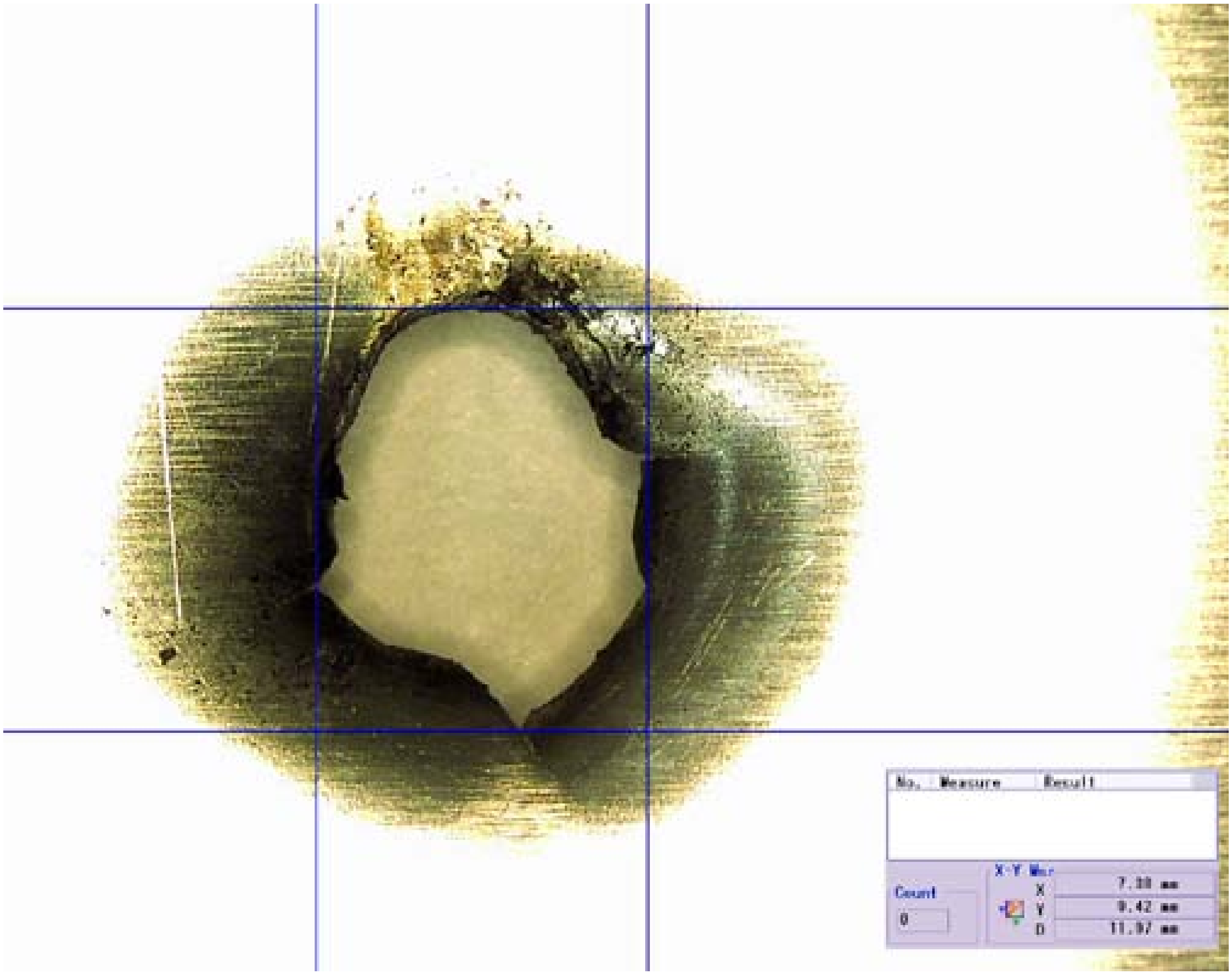


Figure 59: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #3 (Keyence 3D Microscope Image)

Test #3, HITF12259

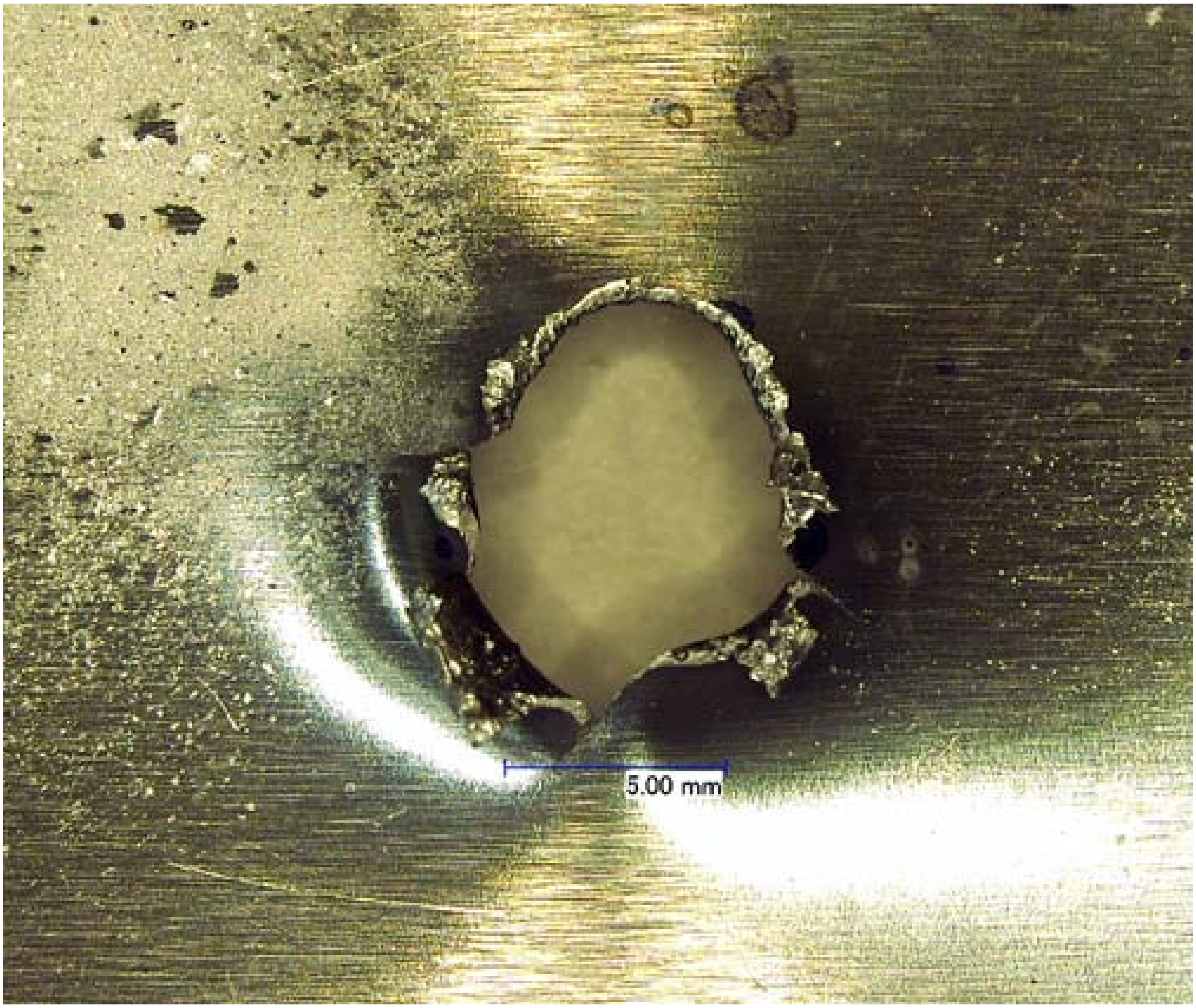


Figure 60: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #3 (Keyence 3D Microscope Image)

Test #3, HITF12259 Rear Wall

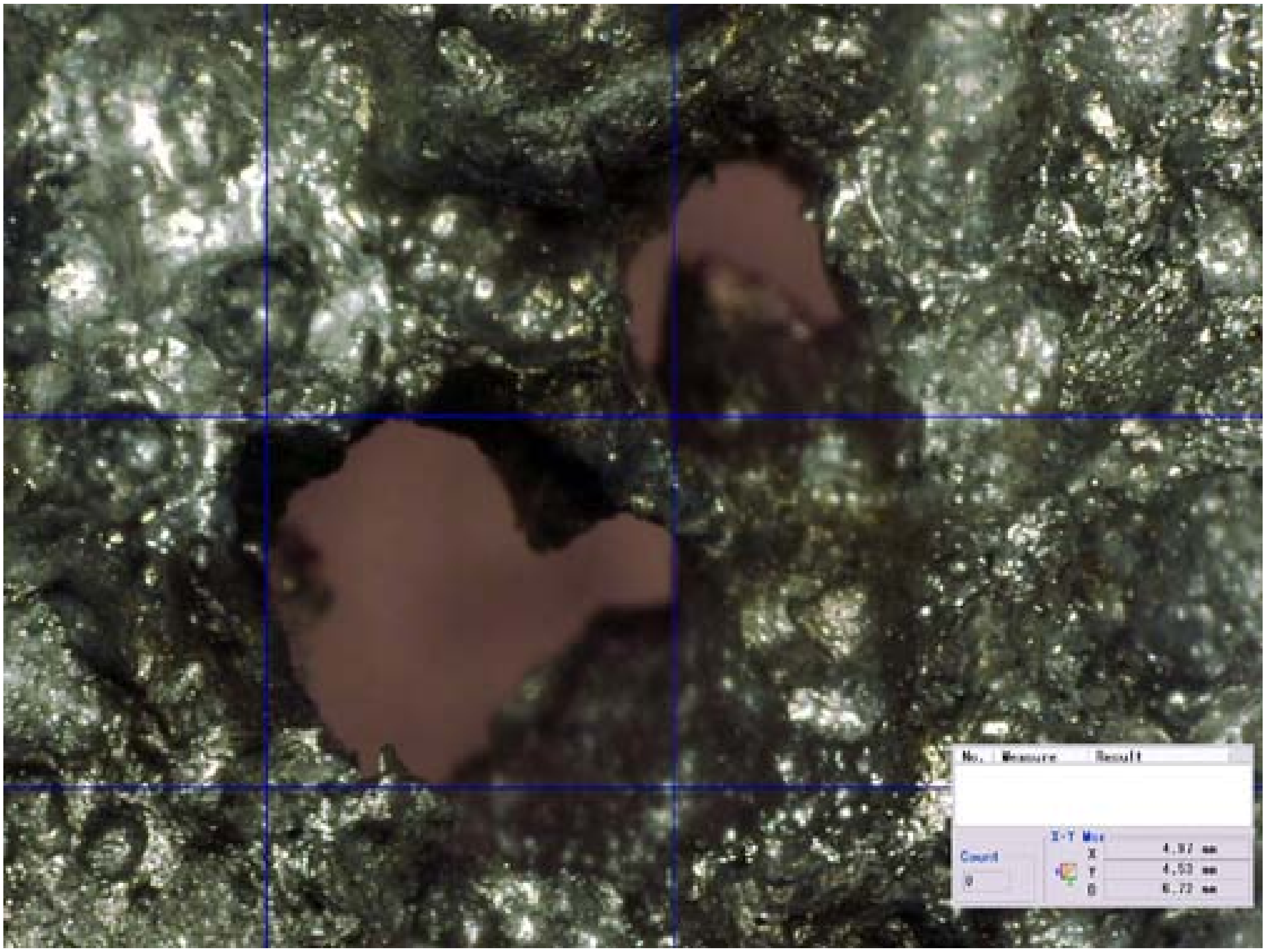


Figure 61: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #3 (Keyence 3D Microscope Image)

Test #3, HITF12259

Figure 62: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #3 (Keyence 3D Microscope Image)

Test #3, HITF12259

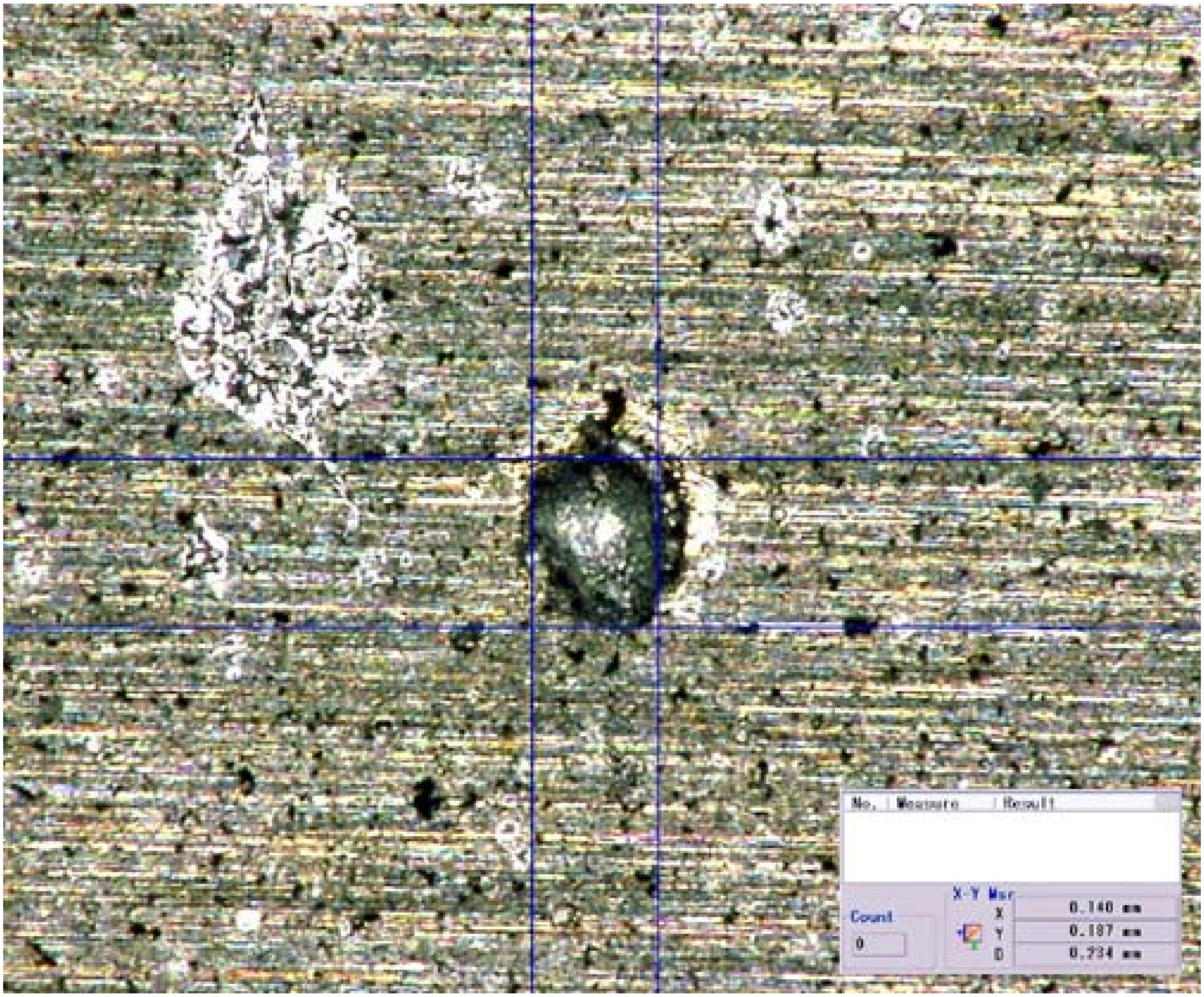


Figure 63: Witness Plate of ISS Soyuz OM Test #3 (Keyence 3D Microscope Image)

Test #3, HITF12259

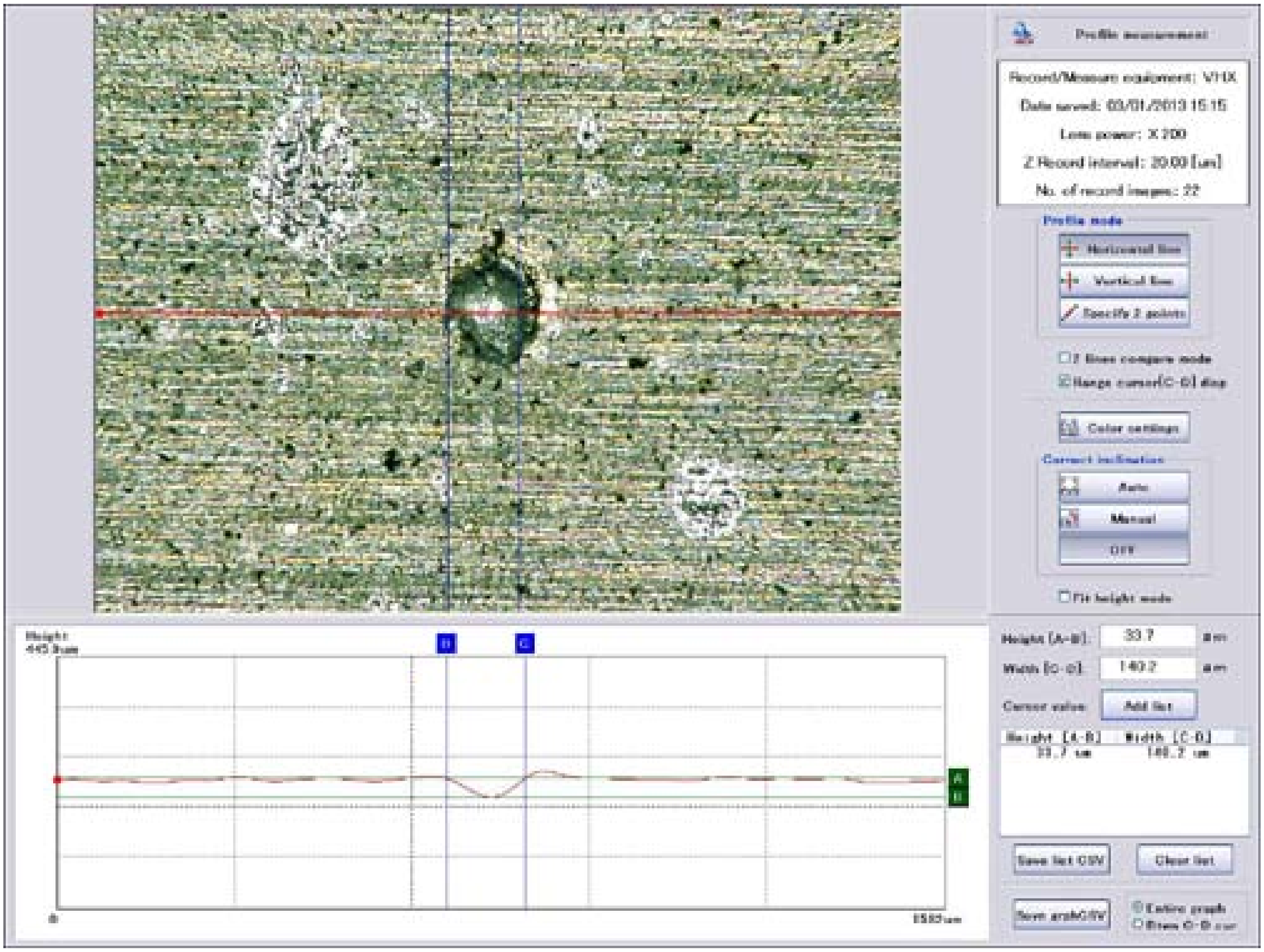


Figure 64: Witness Plate of ISS Soyuz OM Test #3 (Keyence 3D Microscope Image)

Test #3, HITF12259

Figure 65: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #3

Figure 66: Front Witness Plate View of ISS Soyuz Orbital Module Test #3

Test #4, HITF12260

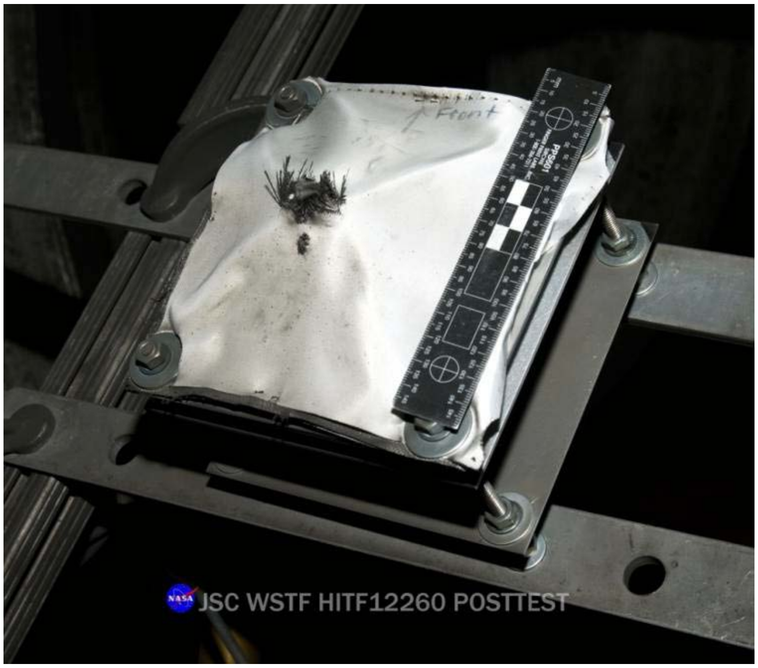


Figure 67: Post-test of ISS Soyuz Orbital Module Test #4 (HITF12260) article mounted in 0.50-caliber target tank.

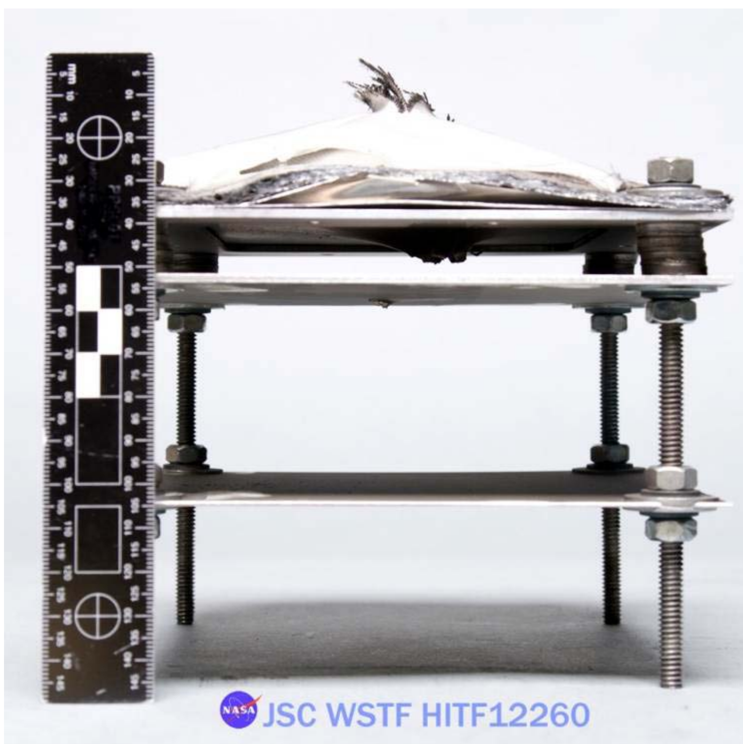


Figure 68: Side View of ISS Soyuz Orbital Module Test #4

Test #4, HITF12260

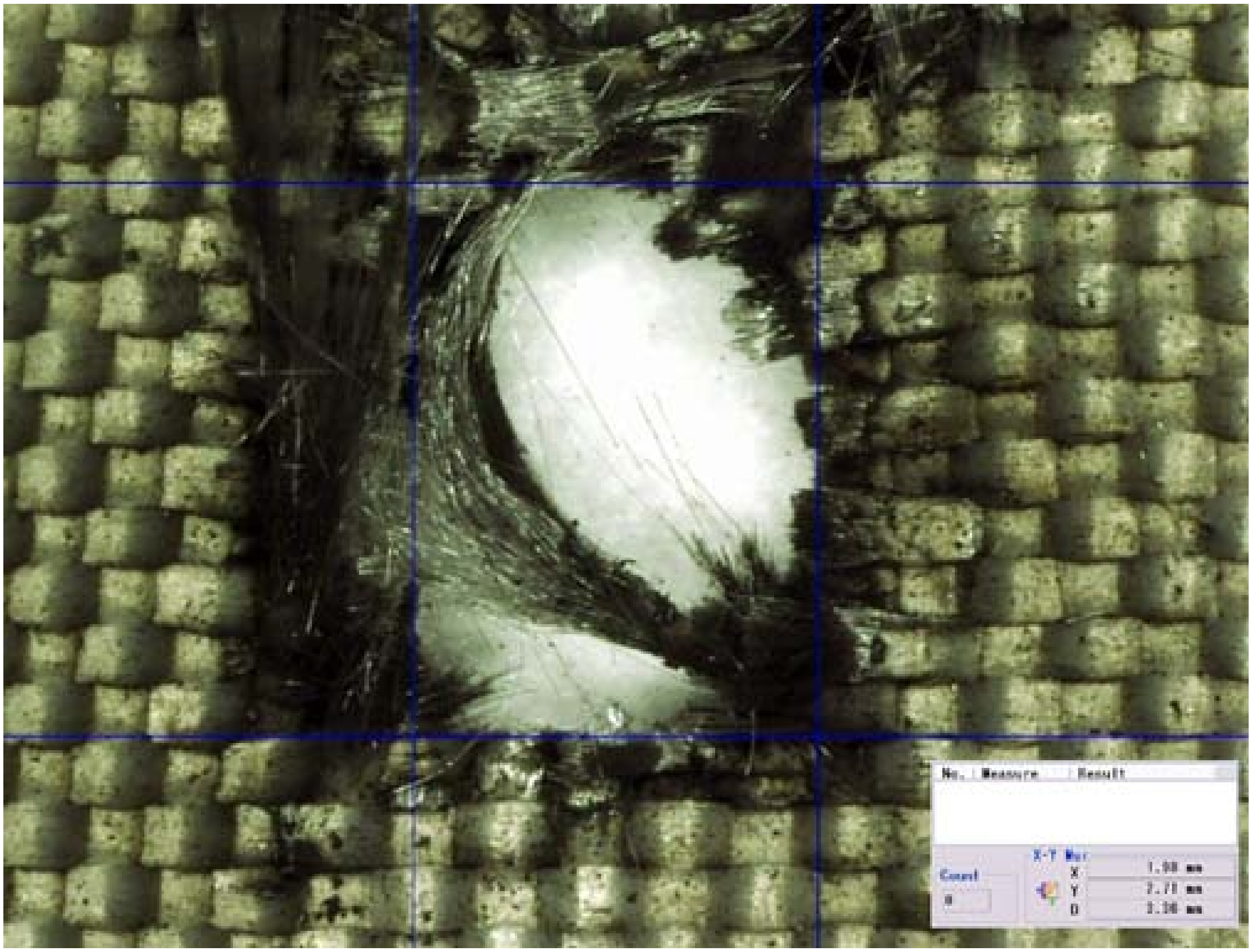


Figure 69: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #4 (Keyence 3D Microscope Image)

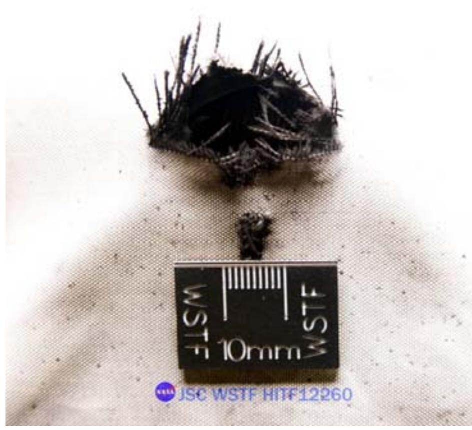


Figure 70: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #4

Test #4, HITF12260

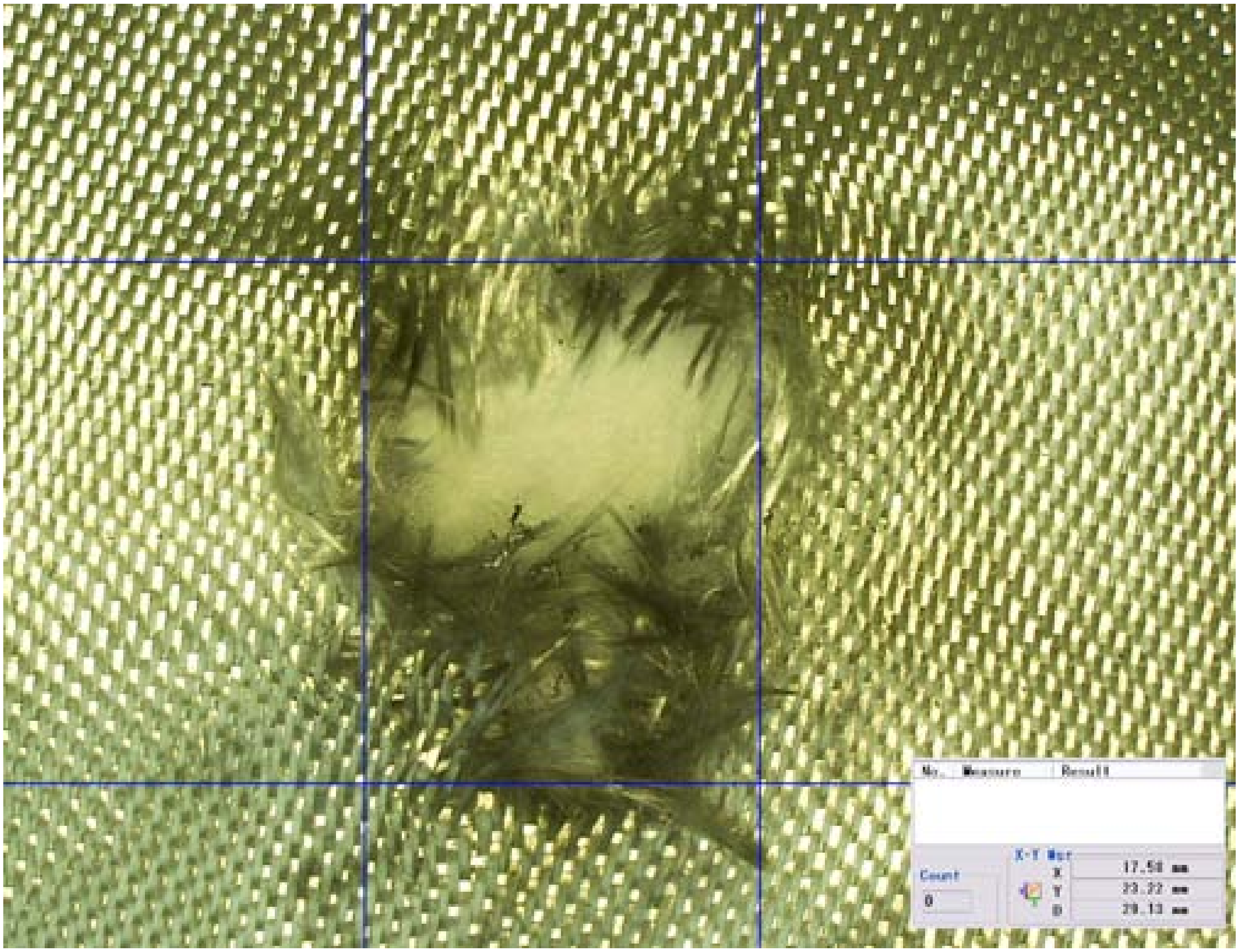


Figure 71: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #4 (Keyence 3D Microscope Image)

Test #4, HITF12260

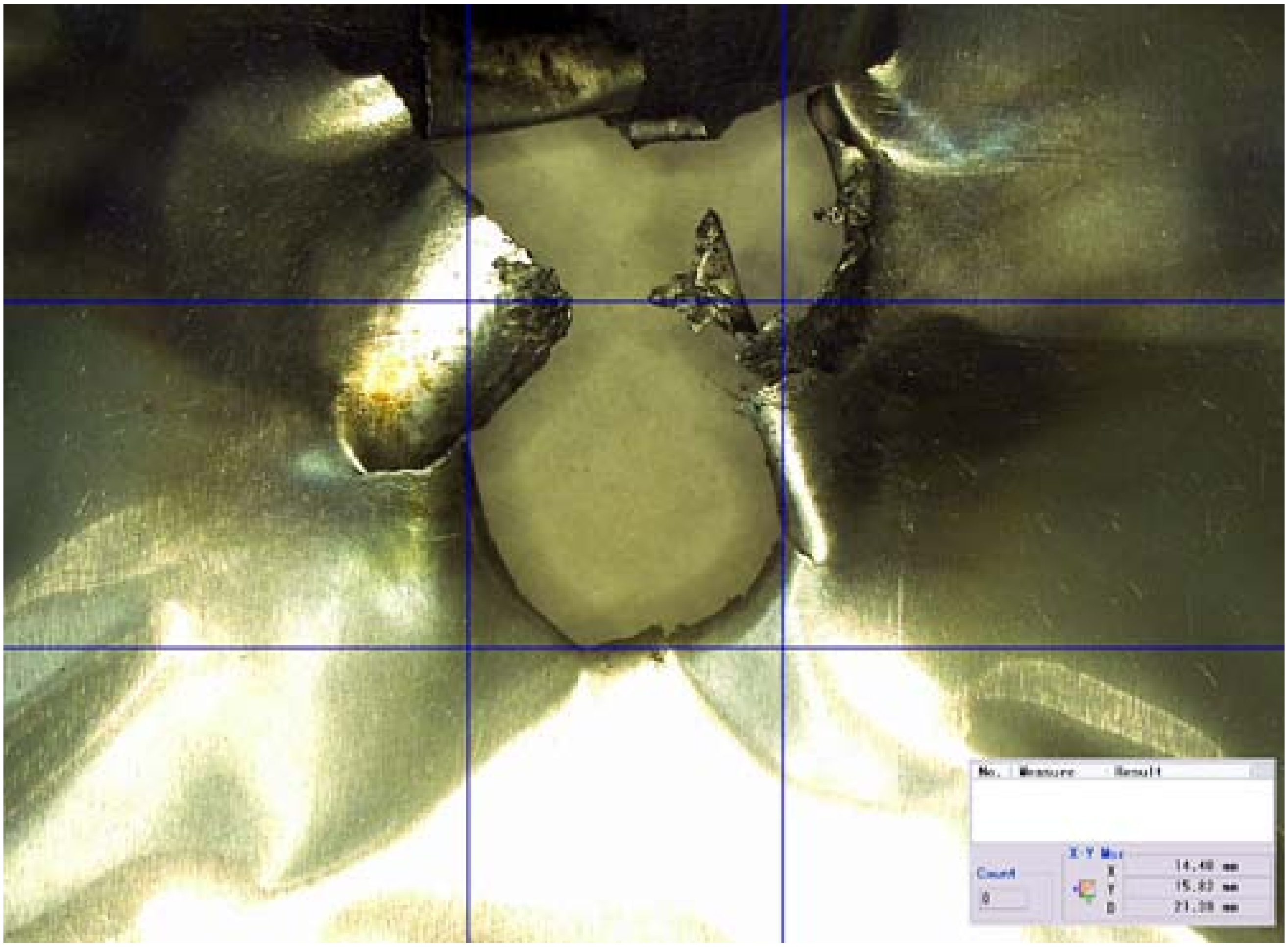


Figure 72: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #4 (Keyence 3D Microscope Image)

Test #4, HITF12260

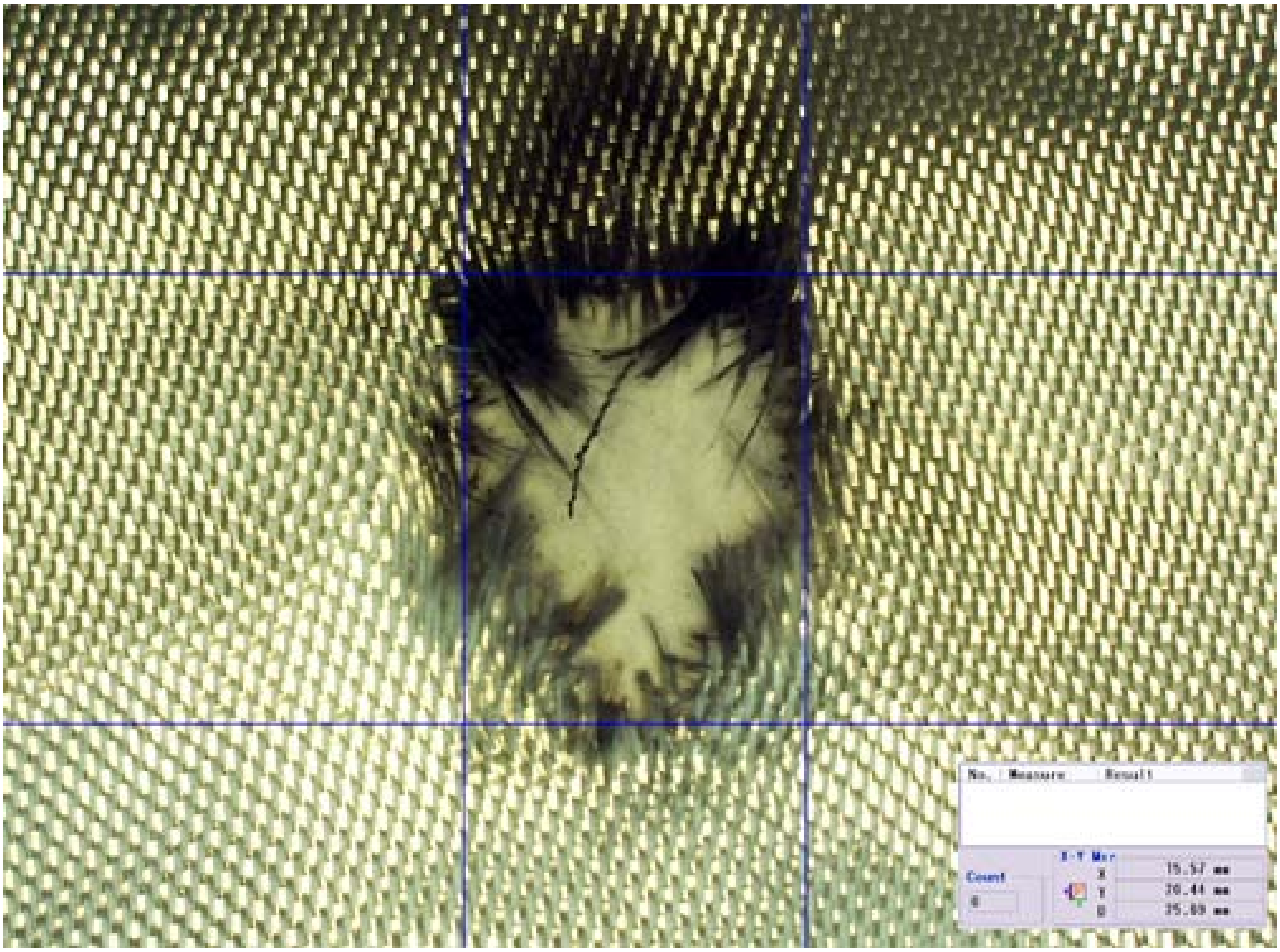


Figure 73: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #4 (Keyence 3D Microscope Image)

Test #4, HITF12260

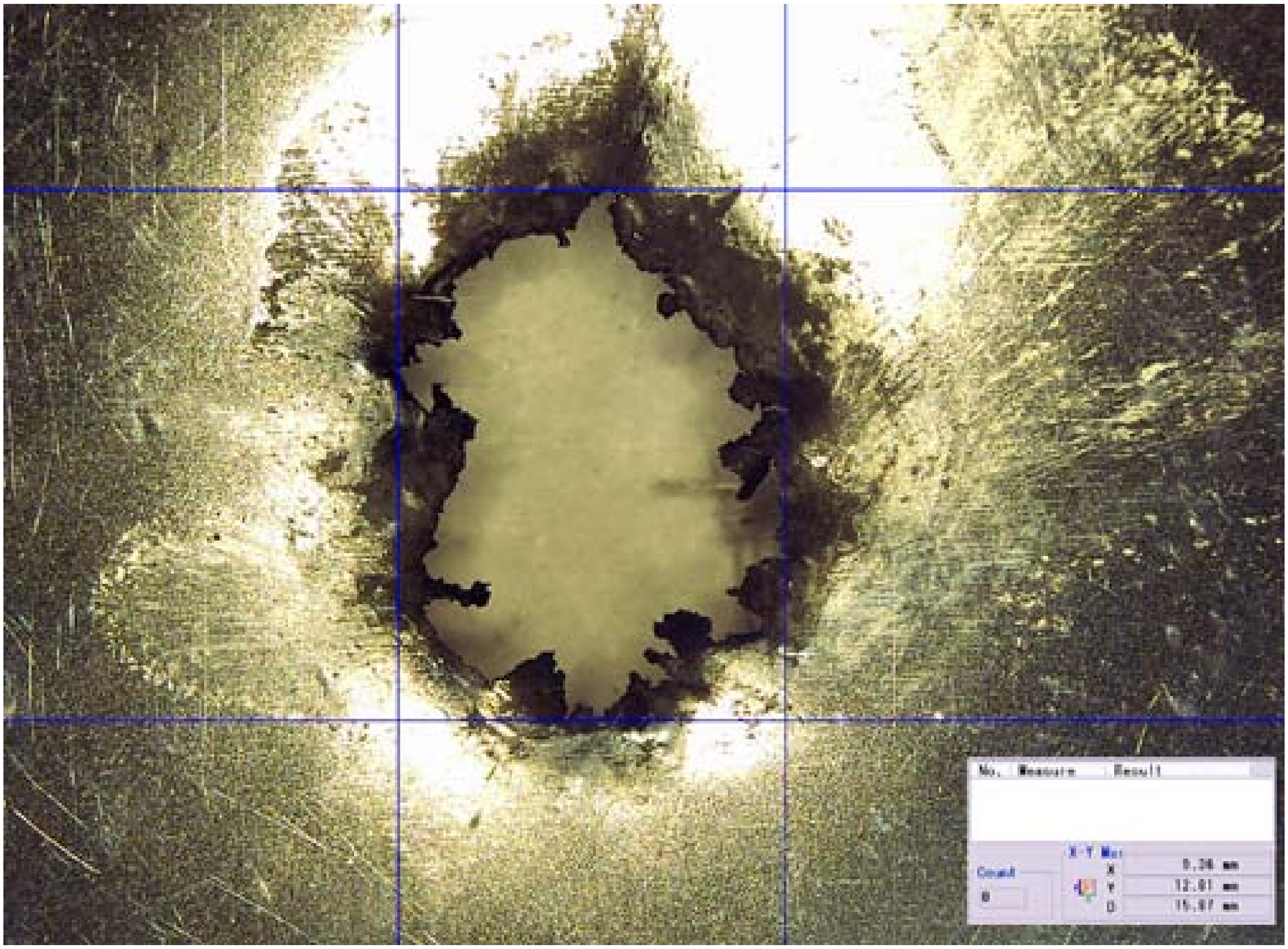


Figure 74: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #4 (Keyence 3D Microscope Image)

Test #4, HITF12260

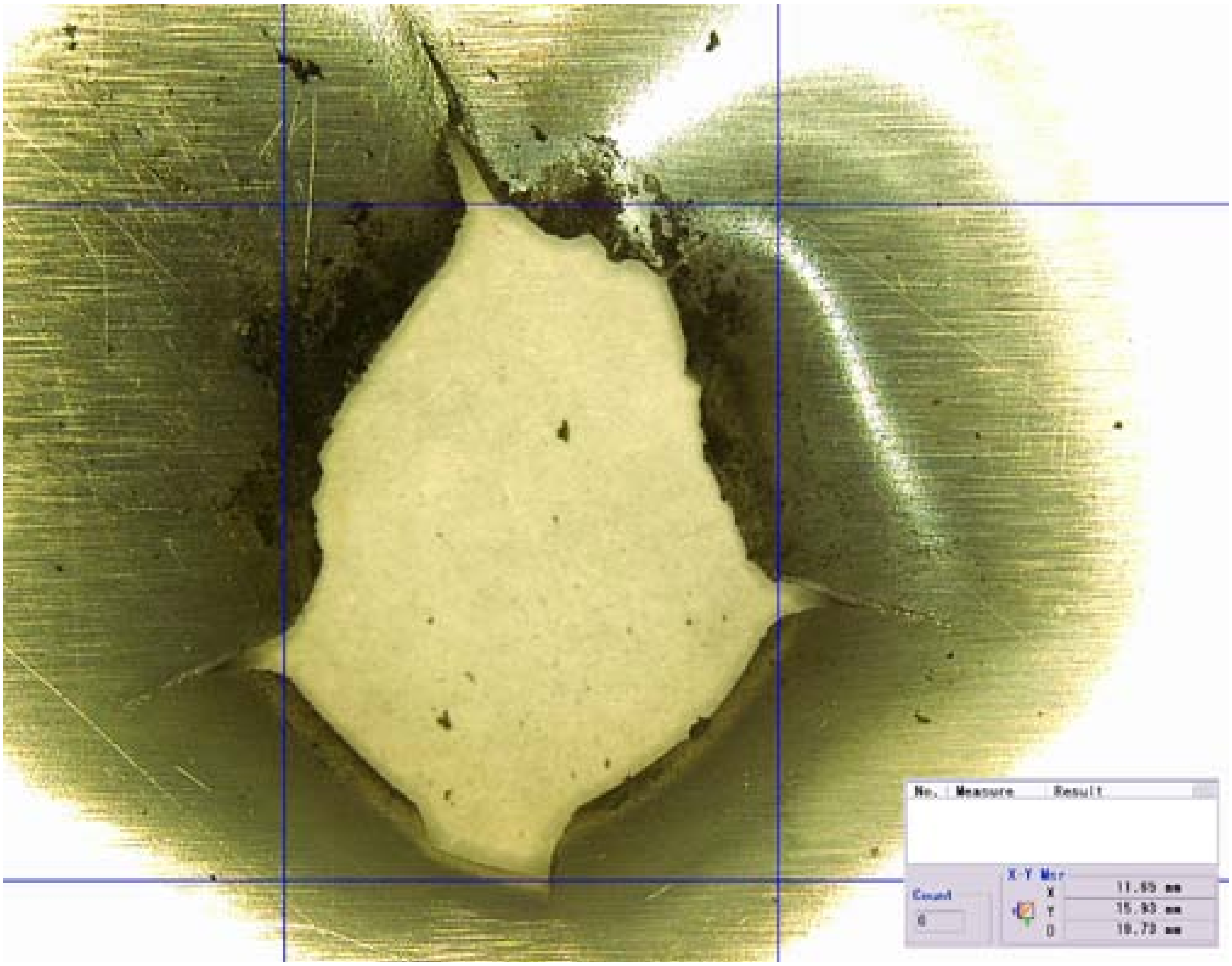


Figure 75: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #4 (Keyence 3D Microscope Image)

Test #4, HITF12260

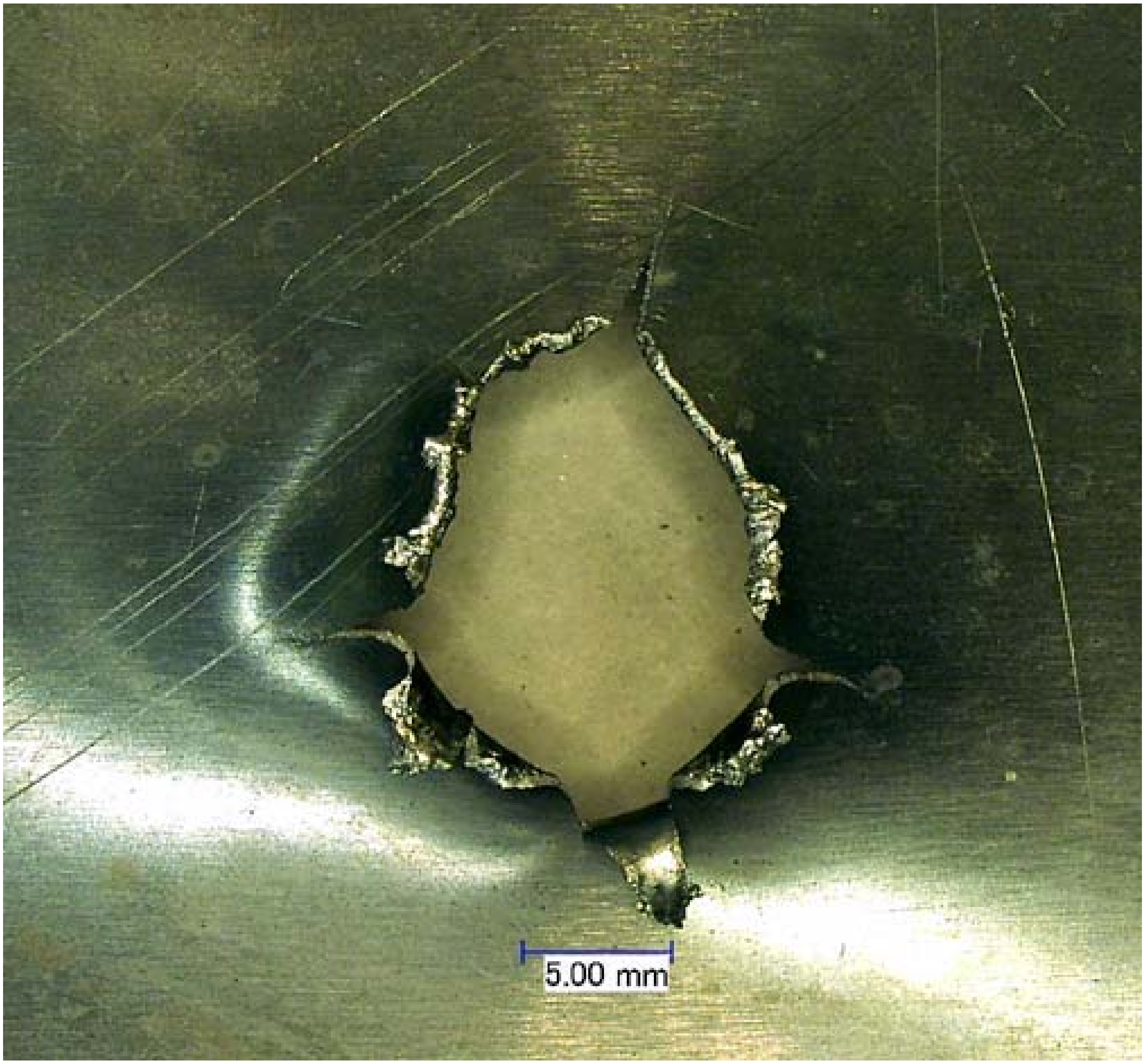


Figure 76: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #4 (Keyence 3D Microscope Image)

Test #4, HITF12260 Rear Wall

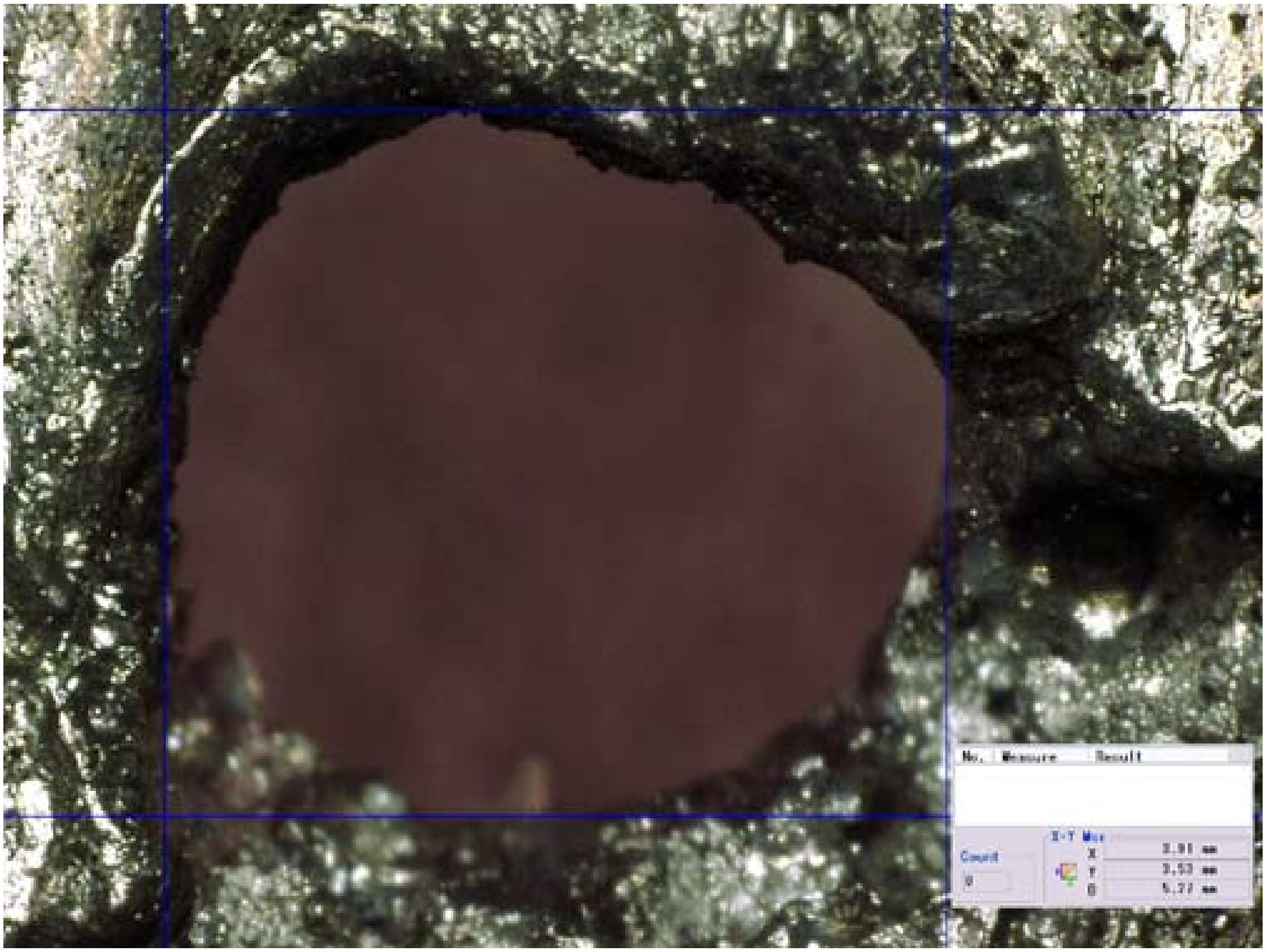


Figure 77: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #4 (Keyence 3D Microscope Image)

Test #4, HITF12260

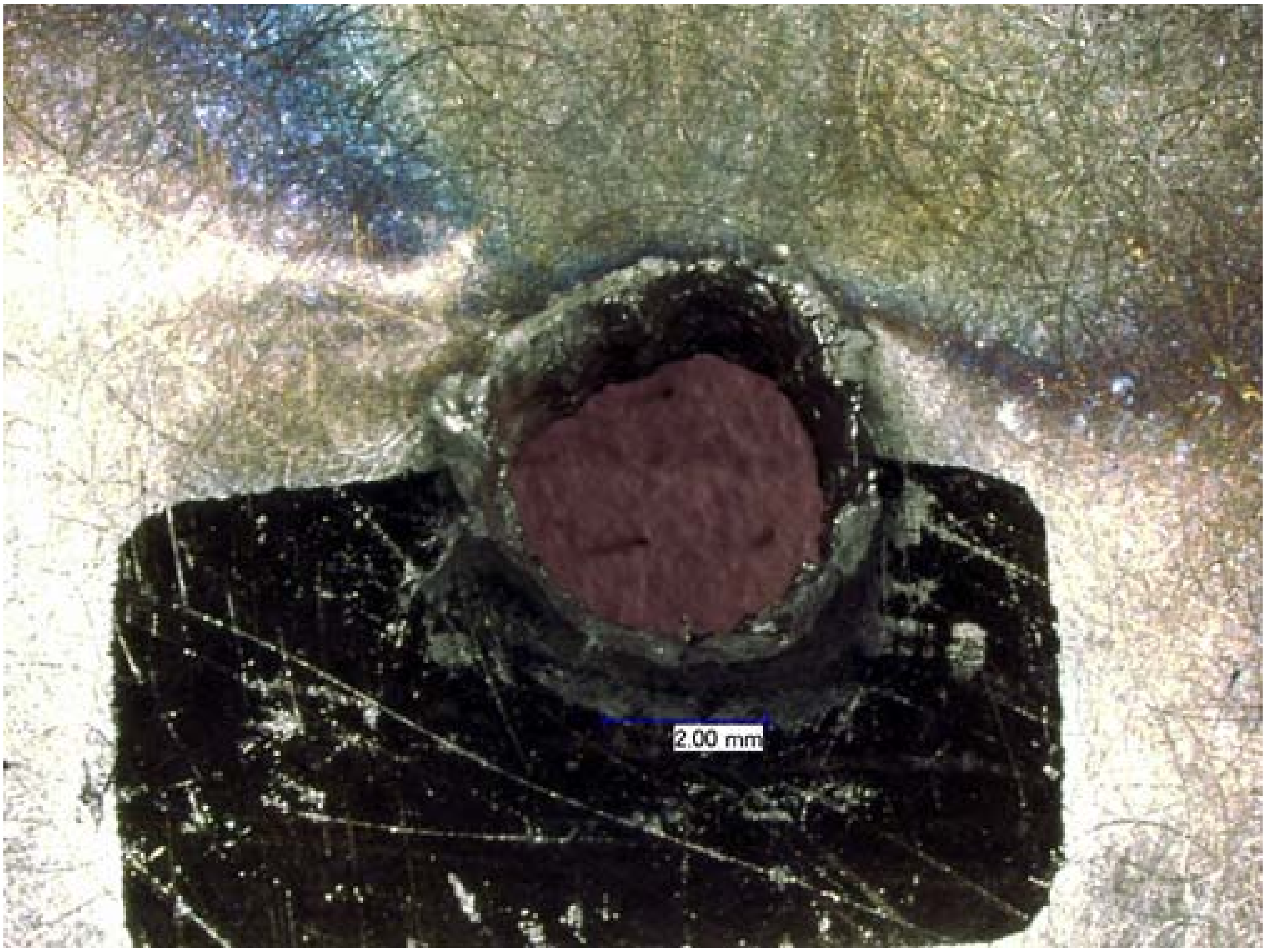


Figure 78: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #4 (Keyence 3D Microscope Image)

Test #4, HITF12260

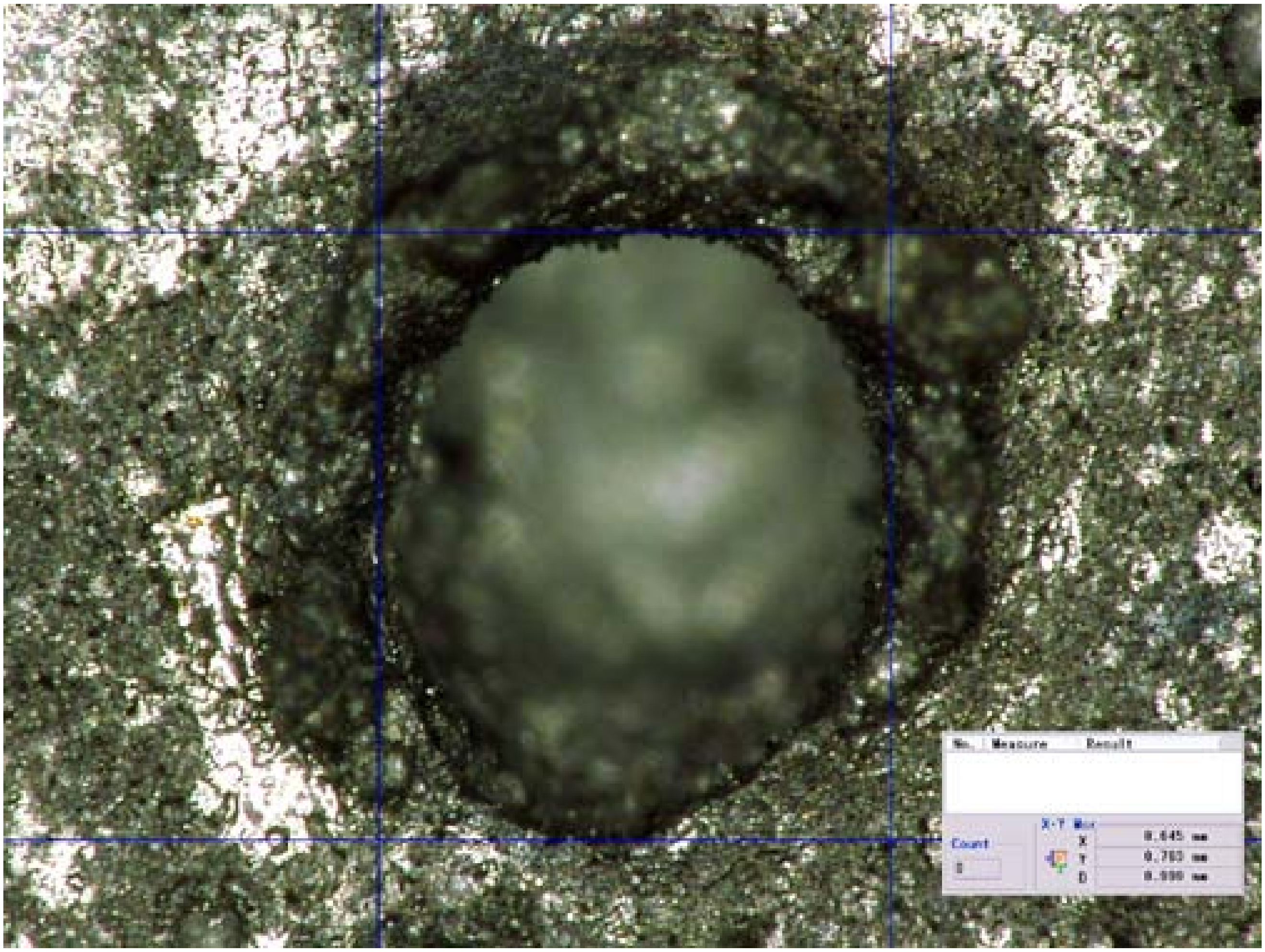


Figure 79: Witness Plate of ISS Soyuz OM Test #4
(Keyence 3D Microscope Image)

Test #4, HITF12260

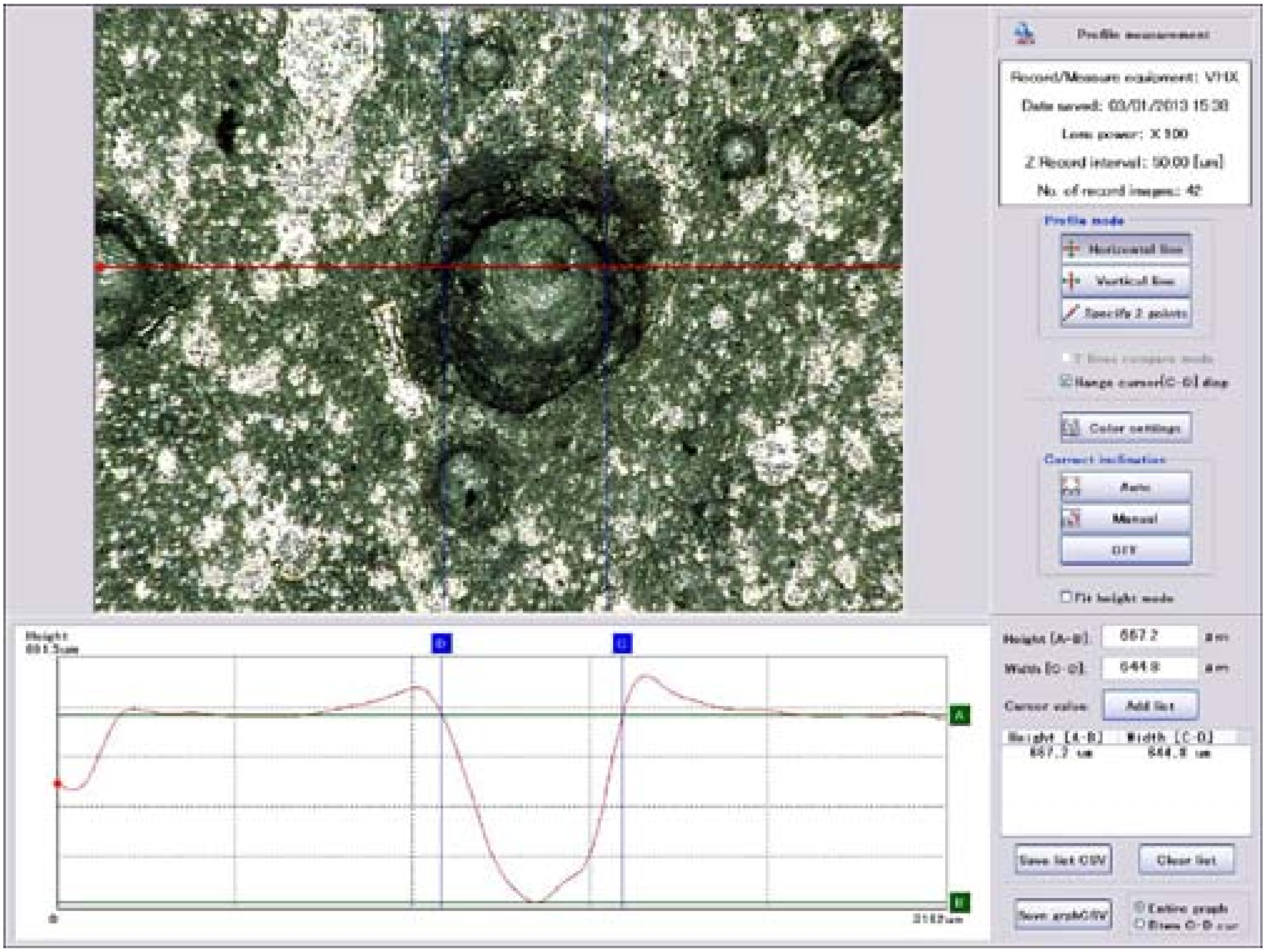


Figure 80: Witness Plate of ISS Soyuz OM Test #4 (Keyence 3D Microscope Image)

Test #4, HITF12260

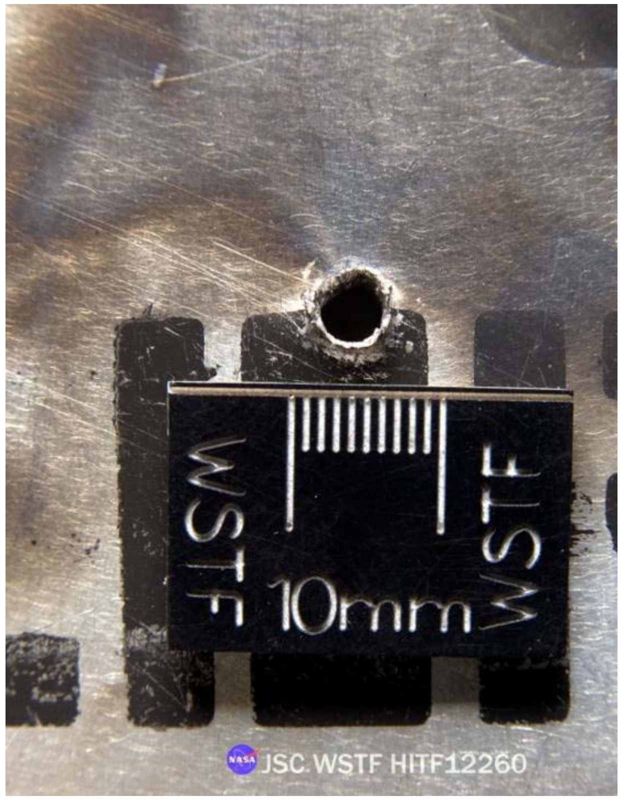


Figure 81: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #4

Figure 82: Front Witness Plate View of ISS Soyuz Orbital Module Test #4

Test #5, HITF12261

Figure 83: Post-test of ISS Soyuz Orbital Module Test #5 (HITF12261) article mounted in 0.17-caliber target tank.

Figure 84: Side View of ISS Soyuz Orbital Module Test #5

Test #5, HITF12261

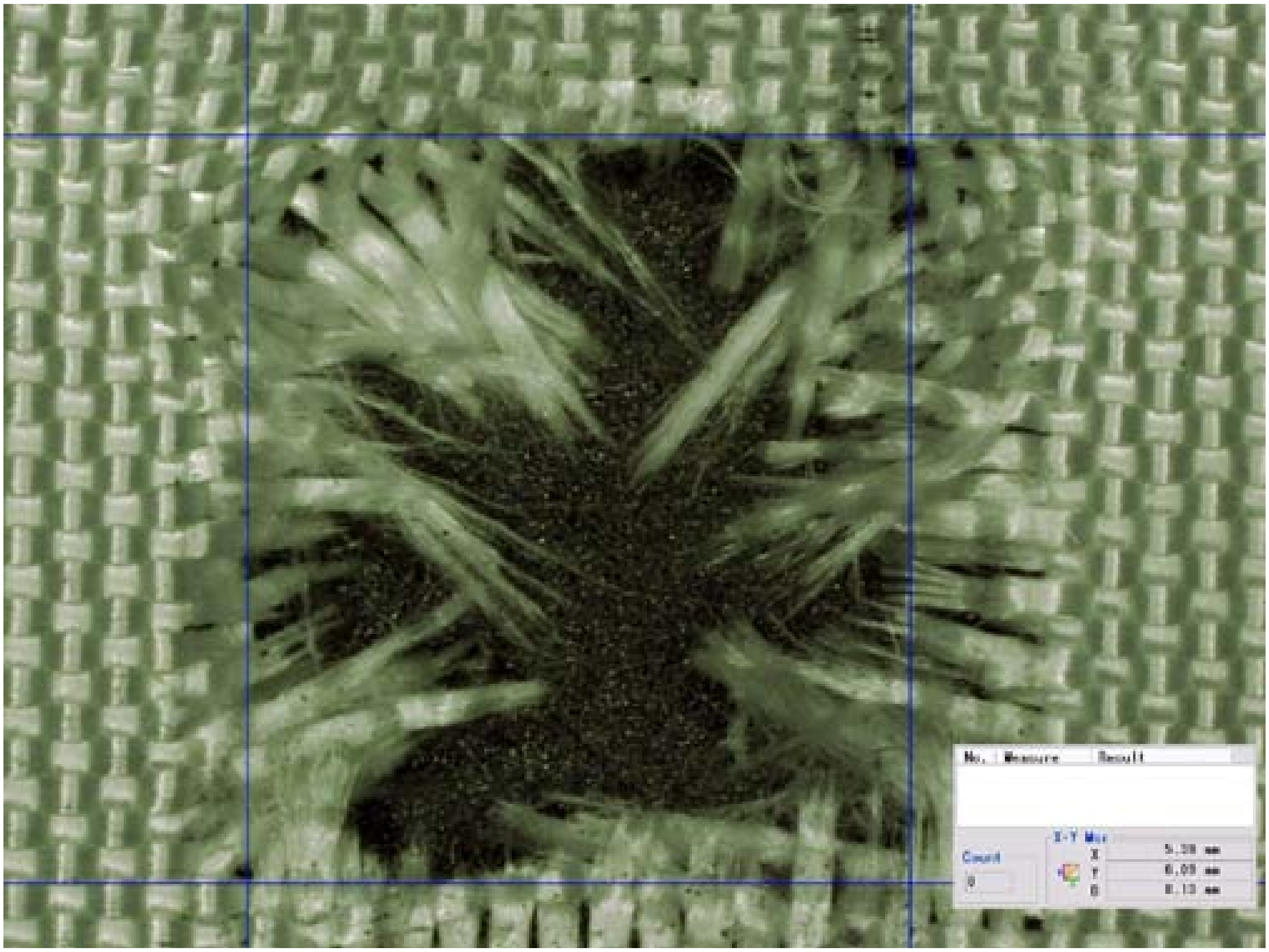


Figure 85: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #5 (Keyence 3D Microscope Image)

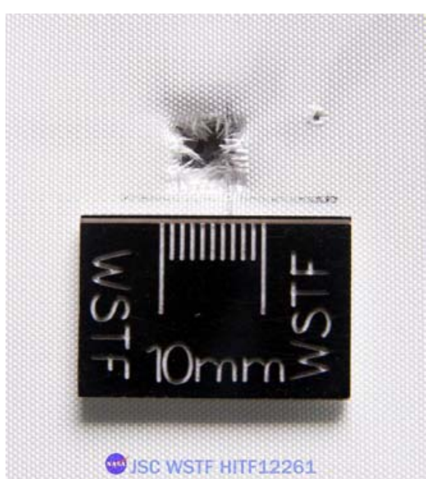


Figure 86: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #5

Test #5, HITF12261

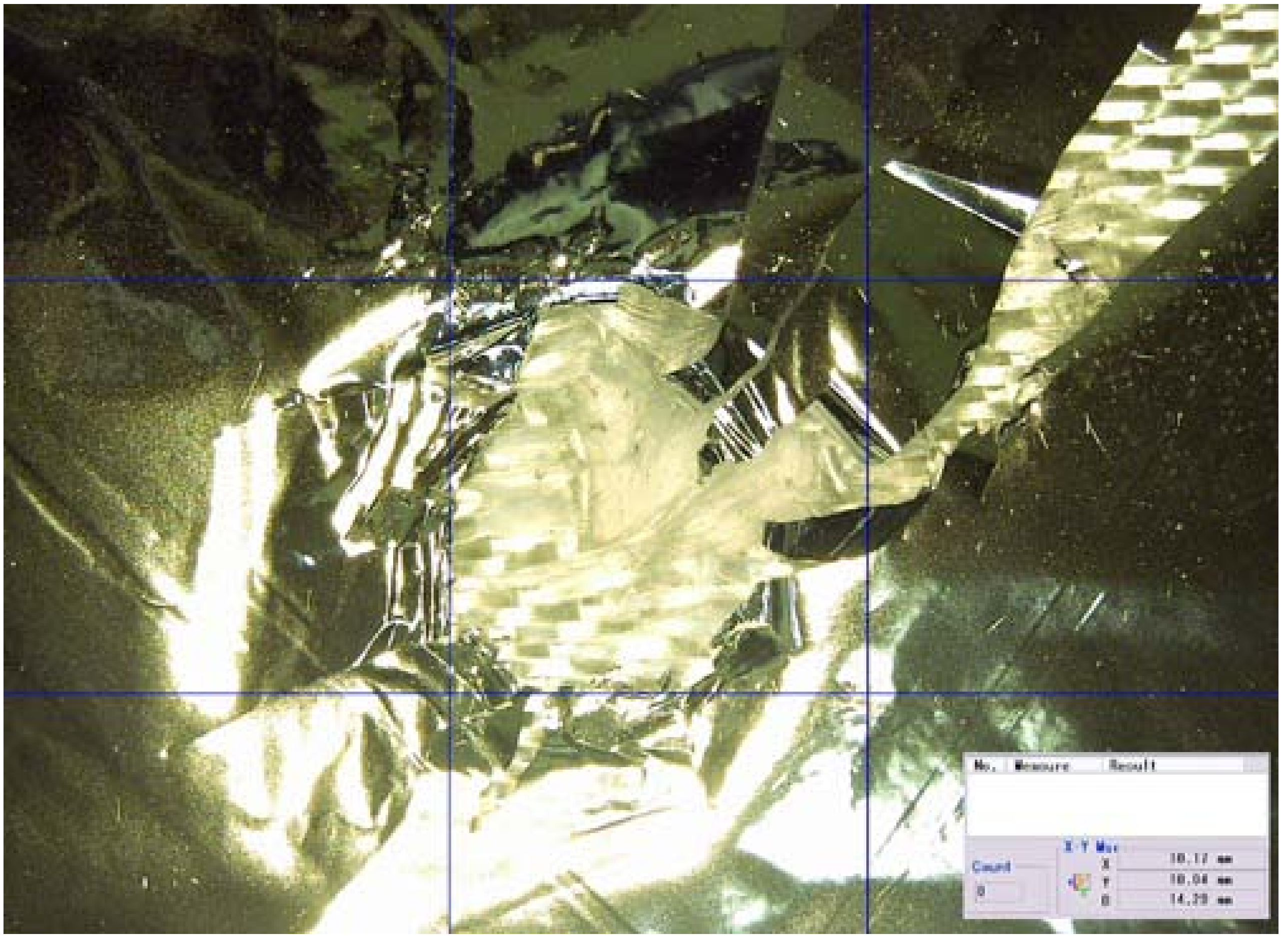


Figure 87: Mylar Film Layer 2 of ISS Soyuz OM Test #5
(Keyence 3D Microscope Image)

Test #5, HITF12261

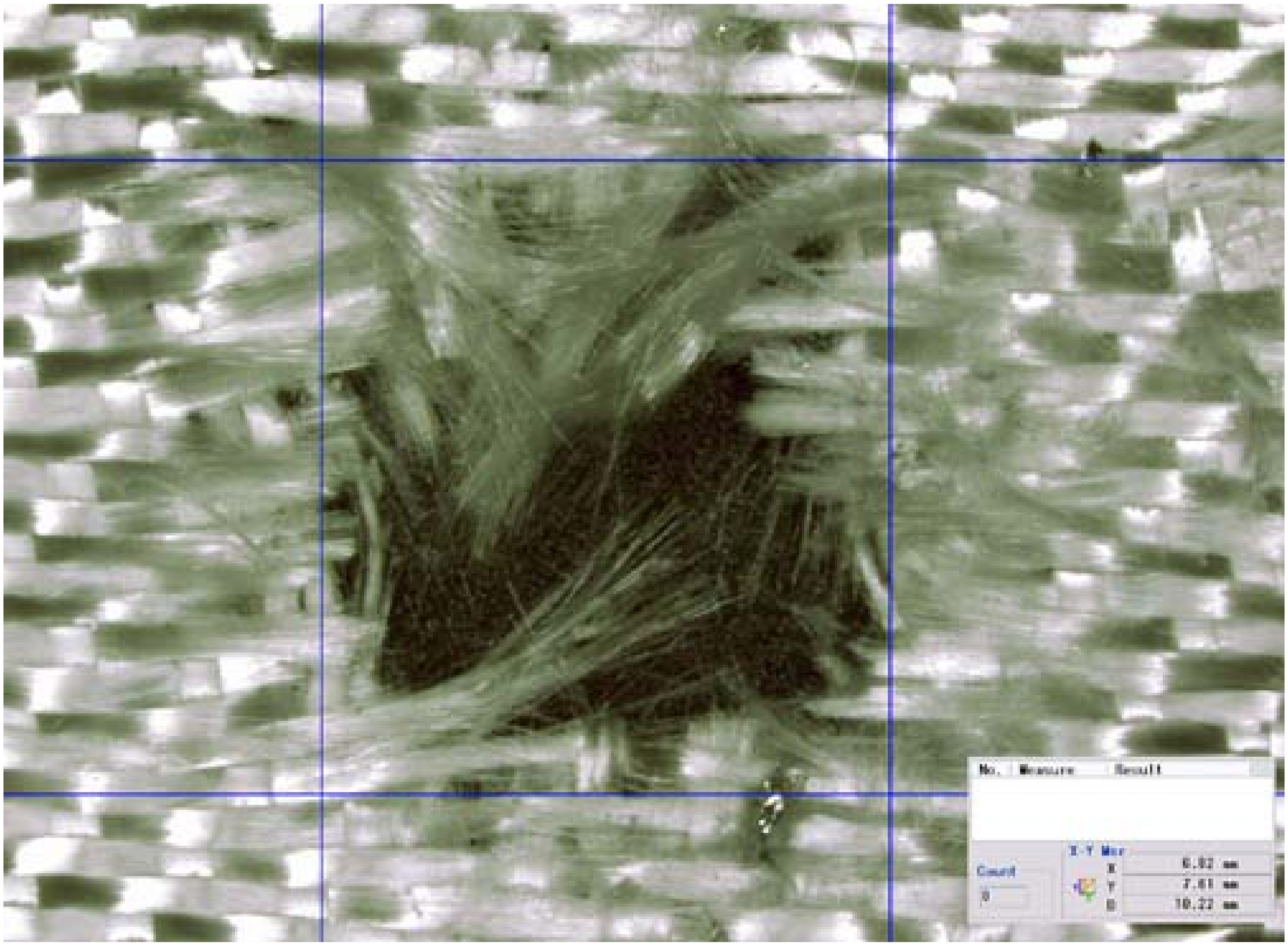


Figure 88: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #5 (Keyence 3D Microscope Image)

Test #5, HITF12261

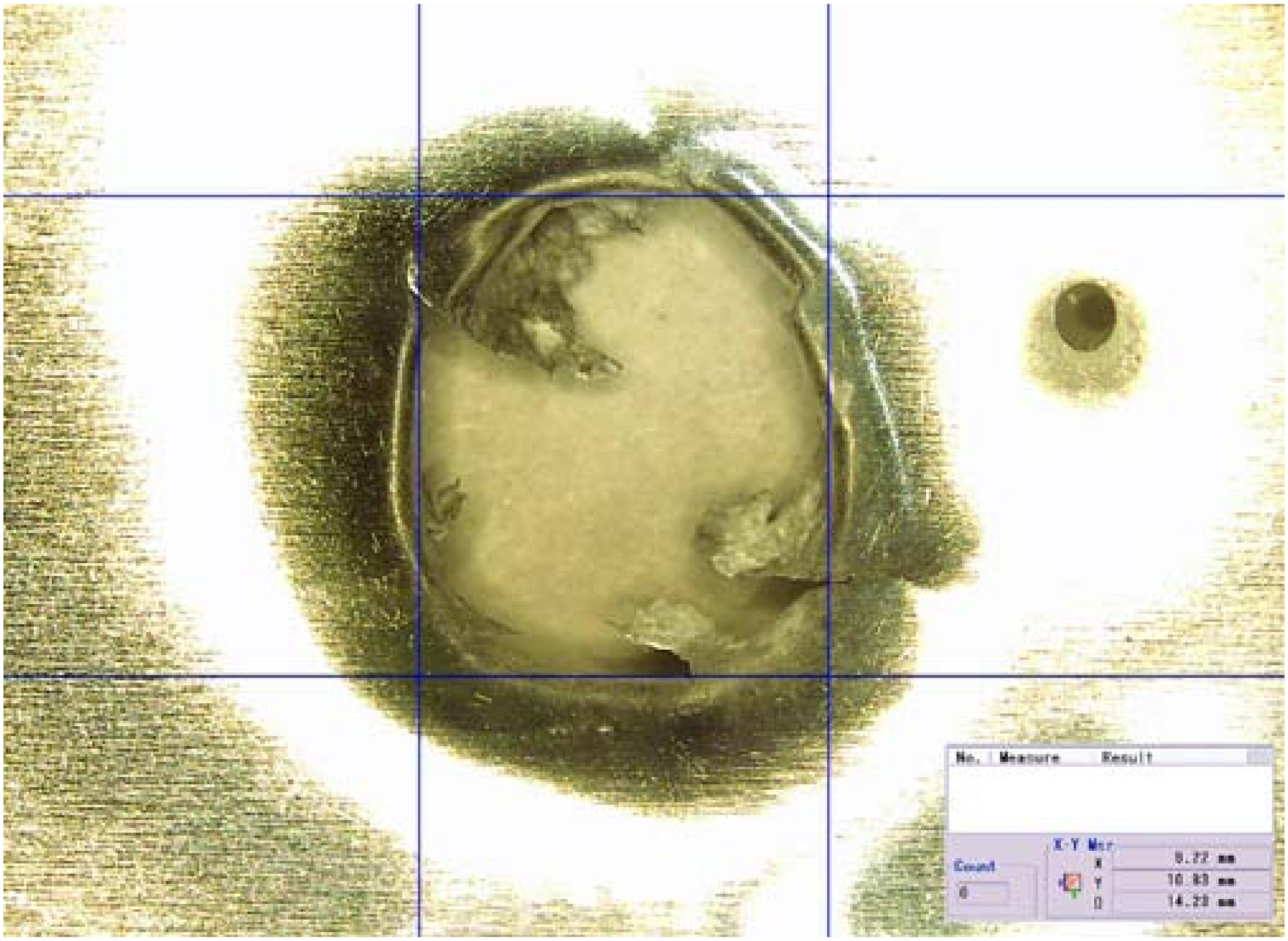


Figure 89: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #5 (Keyence 3D Microscope Image)

Test #5, HITF12261

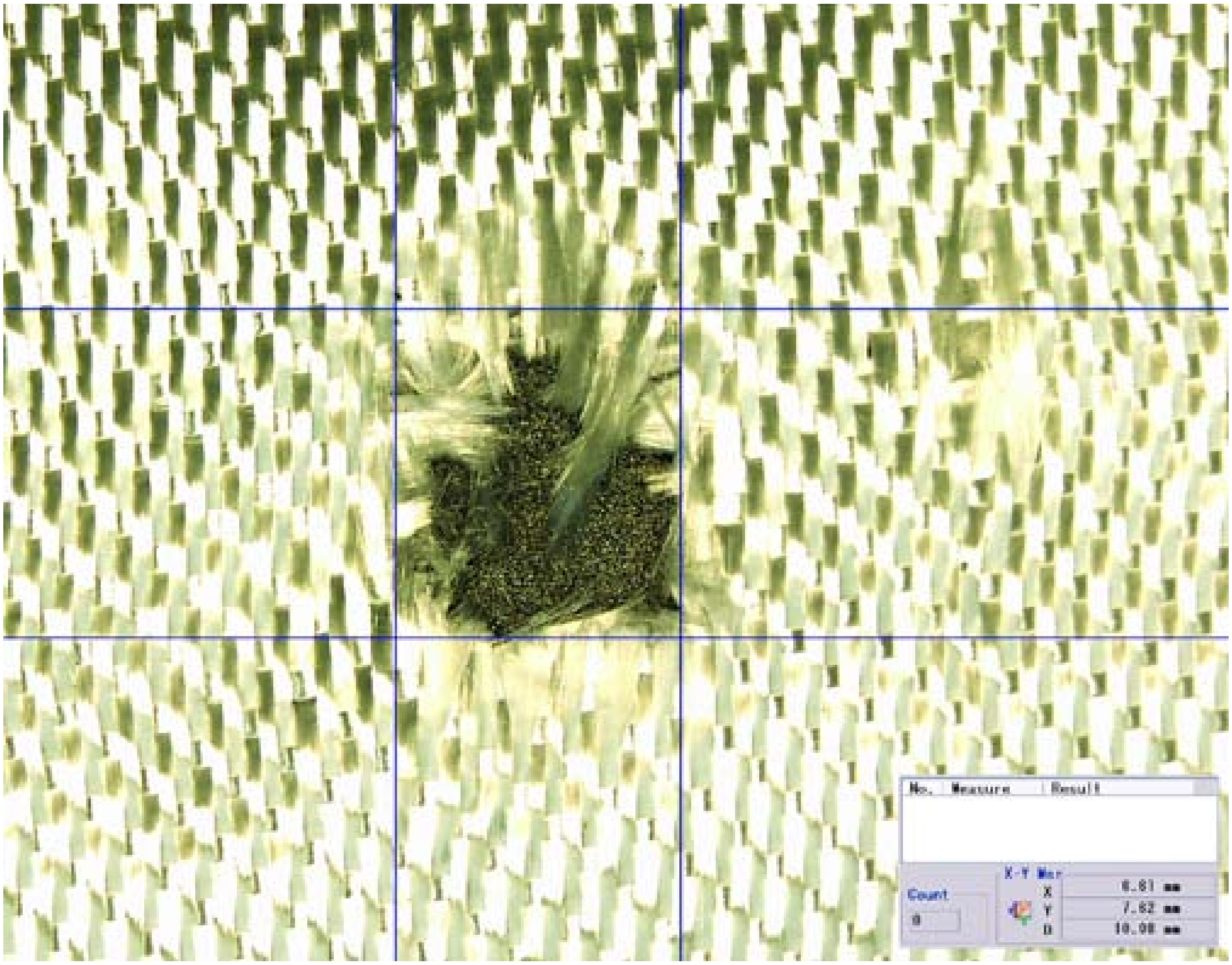


Figure 90: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #5 (Keyence 3D Microscope Image)

Test #5, HITF12261

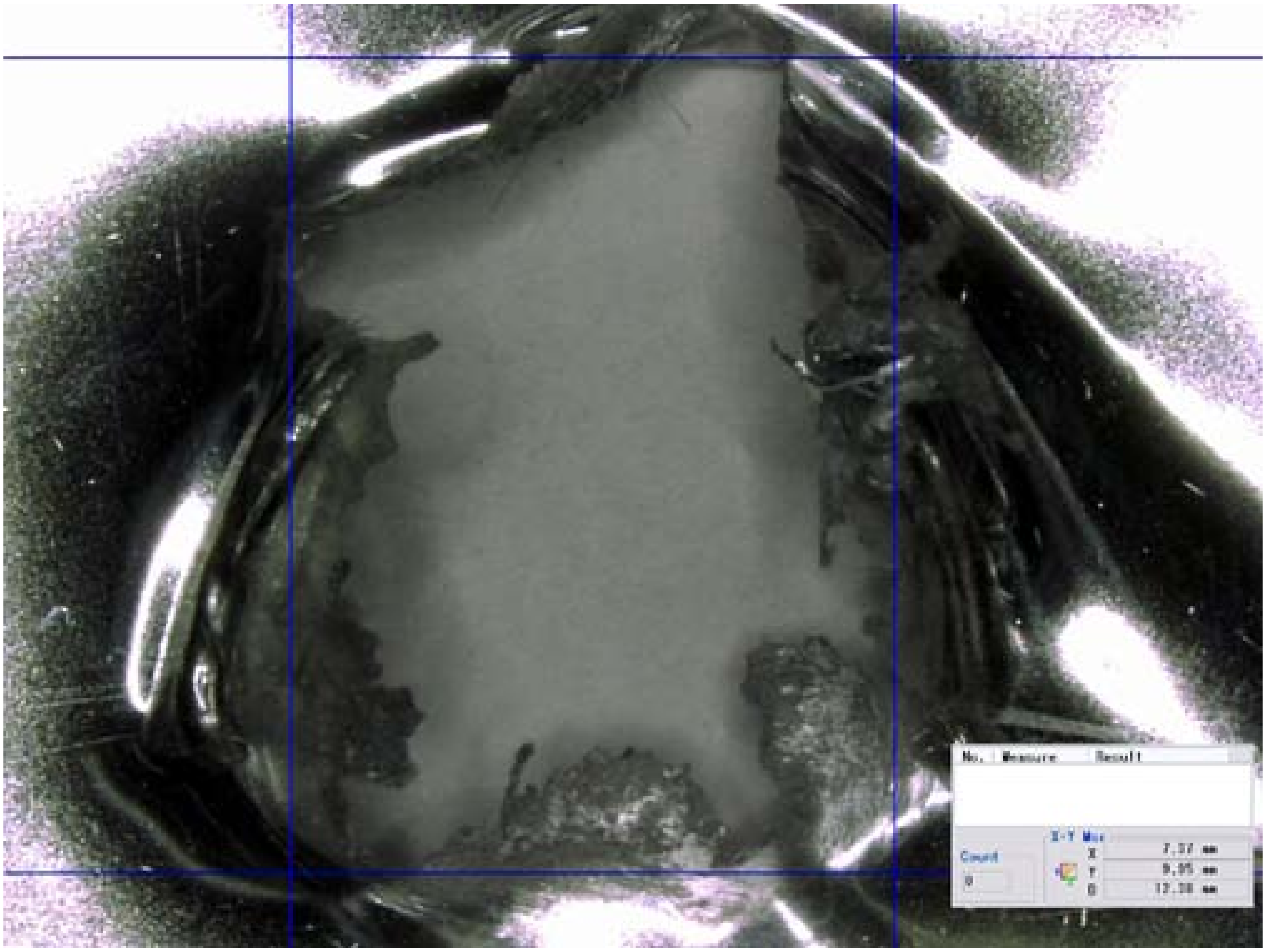


Figure 91: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #5 (Keyence 3D Microscope Image)

Test #5, HITF12261

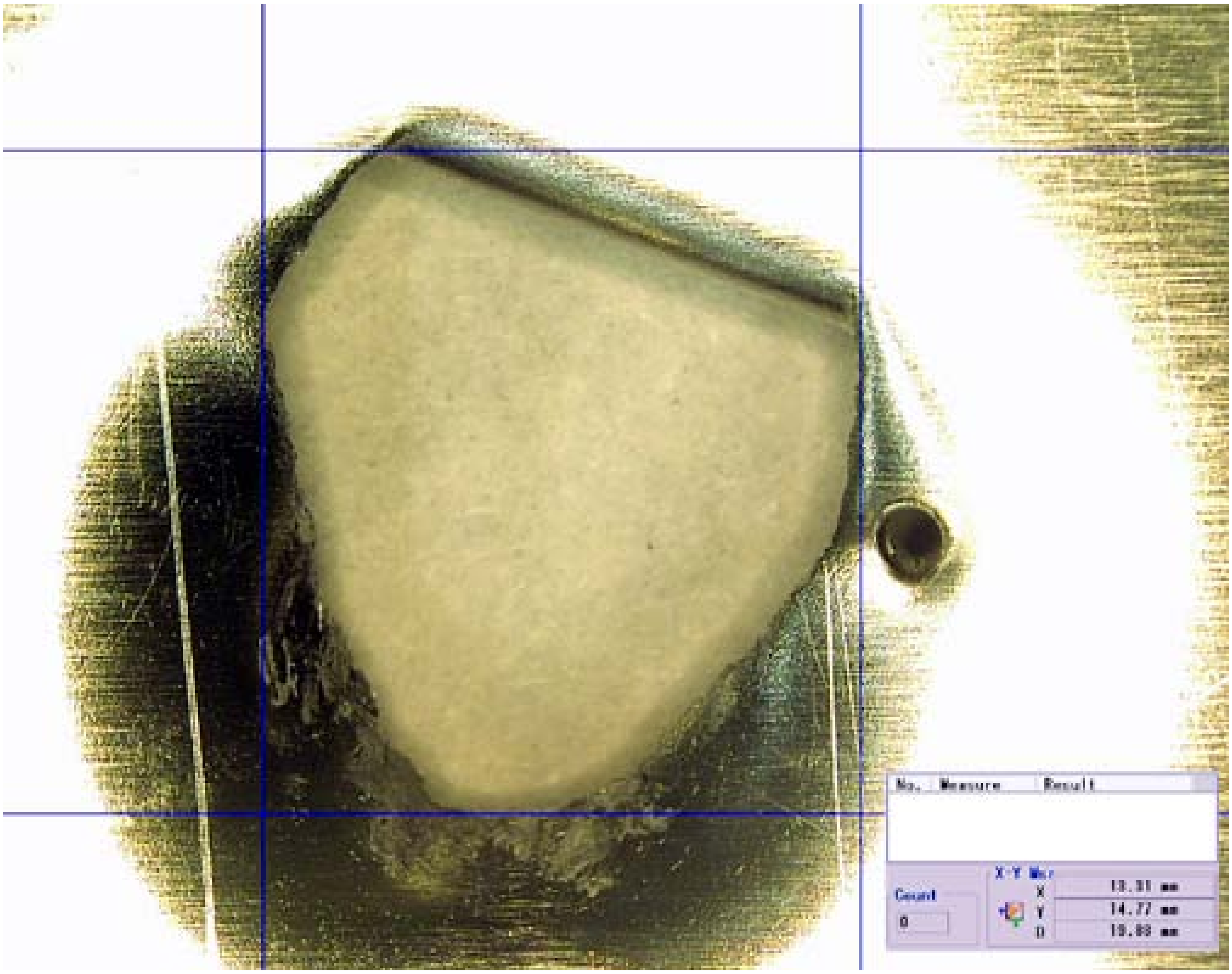


Figure 92: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #5 (Keyence 3D Microscope Image)

Test #5, HITF12261

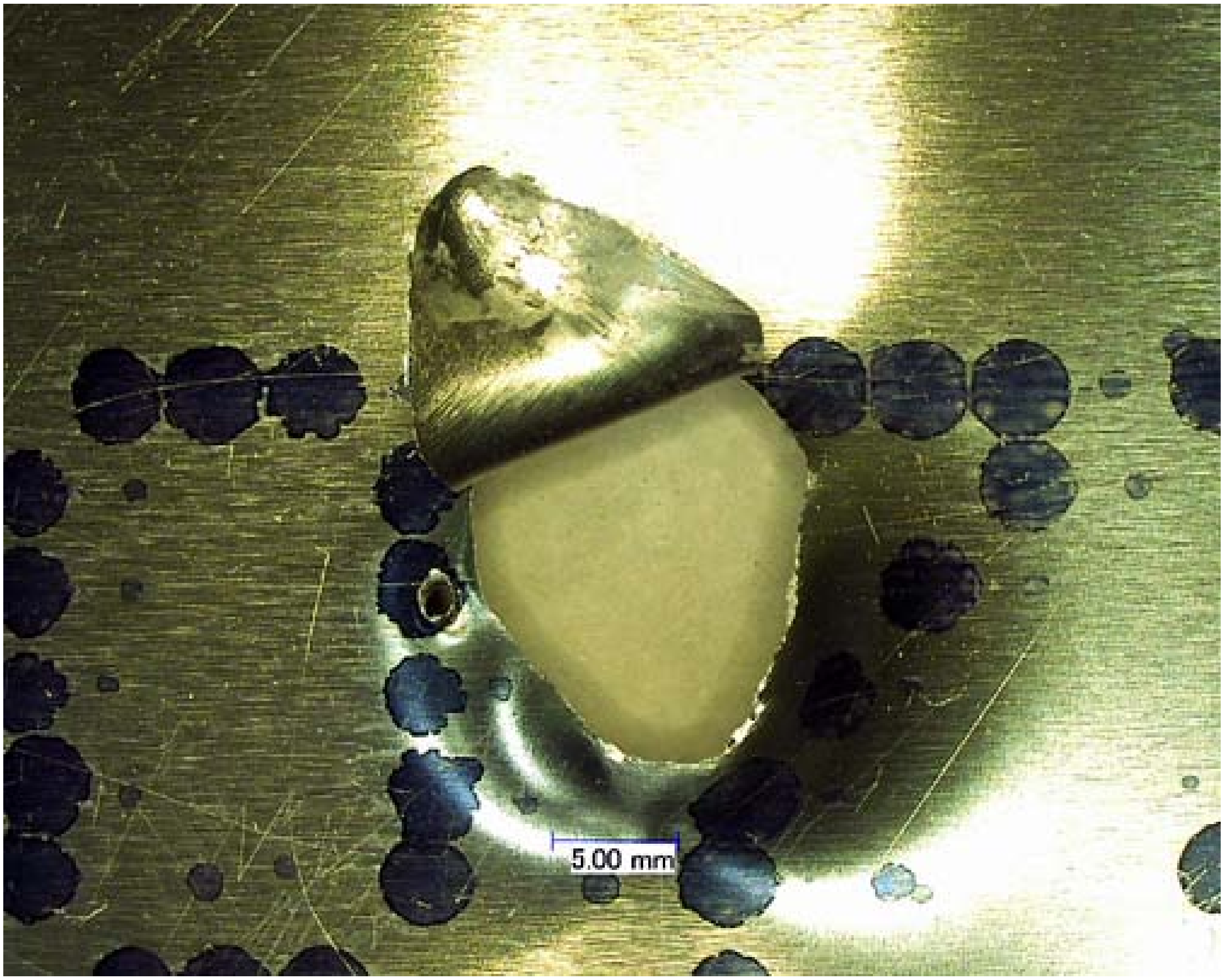


Figure 93: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #5 (Keyence 3D Microscope Image)

Test #5, HITF12261 Rear Wall

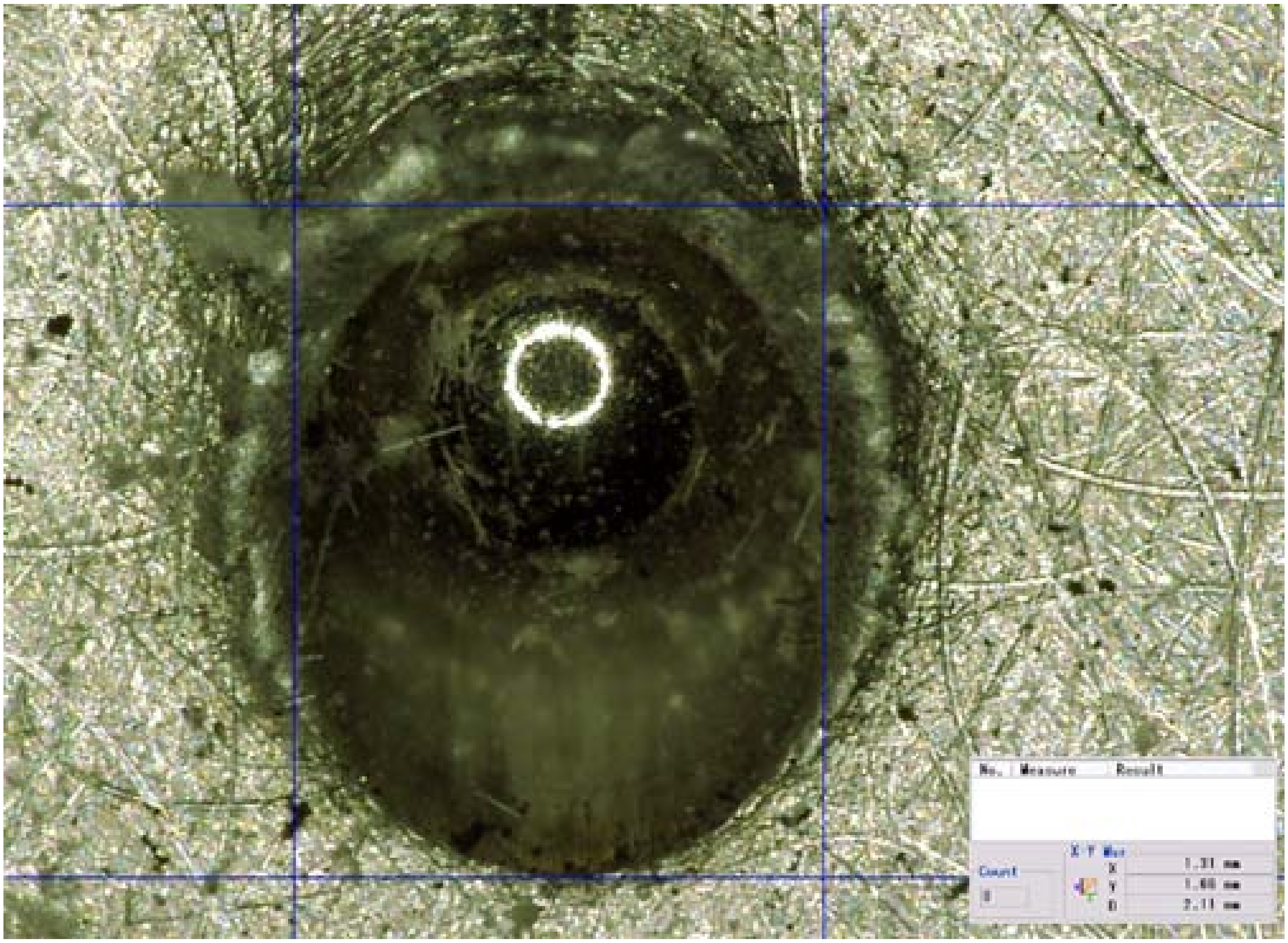


Figure 94: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #5 (Keyence 3D Microscope Image)

Test #5, HITF12261

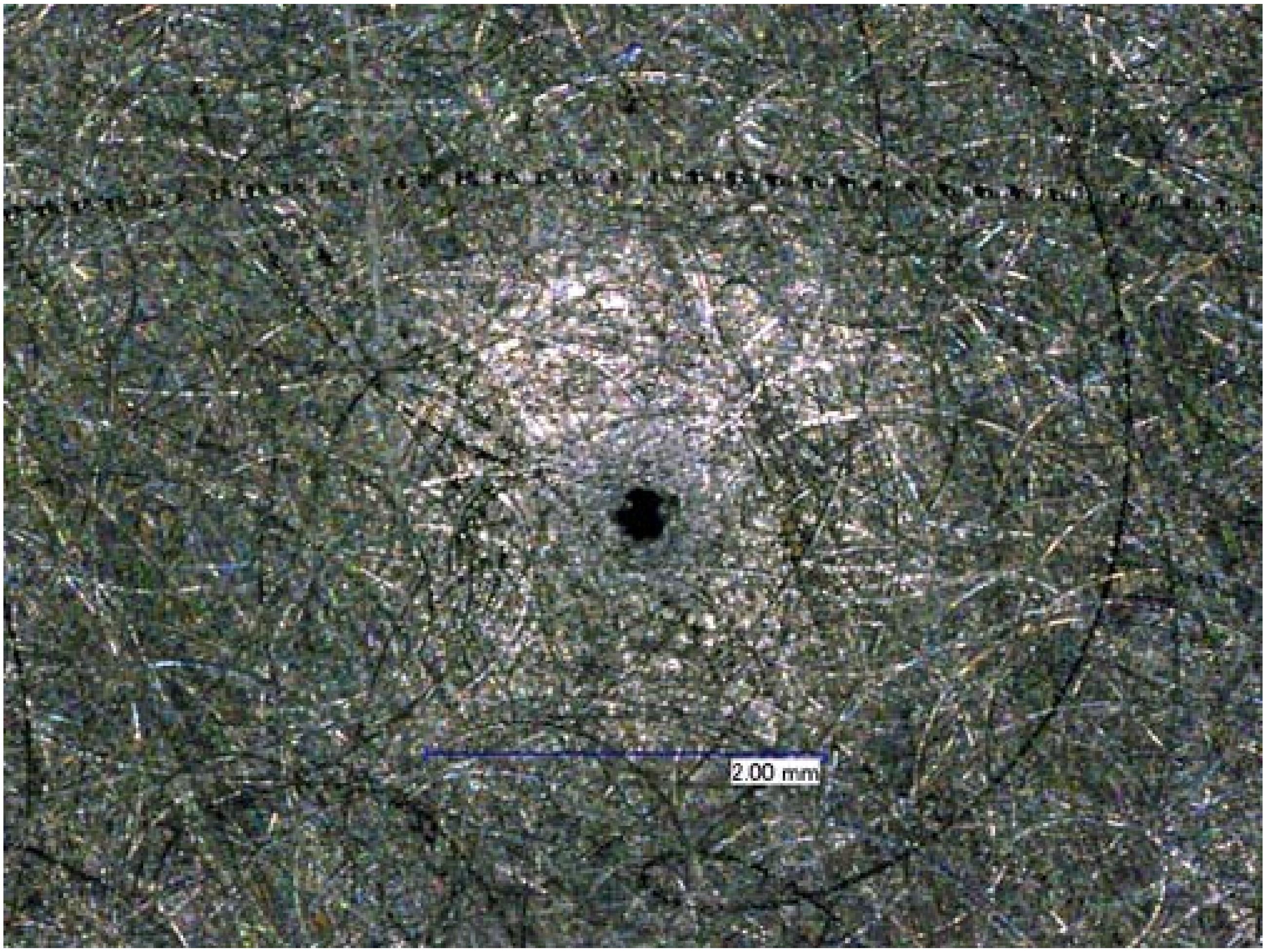


Figure 95: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #5 (Keyence 3D Microscope Image)

Test #5, HITF12261

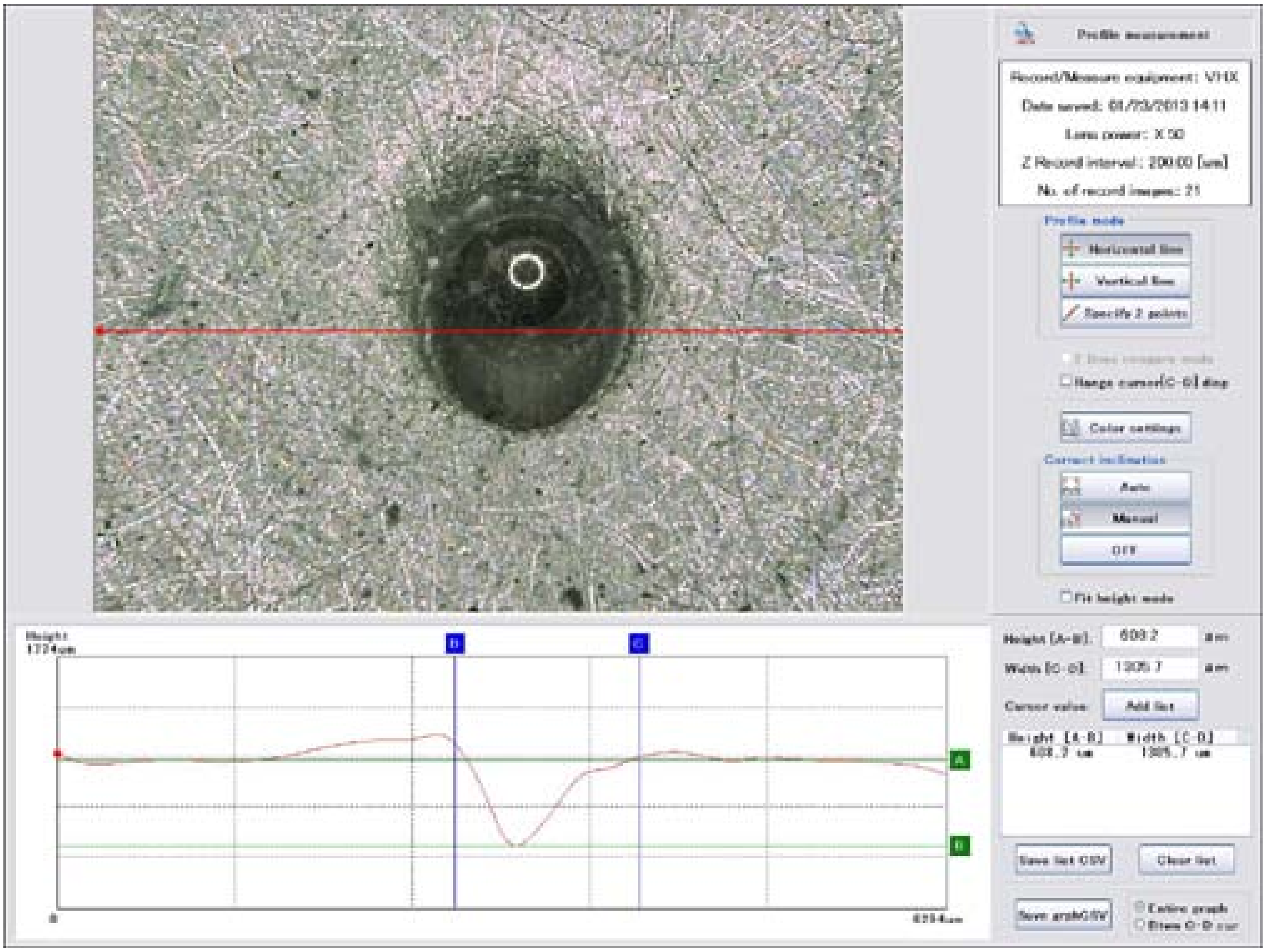


Figure 96: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #5 (Keyence 3D Microscope Image)

Test #5, HITF12261

Figure 97: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #5

Test #6B, HITF12262

Figure 98: Post-test of ISS Soyuz Orbital Module Test #6B (HITF12262) article mounted in 0.50-caliber target tank.

Figure 99: Side View of ISS Soyuz Orbital Module Test #6B

Test #6B, HITF12262

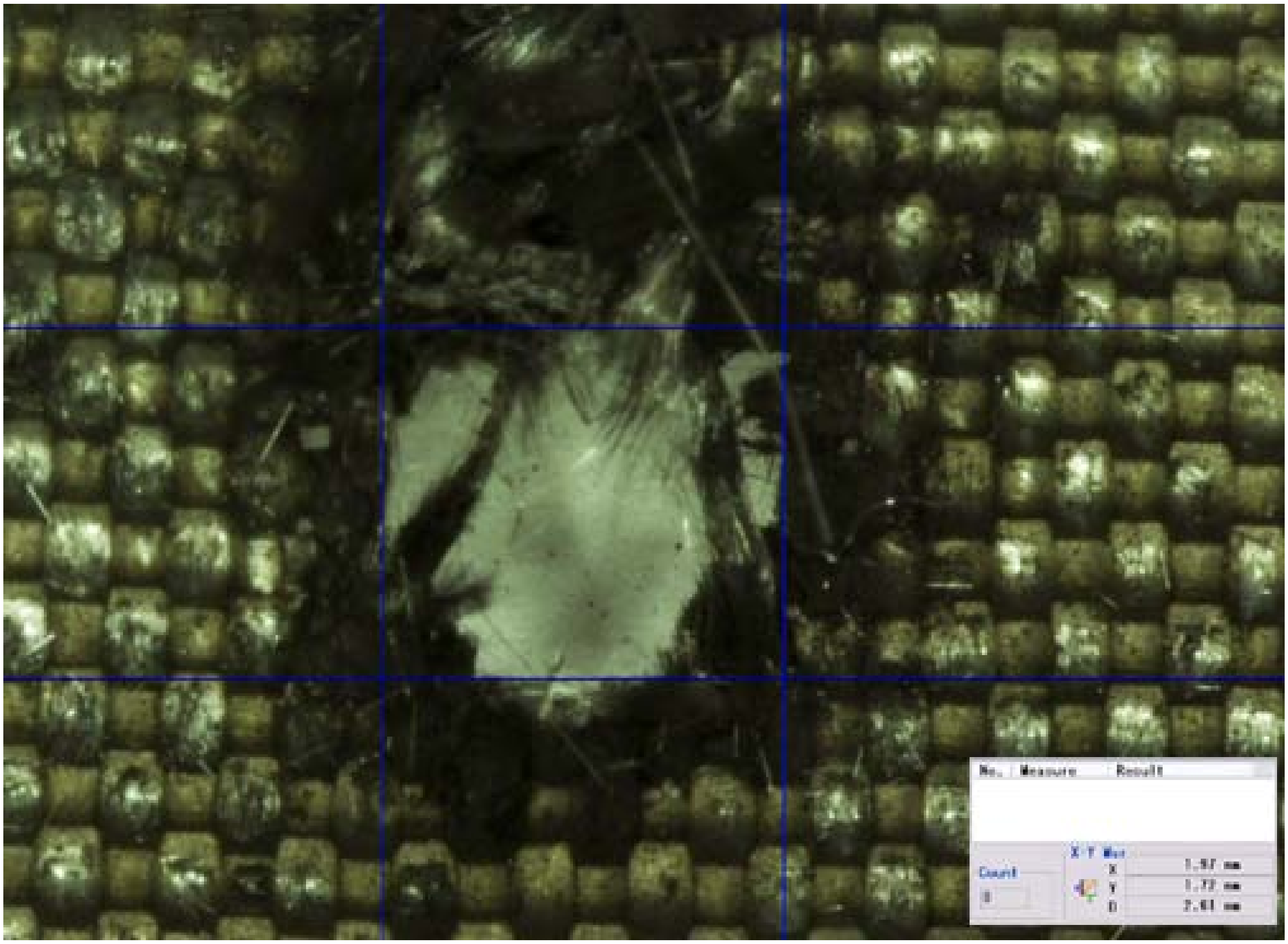


Figure 100: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Figure 101: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #6B

Test #6B, HITF12262

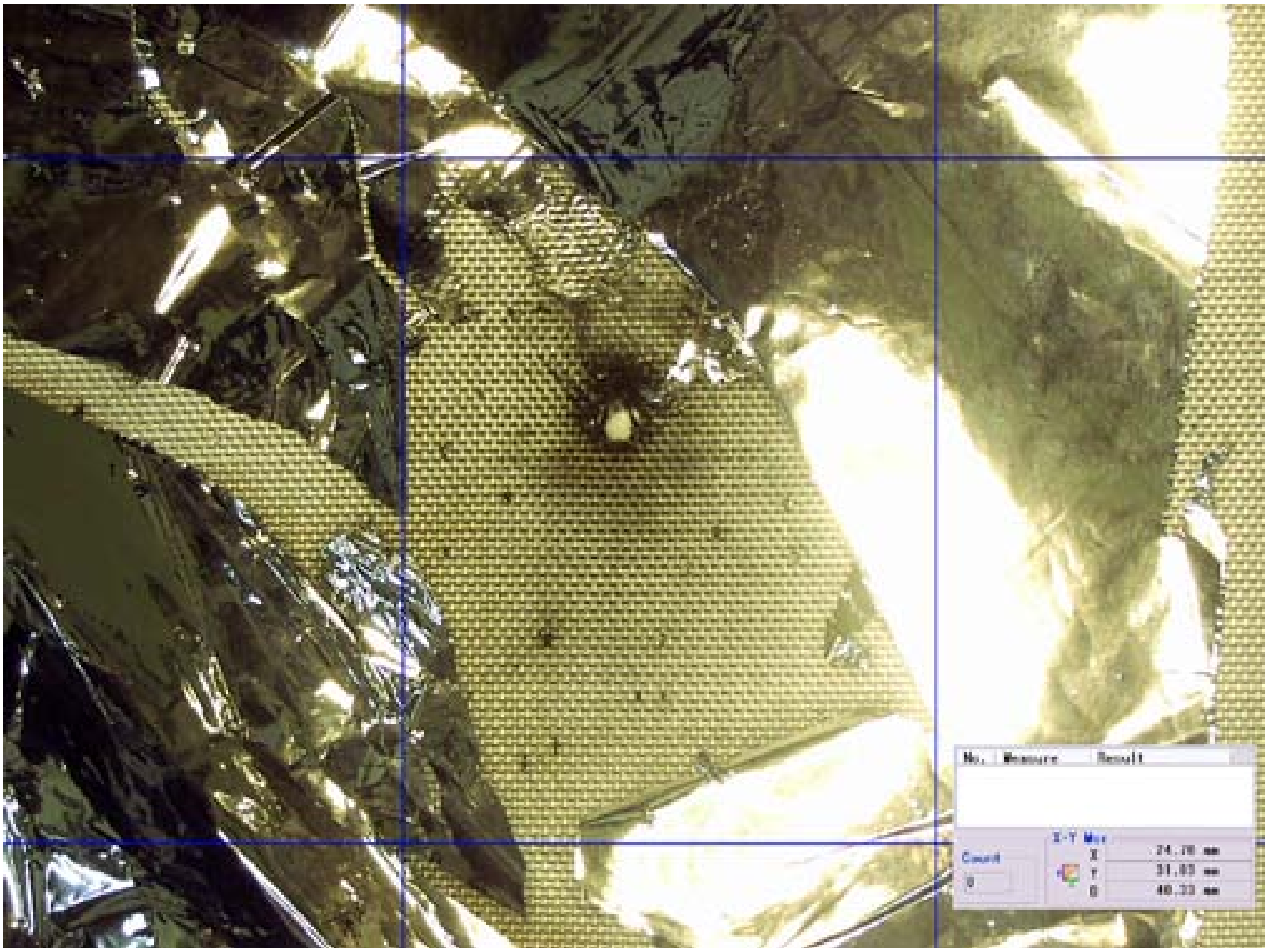


Figure 102: Mylar Film Layer 2 of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262

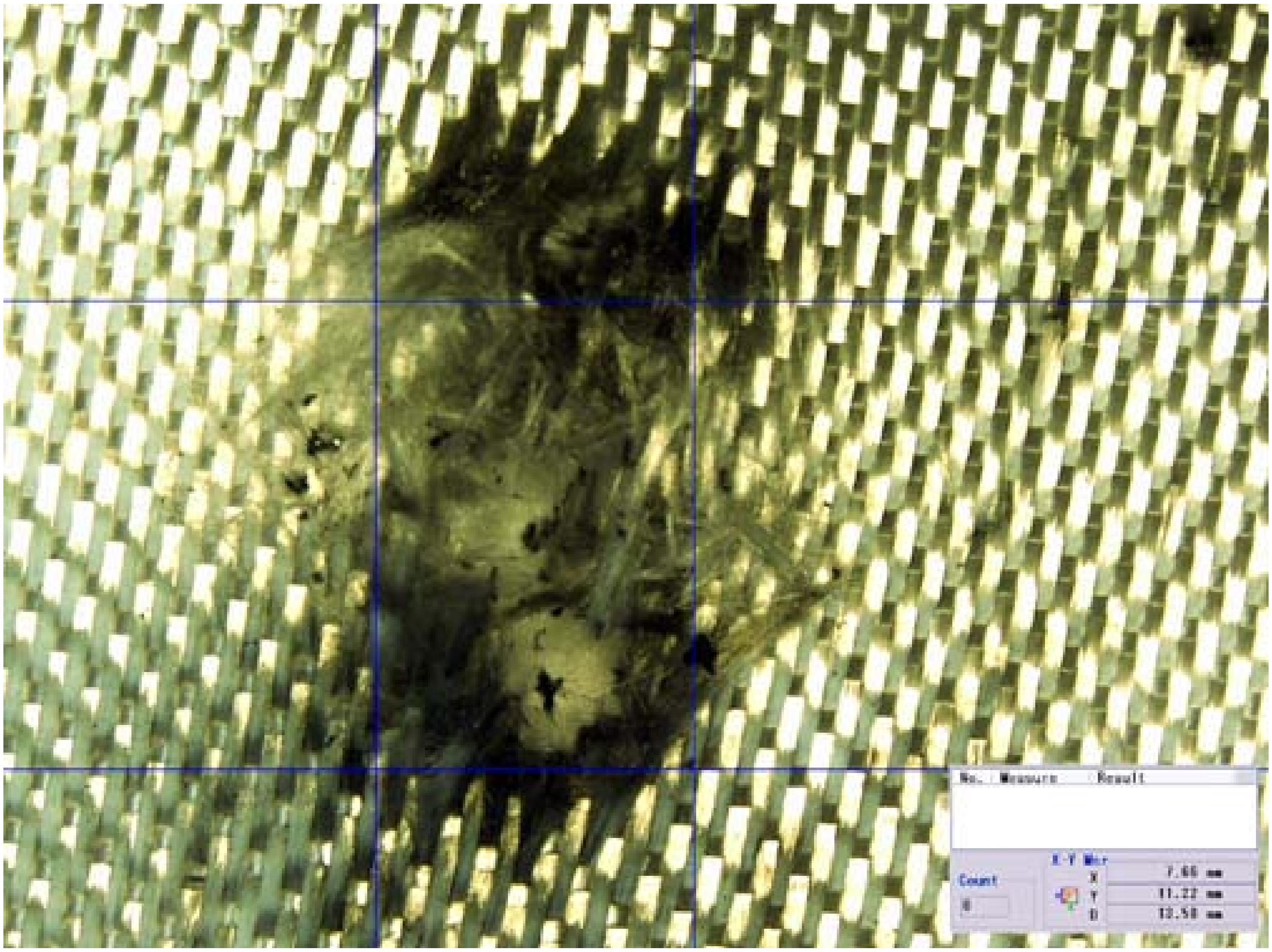


Figure 103: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262

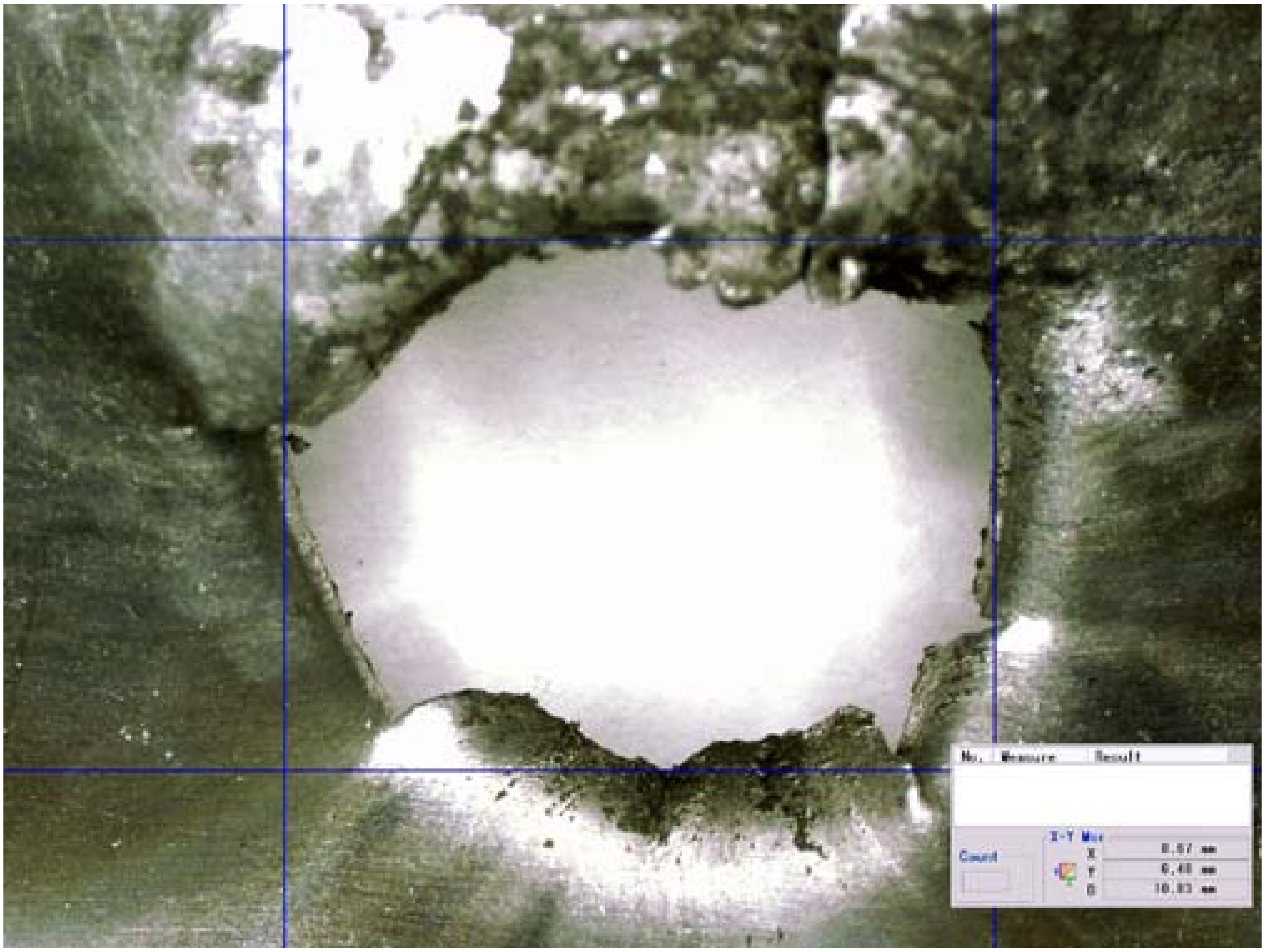


Figure 104: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262

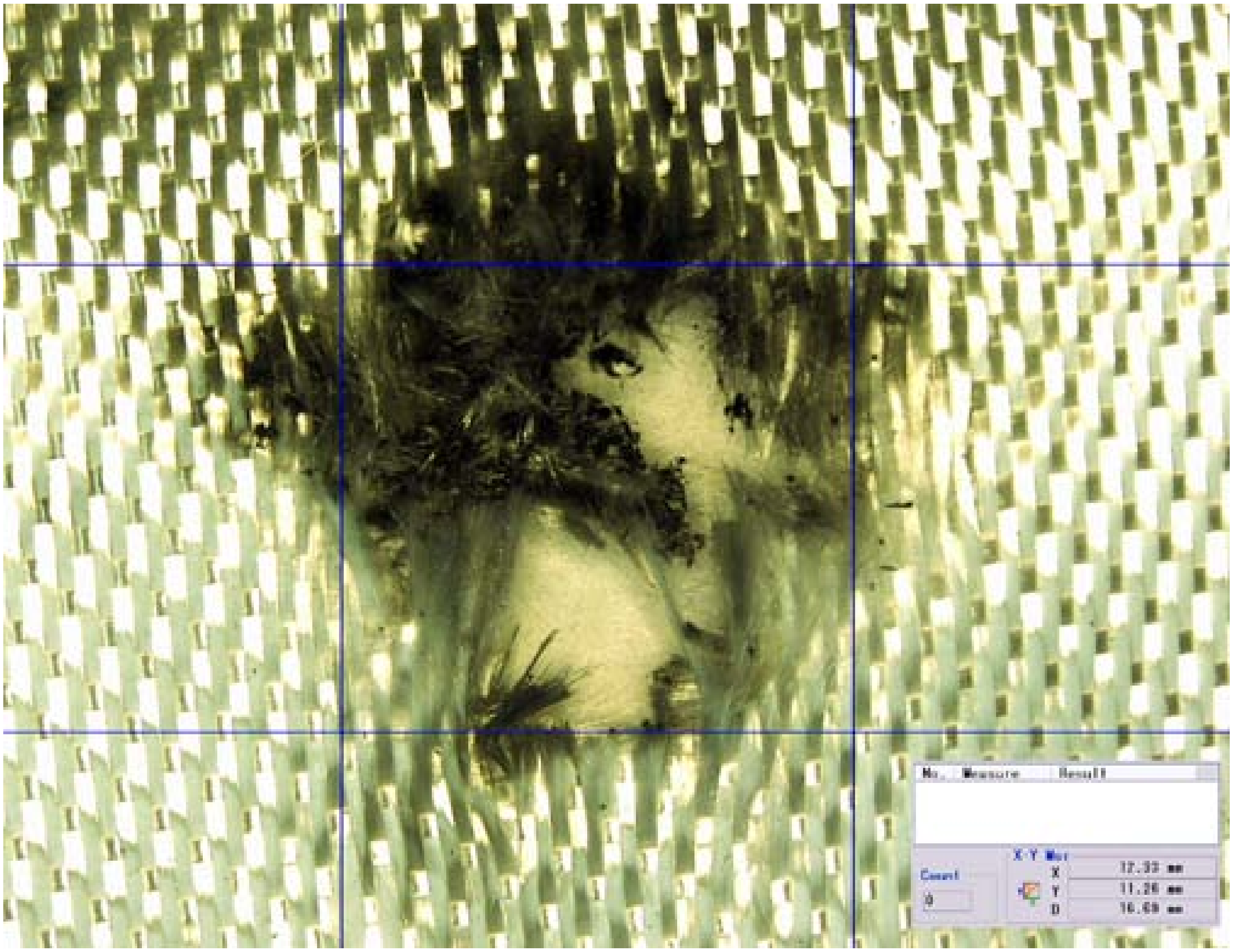


Figure 105: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262

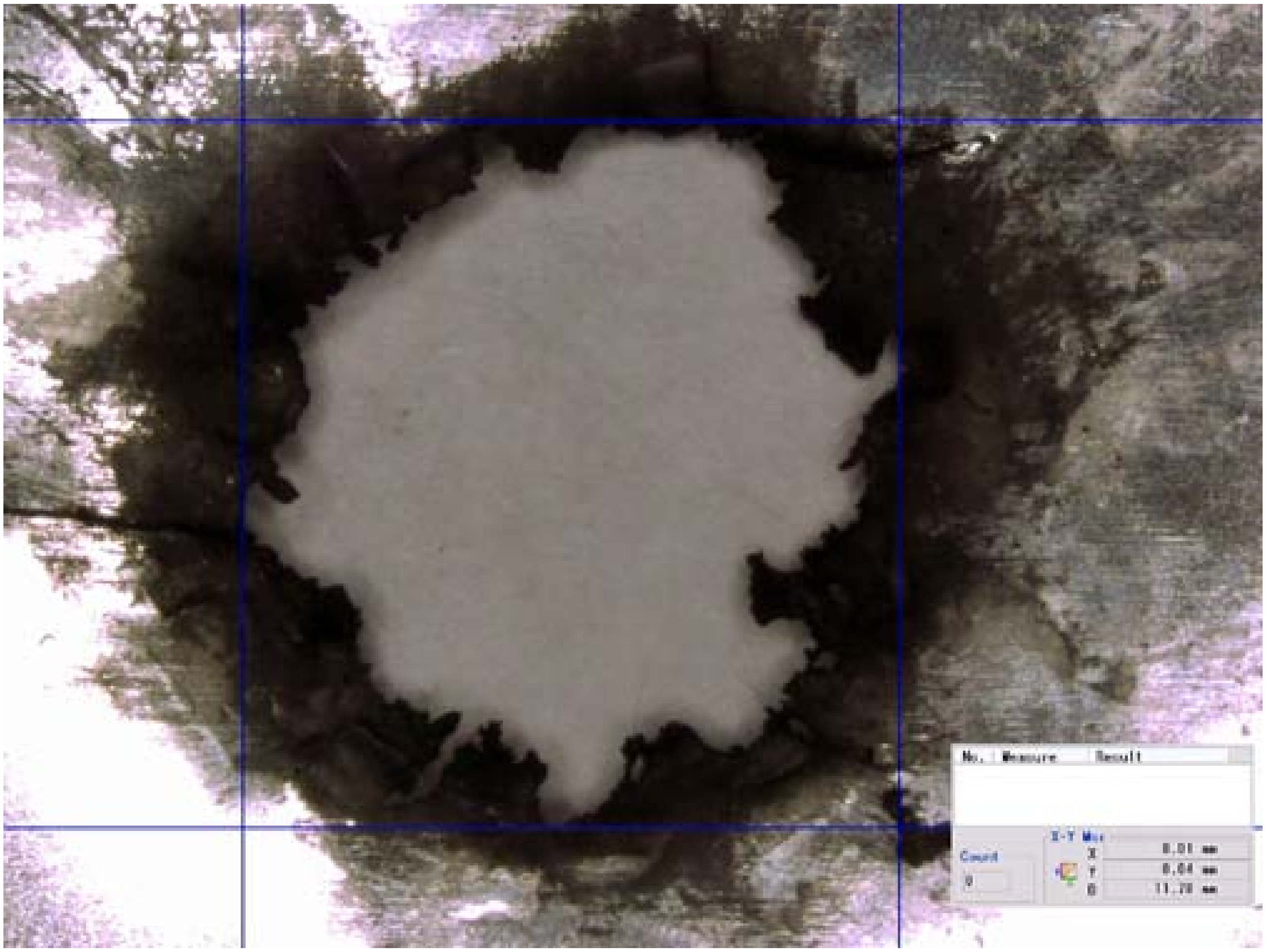


Figure 106: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262

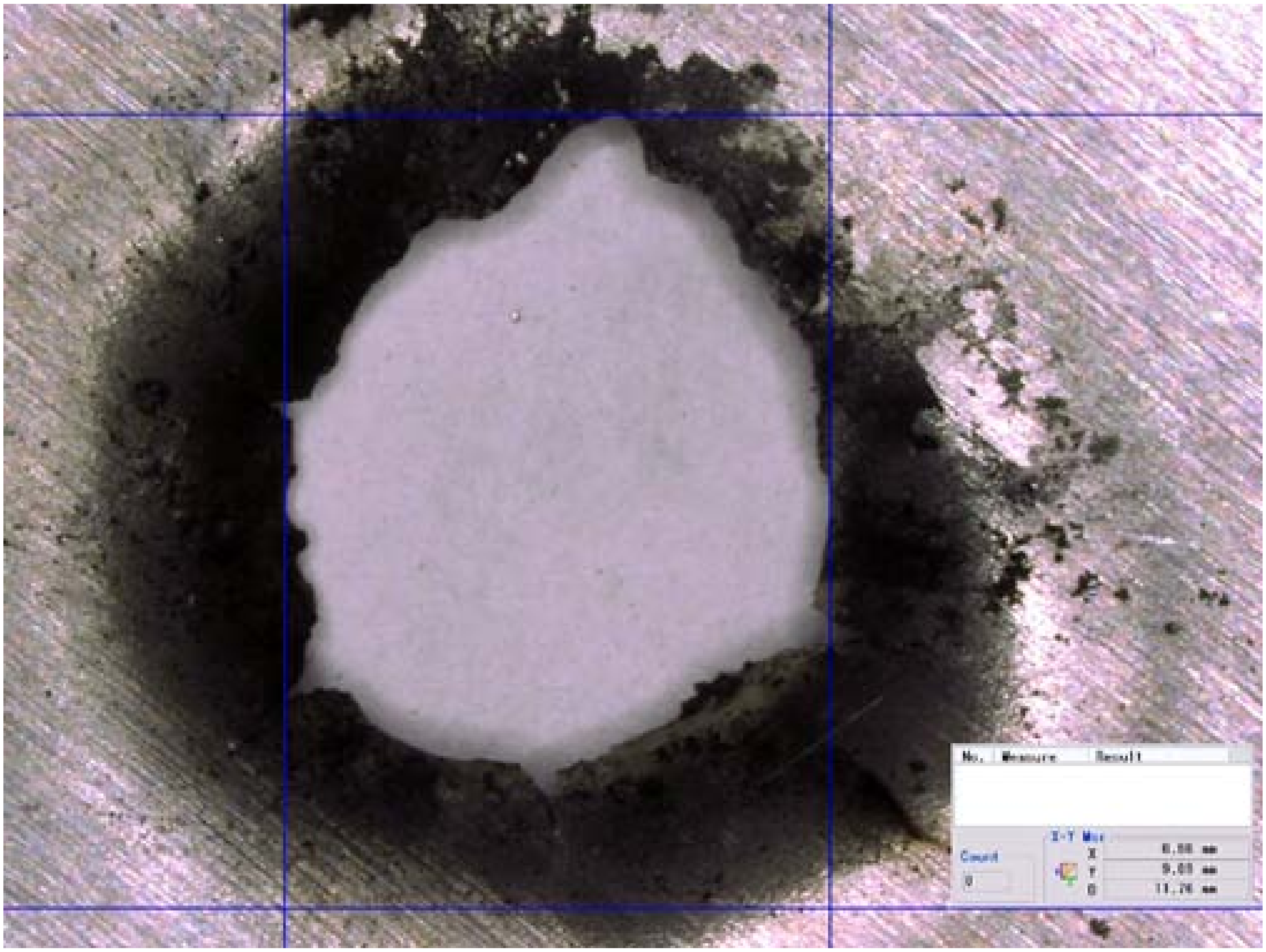


Figure 107: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262

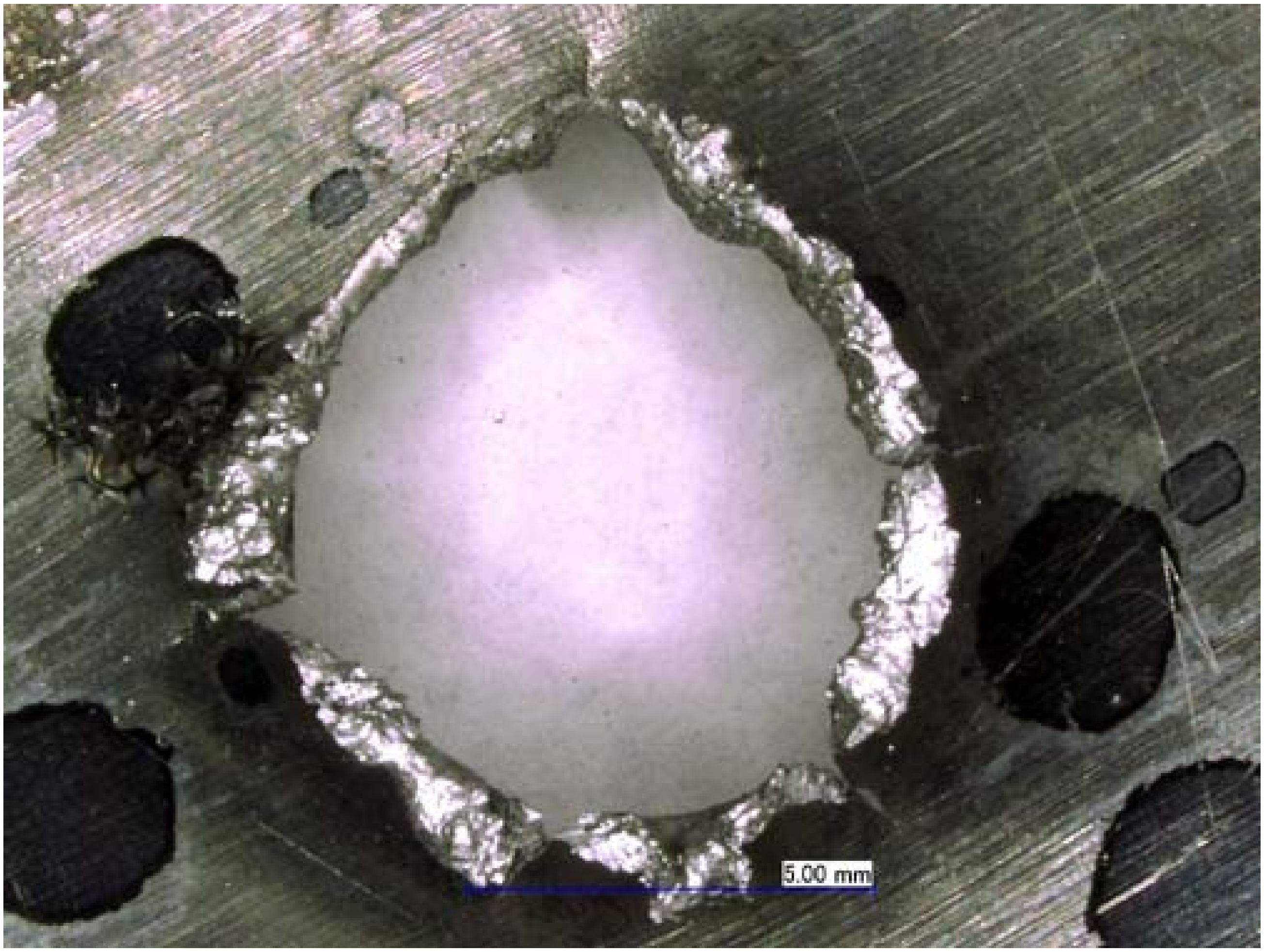


Figure 108: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262 Rear Wall

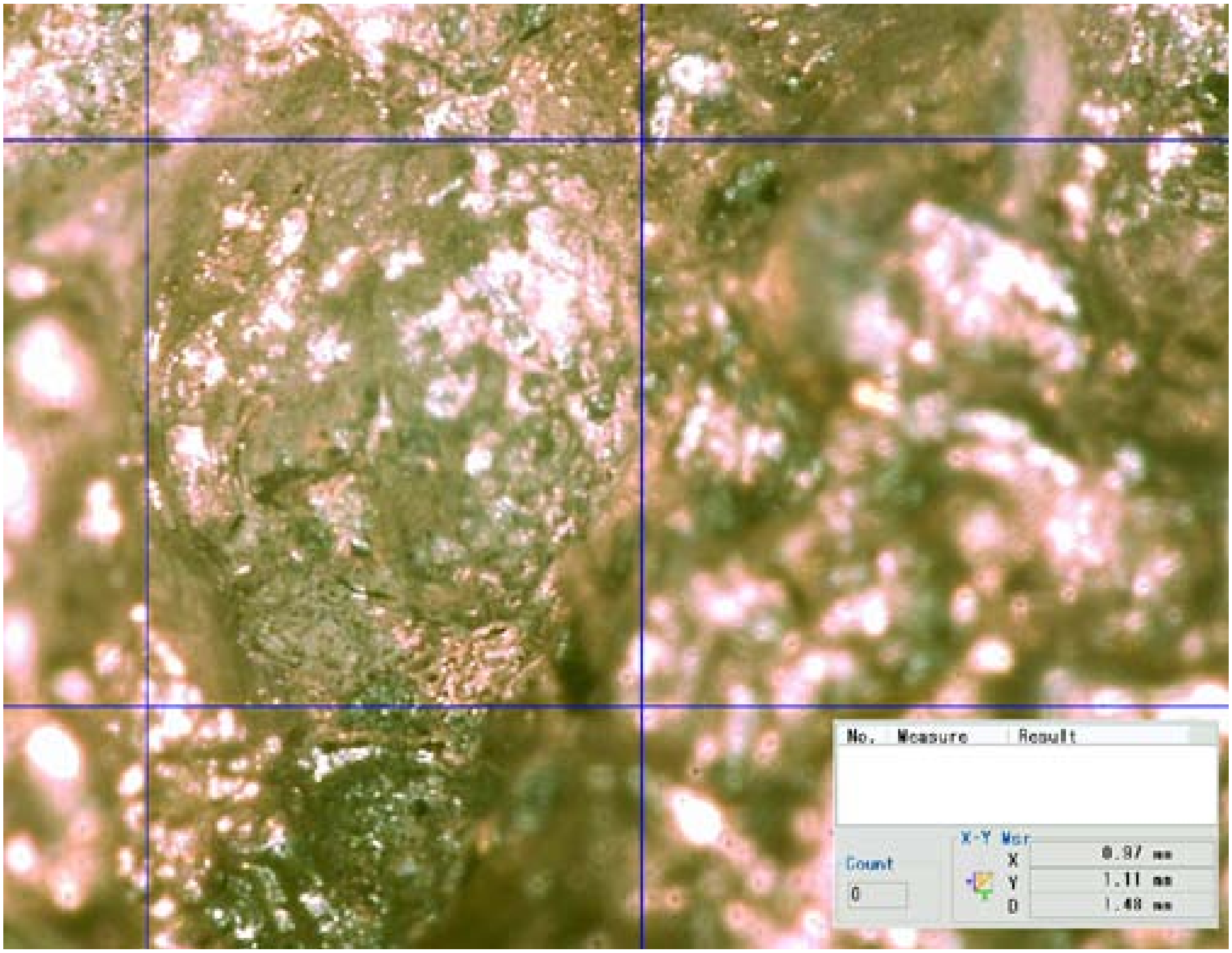


Figure 109: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262

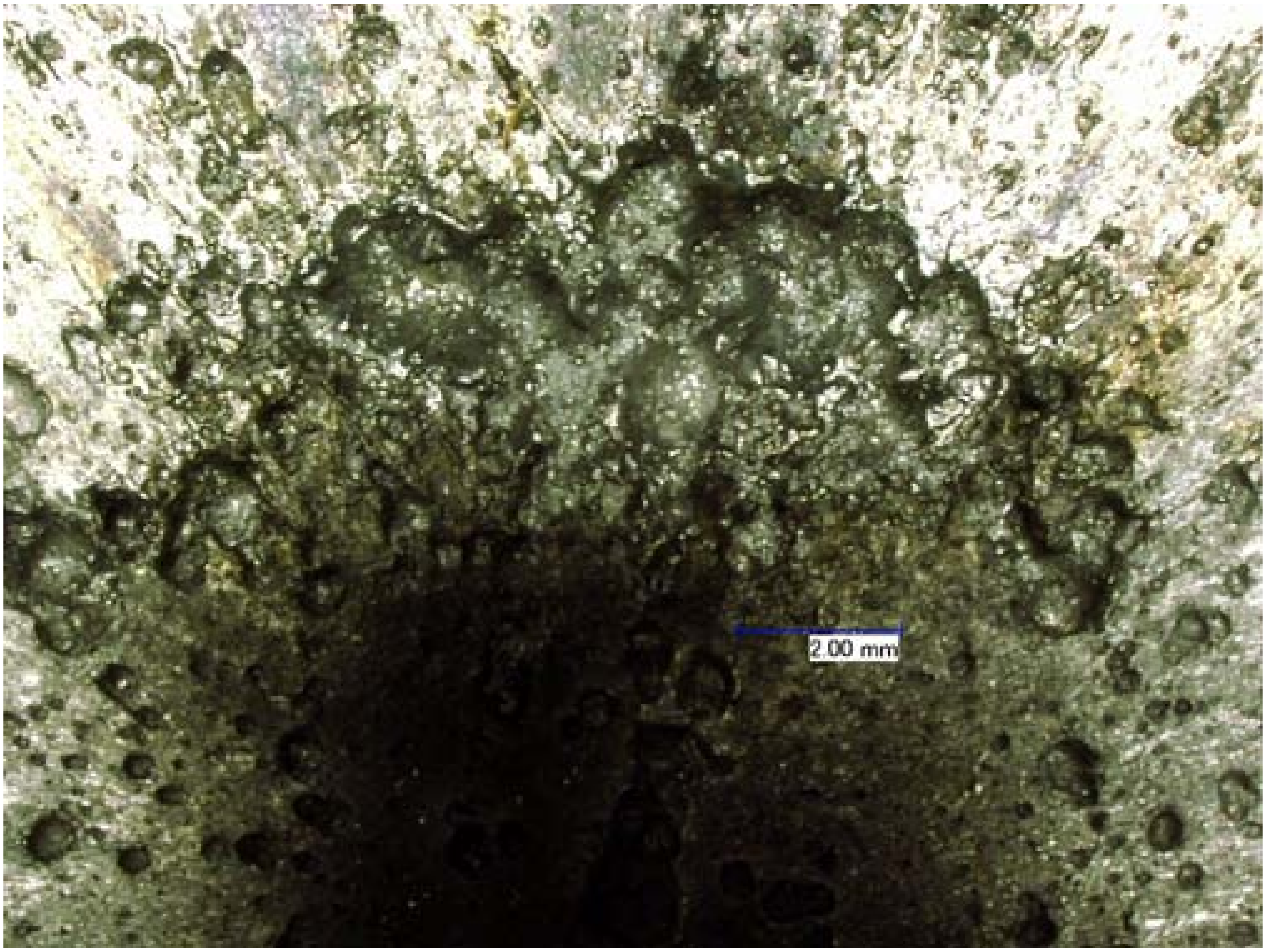


Figure 110: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262

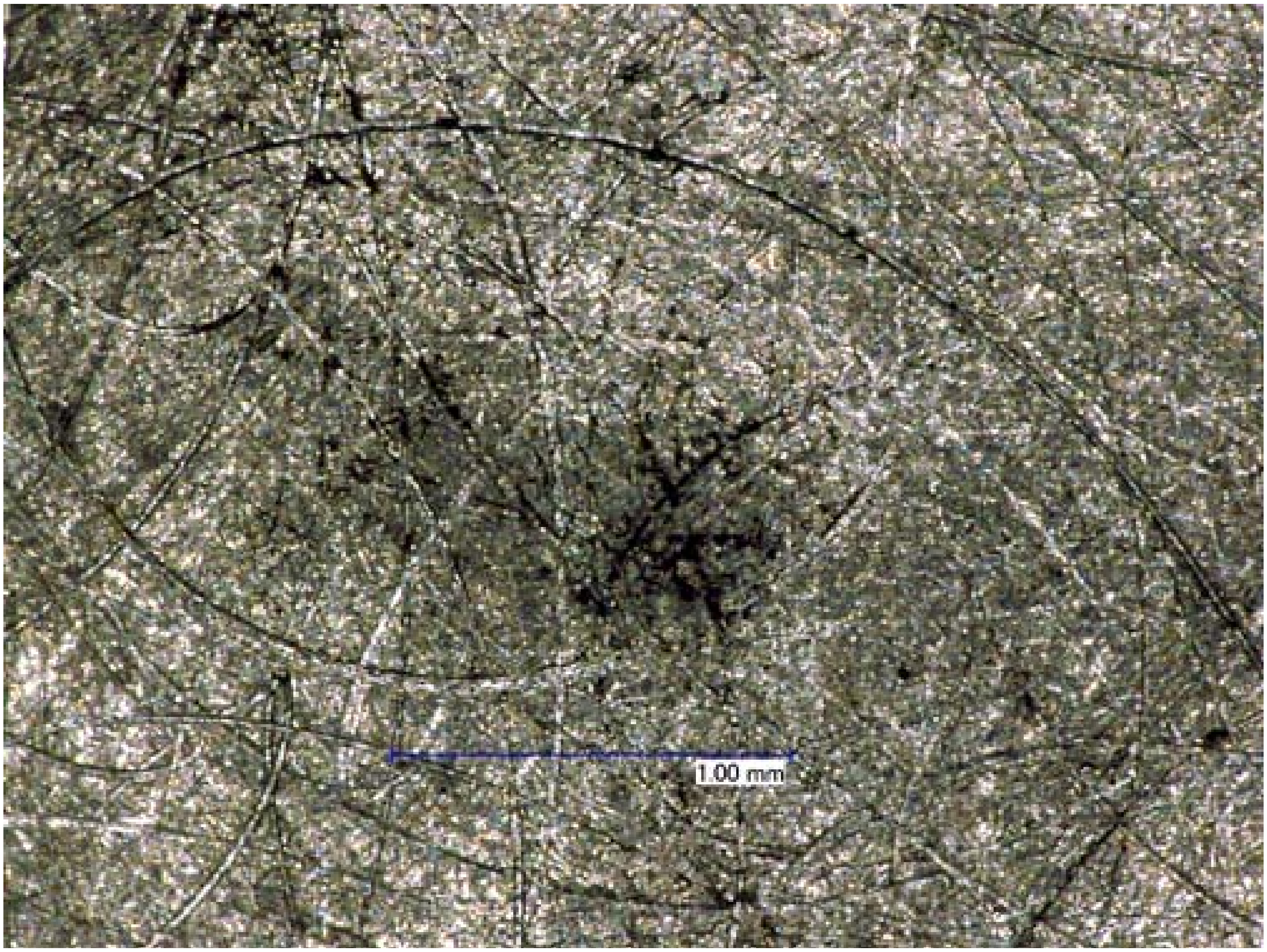


Figure 111: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262

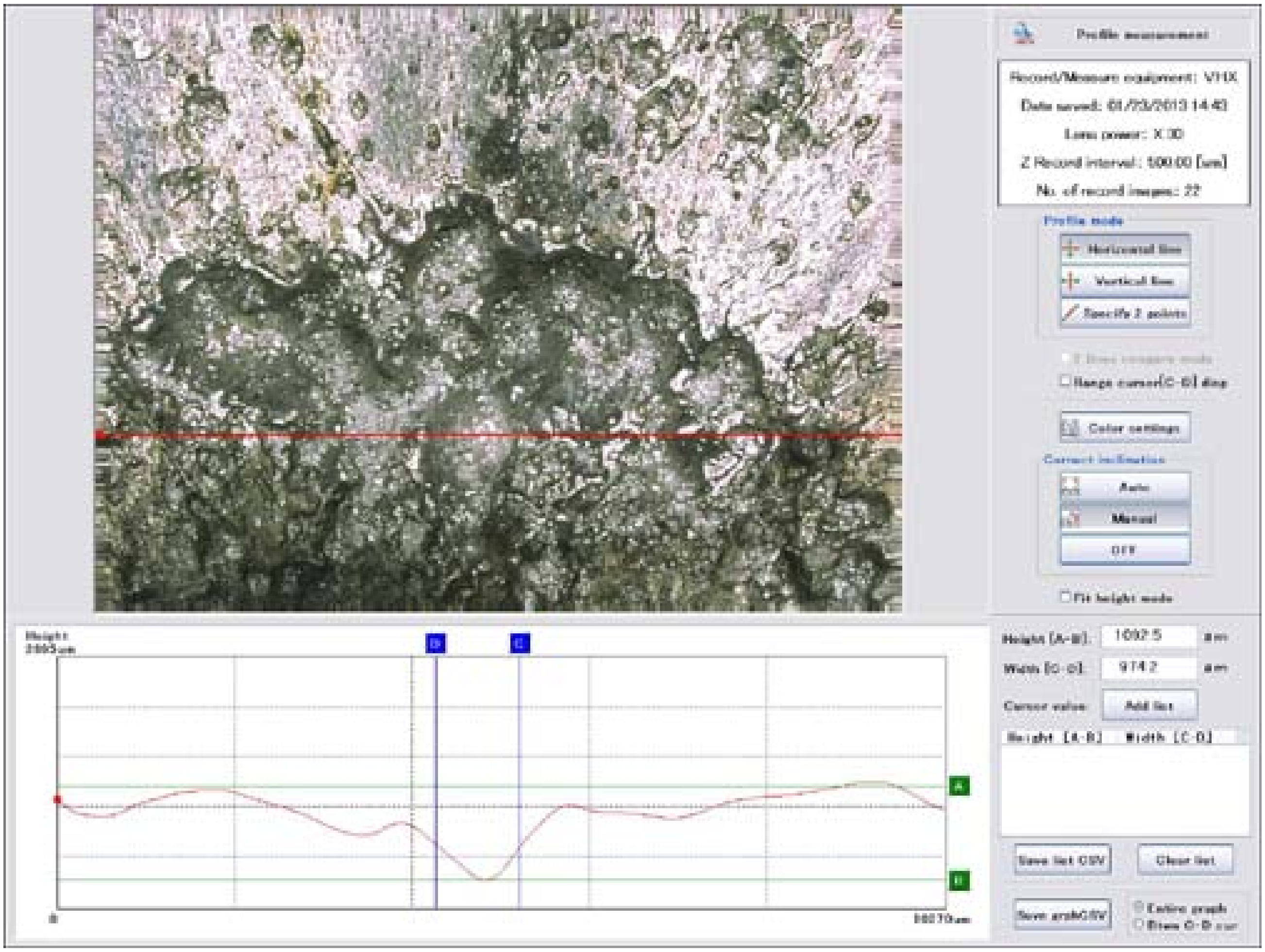


Figure 112: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #6B (Keyence 3D Microscope Image)

Test #6B, HITF12262

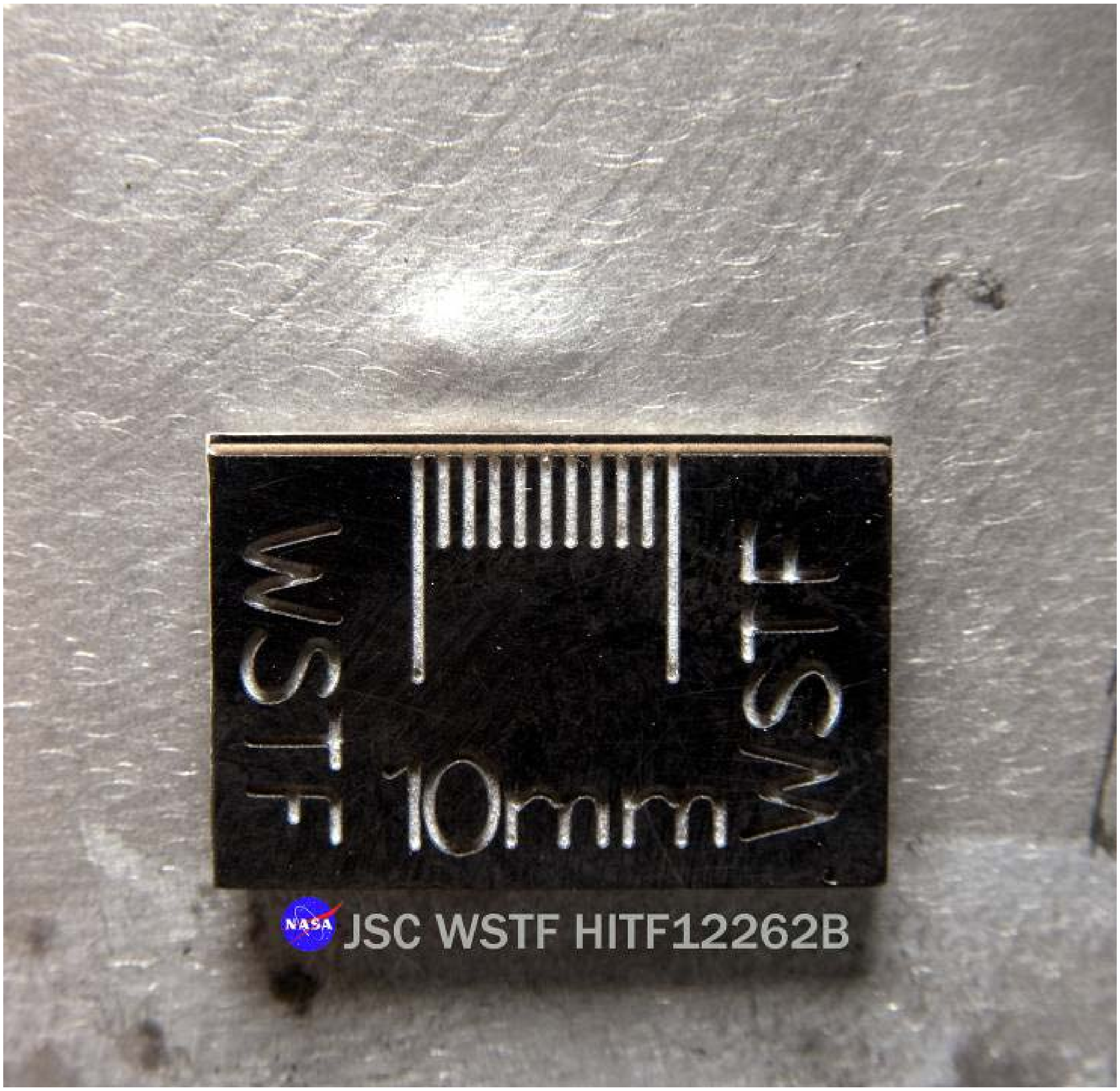


Figure 113: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #6B

Test #7, HITF12263

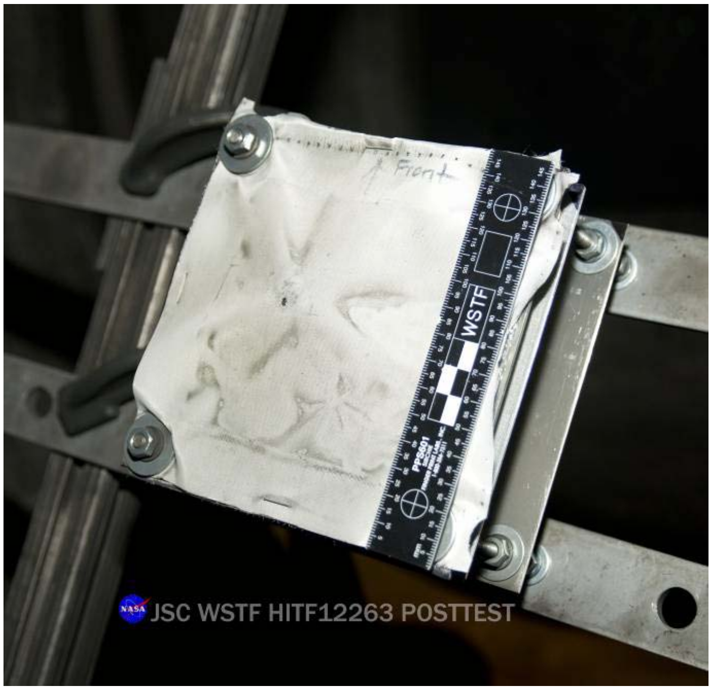


Figure 114: Post-test of ISS Soyuz Orbital Module Test #7 (HITF12263) article mounted in 0.50-caliber target tank.

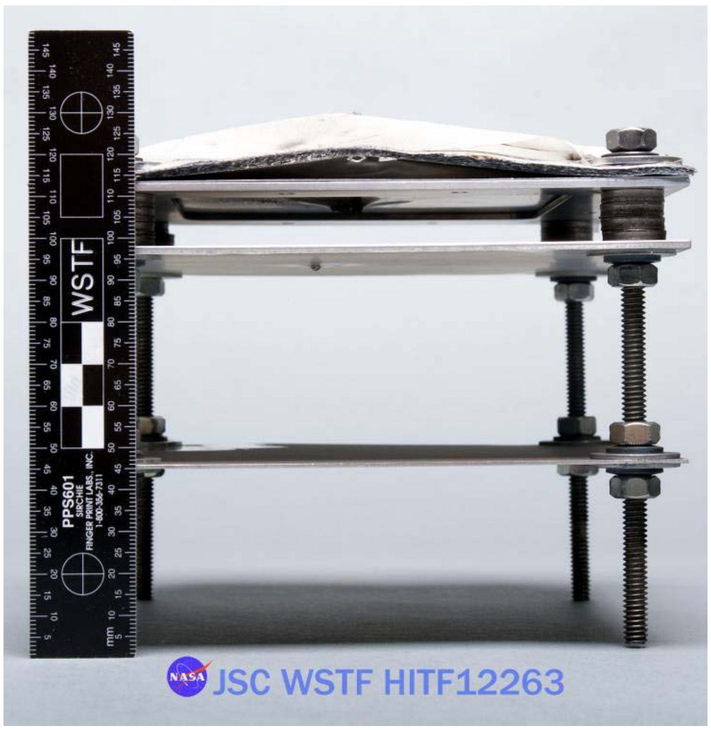


Figure 115: Side View of ISS Soyuz Orbital Module Test #7

Test #7, HITF12263

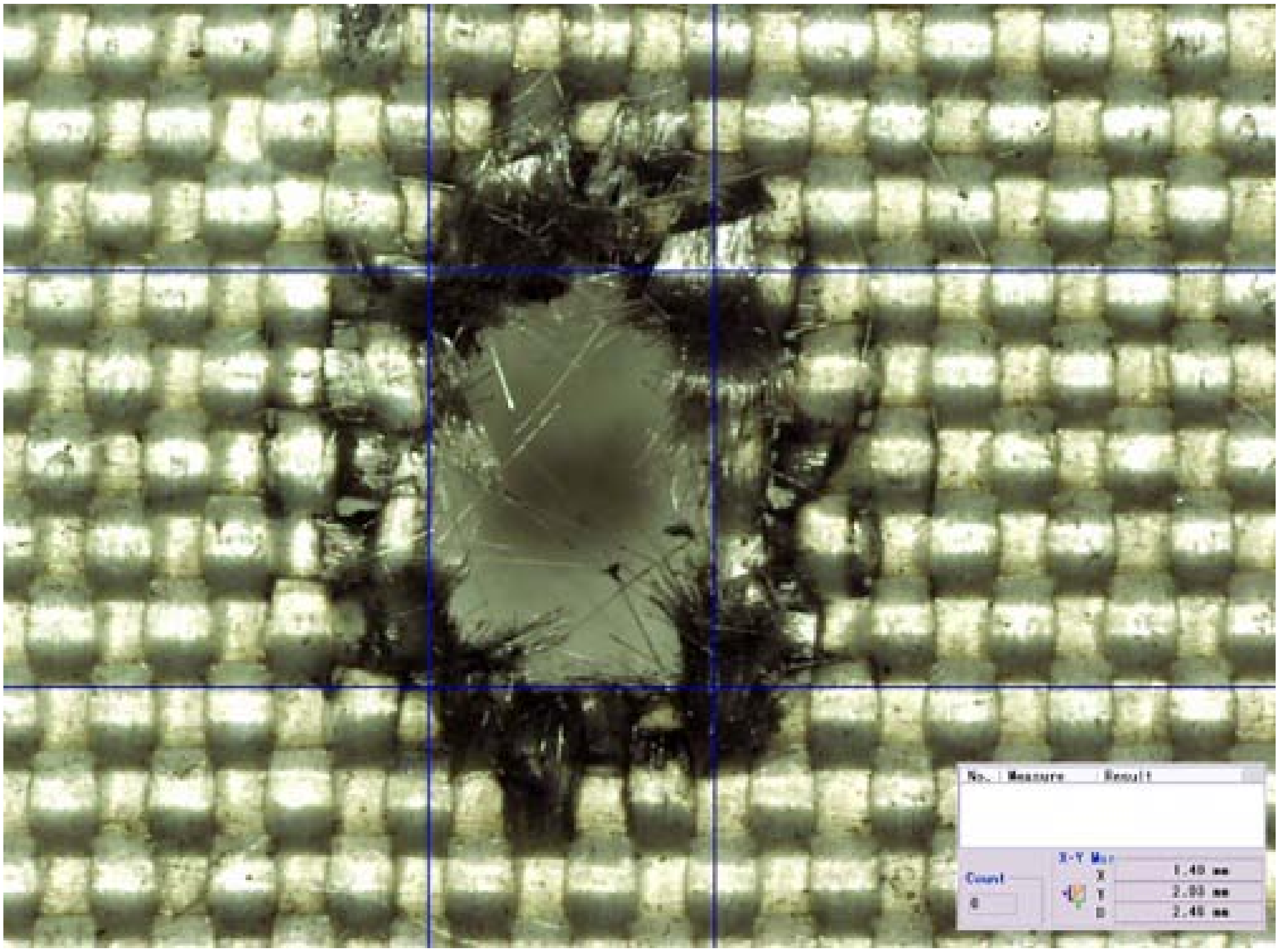


Figure 116: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

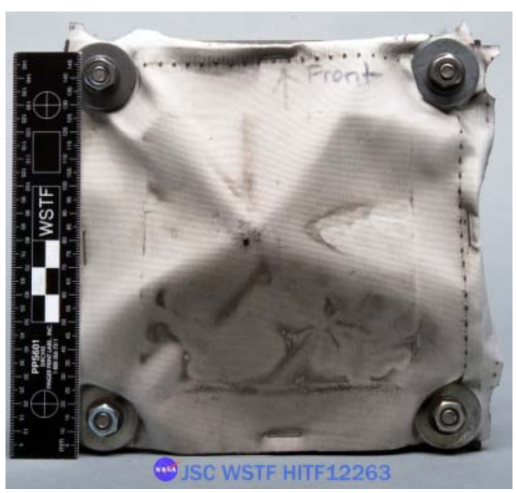


Figure 117: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #7

Test #7, HITF12263

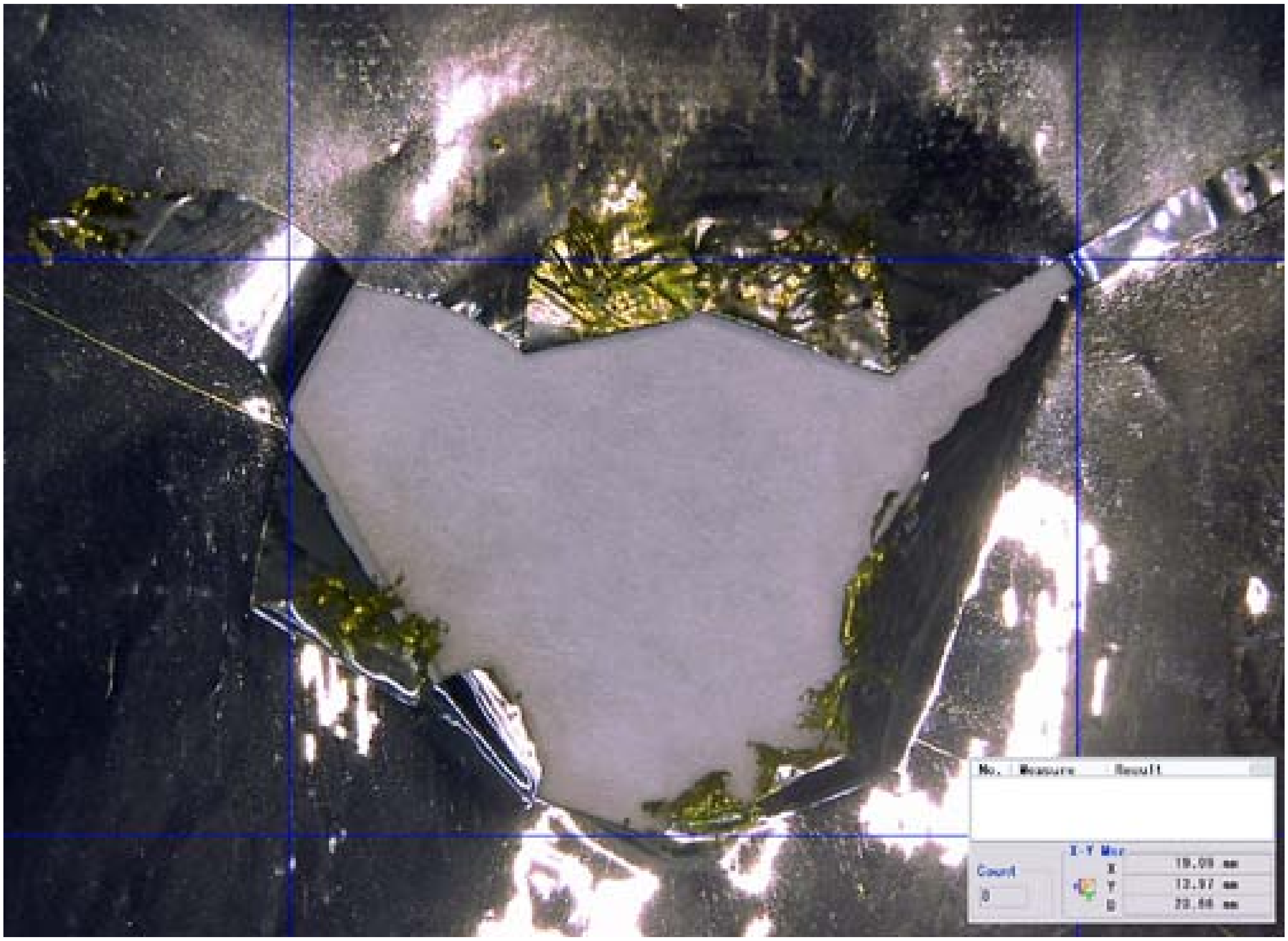


Figure 118: Mylar Film Layer 2 of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263

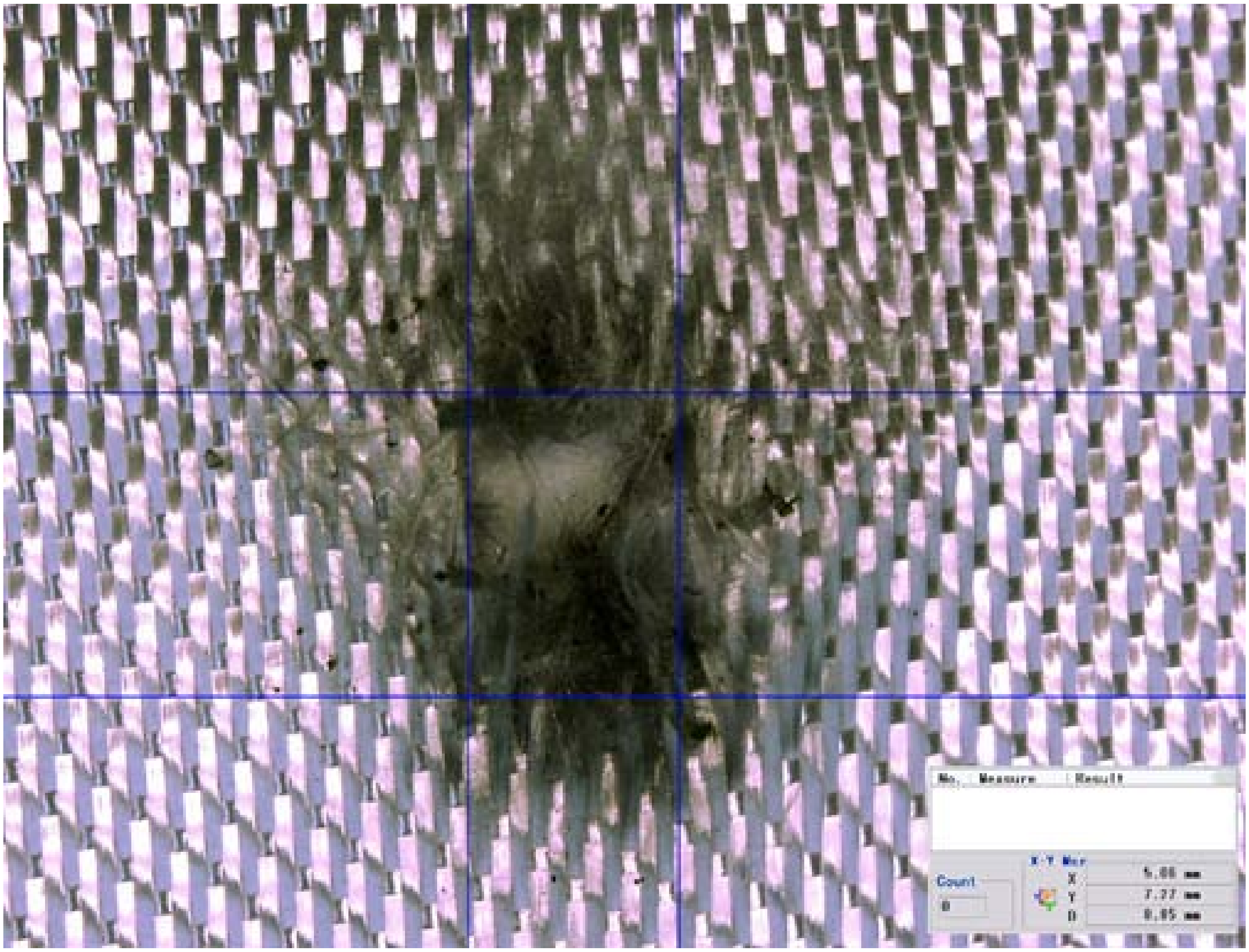


Figure 119: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263

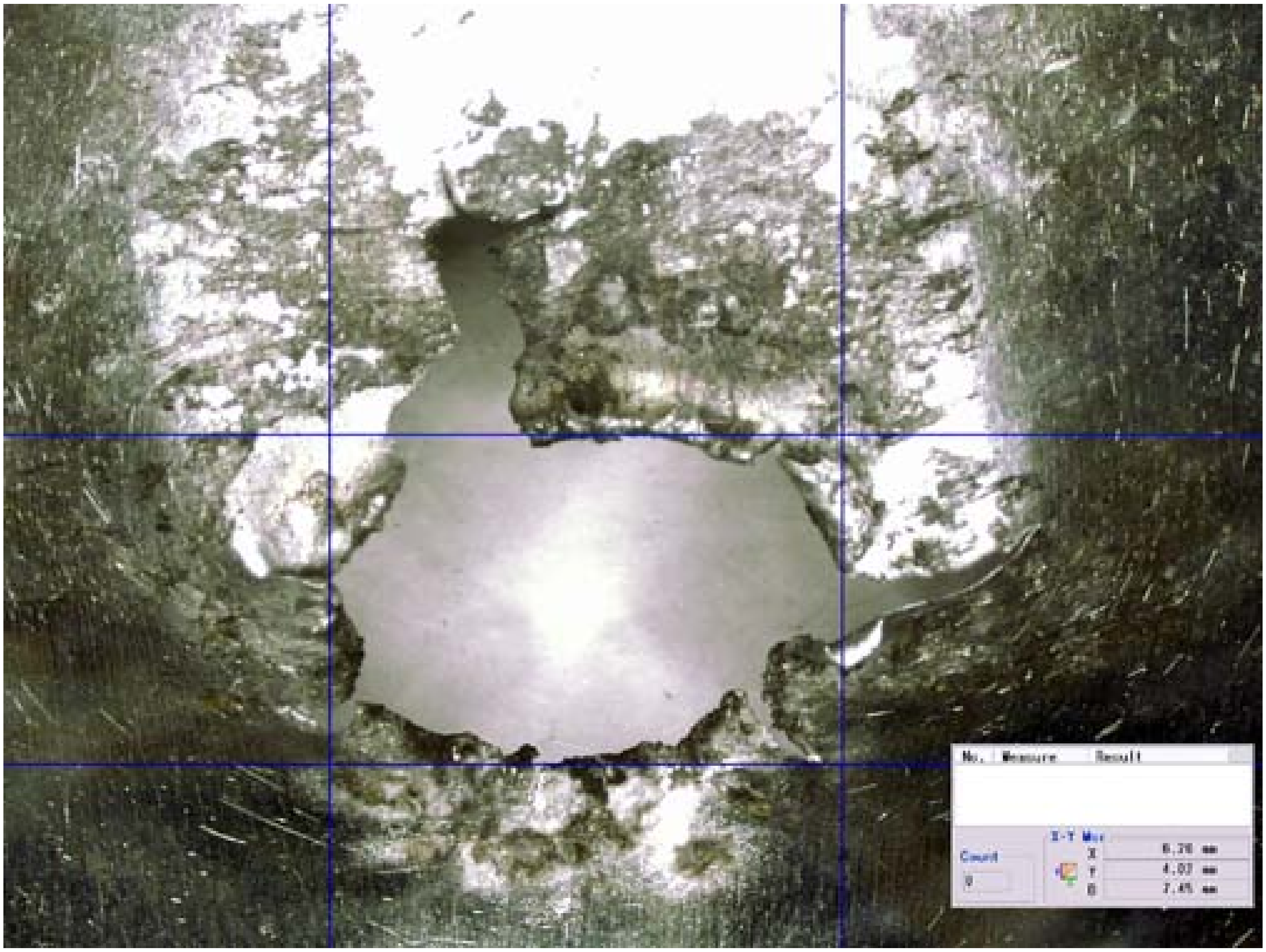


Figure 120: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263

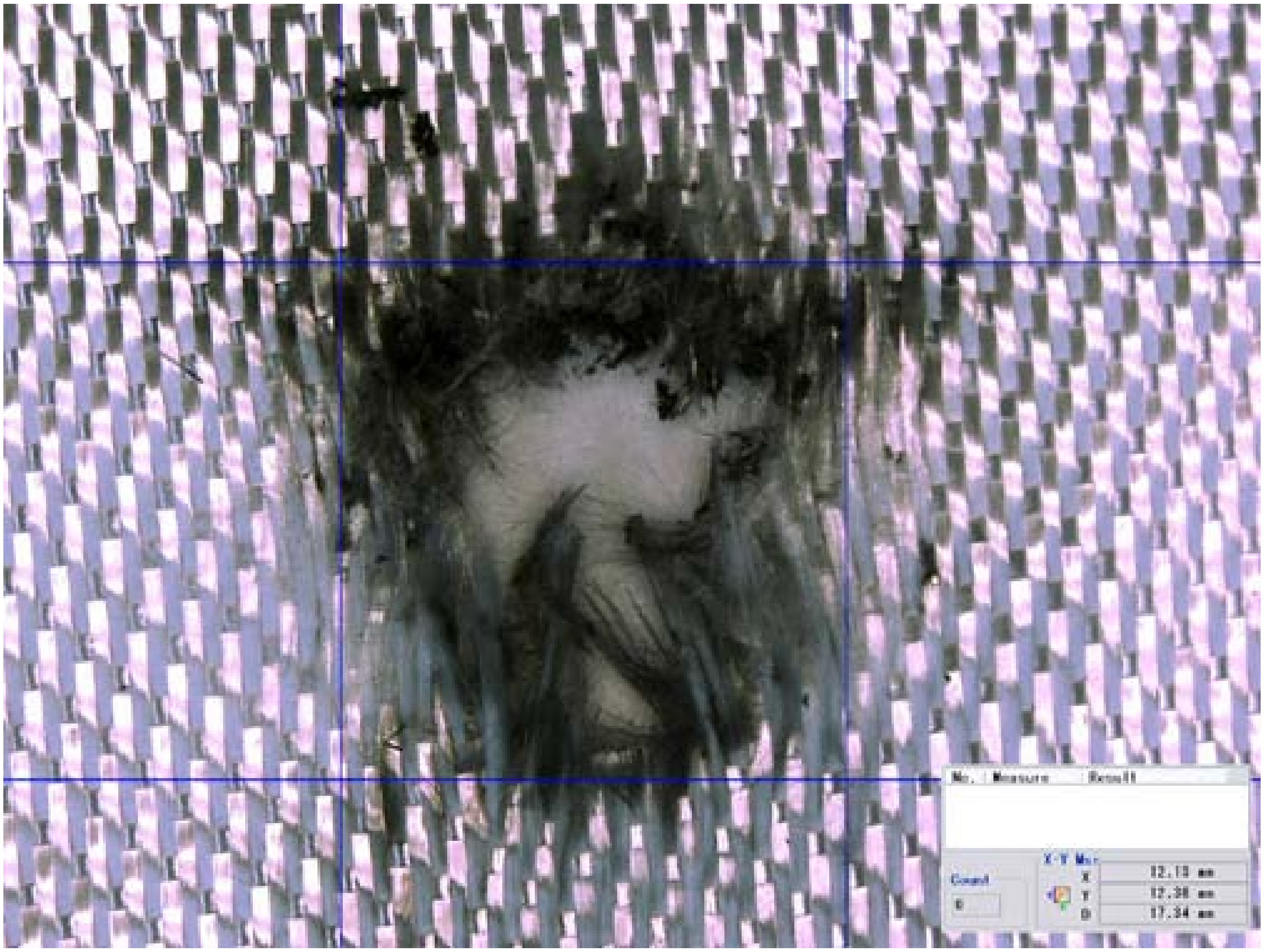


Figure 121: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263

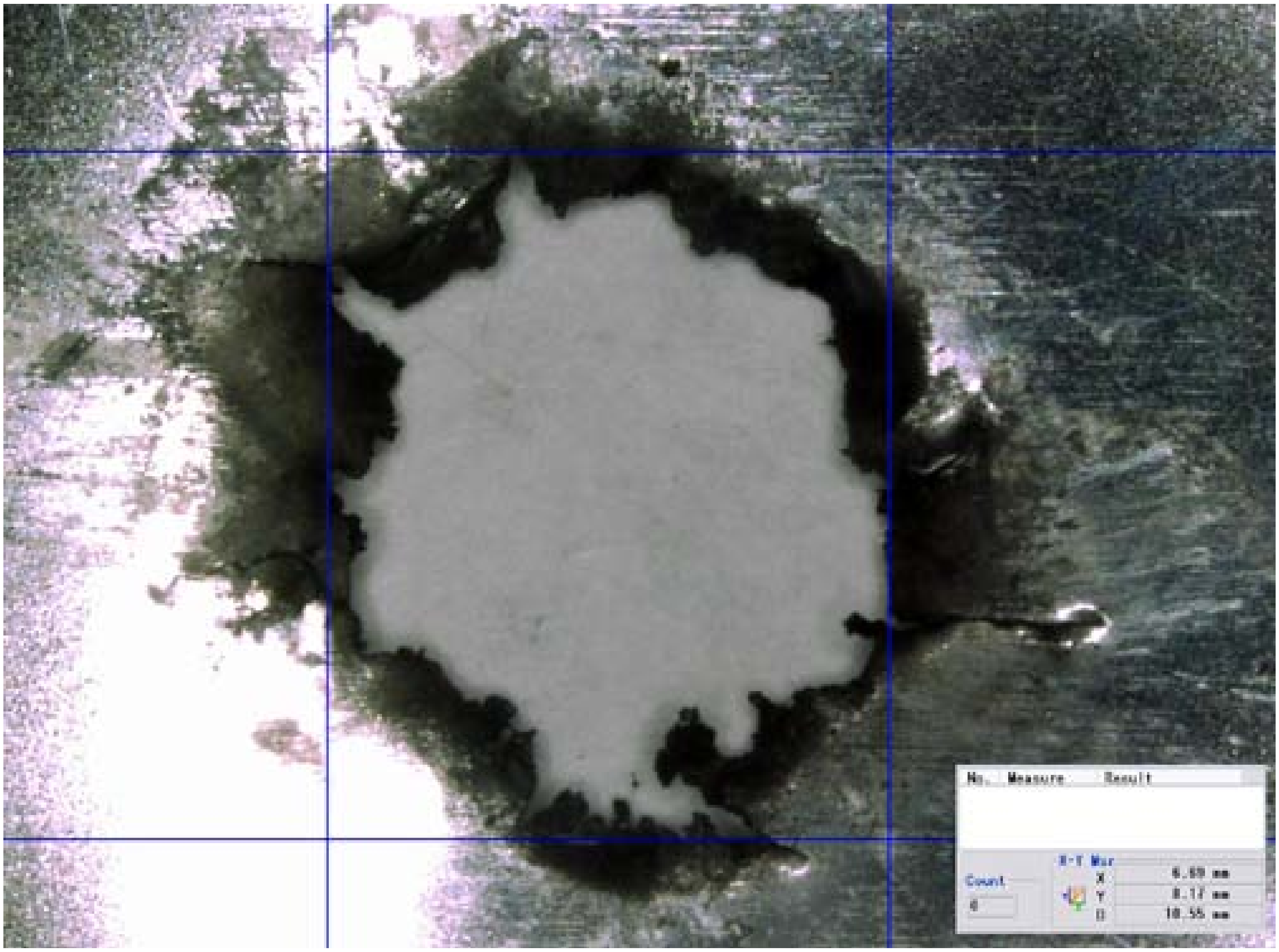


Figure 122: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263

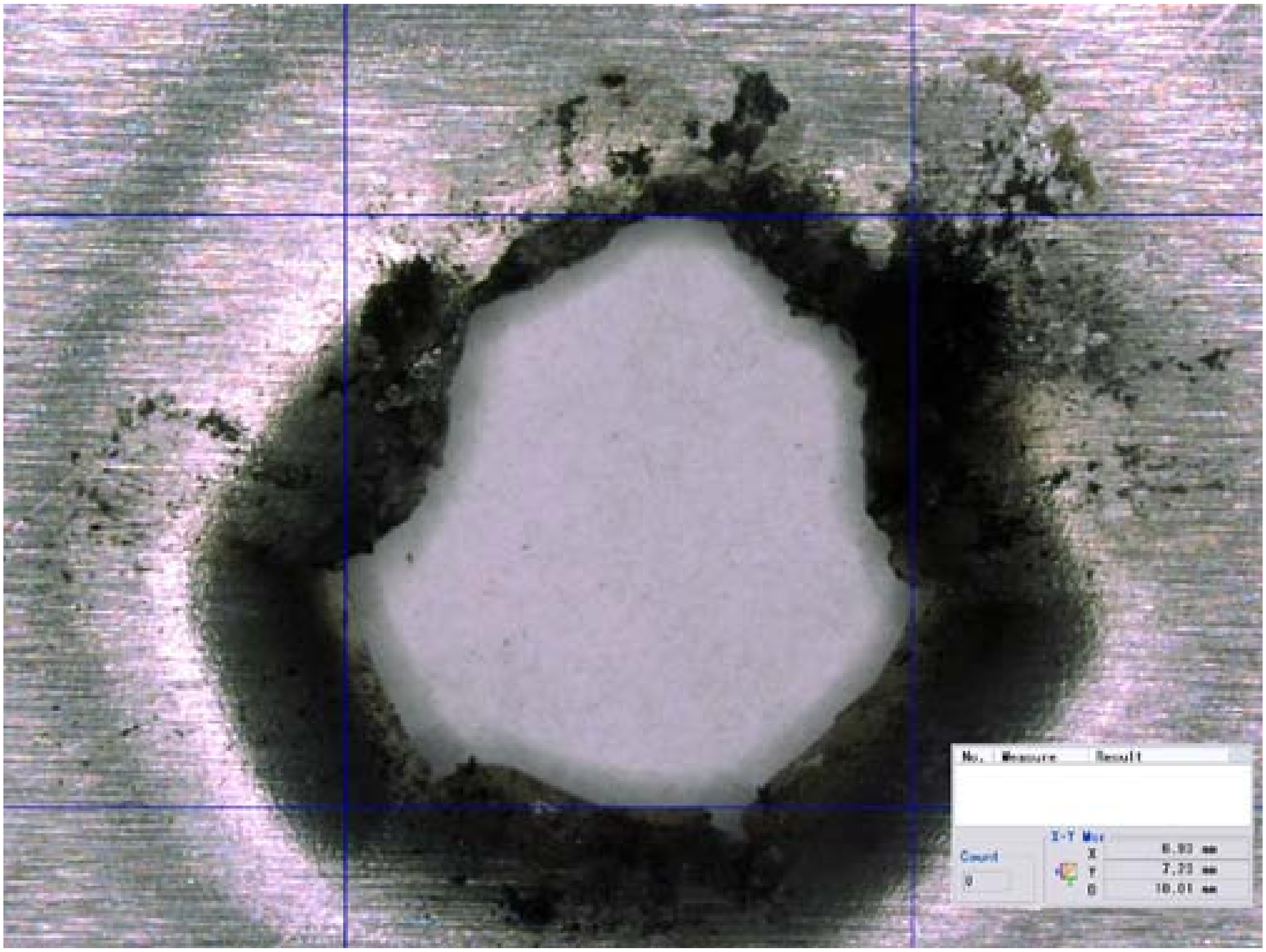


Figure 123: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263

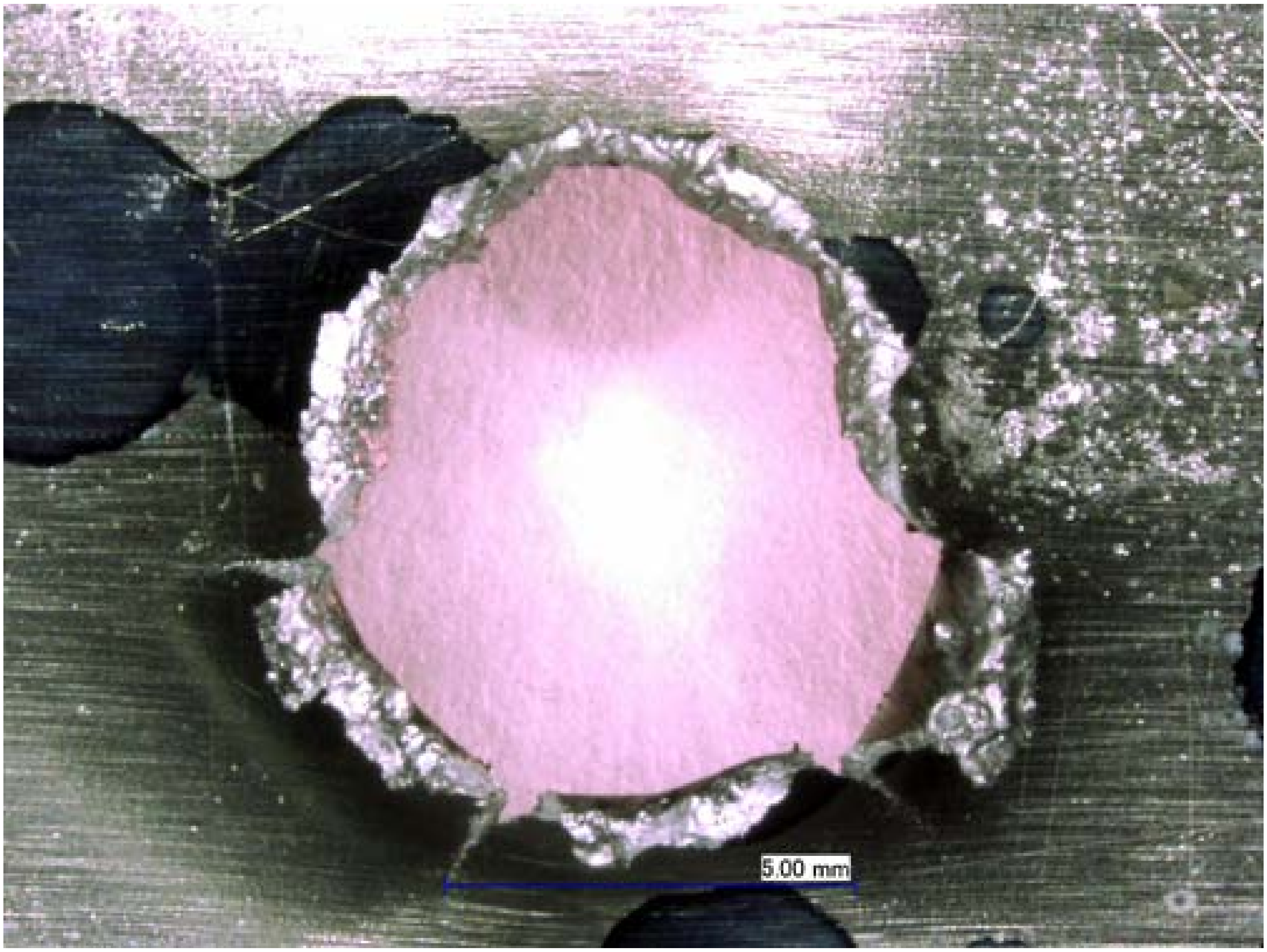


Figure 124: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263 Rear Wall

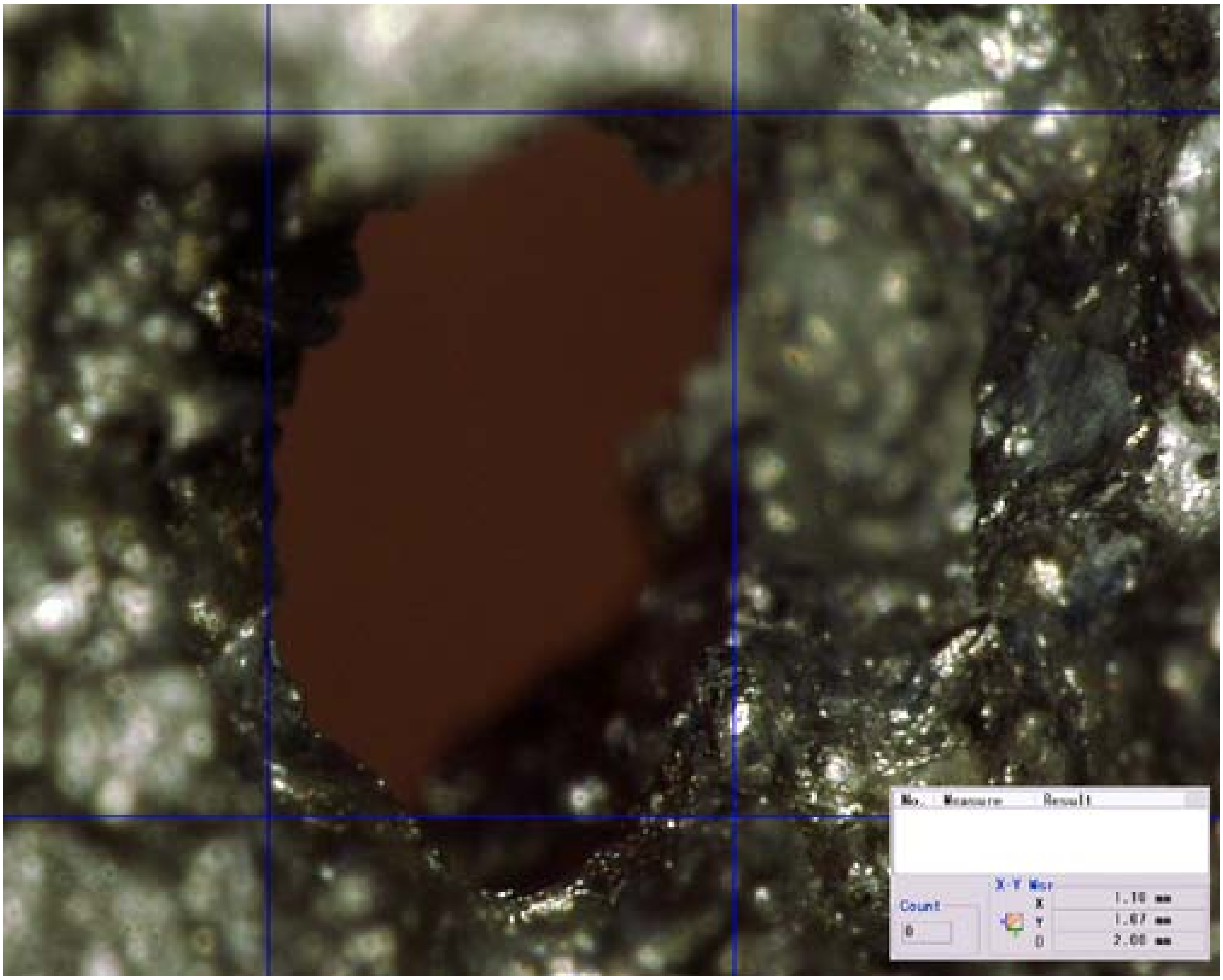


Figure 125: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263

Figure 126: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263

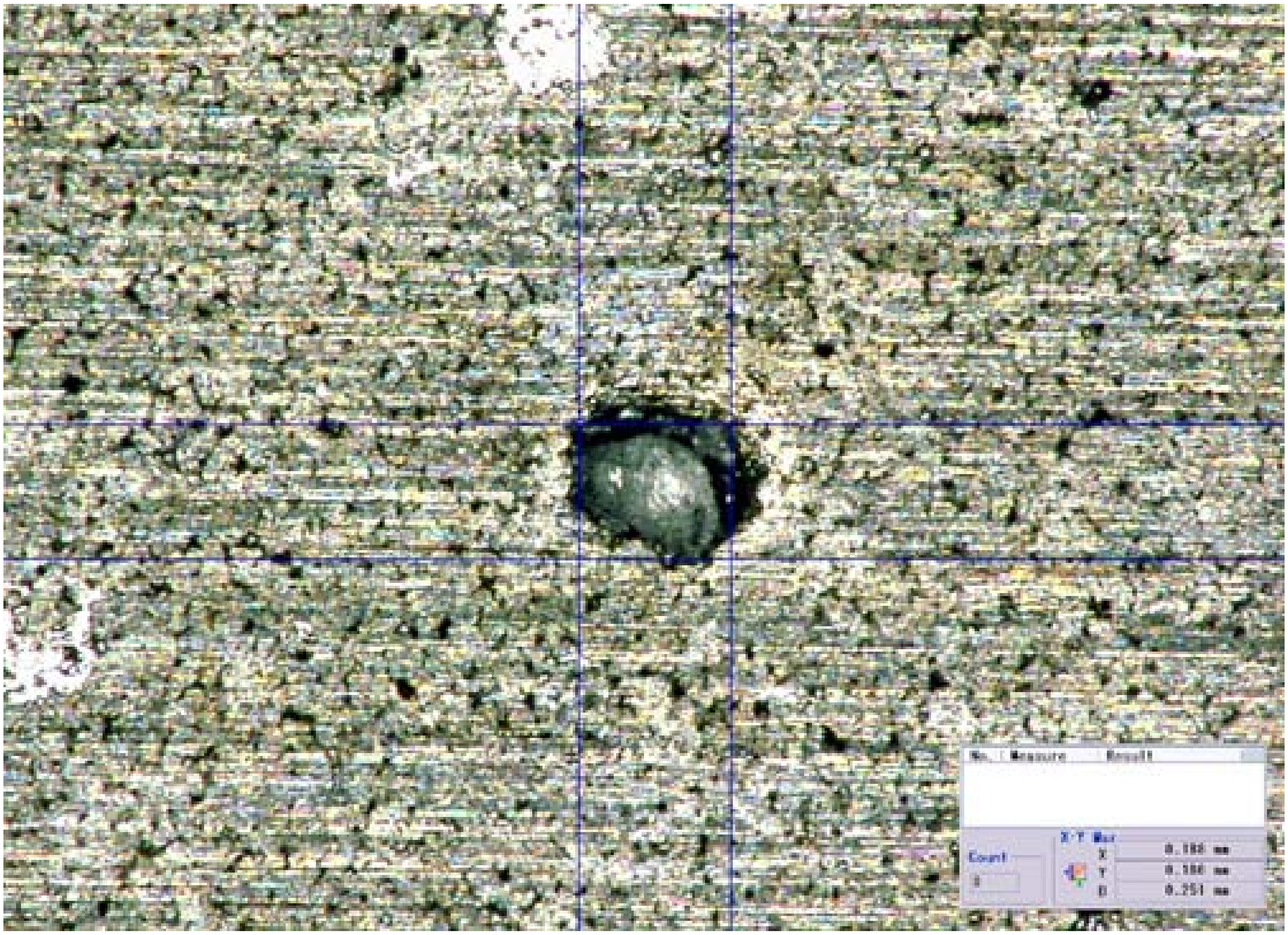


Figure 127: Witness Plate of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263

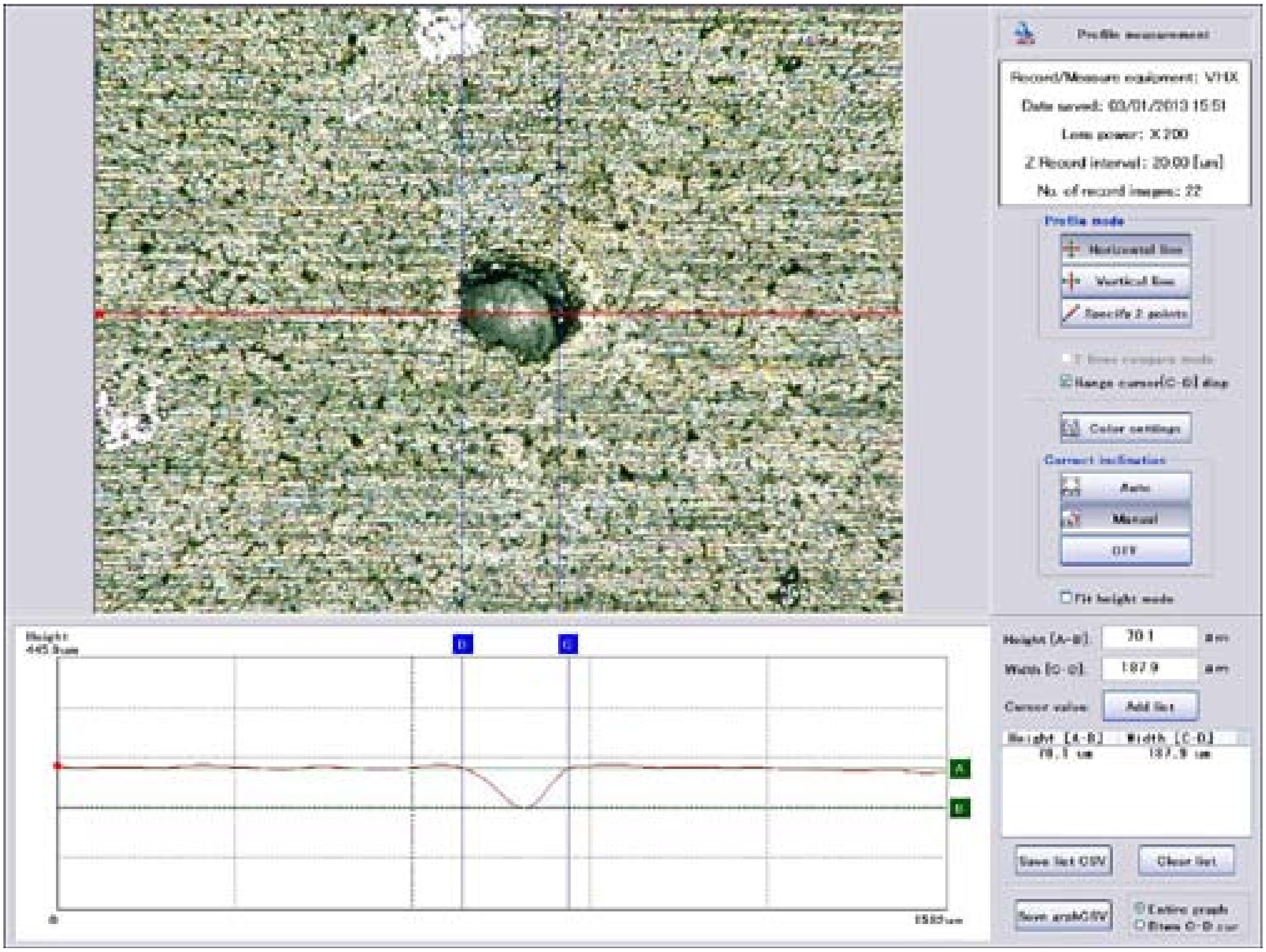


Figure 128: Witness Plate of ISS Soyuz OM Test #7 (Keyence 3D Microscope Image)

Test #7, HITF12263

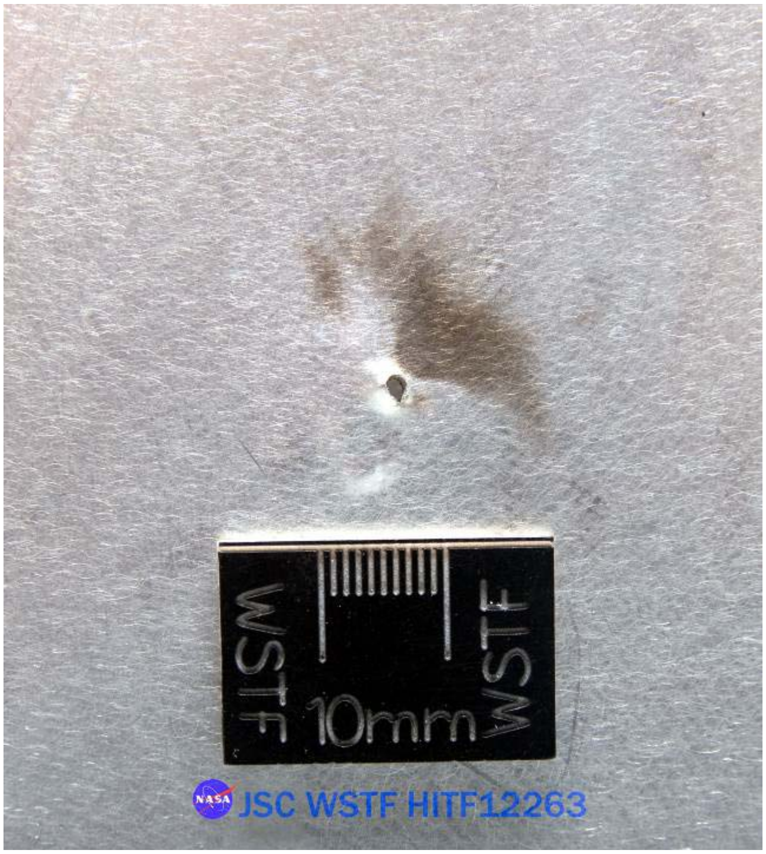


Figure 129: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #7

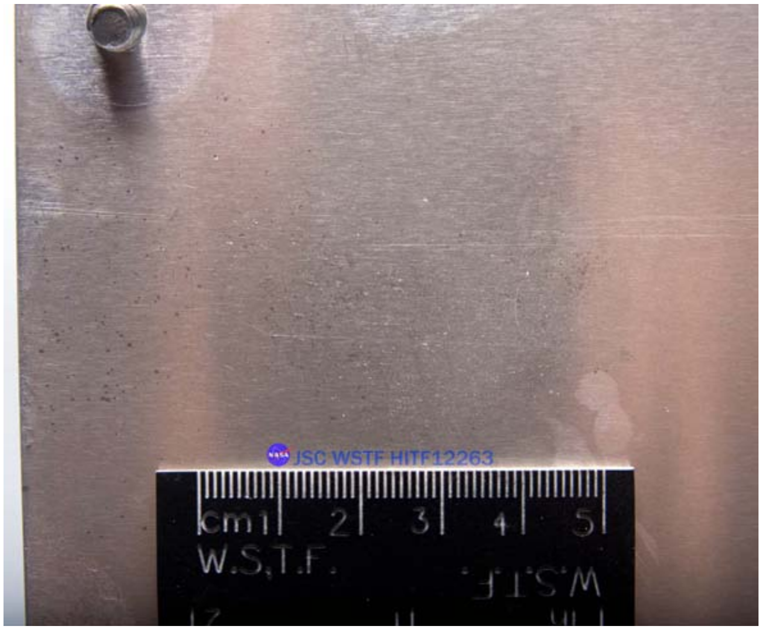


Figure 130: Front Witness Plate View of ISS Soyuz Orbital Module Test #7

Test #8, HITF12264

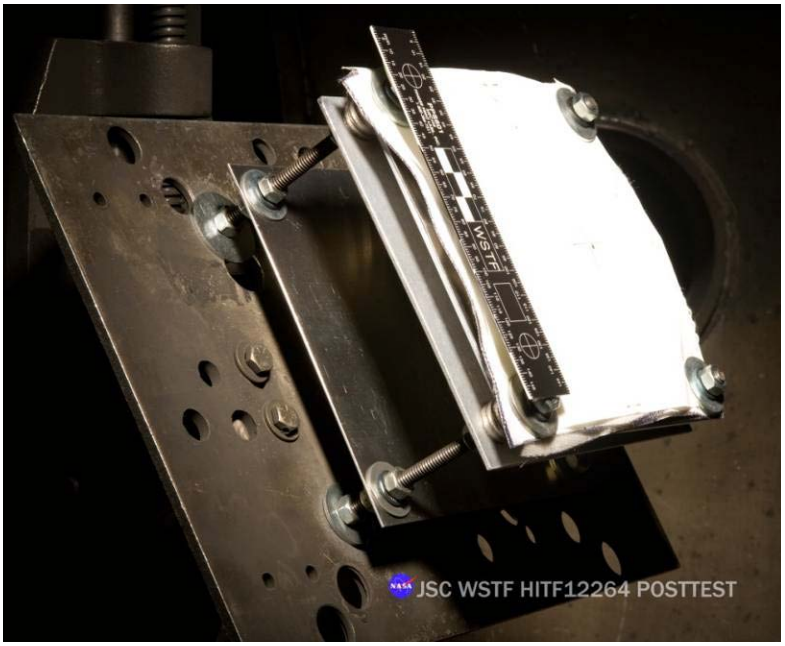


Figure 131: Post-test of ISS Soyuz Orbital Module Test #8 (HITF12264) article mounted in 0.17-caliber target tank.

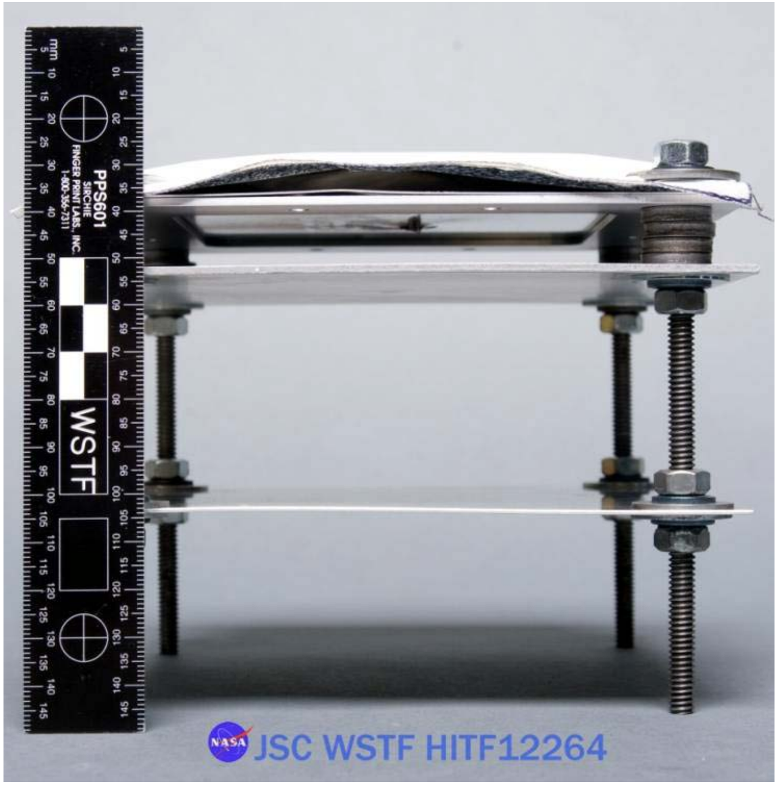


Figure 132: Side View of ISS Soyuz Orbital Module Test #8

Test #8, HITF12264

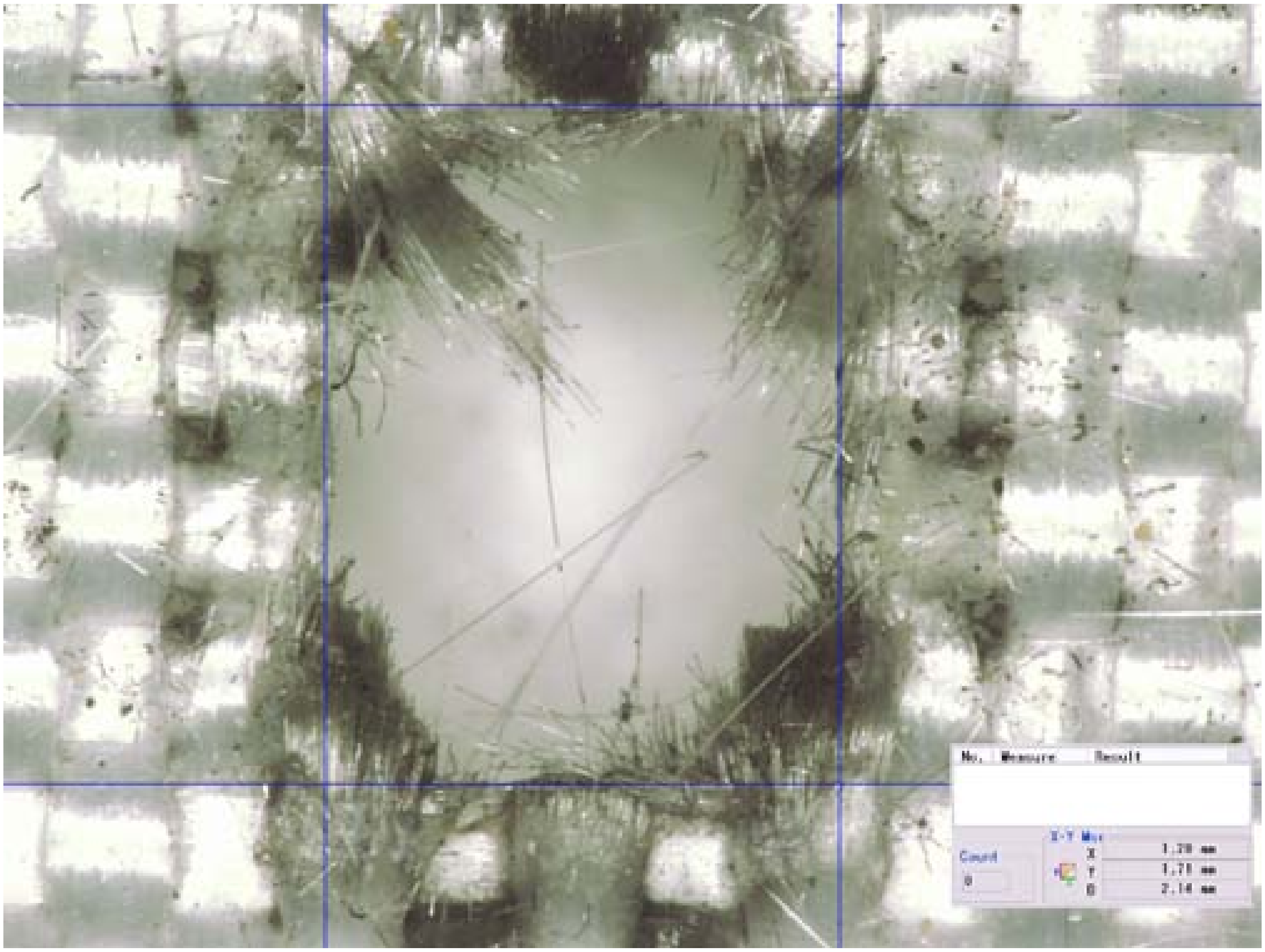


Figure 133: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

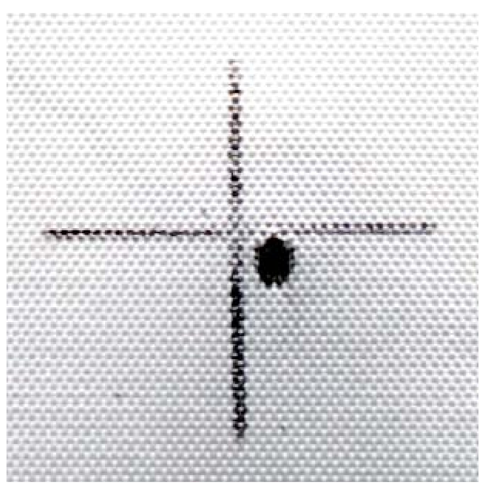


Figure 134: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #8

Test #8, HITF12264

Figure 135: Mylar Film Layer 2 of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264

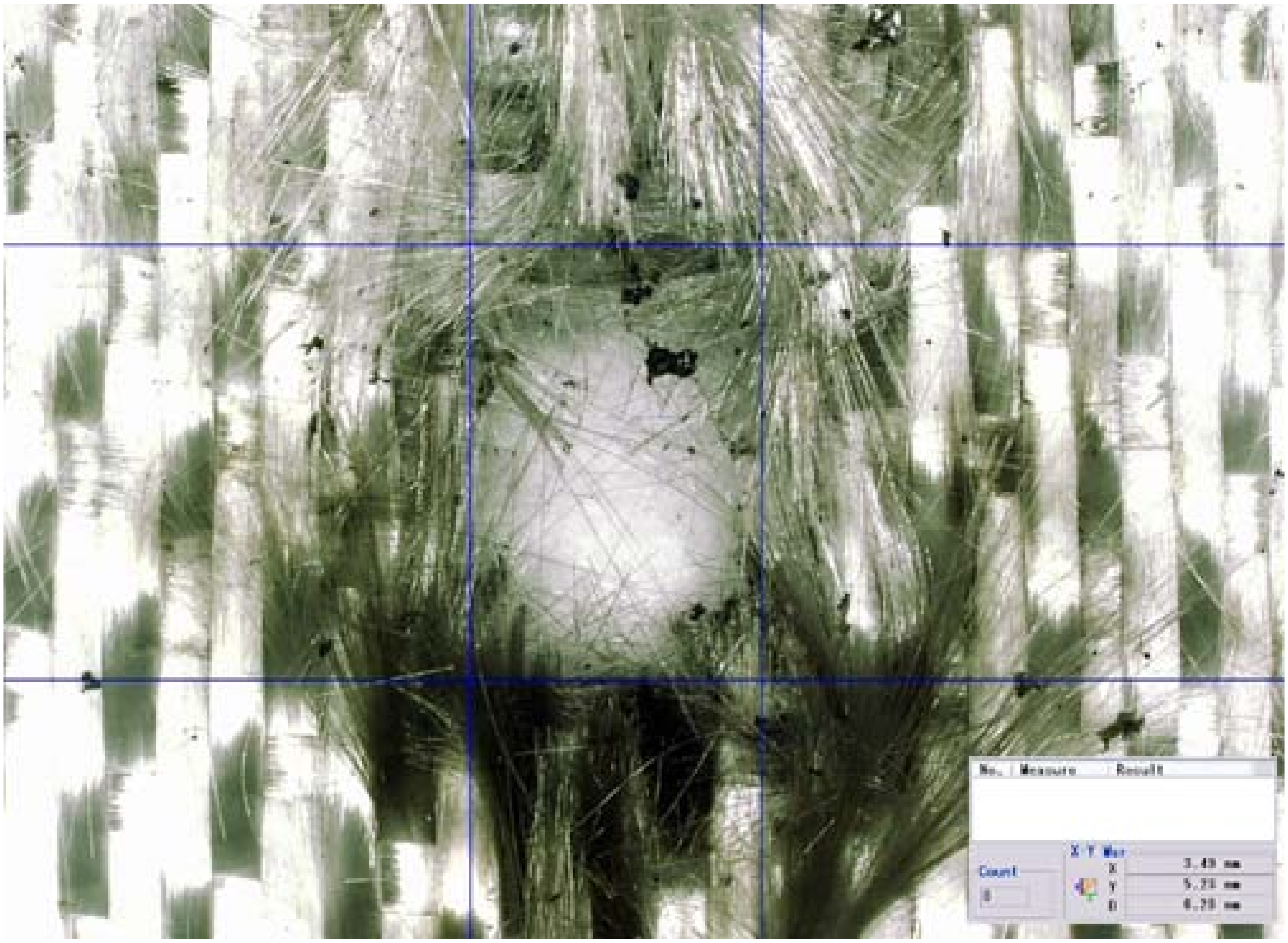


Figure 136: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264

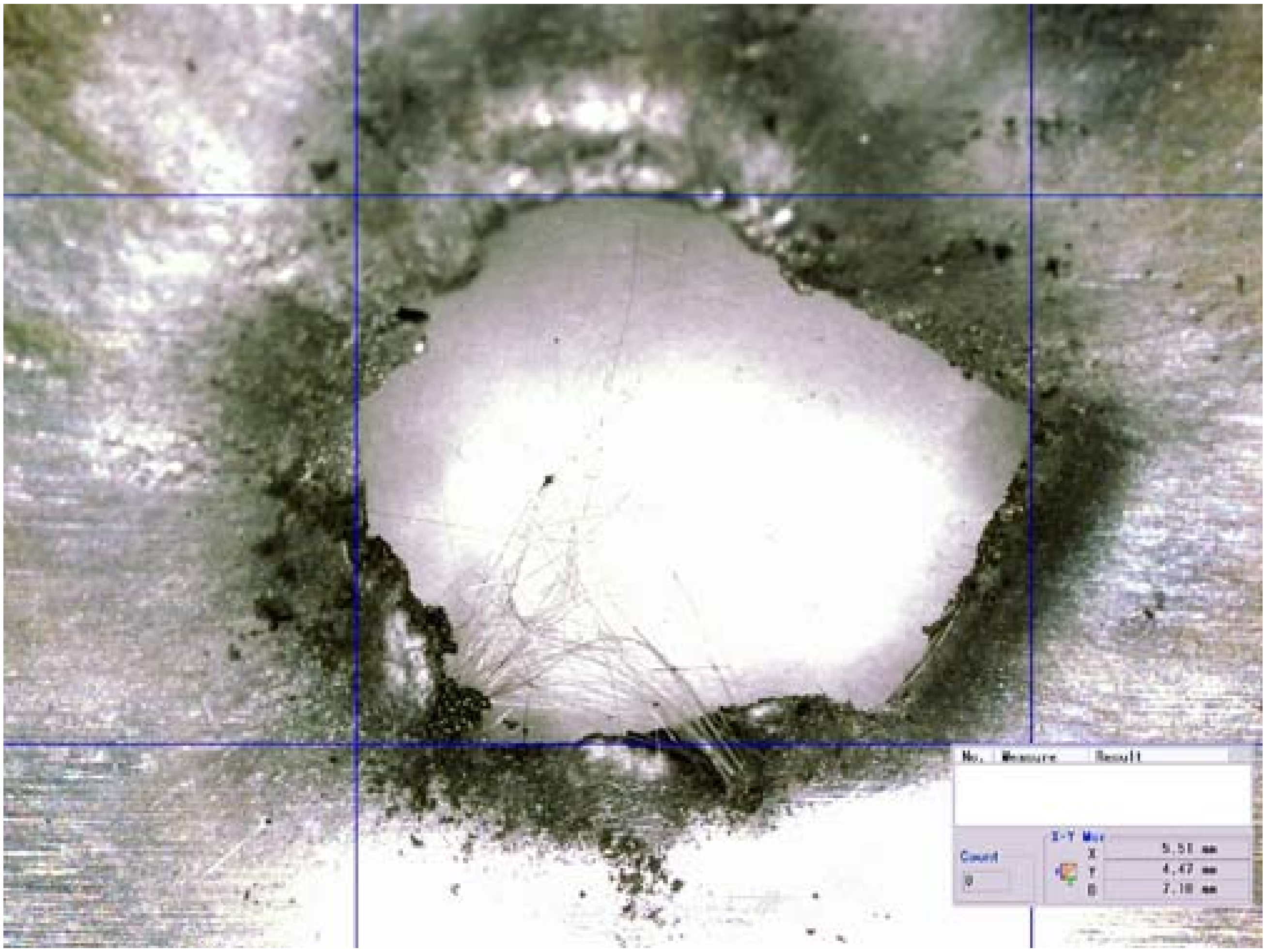


Figure 137: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264

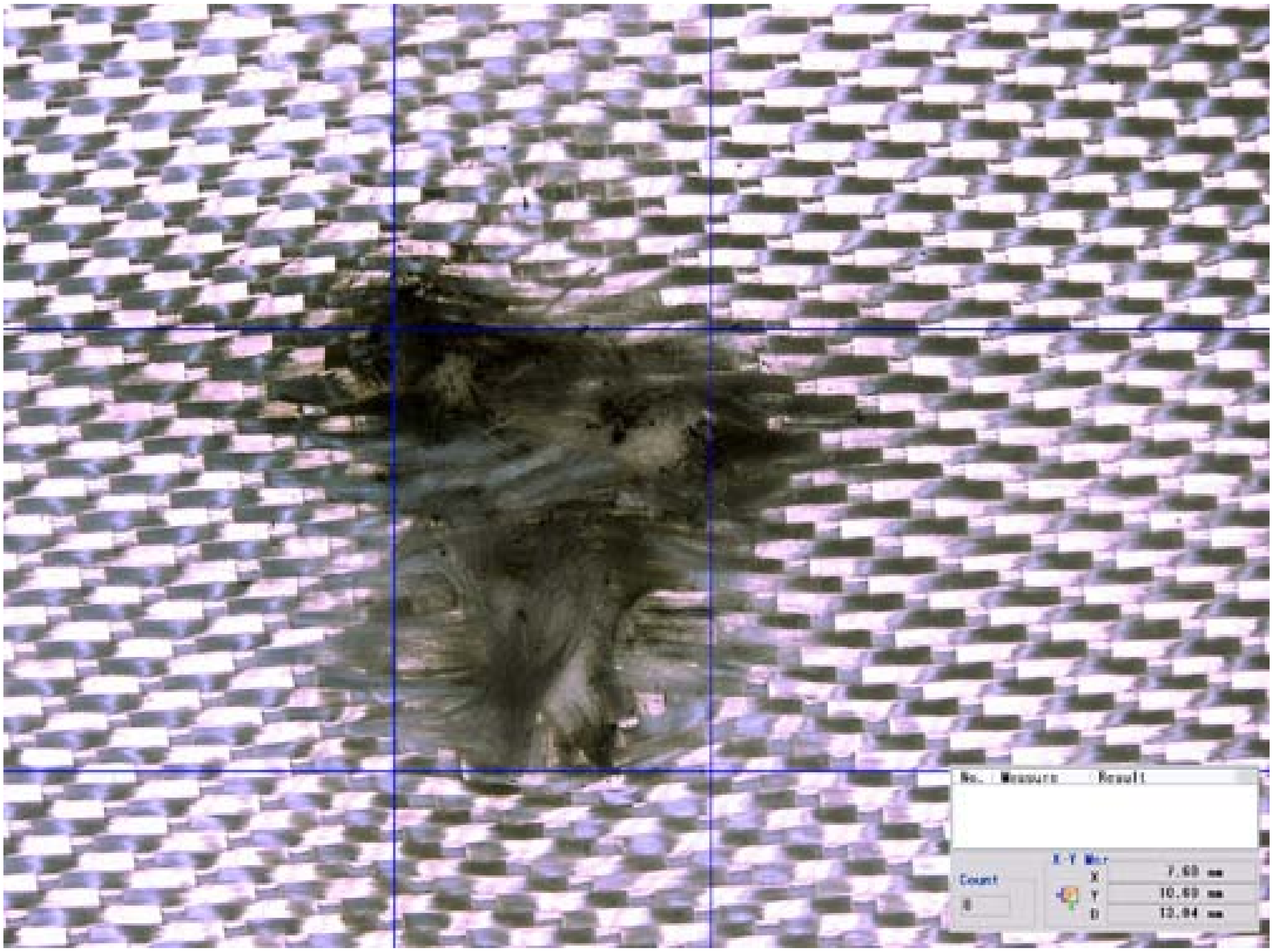


Figure 138: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264

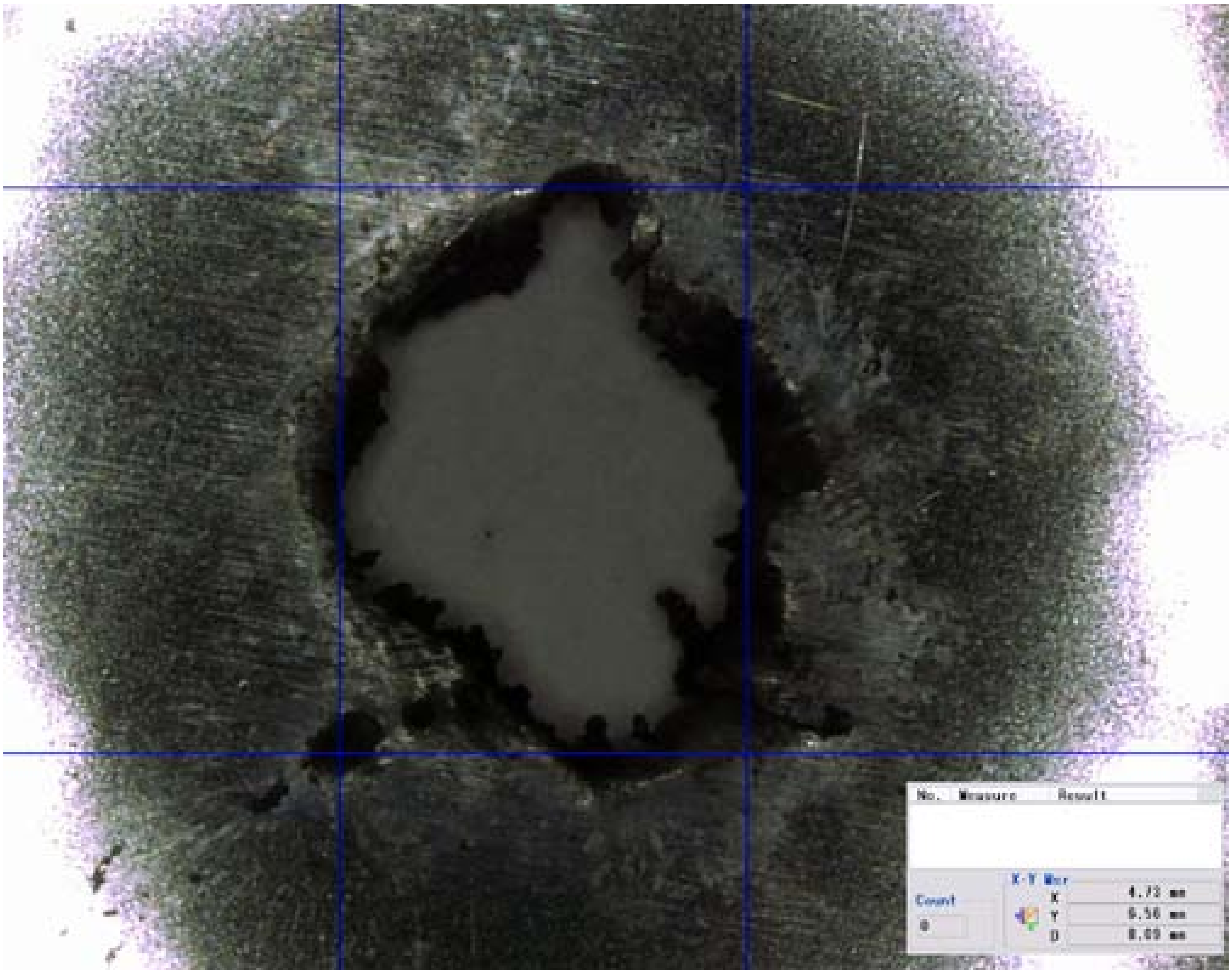


Figure 139: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264

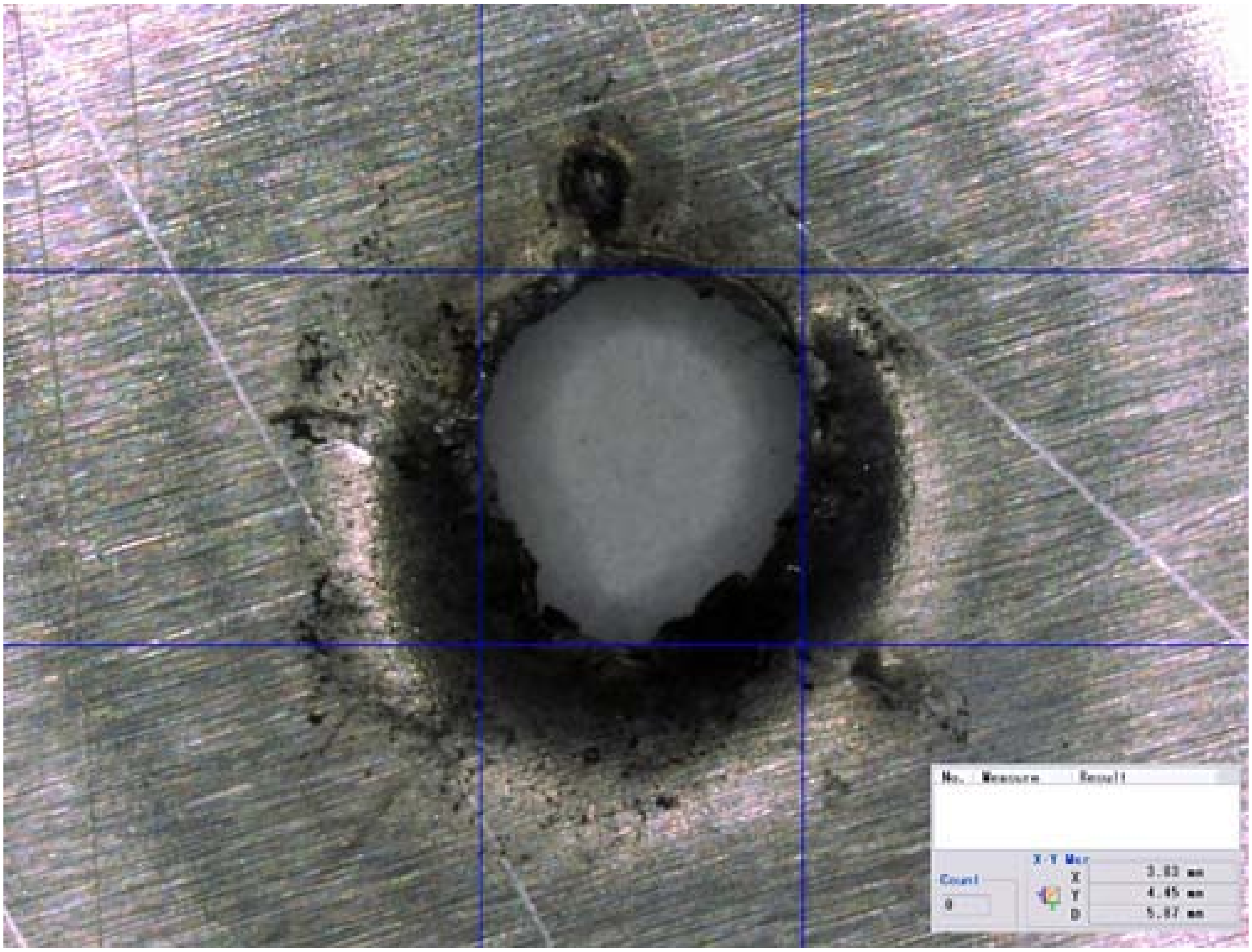


Figure 140: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264

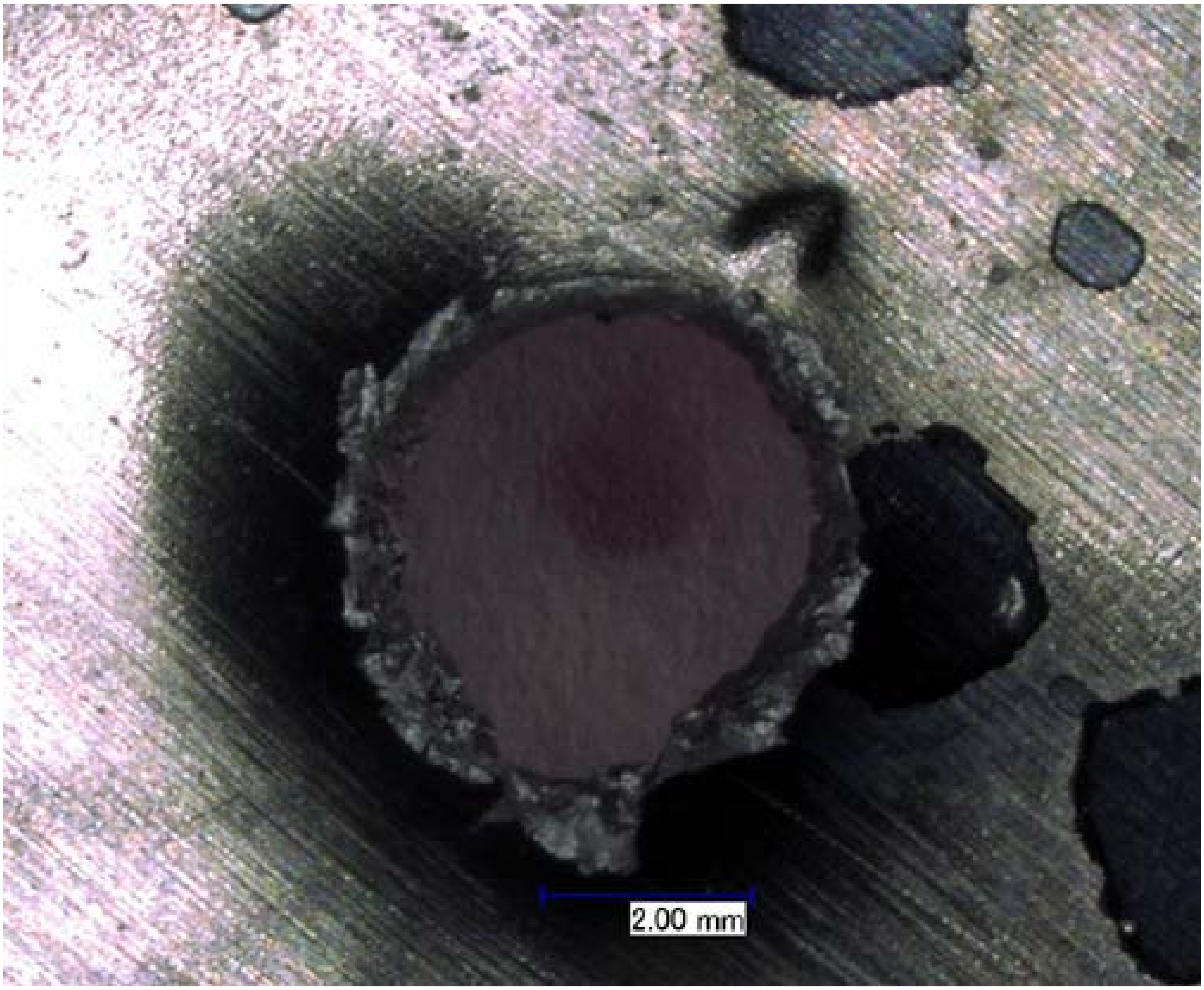


Figure 141: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264 Rear Wall

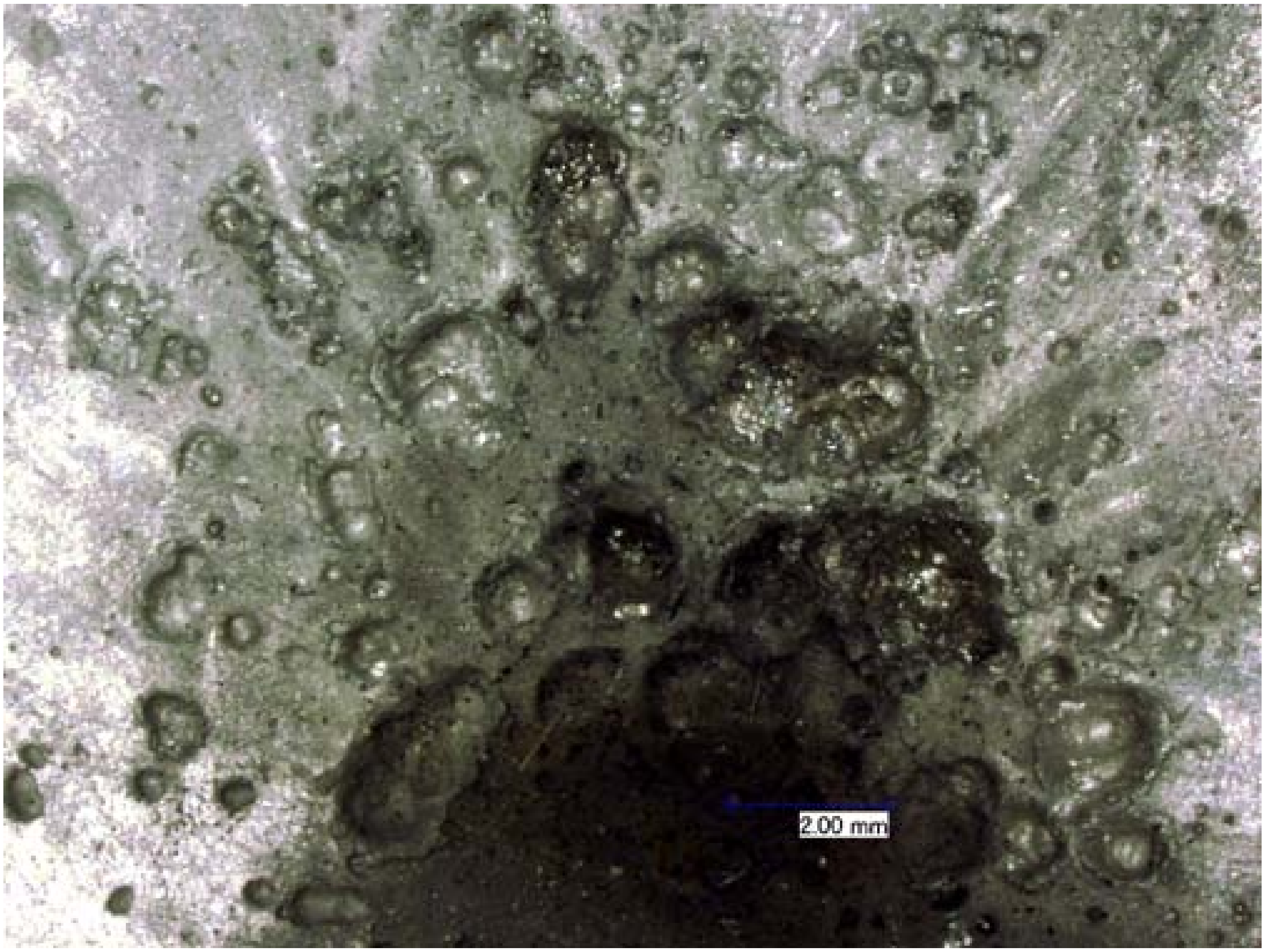


Figure 142: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264

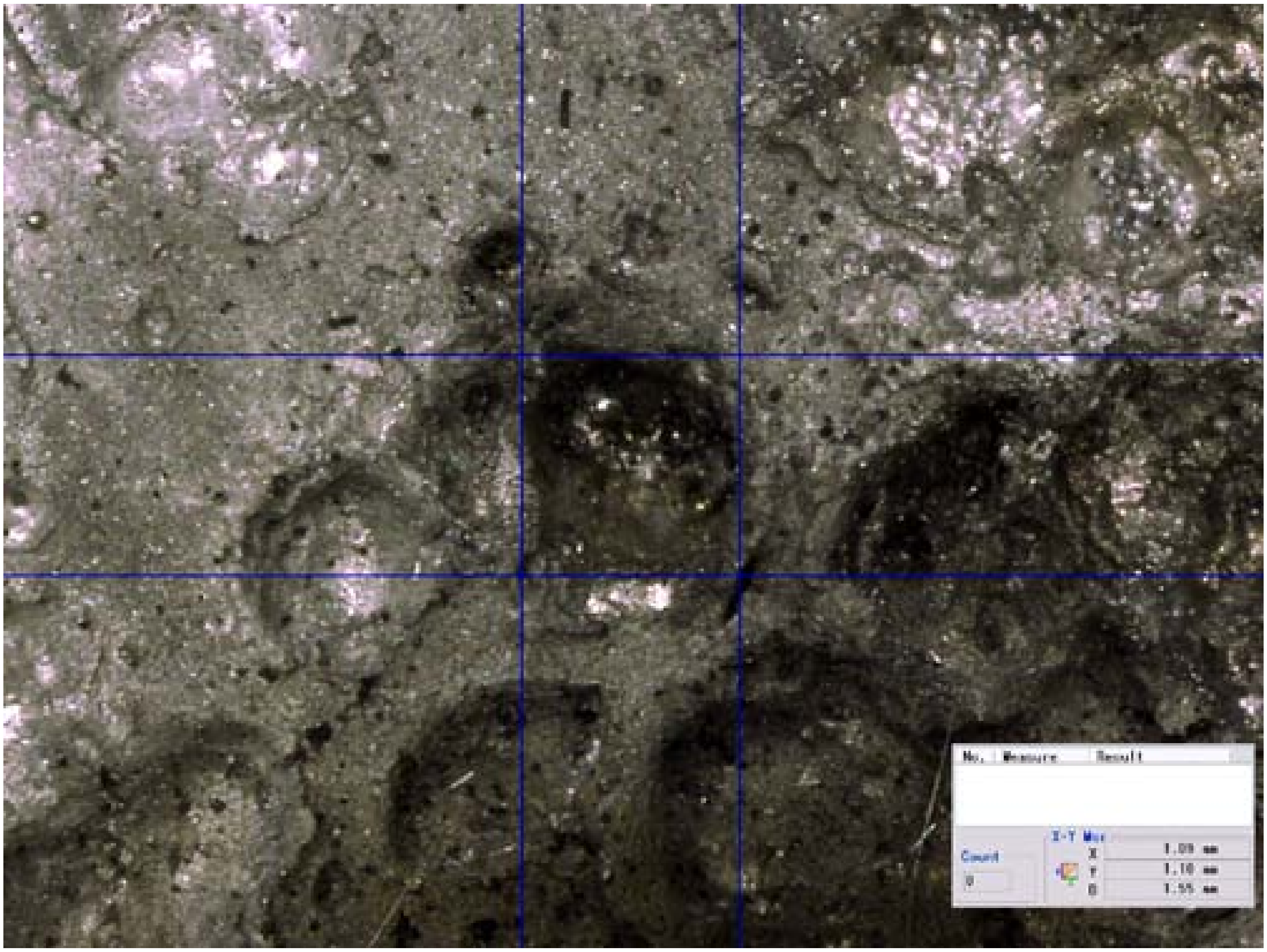


Figure 143: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264

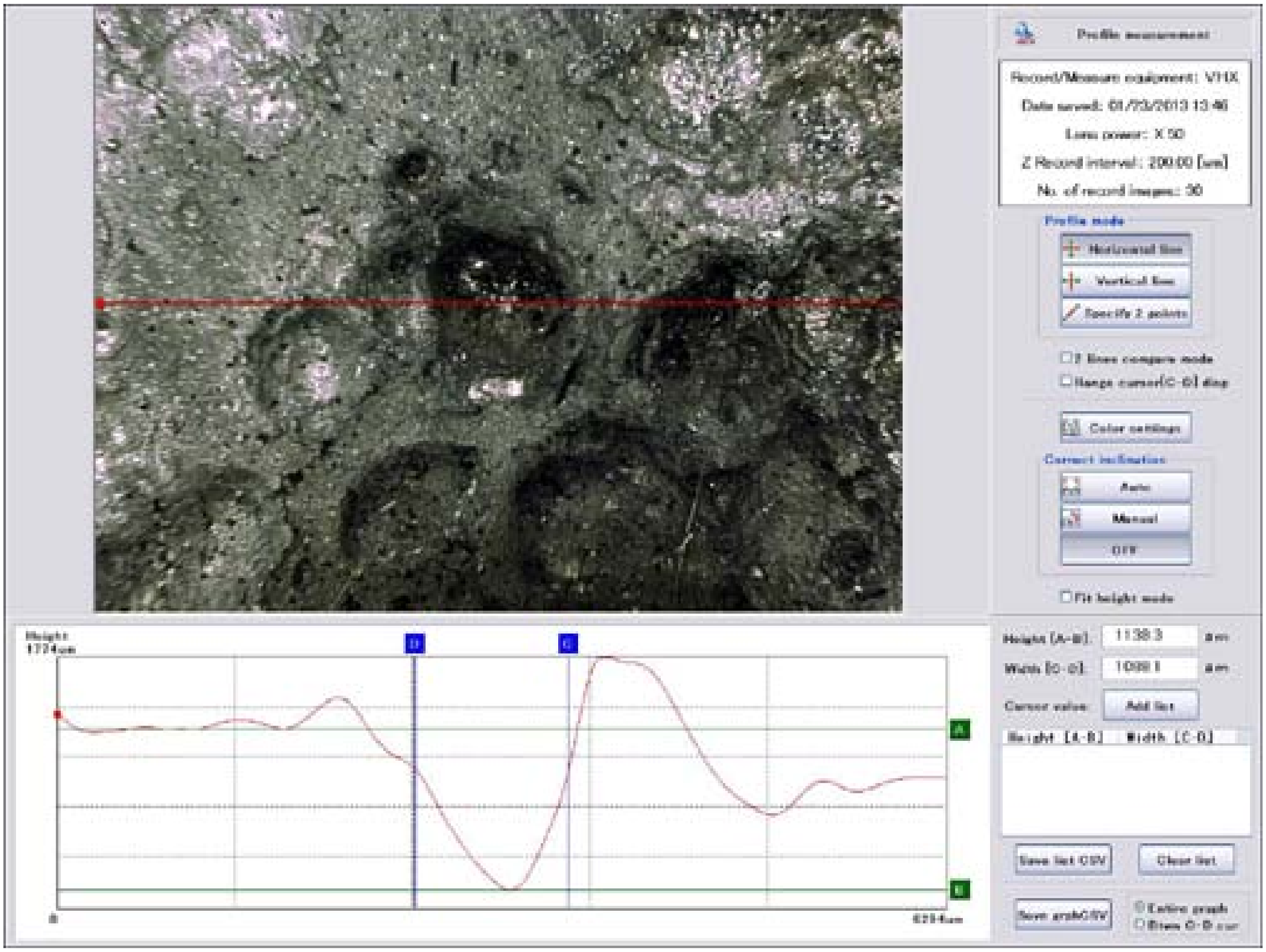


Figure 144: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264

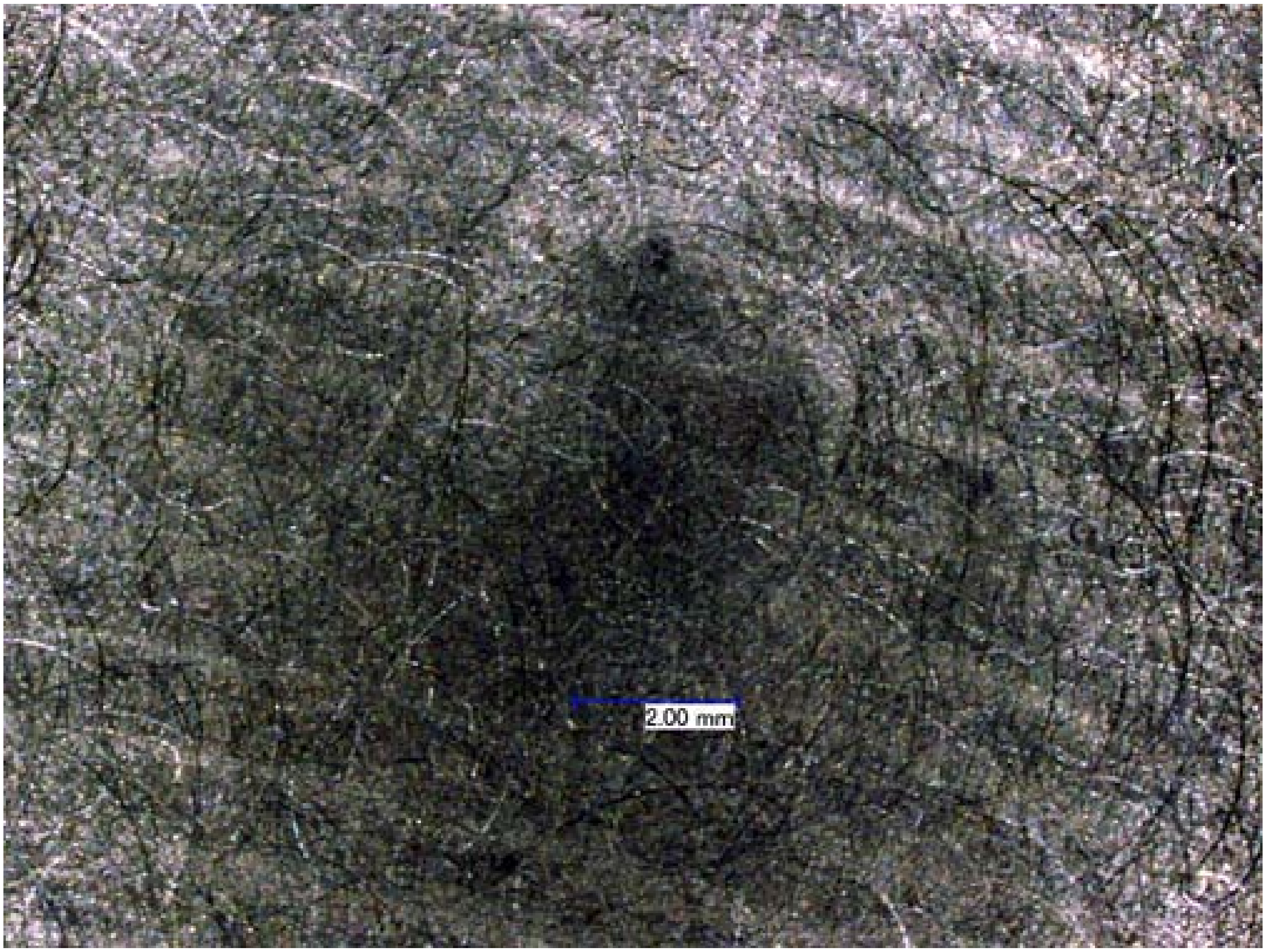


Figure 145: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #8 (Keyence 3D Microscope Image)

Test #8, HITF12264

Figure 146: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #8

Test #9, HITF12265

Figure 147: Post-test of ISS Soyuz Orbital Module Test #9 (HITF12265) article mounted in 0.50-caliber target tank.

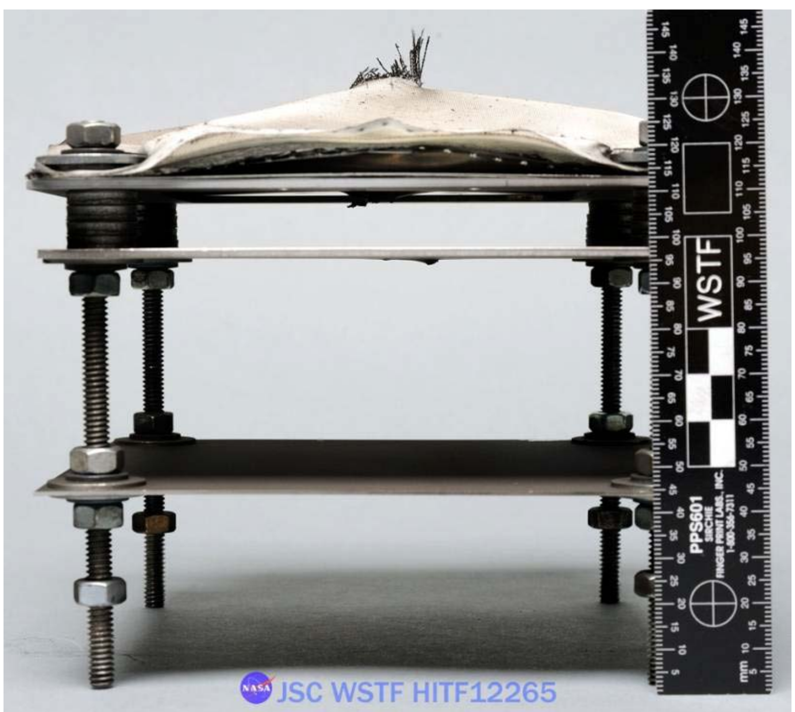


Figure 148: Side View of ISS Soyuz Orbital Module Test #9

Test #9, HITF12265

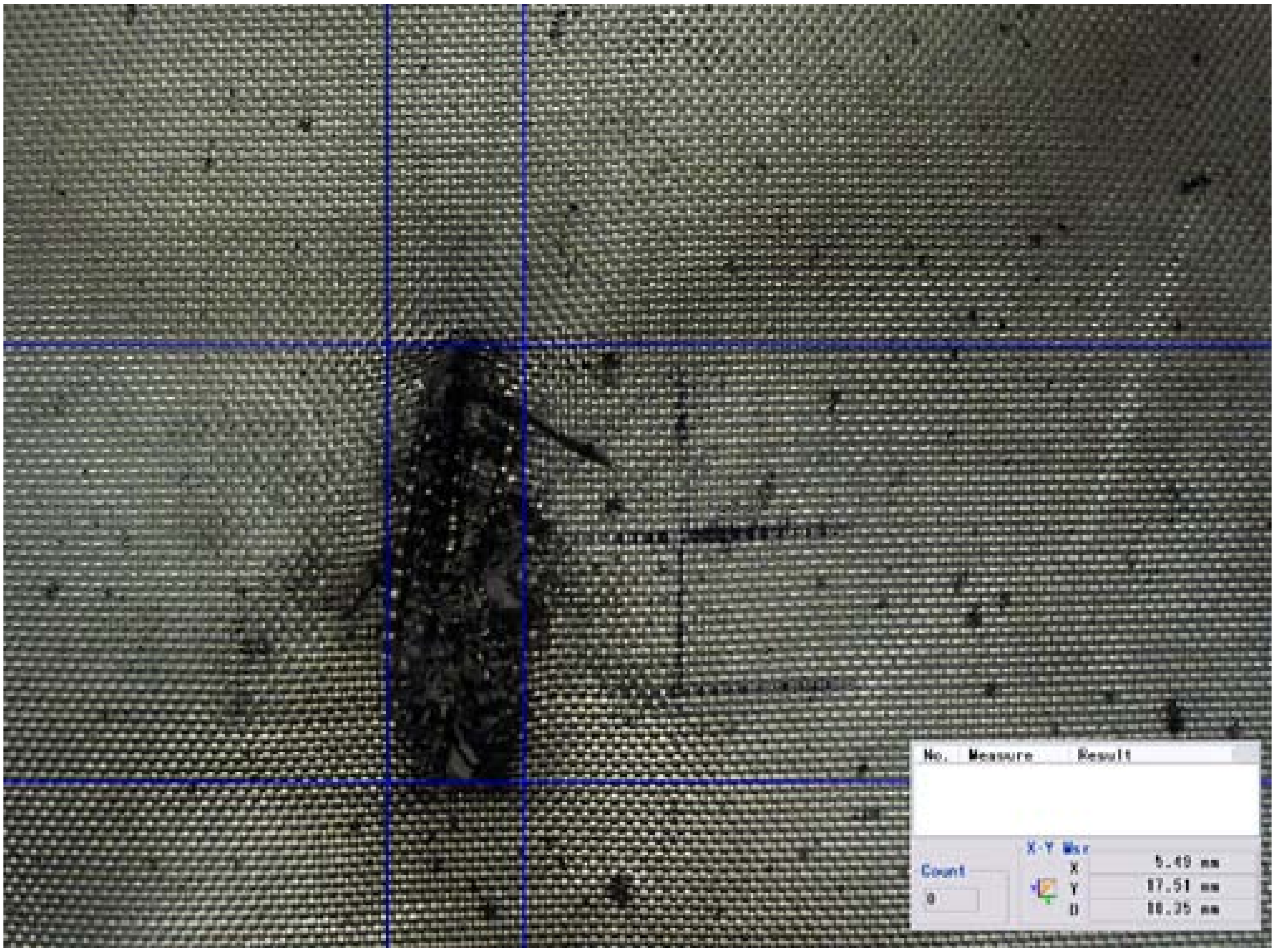


Figure 149: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #9 (Keyence 3D Microscope Image)

Figure 150: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #9

Test #9, HITF12265

Figure 151: Mylar Film Layer 2 of ISS Soyuz OM Test #9 (Keyence 3D Microscope Image)

Test #9, HITF12265

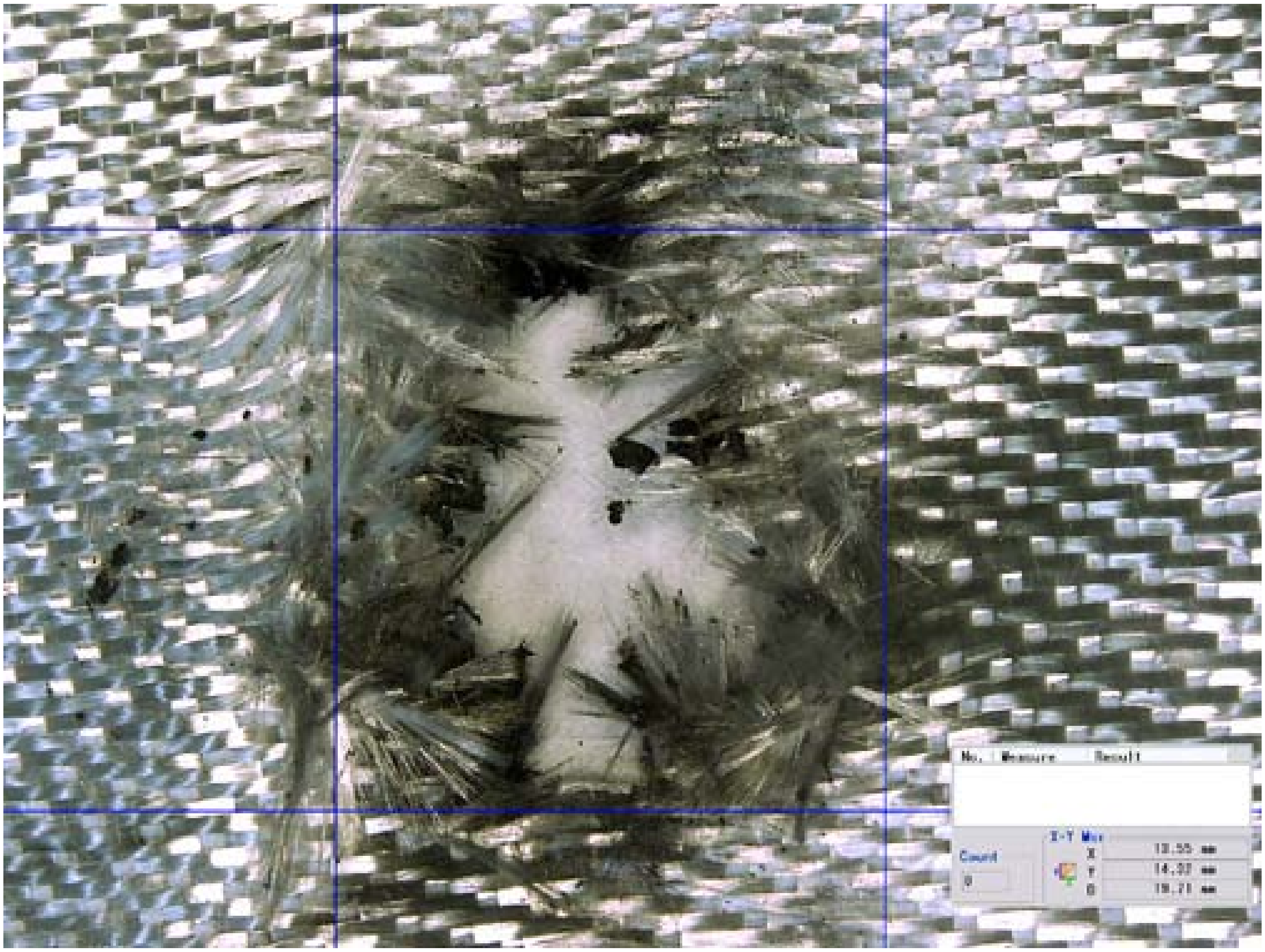


Figure 152: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #9 (Keyence 3D Microscope Image)

Test #9, HITF12265

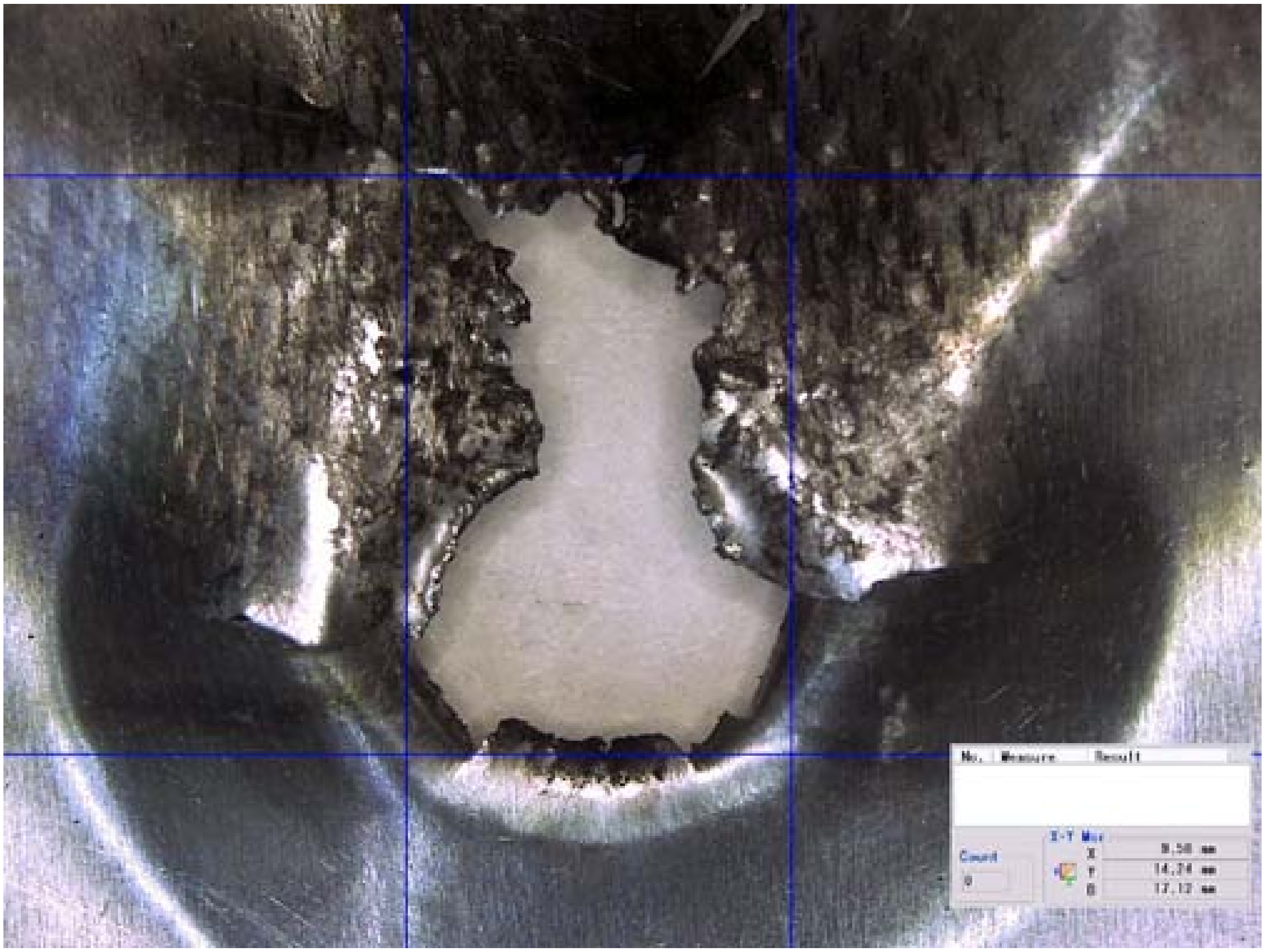


Figure 153: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #9
(Keyence 3D Microscope Image)

Test #9, HITF12265

Figure 154: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #9 (Keyence 3D Microscope Image)

Test #9, HITF12265

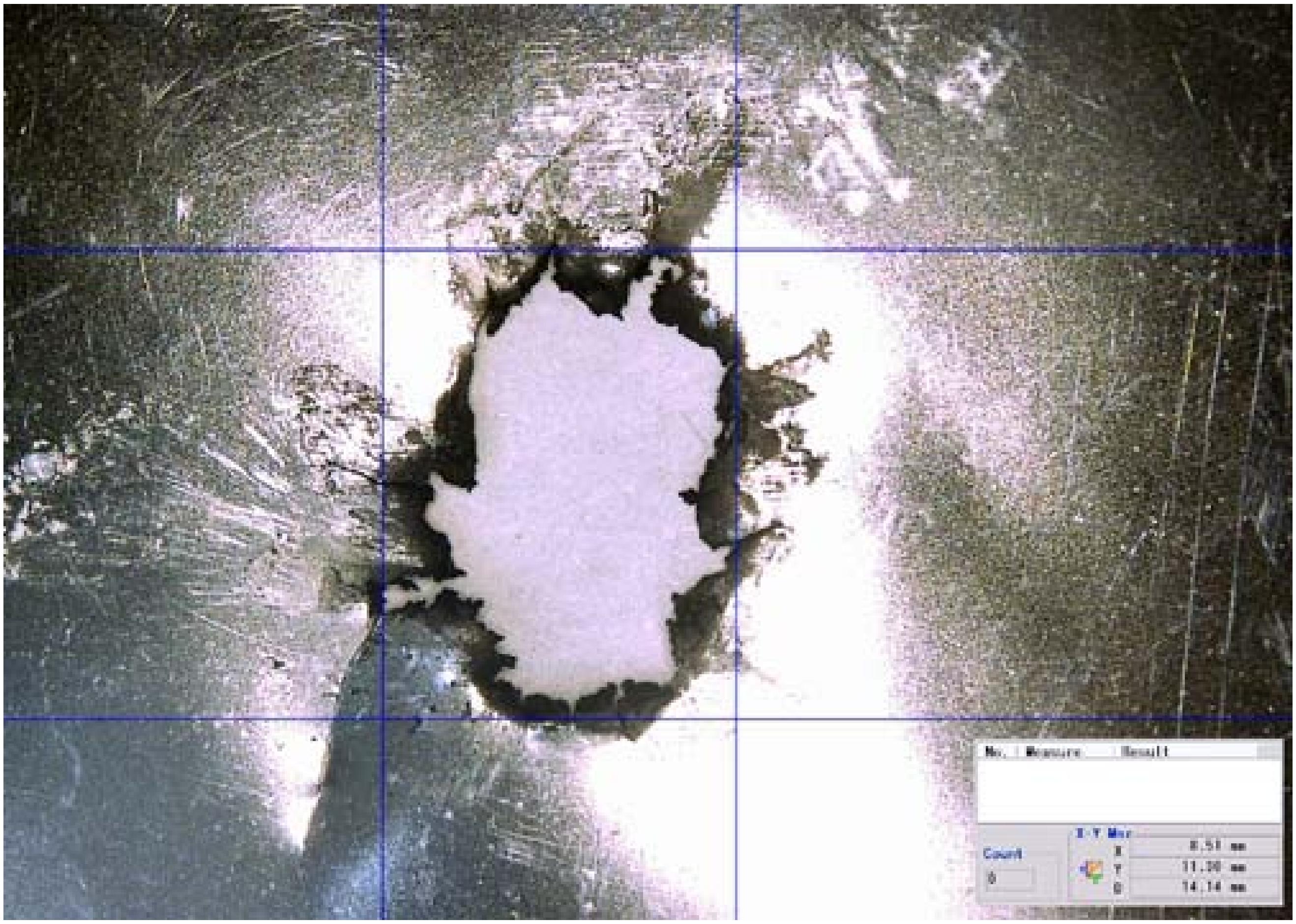


Figure 155: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #9 (Keyence 3D Microscope Image)

Test #9, HITF12265

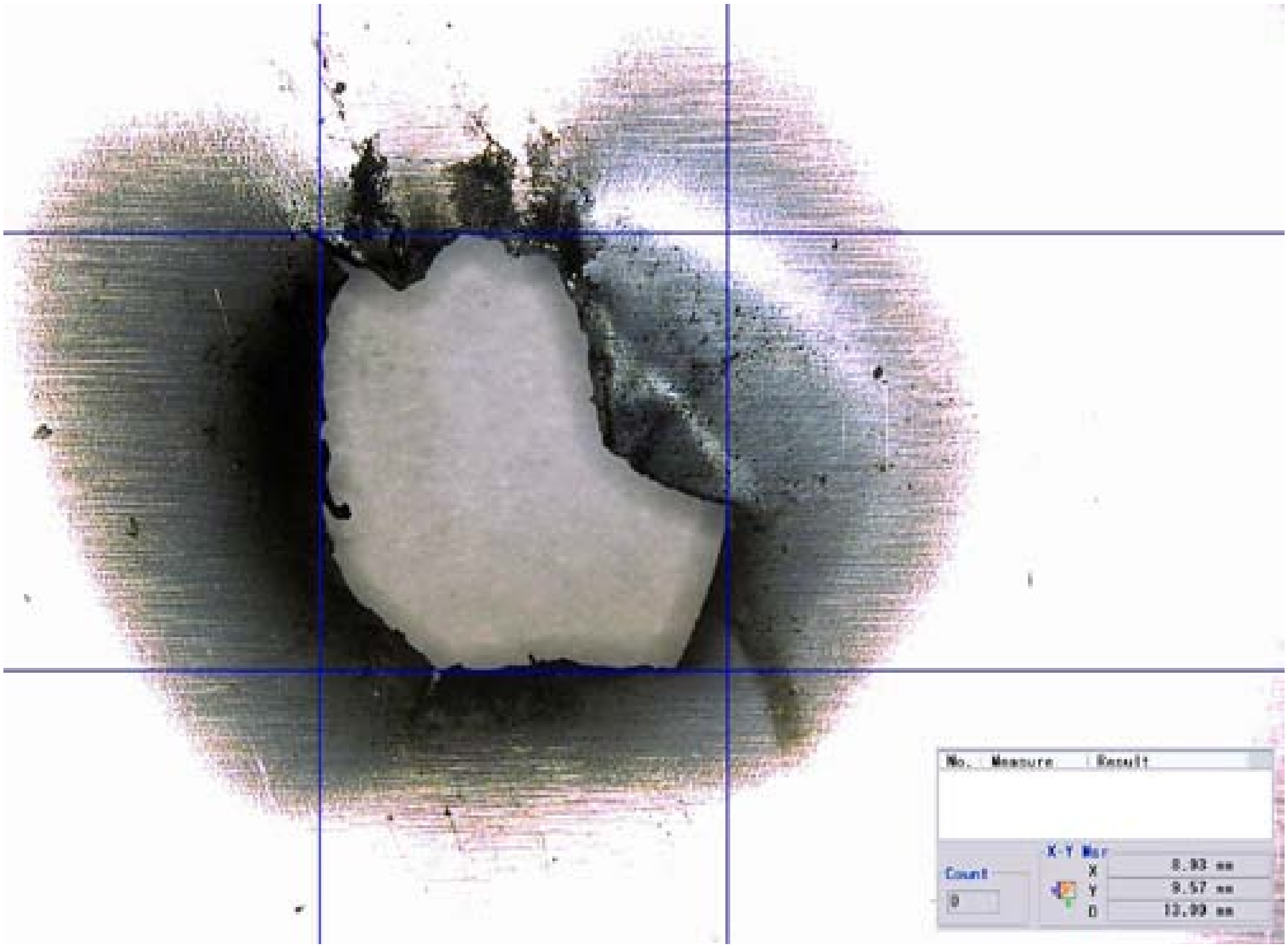


Figure 156: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #9 (Keyence 3D Microscope Image)

Test #9, HITF12265

Figure 157: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #9 (Keyence 3D Microscope Image)

Test #9, HITF12265 Rear Wall

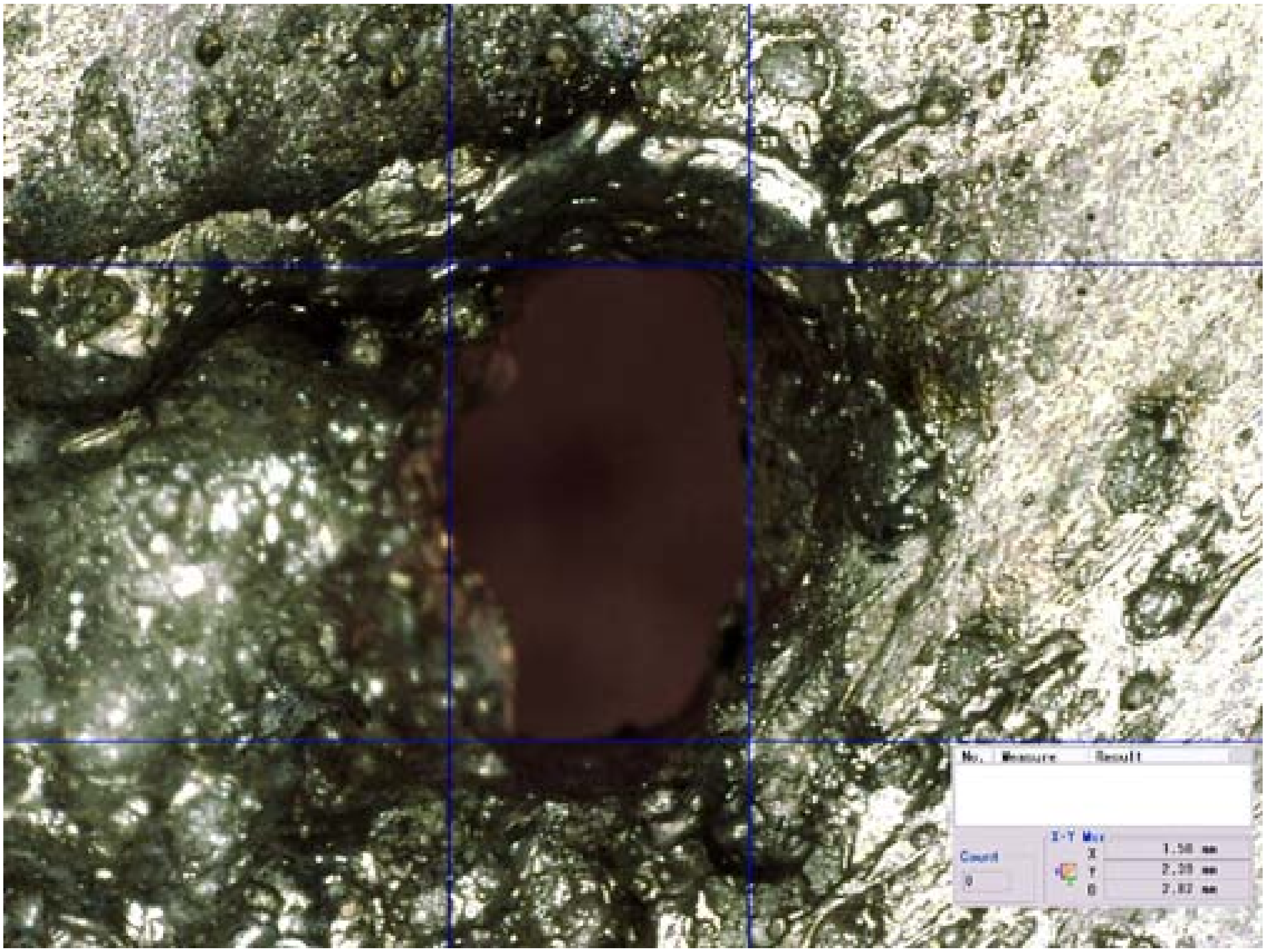


Figure 158: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #9 (Keyence 3D Microscope Image)

Test #9, HITF12265

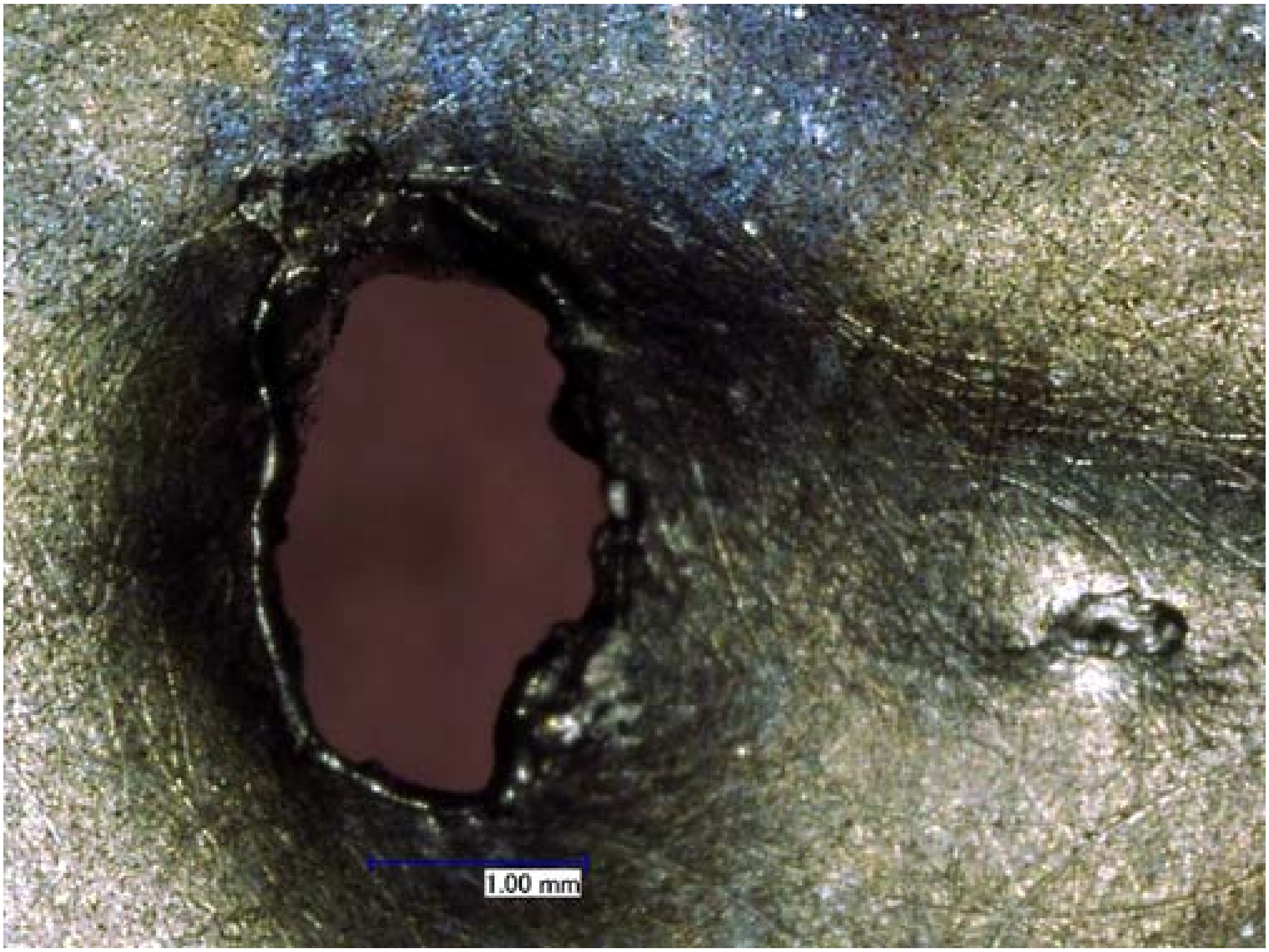


Figure 159: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #9 (Keyence 3D Microscope Image)

Test #9, HITF12265

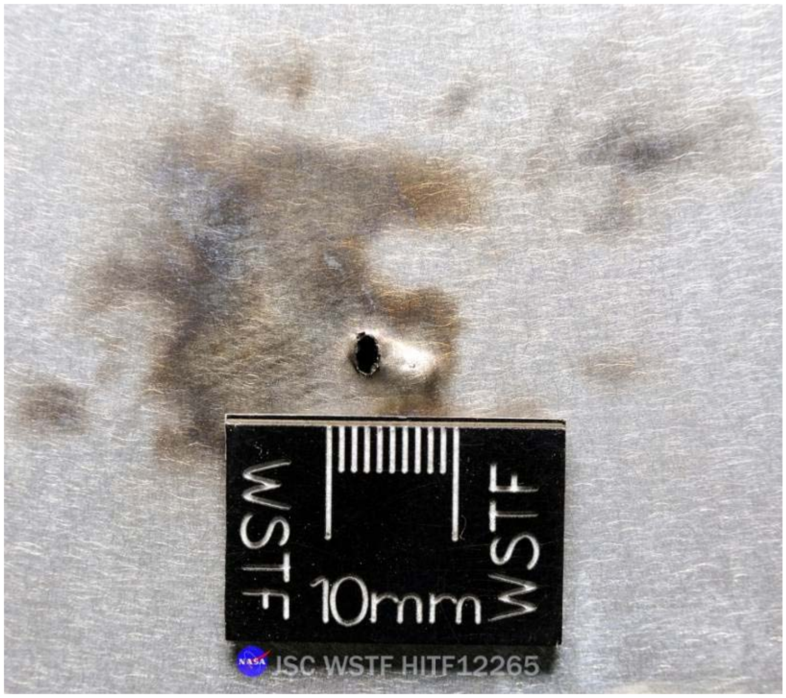


Figure 160: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #9

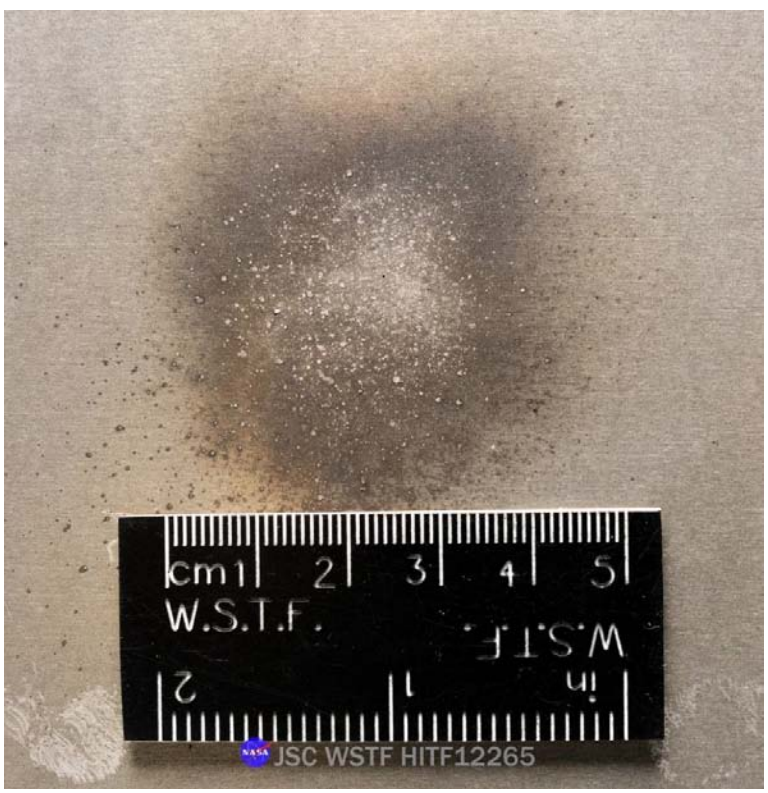


Figure 161: Front Witness Plate View of ISS Soyuz Orbital Module Test #9

Test #10, HITF12266

Figure 162: Post-test of ISS Soyuz Orbital Module Test #10 article mounted in 0.17-caliber target tank.

Figure 163: Side View of ISS Soyuz Orbital Module Test #10

Test #10, HITF12266

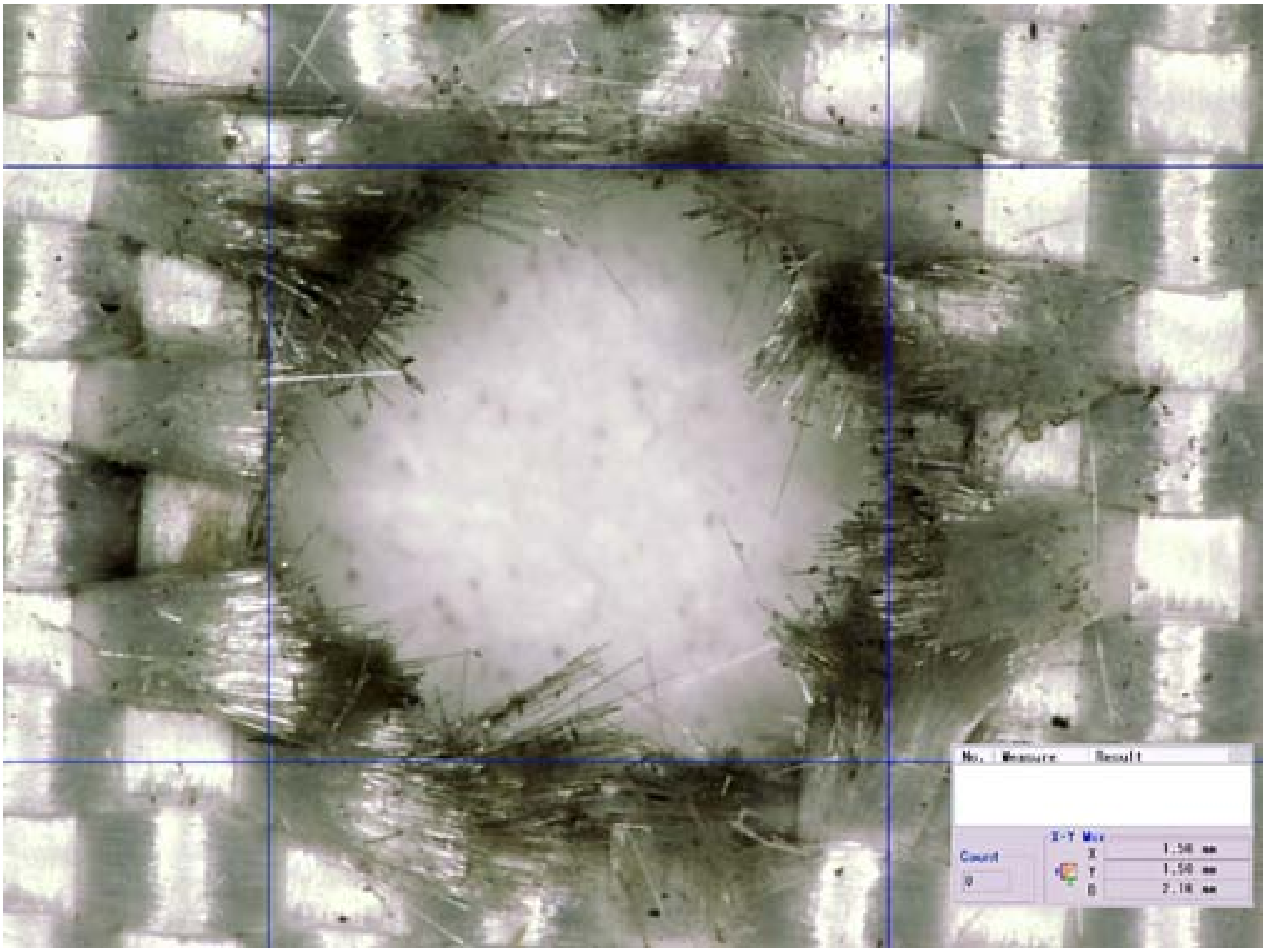


Figure 164: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

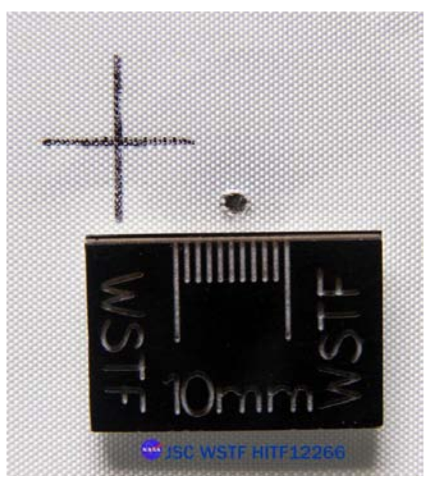


Figure 165: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #10

Test #10, HITF12266

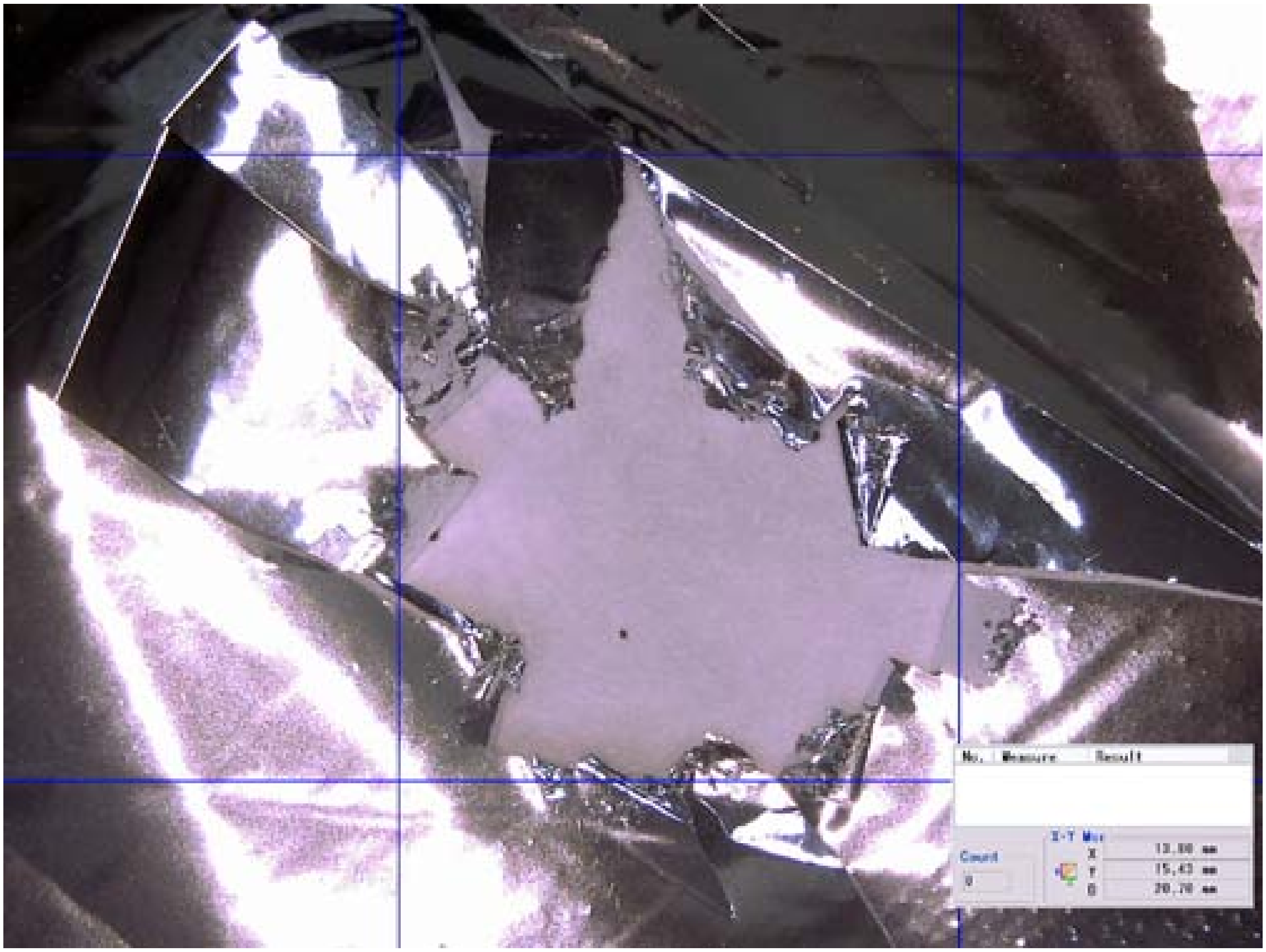


Figure 166: Mylar Film Layer 2 of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266

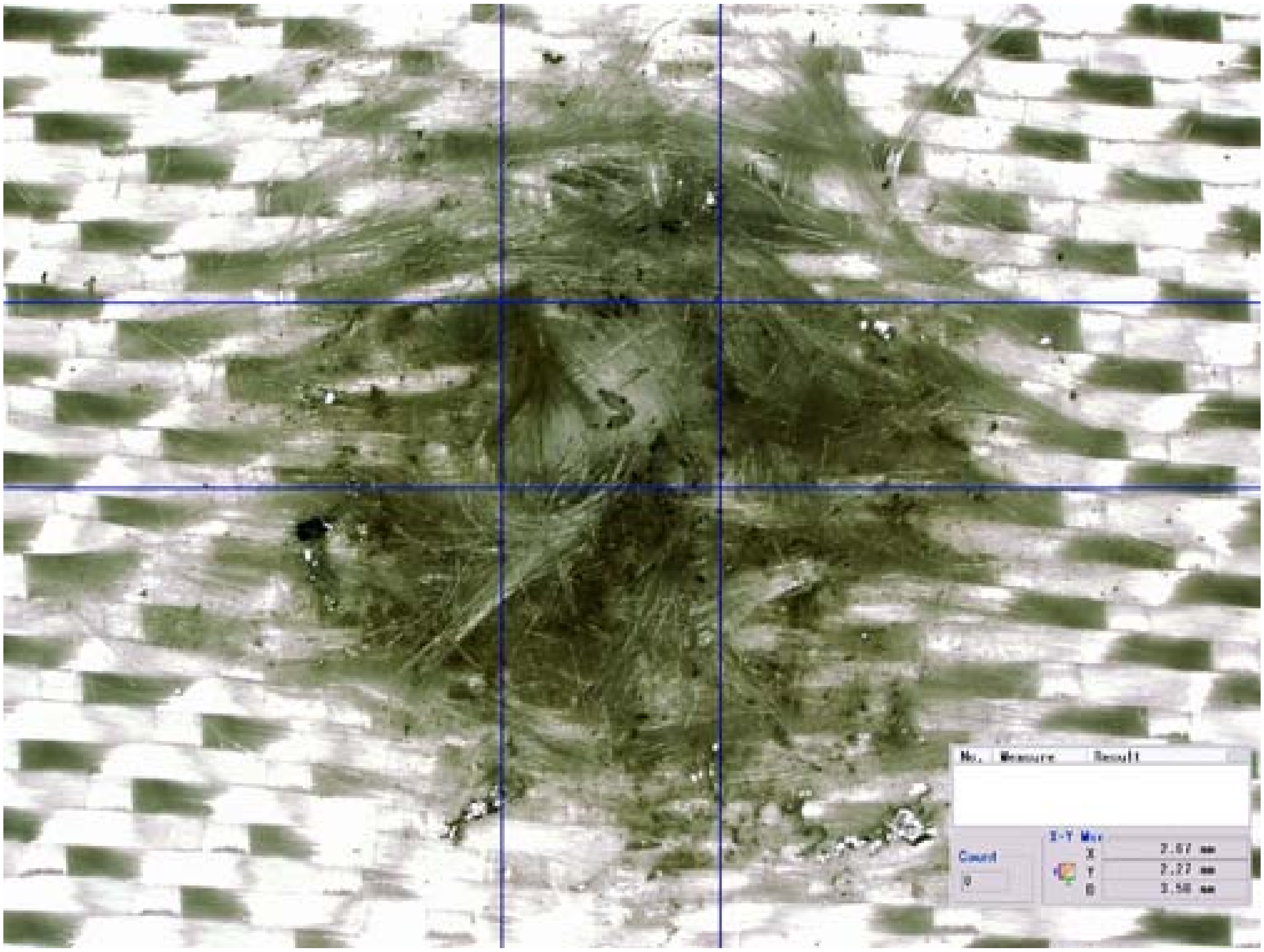


Figure 167: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266

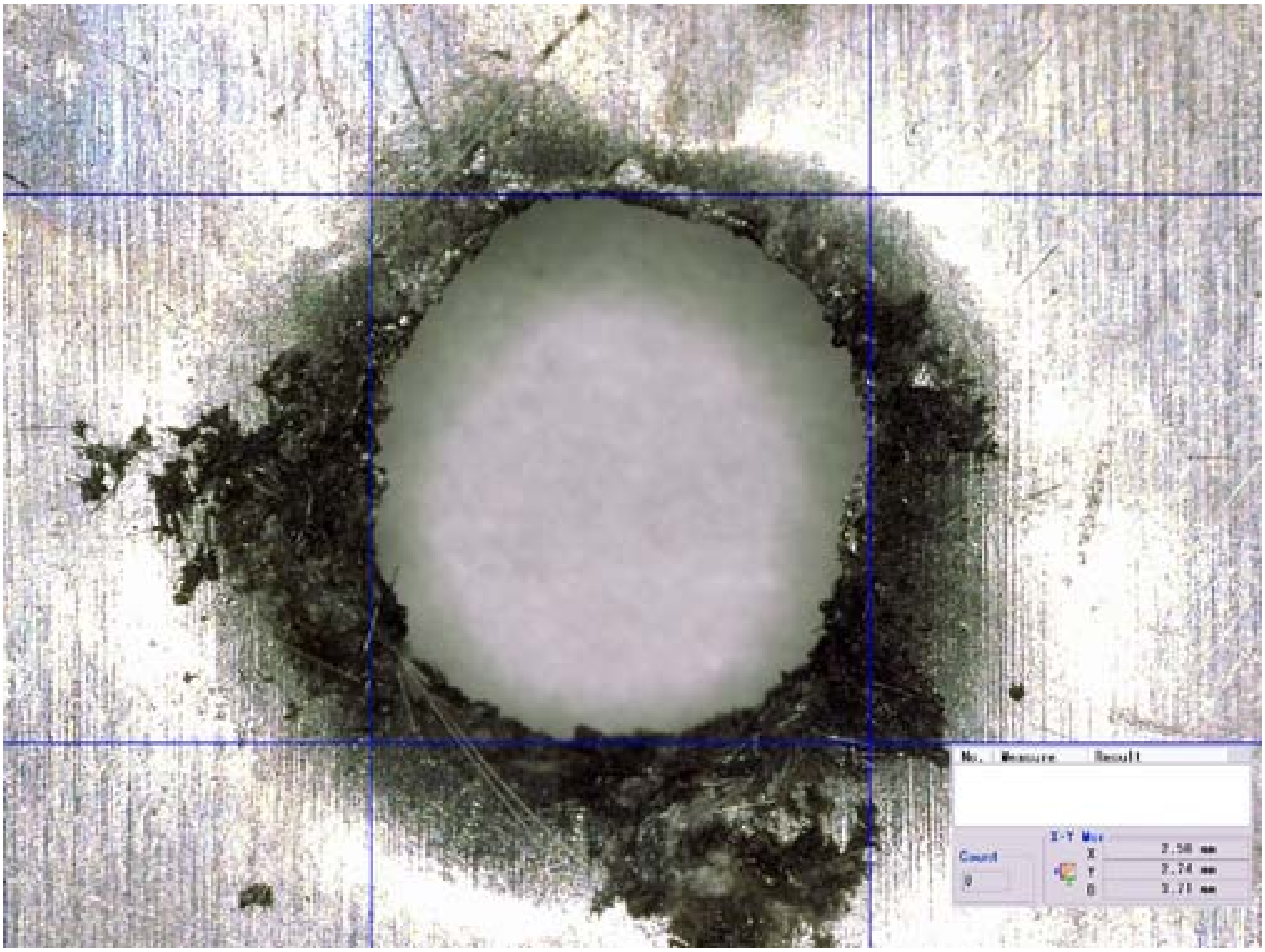


Figure 168: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266

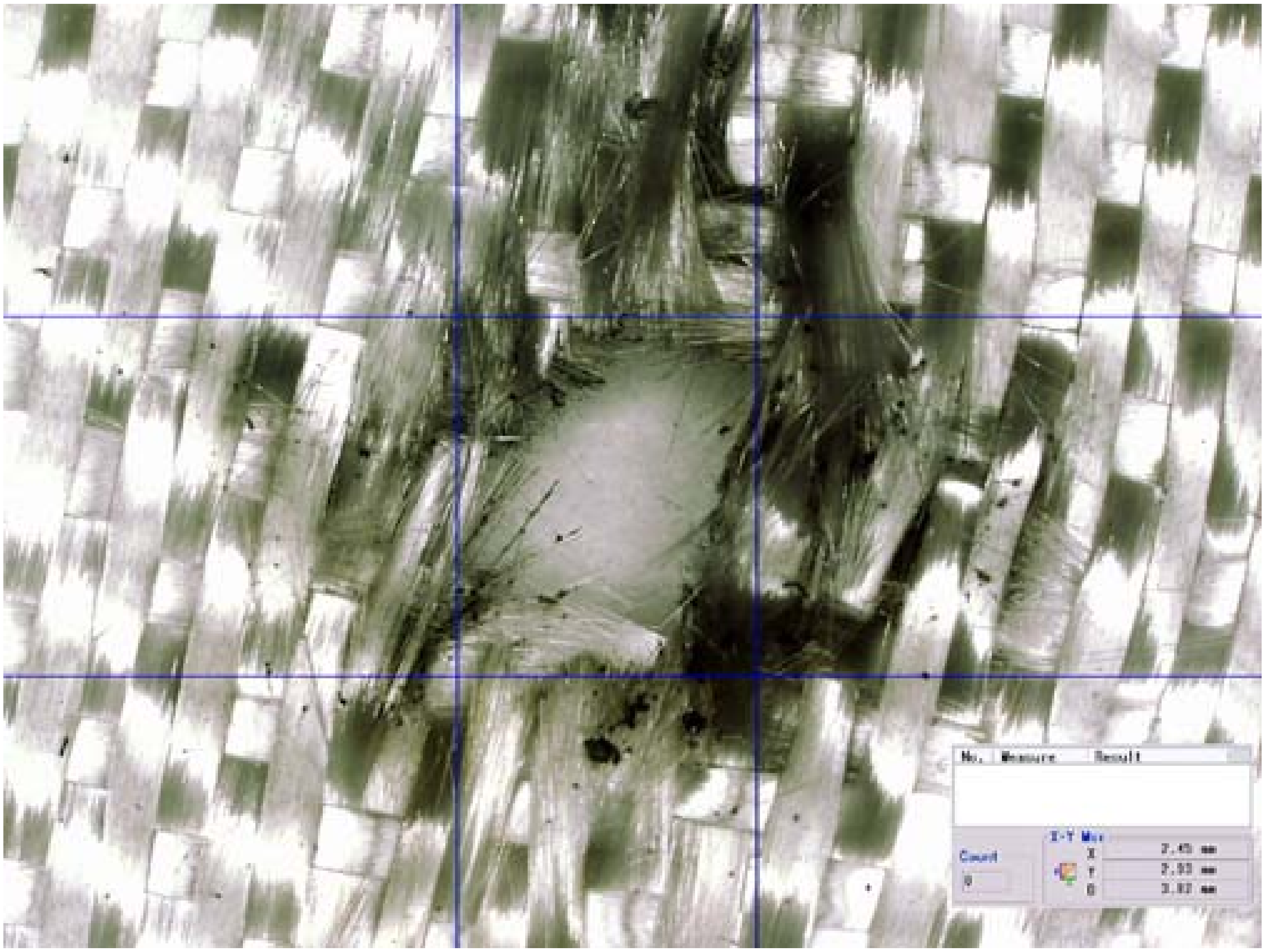


Figure 169: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266

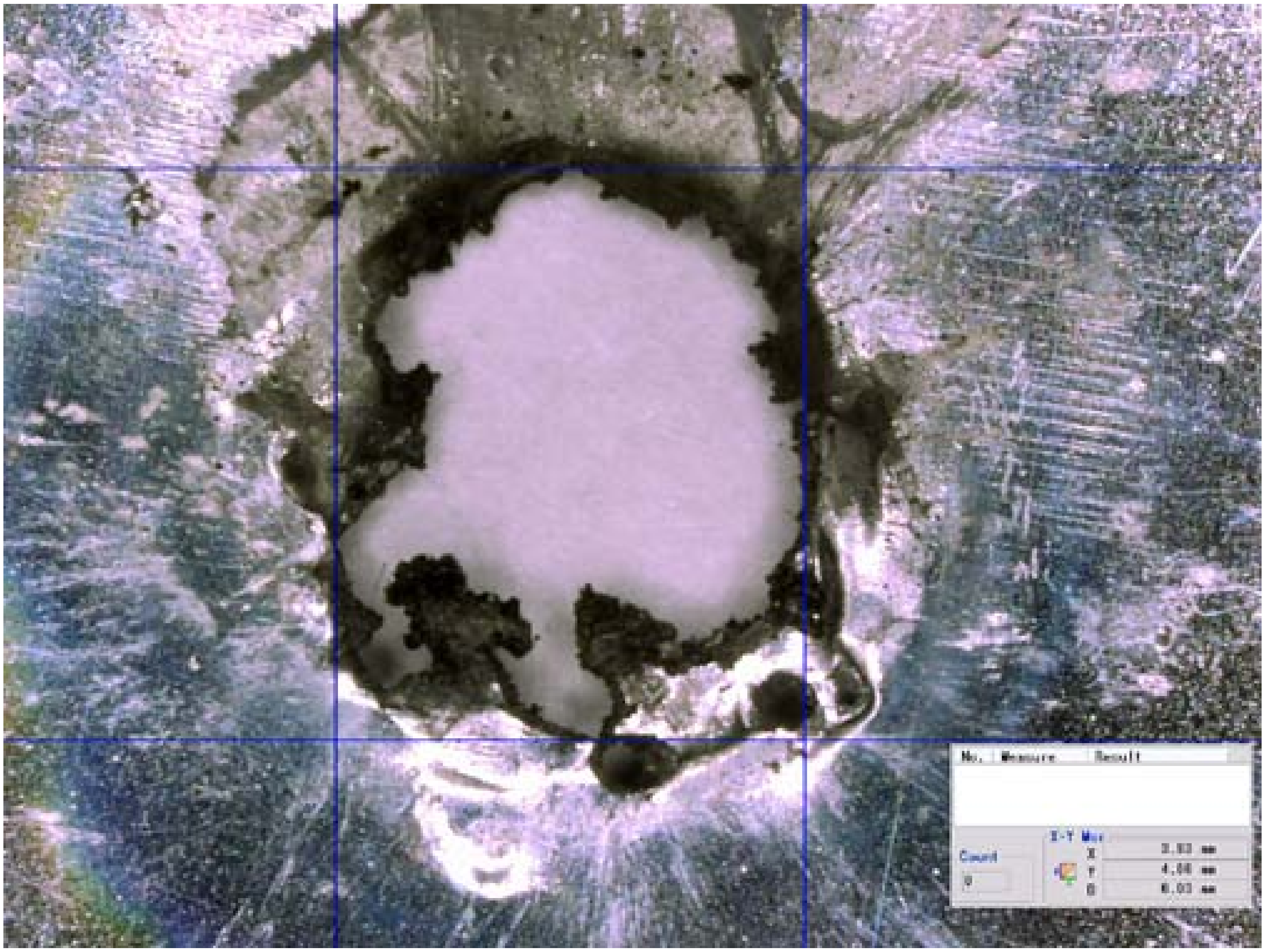


Figure 170: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266

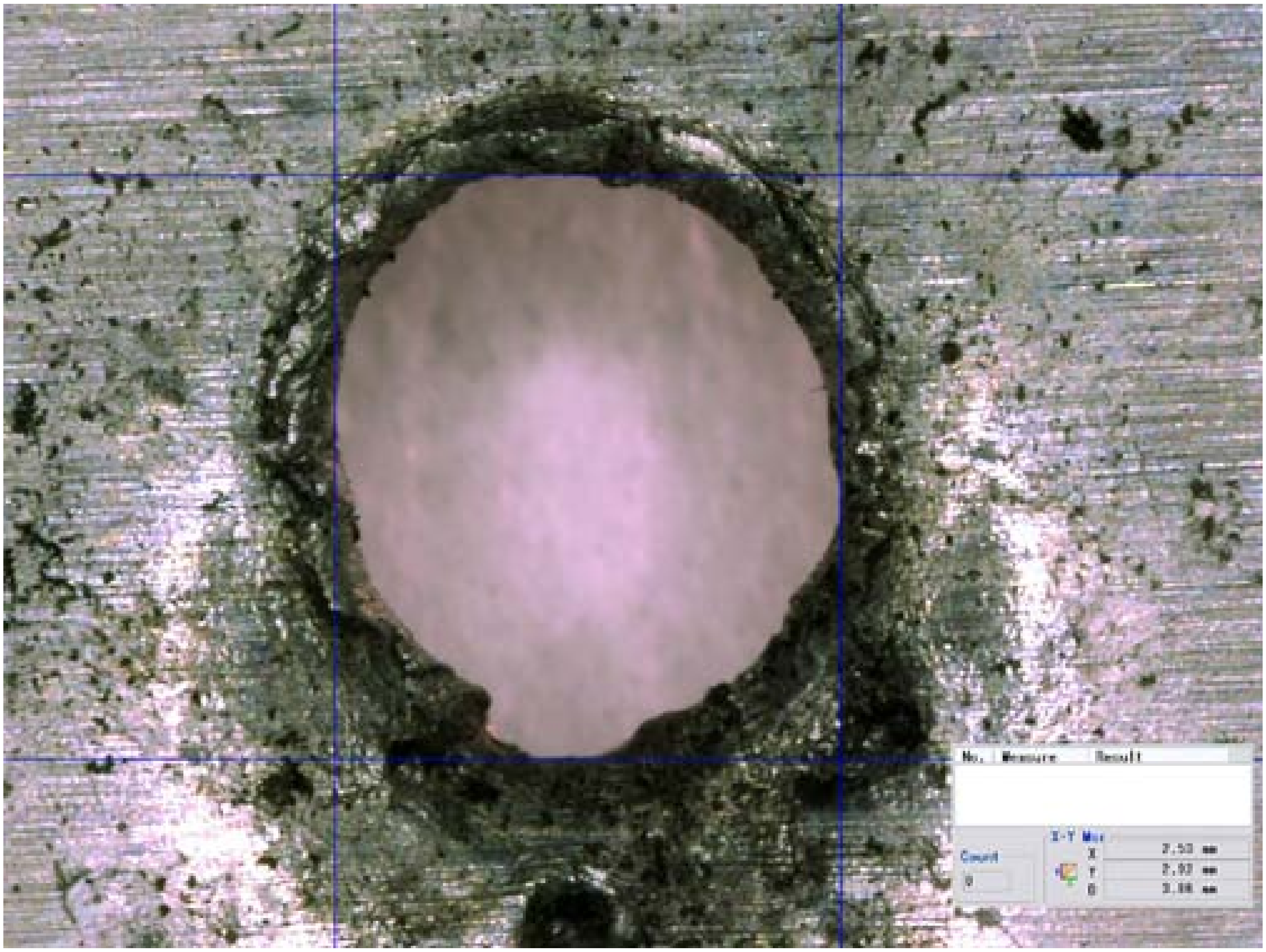


Figure 171: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266

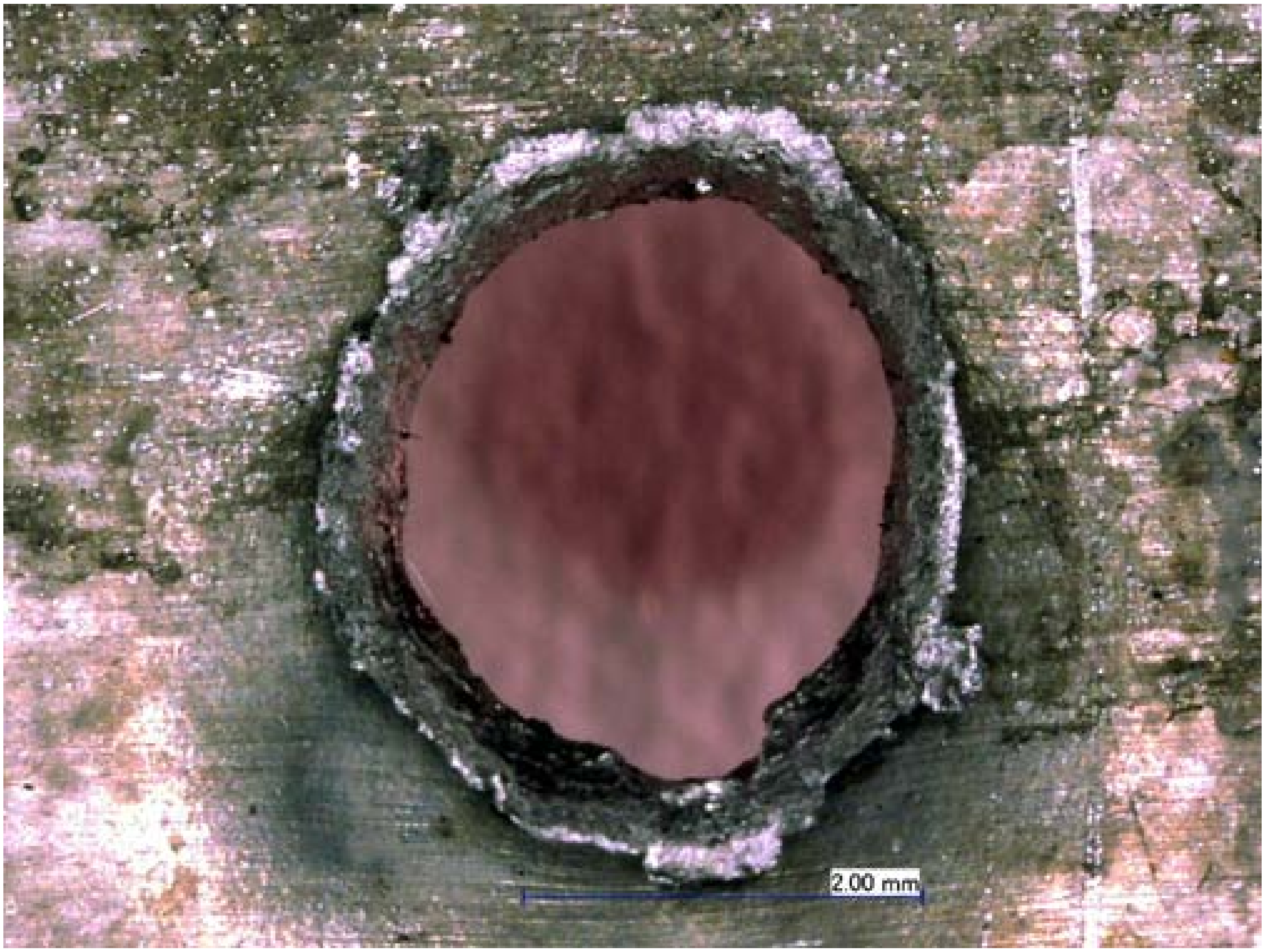


Figure 172: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266 Rear Wall

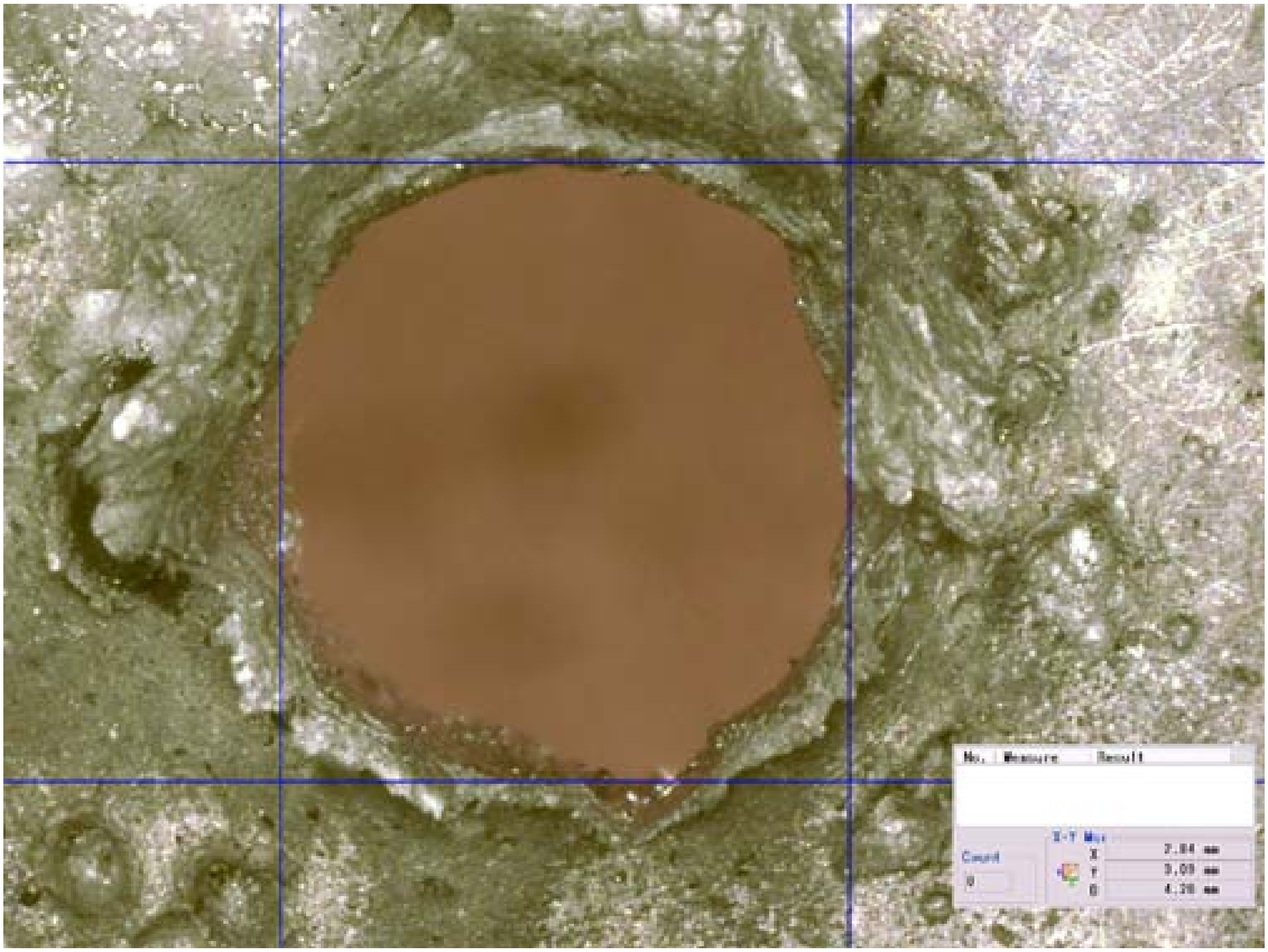


Figure 173: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266

Figure 174: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266

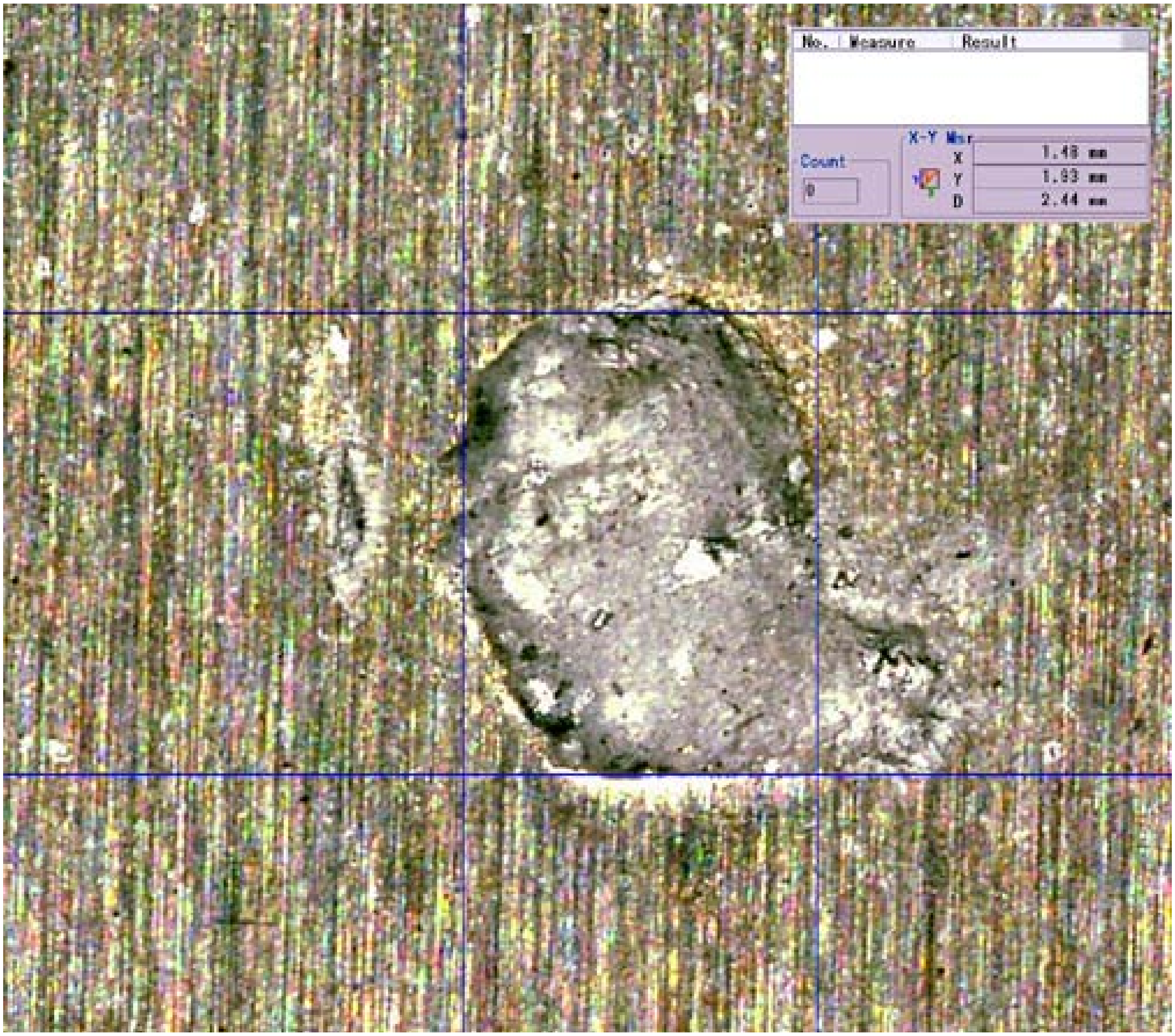


Figure 175: Witness Plate of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266

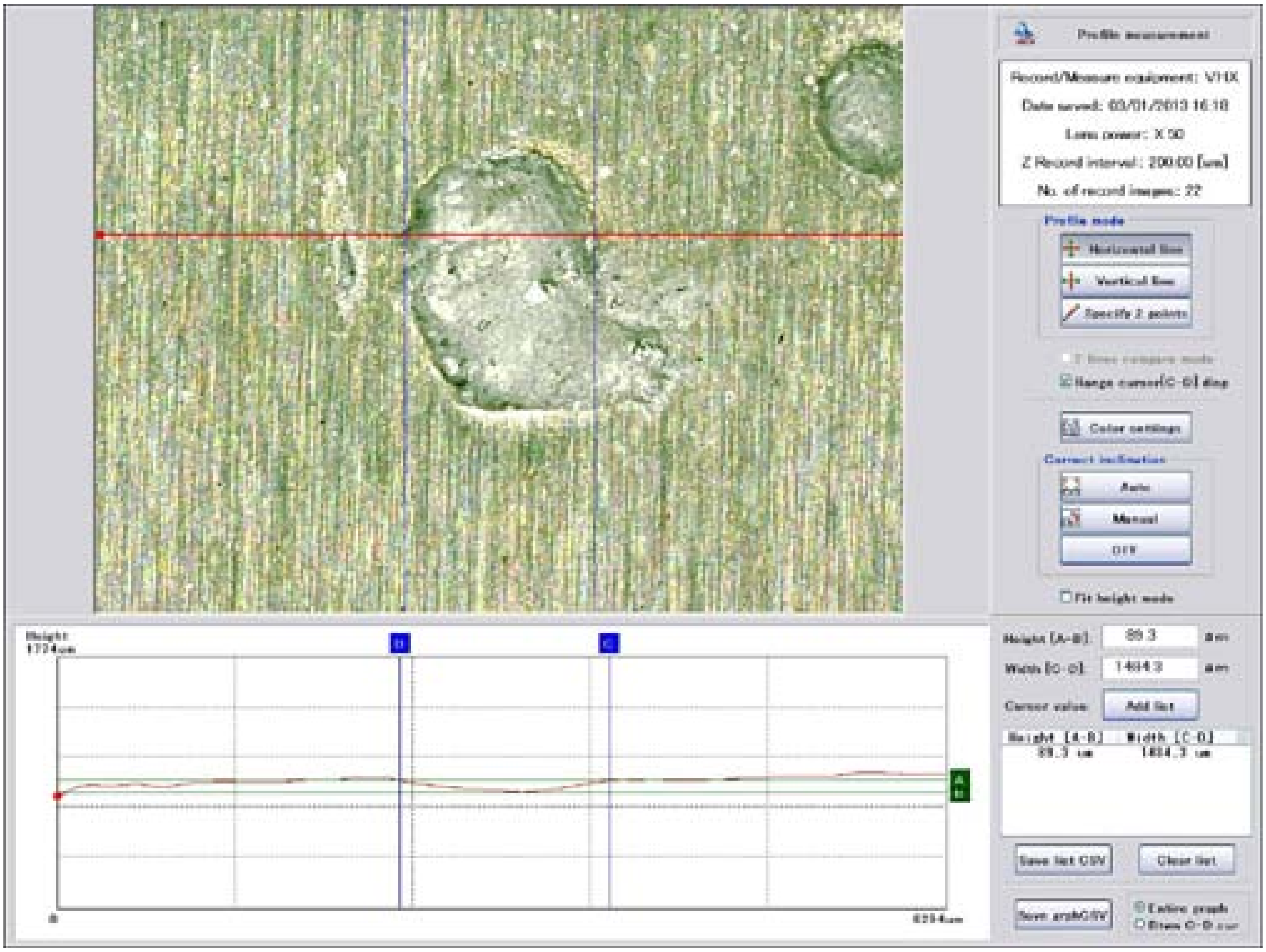


Figure 176: Witness Plate of ISS Soyuz OM Test #10
(Keyence 3D Microscope Image)

Test #10, HITF12266

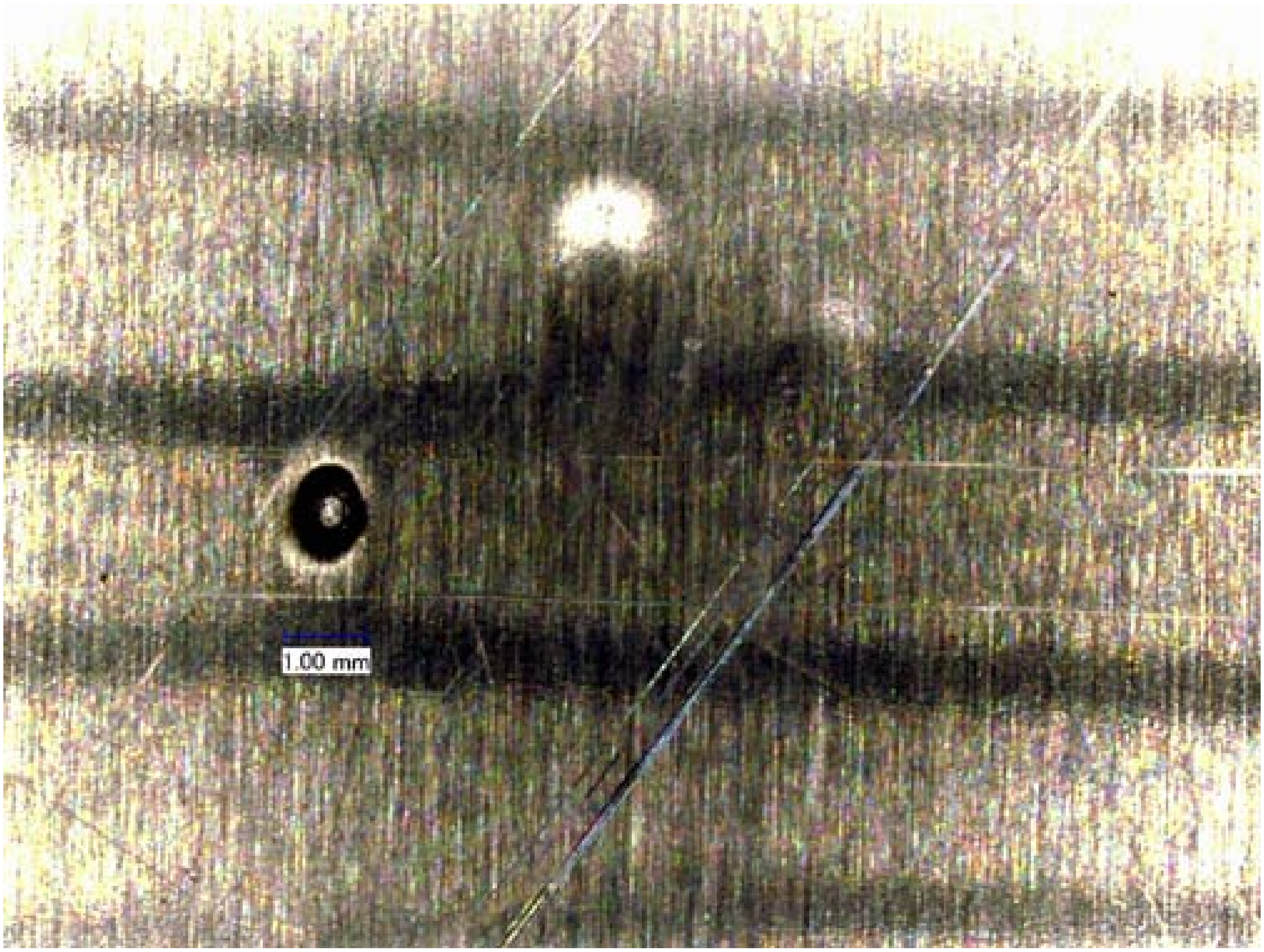


Figure 177: Witness Plate of ISS Soyuz OM Test #10 (Keyence 3D Microscope Image)

Test #10, HITF12266

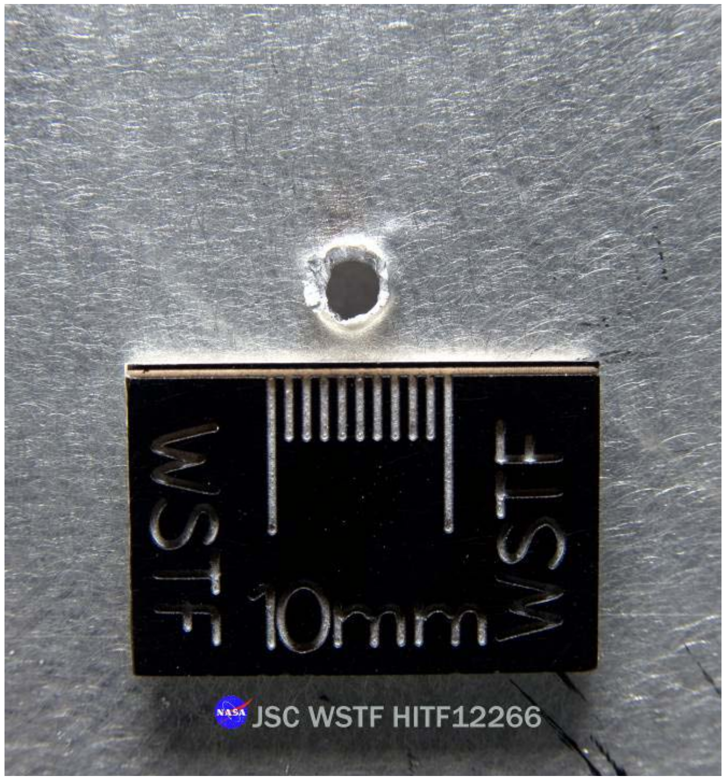


Figure 178: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #10

Figure 179: Front Witness Plate View of ISS Soyuz Orbital Module Test #10

Test #11, HITF12271

Figure 180: Post-test of ISS Soyuz Orbital Module Test #11 (HITF12271) article mounted in 0.50-caliber target tank.

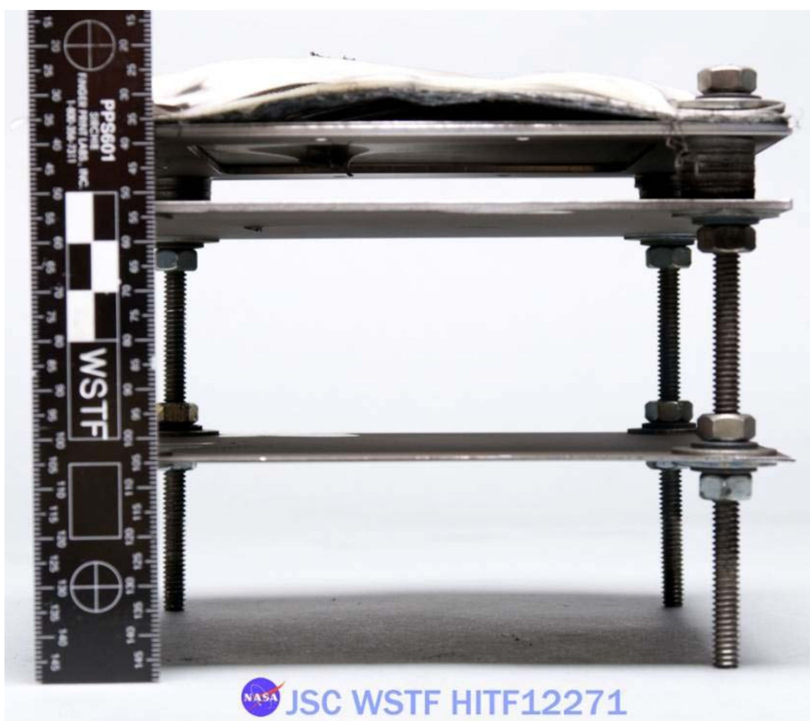


Figure 181: Side View of ISS Soyuz Orbital Module Test #11

Test #11, HITF12271

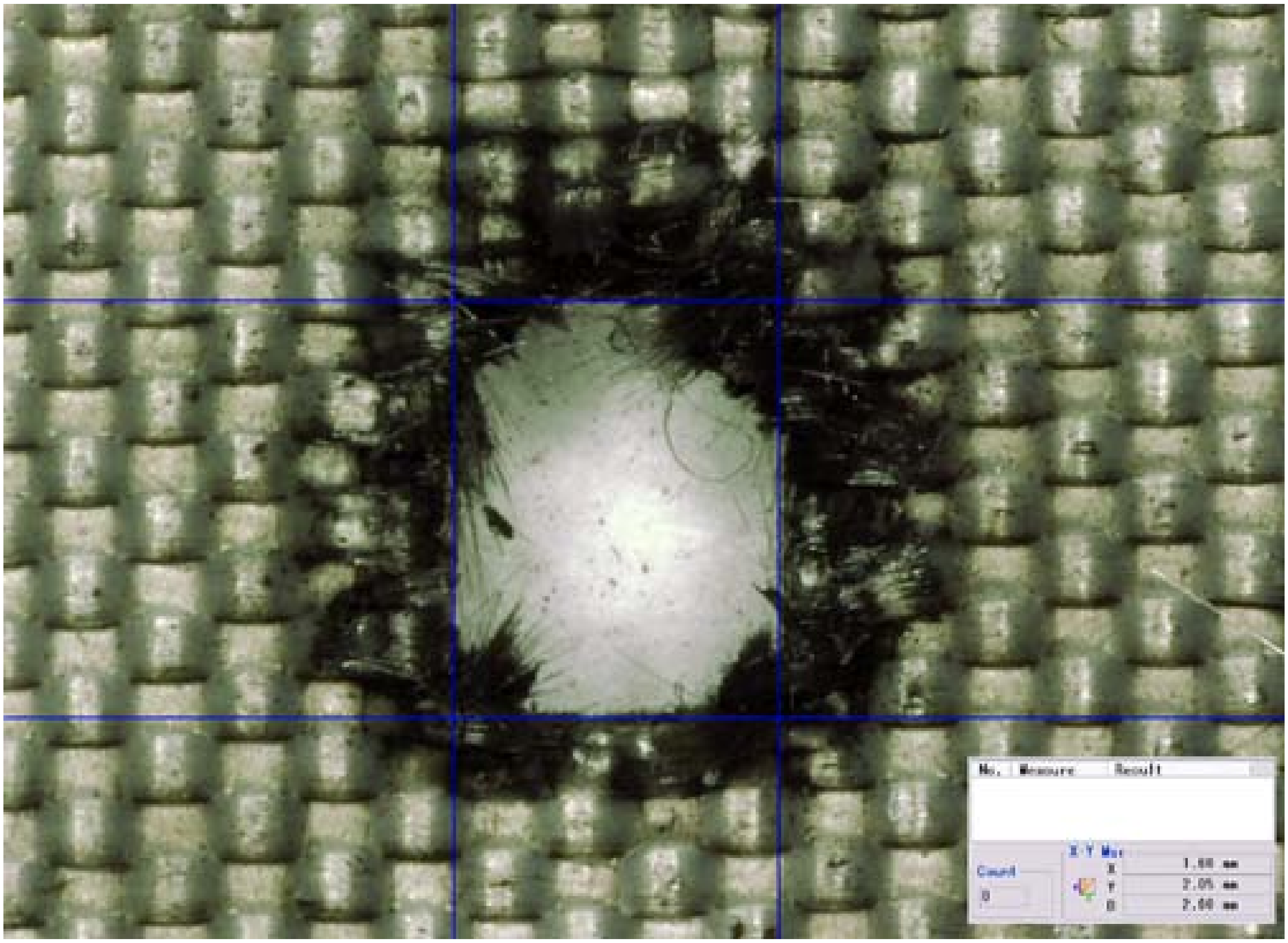


Figure 182: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #11 (Keyence 3D Microscope Image)

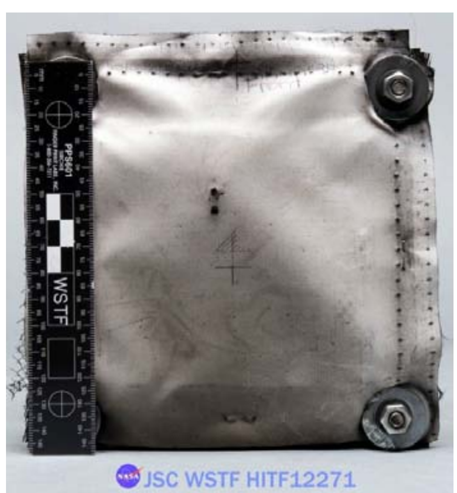


Figure 183: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #11

Test #11, HITF12271

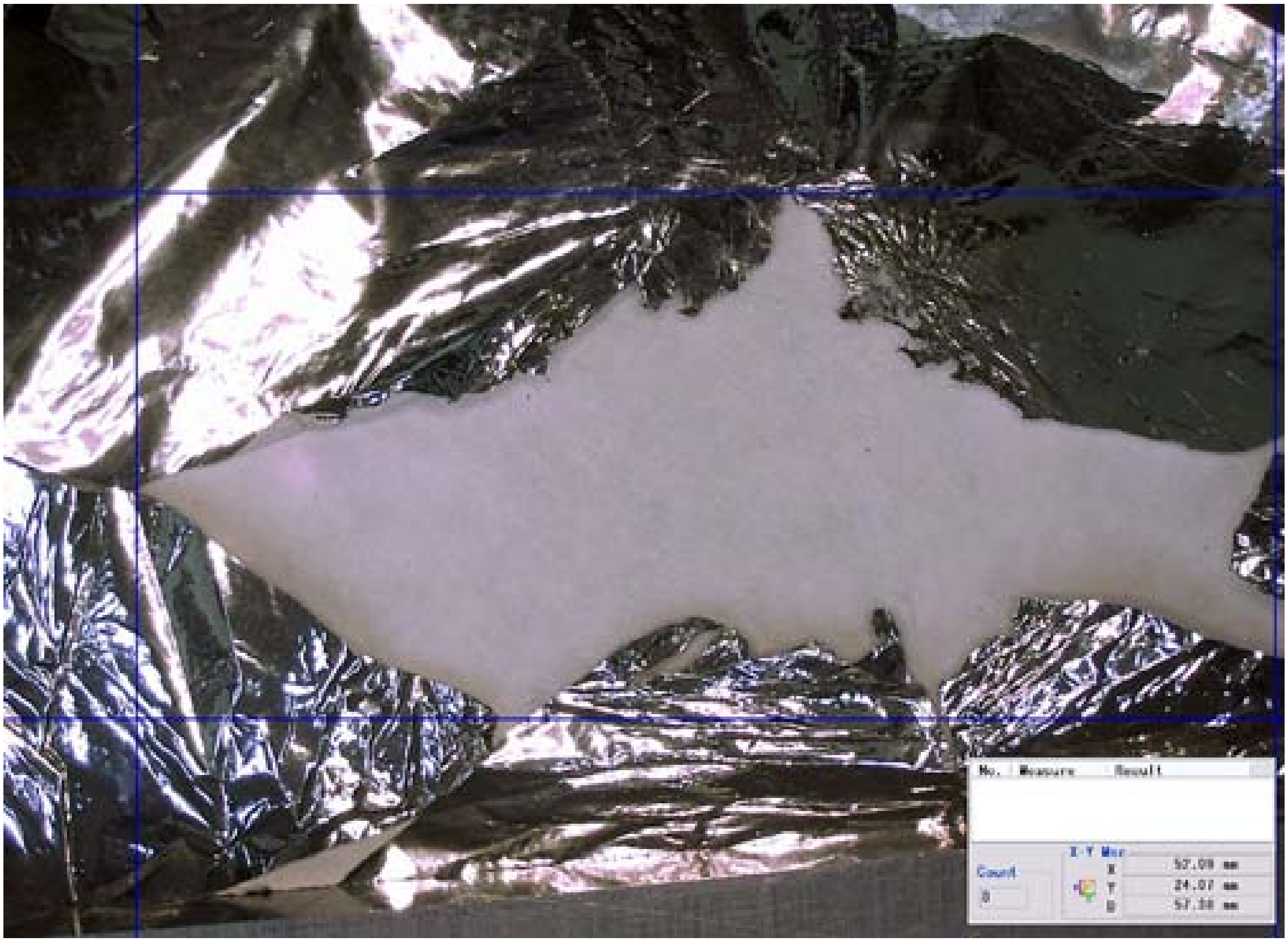


**Figure 184: Mylar Film Layer 2 of ISS Soyuz OM Test #11
(Keyence 3D Microscope Image)**

Test #11, HITF12271

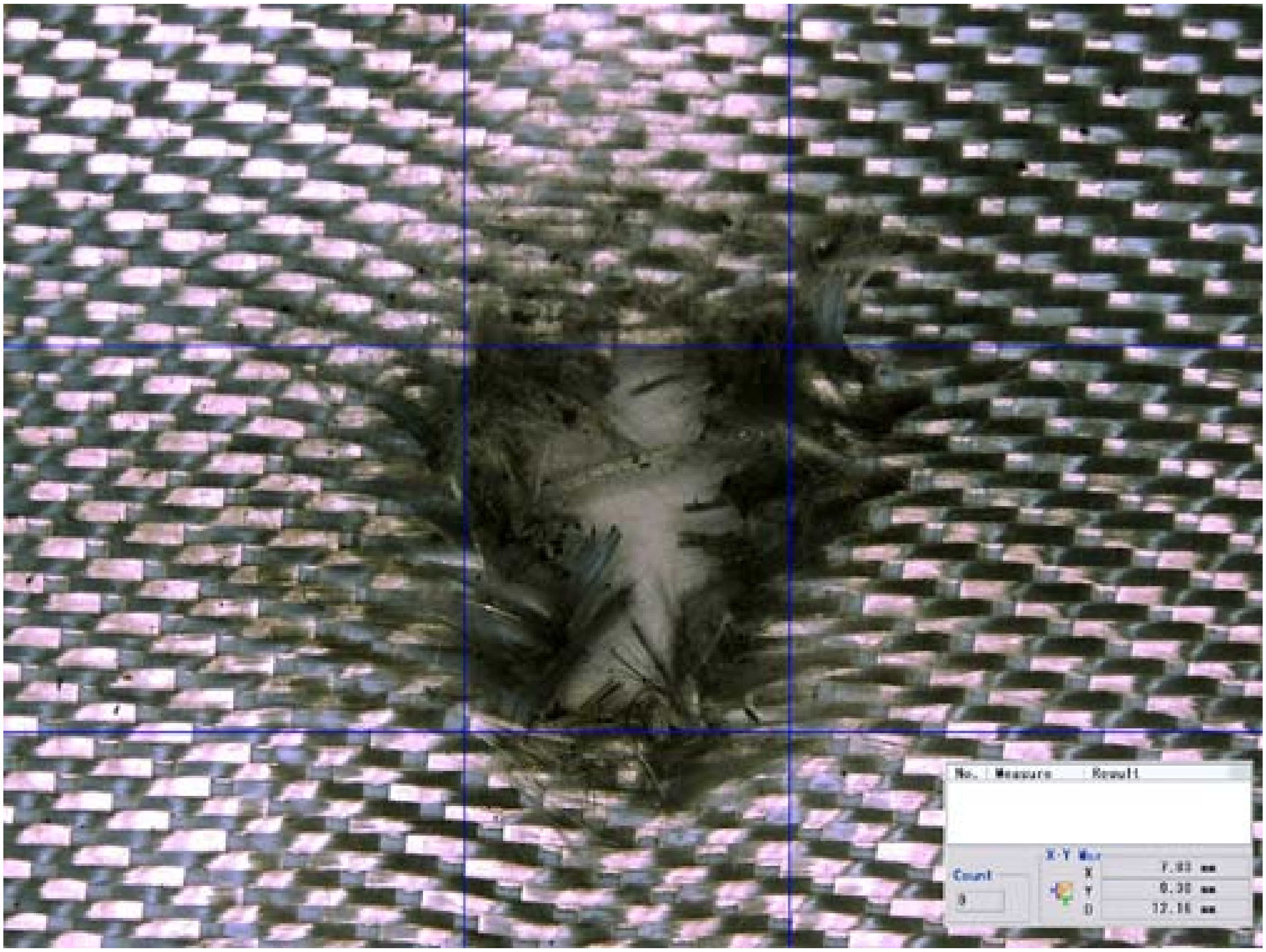


Figure 185: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #11 (Keyence 3D Microscope Image)

Test #11, HITF12271

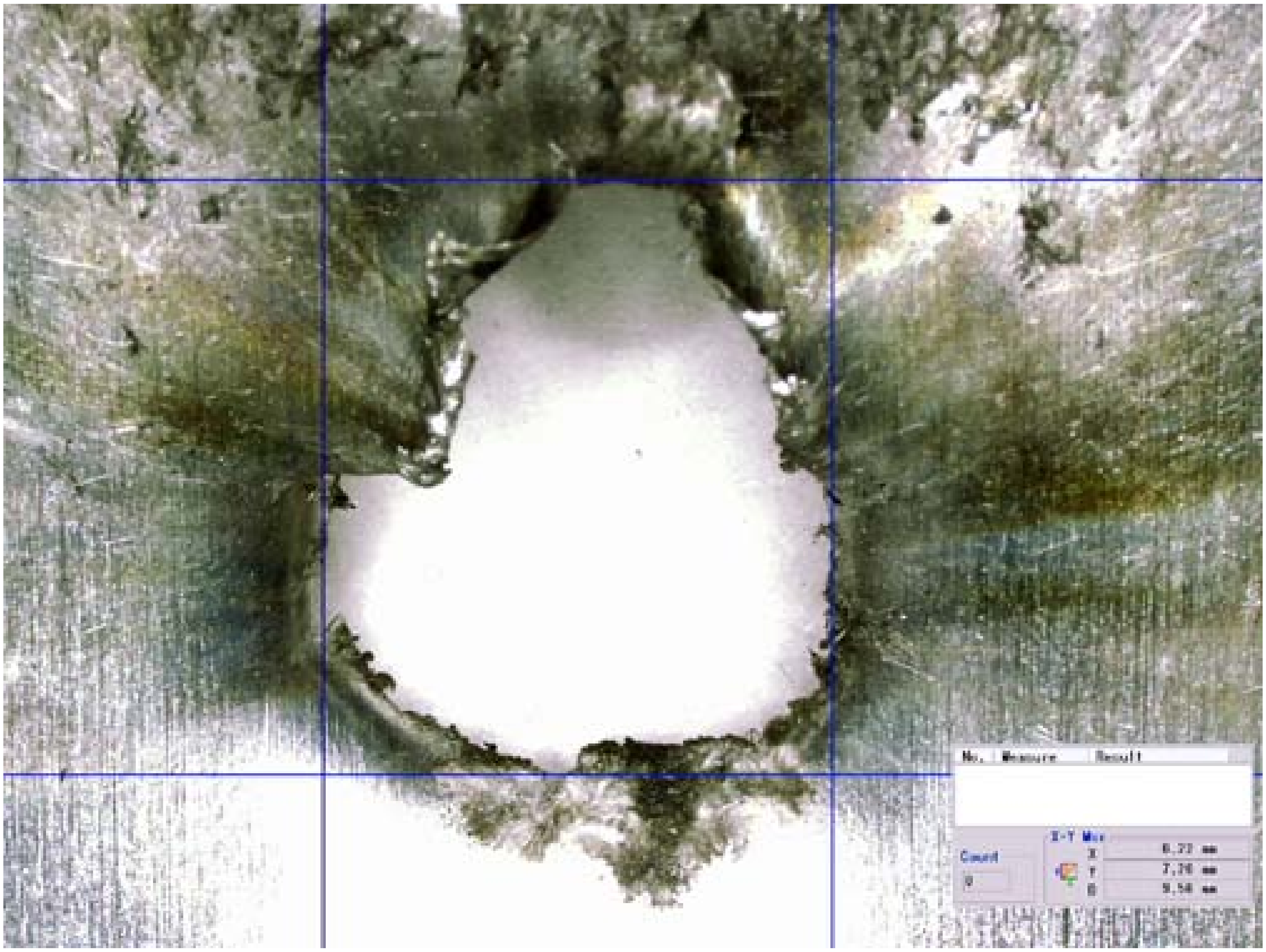


Figure 186: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #11 (Keyence 3D Microscope Image)

Test #11, HITF12271

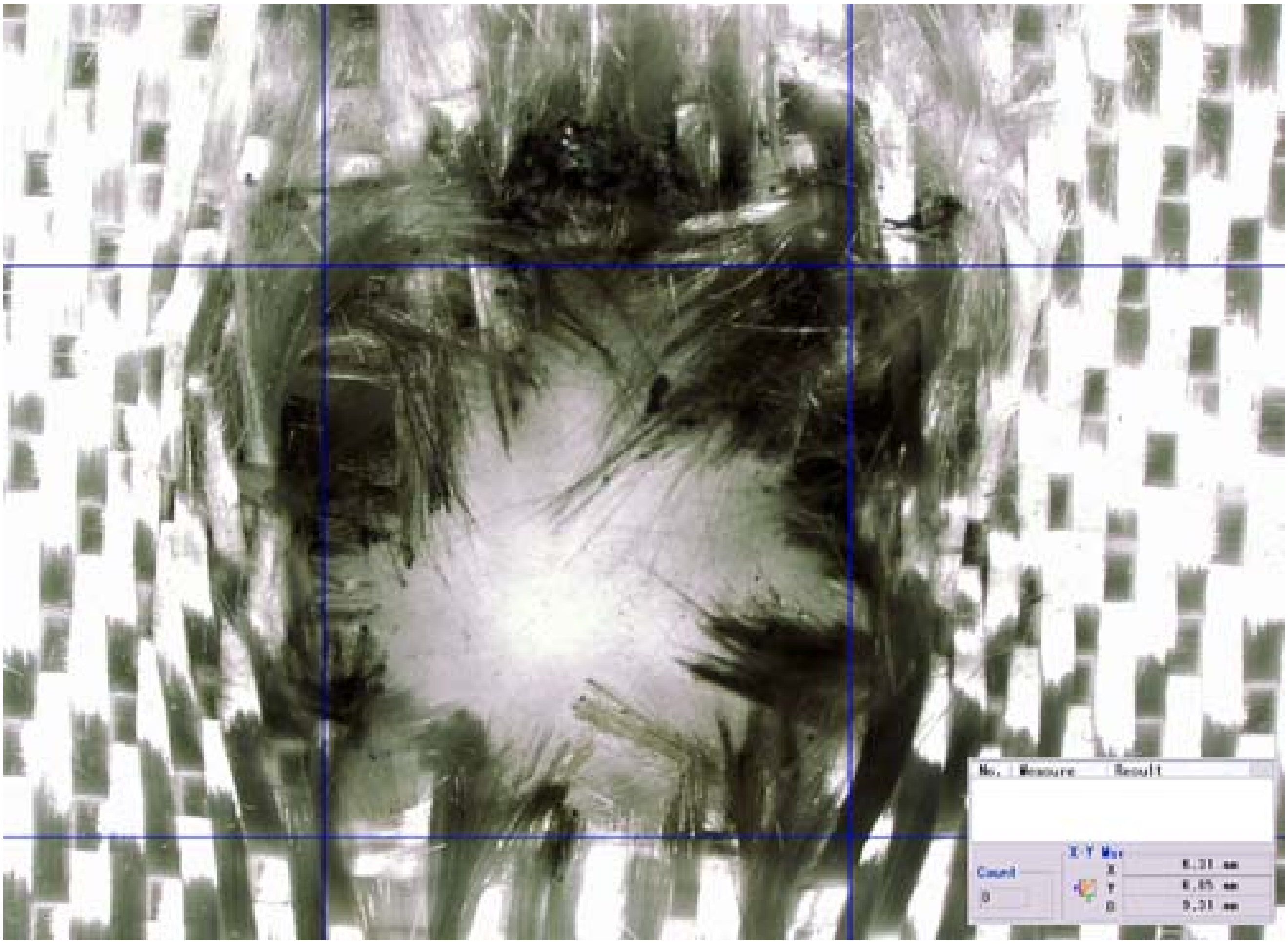


Figure 187: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #11 (Keyence 3D Microscope Image)

Test #11, HITF12271

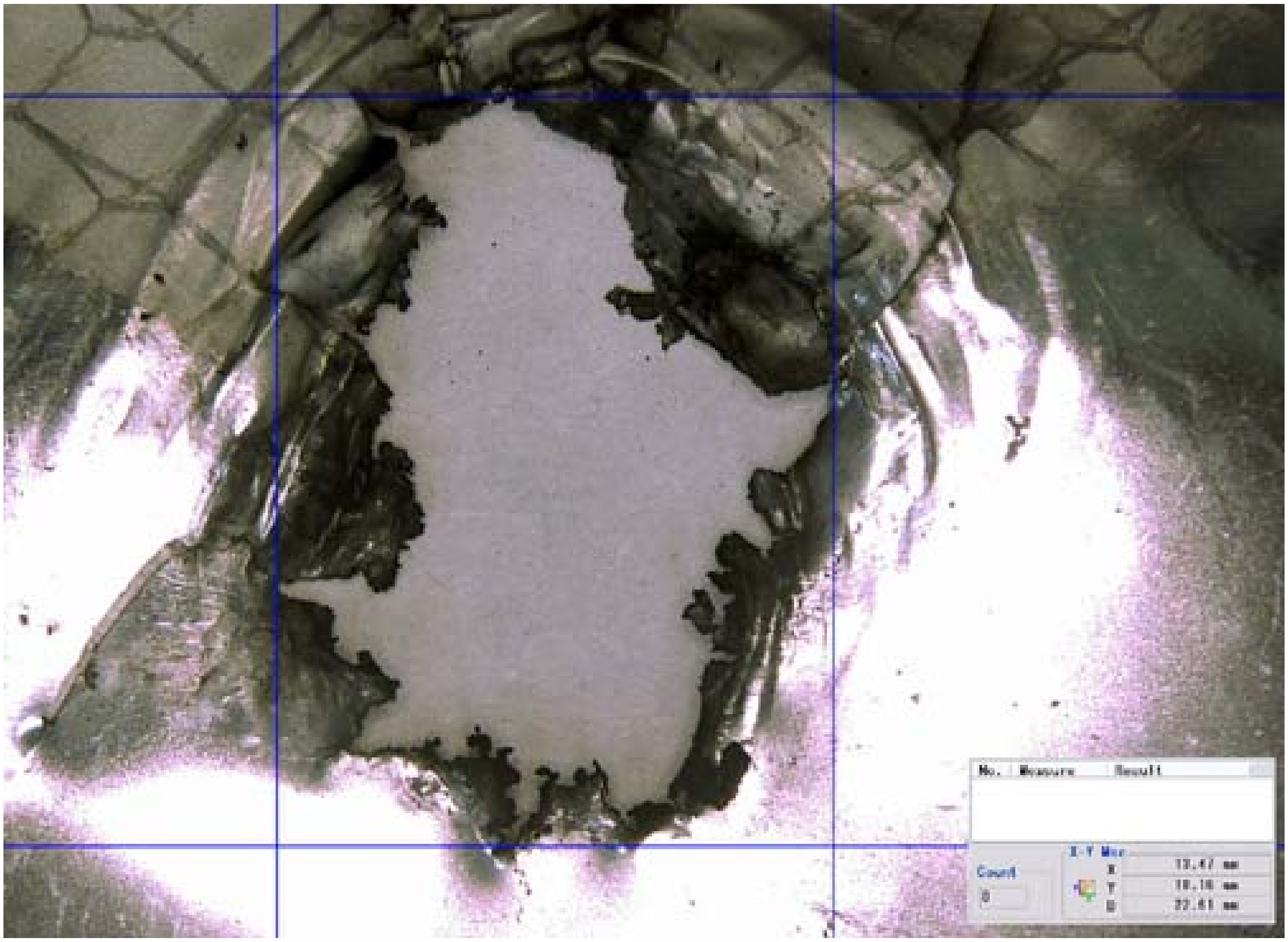


Figure 188: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #11
(Keyence 3D Microscope Image)

Test #11, HITF12271

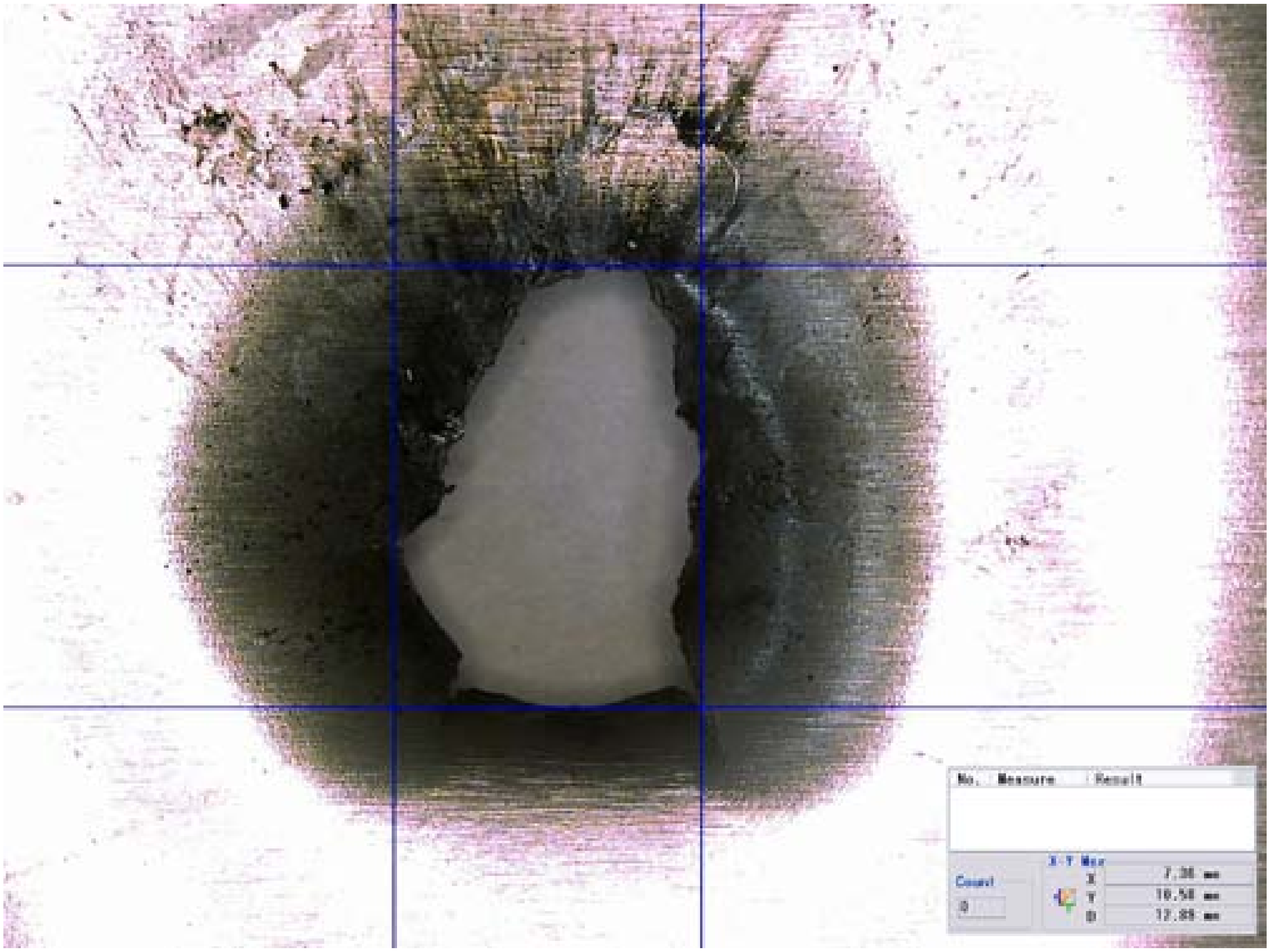


Figure 189: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #11 (Keyence 3D Microscope Image)

Test #11, HITF12271

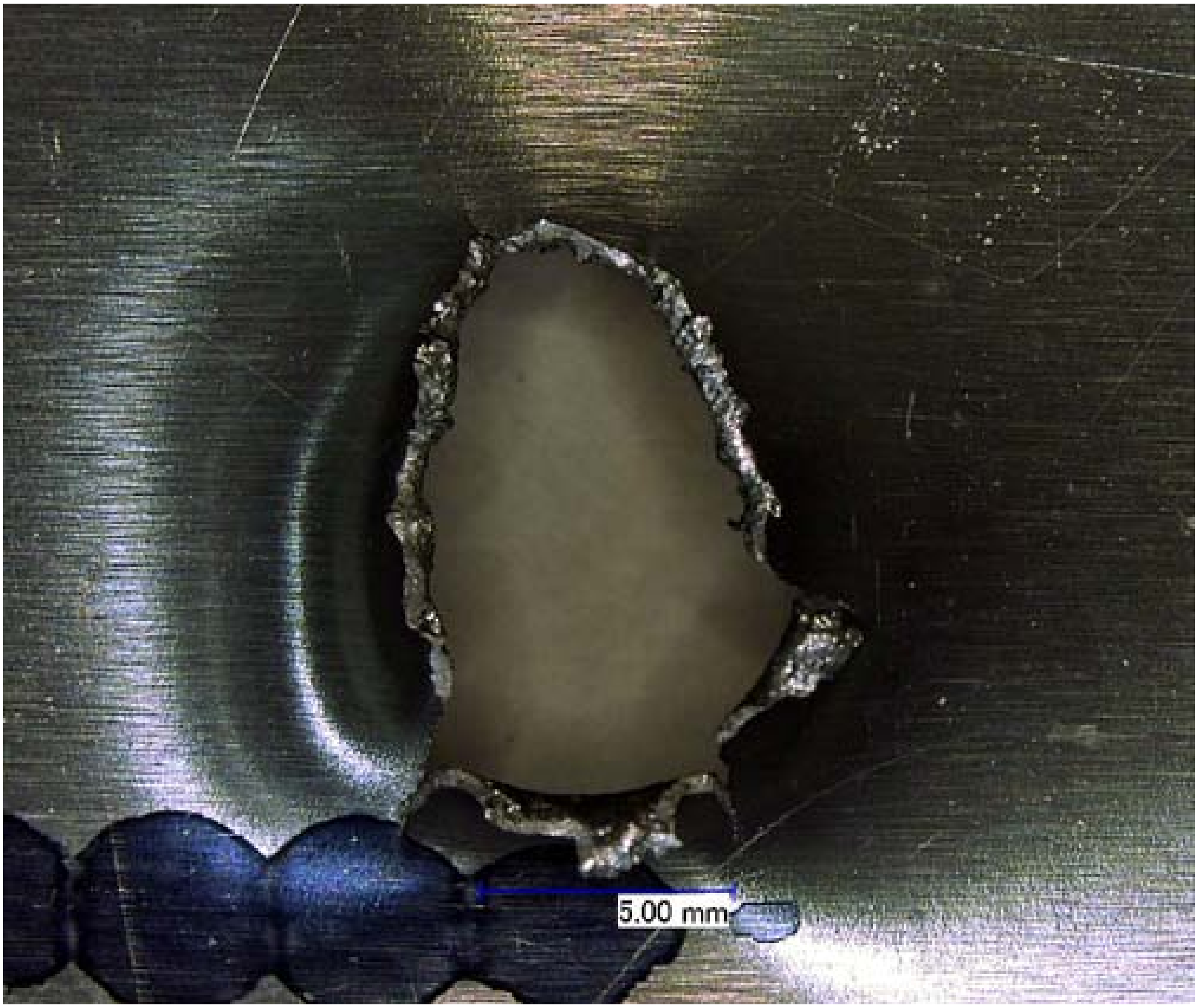


Figure 190: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #11 (Keyence 3D Microscope Image)

Test #11, HITF12271 Rear Wall

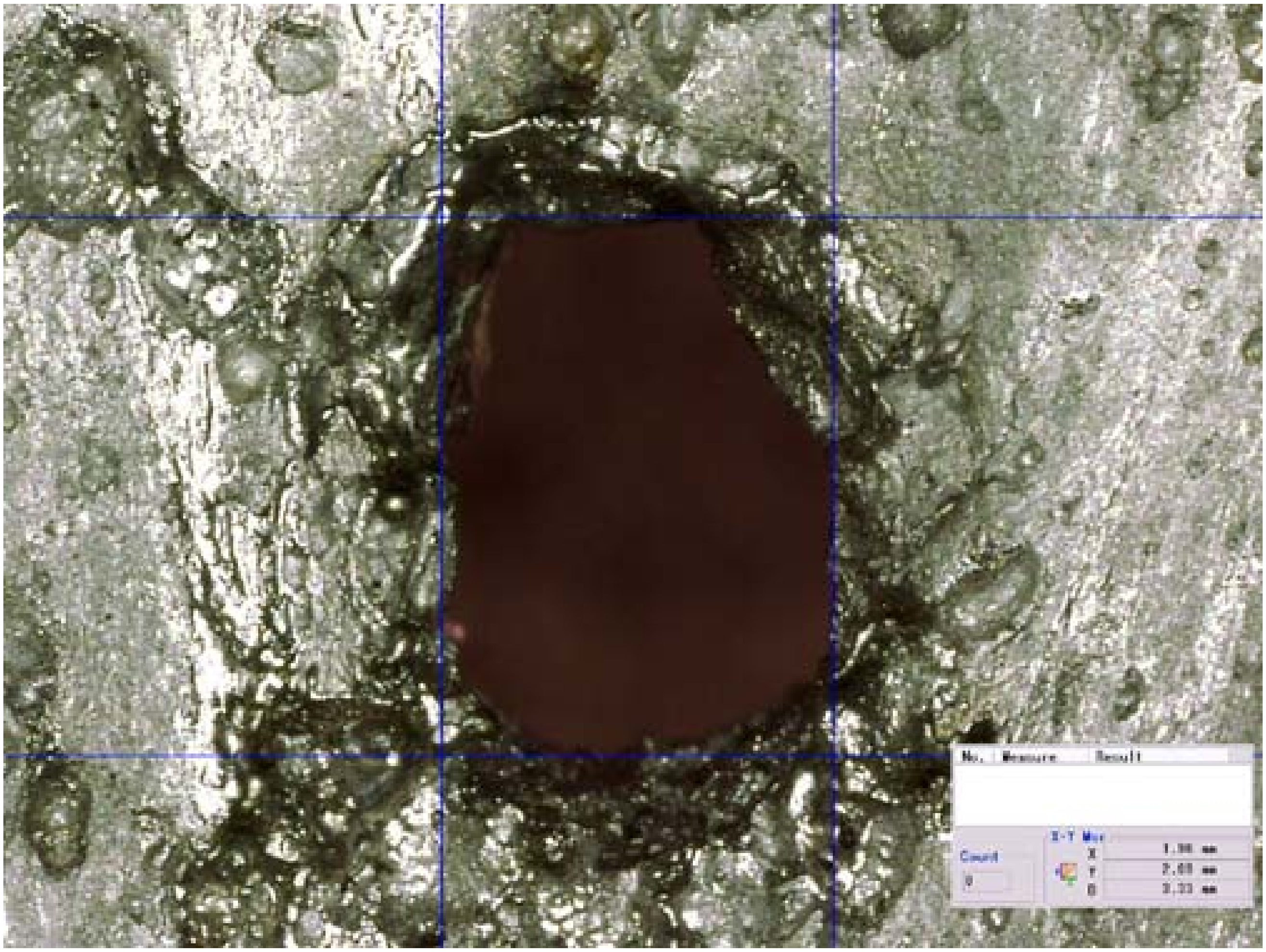


Figure 191: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #11 (Keyence 3D Microscope Image)

Test #11, HITF12271

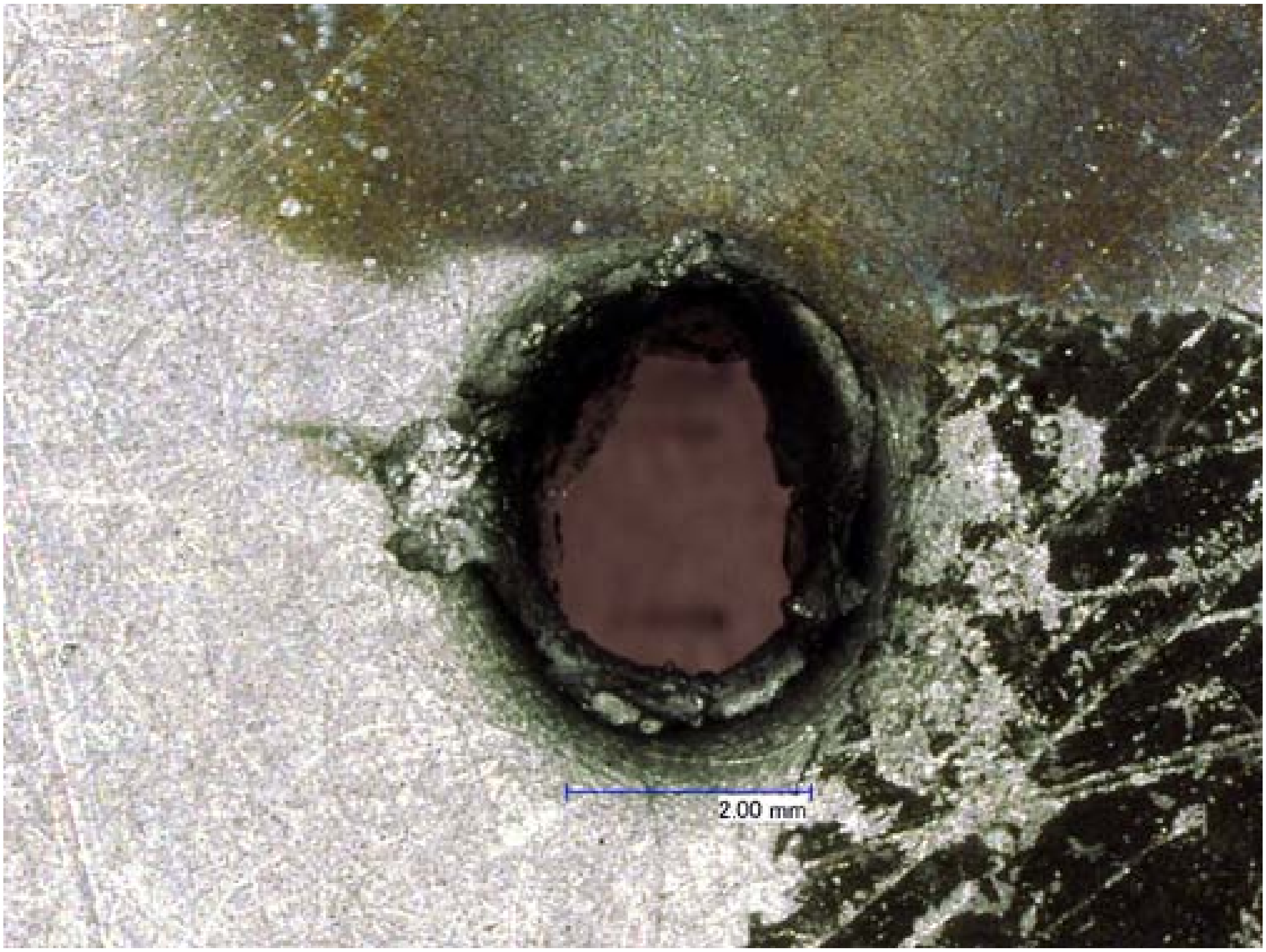


Figure 192: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #11 (Keyence 3D Microscope Image)

Test #11, HITF12271

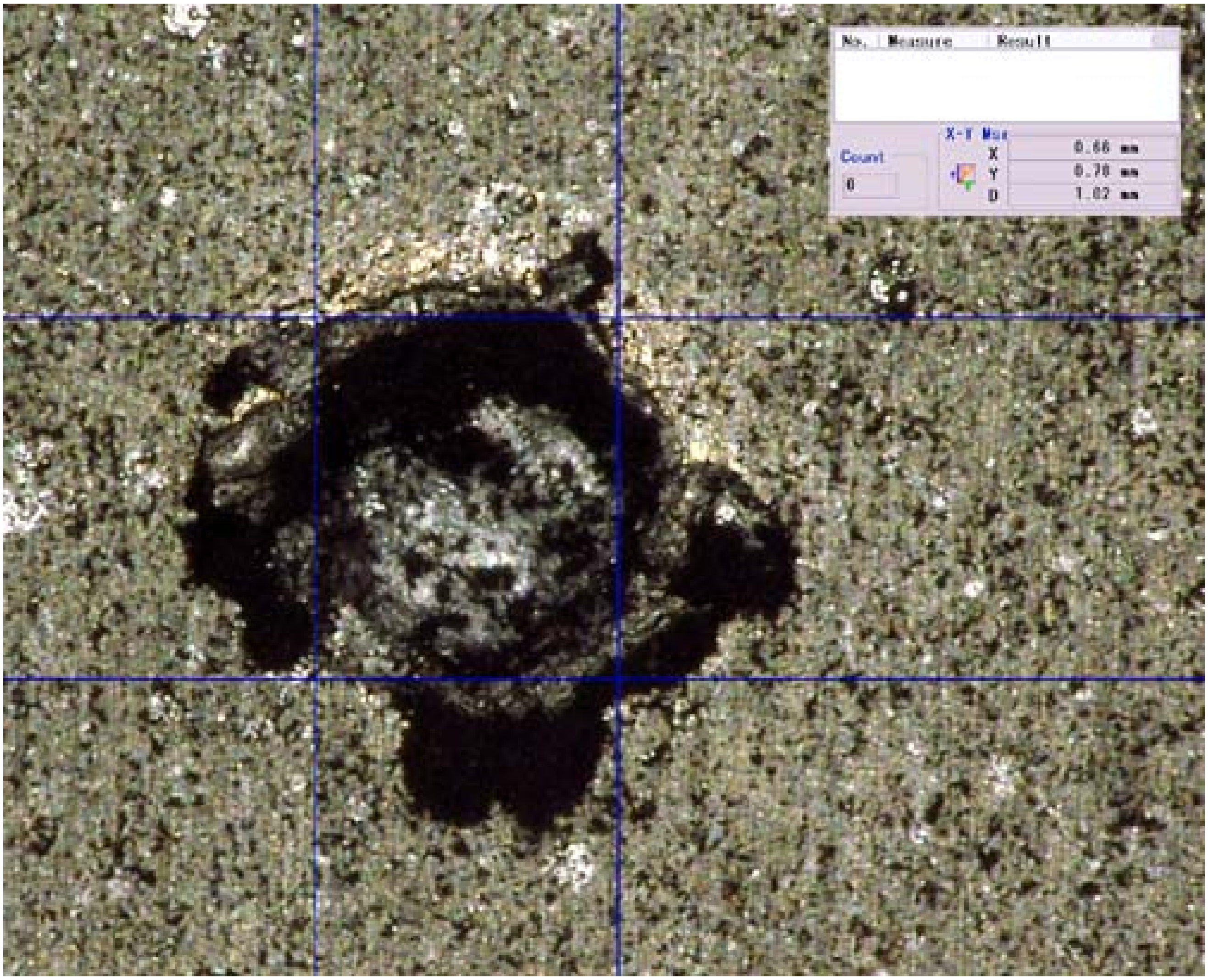


Figure 193: Witness Plate of ISS Soyuz OM Test #11 (Keyence 3D Microscope Image)

Test #11, HITF12271

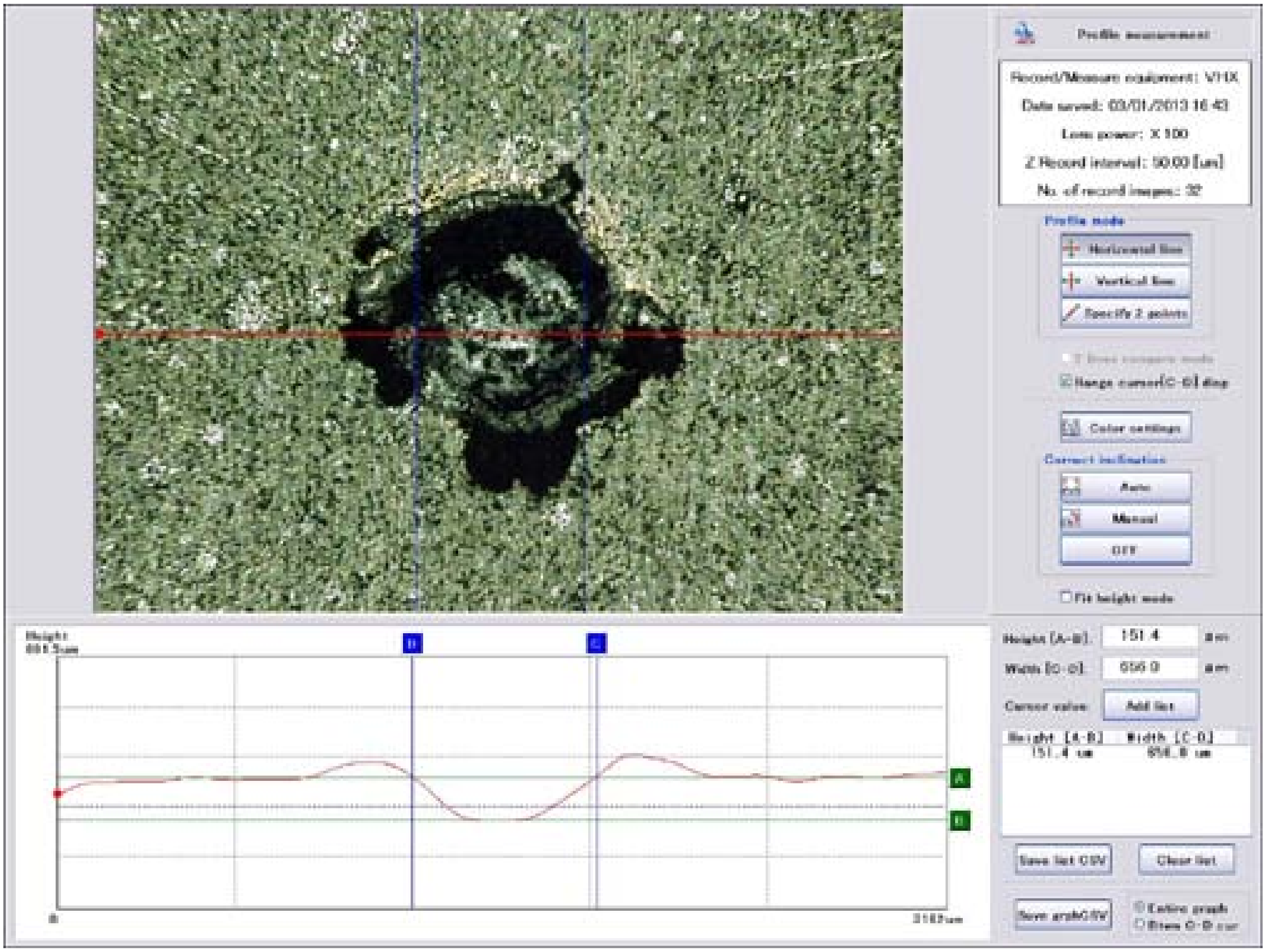


Figure 194: Witness Plate of ISS Soyuz OM Test #11
(Keyence 3D Microscope Image)

Test #11, HITF12271

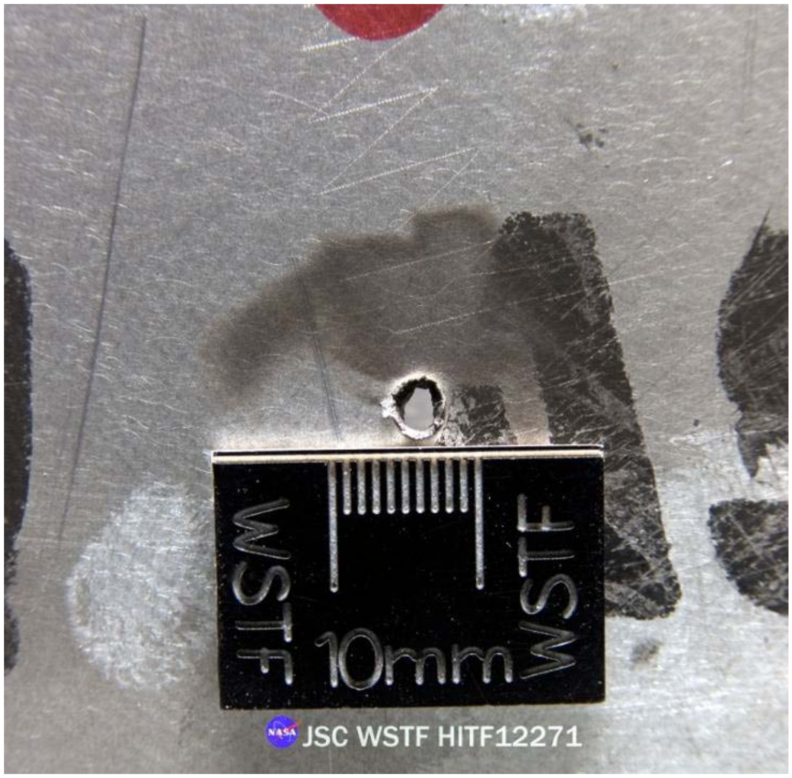


Figure 195: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #11

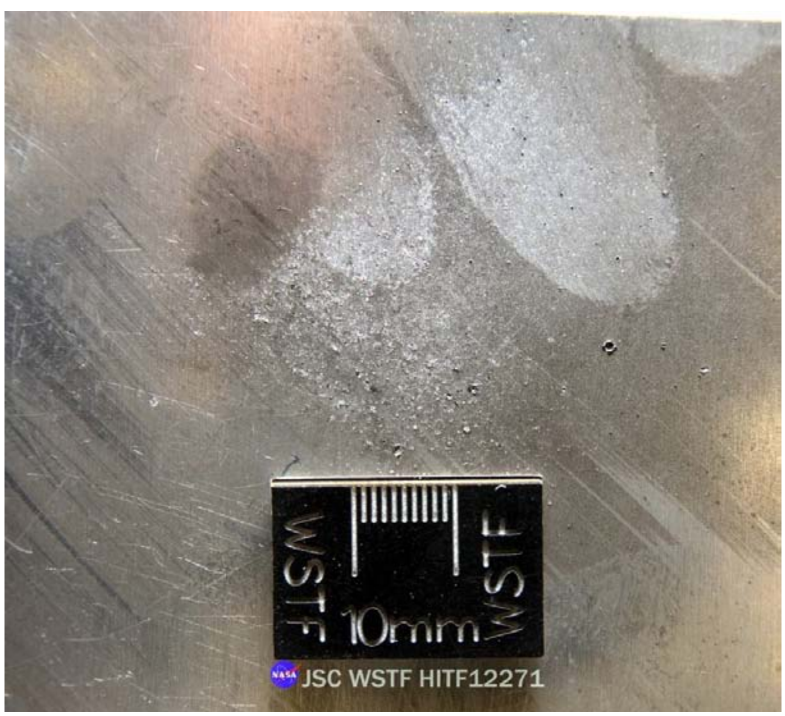


Figure 196: Front Witness Plate View of ISS Soyuz Orbital Module Test #11

Test #12, HITF12272

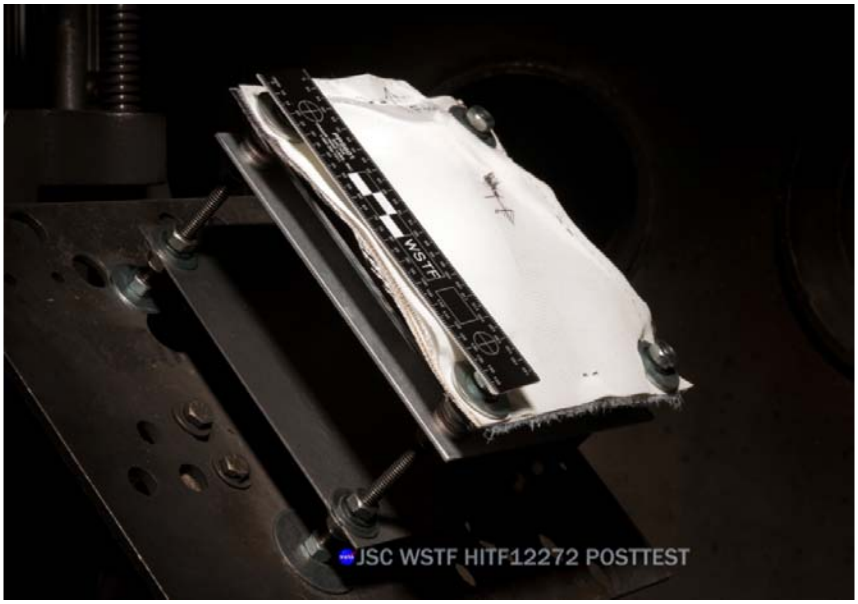


Figure 197: Post-test of ISS Soyuz Orbital Module Test #12 (HITF12272) article mounted in 0.17-caliber target tank.

Figure 198: Side View of ISS Soyuz Orbital Module Test #12

Test #12, HITF12272

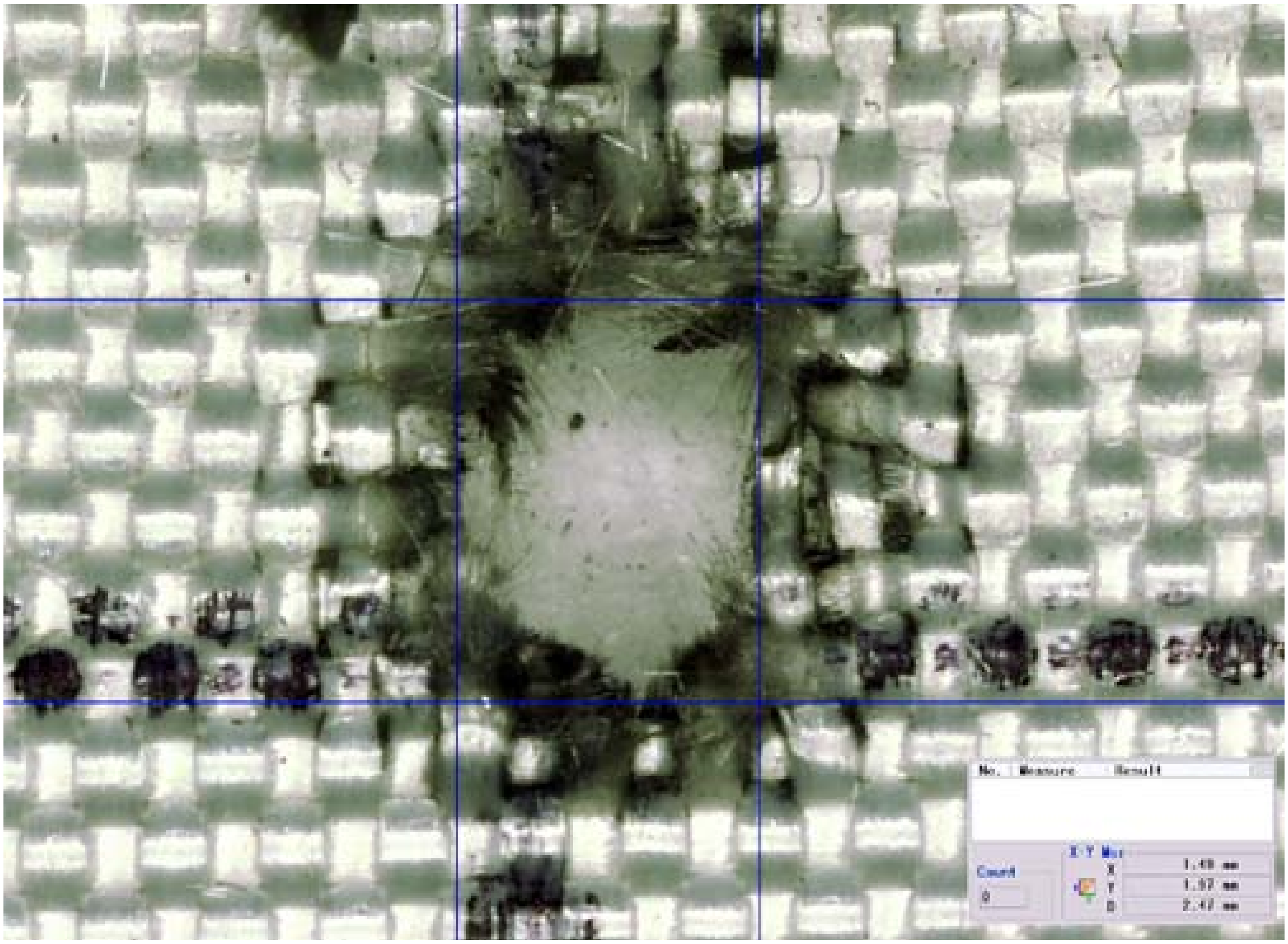


Figure 199: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #12
(Keyence 3D Microscope Image)

Figure 200: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #12

Test #12, HITF12272

Figure 201: Mylar Film Layer 2 of ISS Soyuz OM Test #12 (Keyence 3D Microscope Image)

Test #12, HITF12272

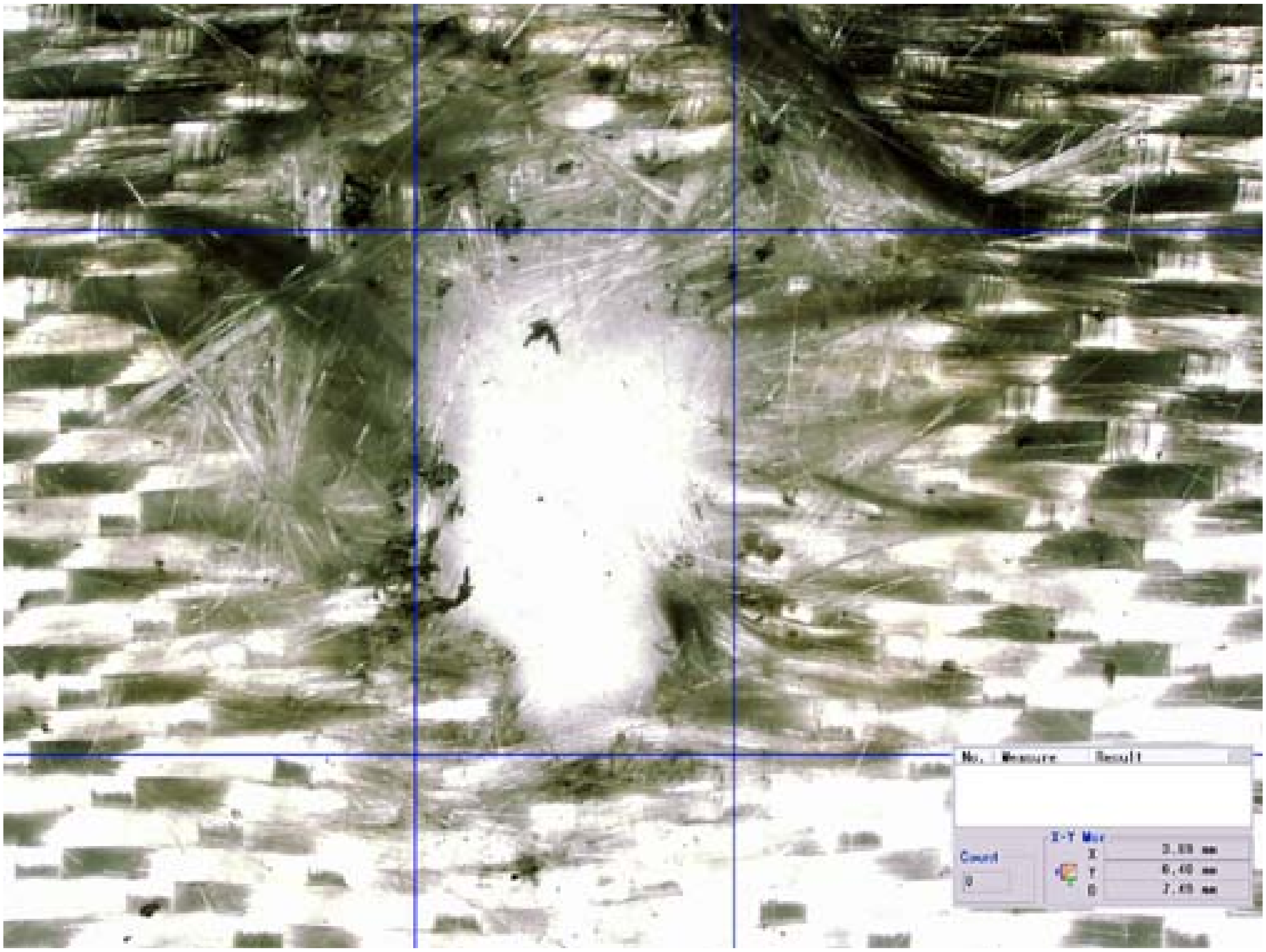


Figure 202: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #12 (Keyence 3D Microscope Image)

Test #12, HITF12272

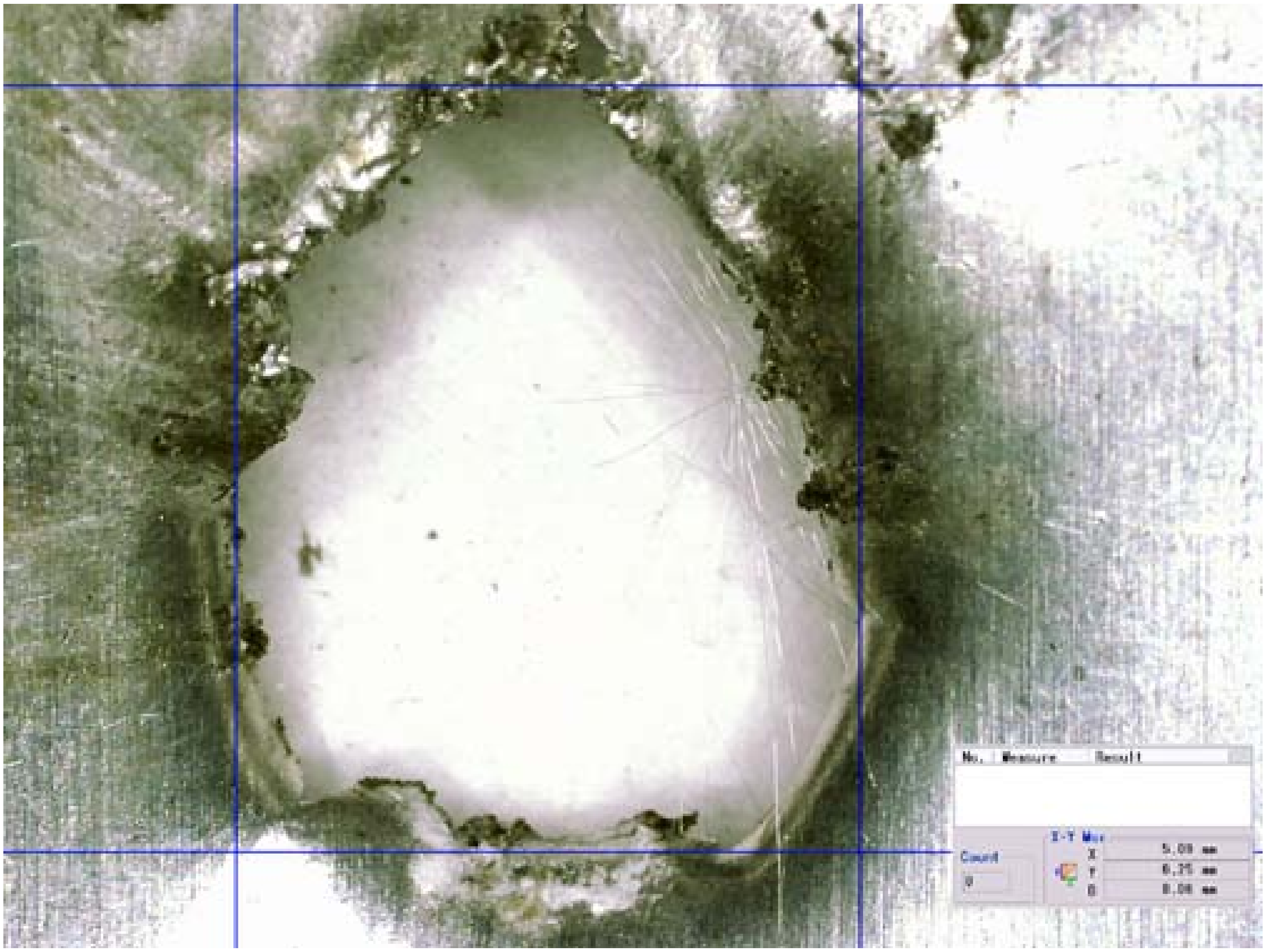


Figure 203: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #12
(Keyence 3D Microscope Image)

Test #12, HITF12272

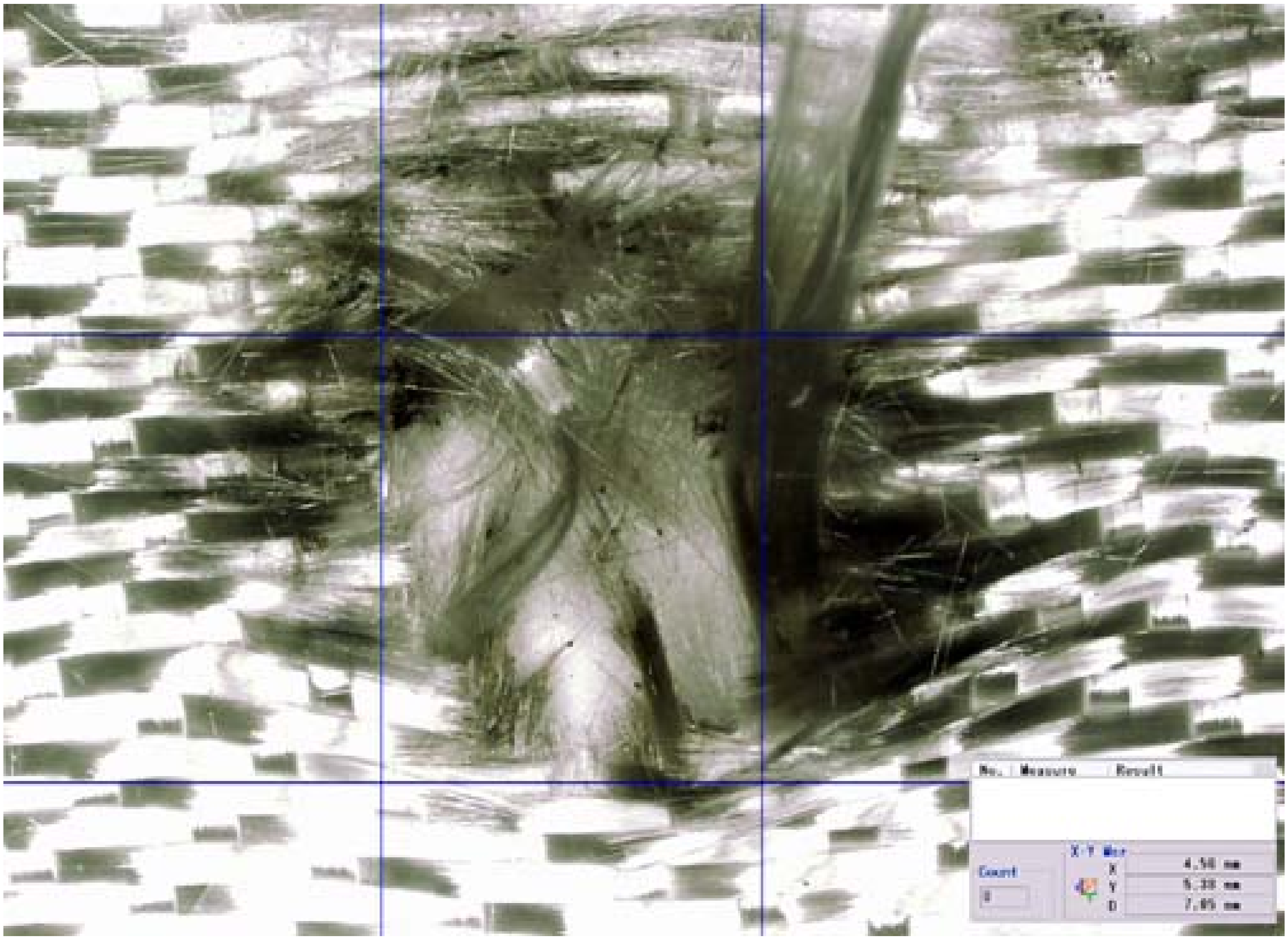


Figure 204: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #12 (Keyence 3D Microscope Image)

Test #12, HITF12272

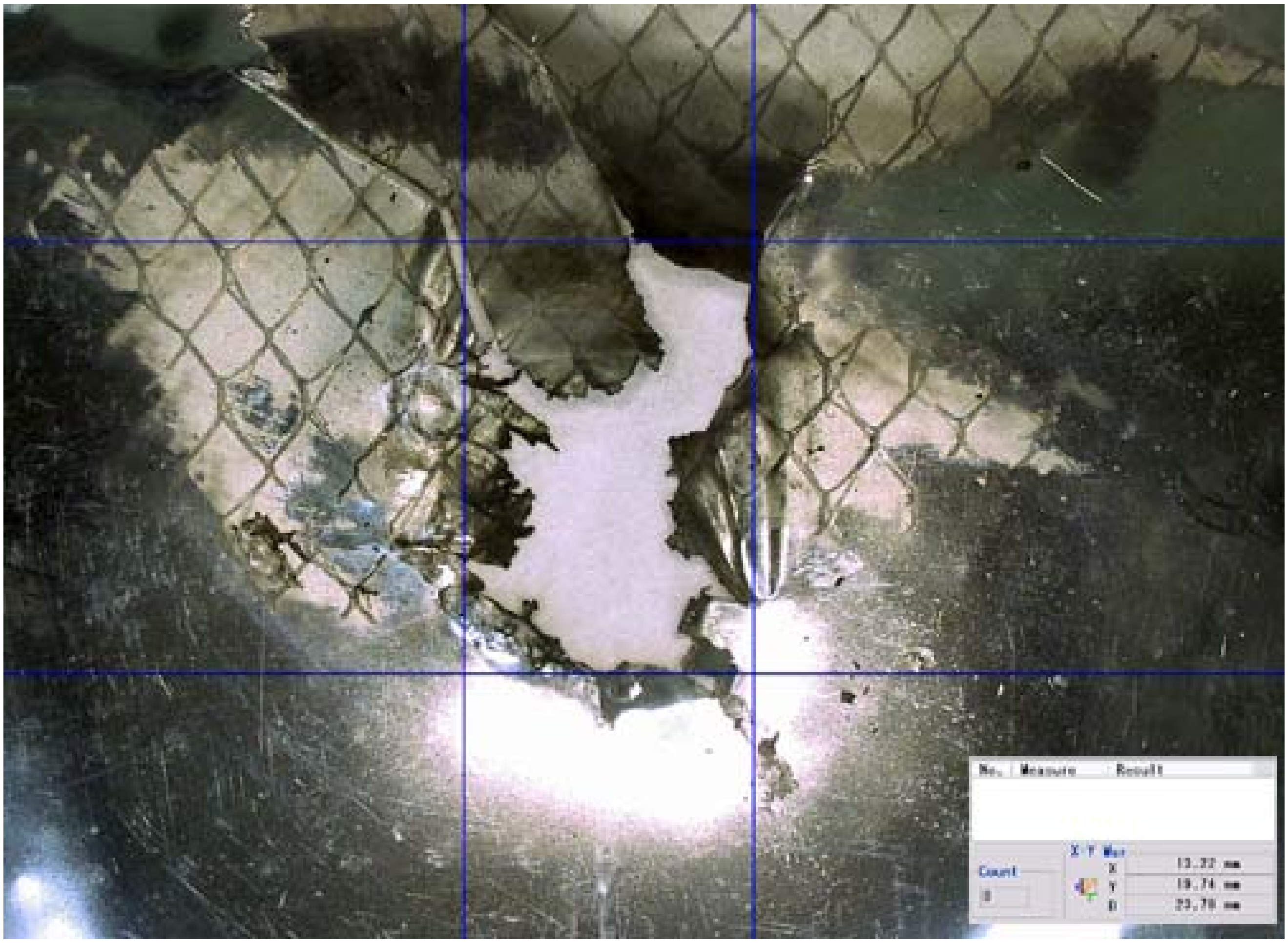


Figure 205: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #12 (Keyence 3D Microscope Image)

Test #12, HITF12272

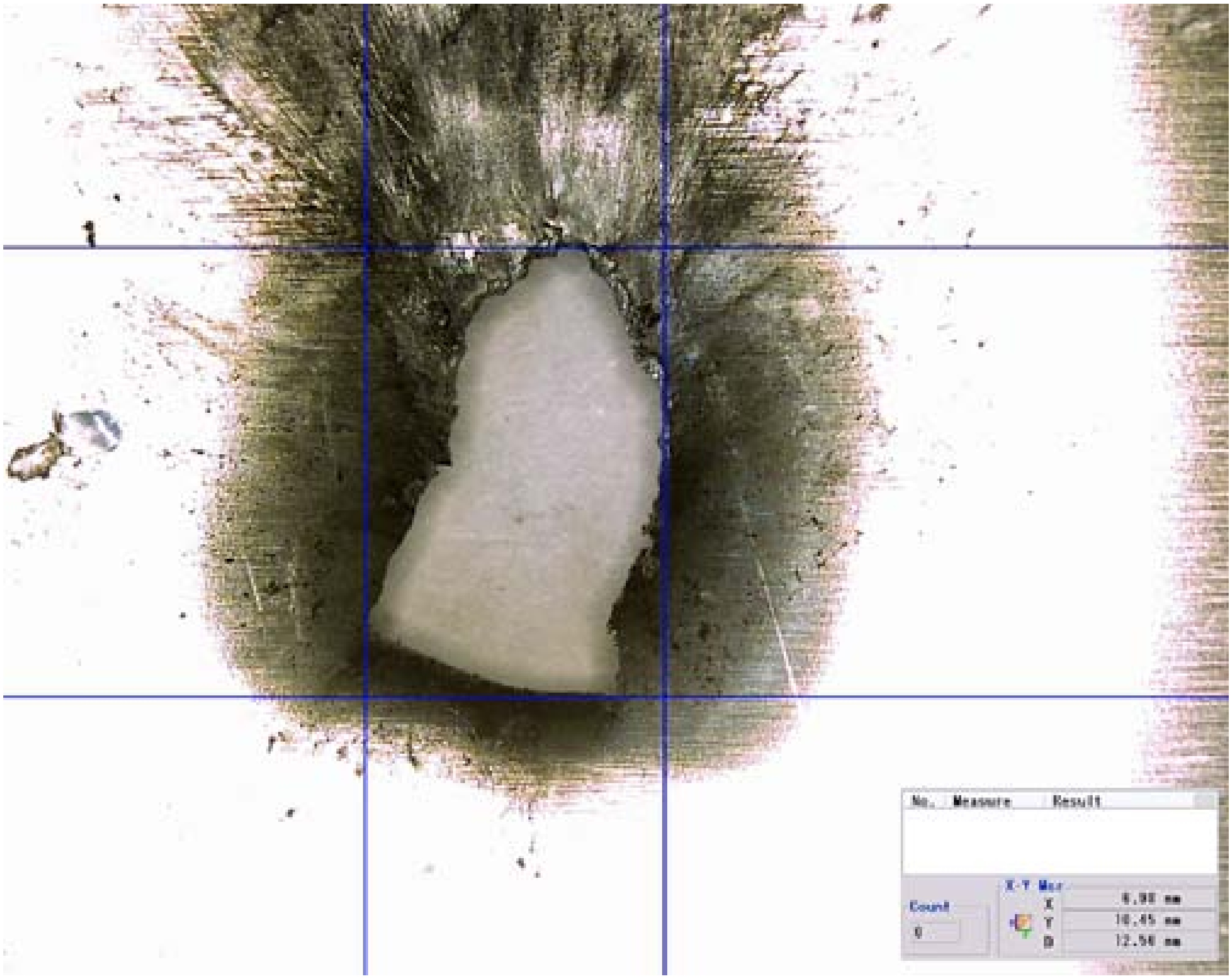


**Figure 206: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #12
(Keyence 3D Microscope Image)**

Test #12, HITF12272

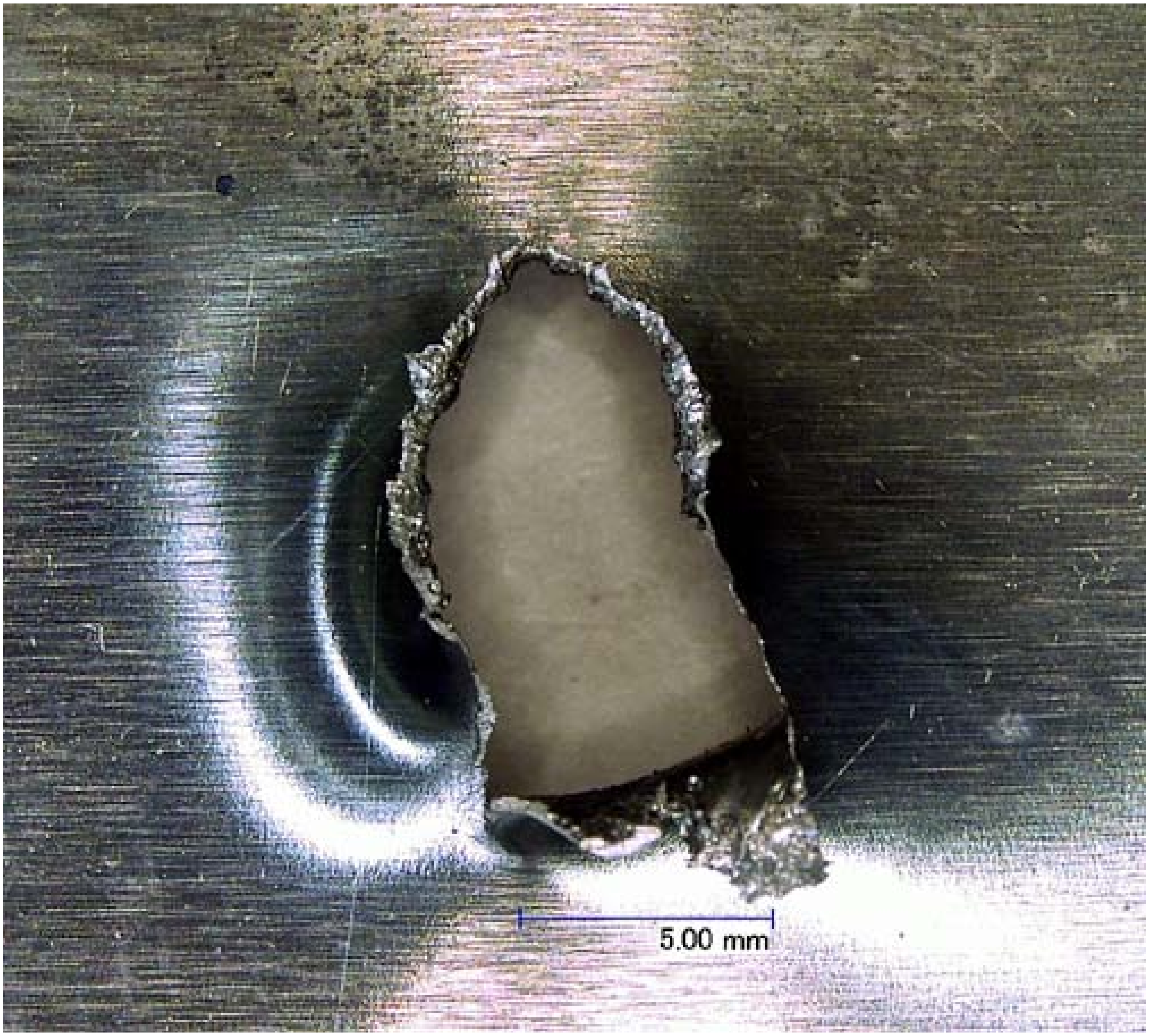


Figure 207: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #12 (Keyence 3D Microscope Image)

Test #12, HITF12272 Rear Wall

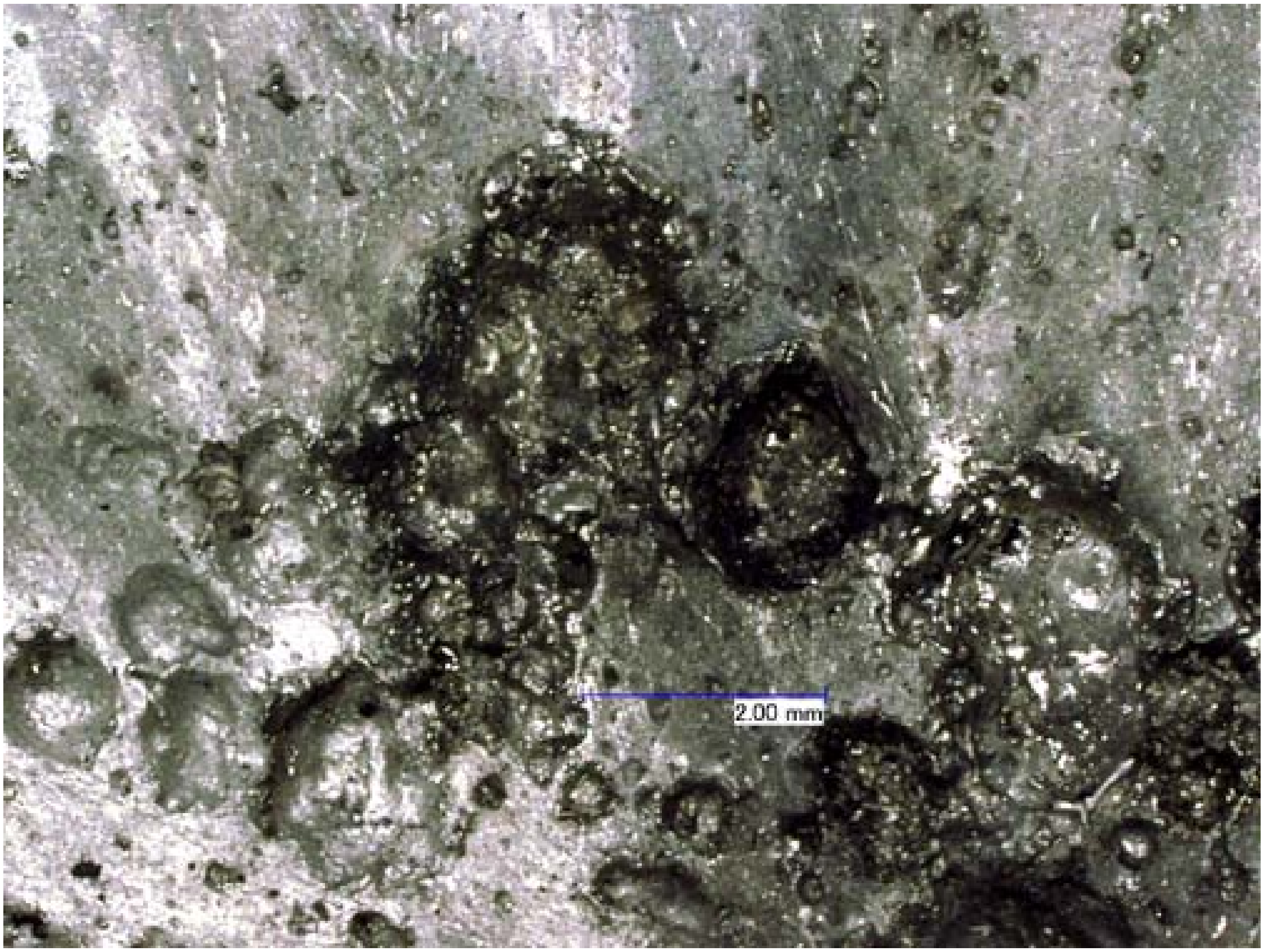


Figure 208: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #12
(Keyence 3D Microscope Image)

Test #12, HITF12272

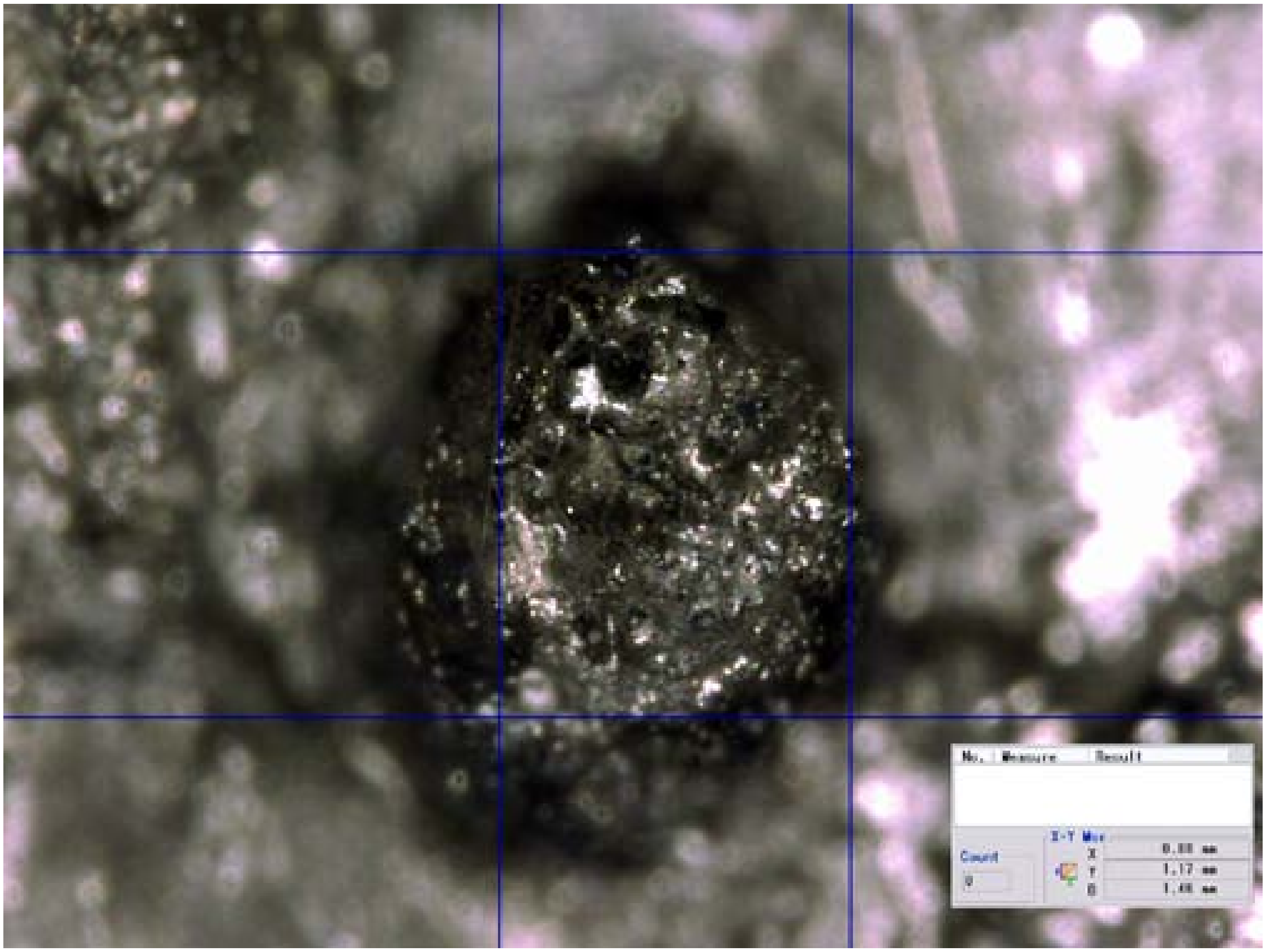


Figure 209: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #12 (Keyence 3D Microscope Image)

Test #12, HITF12272

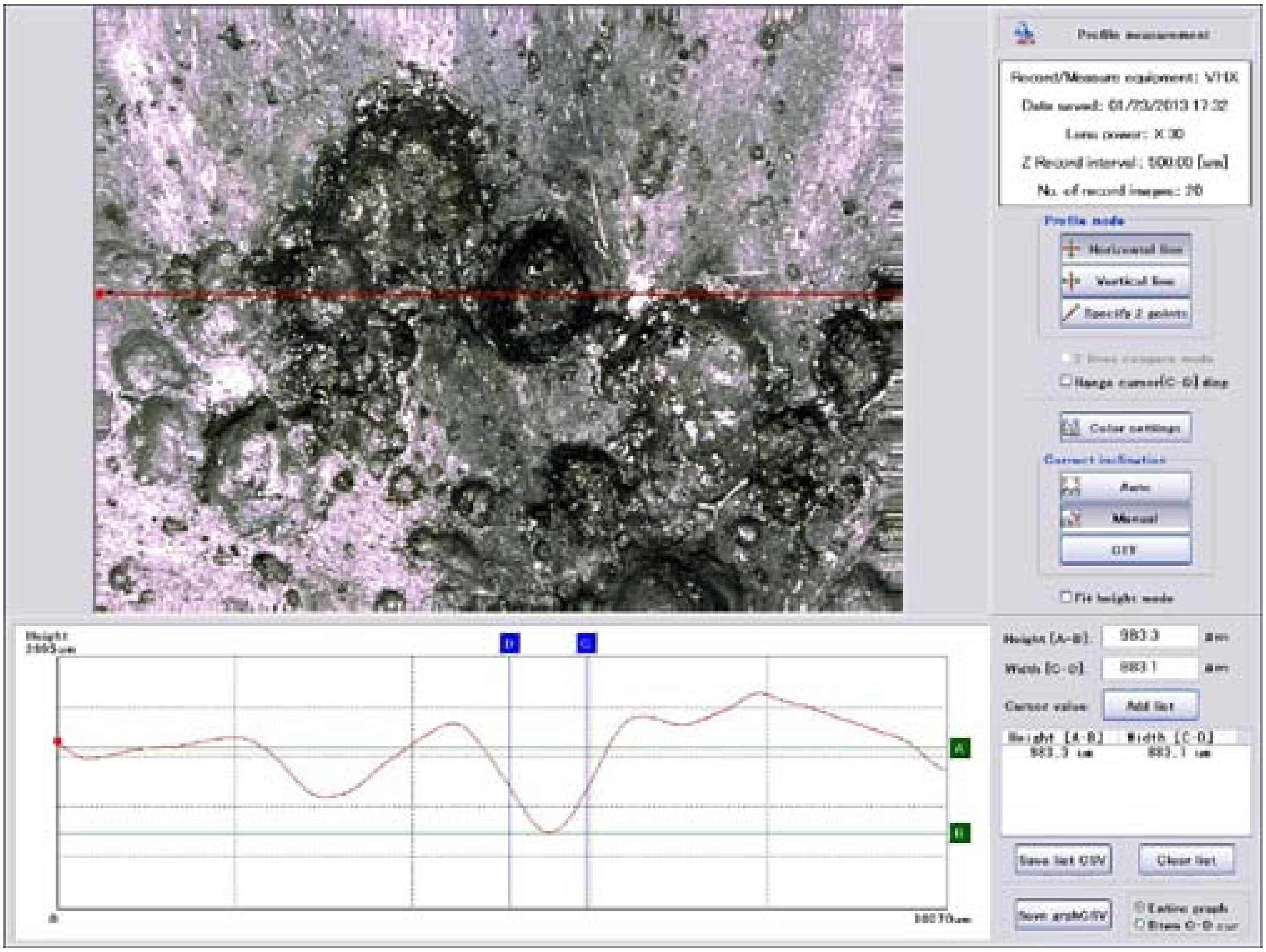


Figure 210: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #12 (Keyence 3D Microscope Image)

Test #12, HITF12272

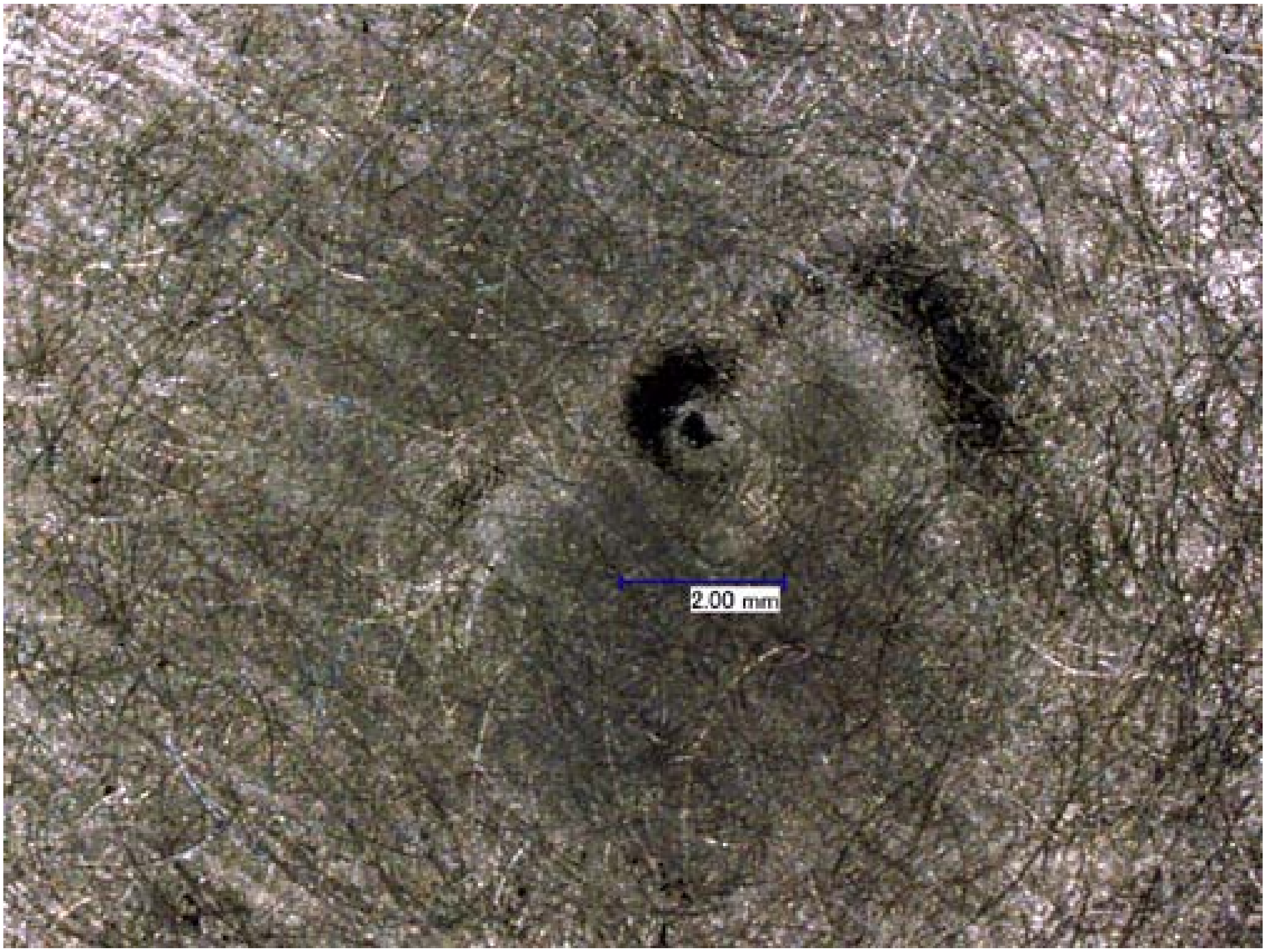


Figure 211: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #12 (Keyence 3D Microscope Image)

Test #12, HITF12272

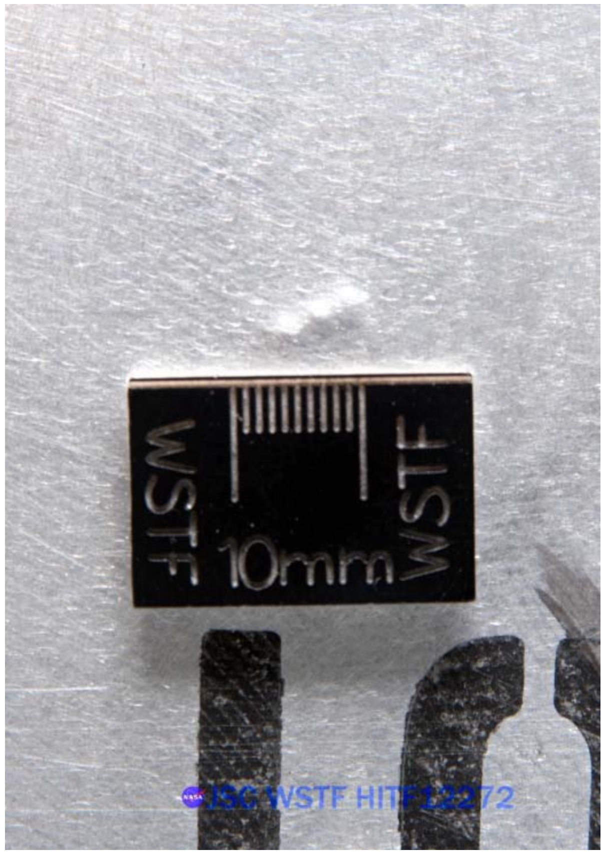


Figure 212: Back Close-up of Al 5456-0 Rear Wall for ISS Soyuz Orbital Module Test #12

Figure 213: Back Witness Plate View of ISS Soyuz Orbital Module Test #12

Test #13B, HITF12273

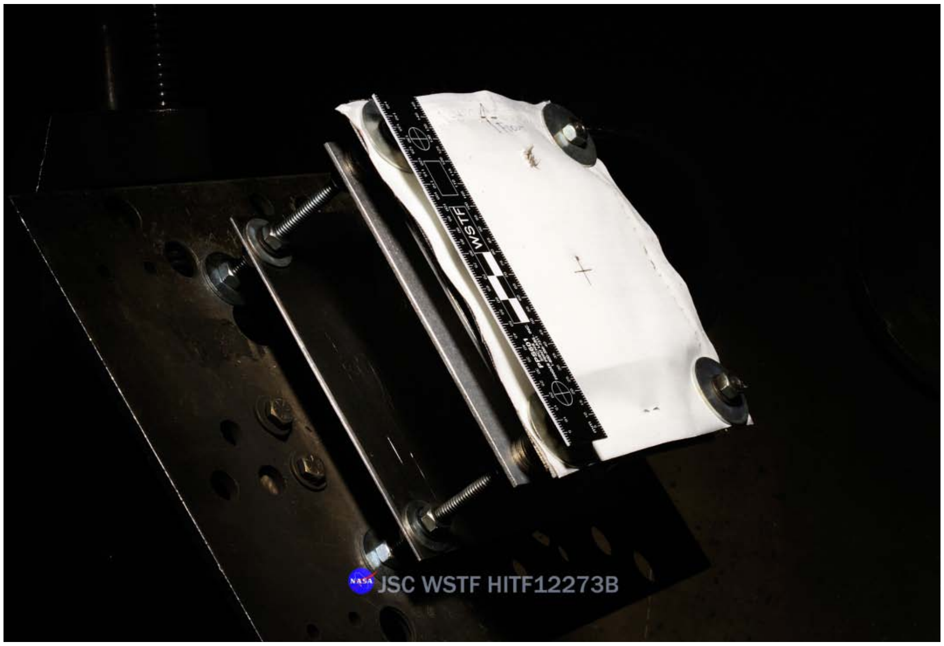


Figure 214: Post-test of ISS Soyuz Orbital Module Test #13B (HITF12273) article mounted in 0.17-caliber target tank.

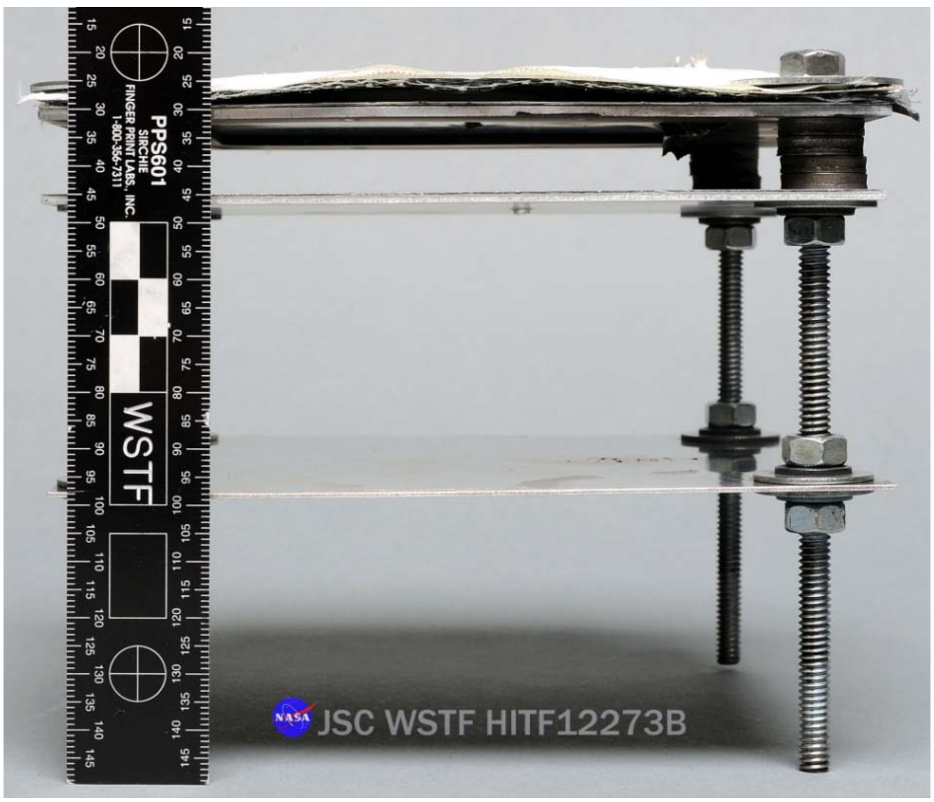


Figure 215: Side View of ISS Soyuz Orbital Module Test #13B

Test #13B, HIT12273

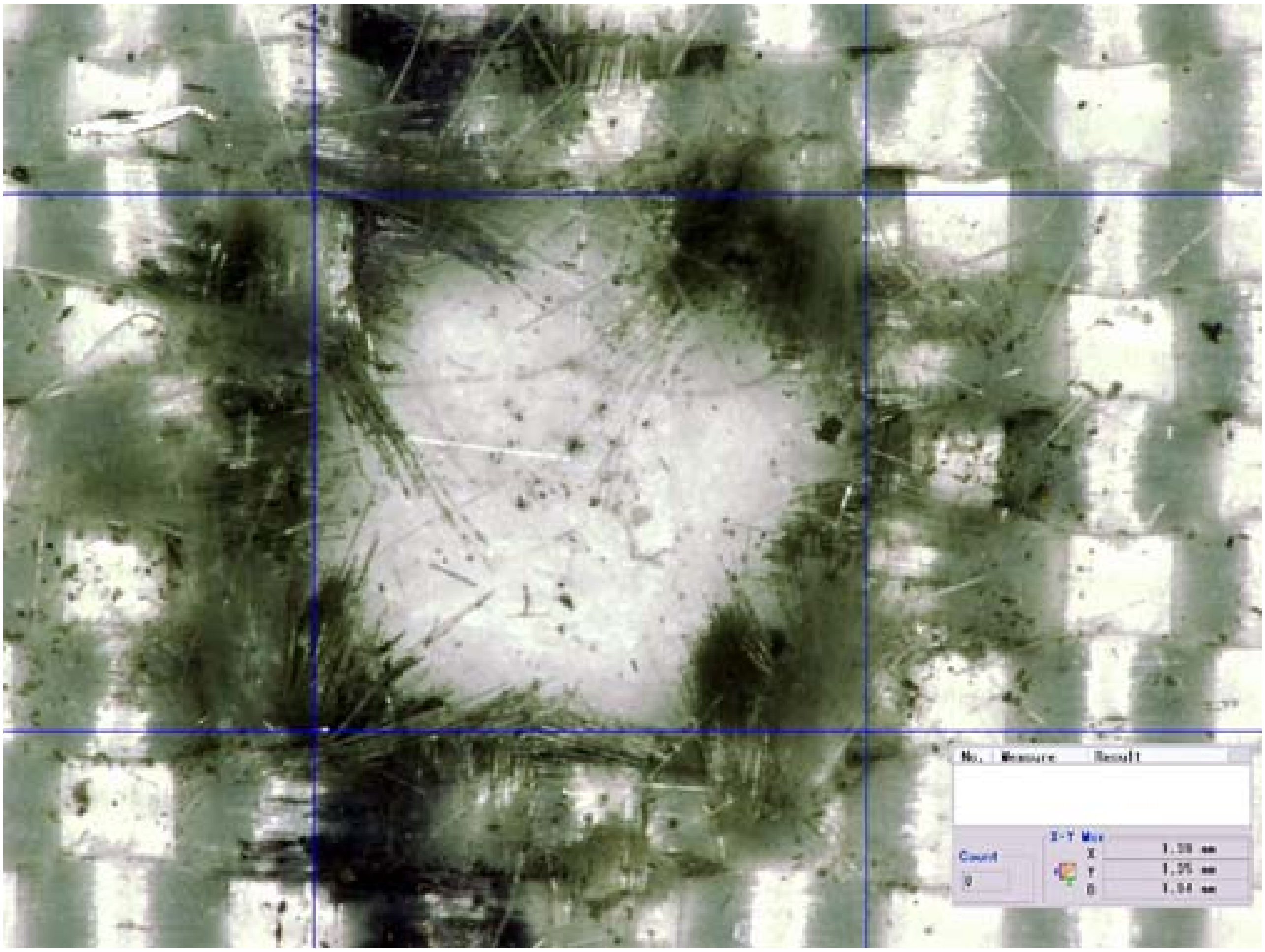


Figure 216: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Figure 217: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #13B

Test #13B, HITF12273

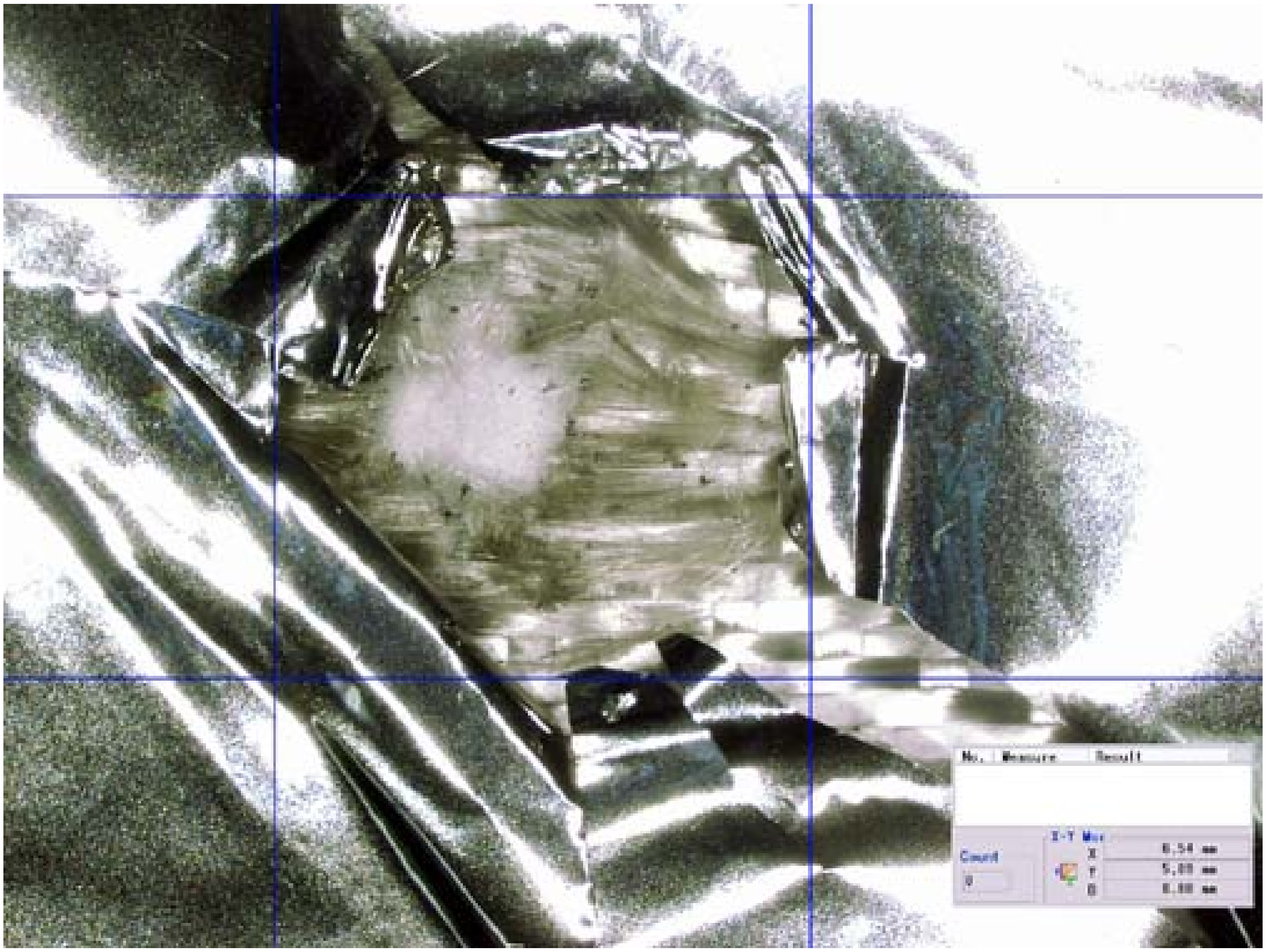


Figure 218: Mylar Film Layer 2 of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273

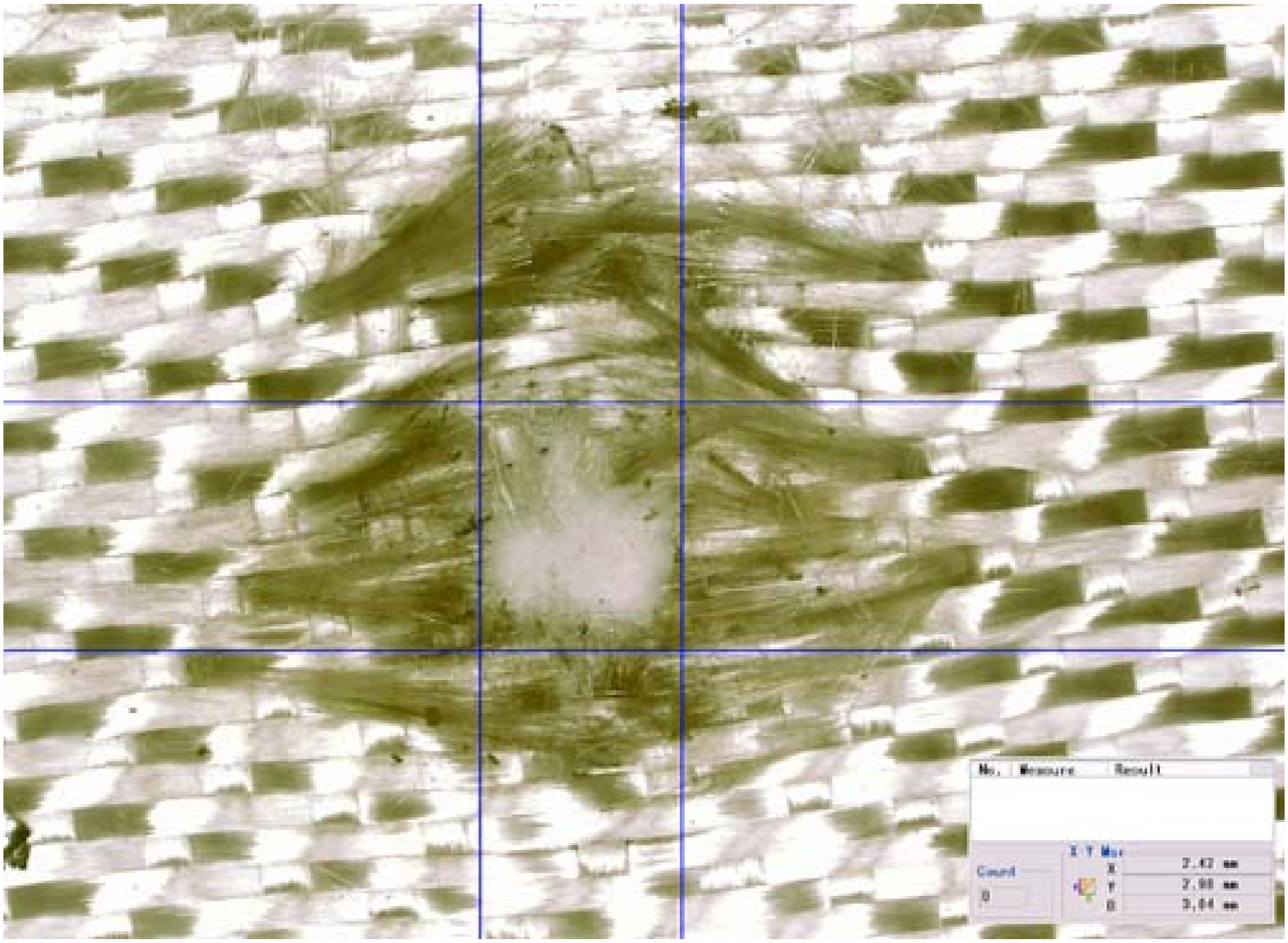


Figure 219: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273

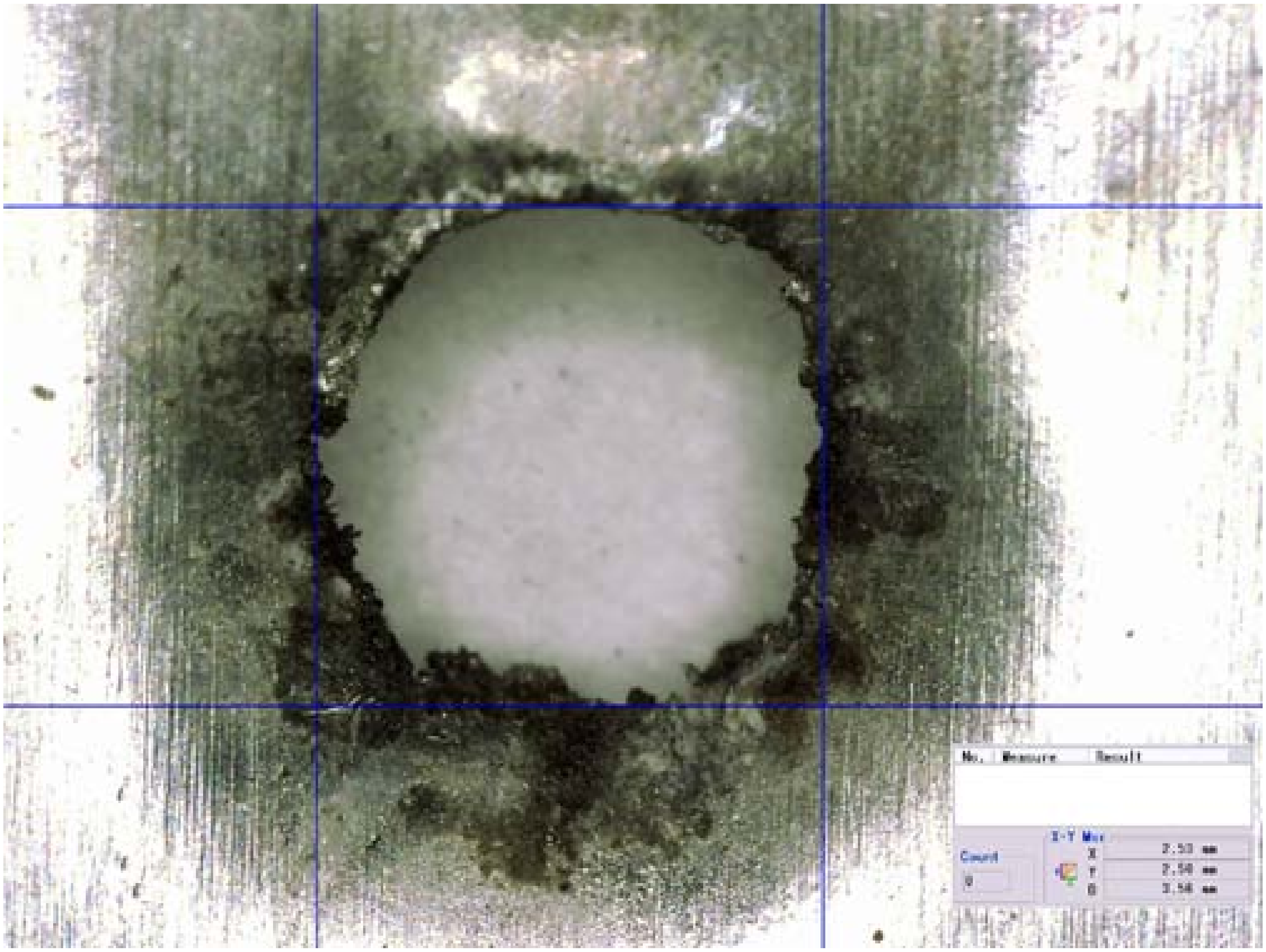


Figure 220: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273

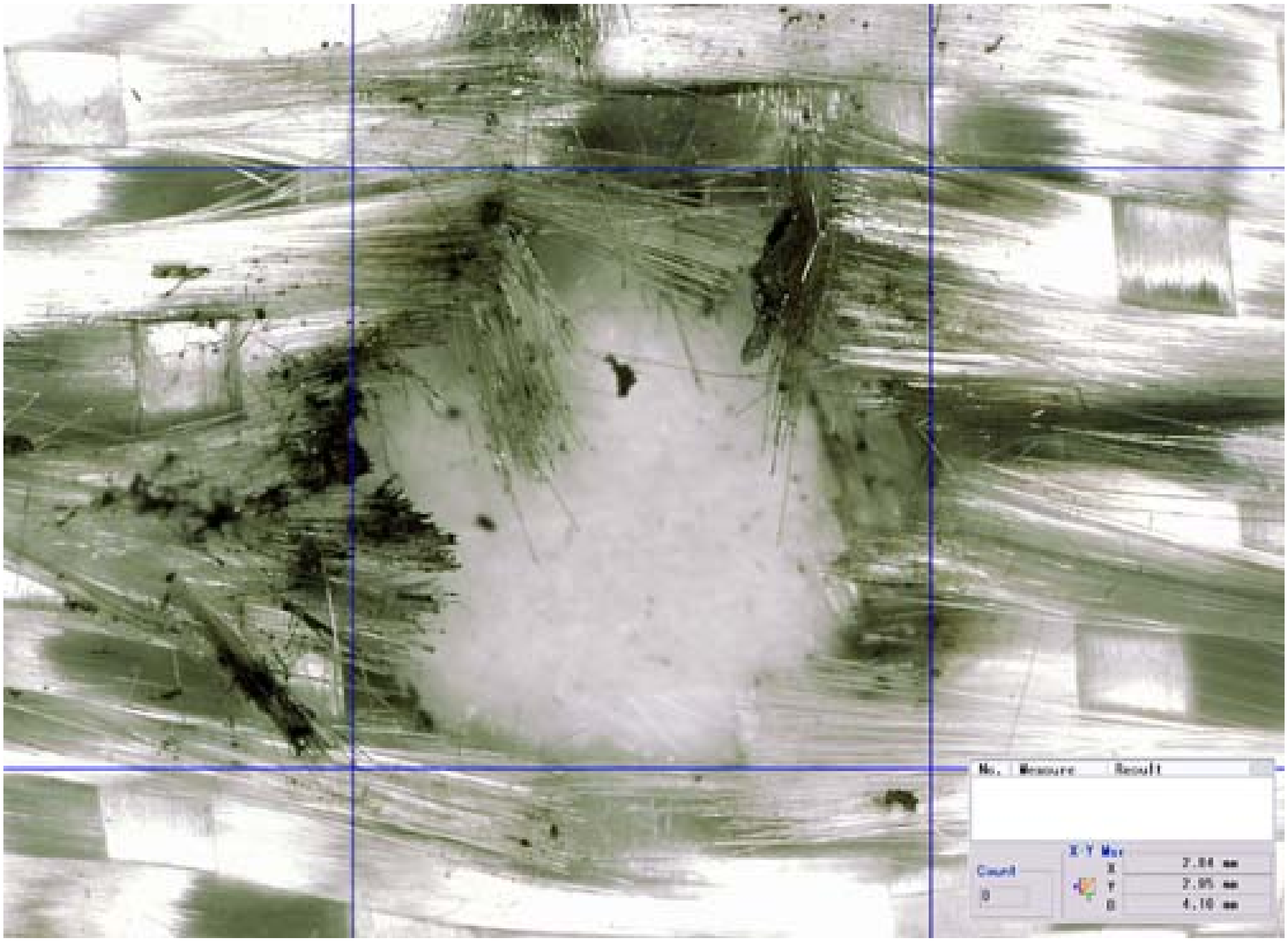


Figure 221: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273

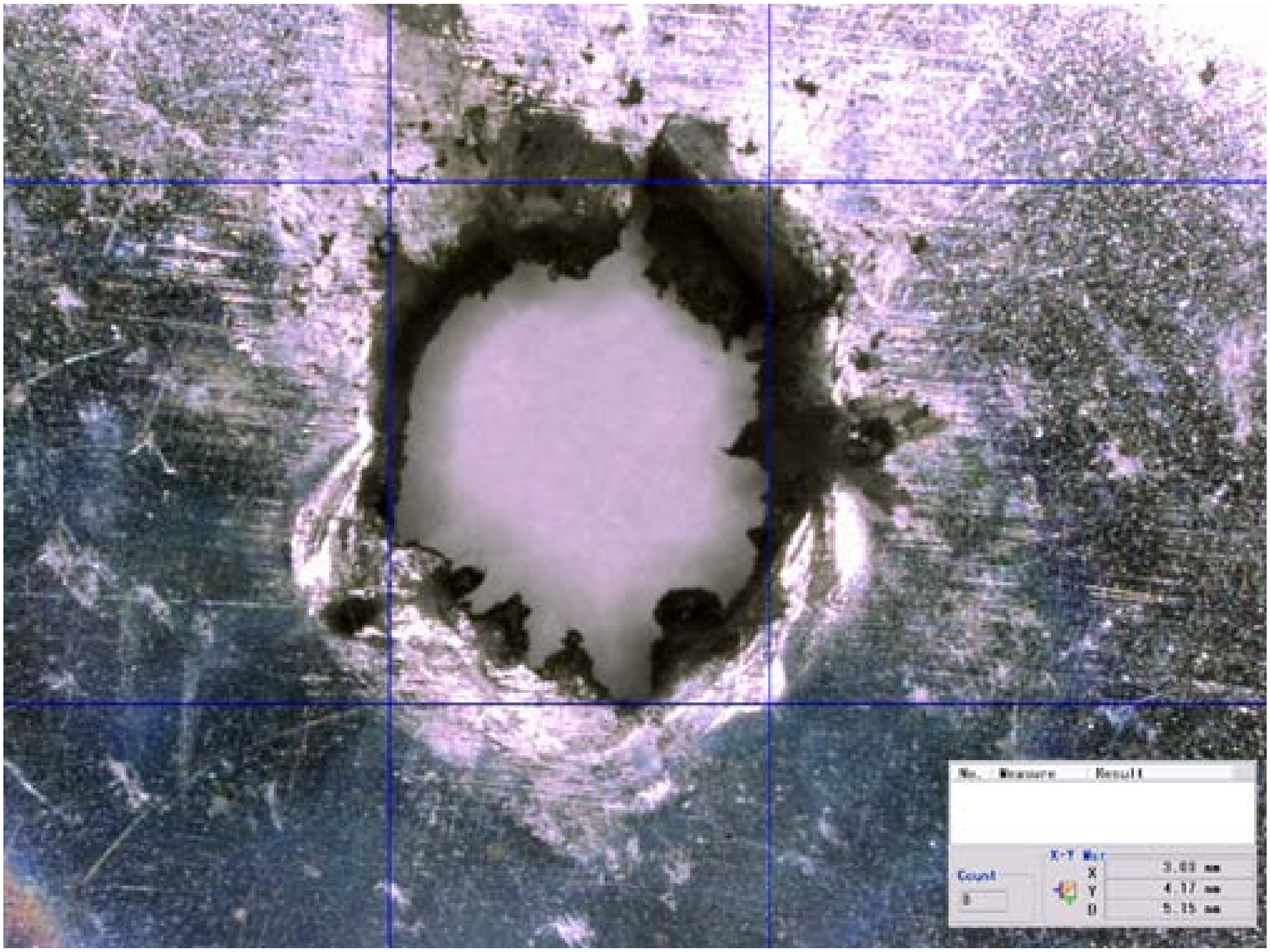


Figure 222: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273

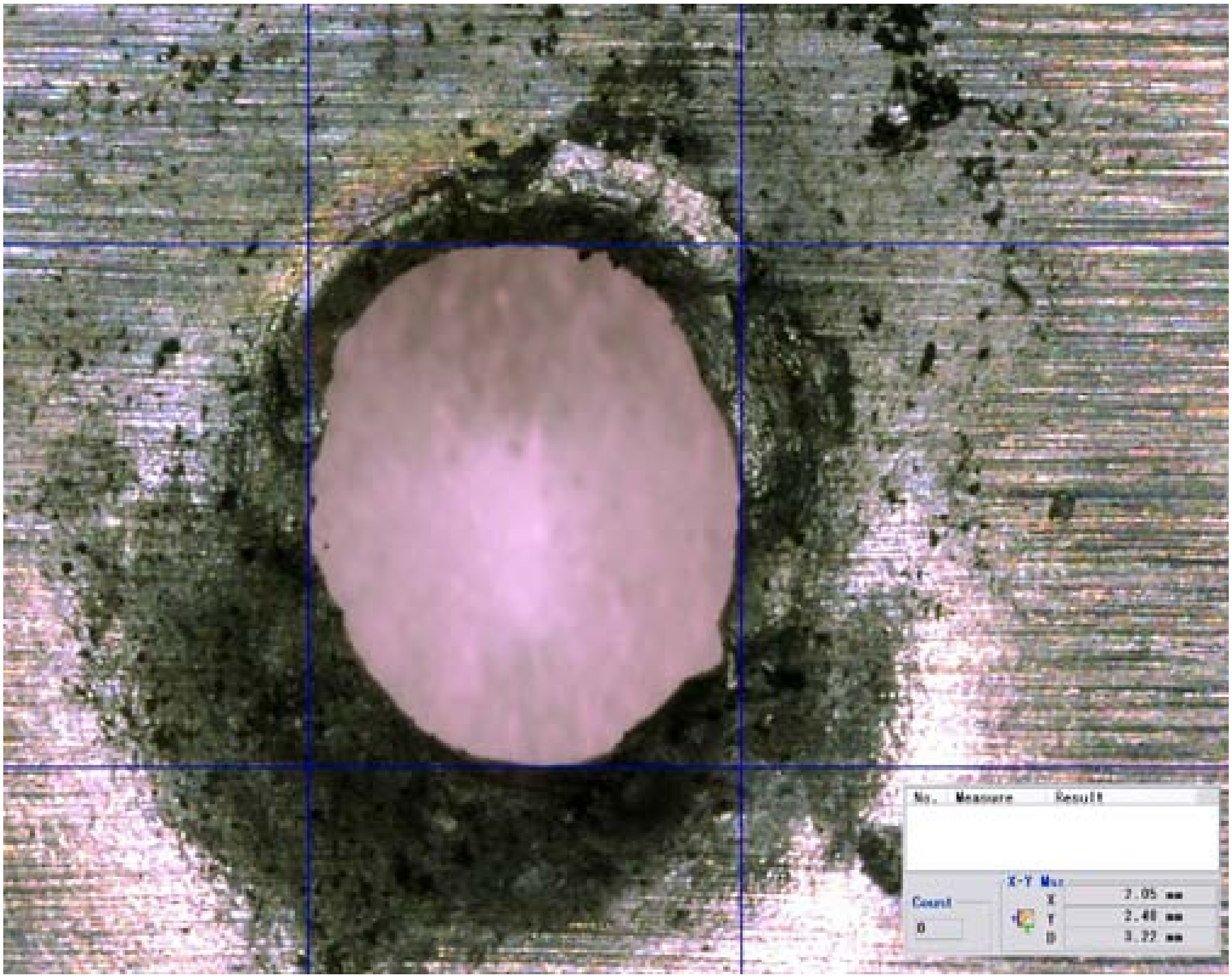


Figure 223: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273

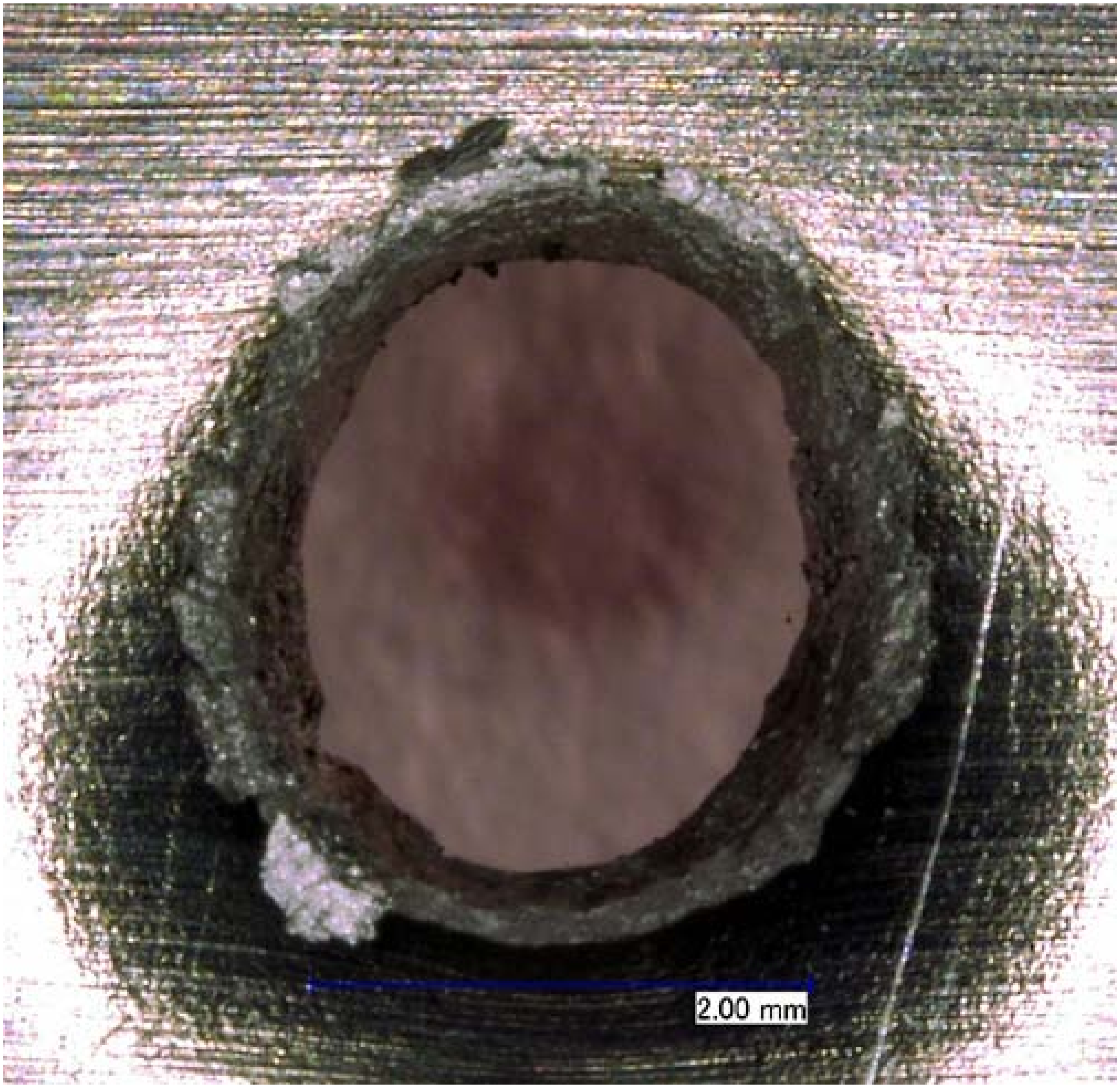


Figure 224: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273 Rear Wall

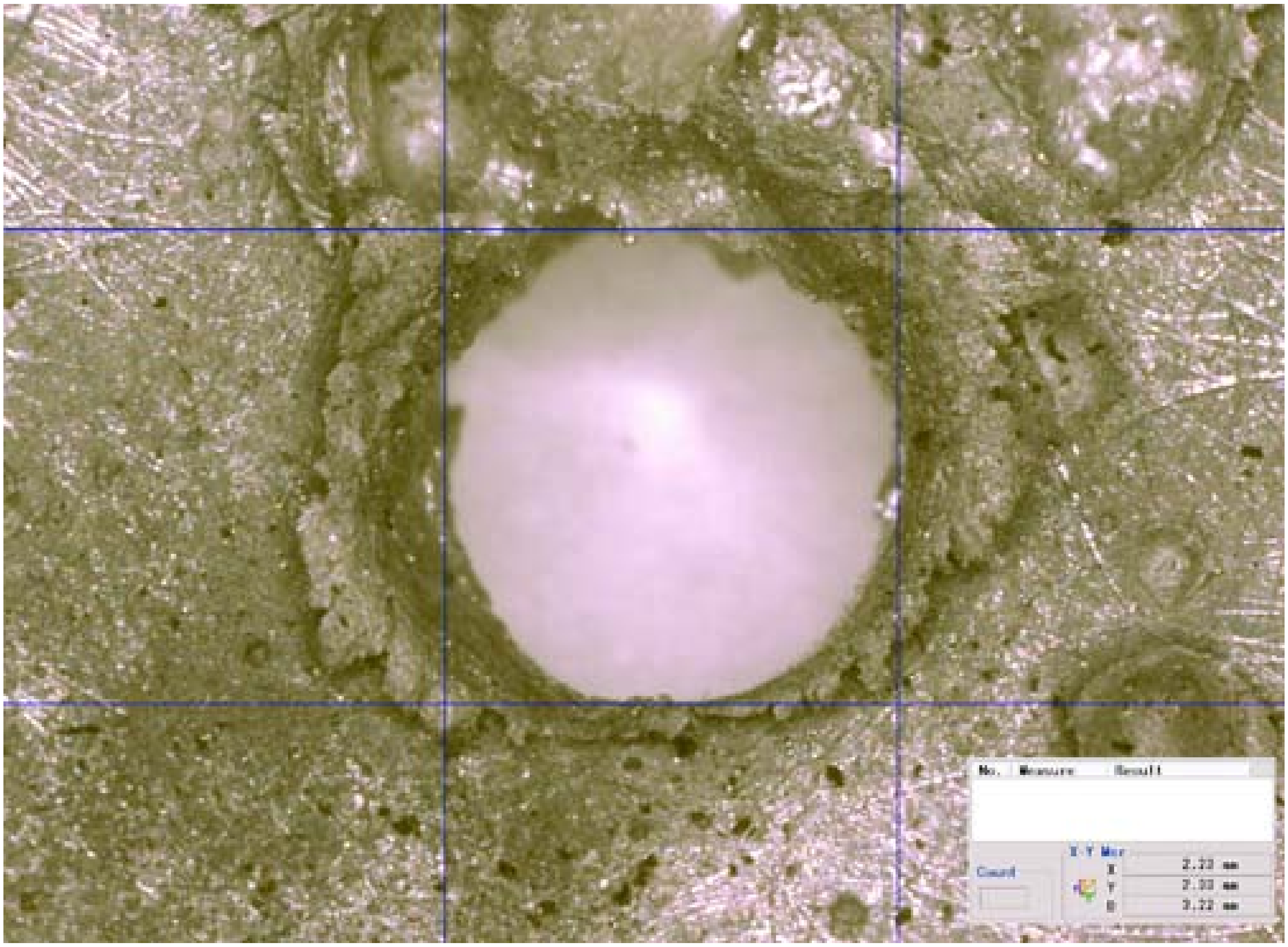


Figure 225: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273

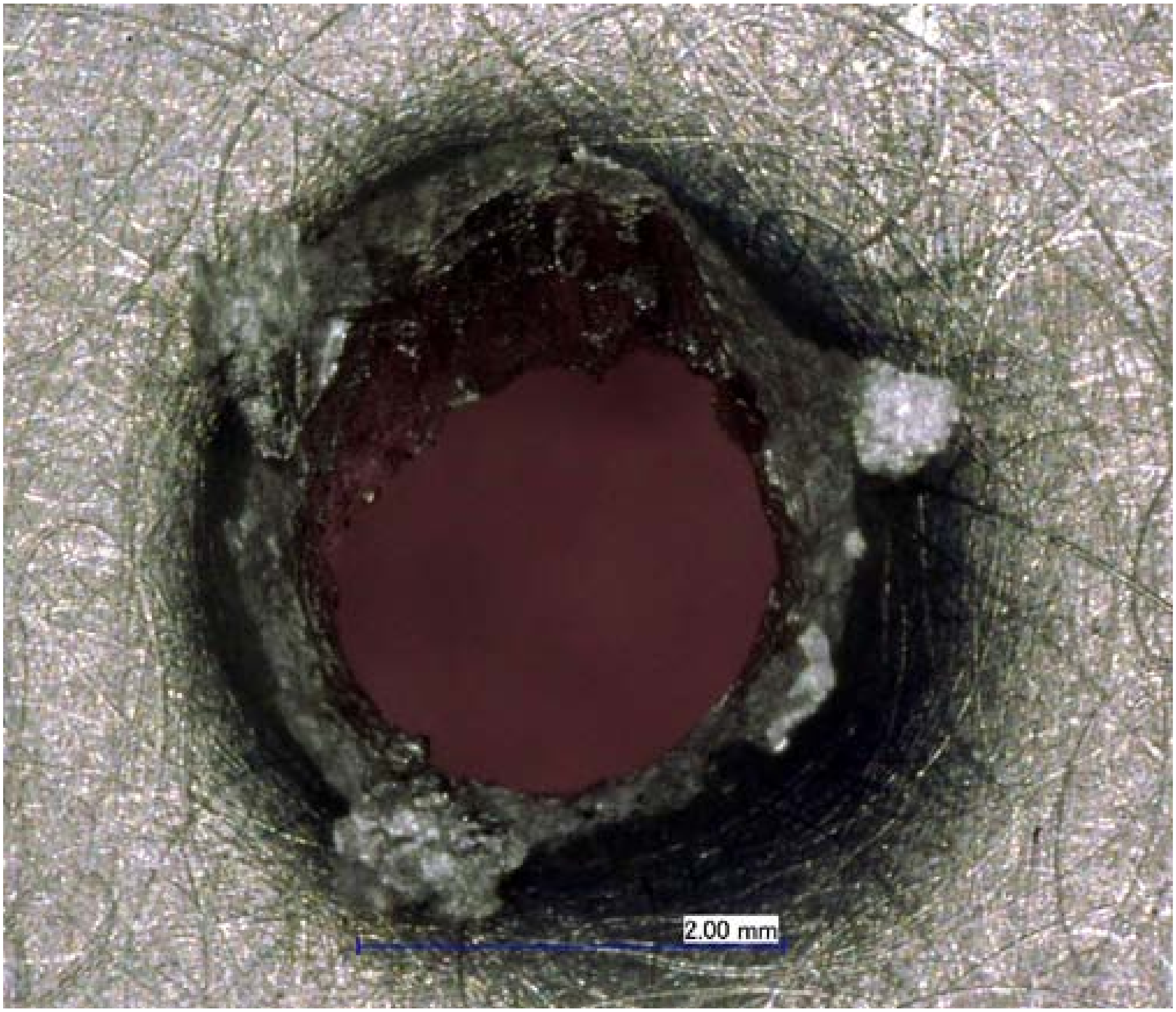


Figure 226: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273

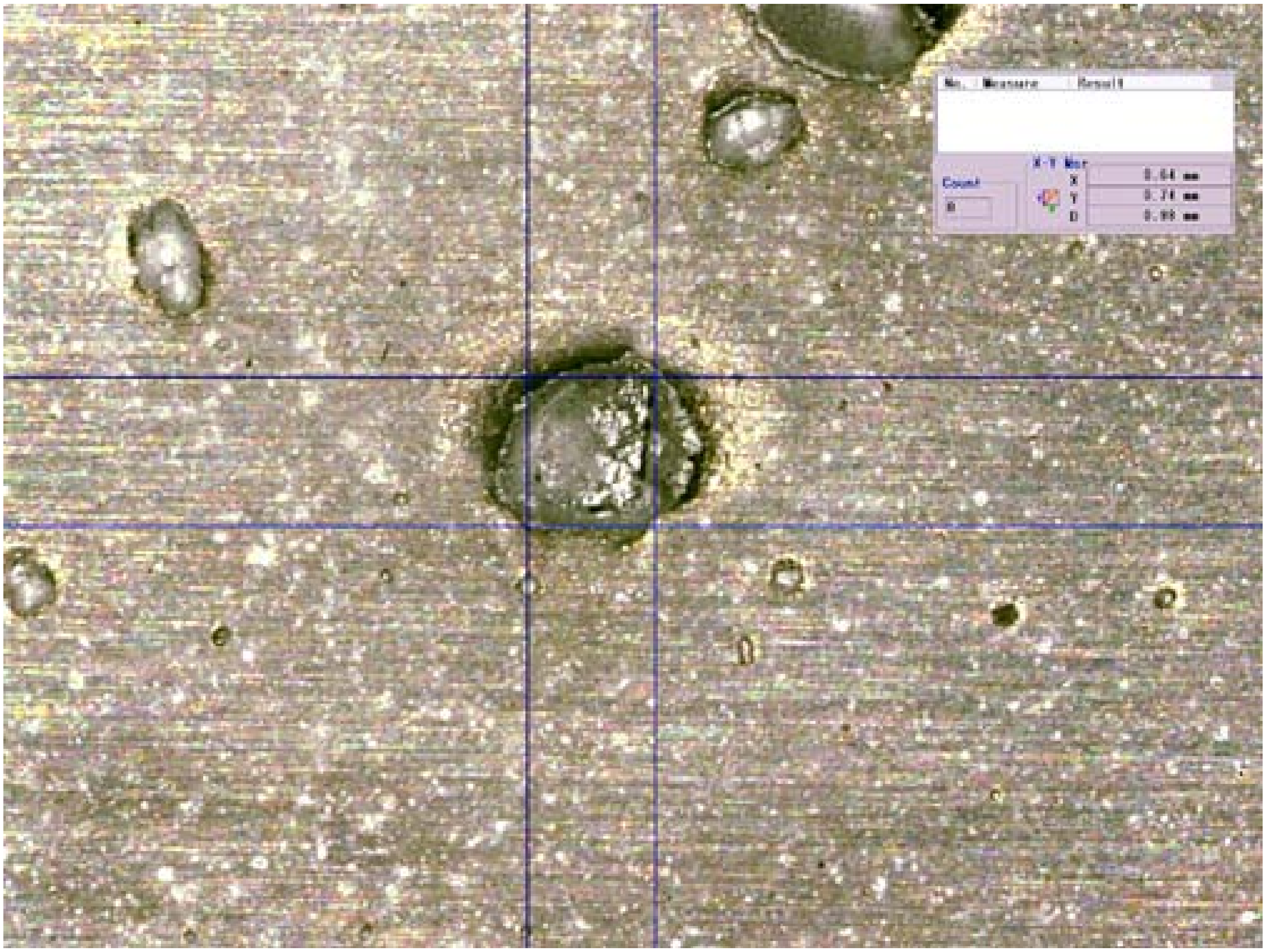


Figure 227: Witness Plate of ISS Soyuz OM Test #13B
(Keyence 3D Microscope Image)

Test #13B, HITF12273

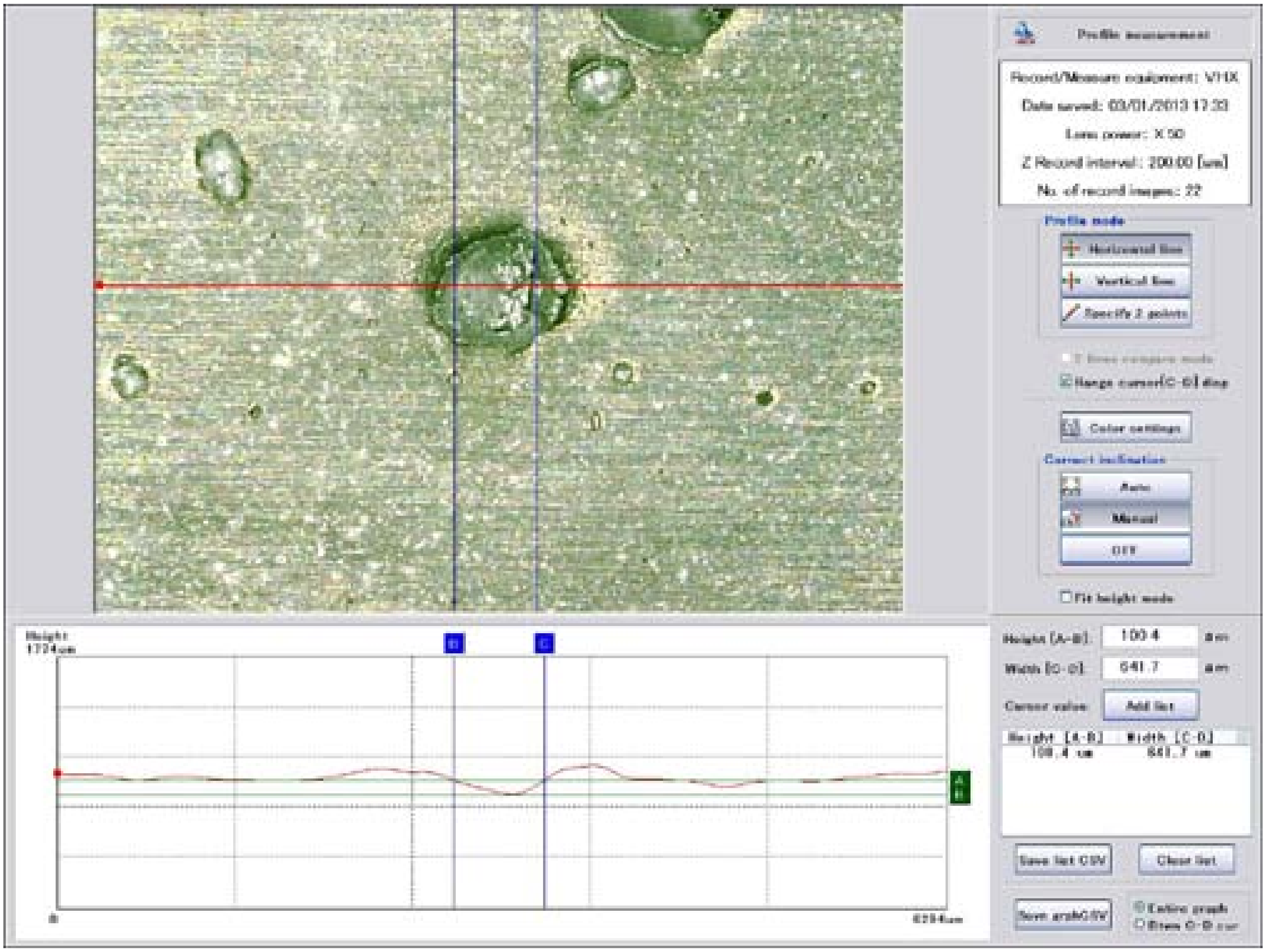


Figure 228: Witness Plate of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273

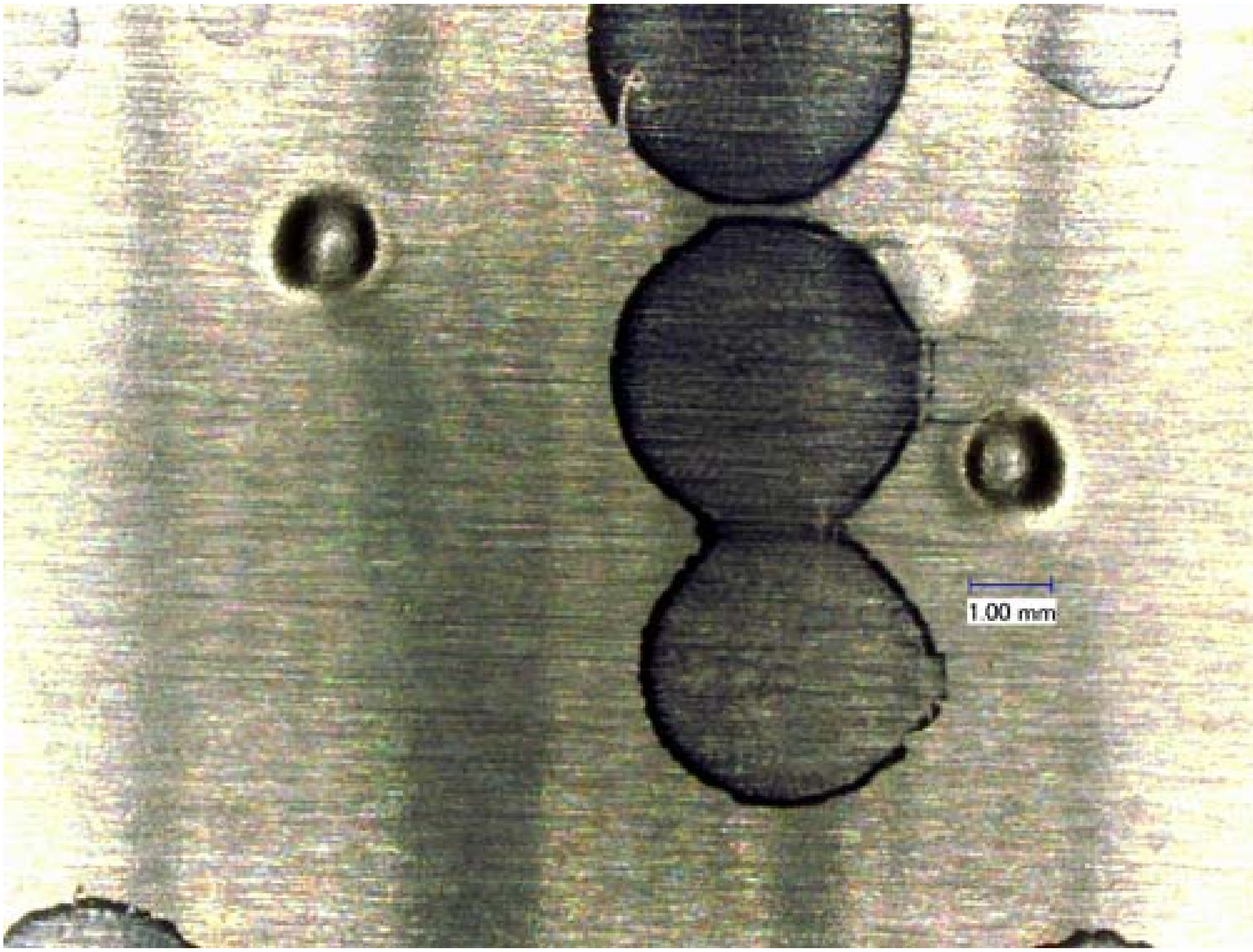


Figure 229: Witness Plate of ISS Soyuz OM Test #13B (Keyence 3D Microscope Image)

Test #13B, HITF12273

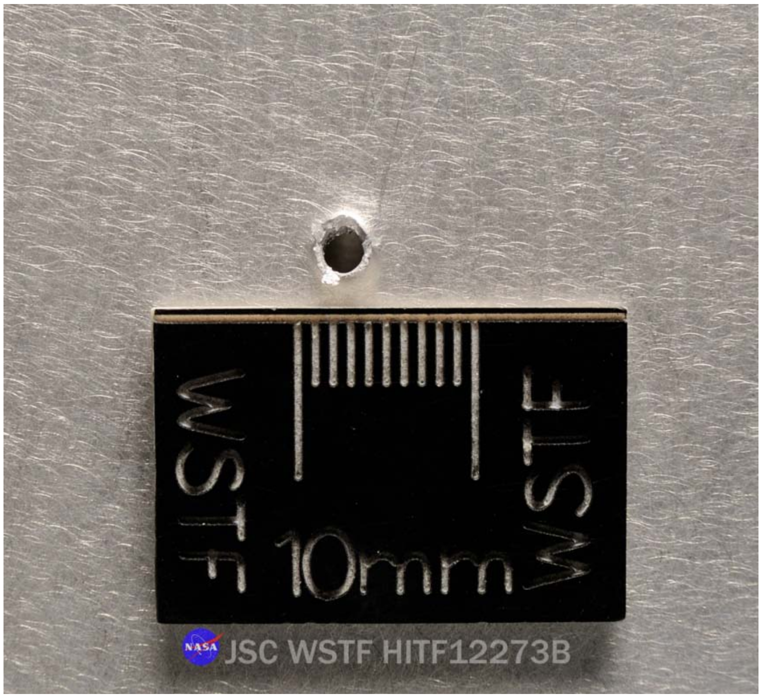


Figure 230: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #13B

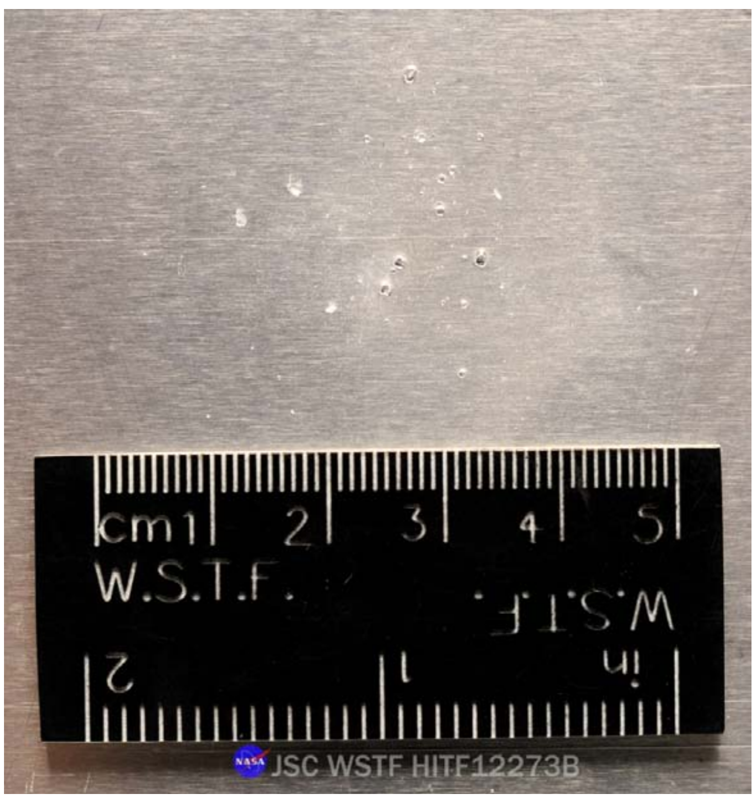


Figure 231: Front Witness Plate View of ISS Soyuz Orbital Module Test #13B

Test #14, HITF12274

Figure 232: Post-test of ISS Soyuz Orbital Module Test #14 (HITF12274) article mounted in 0.17-caliber target tank.

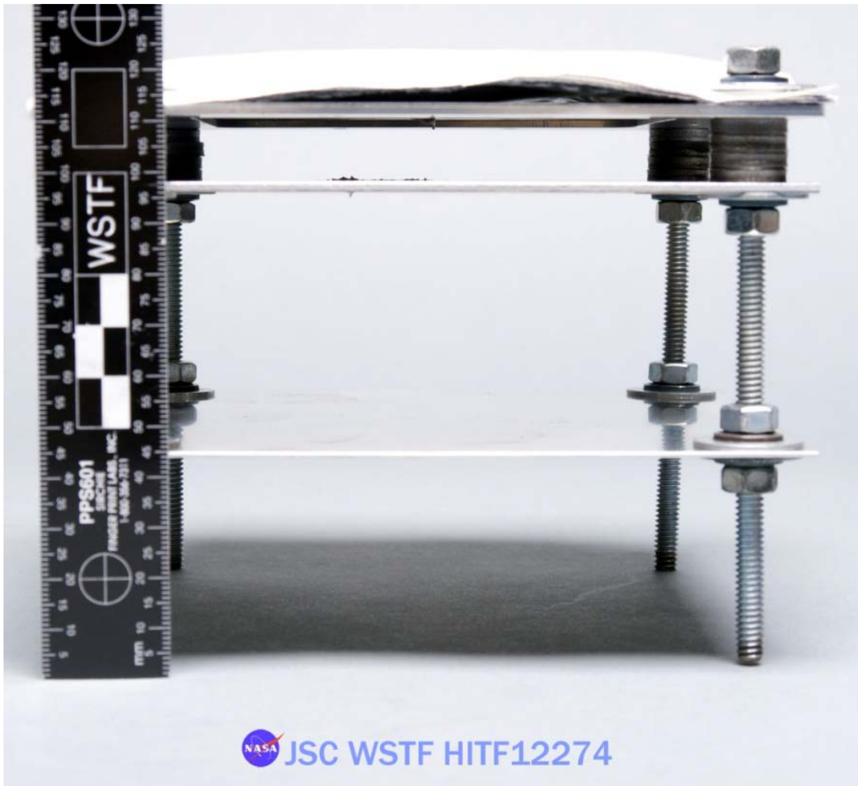


Figure 233: Side View of ISS Soyuz Orbital Module Test #14

Test #14, HITF12274

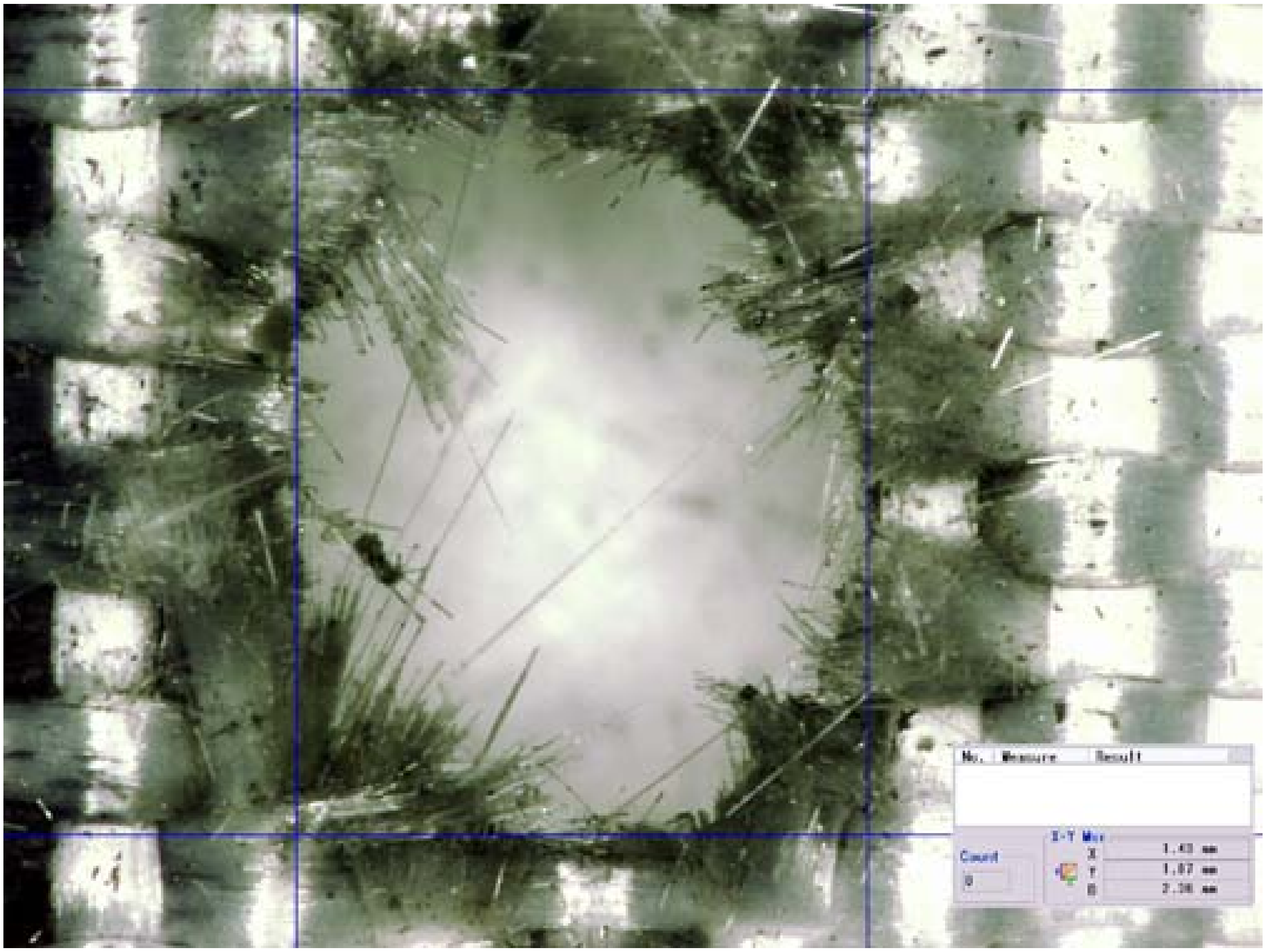


Figure 234: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

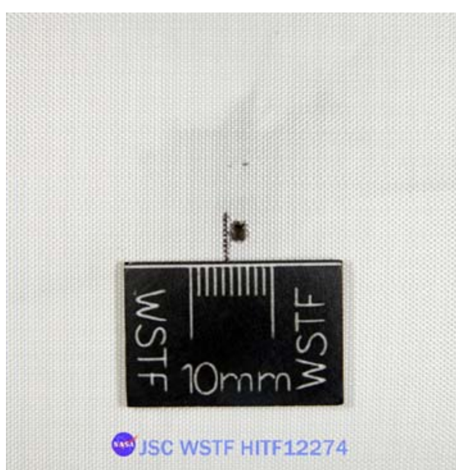


Figure 235: Beta Cloth Bumper of ISS Soyuz Orbital Module Test #14

Test #14, HITF12274

Figure 236: Mylar Film Layer 2 of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

Test #14, HITF12274

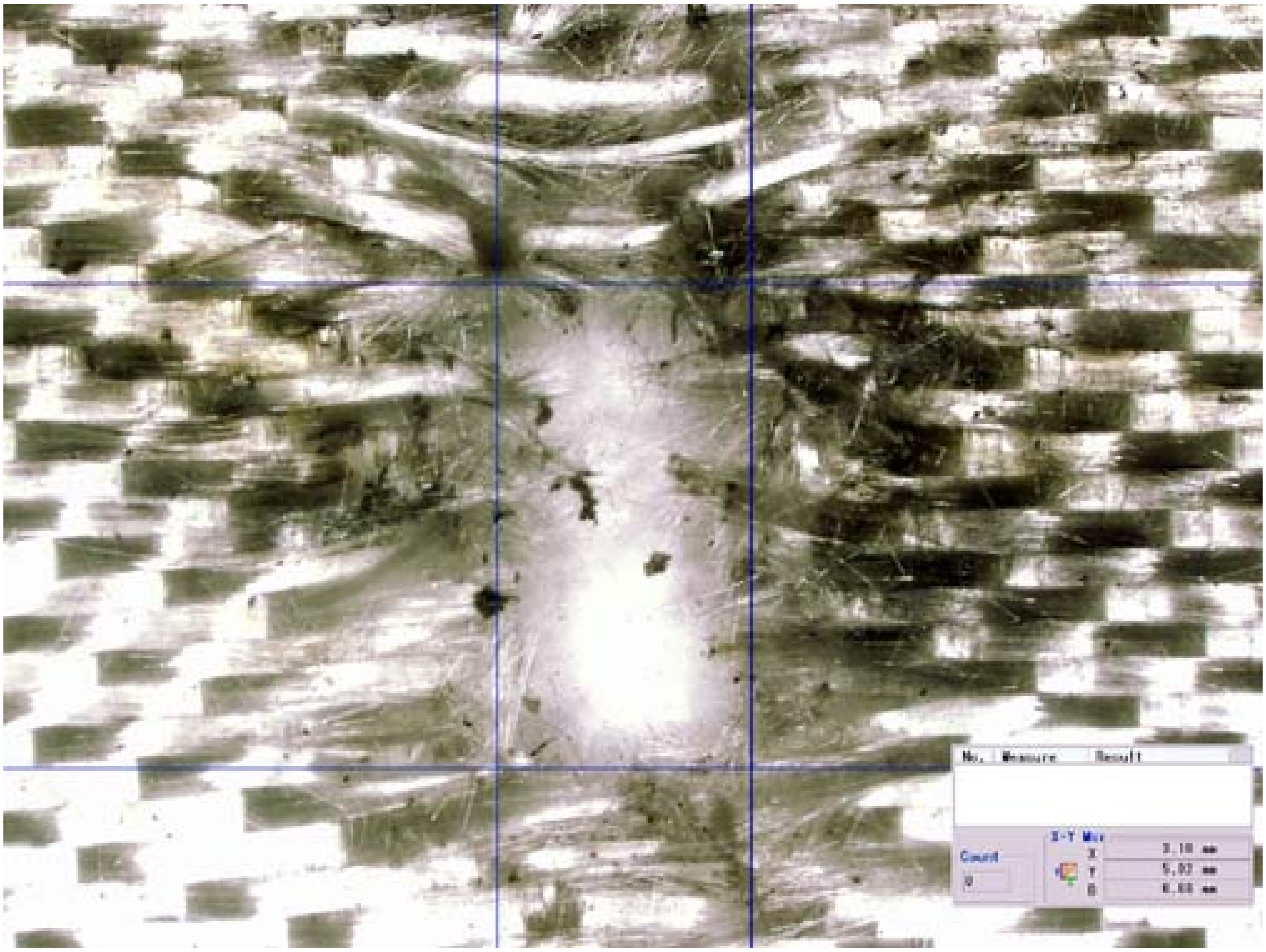


Figure 237: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

Test #14, HITF12274

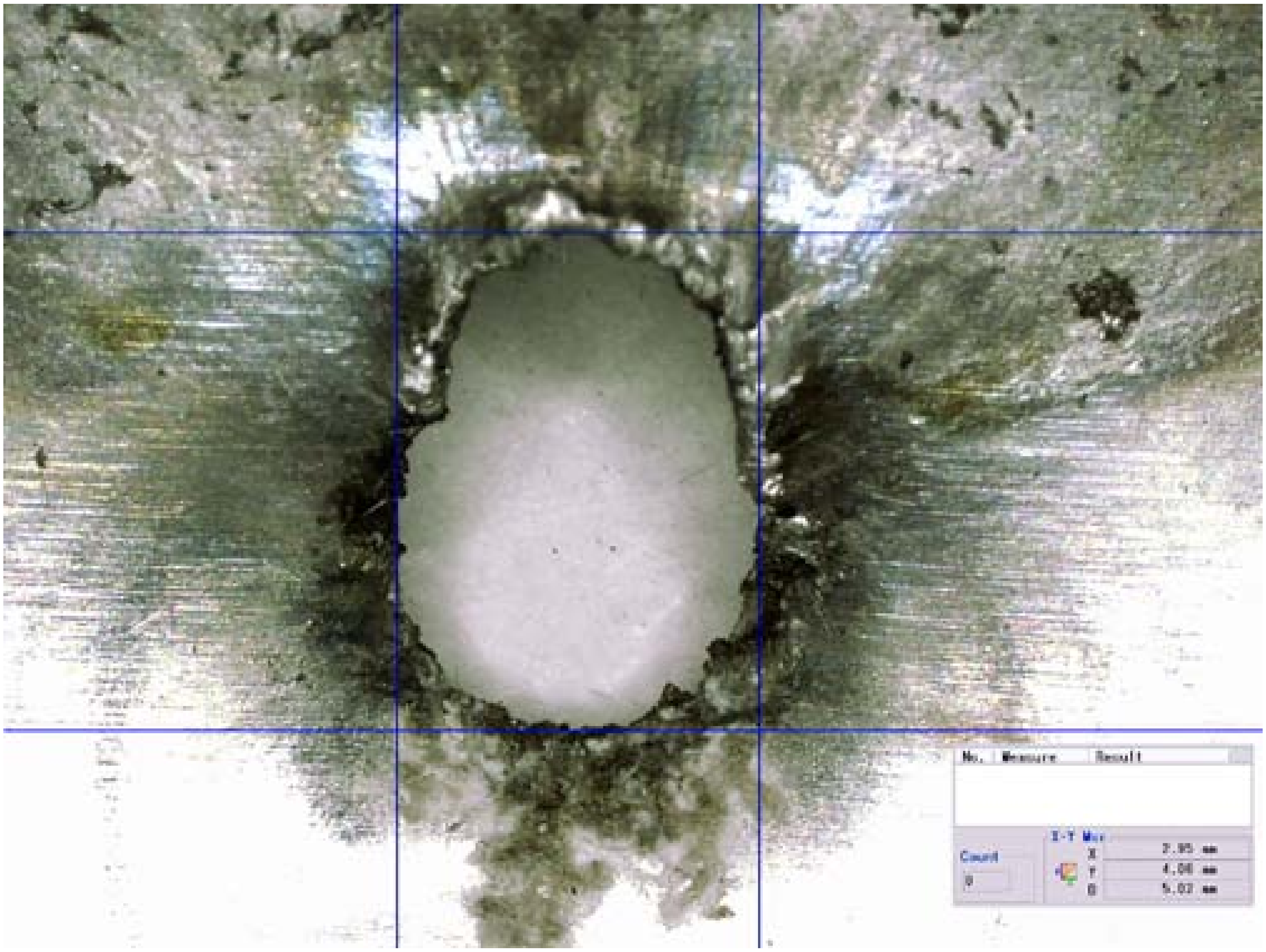


Figure 238: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

Test #14, HITF12274

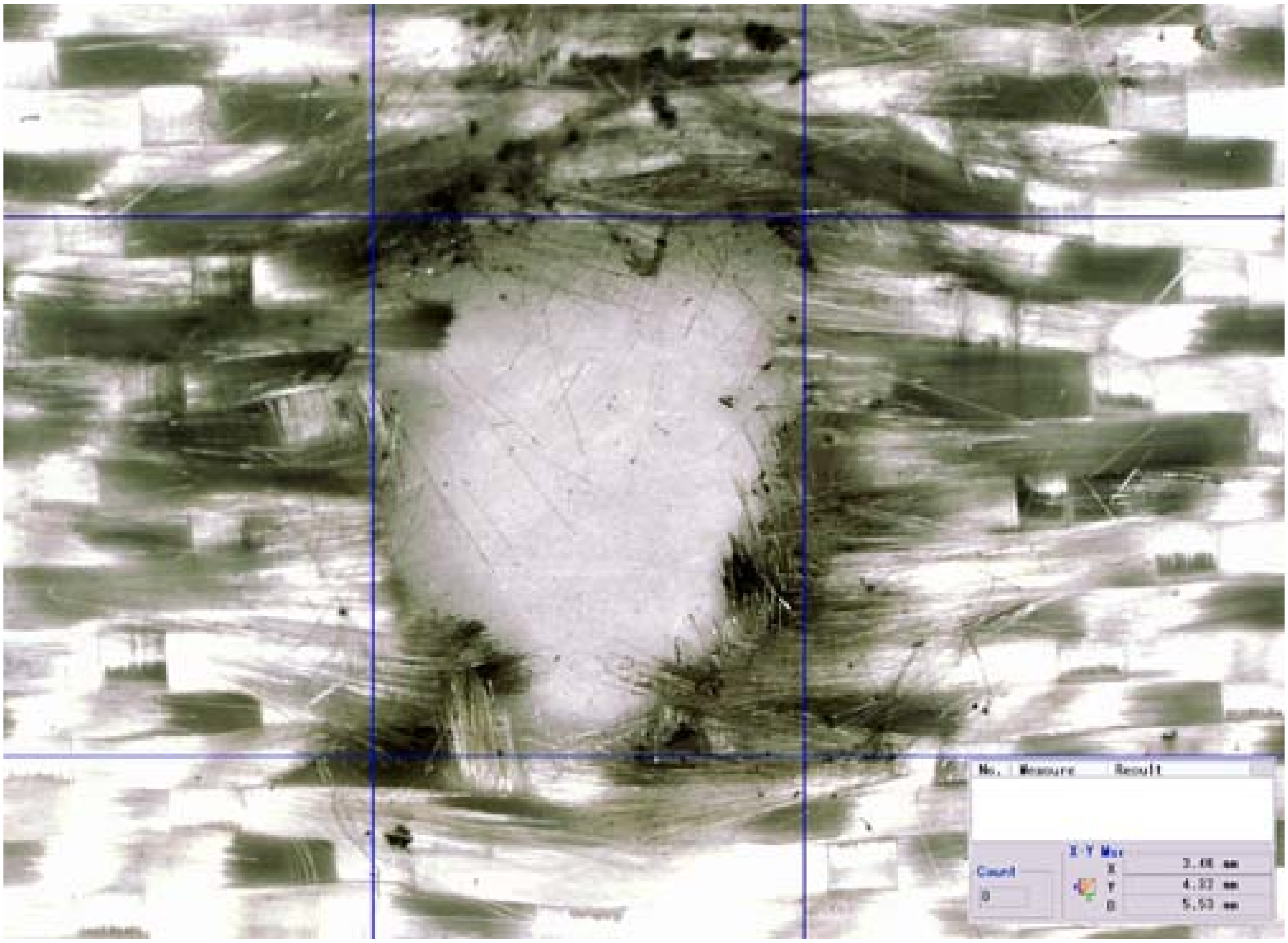


Figure 239: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

Test #14, HITF12274

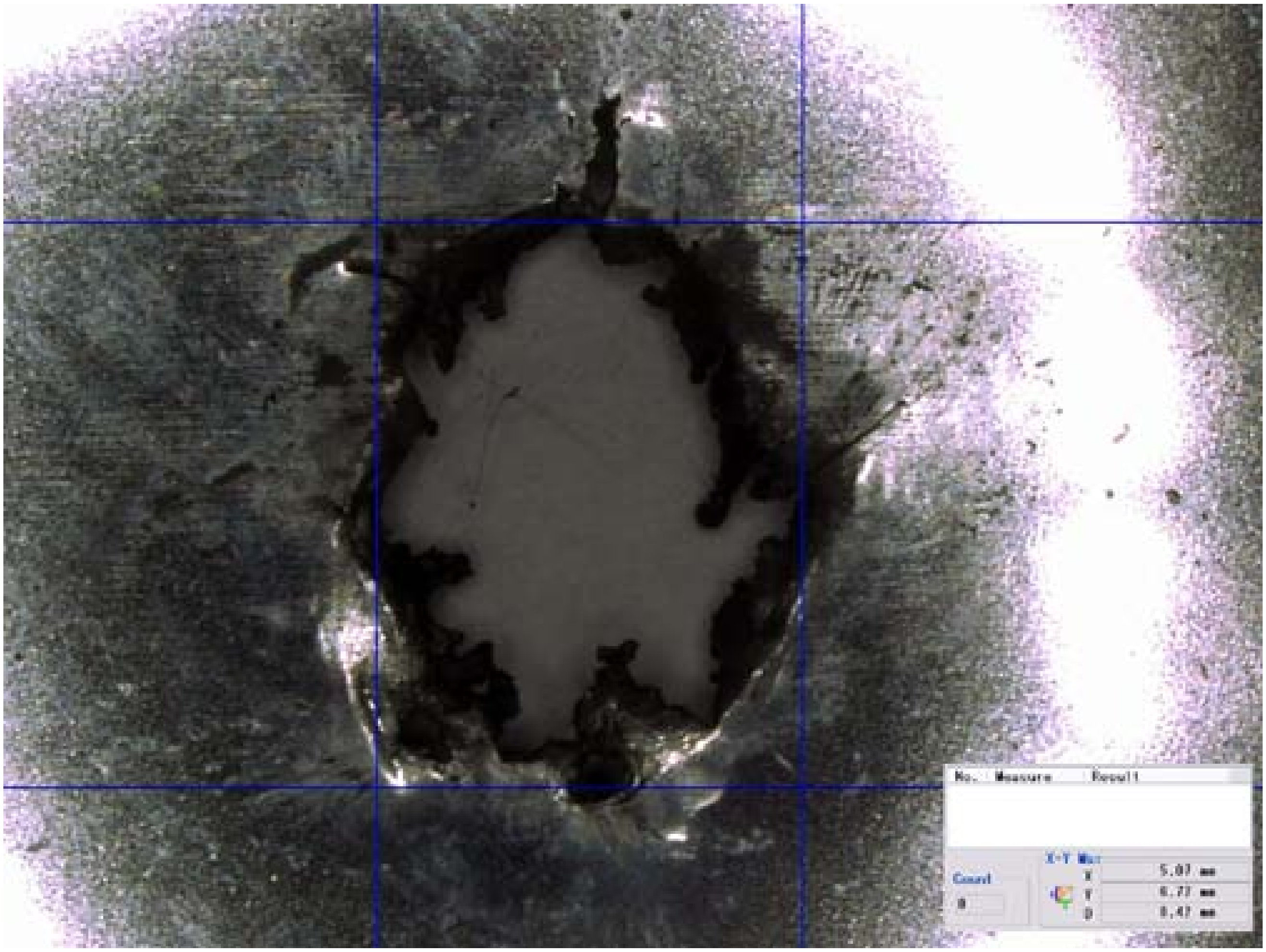


Figure 240: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

Test #14, HITF12274

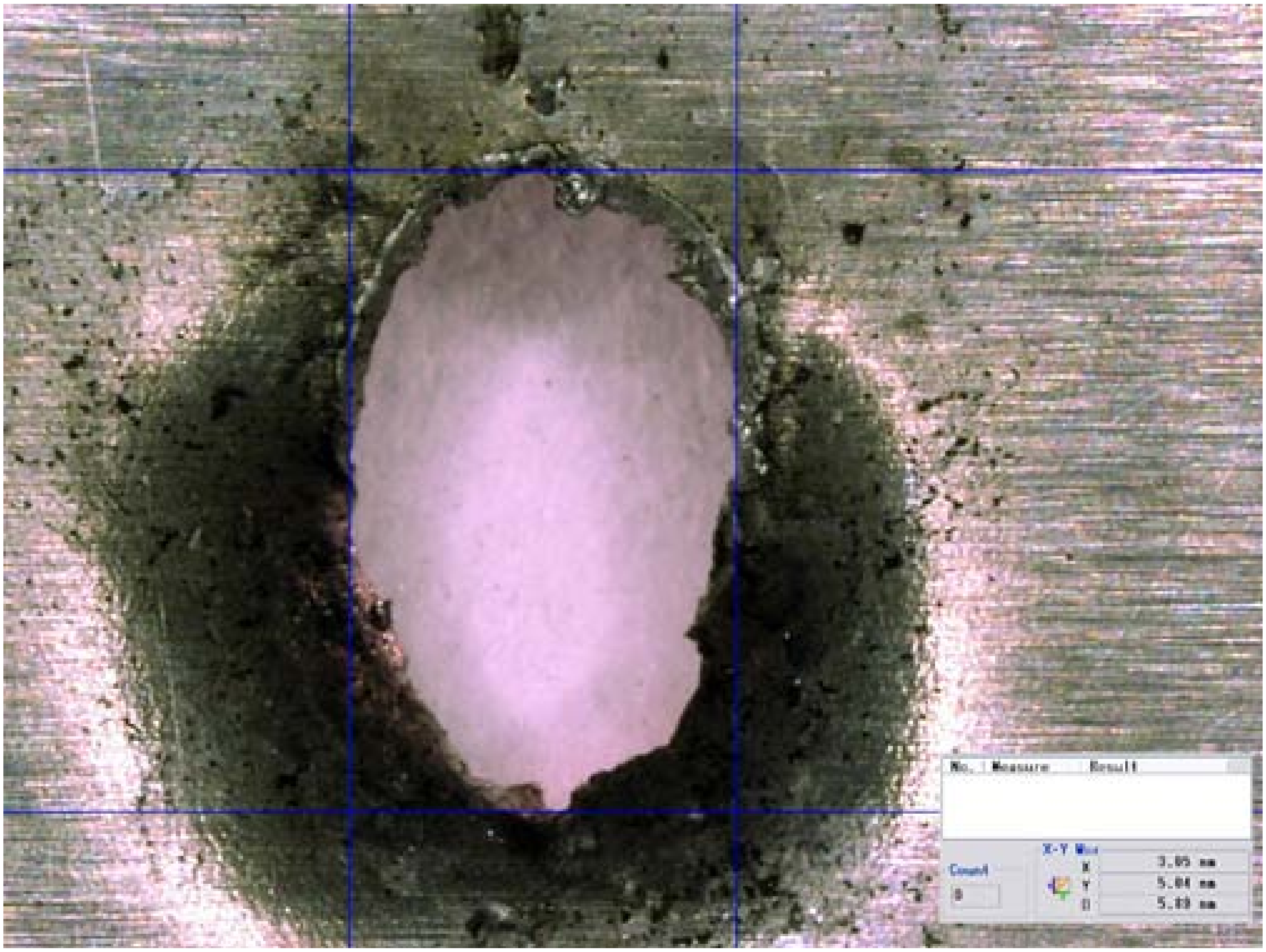


Figure 241: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

Test #14, HITF12274

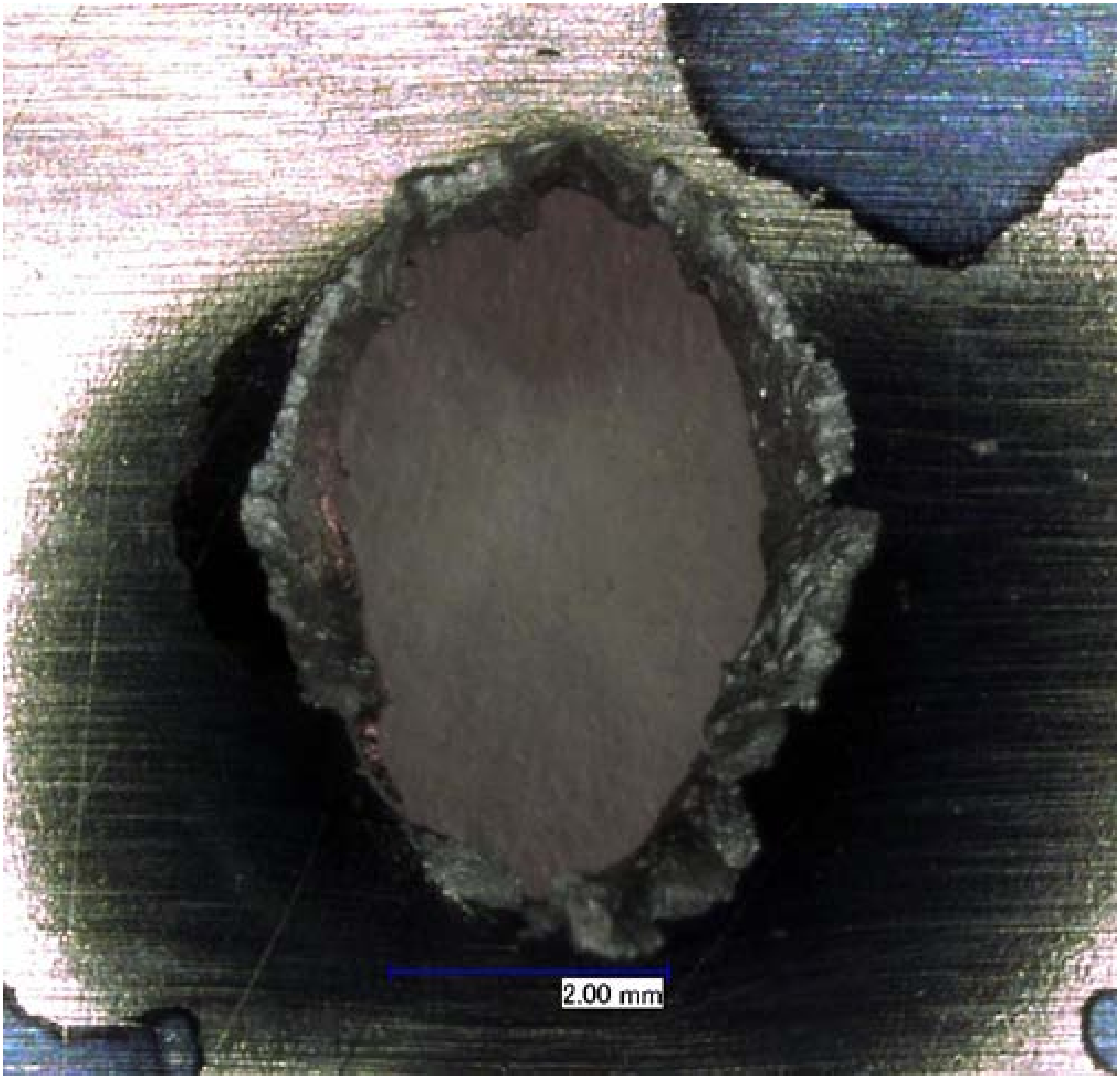


Figure 242: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

Test #14, HITF12274 Rear Wall

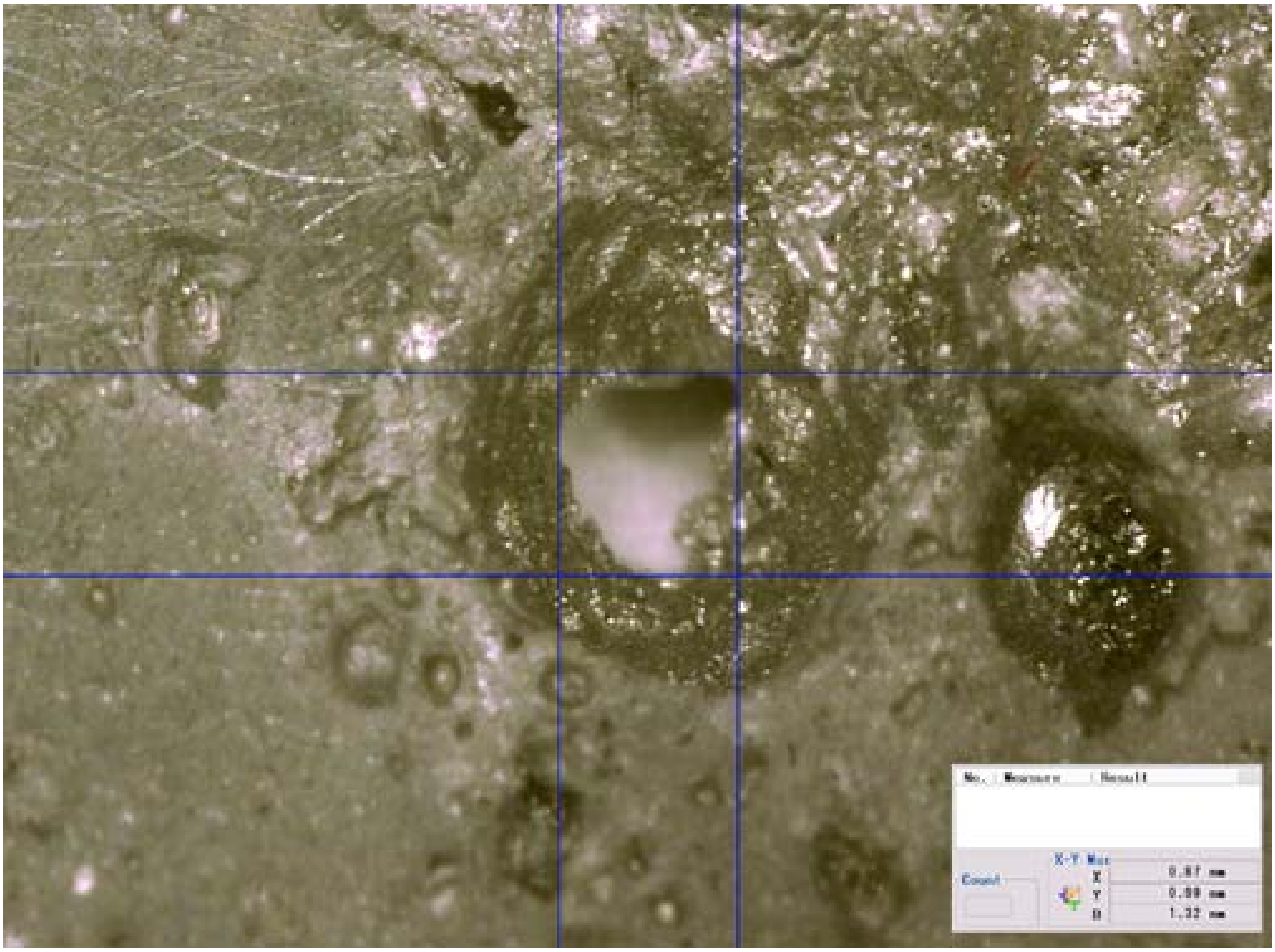


Figure 243: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

Test #14, HITF12274

Figure 244: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

Test #14, HITF12274

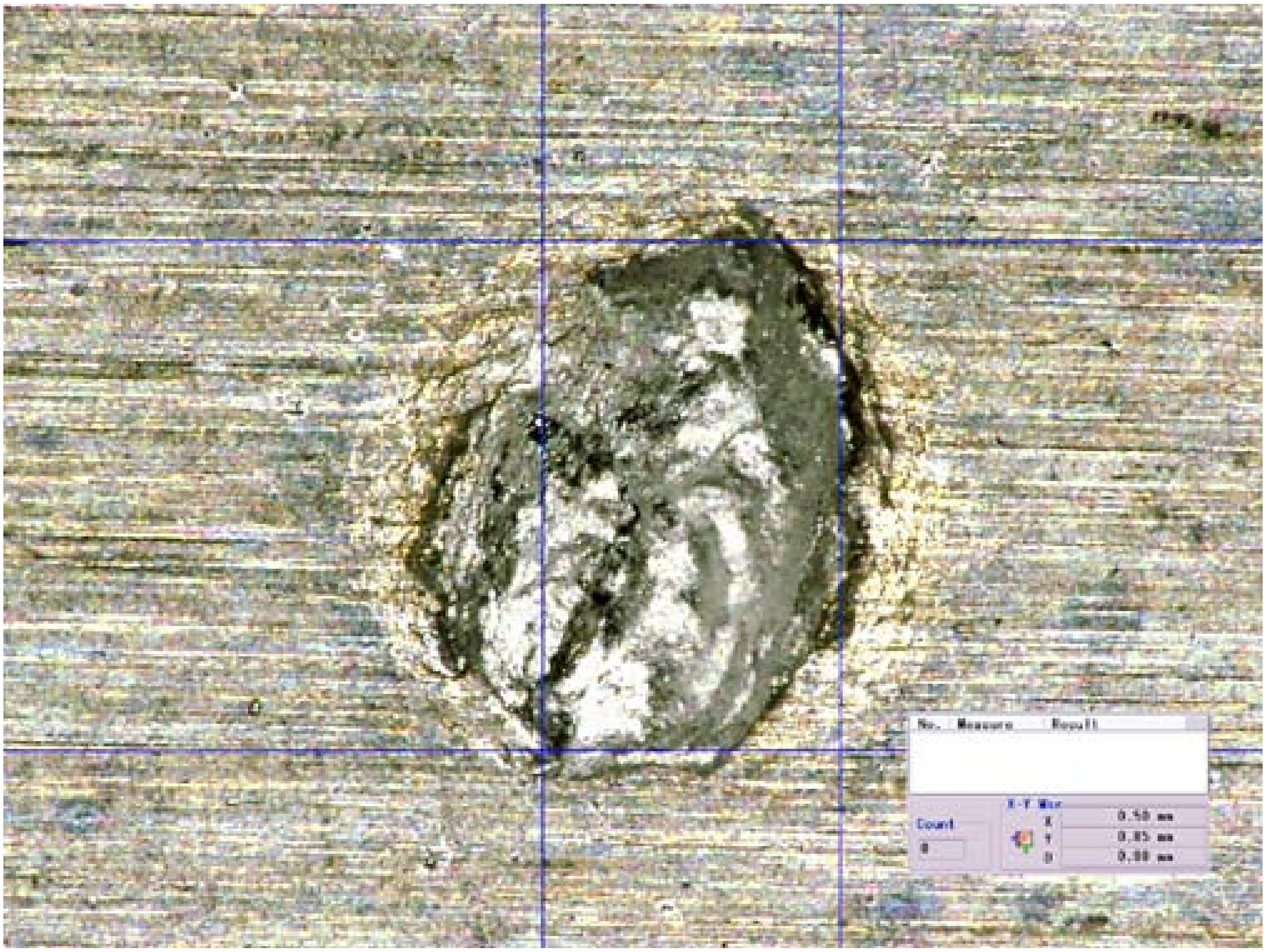


Figure 245: Witness Plate of ISS Soyuz OM Test #14 (Keyence 3D Microscope Image)

Test #14, HITF12274

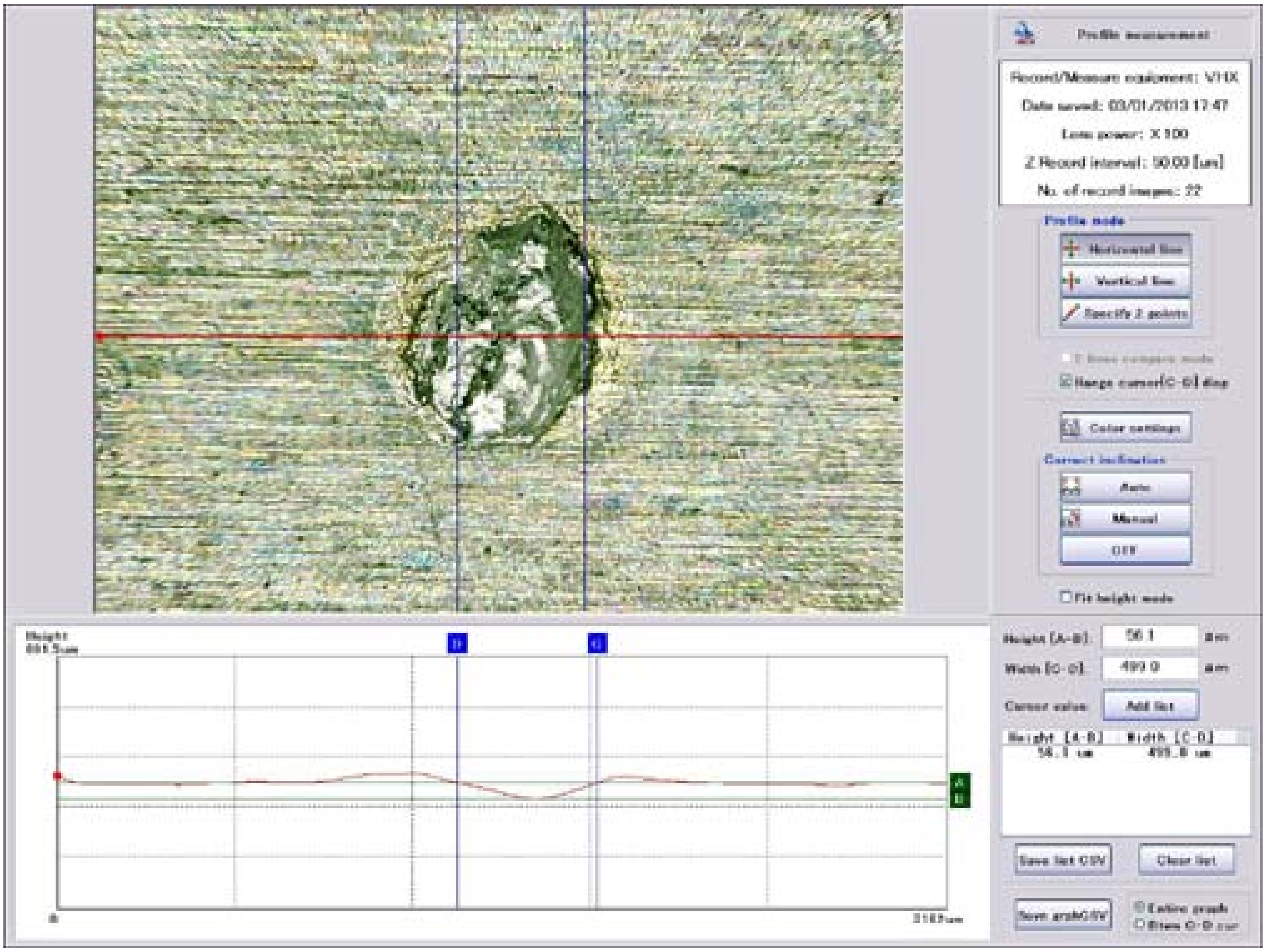


Figure 246: Witness Plate of ISS Soyuz OM Test #14
(Keyence 3D Microscope Image)

Test #14, HITF12274

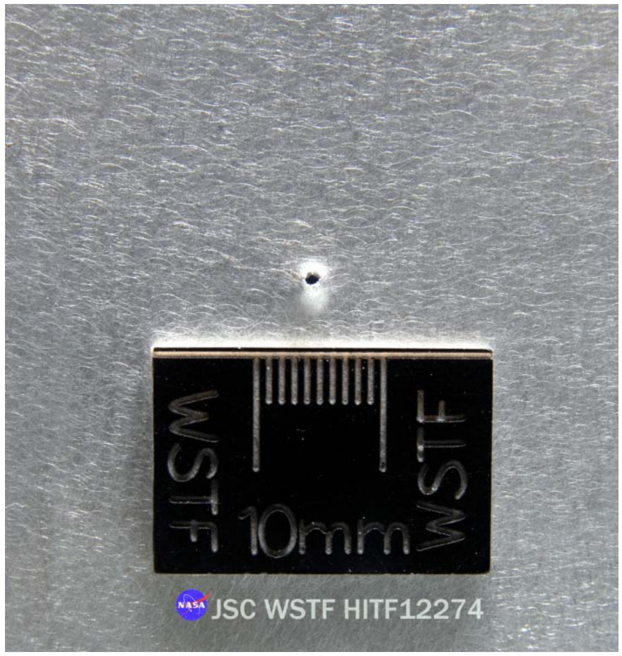


Figure 247: Al 5456-0 Rear Wall (Front) for ISS Soyuz Orbital Module Test #14

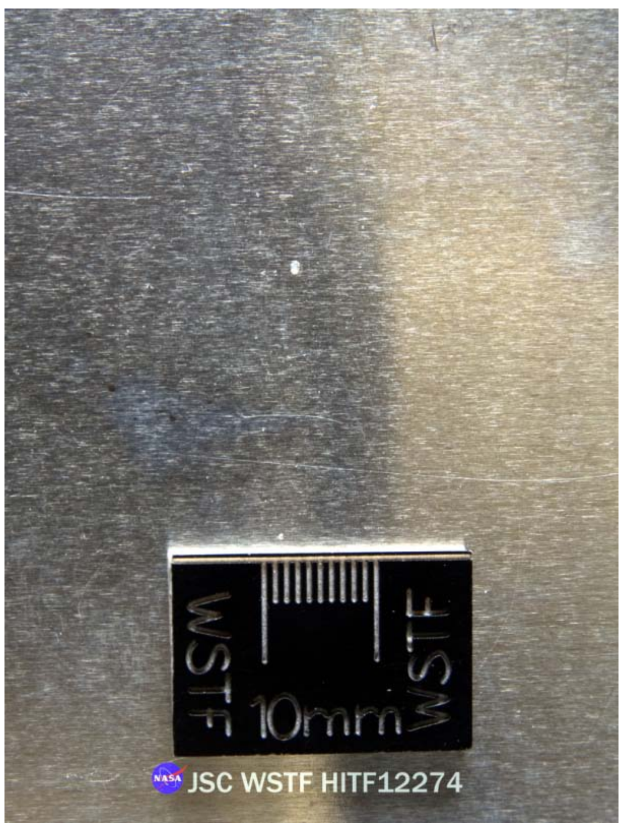


Figure 248: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #14

Test #14, HITF12274

Figure 249: Back Witness Plate View of ISS Soyuz Orbital Module Test #14

Test #15C, HITF12275

Figure 250: Post-test of ISS Soyuz Orbital Module Test #15C (HITF12275) article mounted in 0.17-caliber target tank.

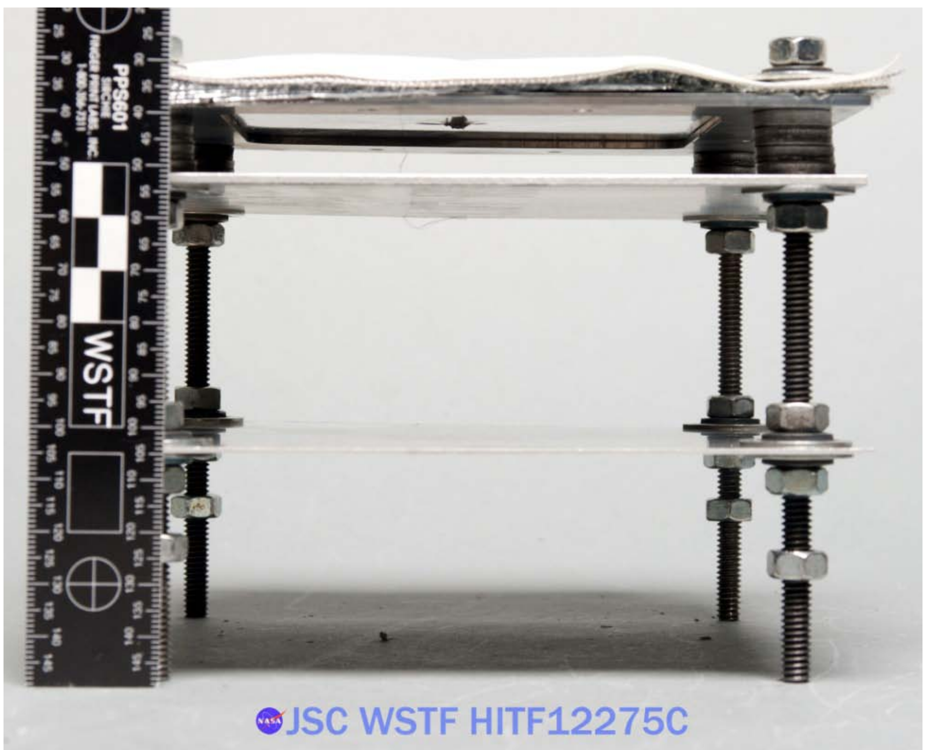


Figure 251: Side View of ISS Soyuz Orbital Module Test #15C

Test #15C, HITF12275

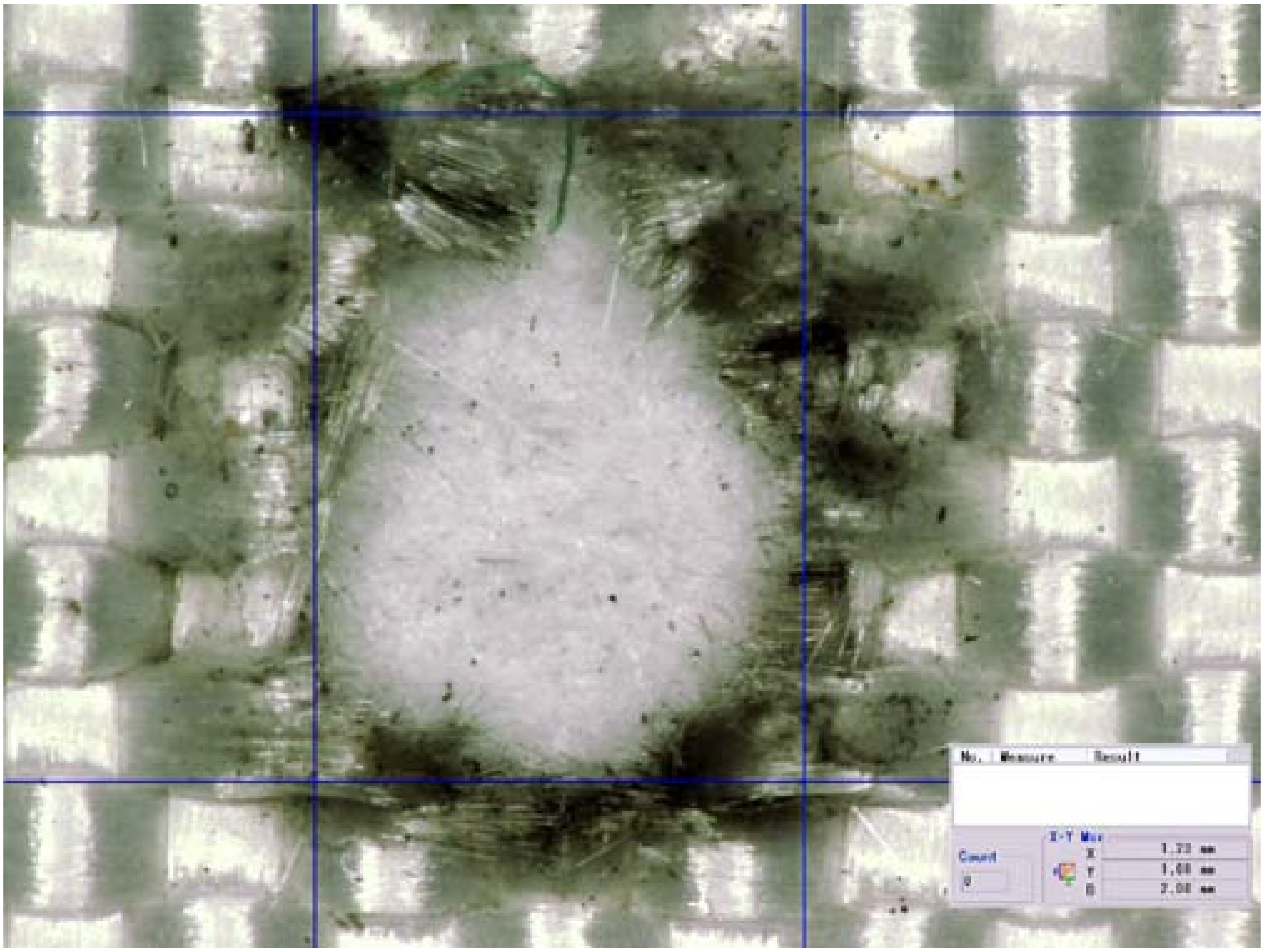


Figure 252: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #15C (Keyence 3D Microscope Image)

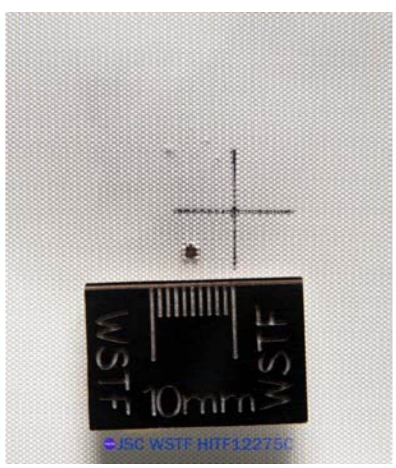


Figure 253: Beta Cloth Bumper Close-up of ISS Soyuz Orbital Module Test #15C

Test #15C, HITF12275

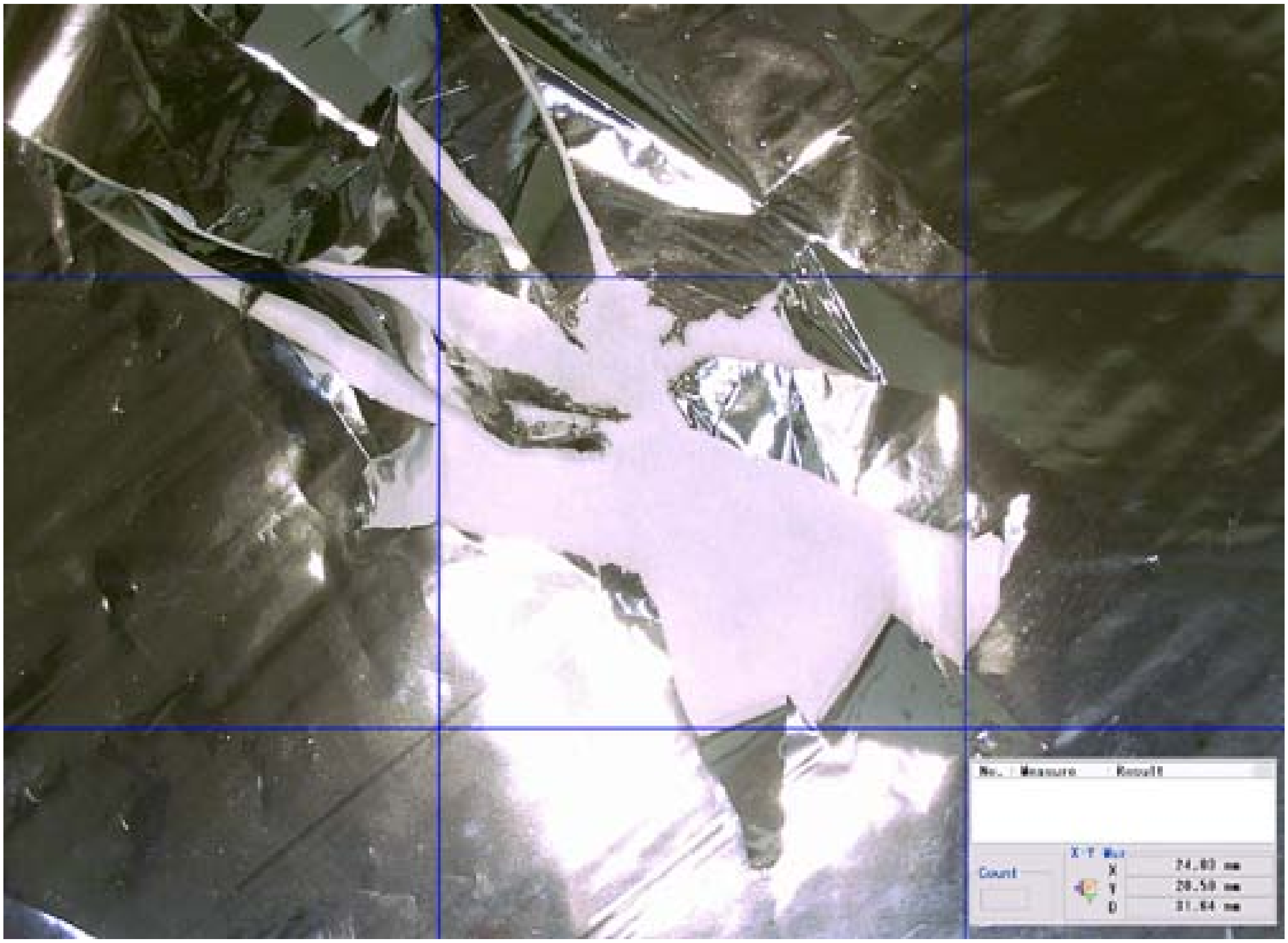


Figure 254: Mylar Film Layer 2 of ISS Soyuz OM Test #15C (Keyence 3D Microscope Image)

Test #15C, HITF12275

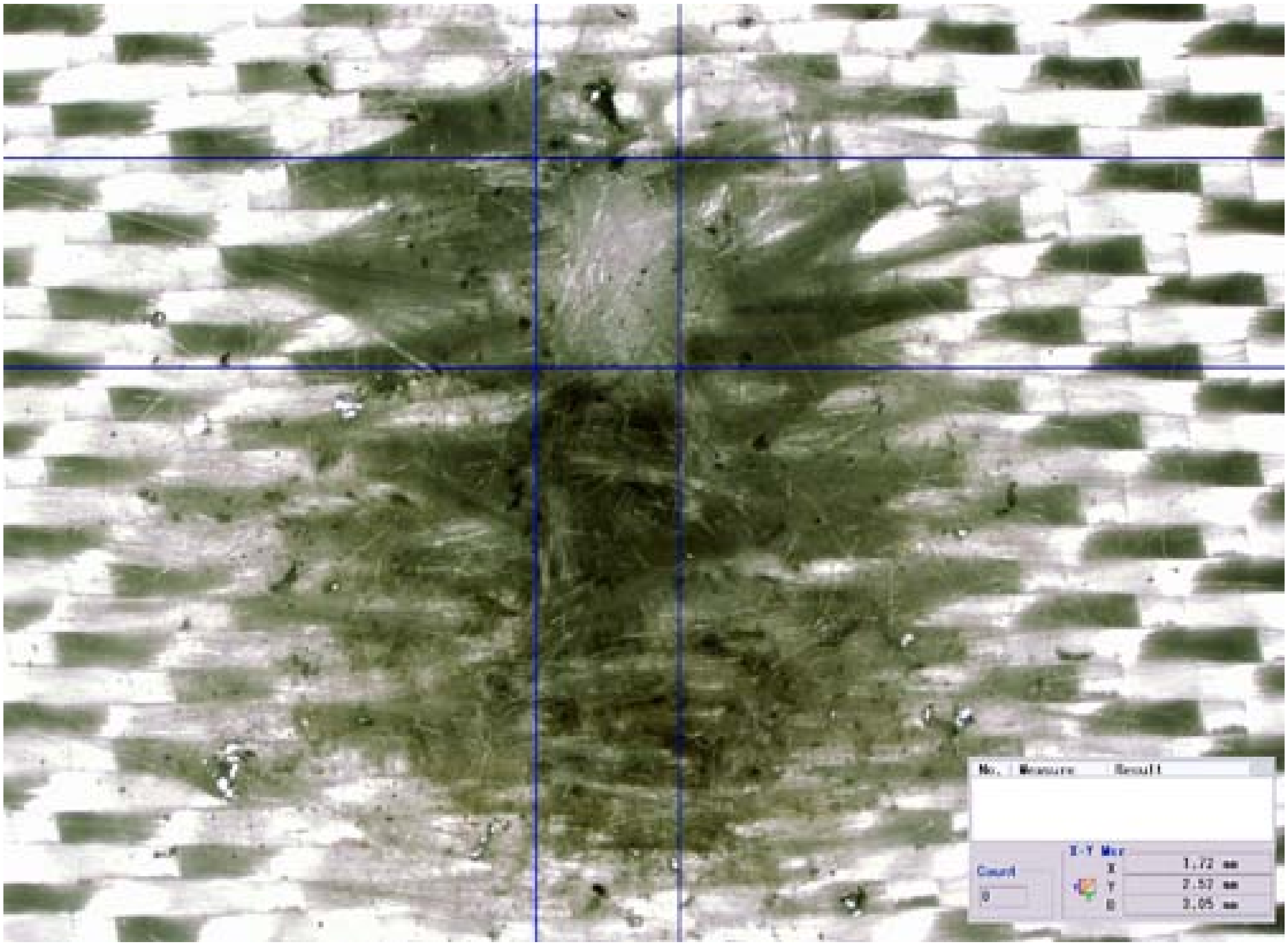


Figure 255: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #15C (Keyence 3D Microscope Image)

Test #15C, HITF12275

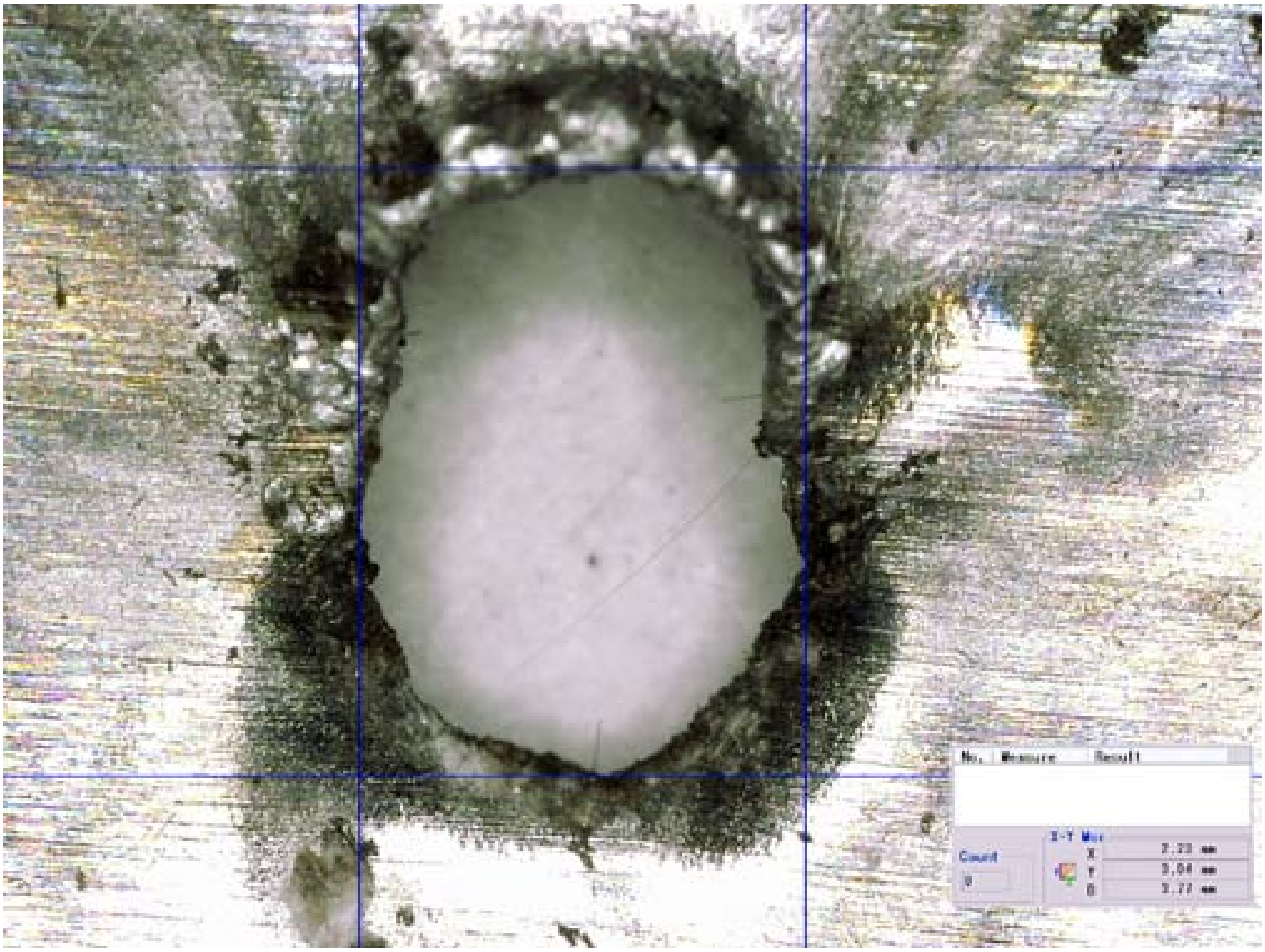


Figure 256: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #15C (Keyence 3D Microscope Image)

Test #15C, HITF12275

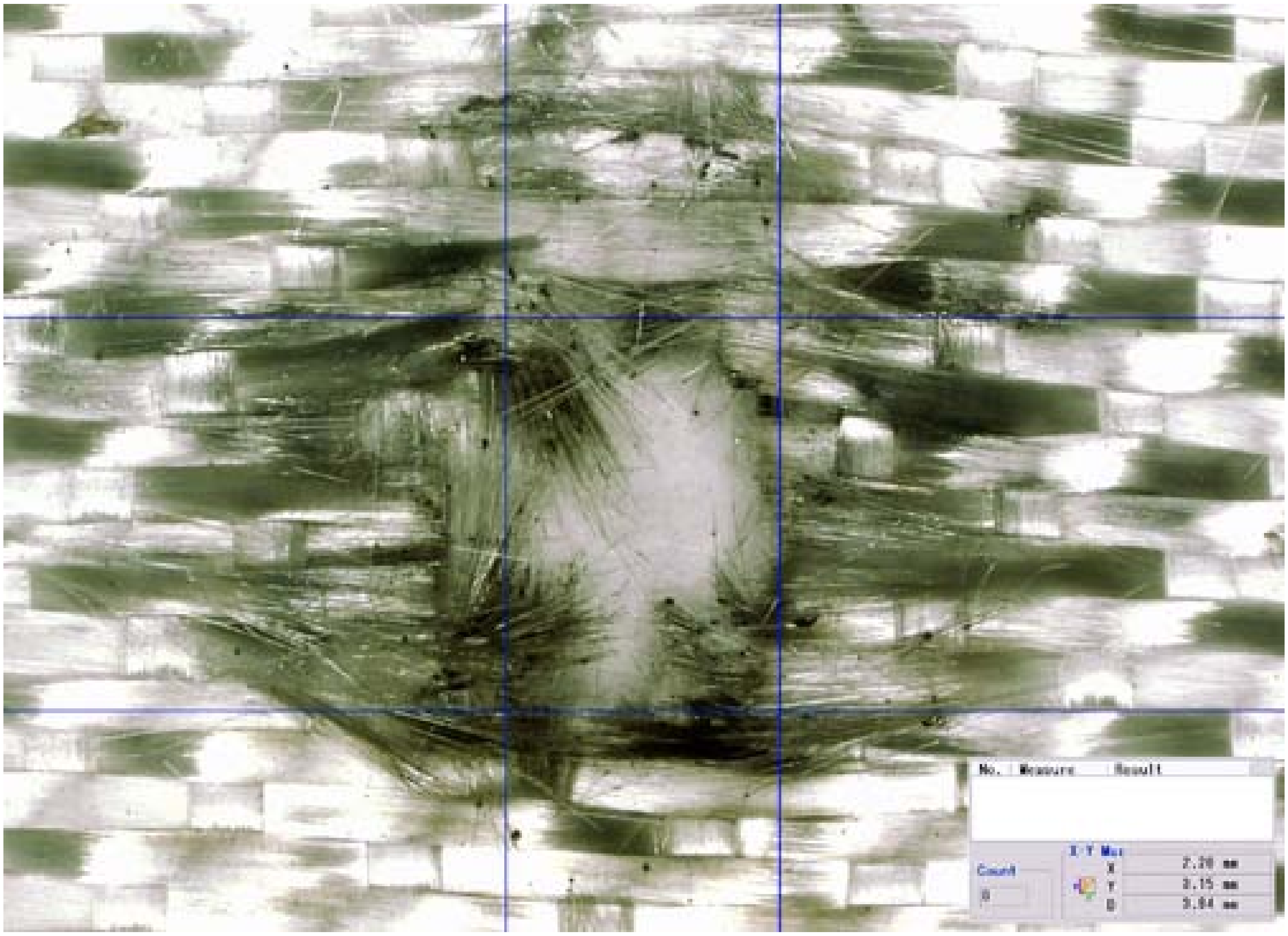


Figure 257: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #15C (Keyence 3D Microscope Image)

Test #15C, HITF12275

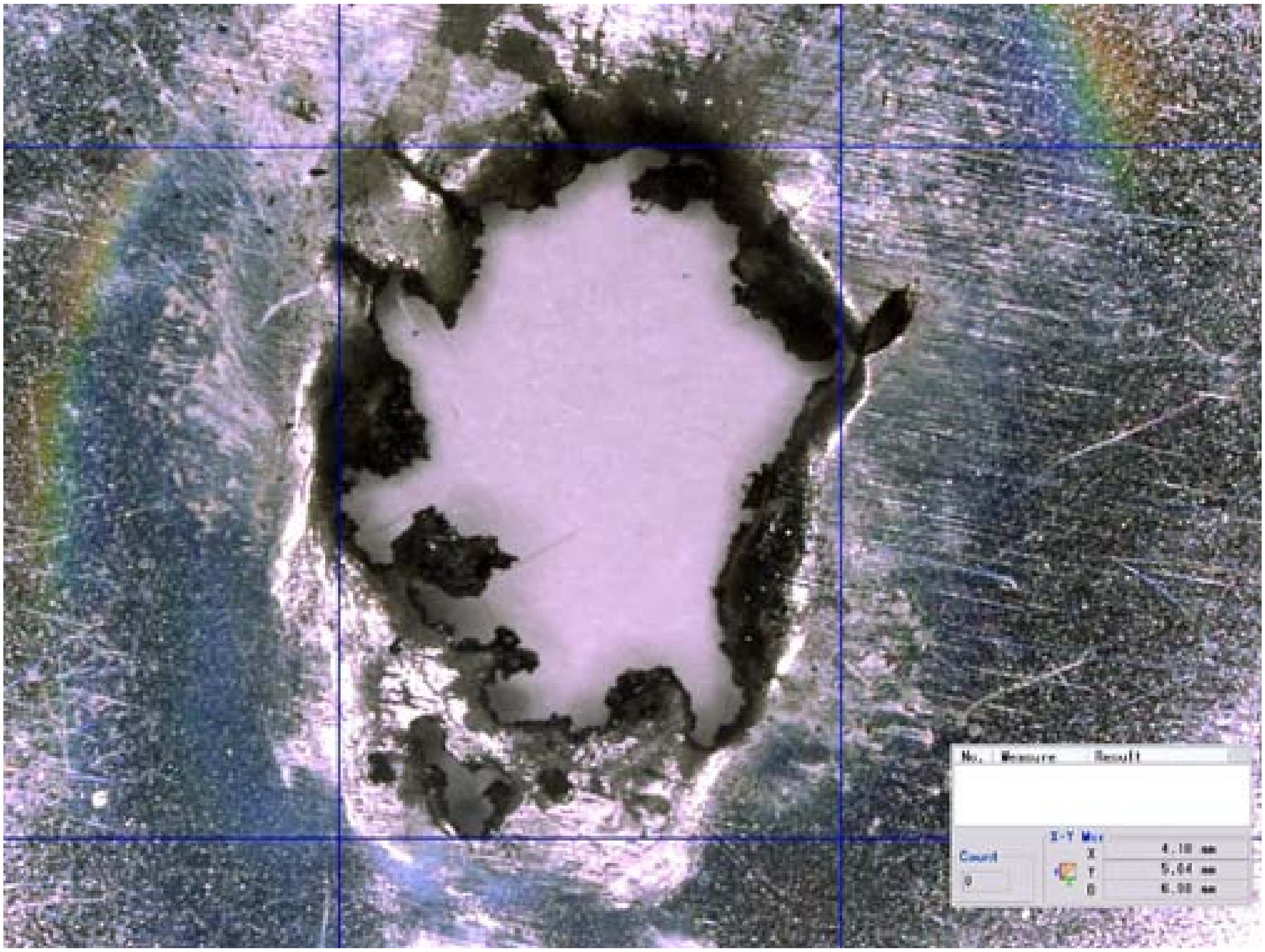


Figure 258: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #15C (Keyence 3D Microscope Image)

Test #15C, HITF12275

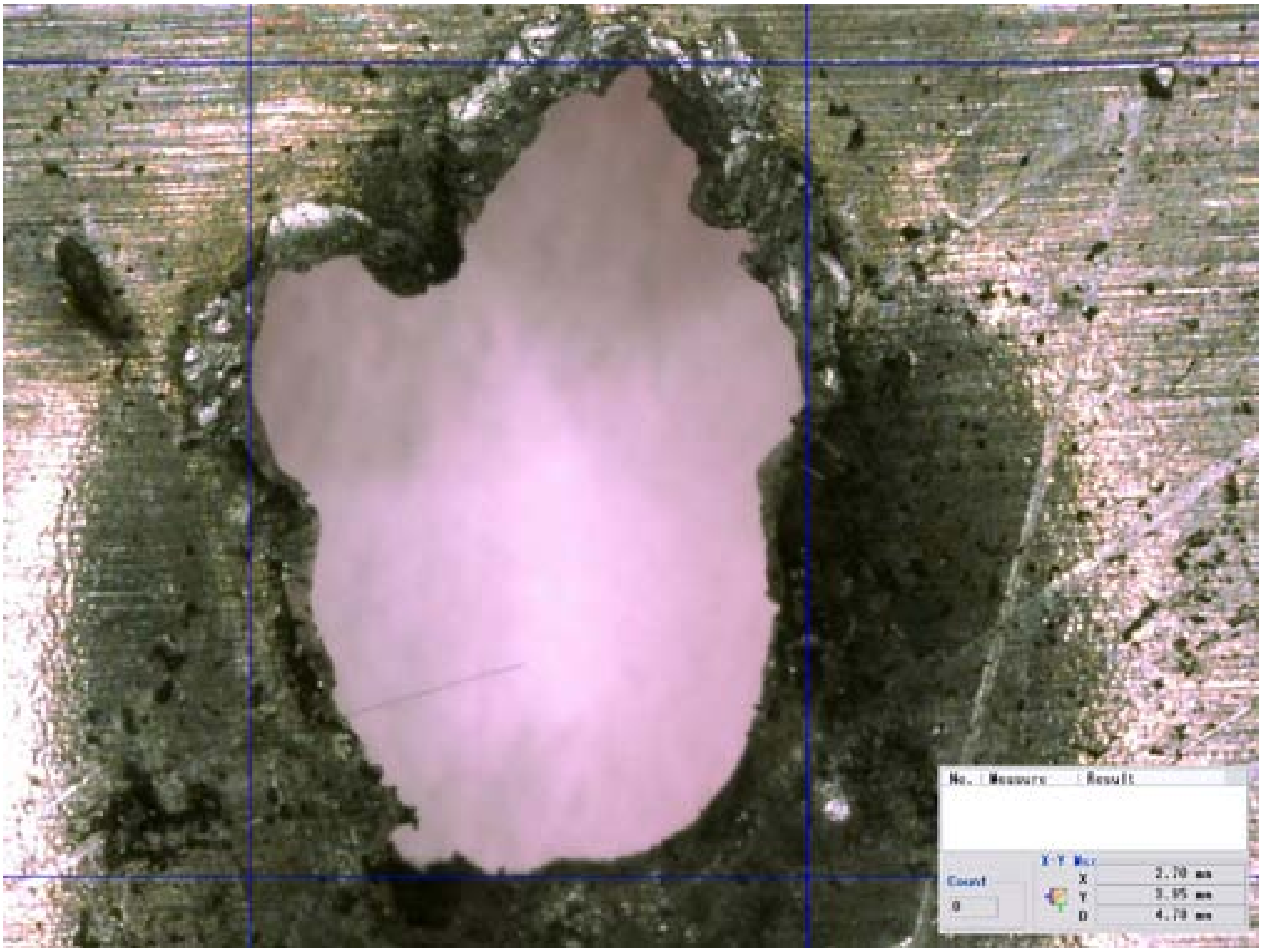


Figure 259: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #15C (Keyence 3D Microscope Image)

Test #15C, HITF12275

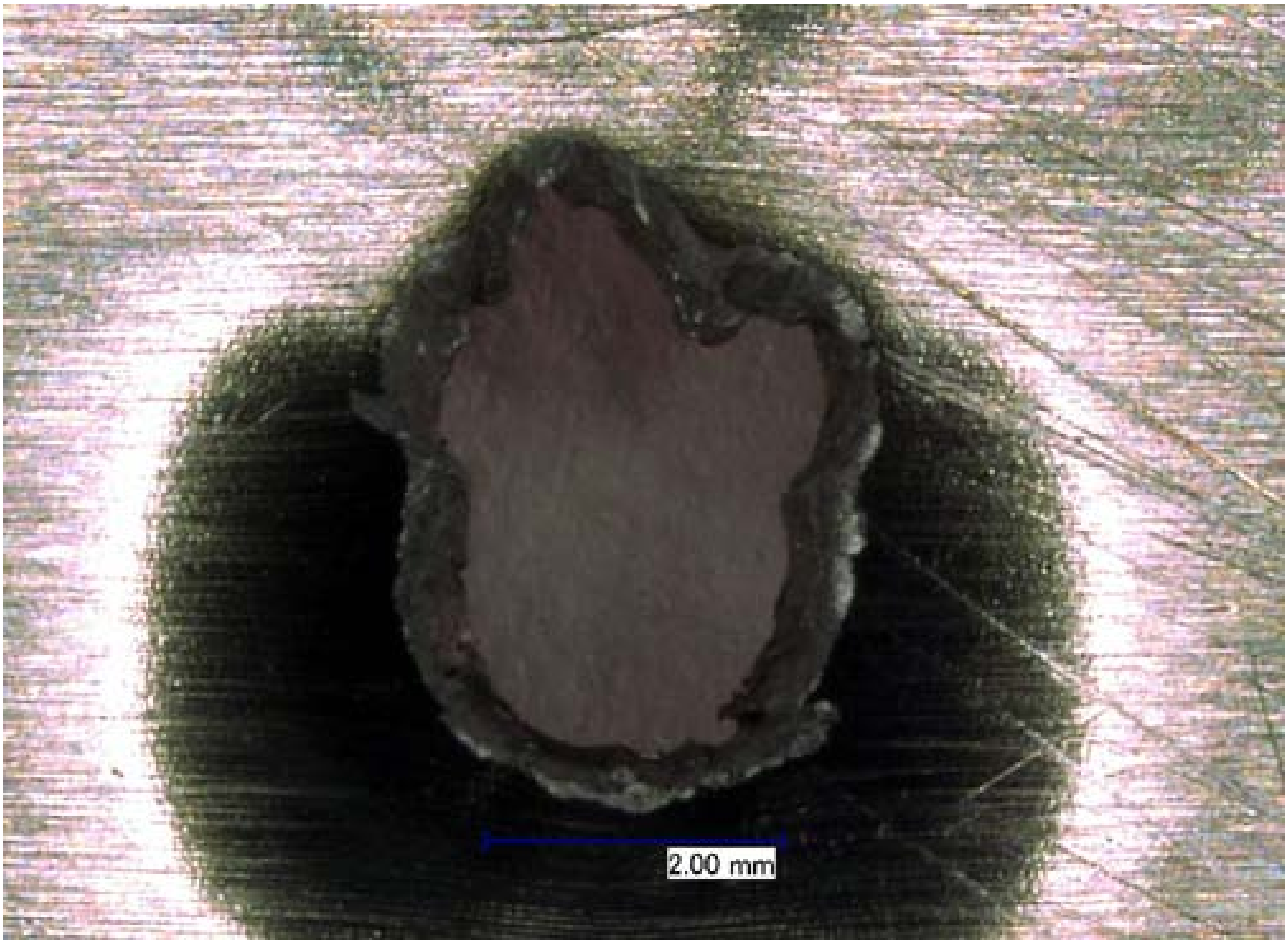


Figure 260: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #15C (Keyence 3D Microscope Image)

Test #15C, HITF12275 Rear Wall

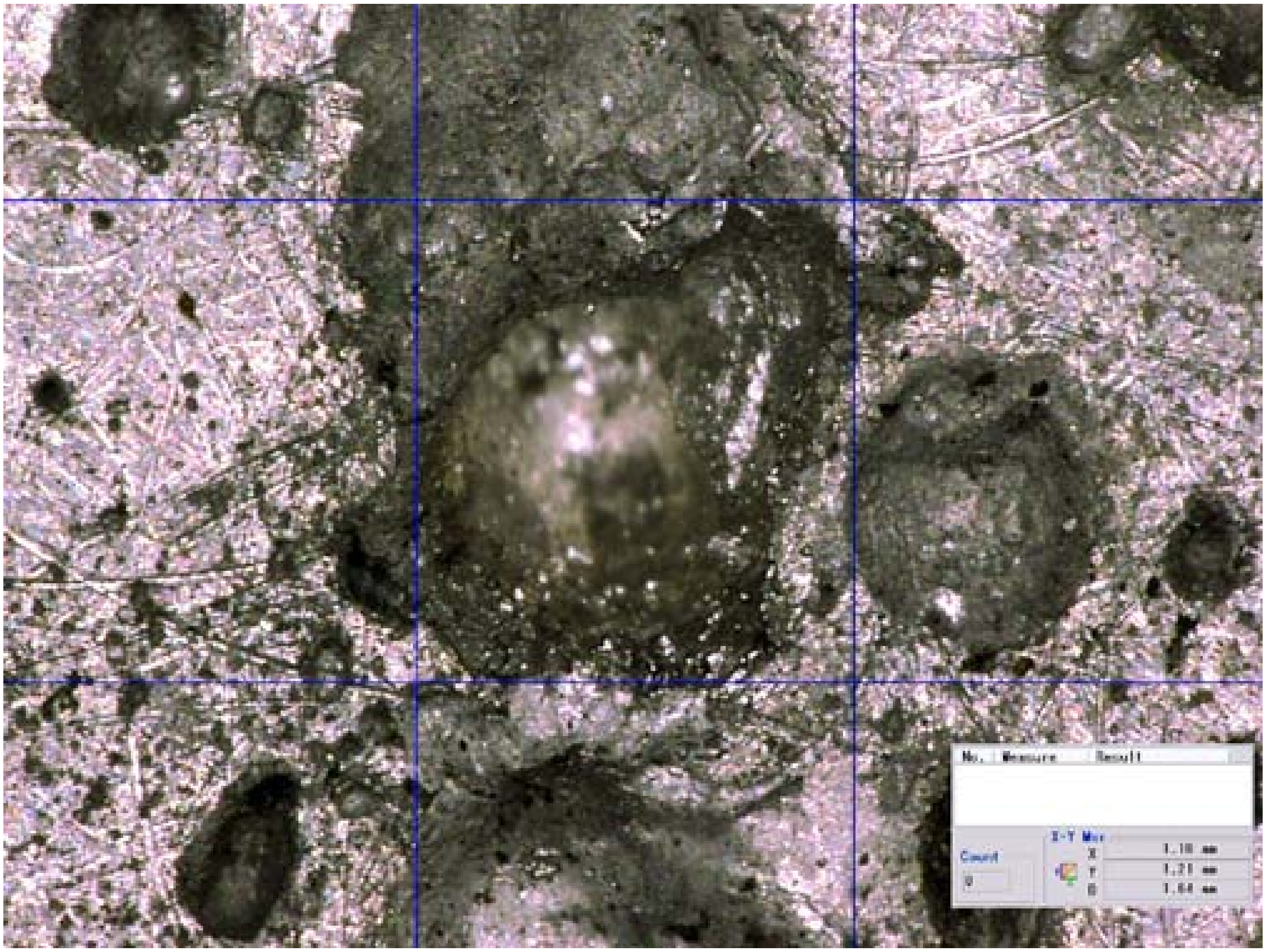


Figure 261: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #15C (Keyence 3D Microscope Image)

Test #15C, HITF12275

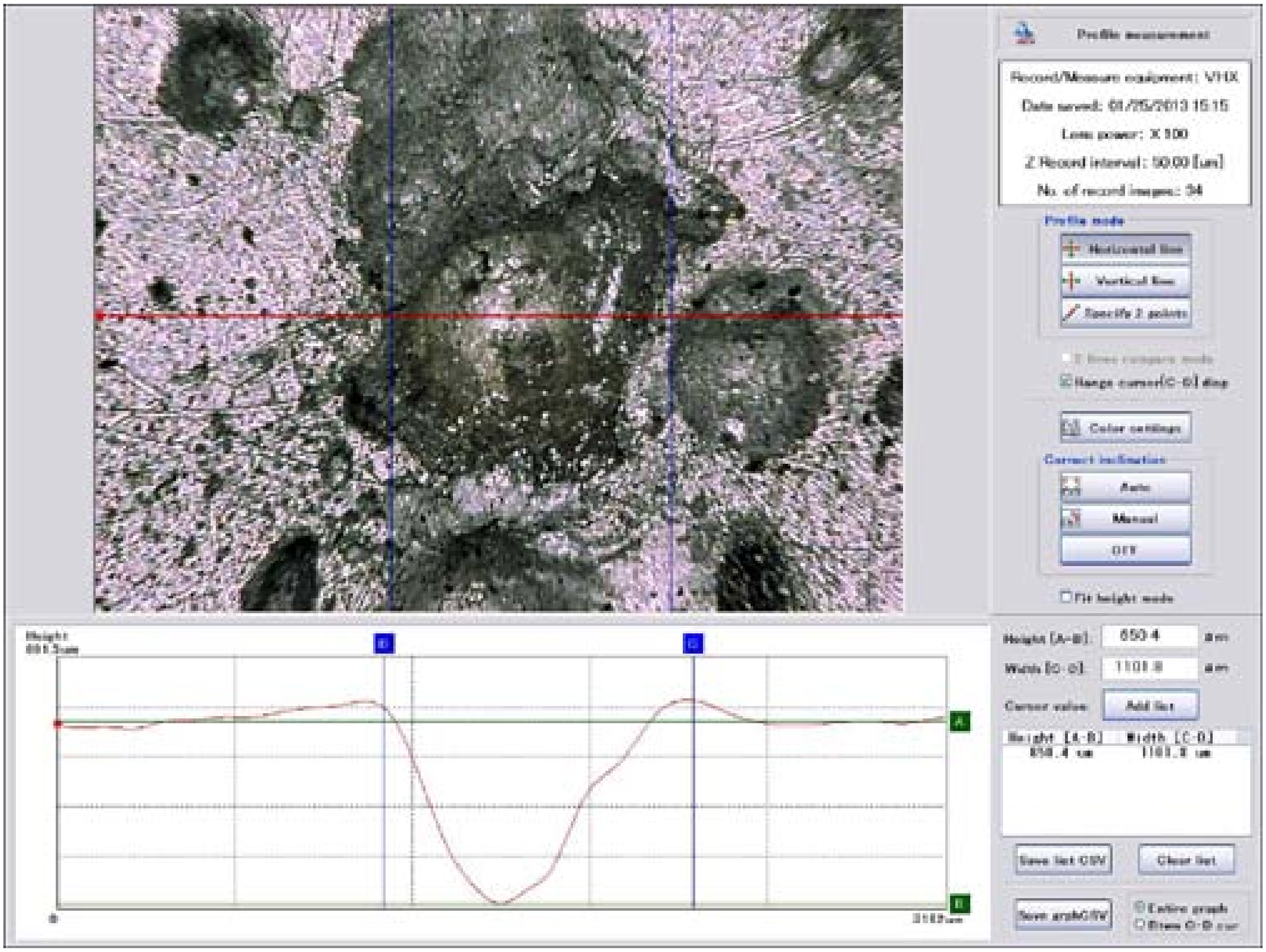


Figure 262: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #15C (Keyence 3D Microscope Image)

Test #15C, HITF12275

Figure 263: Back Witness Plate View of ISS Soyuz Orbital Module Test #15C

Test #16, HITF12276

Figure 264: Post-test of ISS Soyuz Orbital Module Test #16 (HITF12276) article mounted in 0.50-caliber target tank.

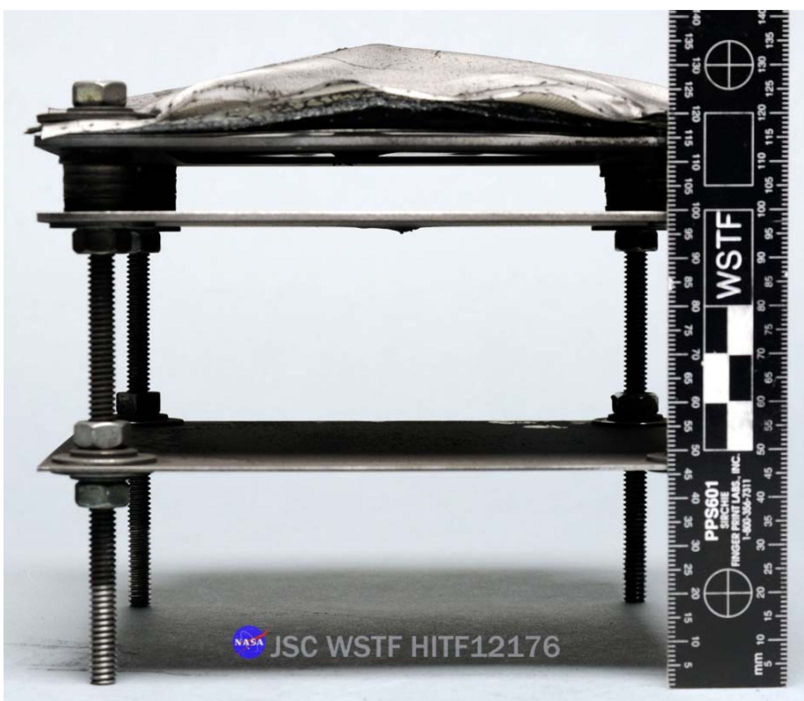


Figure 265: Side View of ISS Soyuz Orbital Module Test #16

Test #16, HITF12276

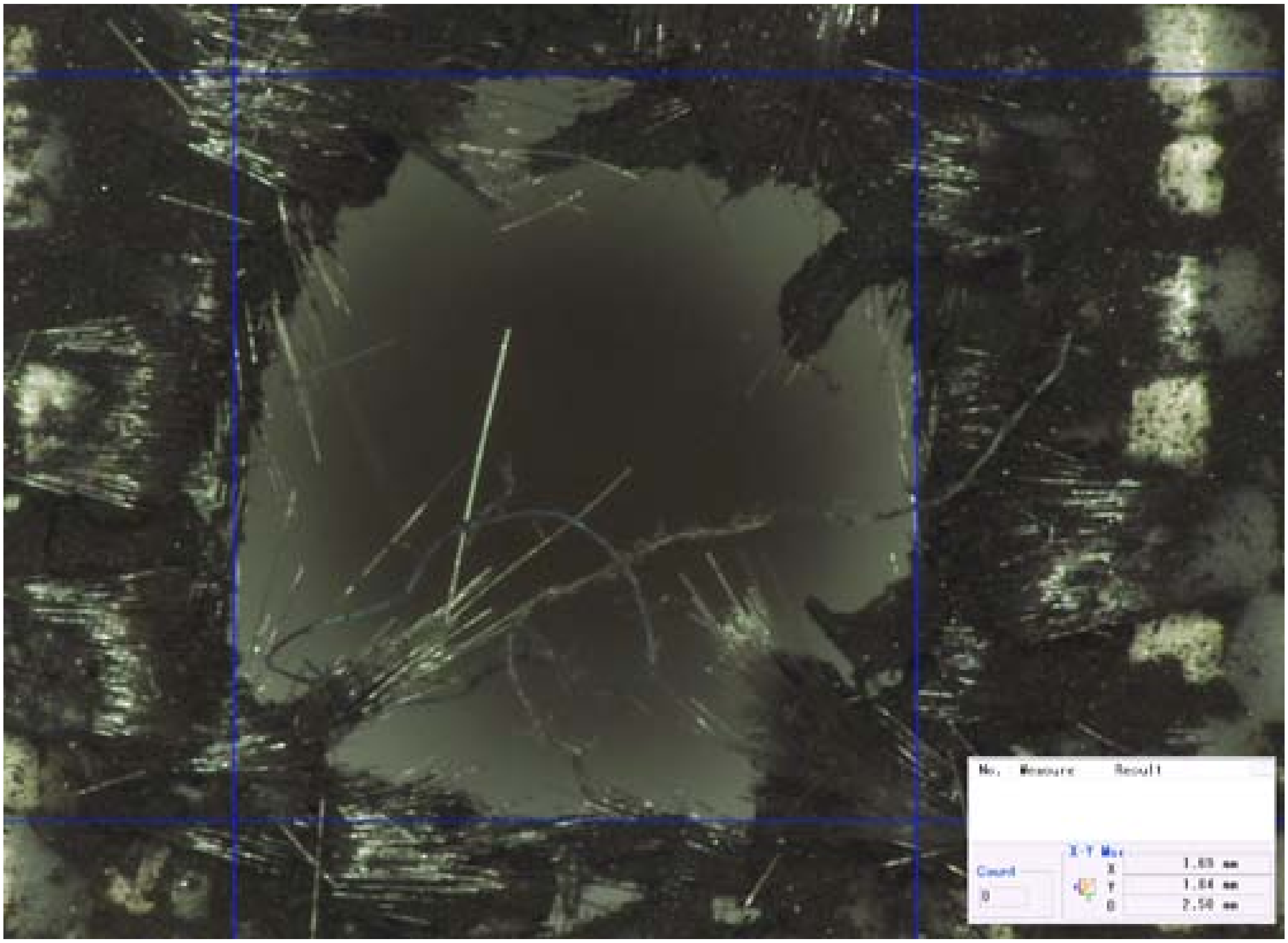


Figure 266: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #16 (Keyence 3D Microscope Image)

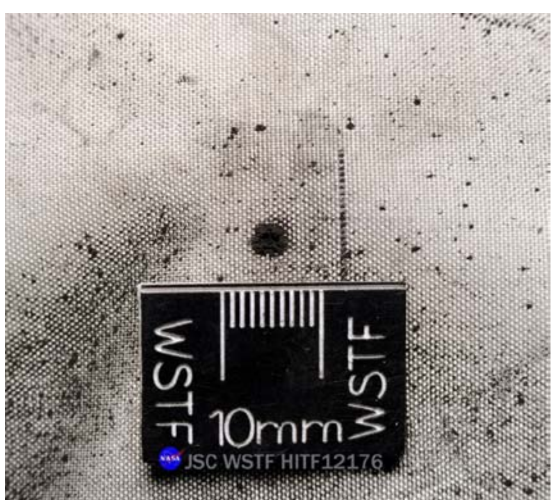


Figure 267: Beta Cloth Bumper Close-up of ISS Soyuz Orbital Module Test #16

Test #16, HITF12276

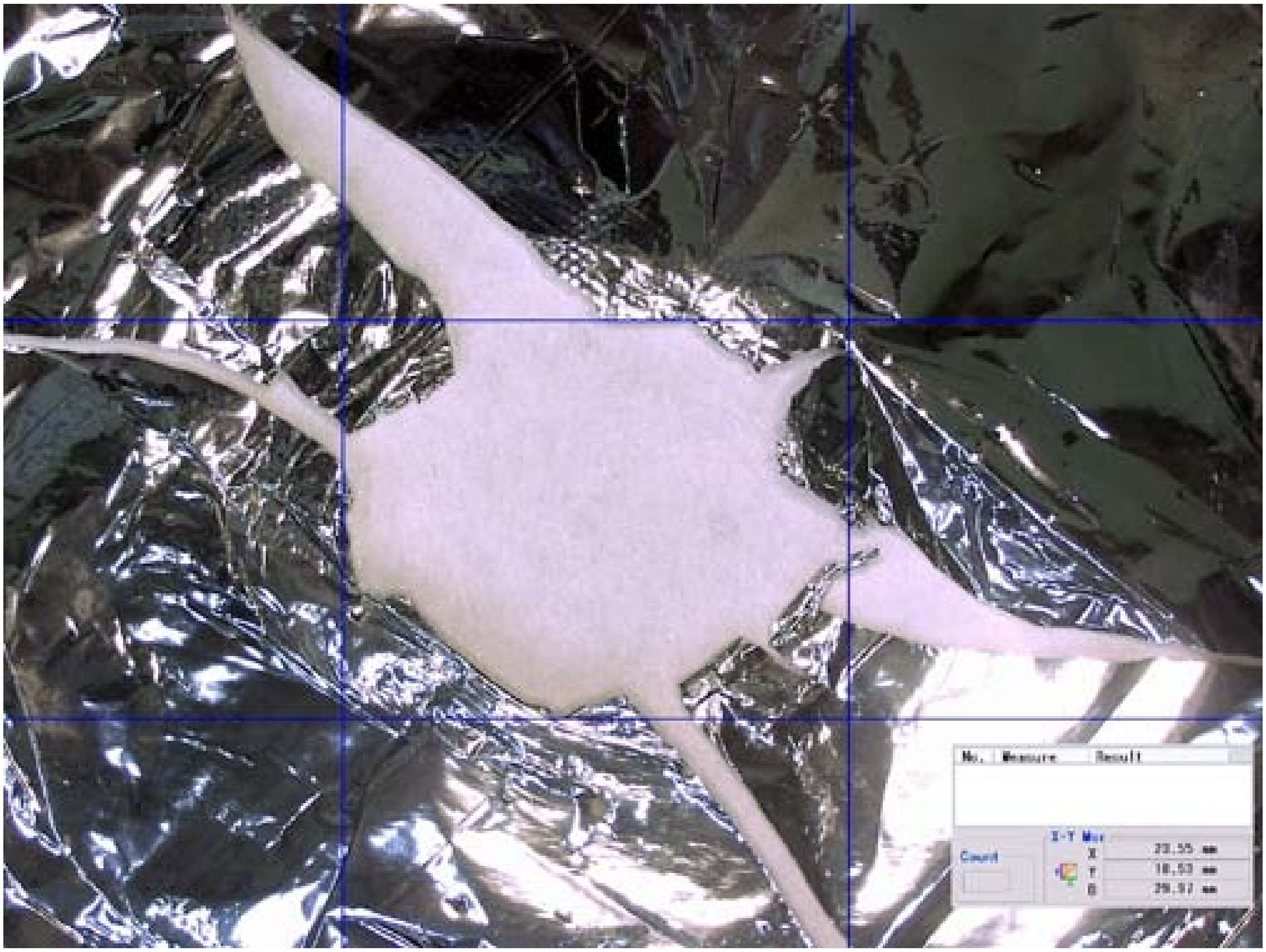


Figure 268: Mylar Film Layer 2 of ISS Soyuz OM Test #16 (Keyence 3D Microscope Image)

Test #16, HITF12276

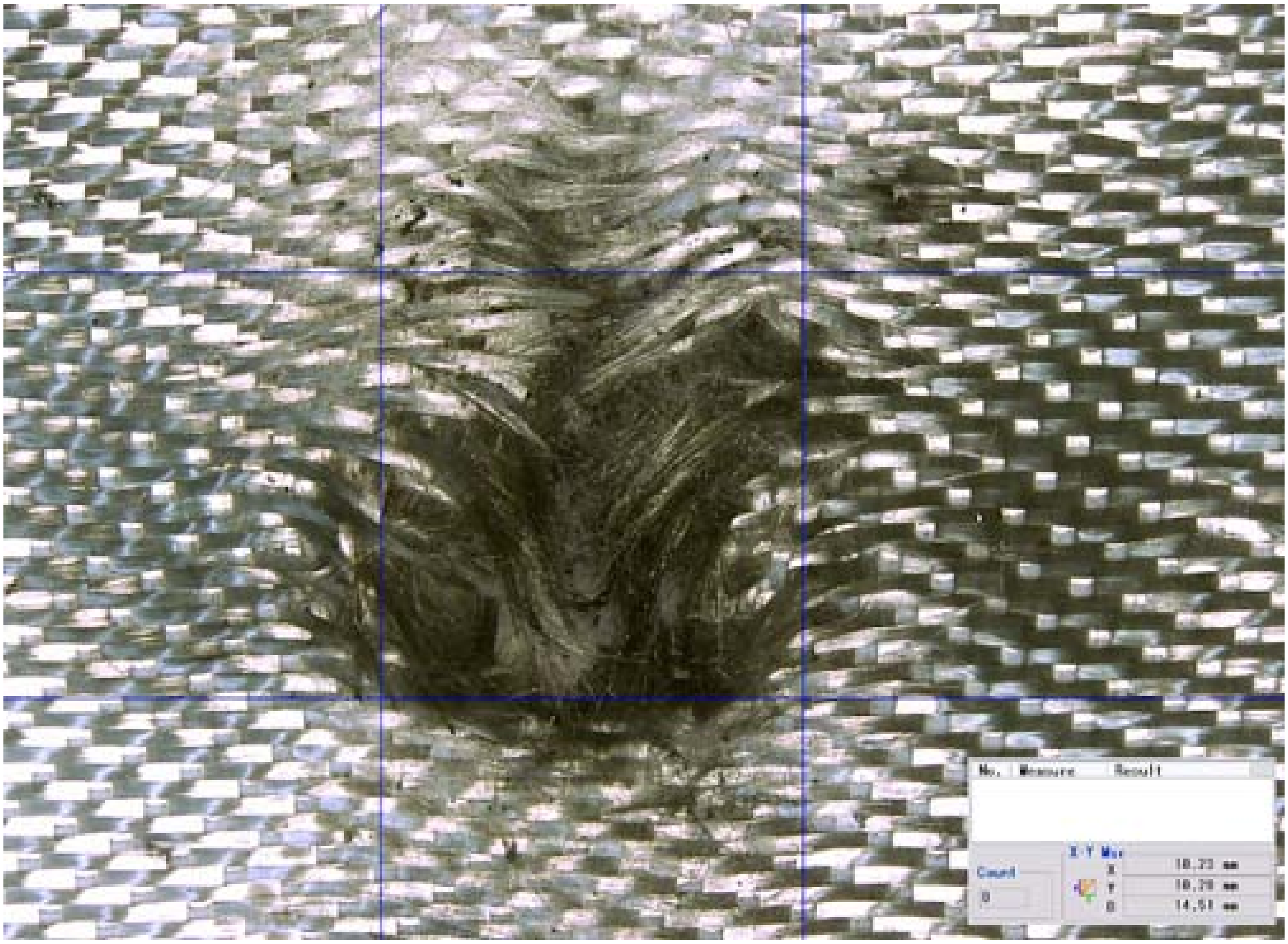


**Figure 269: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #16
(Keyence 3D Microscope Image)**

Test #16, HITF12276

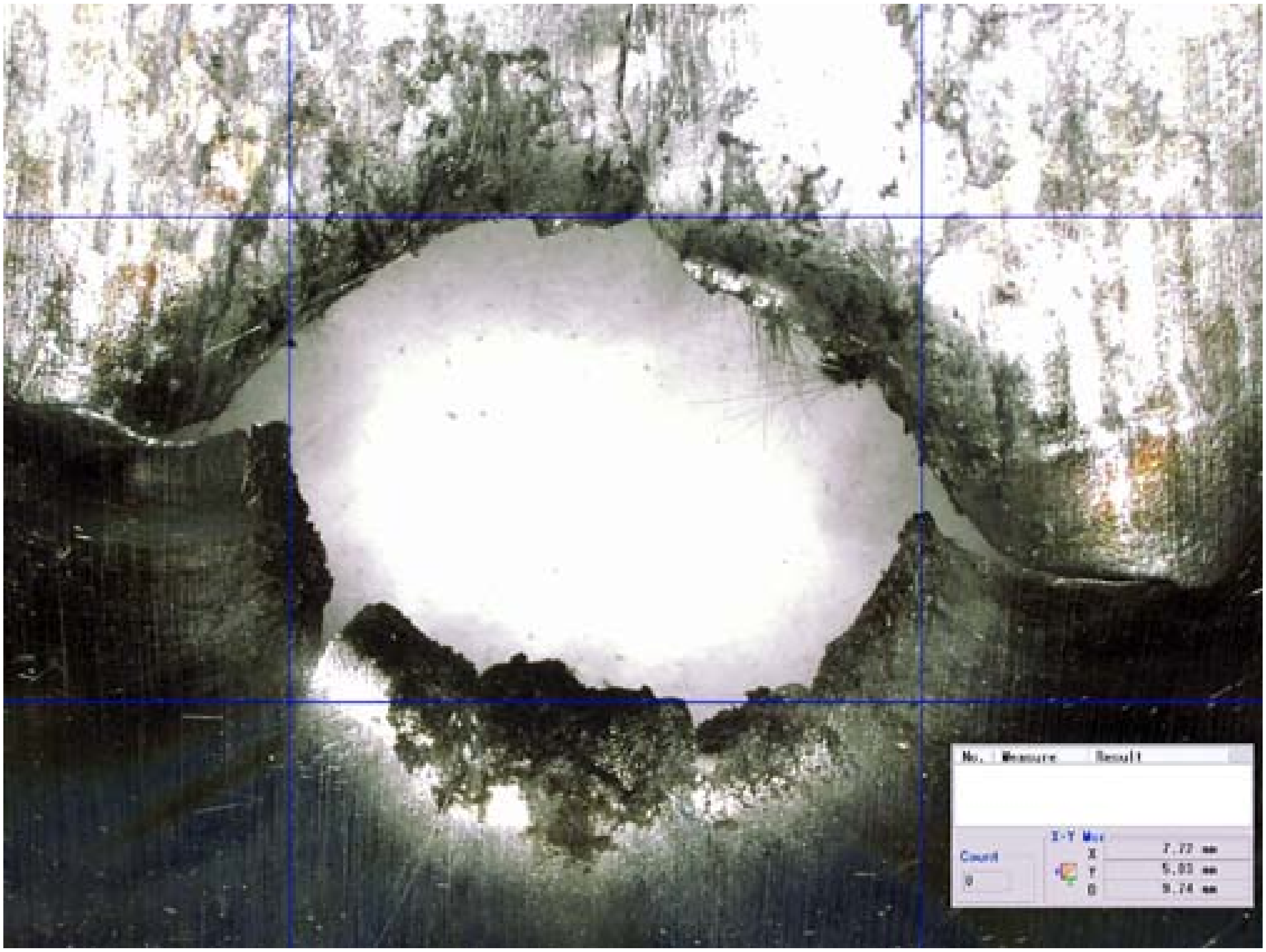


Figure 270: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #16 (Keyence 3D Microscope Image)

Test #16, HITF12276

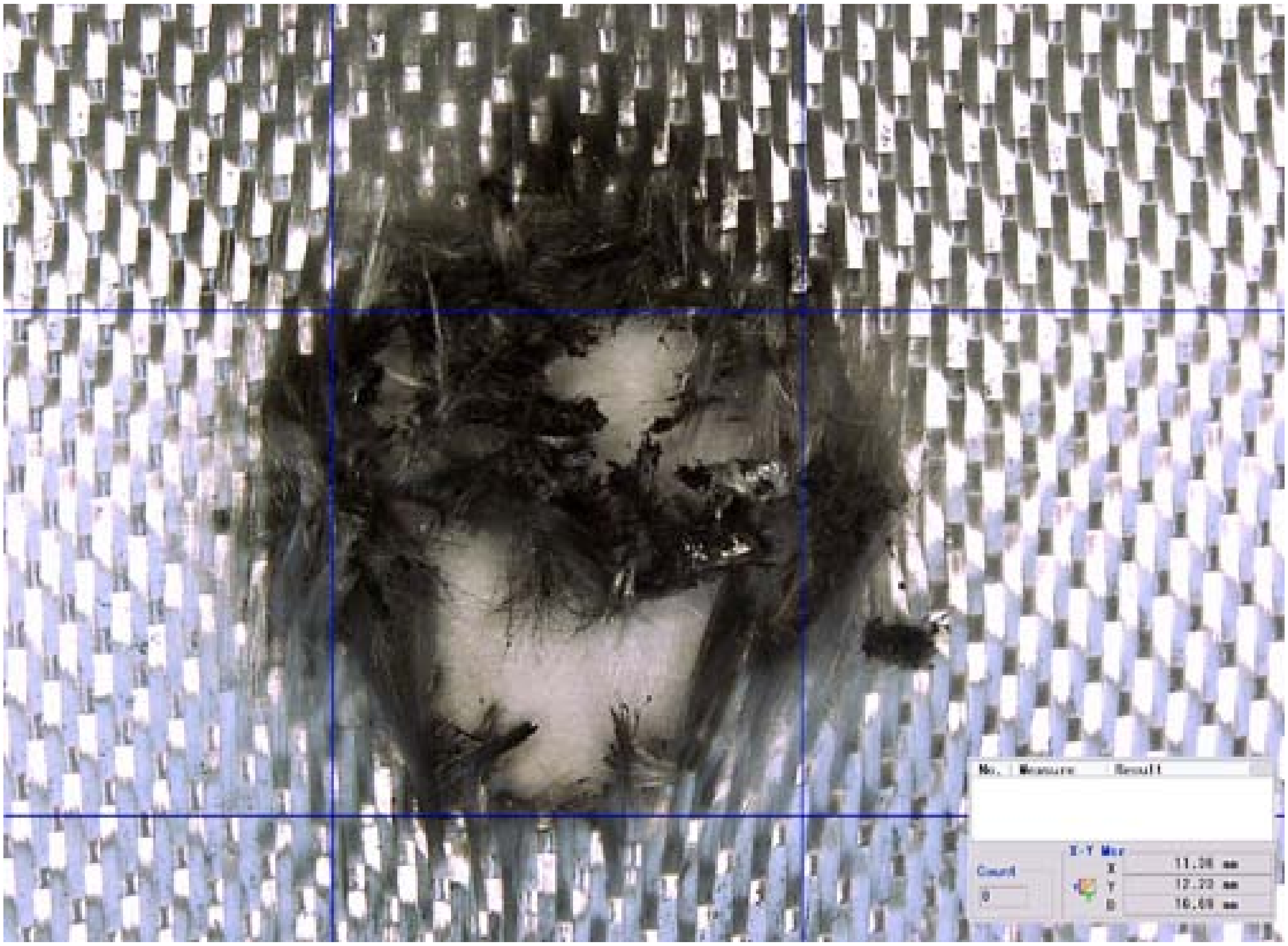


Figure 271: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #16 (Keyence 3D Microscope Image)

Test #16, HITF12276

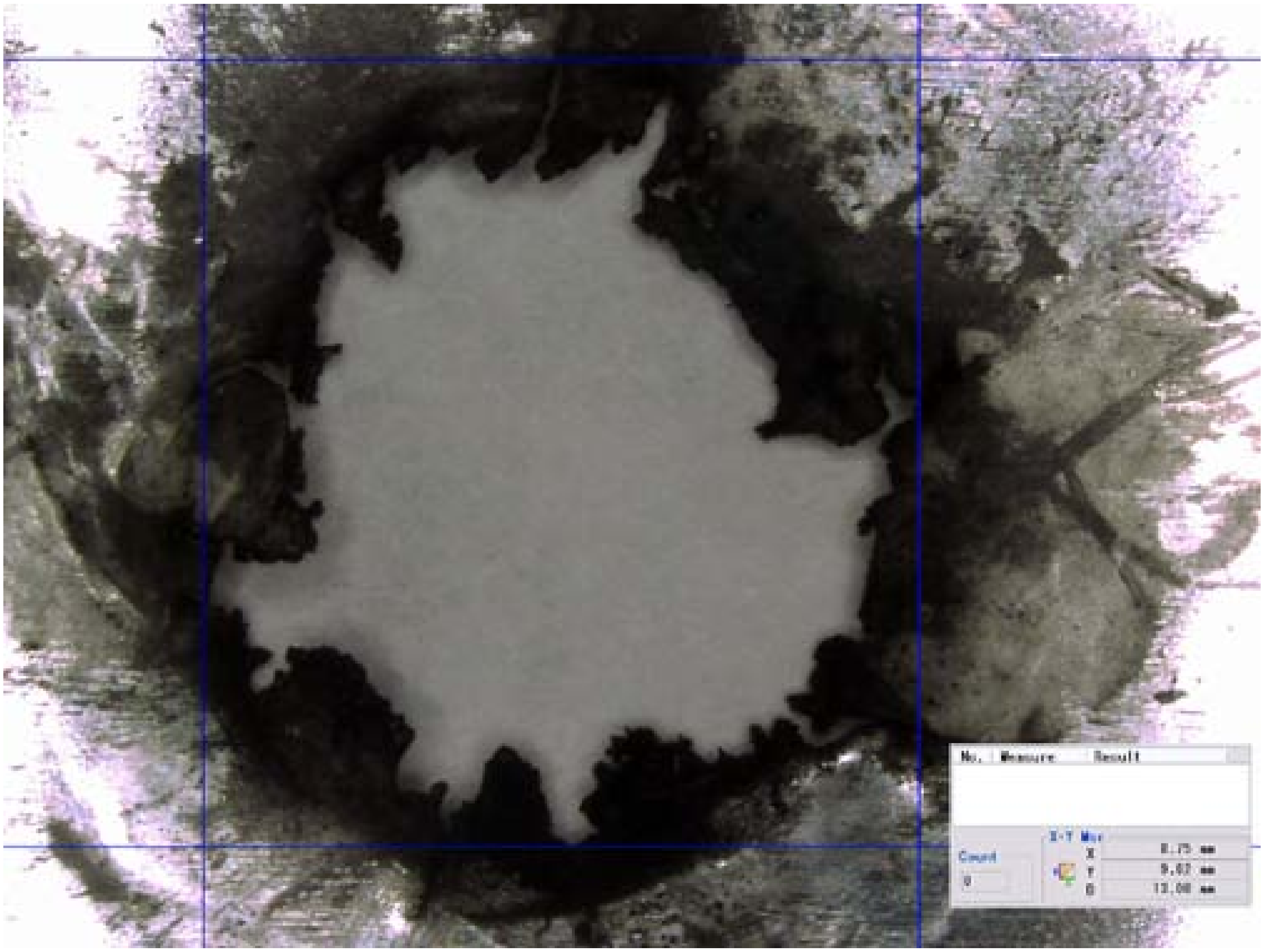


Figure 272: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #16 (Keyence 3D Microscope Image)

Test #16, HITF12276

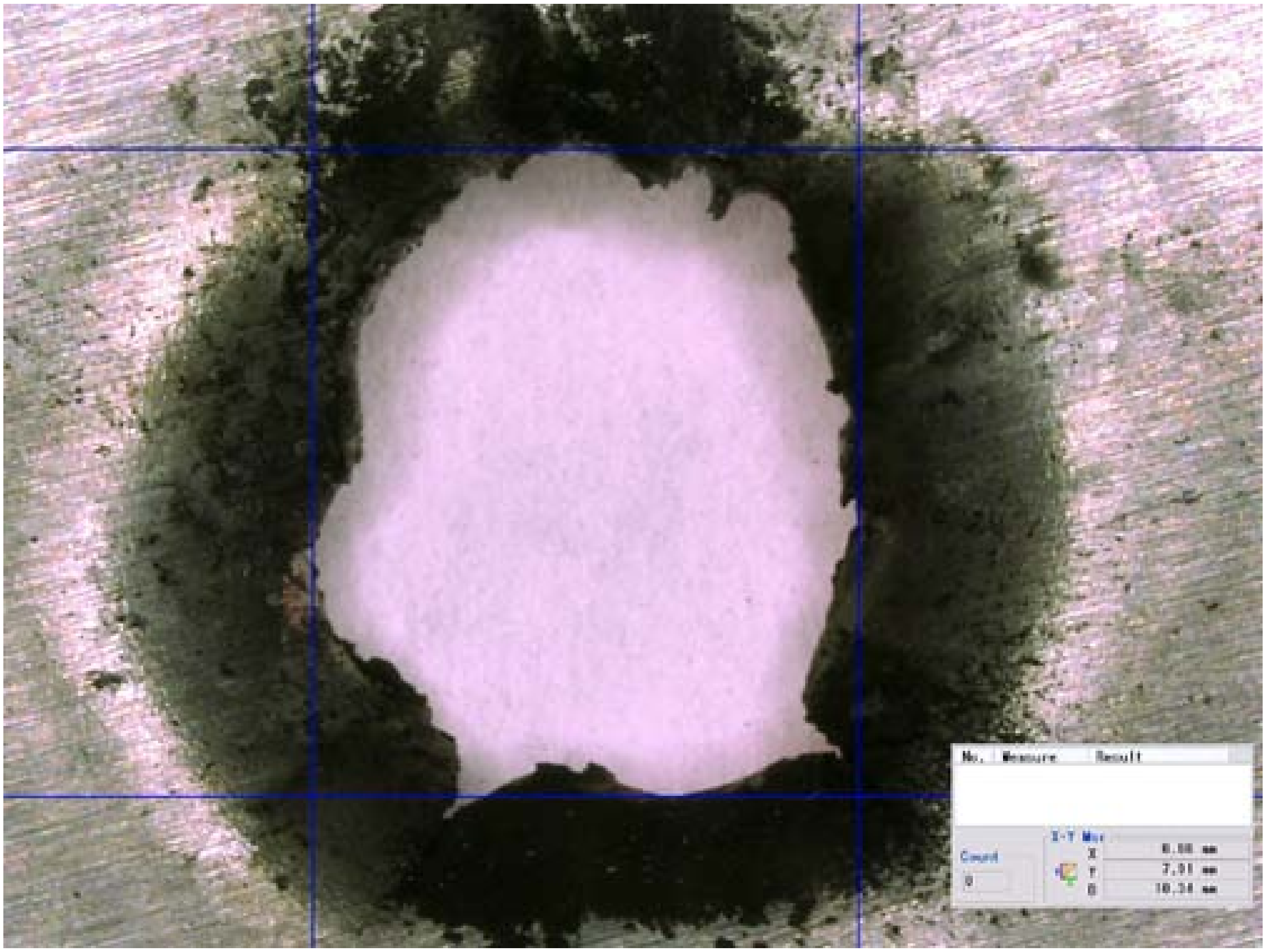


Figure 273: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #16 (Keyence 3D Microscope Image)

Test #16, HITF12276

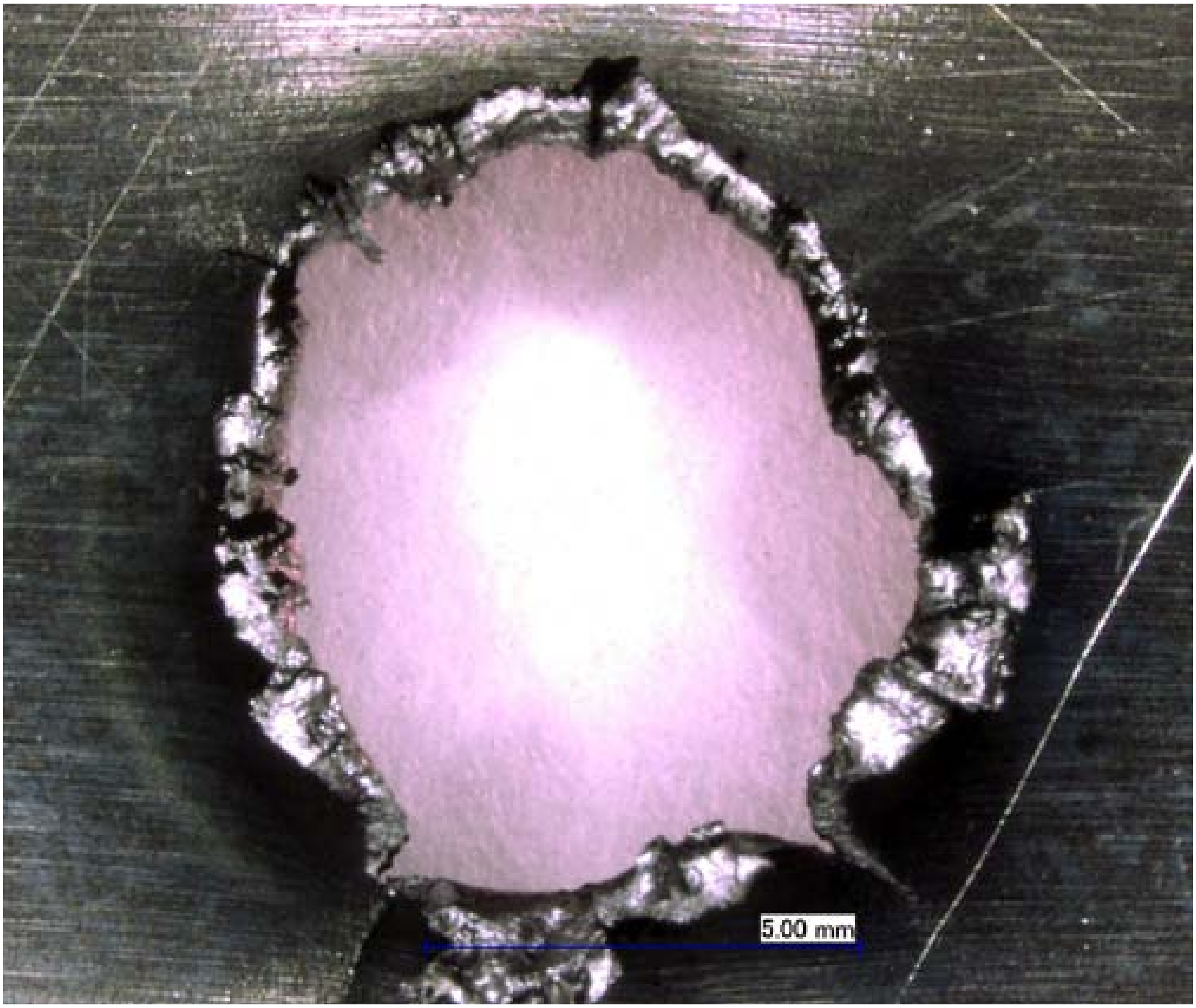


Figure 274: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #16 (Keyence 3D Microscope Image)

Test #16, HITF12276 Rear Wall

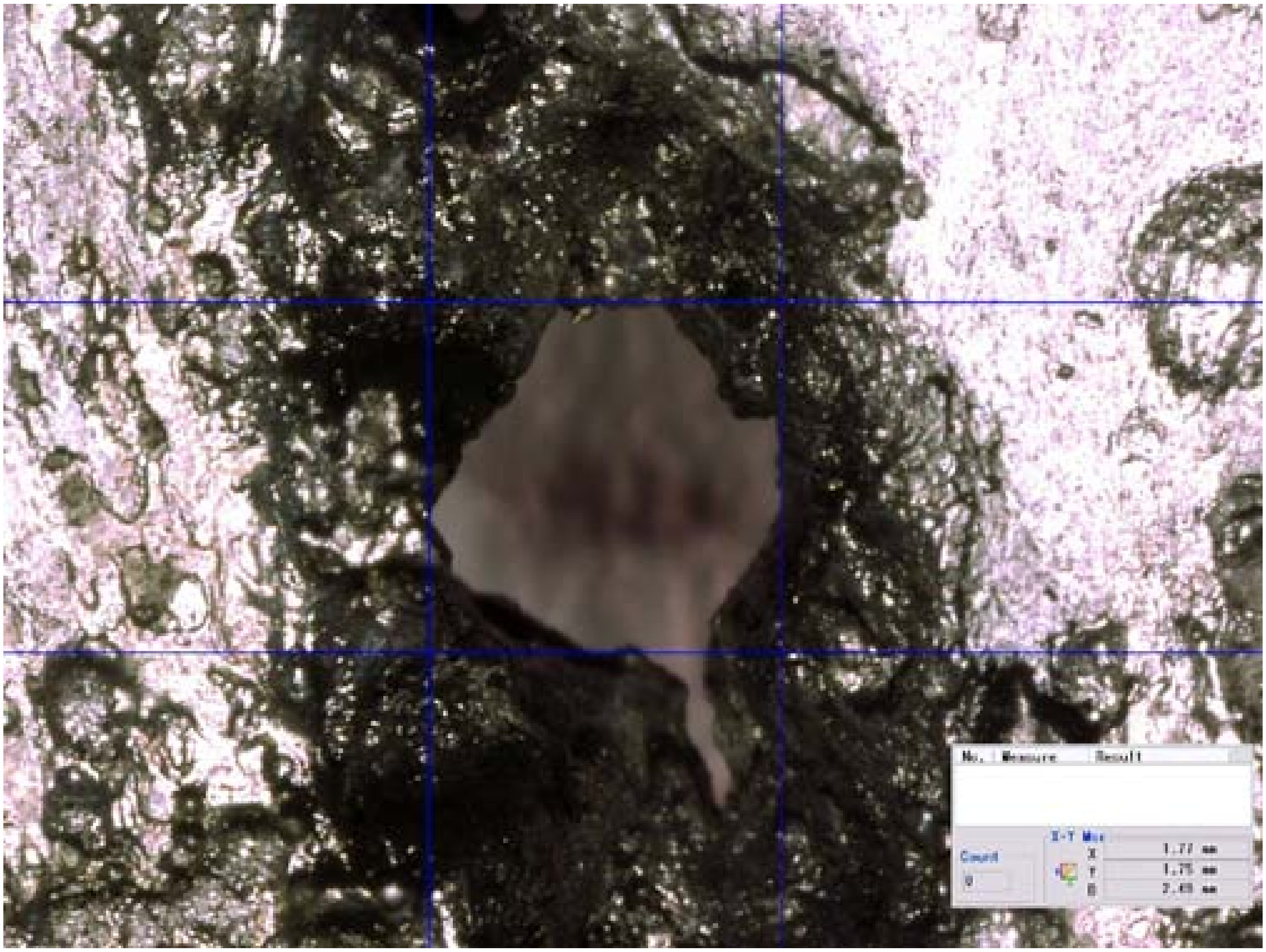


Figure 275: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #16 (Keyence 3D Microscope Image)

Test #16, HITF12276

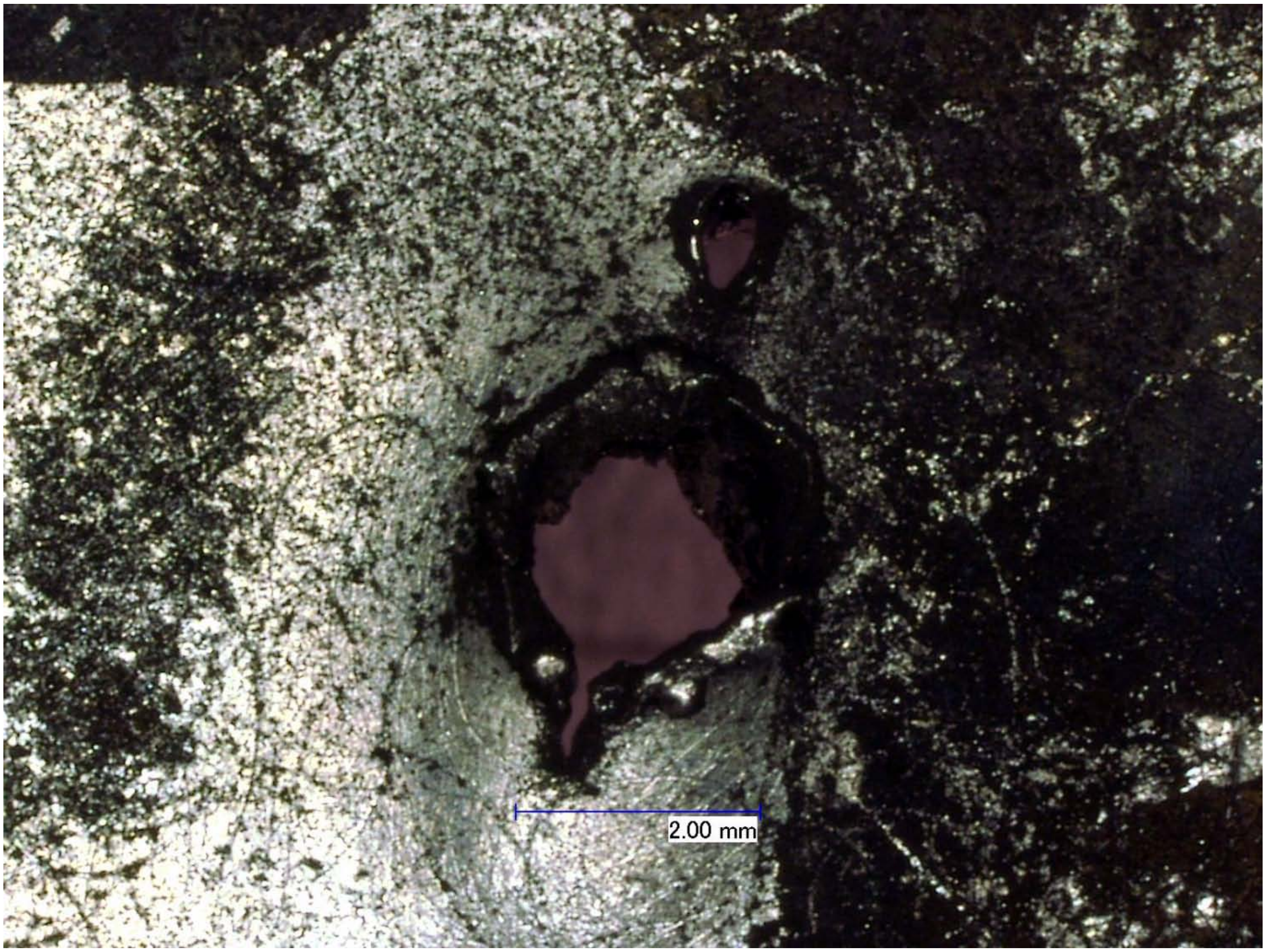


Figure 276: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #16 (Keyence 3D Microscope Image)

Test #16, HITF12276

Figure 277: Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #16

Figure 278: Close-up of Al 5456-0 Rear Wall (Back) for ISS Soyuz Orbital Module Test #16

Test #16, HITF12276

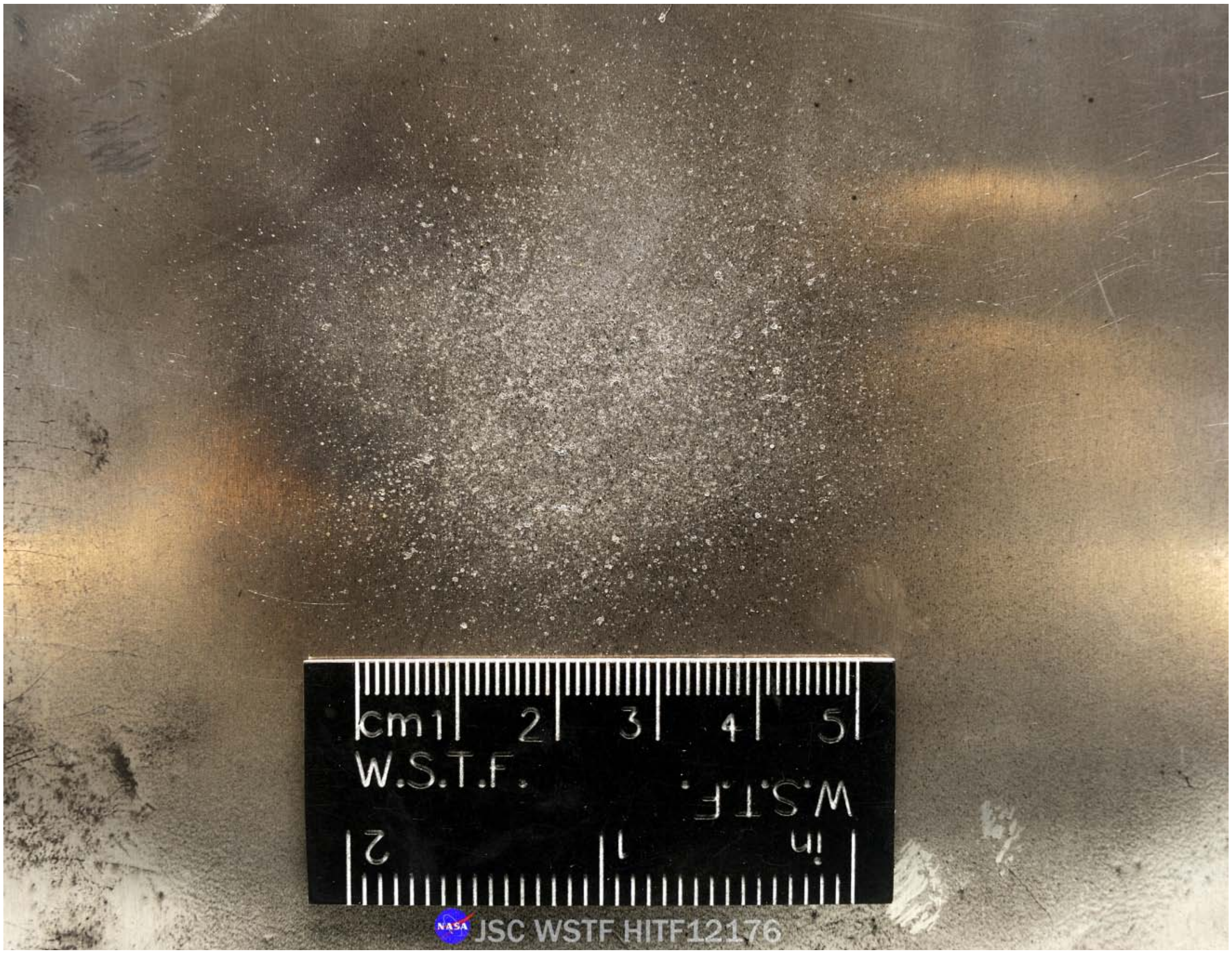


Figure 279: Front Witness Plate View of ISS Soyuz Orbital Module Test #16

Test #17, HITF12277

Figure 280: Post-test of ISS Soyuz Orbital Module Test #17 (HITF12277) article mounted in 0.17-caliber target tank.

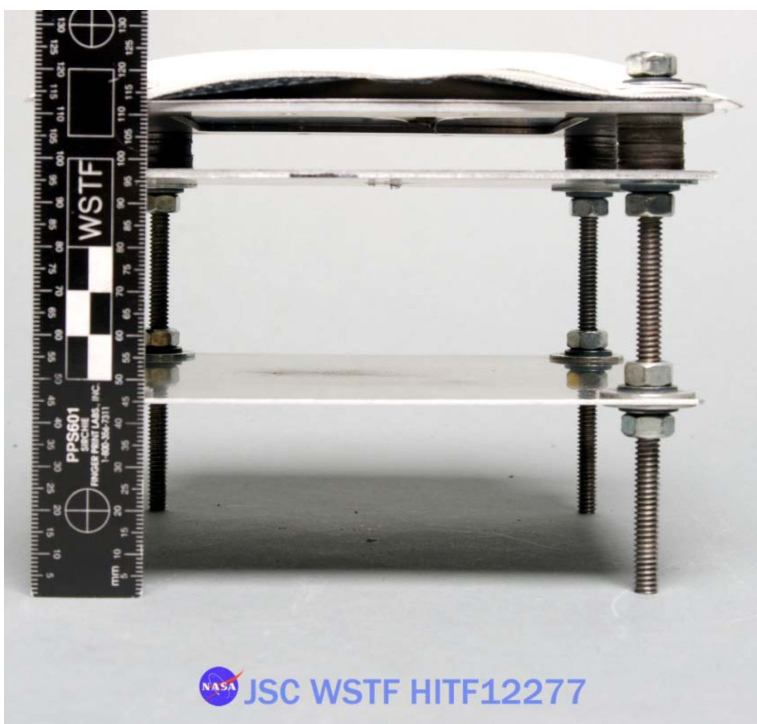


Figure 281: Side View of ISS Soyuz Orbital Module Test #17

Test #17, HITF12277

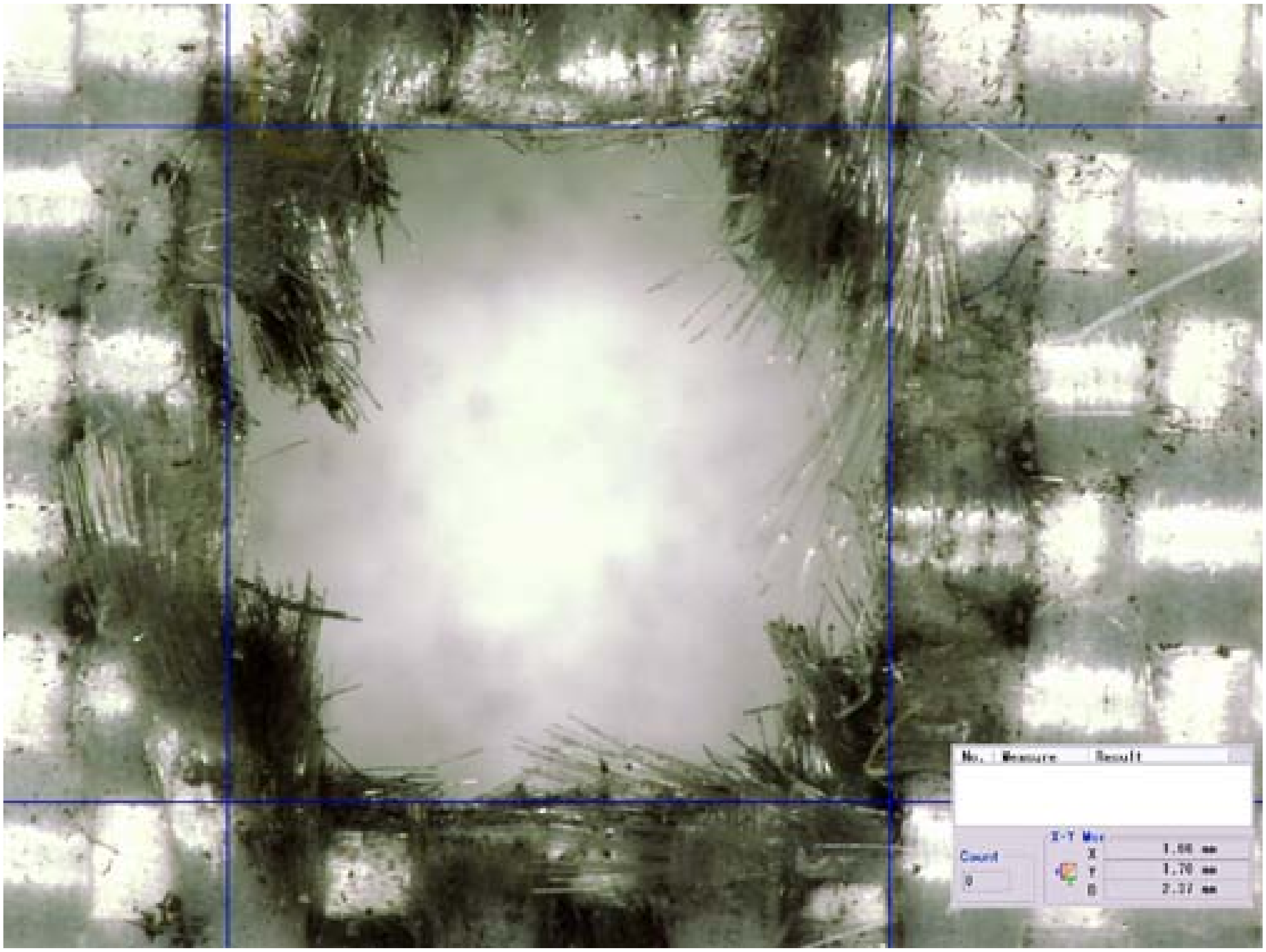


Figure 282: Beta Cloth Bumper Layer 1 of ISS Soyuz OM Test #17 (Keyence 3D Microscope Image)

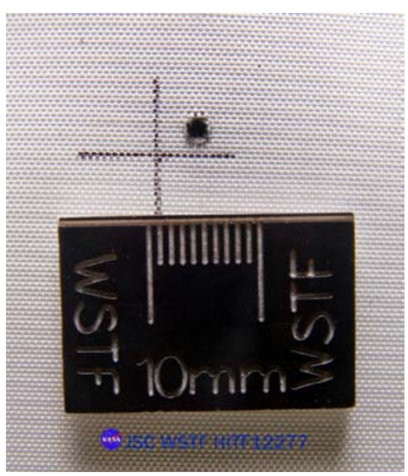


Figure 283: Beta Cloth Bumper Close-up of ISS Soyuz Orbital Module Test #17

Test #17, HITF12277

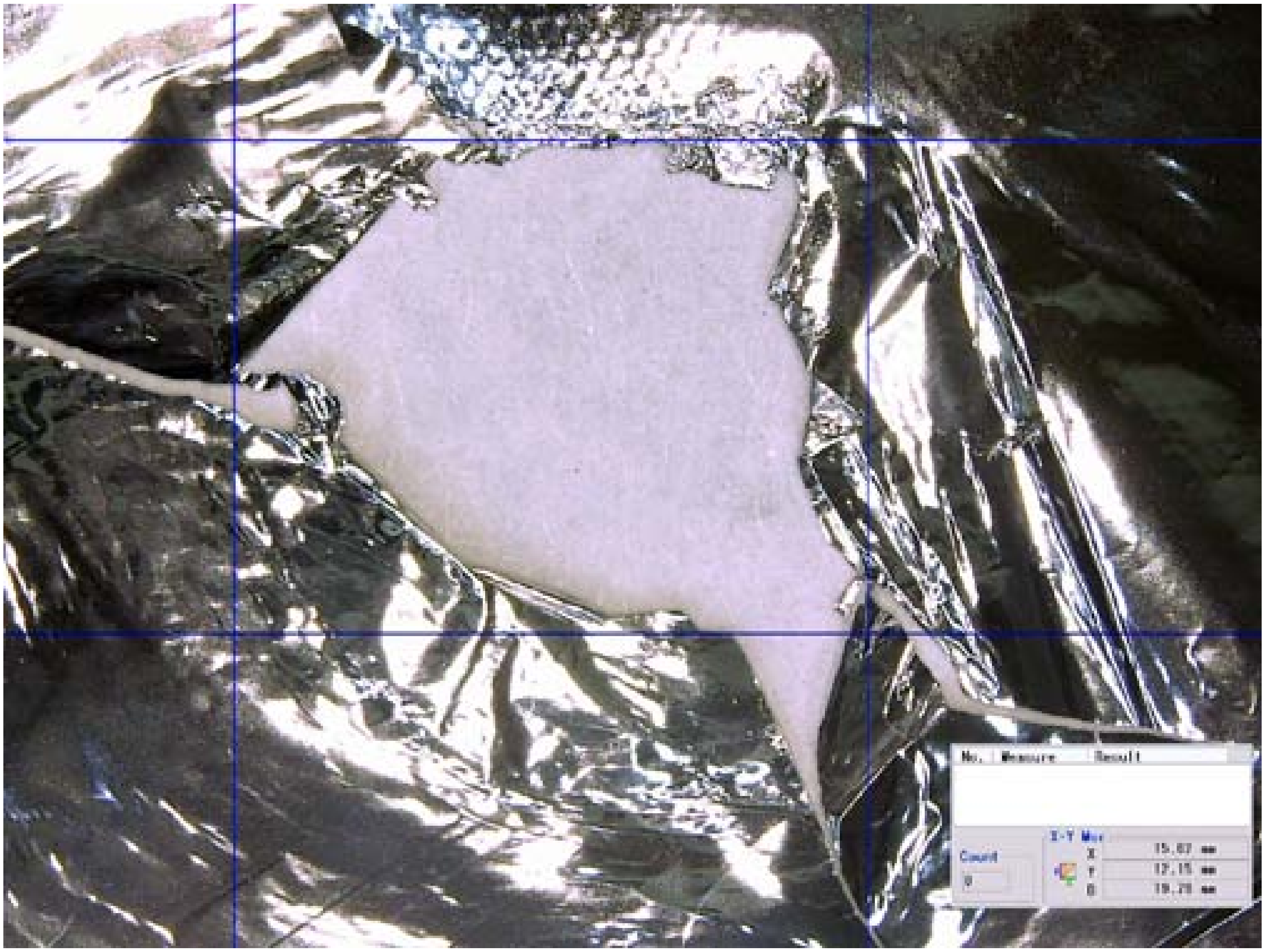


Figure 284: Mylar Film Layer 2 of ISS Soyuz OM Test #17 (Keyence 3D Microscope Image)

Test #17, HITF12277

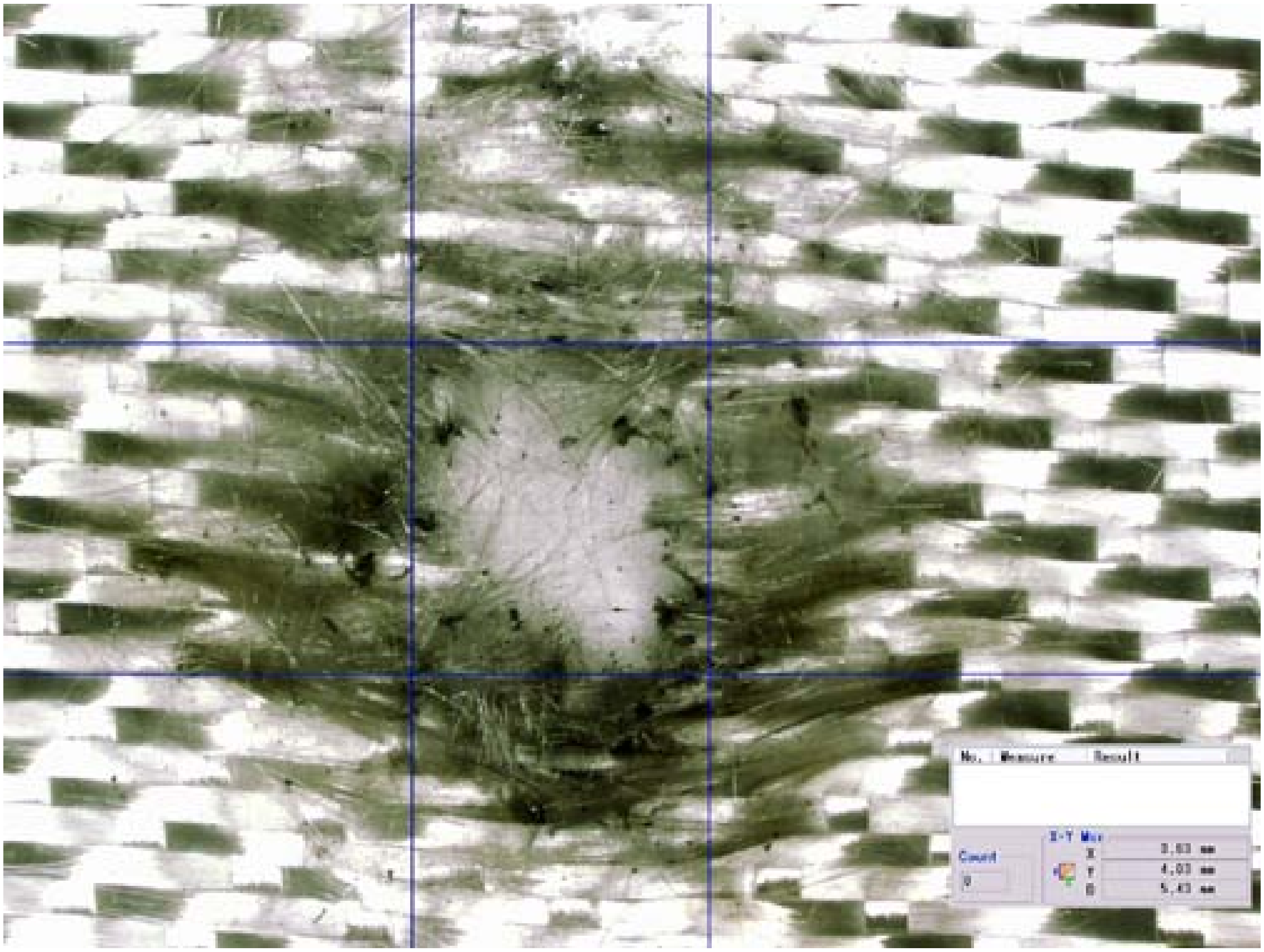


Figure 285: Fiberglass-7781 Layer 3 of ISS Soyuz OM Test #17 (Keyence 3D Microscope Image)

Test #17, HITF12277

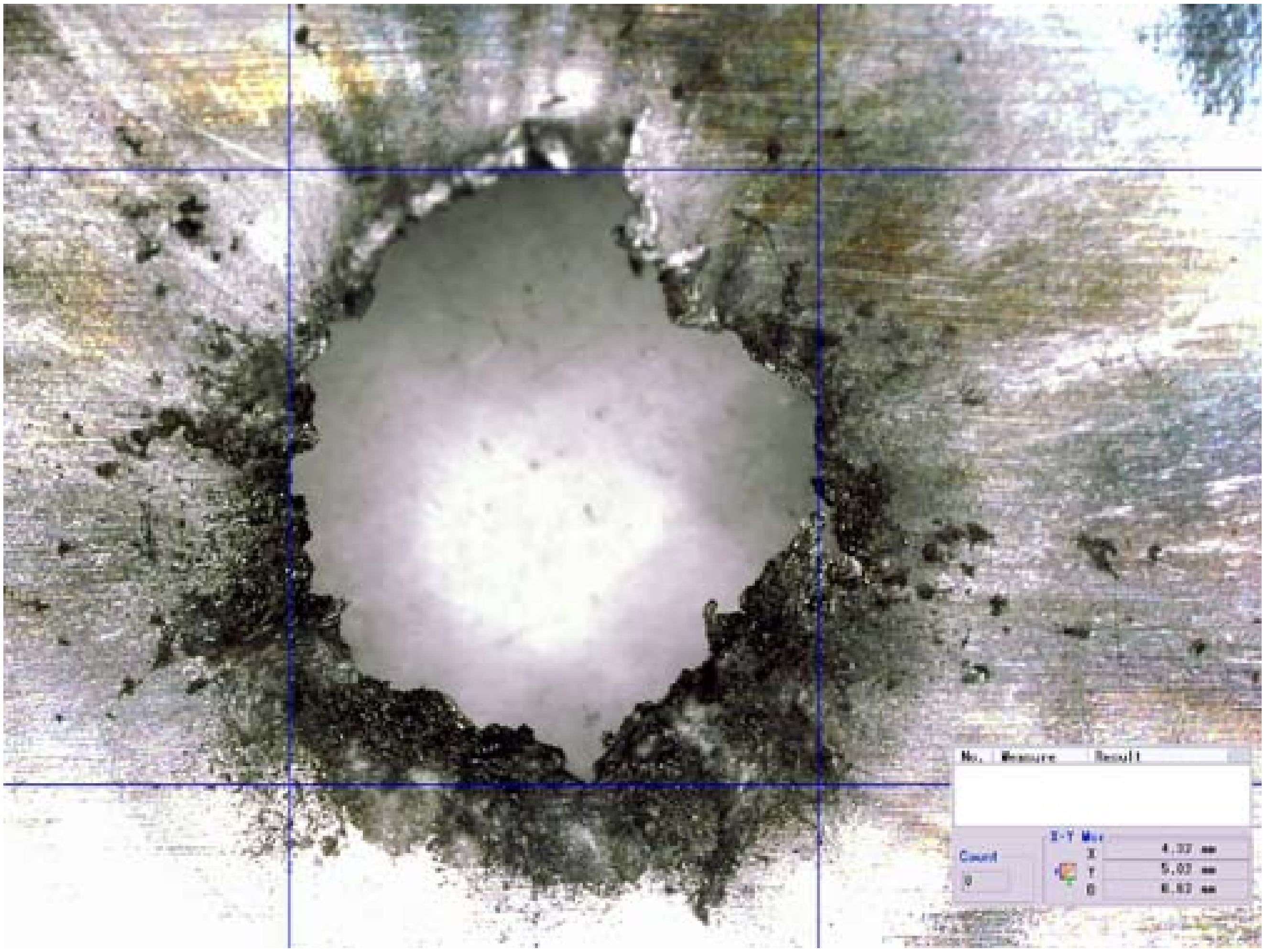


Figure 286: Al 6061 Foil Layer 4 of ISS Soyuz OM Test #17 (Keyence 3D Microscope Image)

Test #17, HITF12277

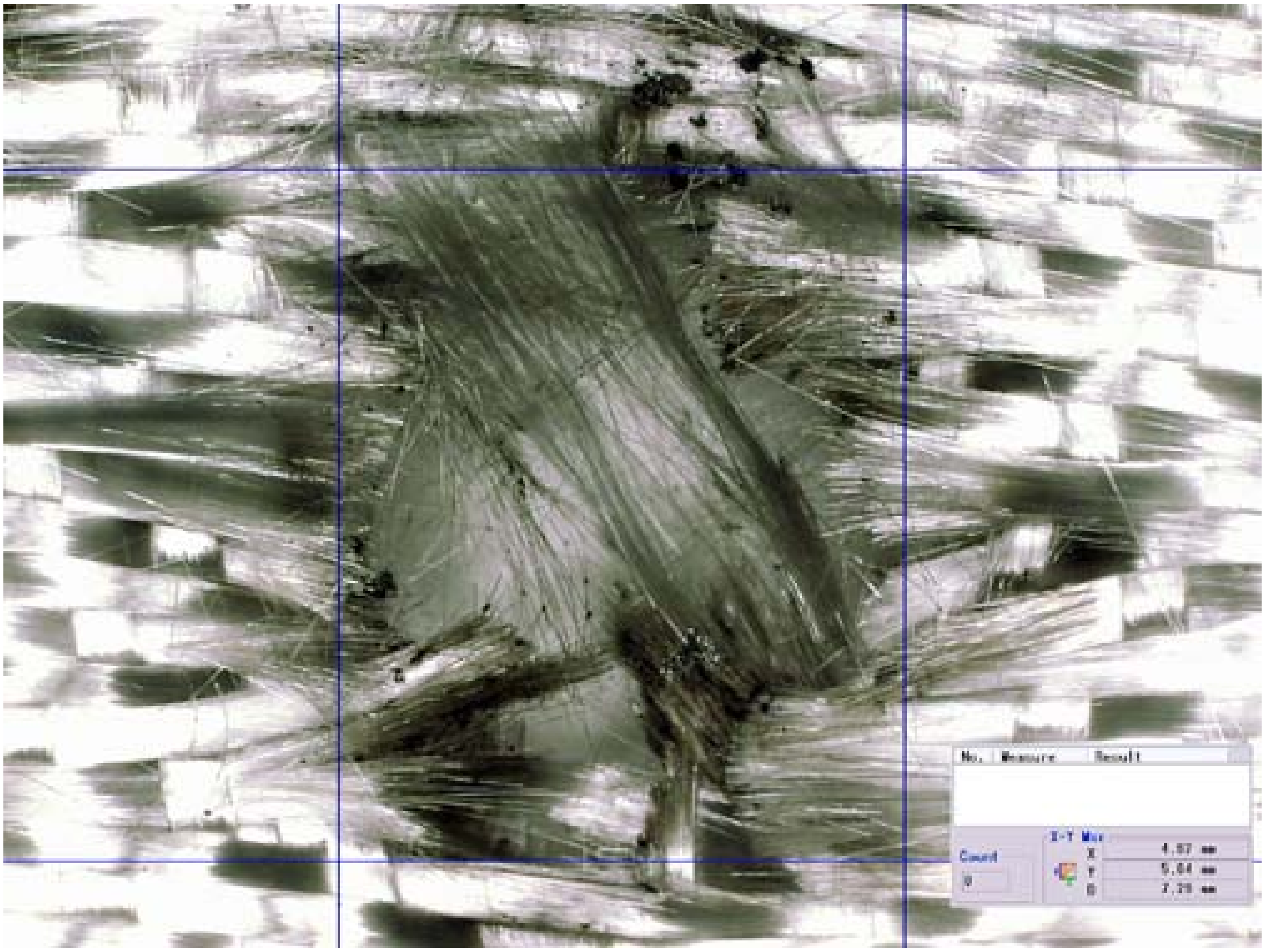


Figure 287: Fiberglass-7781 Layer 5 of ISS Soyuz OM Test #17
(Keyence 3D Microscope Image)

Test #17, HITF12277

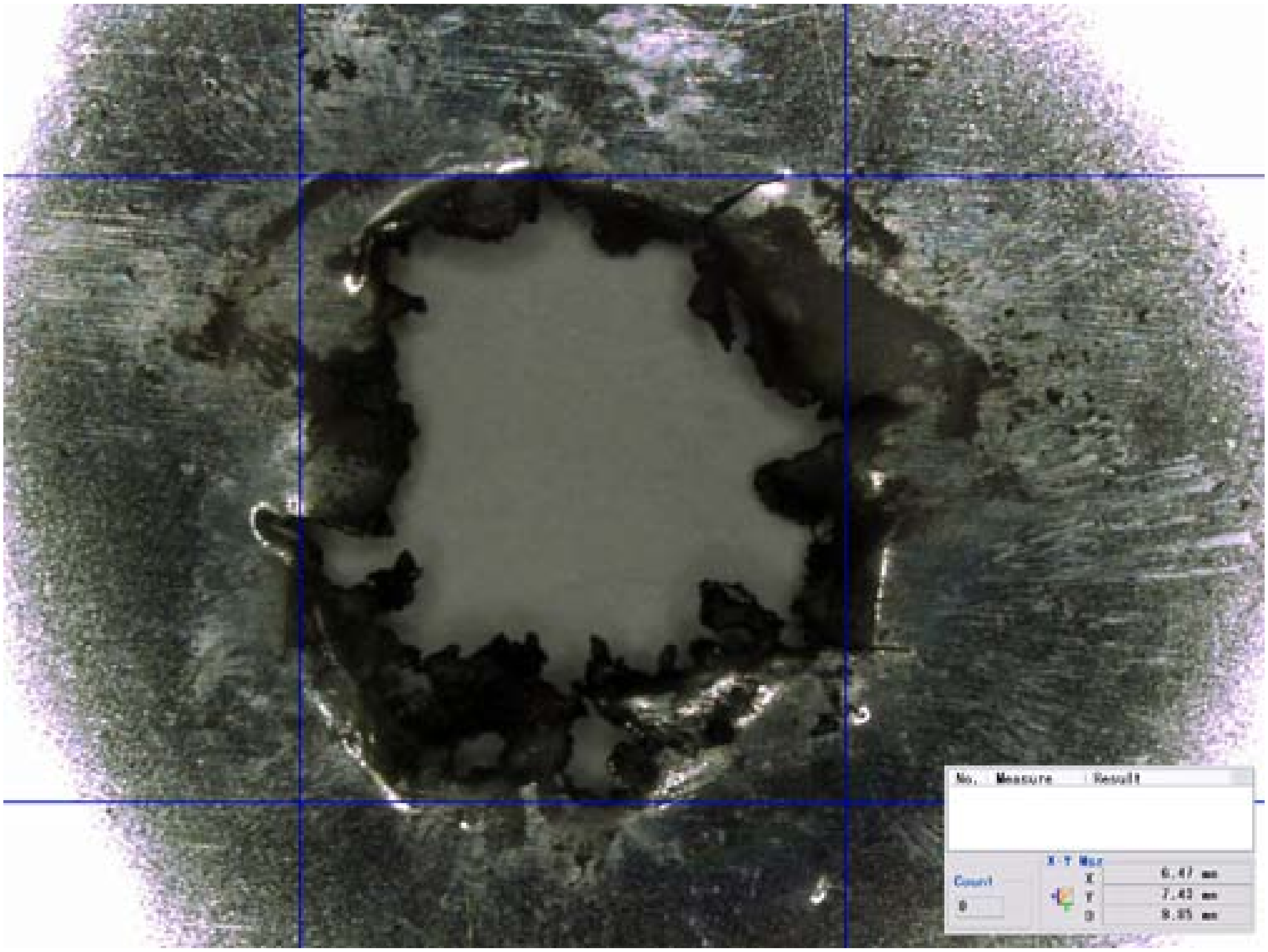


Figure 288: Multi-layer Insulation Aluminized Mylar Layer 6 Back of ISS Soyuz OM Test #17 (Keyence 3D Microscope Image)

Test #17, HITF12277

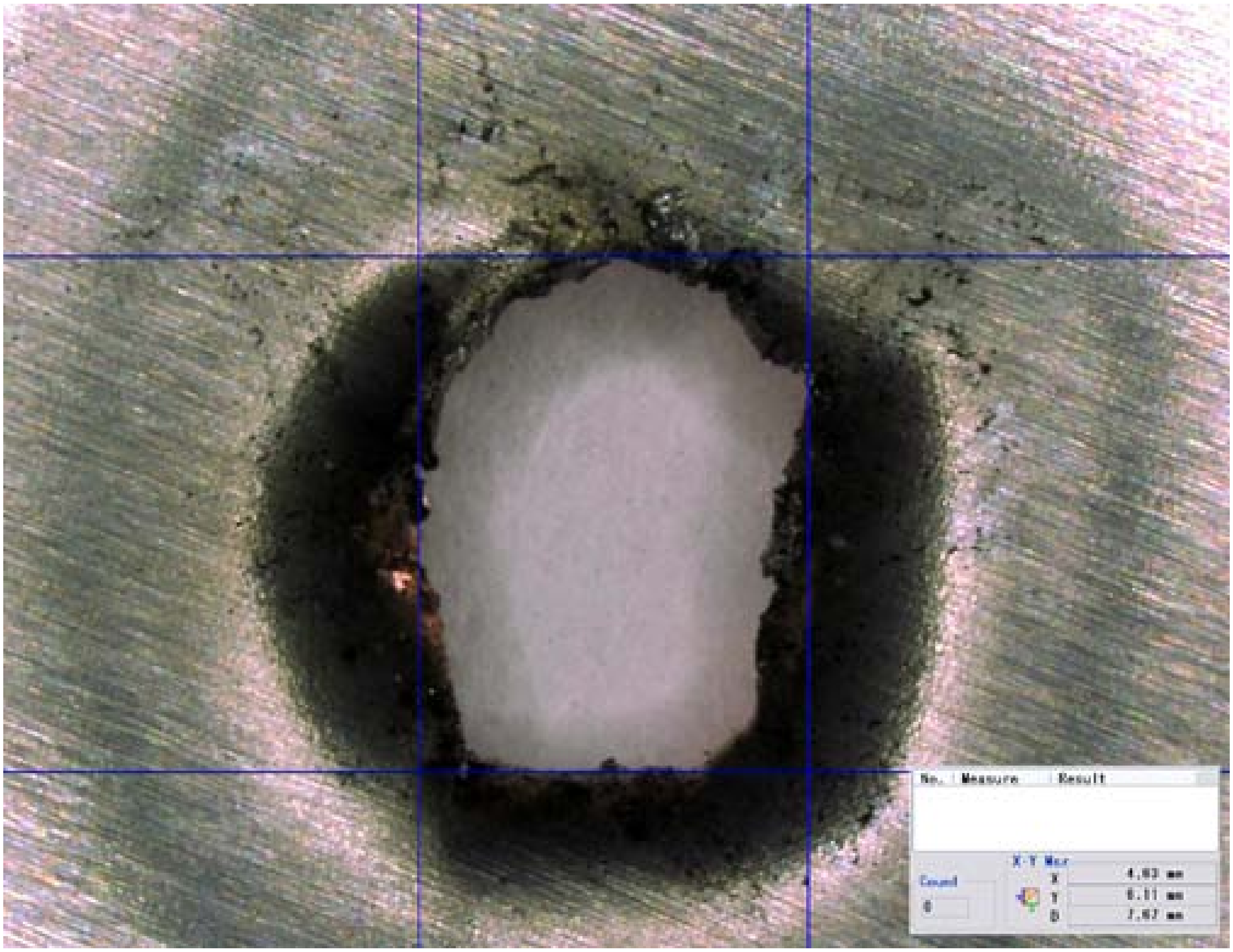


Figure 289: Al 6061-T6 Layer 7 Front of ISS Soyuz OM Test #17
(Keyence 3D Microscope Image)

Test #17, HITF12277

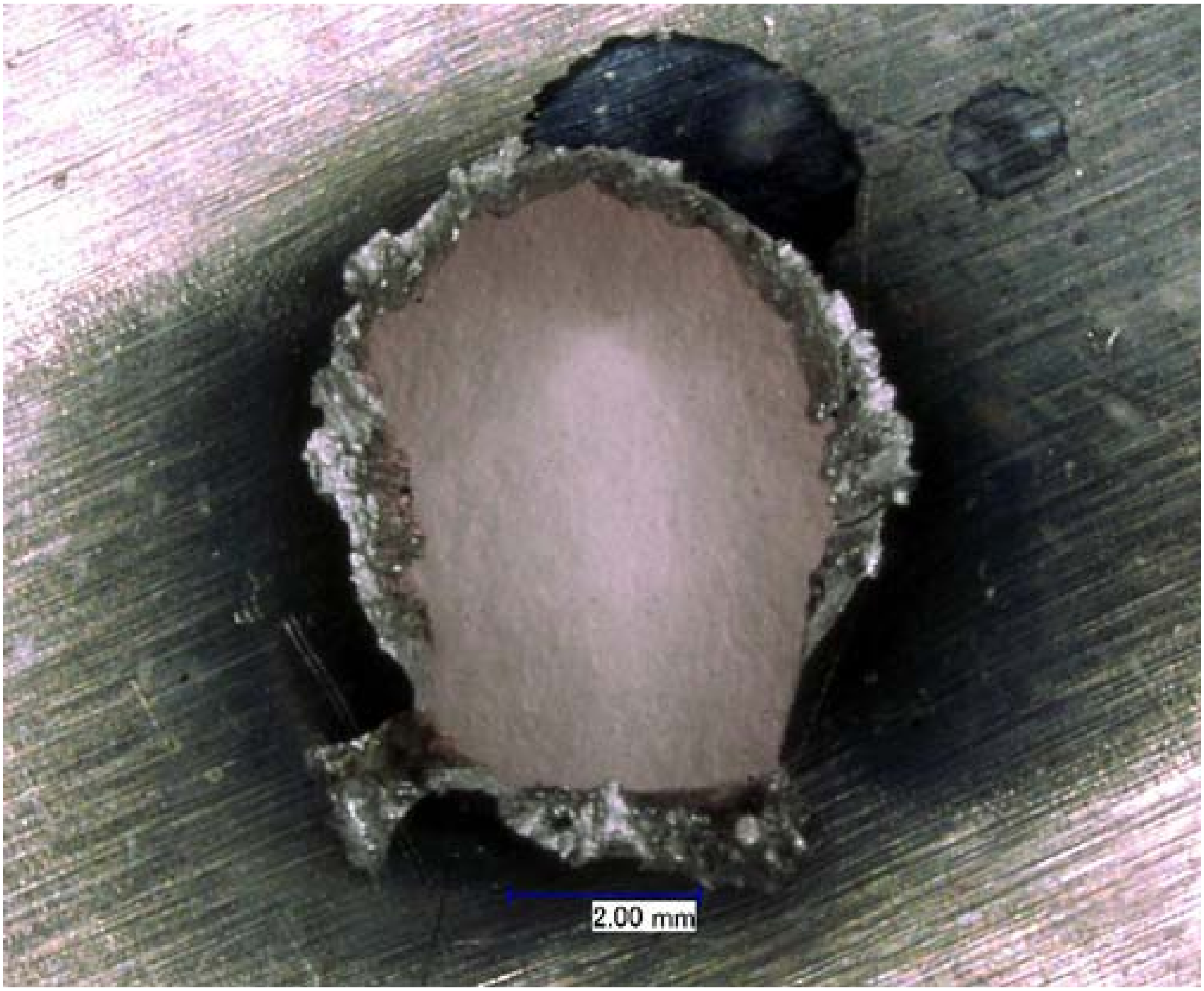


Figure 290: Al 6061-T6 Layer 7 Back of ISS Soyuz OM Test #17 (Keyence 3D Microscope Image)

Test #17, HITF12277 Rear Wall

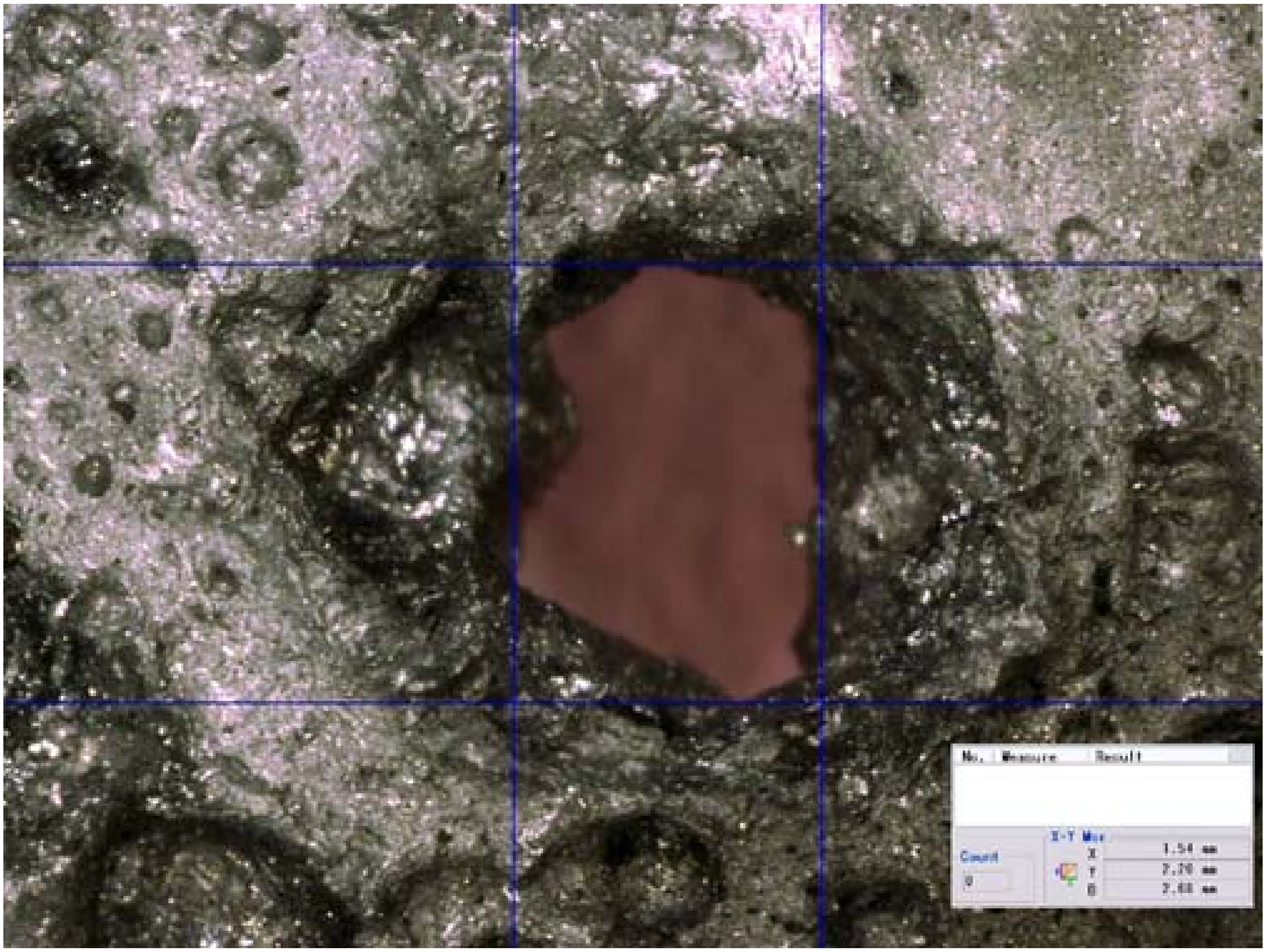


Figure 291: Al 5456-0 Rear Wall Layer 8 Front of ISS Soyuz OM Test #17 (Keyence 3D Microscope Image)

Test #17, HITF12277

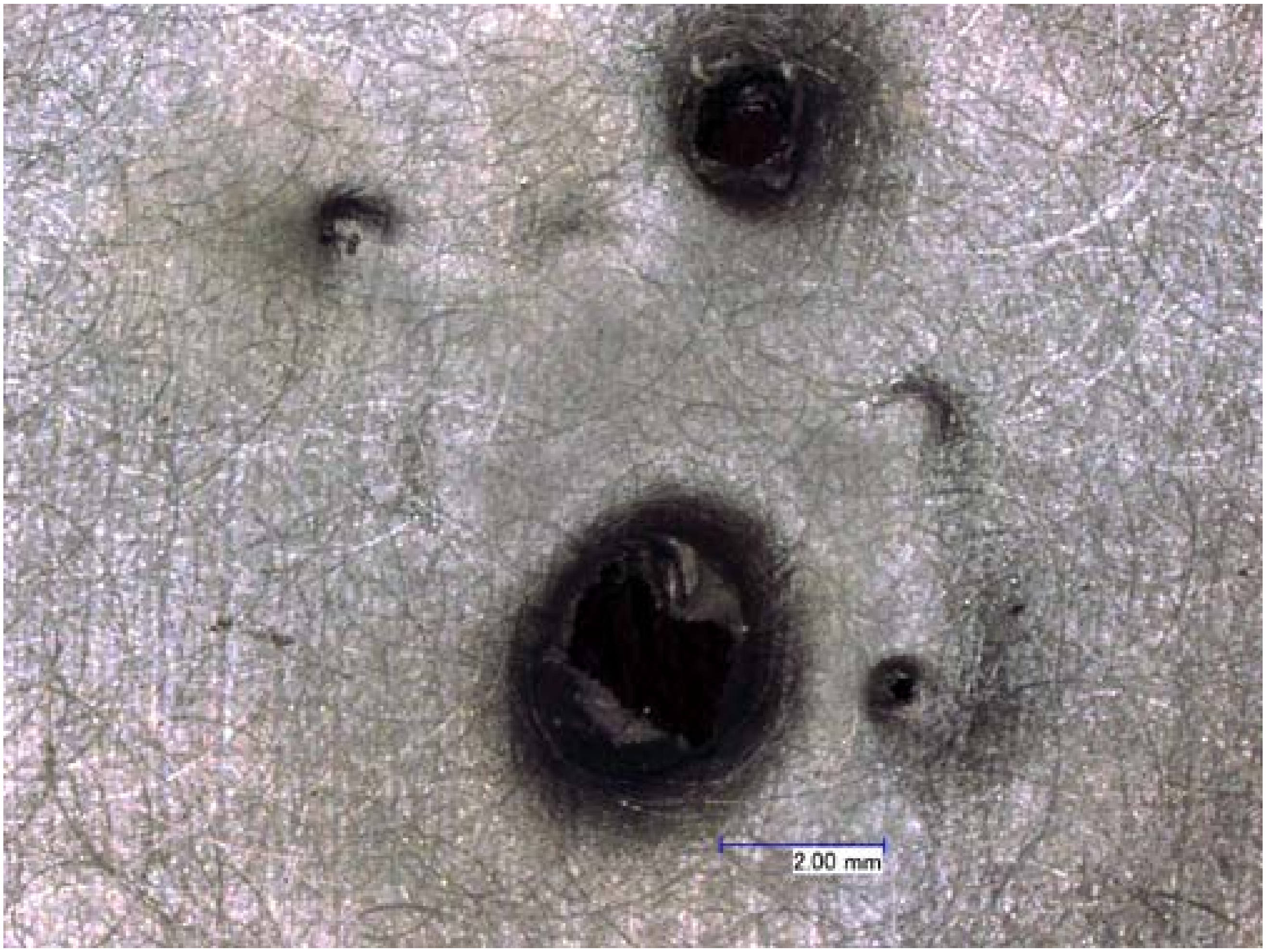


Figure 292: Al 5456-0 Rear Wall Layer 8 Back of ISS Soyuz OM Test #17 (Keyence 3D Microscope Image)

Test #17, HITF12277

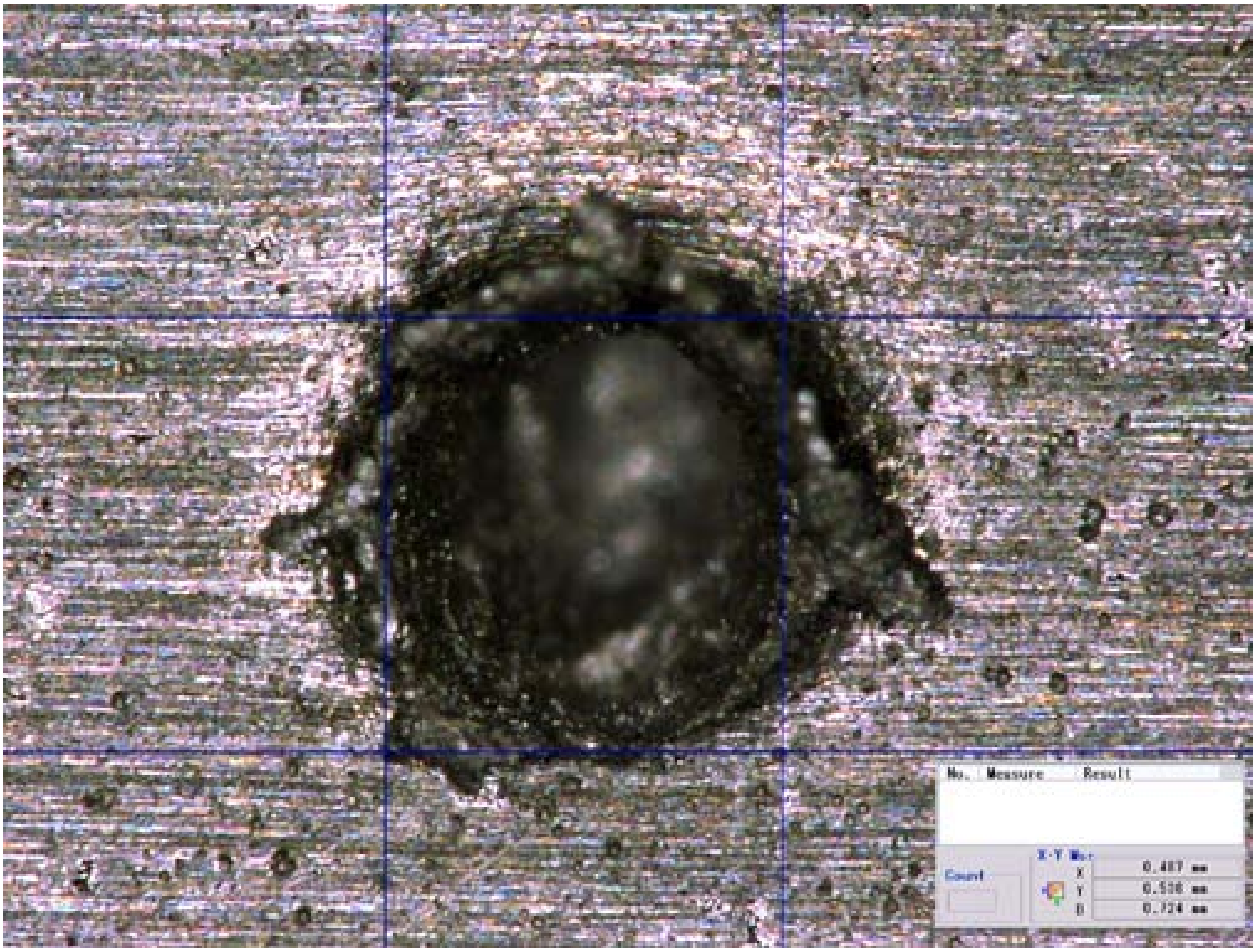


Figure 293: Witness Plate of ISS Soyuz OM Test #17
(Keyence 3D Microscope Image)

Test #17, HITF12277

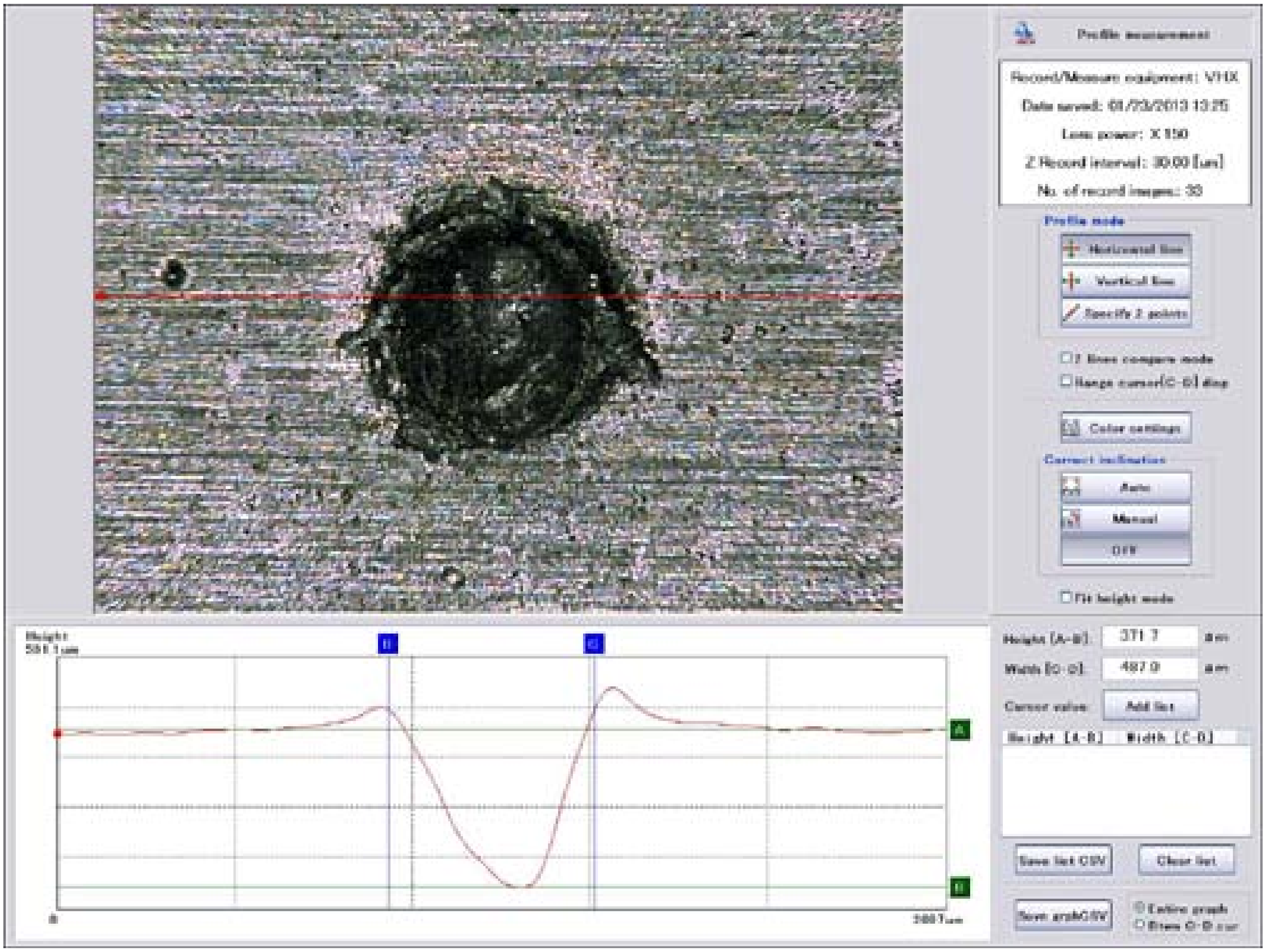


Figure 294: Witness Plate of ISS Soyuz OM Test #17 (Keyence 3D Microscope Image)

Test #17, HITF12277

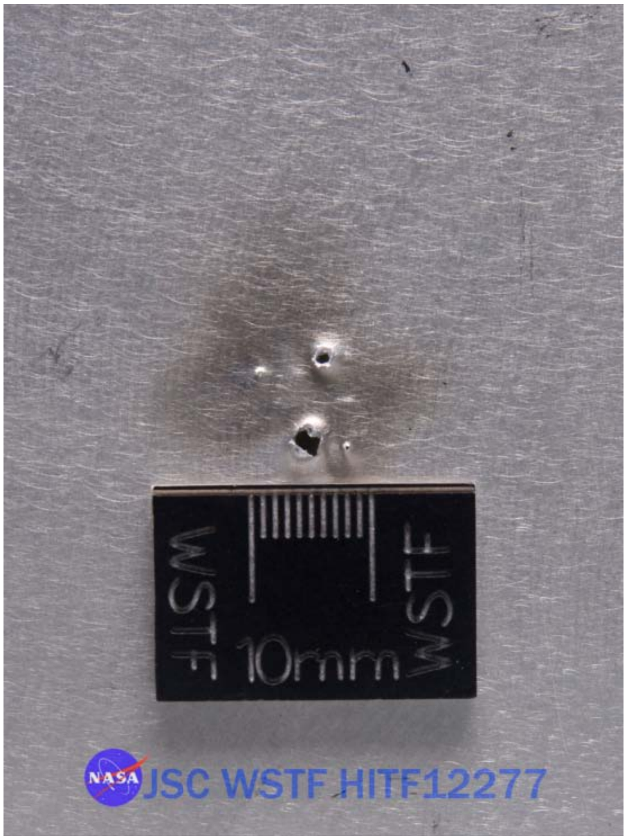


Figure 295: Back Close-up of Al 5456-0 Rear Wall for ISS Soyuz Orbital Module Test #17

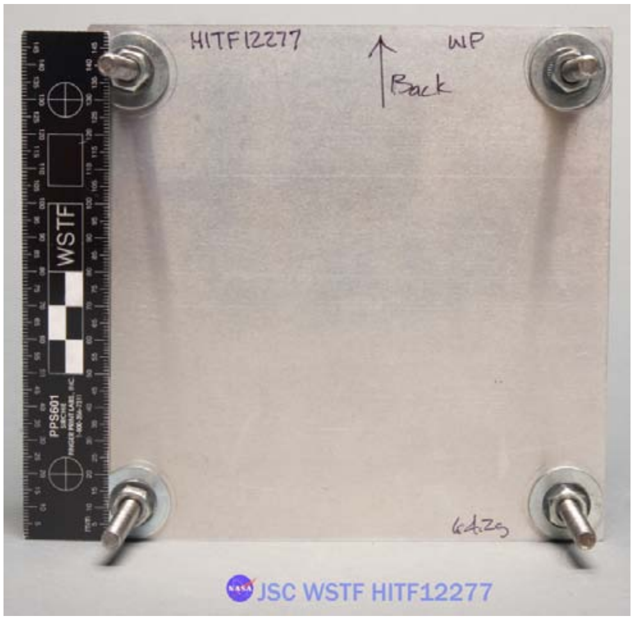


Figure 296: Back Witness Plate View of ISS Soyuz Orbital Module Test #17

Test #17, HITF12277

Figure 297: Front Close-up Witness Plate View of ISS Soyuz Orbital Module Test #17

8. CONCLUSIONS

NASA JSC HVIT completed seventeen (17) hypervelocity impact tests on the ISS Soyuz Orbital Module Steel Ballistic Limits to determine the ballistic limit particle size for 440C stainless steel spherical projectiles on shielding at several impact conditions. The rear wall was 0.080" (2.0mm) thick aluminum 5456-0 plate and the failure criteria for this test series was defined as perforation (complete penetration) or through-crack in the rear wall (pressure shell). Impact tests were performed at 3.0 ±0.2 km/s, 5.0 ±0.2 km/s, 6.0 ±0.2 km/s and 7.0 ±0.2 km/s with the velocity vectors 30° and 45° (0° impact angle is normal) to the surface of the bumper. The results were as follows:

- Fail using 1.29mm 440C Steel projectiles at **3.0** km/s and 3**0**°.
- Pass using 1.29mm and Fail using 1.5mm 440C Steel projectiles at **5.0** km/s and 3**0**°.
- Fail using 1.49mm 440C Steel projectiles at **6.0** km/s and 3**0**°.
- Pass using 1.49mm and Fail using 1.6mm 440C Steel projectiles at **7.0** km/s and 3**0**°.
- Pass using 1.0mm and Fail using 1.3mm 440C Steel projectiles at **4.0** km/s and 45°.
- Pass using 1.4mm and Fail using 1.5mm 440C Steel projectiles at **6.0** km/s and 45°.
- Fail using 1.6mm 440C Steel projectiles at **7.0** km/s and 45°.

As the result of testing the ISS Soyuz Orbital Module Steel Ballistic Limits had to be reduced by approximately 0.125mm for the low and high velocity ranges and by approximately 0.4mm for the medium velocity ranges.

9. REFERENCES

1. E.L. Christiansen and J.L. Crews, *the NASA JSC Hypervelocity Impact Test (HVIT) Group*, AIAA 92-1640, 1992.
2. J. Hyde, *Soyuz OM Shield with US materials,* Power Point document, October 1, 2012.
3. J.C. Anderson, D.J. Henderson, K.M. Rodriguez, *.17-caliber Light Gas Gun Velocity Measurement Uncertainty Analysis*, WSTF-IR-1086-001-07, February 15, 2012.
4. J.C. Anderson, D.J. Henderson, K.M. Rodriguez, *.50-caliber Light Gas Gun Velocity Measurement Uncertainty Analysis*, WSTF-IR-1103-001-08.C, January 18, 2012.
5. E.L. Christiansen and D.M. Lear, *Status of ballistic limit equations for steel and aluminum projectiles* Power Point document, January 30, 2013.
6. M.D. Bjorkman, Preliminary changes to certain BLEs to account for deeper penetration by steel projectiles, 29 August 2012

10. APPENDIX A: Test Control Documents

Test Matrix

The following table provides the preliminary test plan using steel projectiles on the Soyuz OM shield test articles. This test matrix was updated during the course of testing. The test matrix updates were provided in Table 2. All projectiles for these tests were spherical. Impact angles were measured from the target normal (i.e., 0^o impact angle is with a projectile shot line that is normal to the target).

Table A.1: Initial Test Matrix for the Evaluation of ISS Soyuz Orbital Module Ballistic Limits using Steel Projectiles

Test No.	Target Type	Projectile Material	Projectile Density (g/cm^3)	Nominal Projectile Diameter (mm)	Calculated Projectile Mass (g)	Desired Impact Velocity (km/s)	Impact Angle (deg)	Comments
1	Soyuz Orbital Module	Steel 440C	7.65	1.8	0.02342	7.0	30	
2	Soyuz Orbital Module	Steel 440C	7.65	1.6	0.01644	5.0	30	
3	Soyuz Orbital Module	Steel 440C	7.65	1.7	0.01972	6.0	30	
4	Soyuz Orbital Module	Steel 440C	7.65	2.0	0.03212	7.0	45	
5	Soyuz Orbital Module	Steel 440C	7.65	1.3	0.00882	3.0	30	
13	Soyuz Orbital Module	Steel 440C	7.65	1.3	0.00882	3.0	30	Repeat of #5 (because no velocity obtained with #5)
6	Soyuz Orbital Module	Steel 440C	7.65	1.5	0.01355	7.0	30	
7	Soyuz Orbital Module	Steel 440C	7.65	1.5	0.01355	6.0	30	
8	Soyuz Orbital Module	Steel 440C	7.65	1.3	0.00882	5.0	30	
9	Soyuz Orbital Module	Steel 440C	7.65	1.6	0.01644	7.0	45	
10	Soyuz Orbital Module	Steel 440C	7.65	1.4	0.01102	3.0	30	
11	Soyuz Orbital Module	Steel 440C	7.65	1.5	0.01355	6.0	45	
12	Soyuz Orbital Module	Steel 440C	7.65	1.4	0.01102	6.0	45	
14	Soyuz Orbital Module	Steel 440C	7.65	1.3	0.00882	4.0	45	
15	Soyuz Orbital Module	Steel 440C	7.65	TBD	TBD	4.0	45	

Table A.1 (Continue): Initial Test Matrix for the Evaluation of ISS Soyuz Orbital Module Ballistic Limits using Steel Projectiles

Test No.	Target Type	Projectile Material	Projectile Density (g/cm^3)	Nominal Projectile Diameter (mm)	Calculated Projectile Mass (g)	Desired Impact Velocity (km/s)	Impact Angle (deg)	Comments
16	Soyuz Orbital Module	Steel 440C	7.65	1.6	0.01644	7.0	30	
17	Soyuz Orbital Module	Steel 440C	7.65	1.5	0.01355	5.0	30	

Hypervelocity Test Failure Criteria

Failure criteria for this test series is defined as perforation (complete penetration) or through-crack in the rear wall (pressure shell).

Criteria for a Successful Test

A successful hypervelocity impact test is defined as meeting the following criteria for each test:

- Clean impact by projectile within the required tolerances of ±0.25” for 0.17 caliber tests at the prescribed conditions
- Determination of projectile impact velocity
- Verification of projectile integrity prior to impact

A good, clean shot shall be defined as being free of anomalies such as sabot, shear plate, piston, or sabot catcher fragments that could influence shot performance.

Quality Requirement

WSTF will provide a designated verifier (DV) to meet quality requirements.

Pre/Post-Test Photographic Coverage

Overall still photographs are required for the pre- and post-test specimen setup conditions for each test.

Test Schedule

Test Readiness Review: N/A
WSTF Receipt of test articles: September 19, 2012
Testing begins: September 20, 2012
Testing complete: December 19, 2012

11. APPENDIX B: Predicted Ballistic Limits

Predicted ballistic limits for Soyuz OM shielding

The following table (Table B.1) provides the predicted ballistic limits for the Soyuz OM shielding, based on the new non-optimum (NNO) equation in Bumper code, and the typical transition velocities used for aluminum-on-aluminum impacts. An updated ballistic limit prediction was made based on moving the high-velocity transition velocity for steel on aluminum impacts to higher velocities, where steel is predicted to melt (approximately 9.5 km/s for normal impact angles). This revision is documented in reference [6]. The results of the impact tests are compared to the predicted ballistic limits in Figures 9, 10 and 11 (see Results section).

Table B.1: Predicted Soyuz OM Shield Ballistics (for 440C steel projectiles) with typical transition velocities based on Al-on-Al impacts (previous BLE)

Stainless Steel 440C Projectiles

	Impact Angle					
Velocity (km/s)	**0°**	**15°**	**30°**	**45°**	**60°**	**75°**
1	0.201	0.211	0.244	0.319	0.506	1.219
2	0.127	0.133	0.153	0.201	0.319	0.768
3	0.119	0.12	0.122	0.153	0.244	0.586
4	0.14	0.14	0.141	0.145	0.201	0.484
5	0.16	0.16	0.16	0.162	0.173	0.417
6	0.181	0.18	0.179	0.179	0.185	0.369
7	0.177	0.179	0.186	0.196	0.198	0.333
8	0.17	0.172	0.178	0.19	0.21	0.305
9	0.163	0.165	0.171	0.183	0.205	0.282
10	0.157	0.159	0.165	0.177	0.198	0.259
11	0.153	0.154	0.16	0.171	0.192	0.239
12	0.148	0.15	0.155	0.166	0.187	0.233

Table B.2: Predicted Soyuz OM Shield Ballistics (for 440C steel projectiles) with updated high-velocity transition speed for Steel-on-Al impacts (updated BLE)

Stainless Steel 440C Projectiles

	Impact Angle					
Velocity (km/s)	**0°**	**15°**	**30°**	**45°**	**60°**	**75°**
1	0.2010	0.2105	0.2435	0.3190	0.5064	0.5064
2	0.1266	0.1326	0.1534	0.2010	0.3190	0.3190
3	0.1131	0.1149	0.1209	0.1534	0.2435	0.2435
4	0.1212	0.1227	0.1279	0.1399	0.2010	0.2010
5	0.1293	0.1305	0.1348	0.1452	0.1732	0.1732
6	0.1374	0.1383	0.1418	0.1505	0.1751	0.1751
7	0.1455	0.1462	0.1488	0.1558	0.1770	0.1770
8	0.1536	0.1540	0.1558	0.1611	0.1789	0.1789
9	0.1617	0.1618	0.1627	0.1664	0.1809	0.1809
10	0.1574	0.1593	0.1652	0.1717	0.1828	0.1828
11	0.1525	0.1543	0.1600	0.1712	0.1847	0.1847
12	0.1482	0.1499	0.1554	0.1663	0.1866	0.1866
13	0.1443	0.1459	0.1513	0.1619	0.1817	0.1817
14	0.1407	0.1424	0.1476	0.1580	0.1773	0.1773
15	0.1375	0.1391	0.1443	0.1544	0.1733	0.1733

Aluminum Projectiles

	Impact Angle					
Velocity (km/s)	**0°**	**15°**	**30°**	**45°**	**60°**	**75°**
1	0.3397	0.3558	0.4115	0.5393	0.8560	0.8560
2	0.2140	0.2241	0.2592	0.3397	0.5393	0.5393
3	0.1949	0.1971	0.2050	0.2592	0.4115	0.4115
4	0.2159	0.2174	0.2231	0.2386	0.3397	0.3397
5	0.2368	0.2377	0.2413	0.2521	0.2928	0.2928
6	0.2578	0.2580	0.2594	0.2656	0.2953	0.2953
7	0.2516	0.2545	0.2640	0.2791	0.2979	0.2979
8	0.2406	0.2434	0.2525	0.2701	0.3005	0.3005
9	0.2314	0.2341	0.2427	0.2597	0.2915	0.2915
10	0.2234	0.2260	0.2344	0.2508	0.2815	0.2815
11	0.2164	0.2189	0.2270	0.2429	0.2727	0.2727
12	0.2102	0.2127	0.2206	0.2360	0.2649	0.2649
13	0.2047	0.2071	0.2147	0.2298	0.2579	0.2579
14	0.1997	0.2020	0.2095	0.2242	0.2516	0.2516
15	0.1952	0.1974	0.2047	0.2191	0.2459	0.2459

12. APPENDIX C: Projectile Verification High-Speed Imagery

Test #1, HITF12257

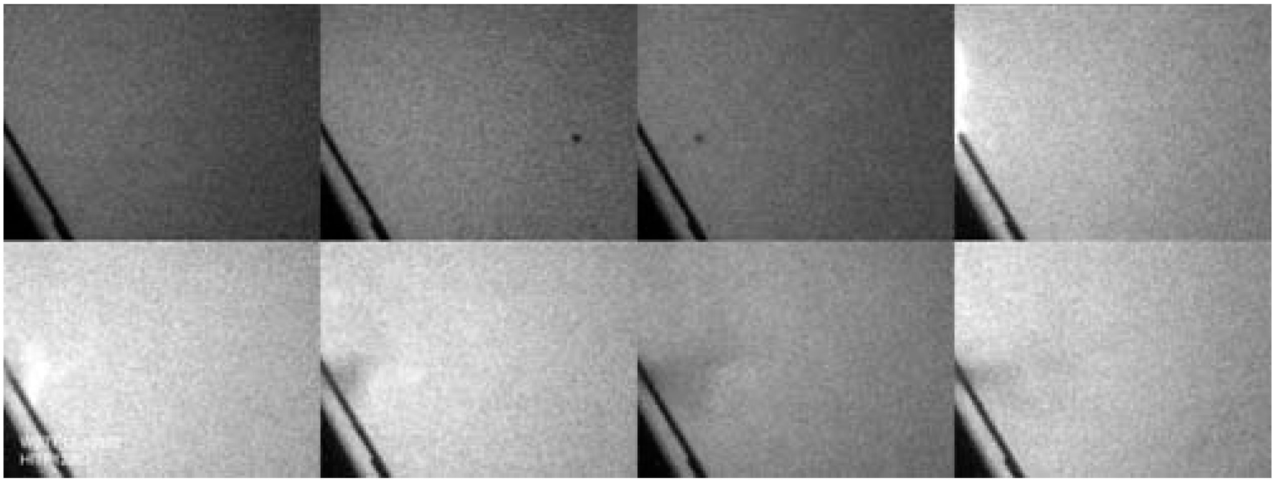


Figure C.1: Blurry high speed video of projectile in flight on Soyuz Orbital Module Test #1 using SIMX-8 High Speed Video Camera

No Phantom v711 Video for Test #1

Test #2, HITF12258

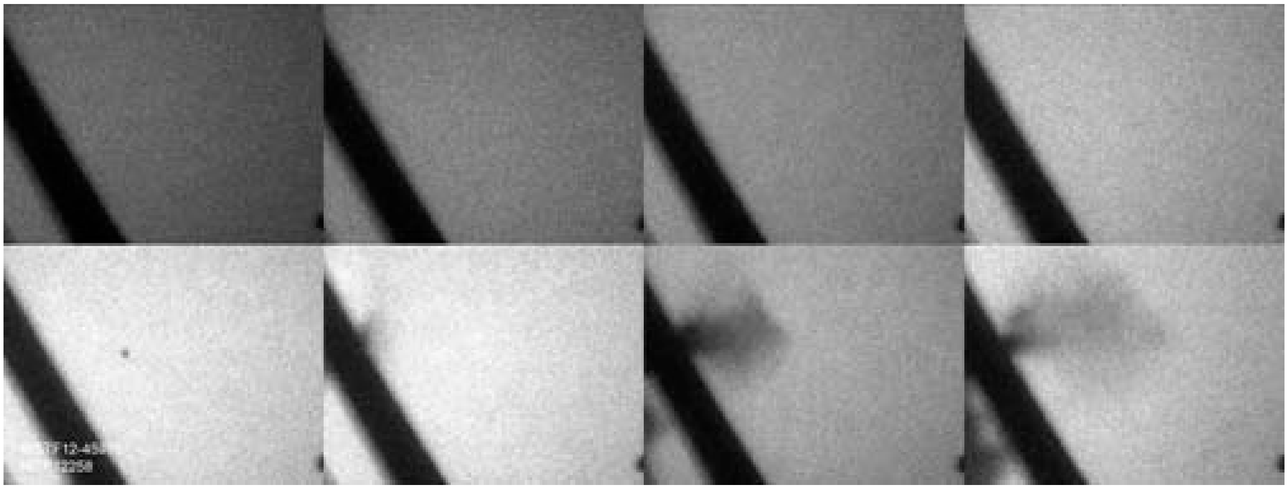


Figure C.2: Blurry high speed video of projectile in flight on Soyuz Orbital Module Test #2 using SIMX-8 High Speed Video Camera

No Phantom v711 Video for Test #2

Test #3, HITF12259

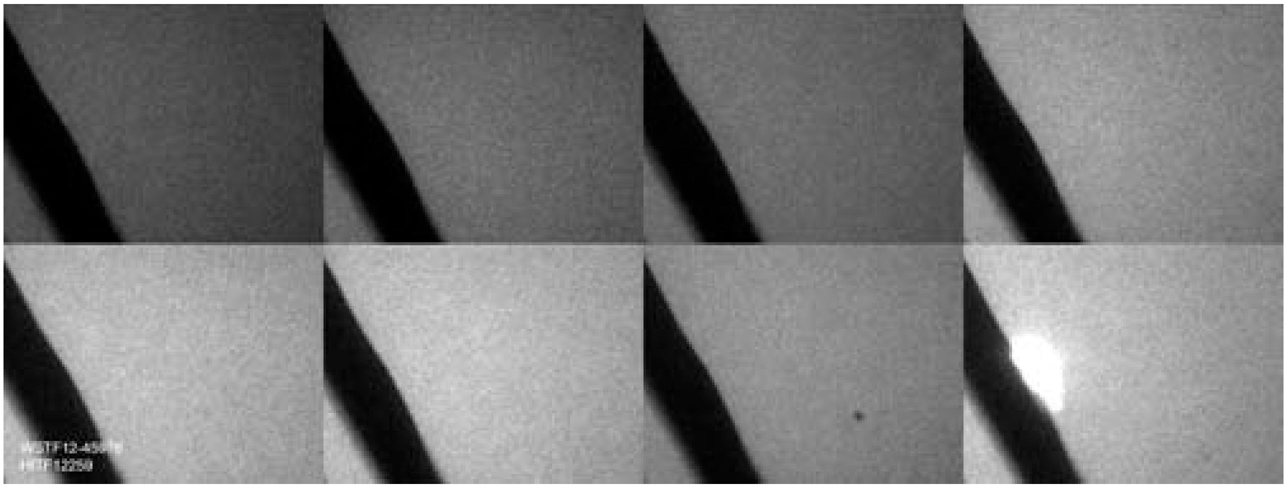


Figure C.3: Blurry high speed video of projectile in flight on Soyuz Orbital Module Test #3 using SIMX-8 High Speed Video Camera

No Phantom v711 Video for Test #3

Test #4, HITF12260

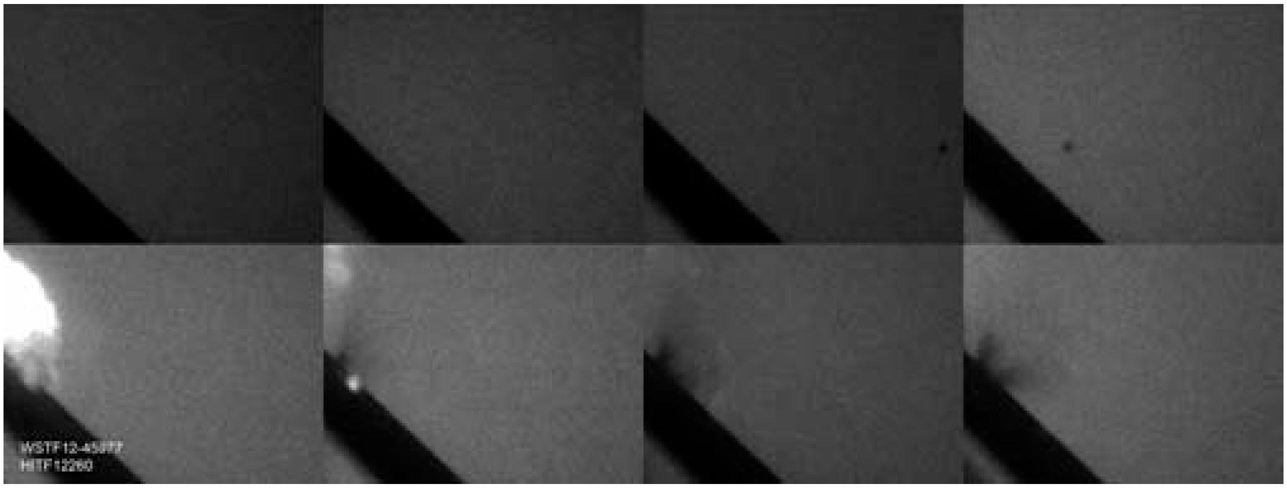


Figure C.4: Blurry high speed video of projectile in flight on Soyuz Orbital Module Test #4 using SIMX-8 High Speed Video Camera

No Phantom v711 Video for Test #4

Test #5, HITF12261

No SIMX-8 Video for Test #5

No Phantom v711 Video for Test #5

Test #6, HITF12262

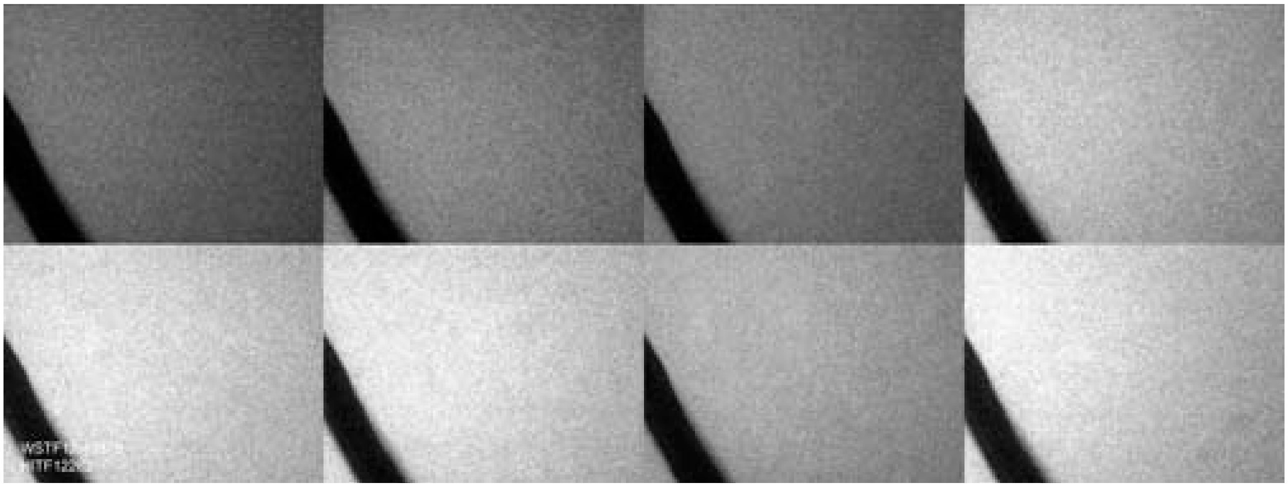


Figure C.5: Projectile not captured in flight on ISS Soyuz OM Test #6 using SIMX-8 High Speed Video Camera

No Phantom v711 Video for Test #6

Test #6B, HITF12262

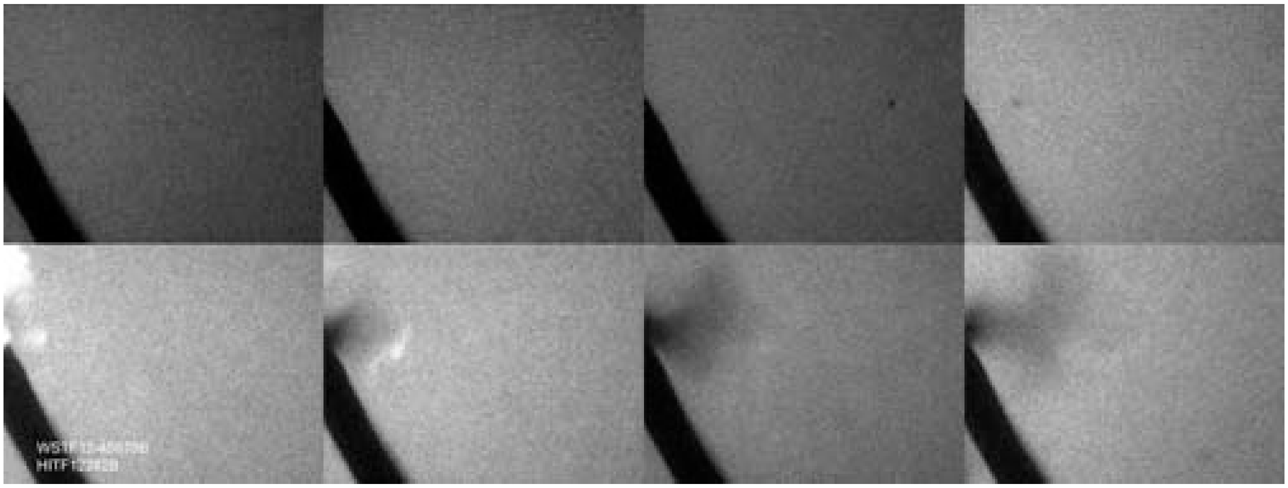


Figure C.6: Faint Image of projectile in flight on ISS Soyuz OM Test #6B using SIMX-8 High Speed Video Camera

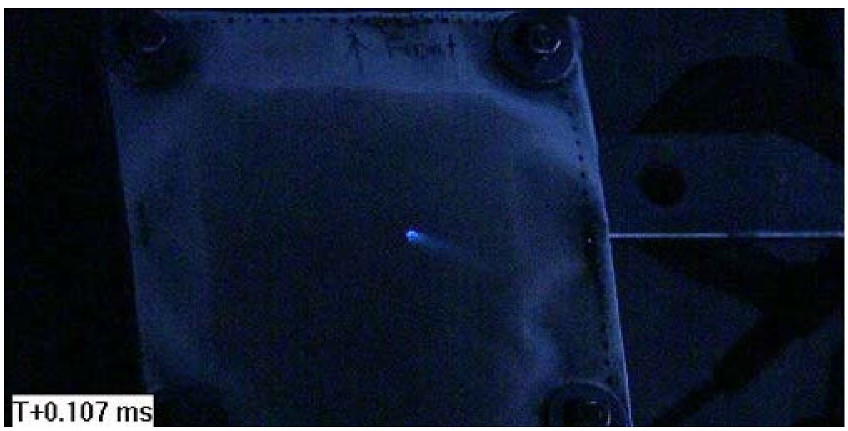


Figure C.7: Test #6B Phantom v711 high speed video image of projectile prior to impact

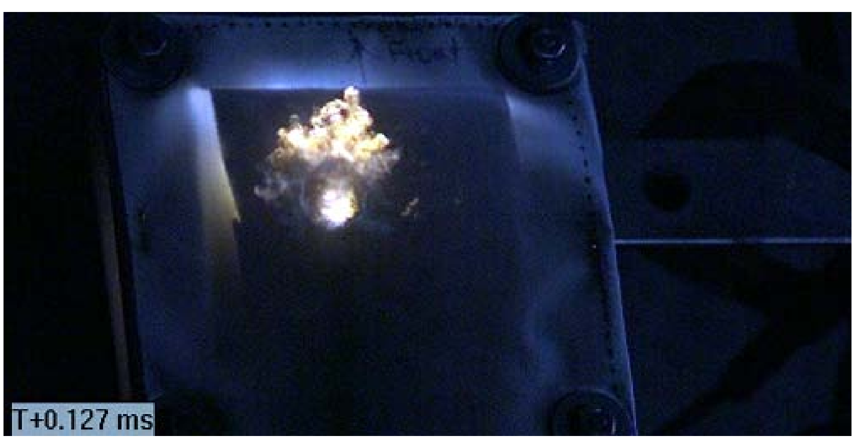


Figure C.8: Phantom v711 video image of projectile impacting Test #6B article

Test #7, HITF12263

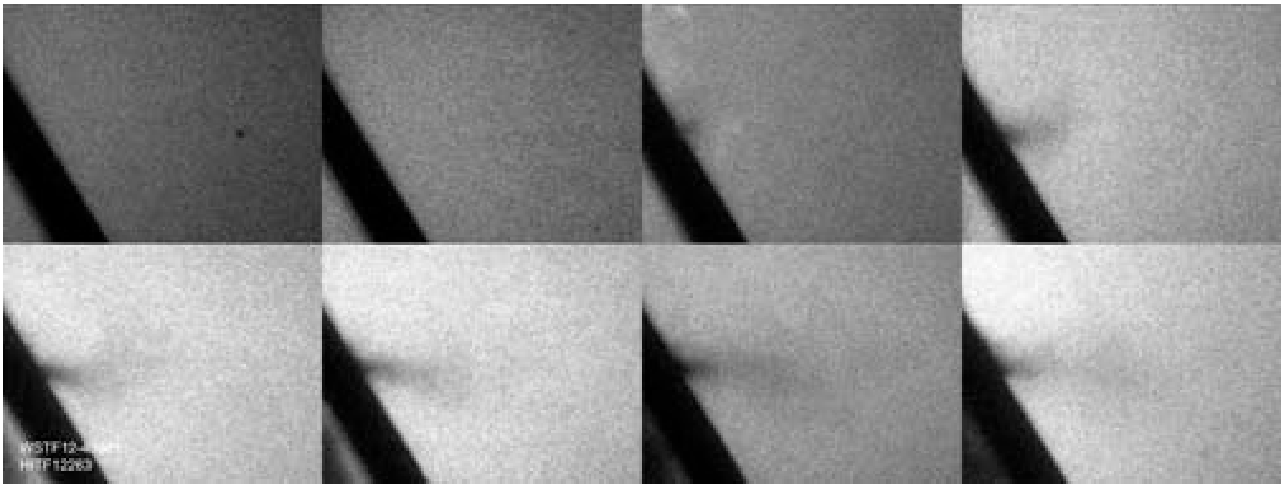


Figure C.9: Blurry high speed video of projectile in flight on Soyuz Orbital Module Test #7 using SIMX-8 High Speed Video Camera

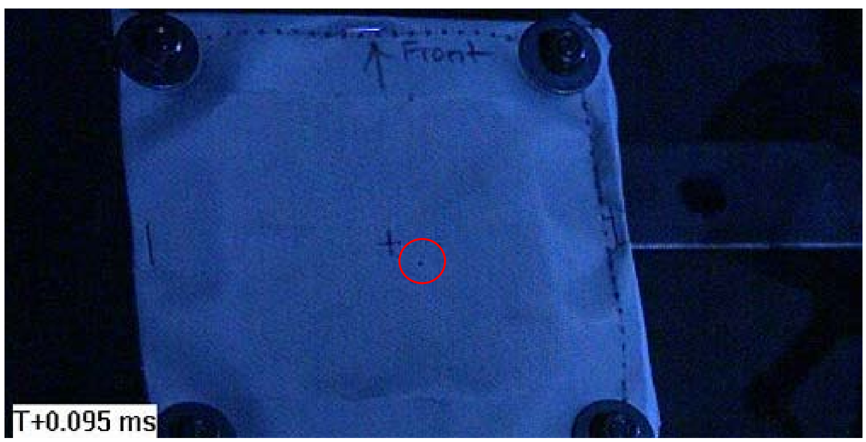


Figure C.10: Test #7 Phantom v711 high speed video image of projectile prior to impact

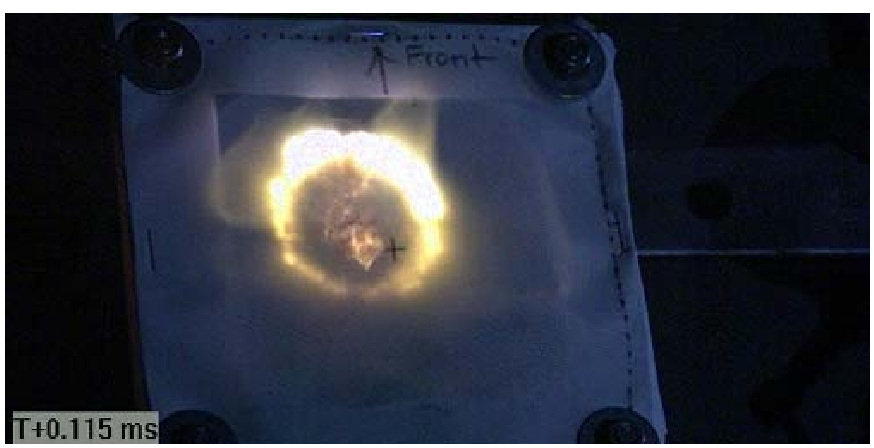


Figure C.11: Phantom v711 video image of projectile impacting Test #7 article

Test #8, HITF12264

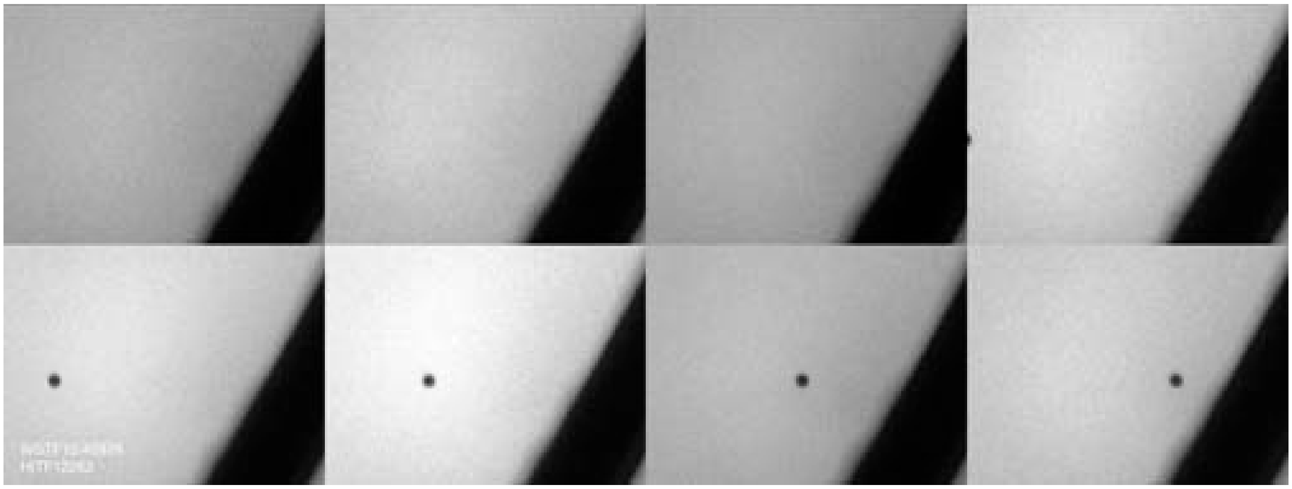


Figure C.12: High speed video of projectile in flight on Soyuz OM Test #8 using SIMX-8 High Speed Video Camera

No Phantom v711 Video for Test #8

Test #9, HITF12265

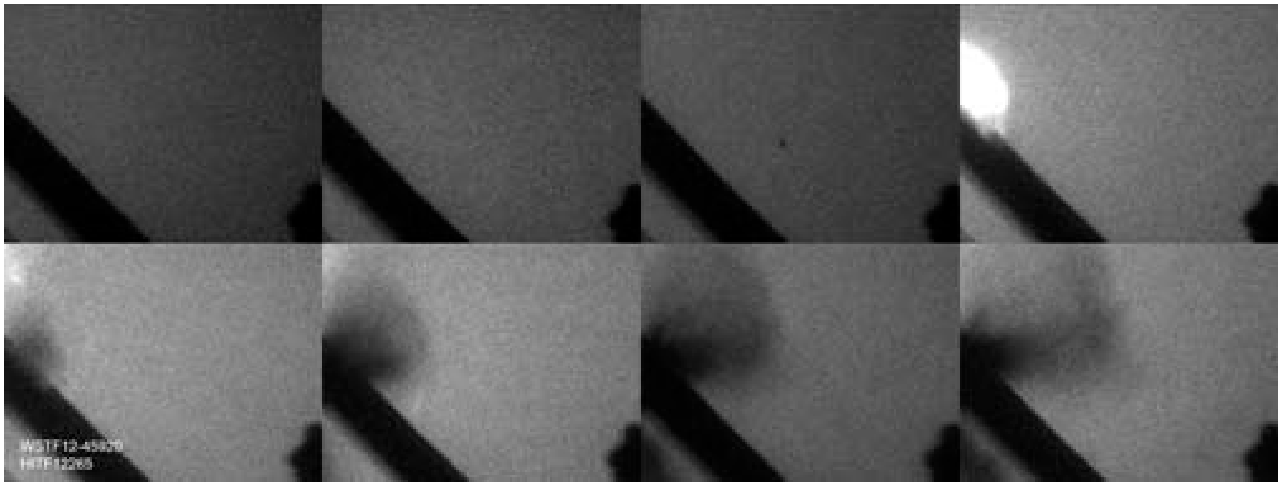


Figure C.13: Blurry high speed video of projectile in flight on Soyuz Orbital Module Test #9 using SIMX-8 High Speed Video Camera

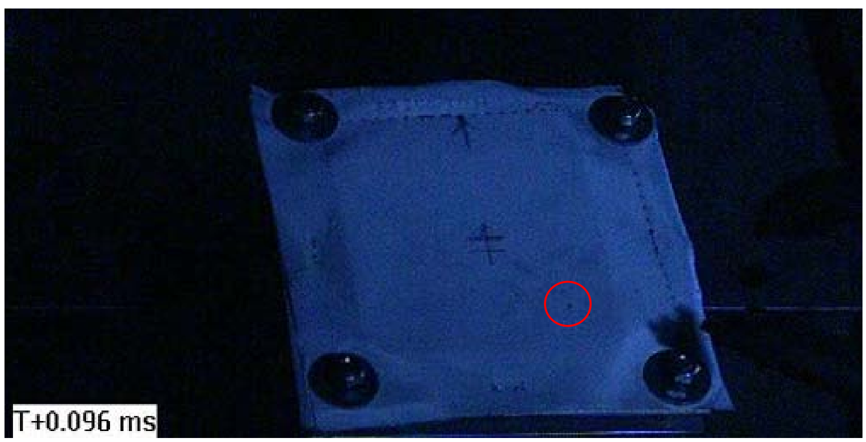


Figure C.14: Test #9 Phantom v711 high speed video image of projectile prior to impact

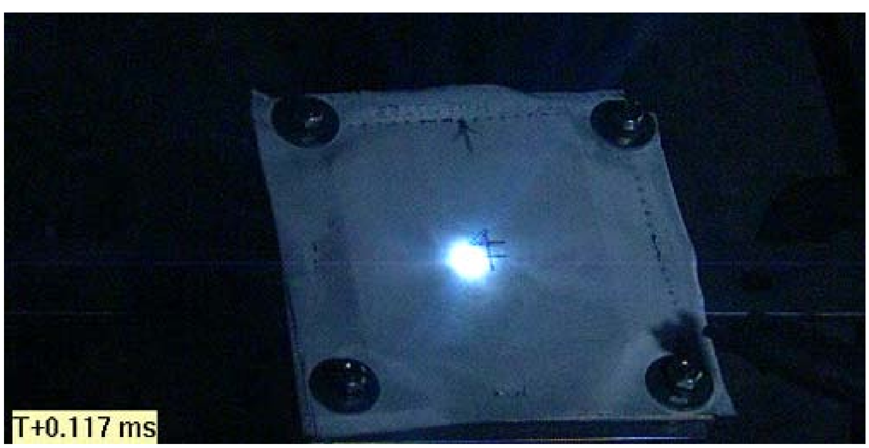


Figure C.15: Phantom v711 video image of projectile impacting Test #9 article

Test #10, HITF12266

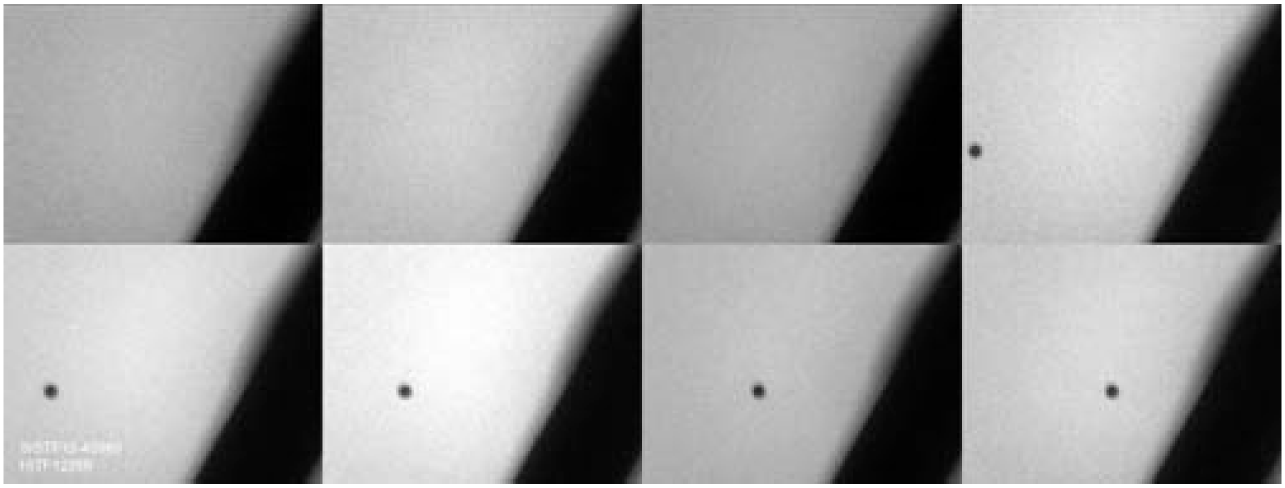


Figure C.16: High speed video of projectile in flight on Soyuz OM Test #10 using SIMX-8 High Speed Video Camera

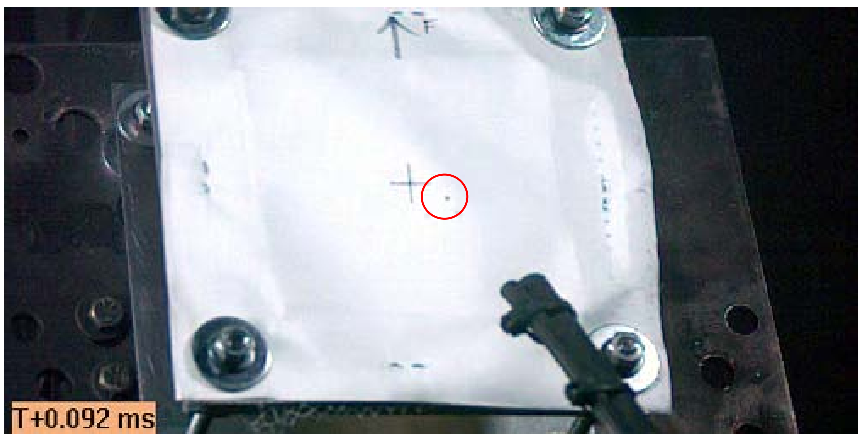


Figure C.17: Test #10 Phantom v711 high speed video image of projectile prior to impact

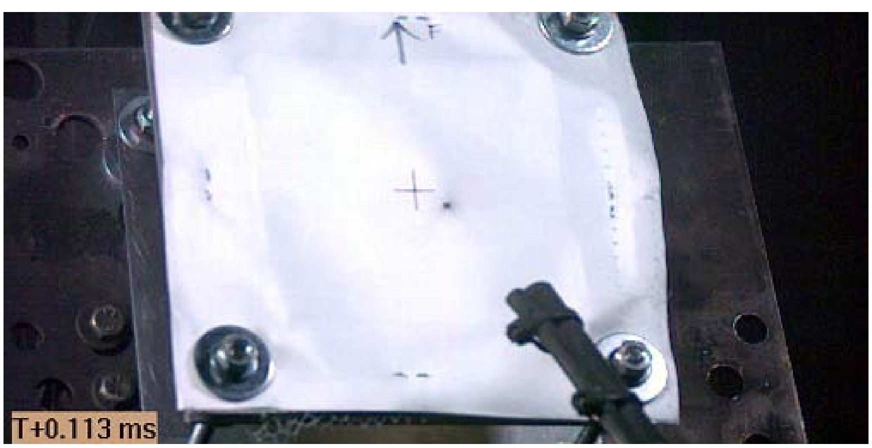


Figure C.18: Phantom v711 video image of projectile impacting Test #10 article

Test #11, HITF12271

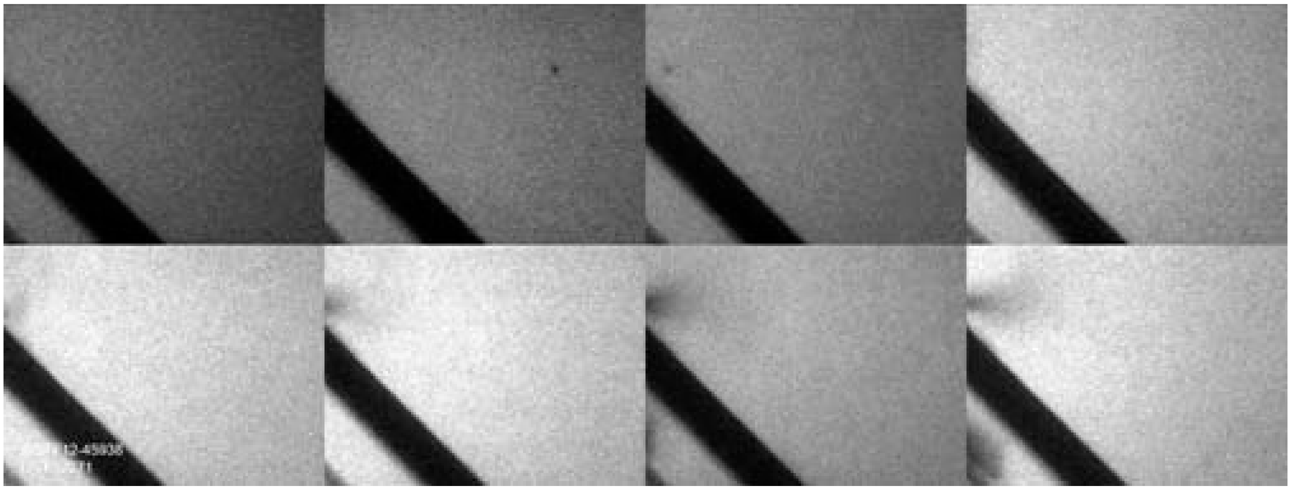


Figure C.19: Blurry high speed video of projectile in flight on Soyuz Orbital Module Test #11 using SIMX-8 High Speed Video Camera

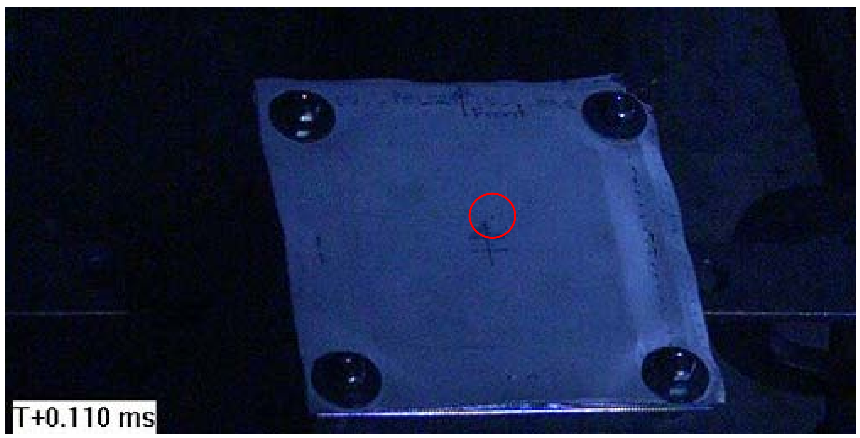


Figure C.20: Test #11 Phantom v711 high speed video image of projectile prior to impact

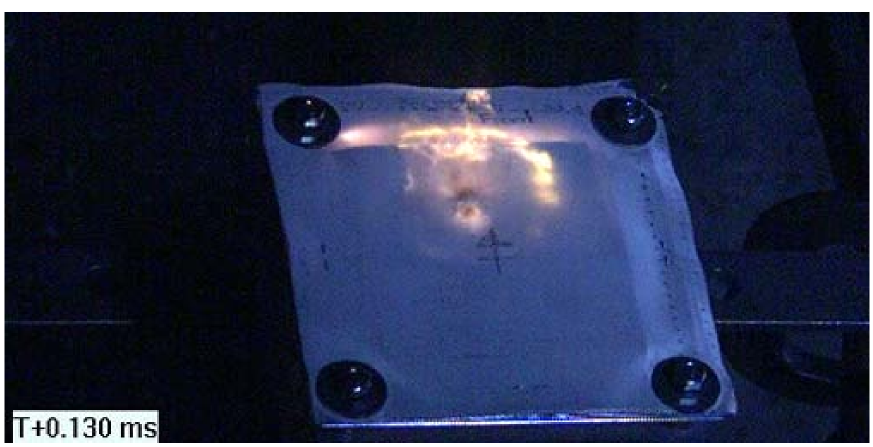


Figure C.21: Phantom v711 video image of projectile impacting Test #11 article

Test #12, HITF12272

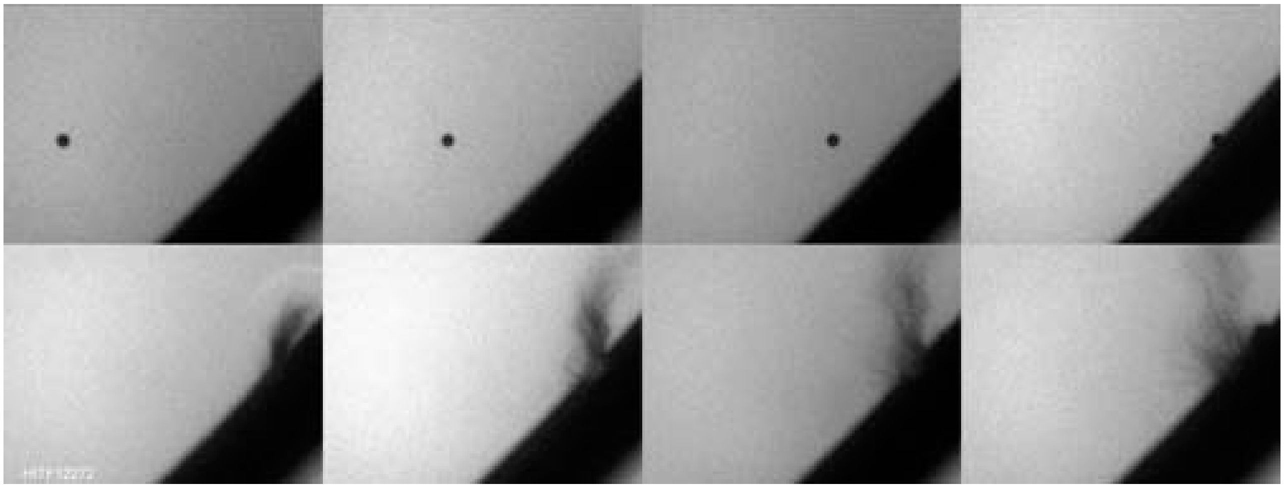


Figure C.22: High speed video of projectile in flight on Soyuz OM Test #12 using SIMX-8 High Speed Video Camera

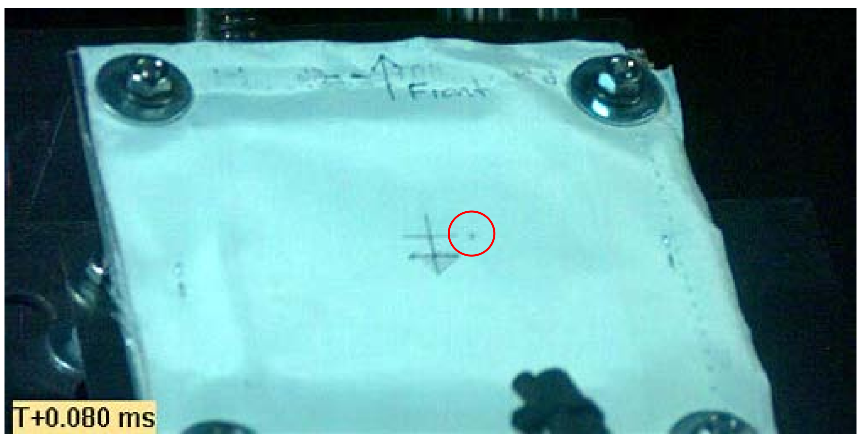


Figure C.23: Test #12 Phantom v711 high speed video image of projectile prior to impact

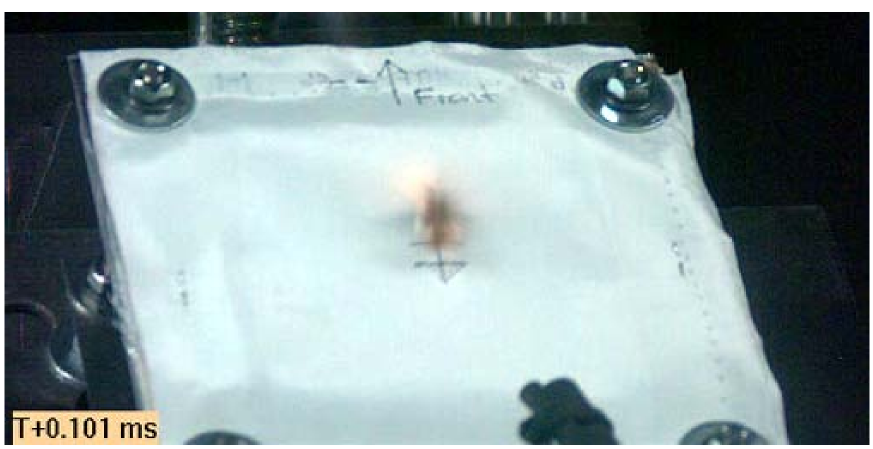


Figure C.24: Phantom v711 video image of projectile impacting Test #12 article

Test #13, HITF12273

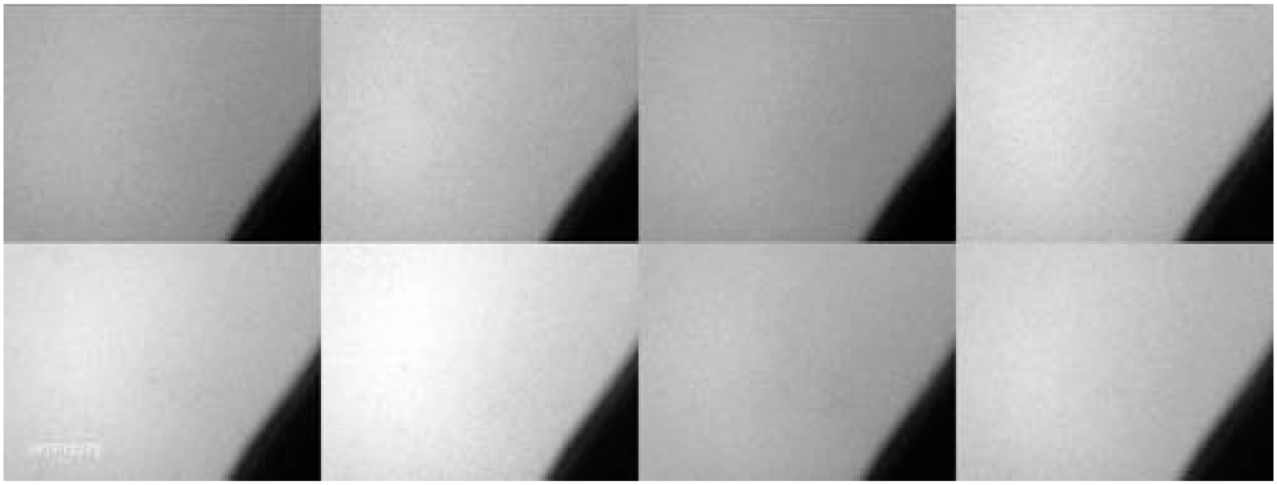


Figure C.25: Projectile not captured in flight on Soyuz Orbital Module Test #13 using SIMX-8 High Speed Video Camera

No Phantom v711 Video for Test #13

Test #13B, HITF12273

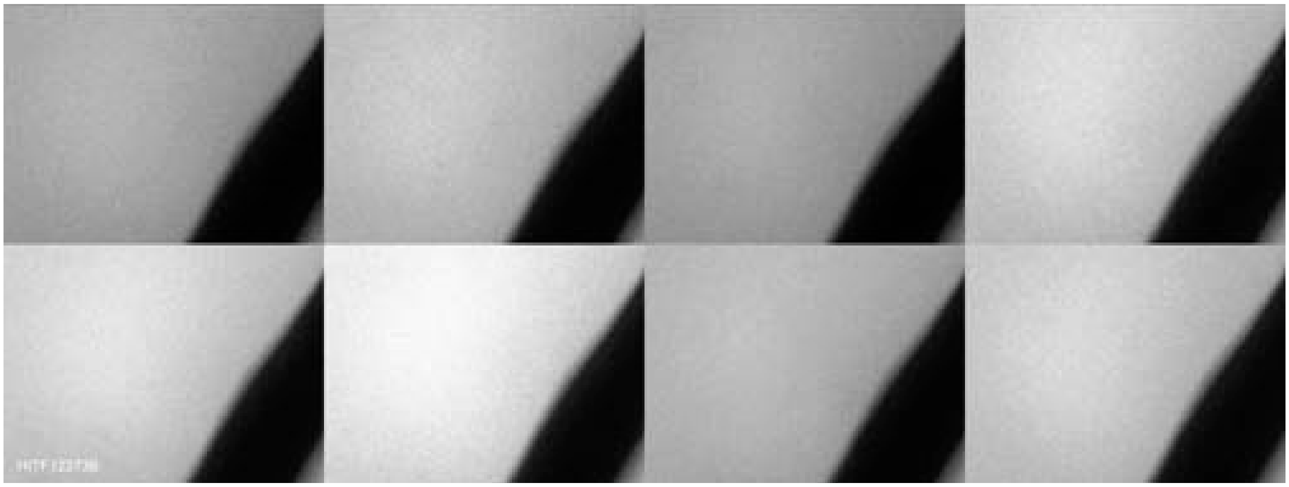


Figure C.26: Projectile not captured in flight on Soyuz Orbital Module Test #13B using SIMX-8 High Speed Video Camera

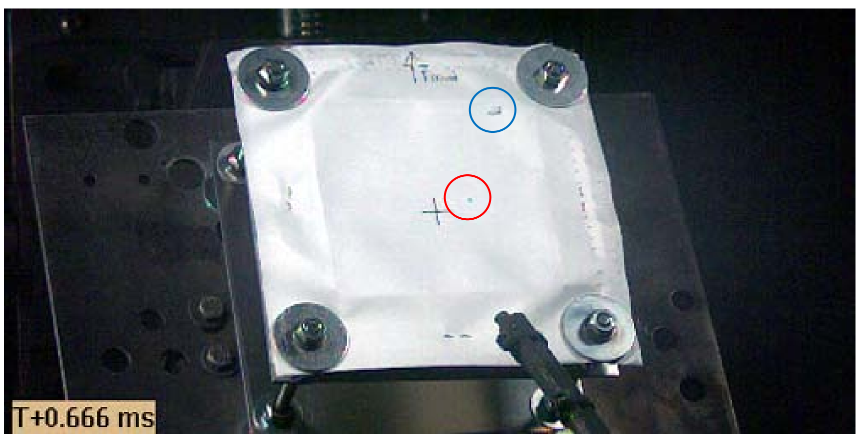


Figure C.27: Test #13B Phantom v711 high speed video image of projectile prior to impact

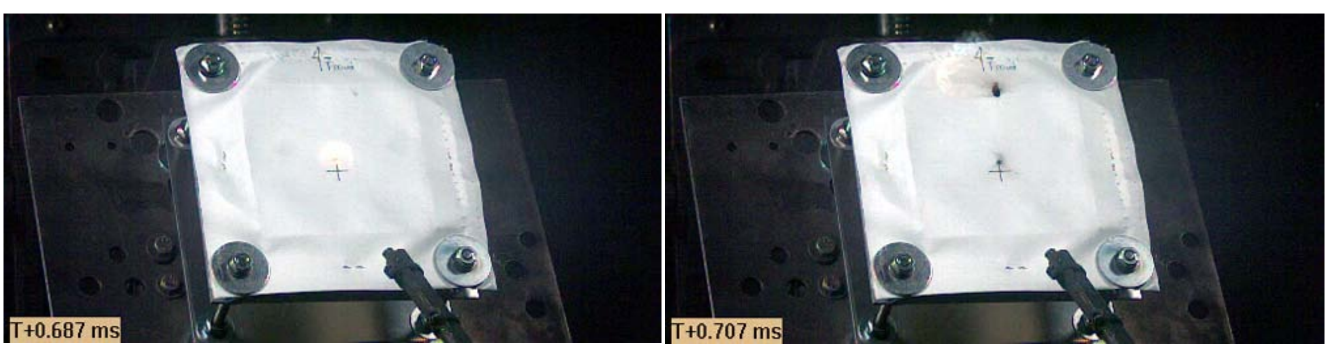


Figure C.28: Phantom v711 video image of projectile impacting Test #13B article

Test #14, HITF12274

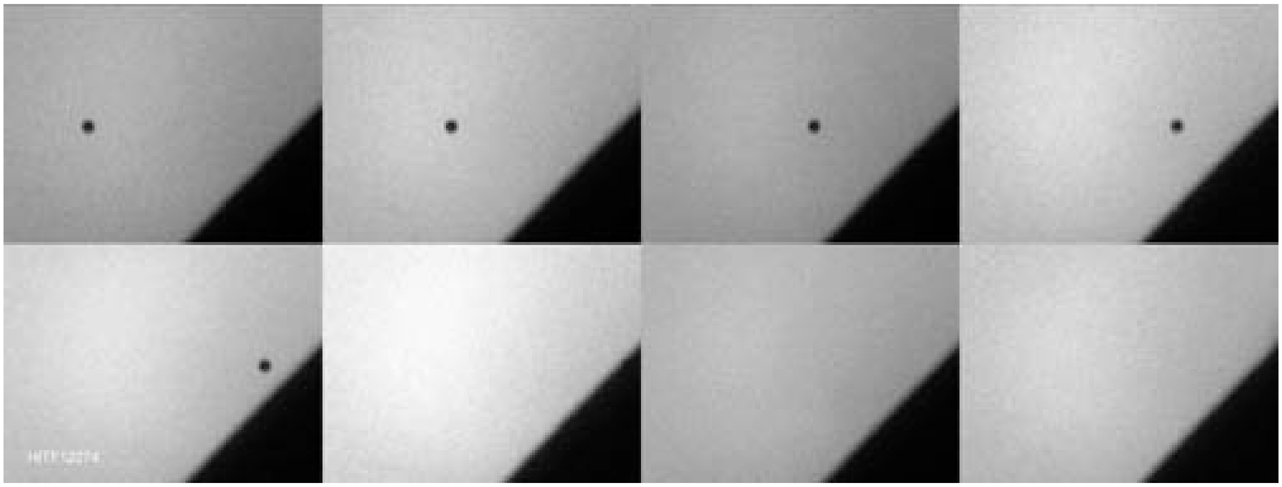


Figure C.29: High speed video of projectile in flight on Soyuz OM Test #14 using SIMX-8 High Speed Video Camera

Figure C.30: Test #14 Phantom v711 high speed video image of projectile prior to impact

Figure C.31: Phantom v711 video image of projectile impacting Test #14 article

Test #15, HITF12275

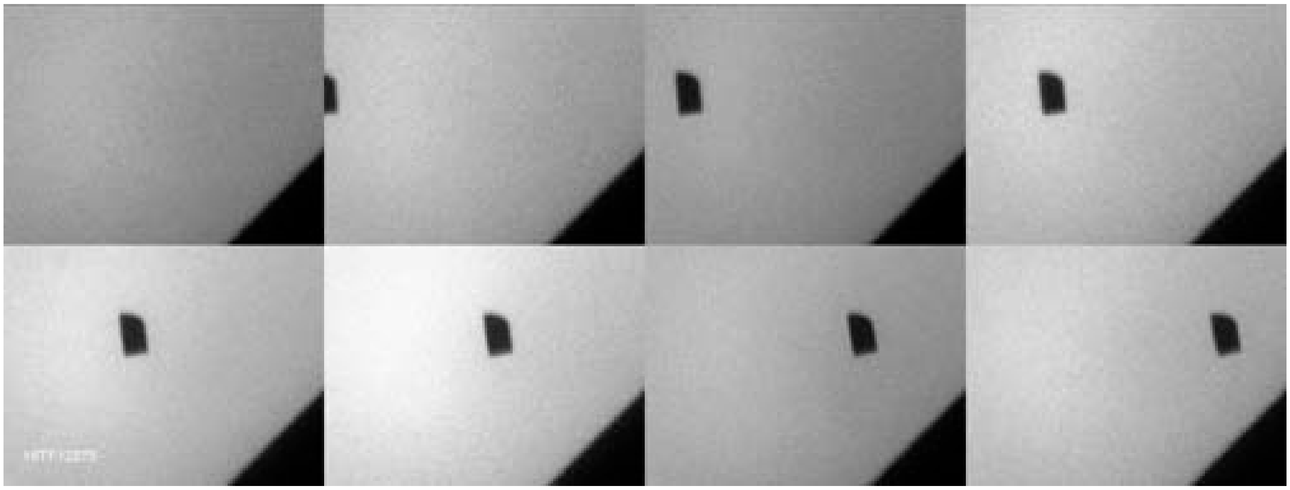


Figure C.32: High speed video of debris in flight on Soyuz OM Test #15 using SIMX-8 High Speed Video Camera

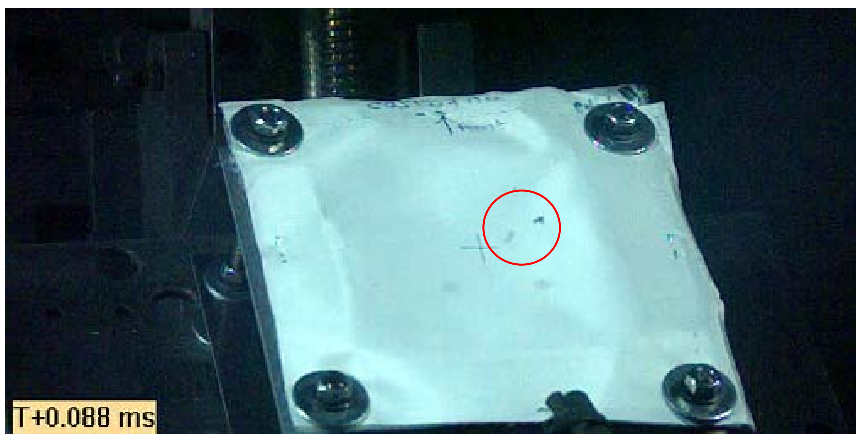


Figure C.33: Test #15 Phantom v711 high speed video image of debris prior to impact

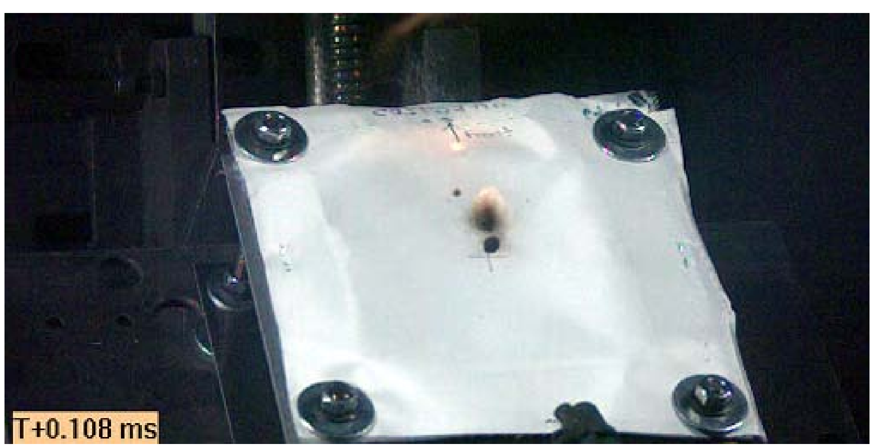


Figure C.34: Phantom v711 video image of projectile impacting Test #15 article

Test #15B, HITF12275

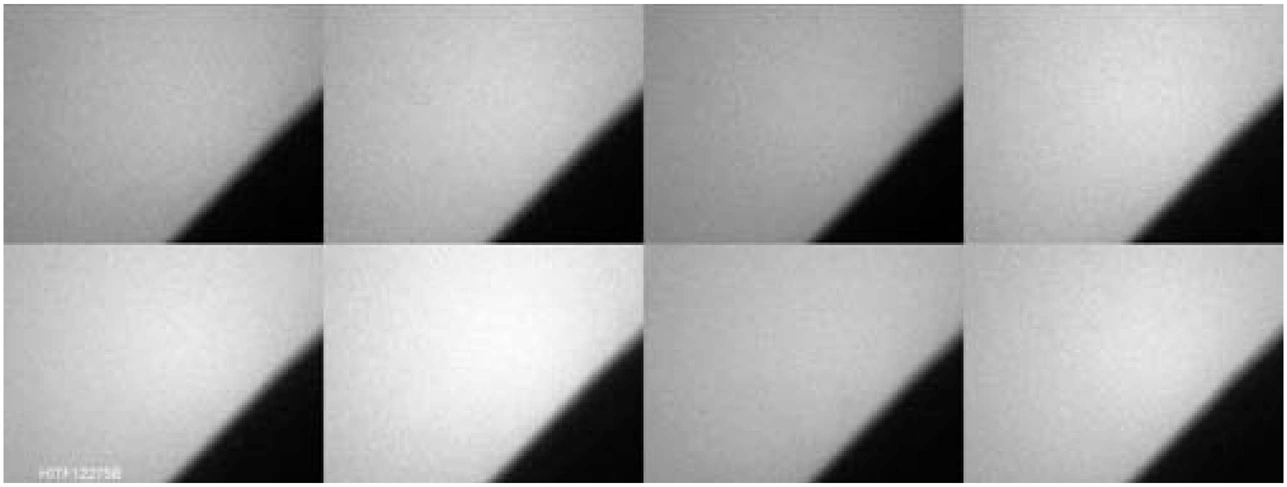


Figure C.35: Projectile not captured in flight on Soyuz Orbital Module Test #15B using SIMX-8 High Speed Video Camera

No Phantom v711 Video for Test #15B

Test #15C, HITF12275

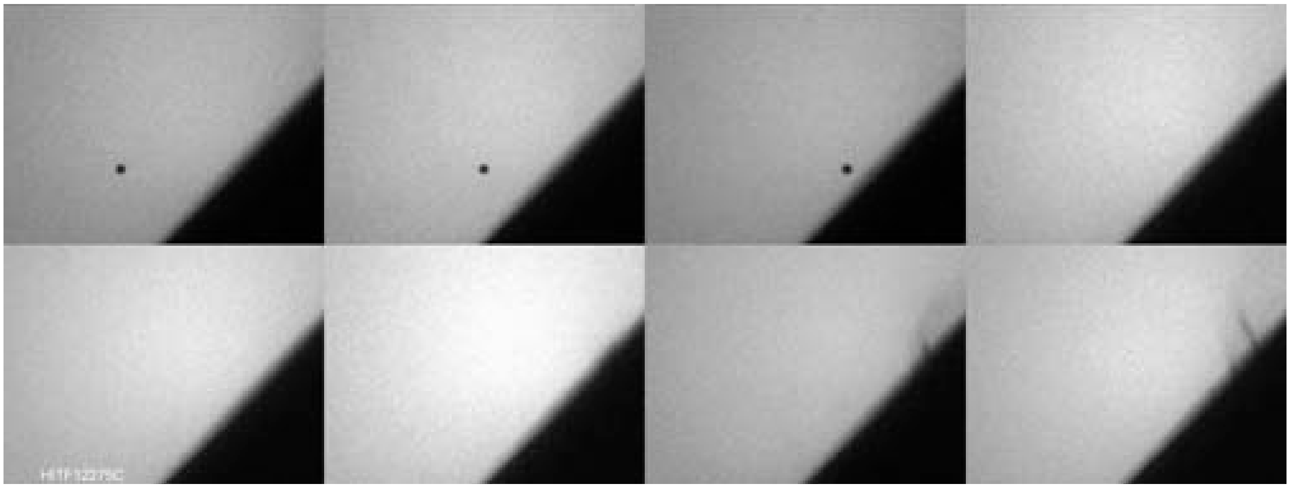


Figure C.36: High speed video of projectile in flight on Soyuz OM Test #15C using SIMX-8 High Speed Video Camera

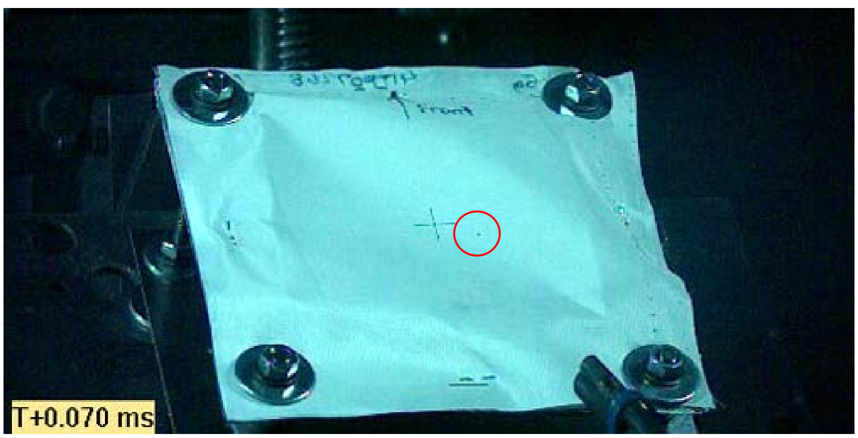


Figure C.37: Test #15C Phantom v711 high speed video image of projectile prior to impact

Figure C.38: Phantom v711 video image of projectile impacting Test #15C article

Test #16, HITF12276

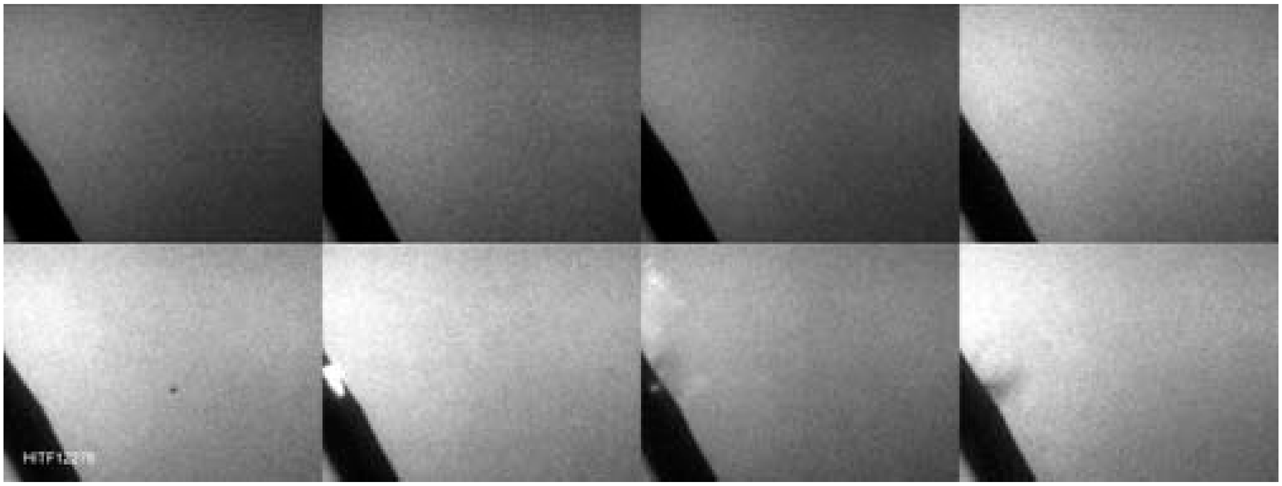


Figure C.39: Blurry high speed video of projectile in flight on Soyuz Orbital Module Test #16 using SIMX-8 High Speed Video Camera

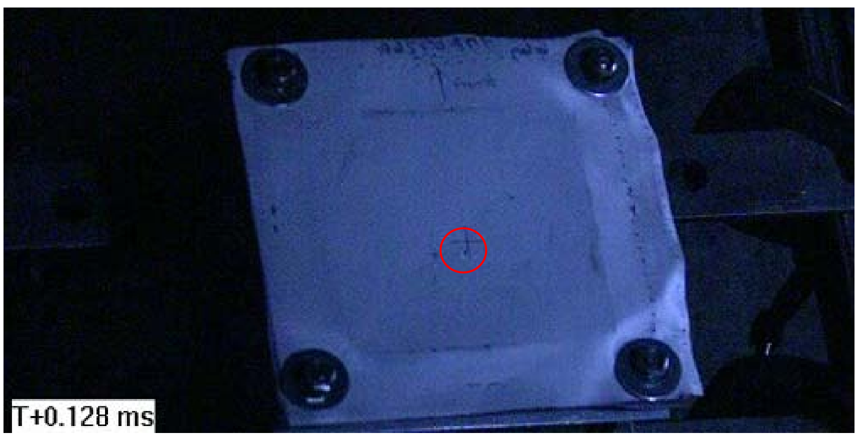


Figure C.40: Test #16 Phantom v711 high speed video image of projectile prior to impact

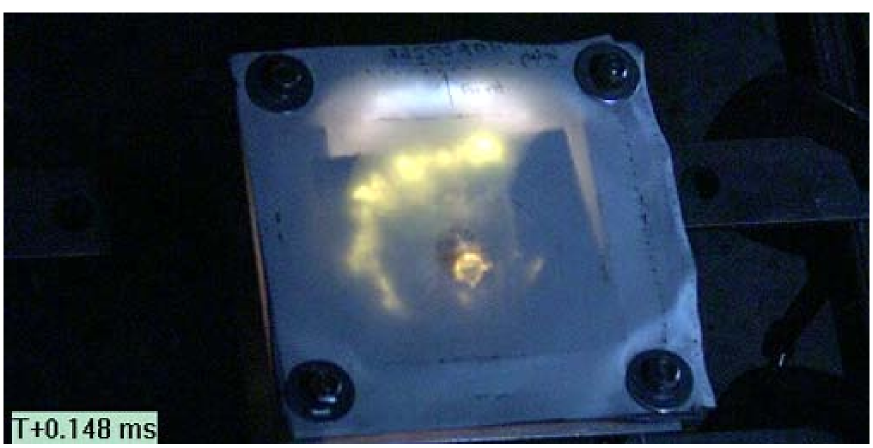


Figure C.41: Phantom v711 video image of projectile impacting Test #16 article

Test #17, HITF12277

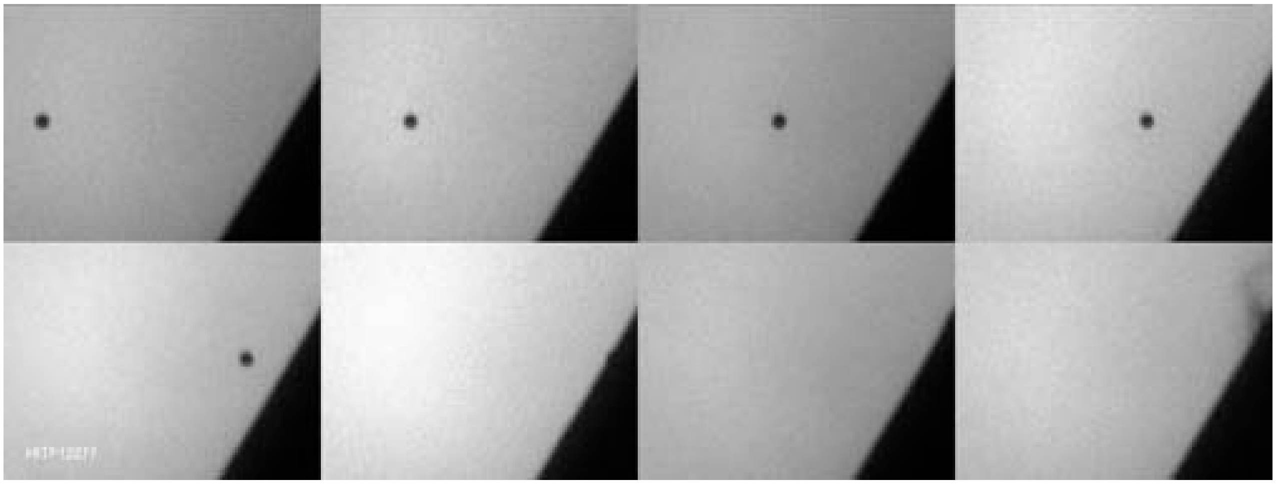


Figure C.42: High speed video of projectile in flight on Soyuz OM Test #17 using SIMX-8 High Speed Video Camera

Figure C.43: Phantom v711 high speed video image of projectile prior to impact

Figure C.44: Phantom v711 video image of projectile impacting Test #17 article