Public Quarterly Report

Date of Report: 3rd *Quarterly Report, June 30, 2025*
Contract Number: *693JK32410012POTA*
Prepared for: *PHMSA*
Project Title: *Development of a Blade Toughness Meter (BTM) for In-situ Pipe Toughness Measurement*
Prepared by: *Massachusetts Materials Technologies*
Contact Information: *Simon Bellemare, s.bellemare@bymmt.com,*
For quarterly period ending: *June 30, 2025*

1: Items Completed During this Quarterly Period:

Table 1 shows a list of items that were completed and invoiced this quarterly period. Task 1.2, Item #2 has been completed with the inclusion of the vendor contract and report of work completed. With the conclusion of this Item, the First Payable Milestone has been reached. Item #5 of Task 1.3 corresponds to the work presented in the prior quarter and finalized this quarter related to blade optimization and coating analysis. Task 2.1, Item #9 began ahead of schedule last quarter and has reached completion of its first billable milestone in the form of the issued mock trial report. Task 2.3, Item #17 began last quarter and was completed this quarter with the delivery of F-250, L-250, and E-250. The 3rd quarterly report was the only new item for completion this quarter.

Table 1 – Tasks completed and invoiced this quarterly period

Item #	*Task #*	*Activity/Deliverable*	*Title*	*Federal Cost*	*Cost Share*
6	***N/A***	***3rd Quarterly Report***	***Submit 3rd quarterly report***	***0.00***	***0.00***
2	***1.2***	***Develop a finite element model for the planing-induced microfracture process***	***A report on findings from the finite element models which include (1) blade optimization design and (2) measurables and their correlations to fracture toughness submitted***	***$22,698.5***	***$22,698.75***
5	***1.3***	***Manufacture blades with optimized design and adjust tool accordingly***	***A summary of blade and tool design changes submitted***	***$21,535.66***	***$21,536.00***
9	***2.1***	***Conduct field trials and modify the tool according to trial feedback***	***A summary of findings and results from field trials submitted***	***$12,150.87***	***$12,150.87***
17	***2.3***	***Optimize the field procedure***	***Developed field procedure submitted***	***$15,705.14***	***$15,705.33***

2: Items Not-Completed During this Quarterly Period:

Table 2 shows a list of items for which work started or continued to take place on following the first quarter, and which have yet to be completed. Work conducted in Quarter 3 for all ongoing tasks were presented to the TAP committee on June 30th, 2025. Progress for Task 1.2 is behind schedule with remaining Items open and decision pending on appropriate follow-up steps. Task 1.3 Item 8 is mostly complete this quarter but will be finalized, presented, and invoiced next quarter. Work on Task 2.1 and Task 2.3, has proceeded at the expected pace and is anticipated to conclude ahead of schedule in Quarter 4. Task 2.2 has begun ahead of schedule this quarter.

Table 2 – Items started but not completed this quarterly period

Item #	*Task #*	*Activity/Deliverable*	*Title*	*Federal Cost*	*Cost Share*
4, 7	***1.2***	***Develop a finite element model for the planing-induced microfracture***	***Progress report with completed Task 1 and Task 2 progress from scope of work.***	***$22,698.50***	***$22,698.75***

		process			
8	*1.3*	***Manufacture blades with optimized design and adjust tool accordingly***	***A summary of blade and tool design changes submitted***	***$21,535.66***	***$21,536.00***
13	*2.2*	***Improve prediction model and develop codes to automatically process of field data.***	***A summary of improved prediction model and data processing algorithms submitted.***	***$16,307.53***	***$16,307.53***
20	*2.3*	***Optimize the field procedure***	***Developed field procedure submitted***	***$31,410.28***	***$31,410.28***

3: Project Financial Tracking During this Quarterly Period:

The total amount billed for ongoing work can be seen in Figure 1, along with a projected invoice schedule for the entire project. MMT is submitting their first invoice for the project his quarter. Expenses correspond to all completed tasks reported on to date. The total invoiced to PHMSA will be $70,927.34 in keeping with applicable cost share. Delay in Task 1.2 Finite Element Modeling items are responsible for the difference between projected and actual invoicing to date. As work is completed related to this task, invoices in future quarters will deviate accordingly as the overall spend comes back into alignment.

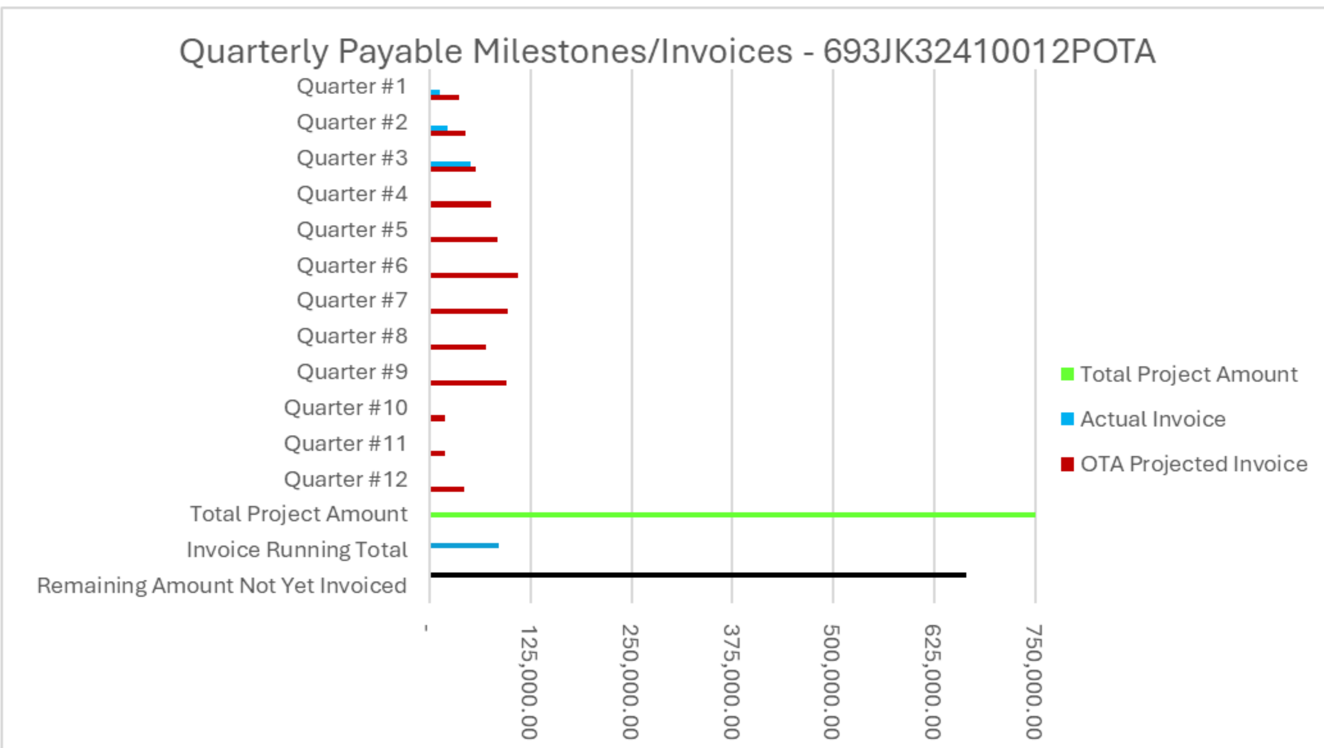


Figure 1 – MMT quarterly payable milestones and invoices

4: Project Technical Status –

Table 3 shows a complete summary of all project progress to date listed by Task as originally defined in our proposal. For each task we have listed the percentage achieved and percentage complete. A percentage achieved less than 100% with a percentage complete of 100% indicates we did not complete all tasks as defined in our original proposal but we are stopping all work associated with the task. This will apply to Task 1.3, wherein objectives pertaining to improvement in measurement consistency, fracture dependance, blade life improvement, and reduction of cut depth were completed. However, aspects of the task related to utilizing findings from finite element modeling of the blade were removed from the scope of Task 1.2 and are therefore unable to be completed. Despite this, empirical testing initiatives were successfully utilized to achieve the key outlined objectives.

Ongoing work in Task 1.2 BTM Finite Element Model Development has reached a roadblock with the delivery of a report from the current vendor which expresses serious difficulty in achieving the outlined scope of work. As a result, only one task is considered complete on this Tasks deliverable milestone path. Remaining items in this task are still being pursued, but will require deeper evaluation and an updated timeline as well as expected approach. An overview of the encountered difficulties and current status can be found in Attachment 1.

Work that began in quarter 2 on Task 2.3 has seen significant progress, which has resulted in a field procedure, laboratory procedure, and engineering specification included here as Attachment 2, 3, and 4, respectively. Task 2.1 has also seen significant progress with a mock trial being conducted. The mock trial utilized all relevant procedures from Task 2.3 and resulted in the completion of a sample report included here as Attachment 5.

Table 3 – Complete project progress summary

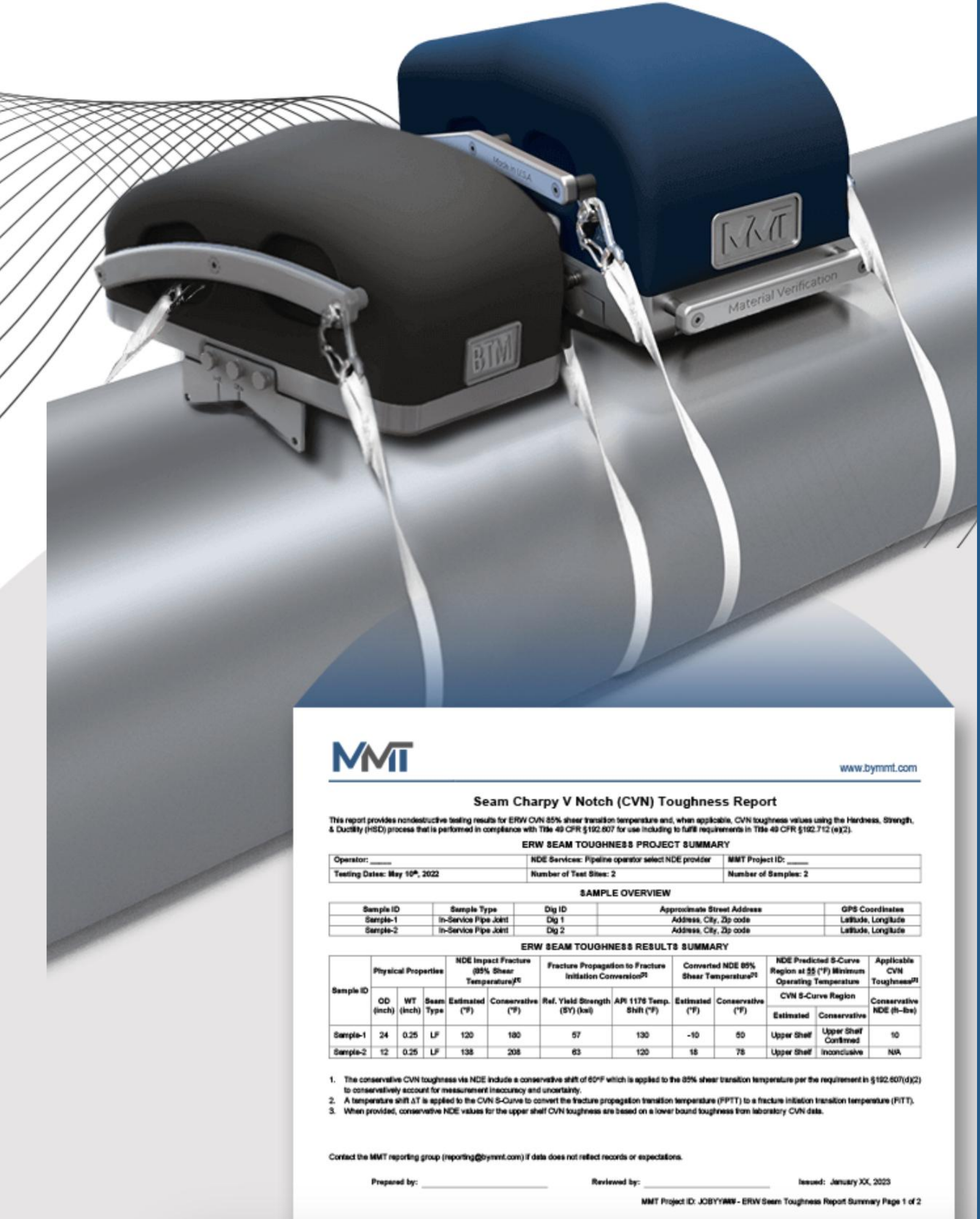
Scope of Work			% Achieved	% Complete
Milestones	**Type**	**Tasks**		
Milestone 1: Blade Optimization for Better Accuracy and Safety	Deliverable	1.1 Literature Review	100	100
	Method	1.2 BTM Finite Element Model Development	33	33
	Hardware	1.3 Blade Design Optimization	75	90
Milestone 2: Field Trials and Evaluation	Hardware	2.1 Field Device Development	40	40
	Software	2.2 Data Process and Analytics Optimization	20	20
	Procedure	2.3 Field Procedure Optimization	66	66
	Deliverable	2.4 Third-Party Validation	5	5
Milestone 3: Test Instrument Design and Evaluation	Hardware	3.1 Field Device Optimization and Automation	0	0
	Software	3.2 Software Development	0	0
	Procedure	3.3 Training Program Development	0	0
	Deliverable	3.4 Engineering Specification for Manufacturing	0	0
Milestone 4: Proof-of-Concept for In-line Adaption	Method	4.1 Feasibility Study	0	0
	Hardware	4.2 Proof-of-Concept Development	0	0
	Deliverable	4.3 Laboratory Mock-up Testing	0	0

Items from Task 2.2 have begun ahead of schedule. The decision to proceed ahead of schedule with items from Task 2.2 is a result of the ongoing success of Task 2.1 and 2.3. Additionally, this work will enable better handling of temperature differences in the field during pilot testing as well as handling of data surrounding reporting generation during pilot program testing in service of Task 2.4.

5: Project Schedule –

A complete project progress summary can be seen in Table 3. This summary includes all tasks that have not been started yet as well as percentage progress for ongoing tasks. Task 1.2 has stalled at 33% and further milestones will be evaluated pending decision on next steps. The schedule will accordingly shift with the remaining three quarters of payable milestones being delayed until a decision is made. Task 1.3 has completed the desired objectives through empirical test plans, though in acknowledgment of the change from finite element modeling informed design changes the final completion is noted at 75%. The remaining work will consist of compiling findings for the next quarterly report. All Task 2 items are now under way ahead of schedule. Task 2.1 is expected to continue until the original end date at year end. Task 2.2 and Task 2.3 are now anticipated to complete ahead of schedule. In recognition of the changing schedule and delivery milestones resulting from Task 1.2 difficulties, the ahead of schedule Task 2 items, and anticipated changes to the commercial hardware development plan; approval has been asked to update the payable milestone chart and Gantt chart.

Attachment 1 – Task 1.2, Task 1.3, Task 2 – June 30th Progress Report



MMT

R&D Project:
Development of the Blade Toughness Meter (BTM) for In-Situ Pipe Toughness Measurement

Co-sponsored By PHMSA
(Project # 1043)

Q2 2025 – Progress Report
06/30/2025

Agenda

- Task 1.2 updates (FEA)
- Task 2.1 updates (Blade Optimization)
- Task 2.2 updates (Analytics Optimization)
- Task 2.3 updates (Field Procedures)
- Expected Updates to Timeline
- End

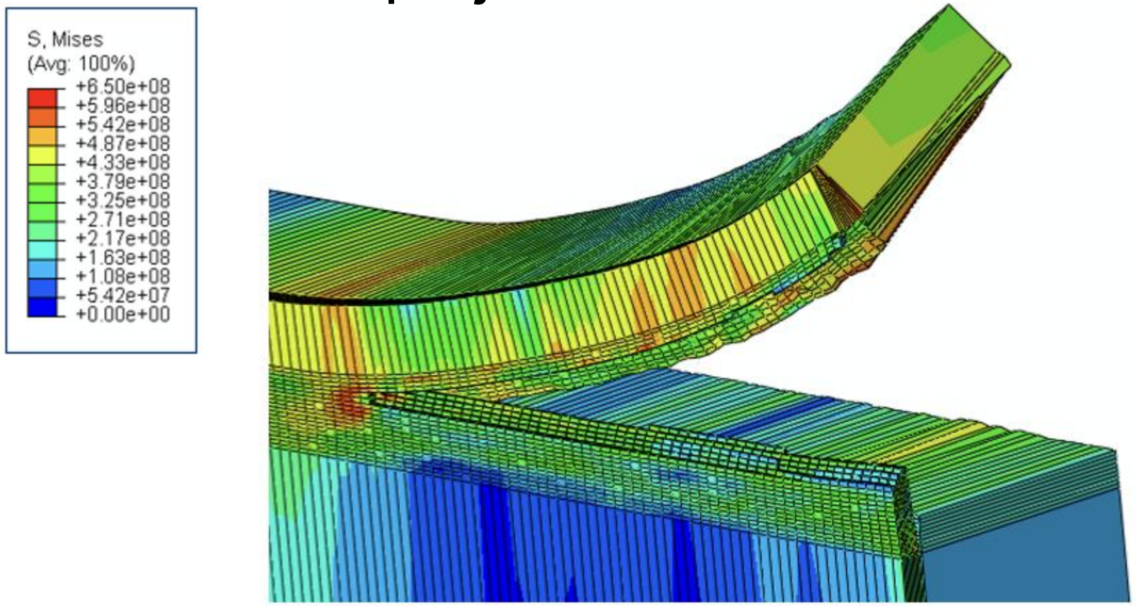
Task 1.2 Finite Element Model Development (Physical modeling)

Status:

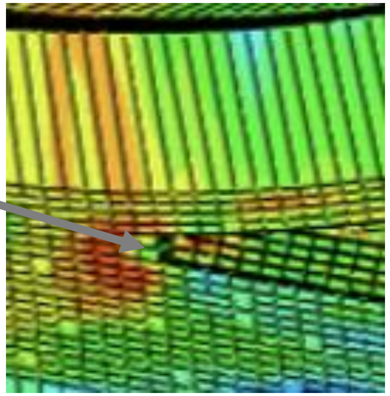
- Consulting the vendor did not reach the milestone
- One valuable lesson learned about element deletion
- Asking for expert opinions on the best approach to take

Task 1.2: Unexpected vendor deliverable

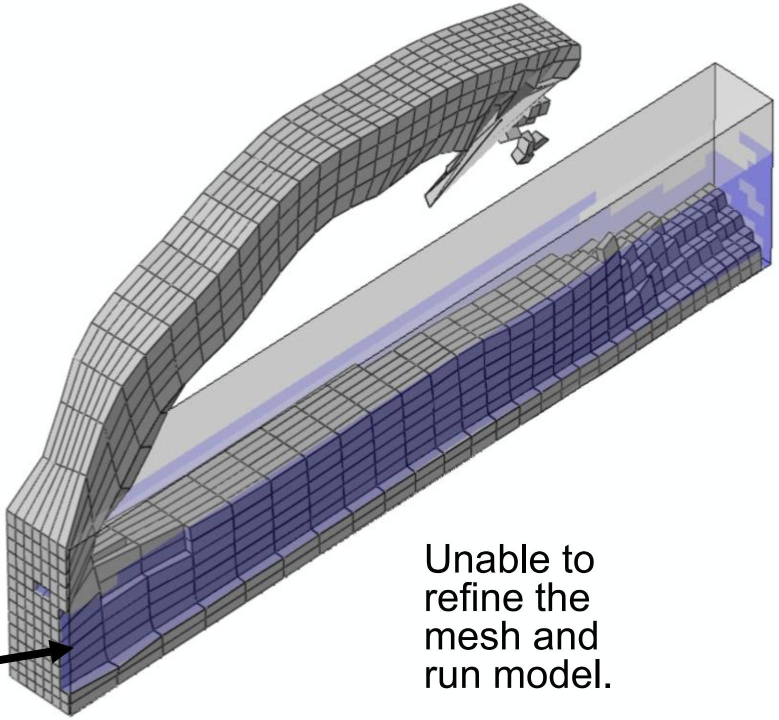
A feasibility study provided before the project:



2 elements deleted at the crack tip



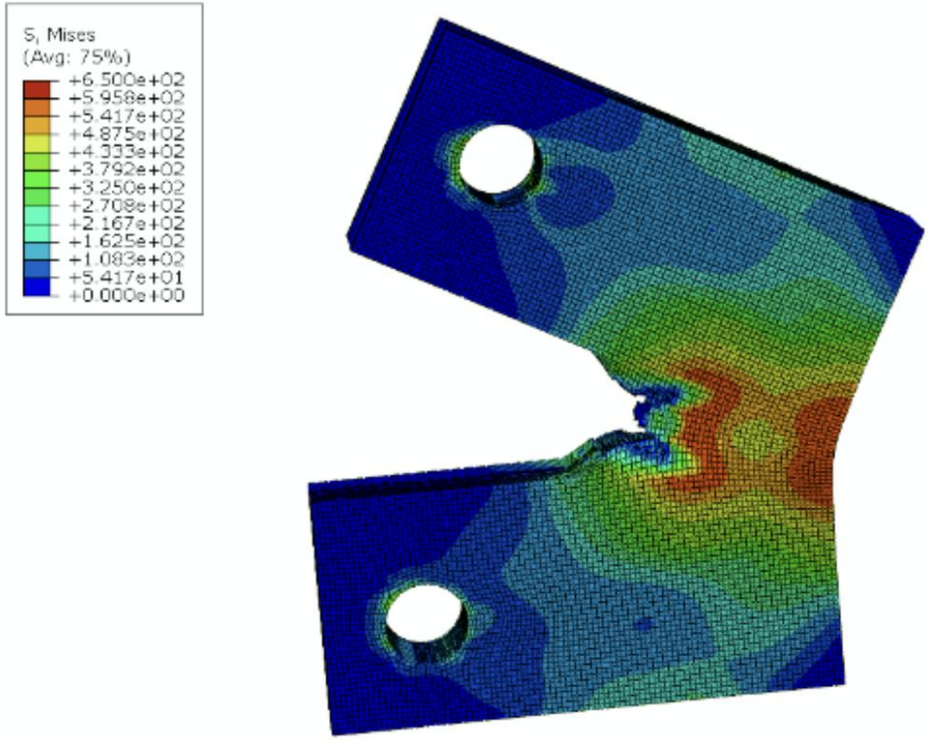
Final deliverable:

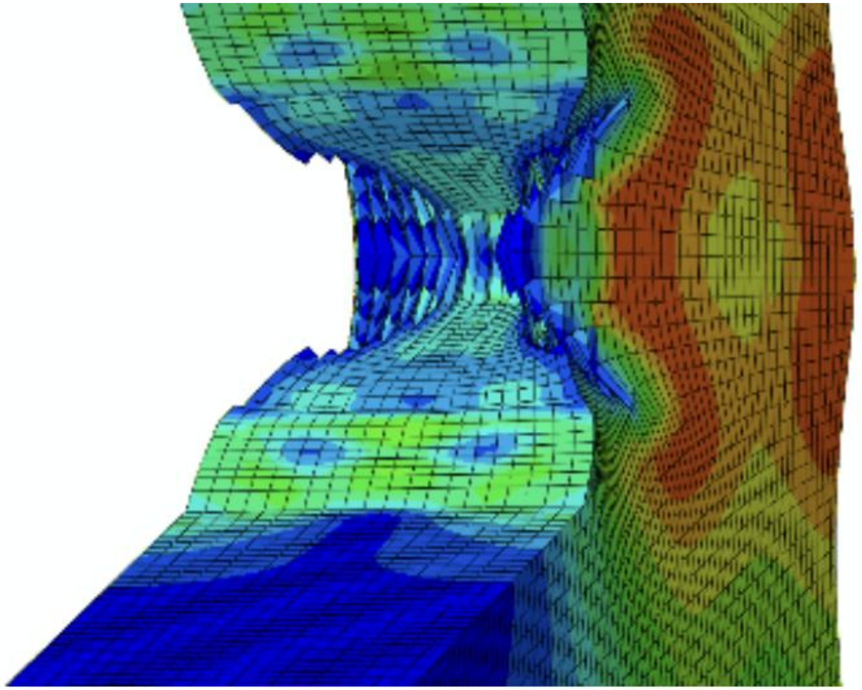


7 elements deleted at the crack tip

Unable to refine the mesh and run model.

Task 1.2: Element deletion

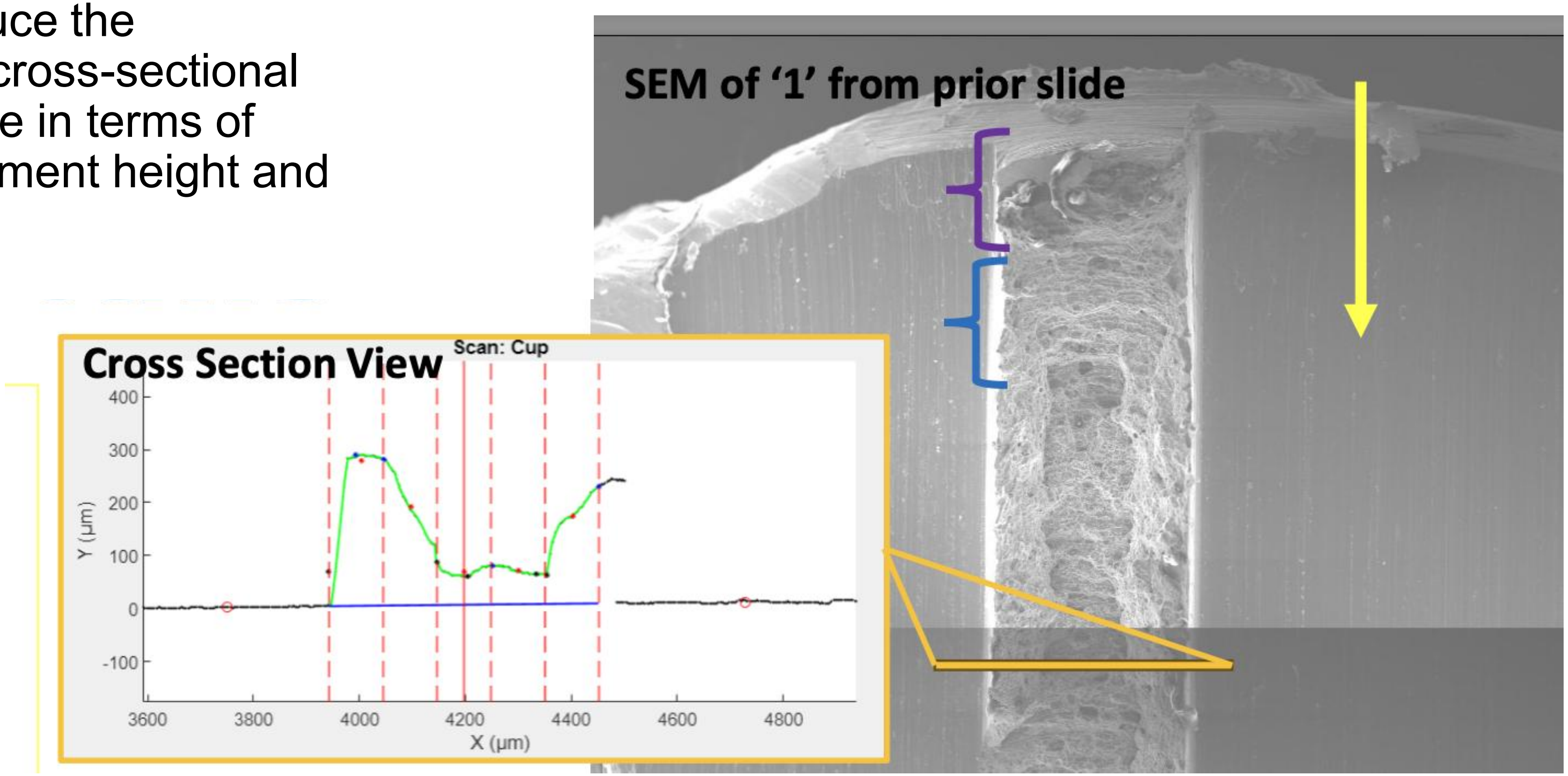




We don't see how this method can provide a reliable cup cone profile.

Task 1.2: Going back to objective provided

Task: Reproduce the experimental cross-sectional ligament profile in terms of combined ligament height and cup width



Task 1.2 Path Forward

The task has not changed.

Key finding: Application of the damage accumulation models and element deletion may hide the crack details
(MMT is searching to see work by a prior vendor had the same issue)

Questions

- Is typical Abaqus Explicit able to do element decohesion to create a surface without causing volumetric loss? We cannot specify the crack plane which probably makers this harder.
- Is XFEM a reliable approach? How specialized is it for Elasto-plastic implementation in Abaqus? Prof. Adeeb brought this up at the beginning of the project, but our initial review suggested that it was most commonly used for elastic simulation, and including plasticity required stacking up different models.

We need to capture the plastic zone around the crack tip as well as the true fracture profile.

Task 1.2 Add’l details (1 of 2)

This is more for Dr. Anderson and Dr. Adeeb (From Simon)

If trying to fix the current work

- Someone said using coupled Eulerian- Lagrangian ECL) better than vendor did (Lagrangian) because the elements that reach 100% damage are still there. I need to follow up because I don’t know how you create a surface
- I am thinking about making the effect of compression and shear irrelevant to damage accumulation (except of course for the hardening) as a practical way to only have the area of triaxiality being where the damage takes place). [Next page as example]. First goal from my standpoint is to get to the cup/cone while still having a simple damage model.
- I did not want to babysit these folks but at this point I don’t know if mass scaling factor or other such are factors into their issues.

Task 1.2 Add’l details (2 of 2)

Table 3 Fracture strain–triaxiality data used in the plasticity model for damage initiation.

Saykin combined shear and fracture model

Criterion 1	Criterion 2		Criterion 3	
Fracture strain	Fracture Strain	Triaxiality	Fracture Strain	Triaxiality
0.148	10.000	-0.333	10.000	-0.333
	0.685	-0.277	~~0.415~~	-0.233
	0.219	-0.230	~~0.364~~	-0.170
	0.064	-0.126	~~0.321~~	-0.100
	0.044	0.000	~~0.281~~	-0.028
	0.064	0.142	0.247	0.036
	0.149	0.333	0.219	0.104
	0.214	0.400	0.191	0.175
	0.129	0.478	0.168	0.239
	0.087	0.550	0.148	0.313
	0.049	0.640	0.130	0.398
	0.022	0.764	0.105	0.436
	0.007	0.930	0.084	0.472
	0.003	1.061	0.060	0.527
	0.001	5.000	0.038	0.603
			0.023	0.694
			0.013	0.790
			0.007	0.908
			0.003	1.010
			0.001	5.000

10

These numbers look very low

Does such model make sense for the application?

(I don’t know how the accumulation is set for this)

Task 2.1 – Field Device Development

- Structural Reinforcements
- Weather-Resistant Cover
  - Cover includes limit switches to reduce pinch point hazards
  - Additional limit switches to avoid unit being able to damage itself
- Accessory item to assist in final surface cleanup
- Expecting ongoing improvement work up until start of Commercial Design in Task 3.1

Task 2.2 – Data Process and Analytics Optimization

- Release Notes for first version of the toughness prediction model have been circulated.
- Preliminary model for Ductile Brittle Transition Temperature of the pipe body.
- Preliminary work to streamline processing and minimize human expertise-driven input to the measurement process.

Task 2.3 – Field Procedures

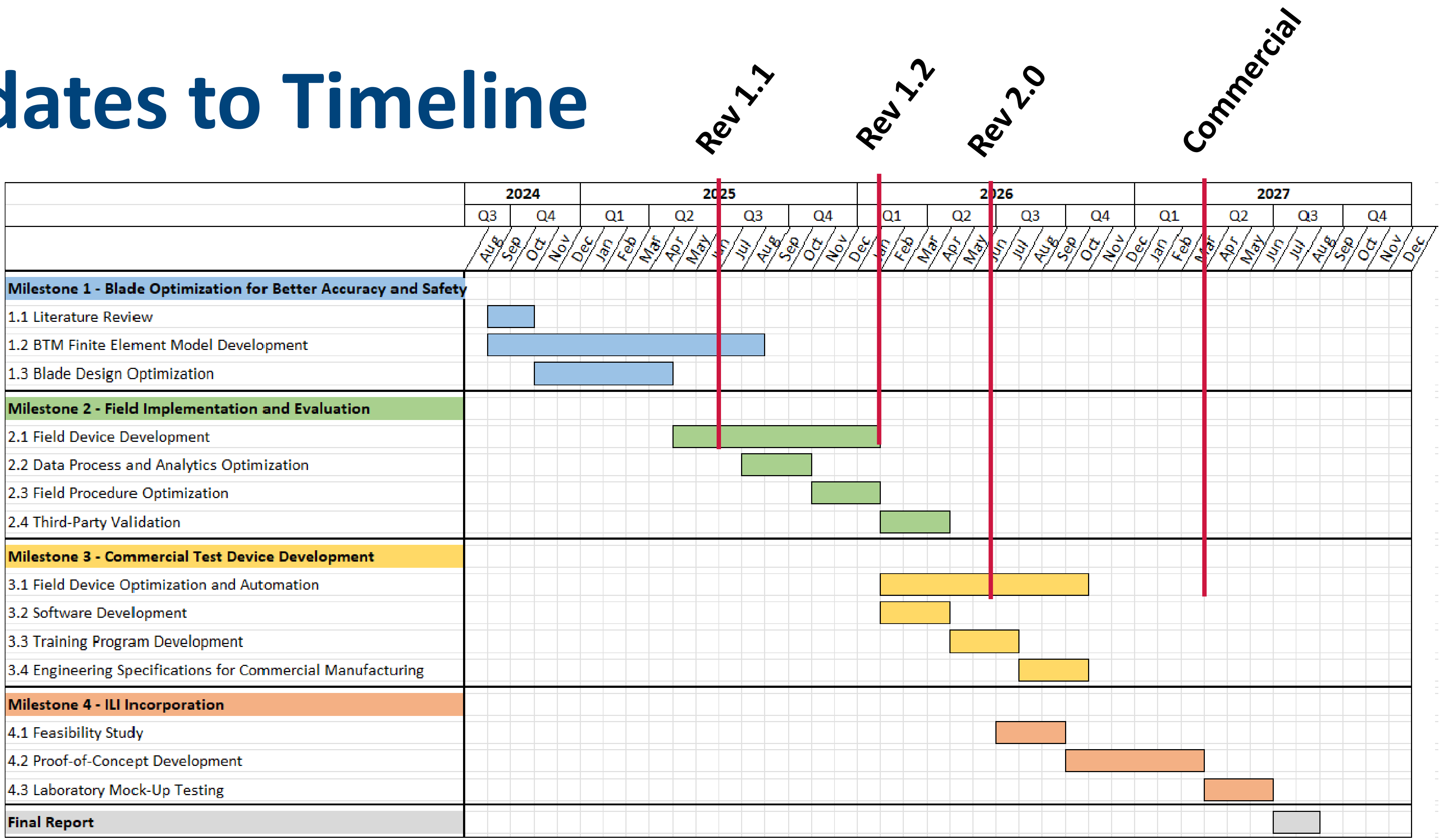
Have completed effort to capture current procedures for field implementation of the tool, as well as the supporting procedures for data handling, processing, and in lab analysis.

- E250 – Engineering Specification
  - Covers method, tool, measurement, analytics, machine learning
- L250 – Laboratory Procedures
  - Covers inspection and acceptance of hardware critical to accuracy or safety, as well as inspection and measurement of features generated in field
- F250 – Field Procedures
  - Covers overview of requirements, techniques, and processes to conduct BTM testing in field.

Milestone 2

- Mock trial of in-ditch work was carried out in preparation for ‘Task 2.4 – Third Party Validation’
- All current procedures were followed, resulting in full sample report being issued

Updates to Timeline



Updates to Timeline (2)

- Rev 1.1 & Rev 1.2
  - Current prototype platform with minor improvements
- Rev 2.0
  - Limited Commercial Release
    - This revision is the cause for deviation. Original plan was to jump straight from a field viable prototype to a full commercial unit. In practice, we now think this is too large of a jump. Rev 2.0 will work to revisit existing systems and revise them to a form which can be fully automated.
- Rev 3.0
  - Full Commercial Release
    - Automation of systems introduced in Rev 2.0. Improvement to form factor.

Questions and General Discussion

Thanks for attending and lending your time and insight!

Prior quarter report on Task 1.3 Item 5:

Task 1.3 Blade Design Optimization

Task 1.3.3: optimize blade life to reduce cost

- General approach explored the implementation of a coating on the existing tungsten carbide blade
- Parallel testing of uncoated and coated blades conducted on X samples.
- Blade Life Comparison:

Task 1.3 Blade Design Optimization

Task 1.3.3: optimize blade life to reduce cost

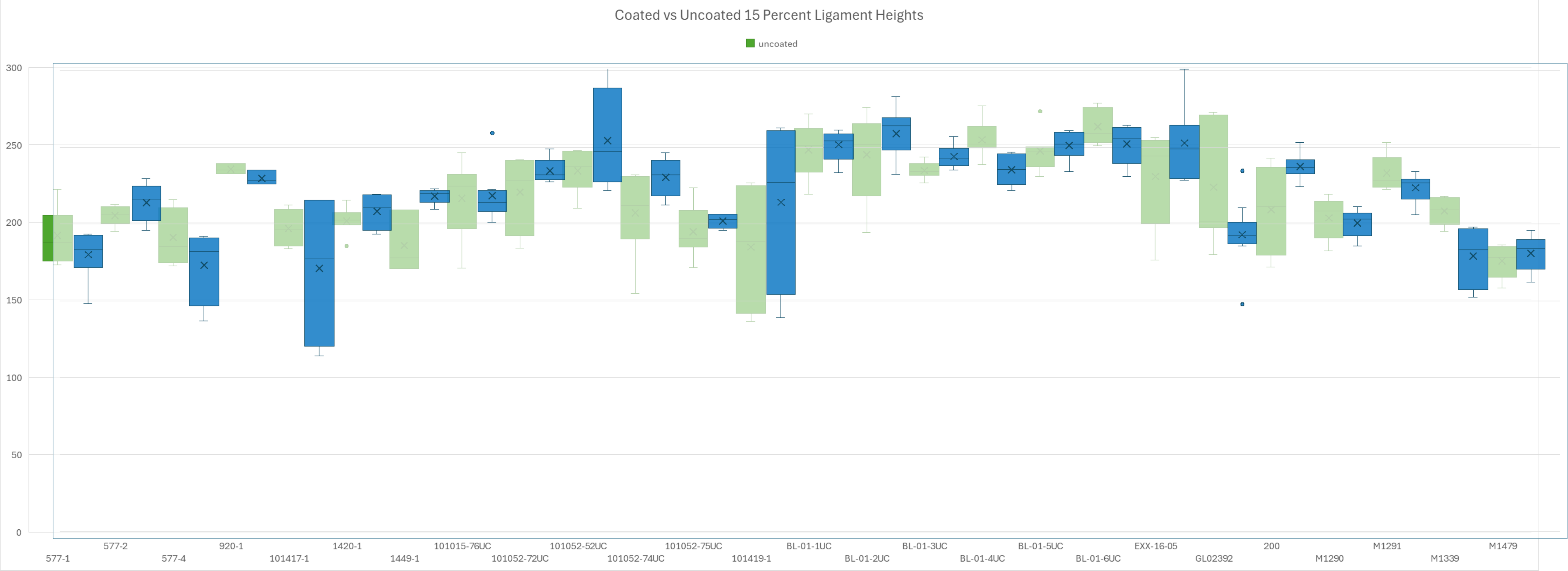
- Need to evaluate influence of coating on material response
  - The change in friction condition which improves blade life could impact material response
  - Need to determine if data produced by coated blades can be utilized along with uncoated
  - If not, need to determine if coated blade data still correlates as expected with toughness properties

20sp coated blade usage	3
20sp coated tests	163
20sp coated tests per blade	54.33
samples per coated blade	6.79

20sp uncoated blade usage	36
20sp uncoated tests	105
20sp uncoated tests per blade	2.92
samples per uncoated blade	0.36

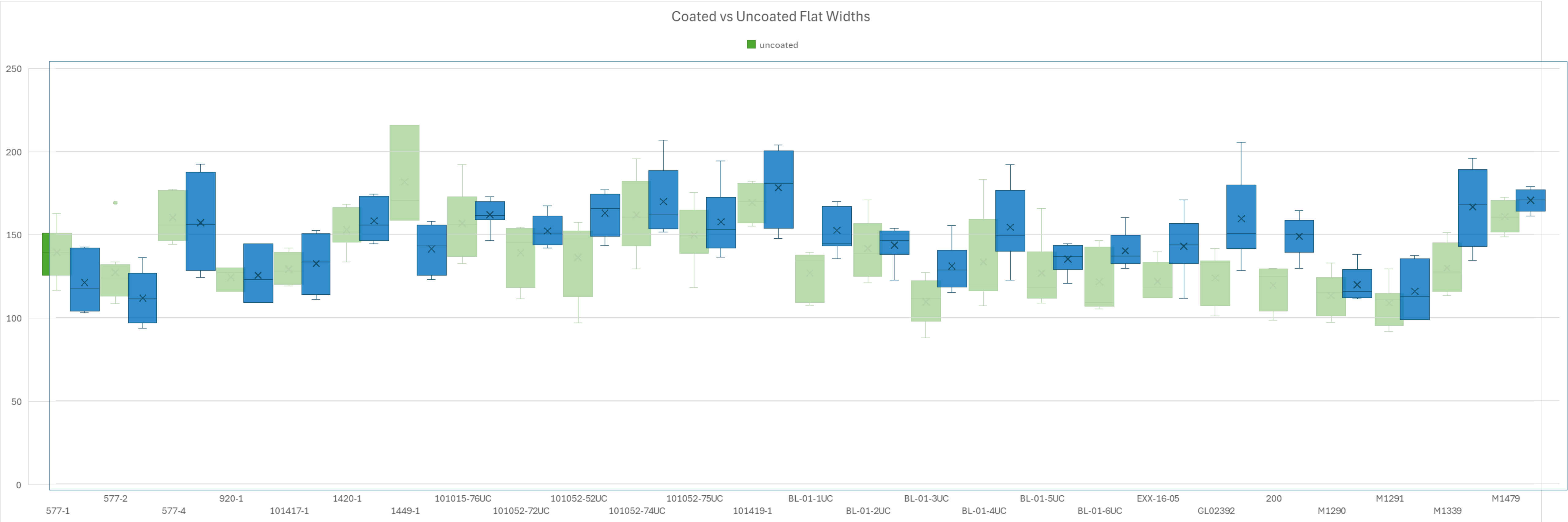
Task 1.3 Blade Design Optimization

Task 1.3.3: optimize blade life to reduce cost – Measurement Comparison



Task 1.3 Blade Design Optimization

Task 1.3.3: optimize blade life to reduce cost – Measurement Comparison



Task 1.3 Blade Design Optimization

Task 1.3.1/1.3.2: optimize material response & reduce cut depth

- General approach is to explore some variations of blade geometry
  - Various tip sharpness, sharper should enable shallower test depths
  - Various curvatures leading into stretch passage could improve material response for test consistency
- Initial testing of these parameters has been carried out. Results as follows:

Sharper Blade Initial 3 pipe results

Attachment 2 – Field Procedure

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Natick, MA 01760
(617) 502 - 5636
sales@bymmt.com
Massachusetts Materials Technologies LLC

F-250: BTM Field Procedure

Prepared by: Bryan Feigel, Ryan Lacy, Josh Norman, Simon Bellemare

Reviewed by: Gene Hurley, Parth Patel

Approved by: Simon Bellemare

REV	DATE	CHANGE	By/Reviewed	Approved
1.0	2025-05-20	Initial Release	Bryan Feigel	Simon Bellemare
1.1	2025-06-10	Addition of Appendix A	Bryan Feigel	Simon Bellemare

Scope

Quality Compliance: This document specifies the field procedures and techniques to be used by field technicians as part of material verification to deliver accurate and reliable results in compliance with 49 CFR §192.607.

Procedure-specific safety guidance: This document provides safety guidelines for using MMT equipment and procedures. However, MMT does not claim completeness of these guidelines, has no authority to ensure compliance with them, and is, therefore, not responsible for third-party personnel safety.

Outside of Scope

Personnel safety: All safety aspects generally covered under OSHA and pipeline OQs are outside the scope of this document. Every employer shall manage its safety programs and promote a safety culture for its respective personnel.

Pipeline safety: The procedures include significant pipe wall thickness removal. The pipeline operator is responsible for the safe operating condition of the pipeline and shall verify that the material removal does not lead to unsafe pipeline conditions.

Contents

1. Roles & Responsibilities

Table 1 summarizes the roles and responsibilities for all parties generally involved with a project.

Table 1: Summary of Roles and Responsibilities

Parties	Responsibilities
All Relevant Parties	1. Safety of own personnel 2. Communicate and help resolve situations where any deviation from this procedure may be needed. 3. Attend the pre-job meeting to ensure thorough logistical coordination.
Pipeline Owner / Operator	1. Accurate completion of the pre-job form with all necessary information. 2. Approve the material removal requirements detailed herein and provide pipeline operating pressure requirements. 3. Assign and manage pre and post testing inspection of tested area.
Site Contractor /Representative	1. Provide safe site access. 2. Meet pipe clearance, coating removal, and surface preparation approval requirements.
NDE Vendor / Certified Individual	1. Perform safety inspections to verify absence of defects, anomalies, and laminations as detailed herein. 2. Certify testing locations are safe to perform preparation and testing.
BTM Trained Personnel	1. Confirm that the flaw inspection was completed. 2. Receive confirmation that the material removal requirement has been approved. 3. Perform BTM Testing in accordance with procedures.

2. Safety

All individuals performing this work are responsible for ensuring their own safety. MMT is not responsible for worker safety and individuals are encouraged to use proper judgement and follow all safety regulations when conducting any work. The following summaries are meant to supplement, and not replace, worker safety requirements.

2.1 Site Safety

Table 2 provides a basis list of common site safety items when applying this procedure.

Table 2: Site Safety Common Considerations

Item	**Description**
Trenching or Excavation (if applicable)	Trenches 5 feet or deeper generally require a protective system, which can include sloping, benching, shoring, or shielding. Workers must have a safe way to enter and exit the trench, including ladders or steps for trenches 4 feet or deeper.
Ladder Access (if applicable)	If a break in elevation is 19 inches or more and no ramp, runway, embankment, or personnel hoist is available, the client must provide a stairway or ladder at all worker points of access.
Ventilation (if applicable)	If the work area is not open and well ventilated, review the site conditions with your supervisor.
General PPE	Hard Hat/Steel-Toed Boots/FR Suits/Hi-Vis Safety Vest/Additional PPE – Individuals performing this work shall wear proper safety clothing and boots as required per the site requirements. Additional PPE may be required in accordance with applicable MMT or customer policies and procedures.

2.2 BTM Specific Safety

Performing BTM testing and procedures requires the use of specific equipment, chemicals, and practices which have associated safety risks. BTM testing should only be performed by appropriately trained individuals. Table 3 provides BTM specific safety recommendations.

Table 3: BTM Specific Safety Considerations

Item	**Description**
Heavy Lifting	BTM equipment pelican has a weight just short of 100lbs and should be lifted with care by more than one individual to avoid injury.
Use of chemicals	This process involves cutting fluids during test island preparation and a replication compound. Individuals must review SDS for all chemicals prior to use to ensure proper handling, safety measures, and incident response.
Equipment operation	This process uses equipment that is potentially dangerous when handled improperly. Individuals must review manufacturer instructions prior to using any equipment to ensure proper and safe handling and operation.
Rotating Machinery	Surface preparation operation utilizes a drill with a non-plunging end mill. Special care should be taken to avoid clothing, jewelry, or other items which can be caught in rotating equipment. No gloves should be utilized during drilling operations as they can cause injury if caught in rotating equipment.
Hearing Protection	Individuals performing this work should wear appropriate hearing protection during use of surface preparation equipment to limit exposure to loud noises.
Metal Dust	A properly fitted respirator is required when performing this work. While chips generated from the BTM and BTM blade testing are not small enough to be a fine particle hazard, any use of the PTX grinder or similar surface grinder may cause finer steel particles to become airborne that can be extremely harmful to the respiratory system. Potential damage to the lungs is high and long-term exposure can lead to permanent interstitial lung diseases. Breathing steel dust can also cause irritation and damage to the soft tissues in your nose, throat, and mouth.

Mechanical Hazard/ Pinch Point	The BTM instrument has moving components which could result in pinch points or other mechanical hazards. Individuals should take care with fingers or other body parts to avoid bodily damage.
Heavy Lifting	BTM tester weighs close to 50 lbs. and should be lifted with care. BTM tester and accompanying accessories exceed 50 lbs. when combined and should be lifted with care by more than one individual.

3. Project Requirements

Table 4 provides the requirements that must be fulfilled to enable BTM testing to be performed.

Table 4: Project Requirements

Requirement	**Detail**
Pre-job Information	Customer will fill out pre job information sheet before technicians arrive onsite. If sufficient information is not provided, a work stop may occur.
Test sample geometry	Test sample must be a straight length of pipe. Acceptable outer diameter between 8" – 48".
Power Supply	120V AC power supply (generator or other) - 2000W
Access to Test Sample	Test sample must be safely accessible in accordance with all applicable standard operating procedures (IE: trenching, confined space, etc.)
Sufficient testing area and clearance	3 ft length (minimum) exposed pipe with 2 ft of clearance all around (360 degree) the pipe circumference. The work area should be dry and free from potentially dangerous obstructions.
Sandblasting post coating removal	Pipe outer diameter should be sandblasted to SSPC-SP5 (NACE #1).
Ensure site access for 8 hours	Ensure sufficient time to complete the job is set aside for the process. If more than one day is required based upon start time, communicate immediately to appropriate personnel.

Approval for wall thickness removal	Expected wall removal of 0.035''. Operator approval required depending on nominal wall thickness, surveyed wall thickness, and other key characteristics of the pipeline.
Complete advanced inspection of BTM test locations prior to testing	BTM testing must be located a safe distance from critical features. MMT requests 2 ft longitudinally and 360 degrees circumferentially to be free of OD and ID crack or crack like defects. MMT requests 1 ft longitudinally, and 6" or 90 degrees circumferentially to be free of seams, or defects such as corrosion wall loss, or laminations.

General Considerations:
Conditions that may delay or preclude execution of this procedure include:

- Wall thickness removal approval cannot be given
- No sufficient test area is absent of internal & external flaws
- Site access could not be maintained until testing was completed

4. Pre-Testing Requirements

Prior to testing the following conditions must be met by each party.

By Operator:

1. Confirmation of approval for material removal

By Site Representative:

2. Authorization for tool use which may generate sparks
    a. Mag drill contains a DC motor
    b. Surface preparation metal to metal contact

By NDE Technician:

3. Completion of advanced inspection for both ID and OD cracks and crack-like defects (see Table 3, last item)

By BTM Technician

4. In-field review of HSD Plus surface yield tensile strength results
5. In-field review of microscopy grain images collected during HSD Plus process

5. BTM Testing Procedure

This section outlines the steps required for BTM testing of a pipe joint. All work shall be performed by a BTM Level 2 technician.

Table 5: BTM process procedure and requirements

Step	**Task**

1.	Confirm 'Pre-Testing Requirements' have been met
2.	Identify desired quadrant placement. Confirm that this placement is a safe distance from all critical features Quadrant 2 shall be located 90 degrees from the long seam, if one is present. Preference shall be given to the top half of the pipe. Quadrant 1 shall be located 180 degrees from the seam if the seam is on the bottom half of the pipe. If the seam is in the top half of the pipe, Quadrant 2 shall be located adjacent to the long seam at no closer than 3 inches circumferentially For seamless pipe, Quadrant 1 and 2 shall be placed no closer than 90 degrees from one another A minimum longitudinal spacing of 8 inches is recommended between quadrants
3.	UT the quadrant, record initial wall thickness
4.	Confirm approval for material removal to final wall thickness corresponds to measured wall thickness minus 0.035"
5.	Attach BTM tester to pipe at quadrant
6.	Utilize mag drill and island preparation end-mill to prepare the test surface
7.	Record the depths of prepared test surface in accordance with F-151 and take pre-test photos of the quadrant
8.	Perform testing of the prepared islands, including collection of chips, casted surface replicas of the quadrant, and post-test photos
9.	Utilize mag drill and cleanup end-mill to clean sharp features off test surface
10.	UT quadrant 1, record final wall thickness
11.	Repeat steps 3. through 11. for remaining quadrant
12.	Utilize PTX Grinder with 600 grit sand paper to remove any residual features from BTM testing, leaving a smooth pipe surface.
13.	Take post cleanup photos of both quadrants
14.	Complete all necessary documentation
15.	Connect to Wi-Fi and complete data/documentation upload
16.	Ship chip samples and replicas to MMT lab facility

Post-Testing Visual Inspection

Once the BTM Testing procedure is complete, a verification of the surface re-finishing shall be performed on behalf of, or by the operator, prior to re-coating to ensure that the surface is smooth and free of sharp corners.

Results Delivery

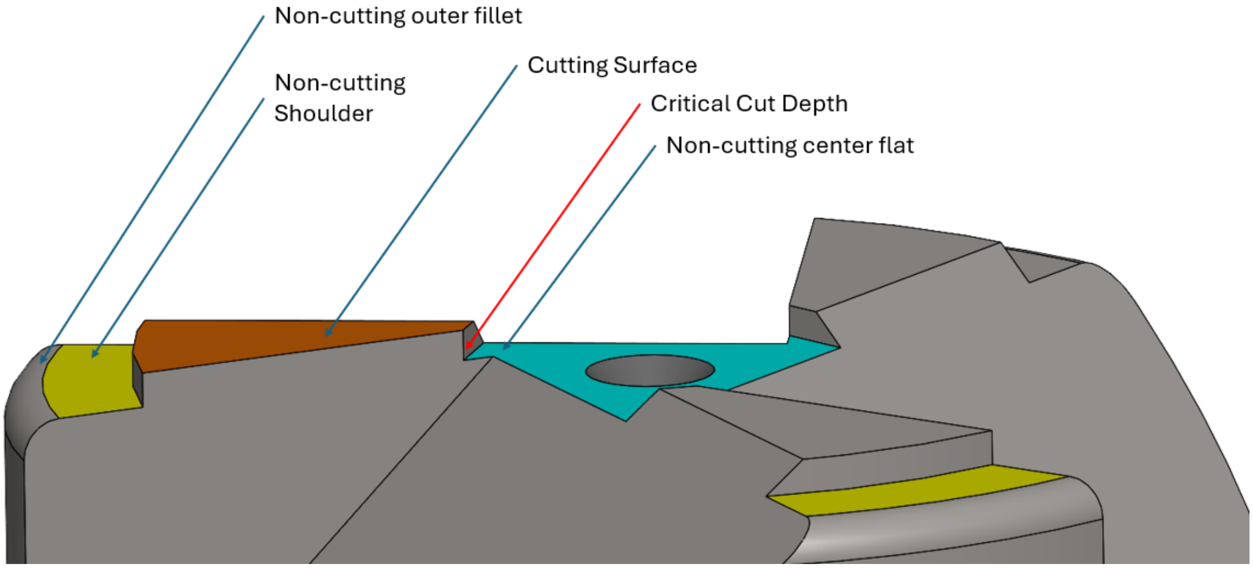
Once MMT receives the chip samples and replicas, allow up to three weeks for data processing and reporting. Expedited processing may be available upon request.

Appendices

Appendix A: Surface Preparation Detail

Machining Bit

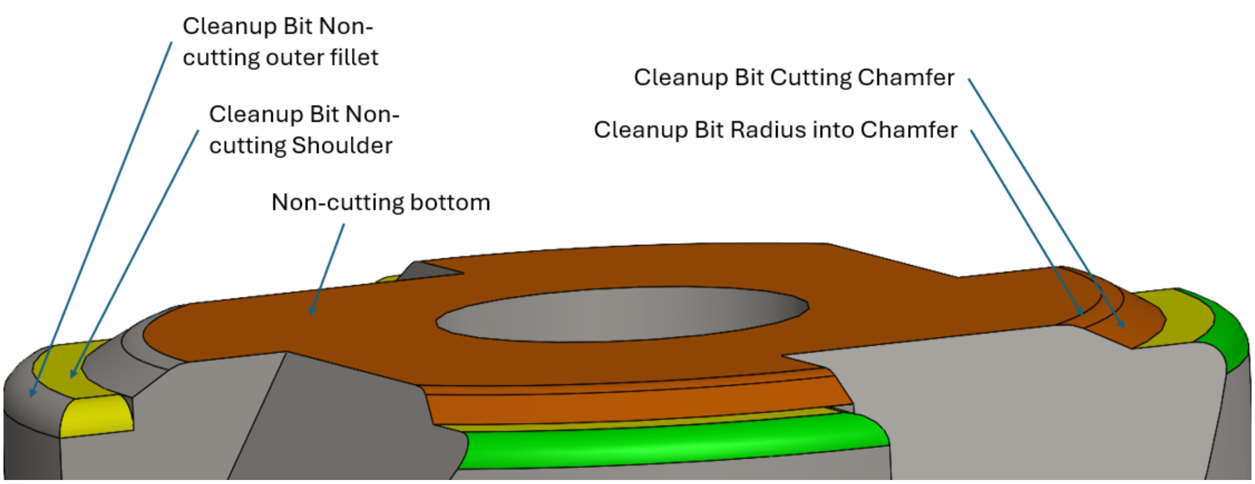
The bit utilized for machining of the islands has the following form factor:



The "Critical Cut Depth" is confirmed by inspection. The two other critical aspects of the bit confirmed by testing and inspection are the non-cutting features at the center flat, as well as at the outside corner fillet.

Cleanup Bit

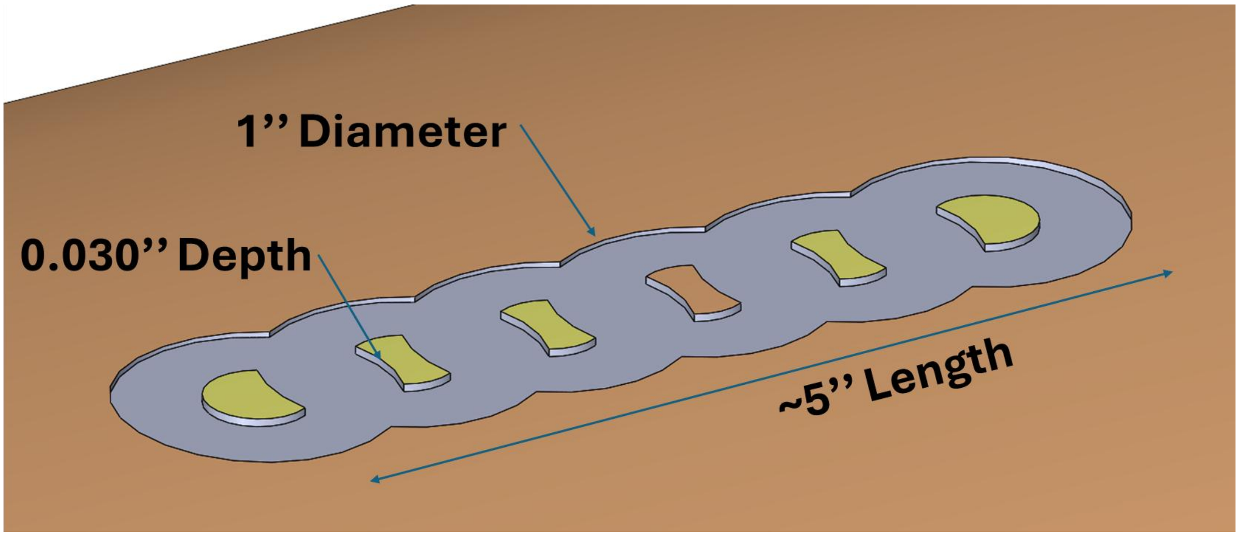
The bit utilized for cleanup of the islands has the following form factor:



The chamfer and chamfer radius are confirmed by inspection. The two other critical aspects of the bit confirmed by testing and inspection are the non-cutting features at the center flat, as well as at the outside corner fillet.

Prepared Surface

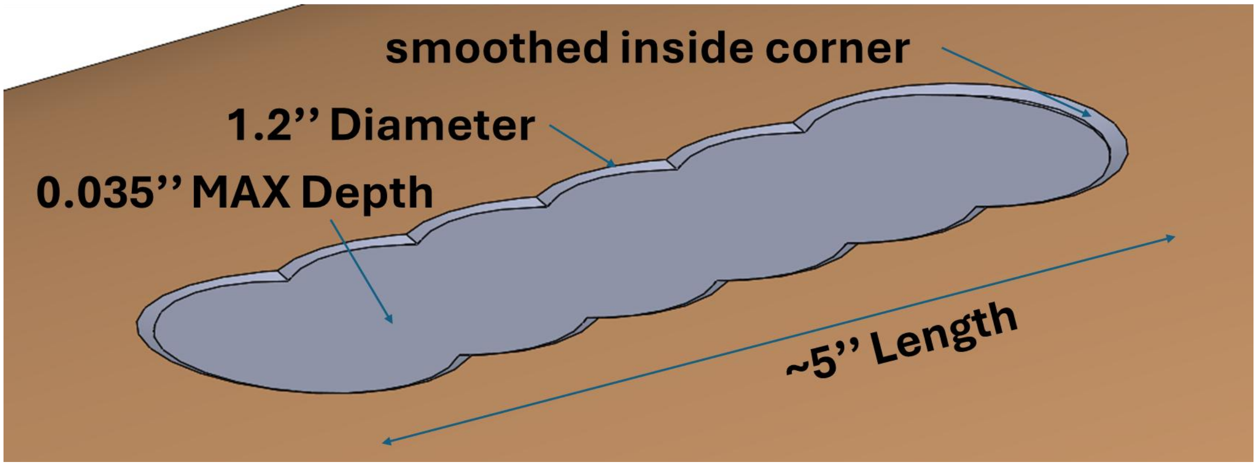
The resulting prepared quadrant following use of the machine bit has the following form factor:



Picture on 12'' pipe OD.

Post Test Cleaned-up Surface

The resulting prepared quadrant following use of the machine bit has the following form factor:



Picture on X" pipe OD.

Attachment 3 – Laboratory Procedure

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L-250: BTM Lab Procedure

Prepared by: Ana Hoffman

Reviewed by: Matt Greenway, Bryan Feigel

Approved by: Simon Bellemare

REV	DATE	CHANGE	By/Reviewed	Approved
00	25xxxx	NA	-	-

Scope

Quality Compliance: This document specifies the in-lab procedures and techniques to be used by MMT personnel as part of material verification to deliver accurate and reliable results in compliance with 49 CFR §192.607.

Procedure-specific guidance: This document provides the best practices for MMT equipment and procedures. Failure to comply with these best practices may result in sub-par measurement accuracy.

Not Part of the Scope

Step-by-Step Instruction:

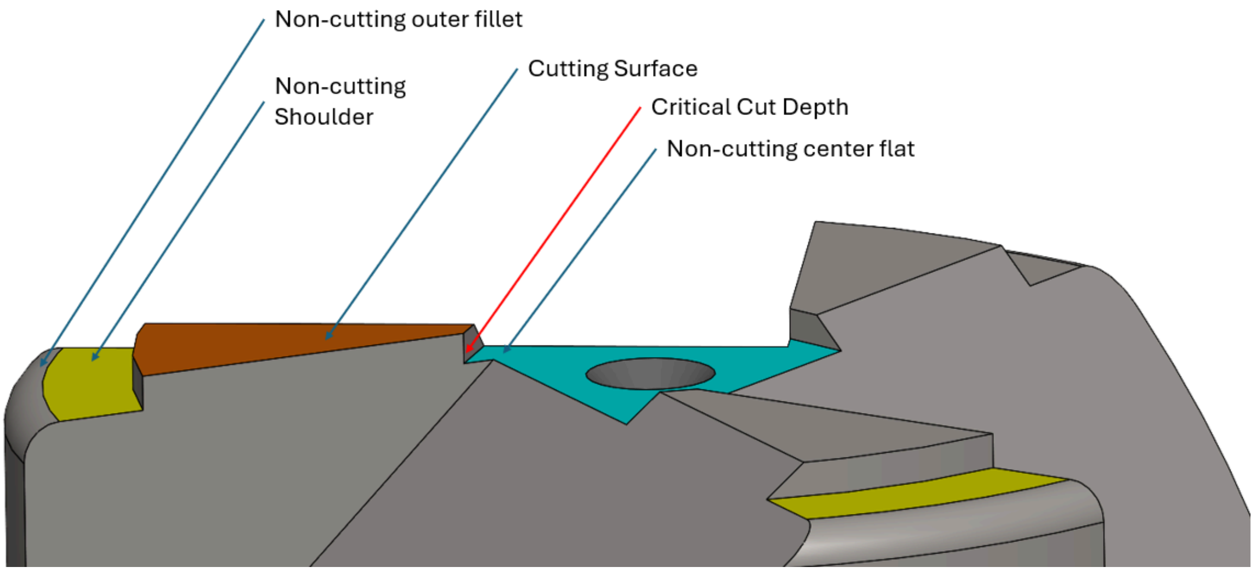
Contents

1. Quality Control of Field Consumables

The BTM Field Testing process requires the utilization of several custom manufactured consumables. Each sub-section herein will focus on one of these items and detail the required quality checks for each.

1.1 Milling Bit

The bit utilized for machining of the islands has the following form factor:



The "Critical Cut Depth" is the most important feature to check the accuracy of. The two other critical aspects of the bit to check are the non-cutting features at the center flat, as well as at the outside corner fillet.

In order to check these features, the following steps will be carried out:

Step	Task
1.	Prepare the inspection sheet (**L261**) by printing a copy generating a bit ID, and filling out the top of the form with the assigned bit lot ID, technician name, and date.
2.	The bit to be verified shall be equipped in the Bridgeport mill in the shop room.
3.	An aluminum plate shall be set up beneath the bit.

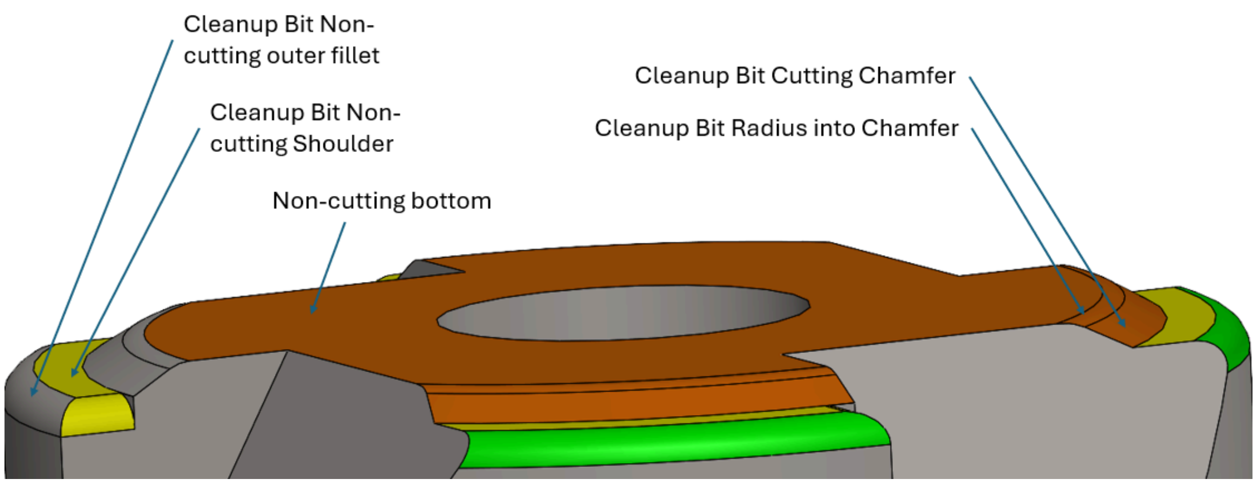
4.	The bit shall be brought into contact with the surface of the aluminum plate.
5.	The Bridgeport digital readout shall be zeroed
6.	Run the Bridgeport and machine the aluminum plate by plunging the bit down.
7.	Continue to machine up until the bit will no longer plunge into the plate.
8.	If the bit is not able to continue to machine through the plate, and bottoms out regardless of applied pressure by the mill, check the box for "Non-Plunging Center Flat", **L261** column 1
9.	Record the measurement of the depth on the Bridgeport digital readout when the bit is fully plunged, **L261** column 2
10.	If the digital readout shows a value between 0.029'' and 0.031'', check the box for "plunge depth is within specification", **L261** column 3
11.	Clean up the oil and machine metal from the Aluminum plate.
12.	Utilize a depth plunger to record the depth of the generated 'island feature', utilize the island as the 'zero' point for the measurement. Record in **L261** column 4.
13.	If the depth plunger recorded depth is between 0.029'' and 0.031'', check the box for "cut depth is within specification", **L261** column 5
14.	Set the aluminum plate at a 30 degree angle within the Bridgeport vice. Utilize the 3d printed 'ramp' to determine this angle, and be sure to remove it before proceeding to the next step.

15.	Attempt to drill into the aluminum plate utilizing the corner of the machining bit.
16.	Record whether the bit successfully machined the plate with the corner by checking the appropriate box on the inspection sheet, **L261** column 6
17.	If the bit fails to meet criteria for any critical features, or if there is apparent visual nonconformance, fill out a “red tag” form (**Q250**) and either create or add to an existing nonconformance report (**Q251**) for the lot.
18.	Upon successful inspection of all criteria, bag or otherwise denote the part as having passed inspection.

If available and verified, a gauge or sample negative of the Milling Bit may be used in lieu of aluminum plate testing. All forms and qualifications should be filled out to the same specifications and documented in the same way if tested with that method.

1.2 Cleanup Bit

The bit utilized for cleanup of the islands has the following form factor:



The chamfer and chamfer radius are the most important features to check the accuracy of. The two other critical aspects of the bit to check are the non-cutting features at the center flat, as well as at the outside corner fillet.

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To check these features, the following steps will be carried out:

Step	Task
1.	Prepare the inspection sheet (**L262**) by printing a copy generating a bit ID, and filling out the top of the form with the assigned bit ID, technician name, and date.
2.	The bit to be verified shall be equipped into the Bridgeport mill in the shop room.
3.	An aluminum plate featuring a pre-prepared island shall be set up beneath the bit. Record the pre-cleanup depth of the island with a depth plunger in **L262** column 1
4.	The cleanup bit shall be brought into contact with the surface of the aluminum plate. Use this to center the island under the cleanup bit
5.	Run the Bridgeport and machine the aluminum plate by plunging the bit down.
6.	Continue to machine until the bit will no longer plunge into the plate.
7.	If the bit is not able to continue to machine through the plate, and bottoms out regardless of applied pressure by the mill, check the box for “center flat is non-plunging”, **L262** column 2
8.	Clean up the oil and machined metal from the aluminum plate.
9.	Inspect the OD of the original aluminum plate feature, if it no longer contains sharp corners – record that the cleanup feature was operational, **L262** column 3

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10.	Utilize a depth plunger to record the depth of the remaining 'island feature', utilize the island as the 'zero' point for the measurement. Record on **L262** column 4
11.	If the depth plunger recorded depth is between 0.029'' and 0.033'', check the box for "cut depth is within specification", **L262** column 5
12.	Set the aluminum plate at a 30 degree angle within the Bridgeport vice. Utilize the 3d printed 'ramp' to determine this angle, and be sure to remove it before proceeding to the next step.
13.	Attempt to drill into the aluminum plate utilizing the corner of the machining bit.
14.	Record whether the bit successfully machined the plate with the corner by checking **L262** column 6
15.	If the bit fails to meet criteria for any critical features, or if there is apparent visual nonconformance, fill out a "red tag" form (**Q250**) and either create or add to an existing nonconformance report (**Q251**) for the lot.
16.	Upon successful inspection of all criteria, bag or otherwise denote the part as having passed inspection.

If available and verified, a gauge or sample negative of the Cleanup Bit may be used in lieu of aluminum plate testing. All forms and qualifications should be filled out to the same specifications and documented in the same way if tested with that method.

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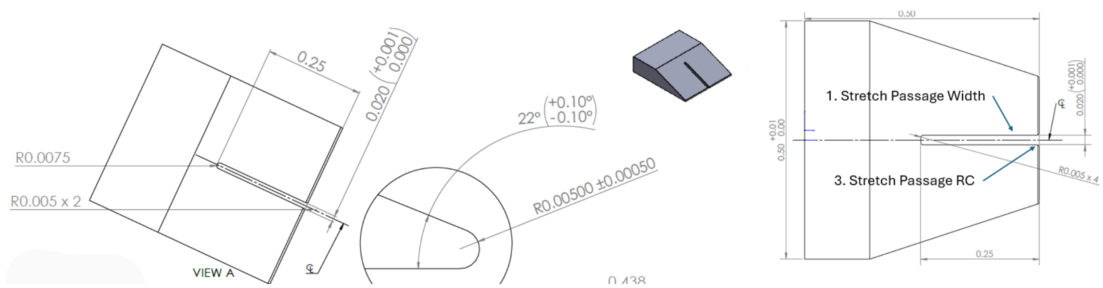
1.3 Dovetail Blunted Blade



1.3.1 Pre-Coating Batch Testing

The blunted blades used in the BTM process are manufactured and then coated. Before sending a batch off for coating, a batch should be tested for proper manufacturing quality of critical features. These features are:

1. Width
2. Thickness

Batches should be tested at a quantity of one (1) blade per batch plus one additional blade per twenty-five blades in the batch. For example, a batch of fifty blades would feature 3 tested blades, and a batch of one-hundred blades would feature 5 tested blades.

To check these features, the following steps will be carried out:

Step	Task
1.	Prepare the inspection sheet (**L263**) by printing a copy generating a blade lot ID, and filling out the top of the form with the assigned blade lot ID, technician name, and date.
2.	Inspect width and thickness using Keyence laser scan, measured against grid in measurement software and note on form **L263**
3.	If the blade fails to meet criteria for either feature, or if there is apparent visual nonconformance, fill out a “red tag” form (**Q250**) and either create or add to an existing nonconformance report (**Q251**) for the lot.
4.	Upon successful inspection of all criteria, bag or otherwise denote the part as having passed inspection.

1.3.2 Post-Coating Blade Testing

After coating, blades should be tested more stringently for quality. The following will be applied to all blades before incorporating them into BTM products.

The blunted blade must have three critical features validated:

1. Stretch passage width
2. Tip radius
3. Stretch passage entry radius

It additionally has three non-critical features to take note of value

1. Blade Angle
2. Width
3. Thickness

To check these features, the following steps will be carried out:

Step	Task
1.	Prepare the inspection sheet (**L263**) by printing a copy and filling out the top of the form with the blade lot ID, technician name, and date.
2.	Use a feeler gauge to inspect the stretch passage width. The stretch passage should accept a feeler gauge of 0.020” but not of 0.021”. If this criteria is satisfied, mark the box in column 1 on form **L263**.
3.	Visually inspect stretch passage entry radius on both sides using the Keyence system and mark in column 2 on form **L263**
4.	Inspect front radius using Keyence laser scan, measured against grid in measurement software and note in column 3 on form **L263.**
5.	Measure blade angle using protractor and mark on form **L263** in column 4. Blade angle should be between 21° and 23°
6.	Inspect width and thickness using Keyence laser scan, measured against grid in measurement software and note in columns 4 and 5 on form **L263.**

	The Width should be between 0.500” and 0.540”, and the thickness should be between 0.130” and 0.150”
7.	If the blade failed to meet criteria for any critical features, or if there is apparent visual nonconformance, fill out a “red tag” form (**Q250**) and either create or add to an existing nonconformance report (**Q251**) for the lot.
8.	Upon successful inspection of all criteria, bag or otherwise denote the part as having passed inspection.

1.4 Non-Dovetail Sharper Blade

1.4.1 Pre-Coating Batch Testing

The non-dovetail sharper blades used in the BTM process are manufactured and then coated. Before sending a batch off for coating, a batch should be tested for proper manufacturing quality of critical features. These features are:

1. Width
2. Thickness

Batches should be tested at a quantity of one (1) blade per batch plus one additional blade per twenty-five blades in the batch. For example, a batch of fifty blades would feature 3 tested blades, and a batch of one-hundred blades would feature 5 tested blades.

To check these features, the following steps will be carried out:

Step	Task
1.	Prepare the inspection sheet (**L264**) by printing a copy generating a blade lot ID, and filling out the top of the form with the assigned blade lot ID, technician name, and date.
2.	Inspect width and thickness using Keyence laser scan, measured against grid in measurement software and note on form **L264**

3.	If the blade fails to meet criteria for either feature, or if there is apparent visual nonconformance, fill out a “red tag” form (**Q250**) and either create or add to an existing nonconformance report (**Q251**) for the lot.
4.	Upon successful inspection of all criteria, bag or otherwise denote the part as having passed inspection.

1.4.2 Post-Coating Blade Testing

After coating, blades should be tested more stringently for quality. The following will be applied to all blades before incorporating them into BTM products.

The non-dovetail sharper blade must have three critical features validated:

1. Stretch passage width
2. Tip radius
3. Stretch passage entry radius

It additionally has three non-critical features to take note of value

1. Blade Angle
2. Width
3. Thickness

To check these features, the following steps will be carried out:

Step	Task
1.	Prepare the inspection sheet (**L264**) by printing a copy and filling out the top of the form with the blade lot ID, technician name, and date.
2.	Use a feeler gauge to inspect the stretch passage width. The stretch passage should accept a feeler gauge of 0.020” but not of 0.021”. If this criteria is satisfied, mark the box in column 1 on form **L264**.
3.	Visually inspect stretch passage entry radius on both sides using the Keyence system and mark in column 2 on form **L264**

4.	Inspect front radius using Keyence laser scan, measured against grid in measurement software and note in column 3 on form **L264**
5.	Measure blade angle using protractor and mark on form **L264** in column 4. Blade angle should be between 21° and 23°
6.	Inspect width and height using Keyence laser scan, measured against grid in measurement software and note in columns 5 and 6 on form **L264.** The Width should be between 0.430” and 0.450” and the Thickness should be between 0.120” and 0.140”.
7.	If the blade fails to meet criteria for any critical features, or if there is apparent visual nonconformance, fill out a “red tag” form (**Q250**) and either create or add to an existing nonconformance report (**Q251**) for the lot.
8.	Upon successful inspection of all criteria, bag or otherwise denote the part as having passed inspection.

2. Post-Field Measurement of Chips and Replicas

Once field testing is accomplished, analysis of the created features (chips and replicas) are crucial to generate data about the sampled pipe. Post-field measurement involves using our Keyence laser scanning to properly measure the created features.

See form **L-251: Chip and Replica Scanning SOP** for all post-field measurement of chips and replicas.

3. BTMGuru Post-Processing of Chips and Replicas

After measurement of the created features, analysis of the data is performed using BTMGuru to determine the characteristics of the created features and the sample from which they were created.

See form **L-252: Test Processing and Analytics SOP** for all post-field processing of chip and replica data.

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4. Compiling Processed Results into Audit Log

All processed results should be denoted with the lot numbers of all associated field consumables for easy identification of any lot-specific problems.

All "red tag" forms and nonconformance reports should be kept together within individual lot numbers and for specific item numbers to allow for tracking of quality and consistency of field consumables. If forms or reports are required at a later date for retrospective or post-mortem presentations, copies should be made in lieu of taking the originals from storage.

5. Sampling Frequency

While this SOP establishes an initial frequency of testing, as control limits are established and both quality and consistency is ensured, the frequency of testing may reduce unless a reason arises to keep it at the initial frequency. Updates to this document should reflect that changed frequency in testing.

6. Nonconformance Review and Approval

If a nonconformance occurs in processing and is filed, that nonconformance is to be reviewed and approved by an MMT Subject Matter Expert and subsequent action such as root cause analysis is to be handled accordingly.

Attachment 4 – Engineering Specification

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E-250: BTM Engineering Specification

Prepared by: Bryan Feigel, Intisar Rizwan I Haque, Simon Bellemare

Reviewed by: Aidan Ryan, Vik Vajda, Gene Hurley

Approved by: Simon Bellemare

REV	DATE	CHANGE	By/Reviewed	Approved
01	2025-06-25	Initial Release	Bryan Feigel	Simon Bellemare

Supporting documents: MMT F-250, MMT L-250

Scope

Compliance: This document specifies the method, tools, procedures, and techniques MMT utilizes to deliver accurate and reliable results in compliance with 49 CFR §192.607.

Personnel and pipeline safety: Personnel safety on construction sites, facilities, travel, and any other work-related activities is paramount, but outside the scope of this document. Employers are responsible for the safety of their personnel. MMT does provide reminders where most appropriate on topics directly related to the use of its technologies. However, MMT has no authority to ensure compliance and is, therefore, not responsible for the safety of third-party personnel.

Data accuracy and reliability: Other than general information to help frame a context for the specifications, this document is focused on factors that could affect the quality and reliability of the result: material properties through Nondestructive Testing (NDT). Activities and processes not directly tied to the accuracy of the material properties are outside of the scope of this document and handled by items such as machine design, software programming, and handling of project information.

Distribution and tracking: This document shall be distributed only to asset owners and their service providers who utilize MMT's testing reports for compliance, pipeline integrity, and risk management. The revision tracking for supporting specifications and operating procedures referred to in this document shall remain within those individual documents. Sample testing and project reports shall contain the revision tracker for these documents.

Risk of technology and human errors: Each testing report package provides product and service limitations stating the risk of outliers to accuracy due to the nature of the measurements made and the risk of human error related to applying the processes involved in collecting, analyzing, and reporting NDT results.

Table of Contents

1. Summary of BTM Testing Process

1.1 Methods

Planing-Induced Microfracture: The BTM technology utilizes the planing-induced microfracture method. This method introduces a subsurface microcrack into a specimen using a specialized blade featuring a central stretch passage. As the blade traverses the specimen surface, the material flowing into the stretch passage experiences tensile stress between the formed chip and the substrate, resulting in a fracture. Subsequently, fracture properties are analyzed to perform a nondestructive evaluation of material fracture toughness.

1.2 Tools

BTM Instrument: The BTM testing process utilizes a specialized endmill, blades with a stretch passage, and a clean-up endmill. These three components are integrated into the BTM instrument.

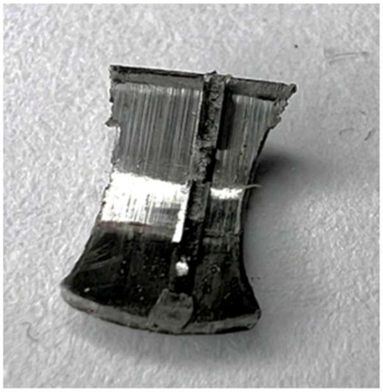



Figure 1: Left – Opposite Facing Cutting Blades Engaged with a Test Island; Right – Resulting chip
(Figure is an excerpt from "Introduction of a Portable Field Instrument for In-ditch Pipe Body Toughness Determination," PPIM 2025.)

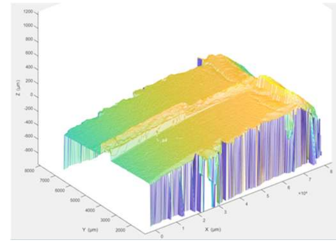
Laser Scanner: High-resolution digital representations of the fractured ligament are acquired using a laser scanner.

1.3 Procedures

Field Documentation: Sample features are documented in accordance with MMT procedures. This documentation includes the sample name, line ID, outer diameter, wall thickness, and other relevant specifications. Additionally, site images, test location images, and post-test images are captured.

Surface Preparation: A custom, non-plunging endmill is employed to machine circular "islands" of material. This process is repeated to create six BTM test locations, one on each side of three islands, as dictated by the instrument design, thereby establishing surfaces for planing-induced microfracture testing.

In-Situ Testing: The BTM instrument generates a planing-induced microfracture at prepared locations on the sample surface. Fracture ligaments from each chip and replicas of the substrate ligaments are collected for post-processing.



3D model of a fracture ligament.

Post-Processing: Three-dimensional models of the fracture ligaments from the chip and substrate are generated using laser scanning technology. Key fracture surface features, such as stretched ligament height at fracture and ligament cross-sectional flat width, are evaluated. Samples are reviewed for consistency and accuracy, with identified inconsistencies investigated and resolved.

Data Evaluation: Processed data is analyzed to determine a nondestructive evaluation of fracture toughness. The final results are reviewed to confirm measurements and assess applicability within the sample range of known laboratory results.

Model Creation: A physical model, replicating the planing-induced microfracture method, is developed. A machine learning model, generated using industry best practices, refines results to enhance the accuracy and reliability of predicted material properties.

1.4 Techniques

Field Technique: Field data collected is acquired by a technician trained to perform the MMT F-250 field procedure.

Lab Technique: Laboratory data evaluated to generate a report is collected by a technician trained to perform the MMT L-250 laboratory procedure.

Data Technique: Data evaluation is performed by an individual trained in and utilizing this engineering specification.

2. Instrument Specification and Usage Factors

Figure 3: Overview of Instrument with reference to subsection 2.1.1, 2.1.2, 2.1.3, 2.1.14 sub-systems

2.1 Functions

2.1.1 Tester Securement

The instrument must be able to attach to the tested sample with the following key criteria satisfied:

1. Securement must be sufficiently forceful to prevent relative motion between the tester, and the sample, during all tool operations
2. Securement methods cannot require power more than what can be run simultaneously to the other functions.

2.1.2 Surface Preparation

The test surface must be prepared for the planing induced microfracture test. This consists of a raised portion of material with the following characteristics:

1. No less than 0.1625" in length for each test

2. No less than 0.025" in height, as measured from the machined surface to the outer surface of the pipe at the shortest point.
3. A minimum of 0.25" preceding of the starting face of the test which is the depth of the machined surface. This provides clearance for access of the blade which machines off the raised portion of prepared material.
4. A width of the raised portion of material no less than 0.125"
5. The surface preparation shall not exceed 0.030" of depth (+/- 0.001") at its deepest location

2.1.3 Blade Holding

The blade which 'cuts' or 'planes' the prepared surface during the planing induced microfracture test must:

1. Be able to withstand the loads seen on the blade during the planing operation (on high strength pipes, loads may be in excess of 125lbs)
2. Can be translated between the various prepared surfaces with minimal difficulty
3. Minimize deflection such that the angle of interaction between the blade and the prepared material remains consistent
4. Not allow the blade to 'skip' or 'jump' through the prepared material during testing as a result of deflection coming and going
5. Not allow the depth of the test to change during the test as a result of the forces experienced on the blade or the holder

2.1.4 Blade Actuation (Planing Induced Microfracture)

The planing induced microfracture test must:

1. Allow the movement of the blade through the prepared surface (if pipe, circumferential test direction). Keep the path consistent without deviation under load, or a path which is misoriented relative to the prepared surface.
2. Move the blade at a rate of 0.002 in/sec (+/- 0.0005 in/sec)
3. Do not allow motion to become inconsistent or stutter as a result of slop, lag, or deformation

2.1.5 Surface Cleanup

The final function of the tool is to leave the tested surface in the following condition:

1. Lacking any sharp (IE: radius of curvature less than 0.010") corners which could act as stress concentrations.
2. A supplementary surface cleanup tool may be allowed. If this approach is taken, the supplementary tool shall be considered a "process accessory" for the purposes of other requirements (IE: field viability).

3. Final surface removal not to exceed 0.035”

2.1.6 Field Viability

The BTM tester is intended for in-field utilization and as such the following criteria should be met:

1. Weight of any individual component of the tester no greater than 50 lbs
2. Weight of entire tester, except for spare hardware, accompanying hardware or process accessories must be less than 100lbs when packed
3. Spare hardware and process accessories necessitated by the tool design must not exceed 20lbs, and be able to fit into a pelican case
4. Tools should remain fully operational under moderate vibration:
    a. Up to 0.6 in/sec velocity
    b. Up to 0.3 in/sec^2 acceleration
    c. Operational at frequencies up to 6-13 Hz
5. Tool should remain fully operational even under direct sunlight and heat ranges from 32 - 115 degrees Fahrenheit

2.2 Design Validation

Any design of the BTM tool must pass the following validation checks to be considered sufficient for field utilization:

Sub-system, #	**Design Validation Check**
Tester Securement, 1	Secure tester onto pipe. Ensure setup will not fall over when exposed to tangential load. Attach load reading pull gauge and apply load to the tester, oriented tangential to pipe, of 150lbs.
Tester Securement, 3	If securement method requires power, perform all surface preparation, blade holding, blade testing operations alongside active securement and confirm correct operation.
Surface Preparation, 1-4	Perform surface preparation. Verify all specified dimensions are satisfied.
Surface Preparation, 5	Attempt to utilize the tool as-is to remove more material than the prescribed 0.030”. Check the material removal afterward to confirm that no more than 0.030” was able to be removed.
Blade Holding, 1 & 3 & 4	Perform testing on a high strength pipe (UTS > 105ksi). Orient a run out gauge such that it can indicate the

	deflection of the blade holder nearby to where it holds the blade. Monitor deflection during the test remains below 0.005". Record the indicator dial to ensure deflection that does occur is smooth and does not 'skip' or 'jump'.
Blade Holding, 2	Move the blade holder setup between all test positions and secure it there, within 5 minutes time.
Blade Holding, 5	After testing on high strength pipe, perform depth gauge measurements to observe the cut depth relative to the machined surface throughout the test. Confirm that the cut depth did not vary by more than 0.003" over the length of the test.
Blade Actuation, 1	Perform testing on a sample of high strength. Record the test from the top and side view. Review the video and confirm the orientation of the test as well as any deviation from the intended path.
Blade Actuation, 2	During testing on a sample of high strength, include a top view with a distance scale (IE: ruler) oriented adjacent to the drive train. Review the video to confirm the distance traveled over a length of time. Calculate to confirm speed.
Blade Actuation, 3	Review video of conducted high strength testing, keeping careful watch for periods of time where the motion of the blade through the test surface is inconsistent.
Surface Cleanup, 1	At the conclusion of the testing of a sample, utilize the tester to perform final cleanup operations. Inspect cleaned-up sample testing area and confirm the absence of sharp corners. This test should be performed on 8" OD pipe as well as a 26" or greater OD pipe.
Surface Cleanup, 2	Utilize the tester to clean up the test area. Continue to utilize the tester to try and remove more than the allowable 0.035" of material. Utilize depth gauge or UT to confirm that more than 0.035" was not able to be removed.
Field Viability, 1 & 2	Weigh the tester subsystems, as they would be separated during transit into and out of the ditch. Ensure no individual subsystem exceeds a 50lbs weight requirement. Pack the full tester and subsystems into its travel case. Ensure total weight does not exceed 100lbs.

Field Viability, 3	Weigh the process accessories, spare hardware, and associated carry case (if applicable). Ensure the weight does not exceed 20lbs.
Field Viability, 4	Testing should be performed on a sample exposed to the vibration and frequency specified. Special note should be taken of damage to the blade, test success rate, and final measurement.
Field Viability, 5	Testing of the electronics and electronic controls should be performed at the bounds of the specified temperature range. Consideration of the effect of direct sunlight on metal components should be performed w.r.t. usability.

2.3 Deployment

Deployment of these standards includes two key items.

The first item is consistent confirmation of - and reference to - the above standards during the design, and design validation process.

The second item is the incorporation of the following validation confirmation table into outgoing release notes:

Sub-system, #	**Design Validation Check**	**Value**
Tester Securement, 1	Tangential loading test	X lbs
Tester Securement, 3	Generator Equipment Testing	P / F
Surface Preparation, 1-4	Prepared Surface Geometry Verification	P / F
Surface Preparation, 5	Depth Limitation Verification (<.030")	P / F
Blade Holding, 1 & 3 & 4	Deflection During High Strength Pipe Test (HSPT) (<0.005)	X.XXX in
Blade Holding, 2	Time to adjust blade to each position	X min
Blade Holding, 5	Change in cut depth over test length under high strength pipe test	X.XXX in
Blade Actuation, 1	Observed deviation of test path during HSPT	X.XXX in
Blade Actuation, 2	Travel Speed Confirmed	P / F

Blade Actuation, 3	Consistent Motion Check	P / F
Surface Cleanup, 1	Surface Cleanup on 8" and 26"+ OD	P / F
Surface Cleanup, 2	Depth Limitation Verification 2 (<.035")	P / F
Field Viability, 1	Highest Subsystem Weight (<50 lbs)	XX lbs,
Field Viability, 2	Total Weight (<100 lbs)	XX lbs
Field Viability, 3	Process Accessories Weight (<20 lbs)	XX lbs
Field Viability, 4	Testing performed under vibration	P / F
Field Viability, 5	Electronics Temperature Tested	P / F

3. Data Procedures

This section outlines the procedures for processing raw data obtained from the Blade Toughness Meter (BTM), quantifying relevant features, and utilizing data analytics, including a Machine Learning (ML) workflow, for material property estimation.

3.1 Data Processing and Property Prediction

Raw data from the BTM instrument's laser profilometer (Section 2.5) is processed using the validated BTMGuru Application. Level I personnel perform the initial processing, which is subsequently checked by Level II personnel.

3.1.1 Data Ingest and Preparation

- **Input:** Raw profilometer scan files (Chip scans and Body scan replicas) are ingested.
- **Metadata Association:** Each scan file is associated with corresponding metadata (e.g., Sample ID, Quadrant, Island, Test Side) upon loading for traceability.
- **Scan Preparation:** Initial software-based steps include:
    - Data integrity verification (e.g., number of tests/scans, label verification).
    - Vertical inversion of Body scan data for consistent spatial orientation.
- **Scan Cropping:** Data is cropped to remove non-relevant background areas, isolating the ligament topography and adjacent cut plane regions.
- **Quality Control:** Preparation quality is confirmed by Level I analysts and/or automated routines. Decisions ensure the preservation of key features and the presence of adequate data according to defined standards. These determinations are tracked.

3.1.2 Scan Alignment and Referencing

- **Reference Definition:** Accurate spatial references are established:
  - A centerline is defined along the ligament using validated automated routines with mandatory operator review and correction capability.
  - The adjacent cut plane reference surface is mathematically modeled (e.g., using first or second-order polynomials based on scan characteristics).
- **Alignment:** Processed Chip and Body scan profiles are aligned. This involves aligning the fracture initiation point on both scans and then applying horizontal shifting and linear stretching algorithms to the Chip scan to align features down the test length, accounting for material deformation. Alignment may be iterated. The "test start" and "test end" are defined as the beginning and end of the region in which the aligned scans overlap.
- **Alignment Quality Control:** Final alignment quality is quantitatively assessed using metrics like the standard deviation of measurements in the steady state response region of the test. Tests not meeting the minimum criteria may be flagged or rejected.

3.1.3 Processing, Review, and Output Generation

- **Core Processing:** Once prepared, referenced, and aligned per validated procedures, algorithms calculate fundamental topographical metrics (e.g., height, width) using controlled parameters.
- **Final Review:** Level II personnel perform a final review, comparing results against visual checks and QA/QC metrics. Notes are recorded, and adherence to standards is confirmed.
- **Outputs:** Validated outputs include:
  - Detailed processed data state files (e.g., AppData.mat format) archiving settings, parameters, and processed data for traceability.
  - Summary output files with key aggregated feature values (e.g., FlatRegionWidth, Ligament Height) for ML models, serving as direct inputs for Section 3.3.

3.2 Feature Quantification

Following raw data processing (3.1), validated MMT computational routines quantify specific features required for the Data Analytics (ML Workflow) (3.3). Features are derived from processed BTM topographical data and HSDPlus data.

3.2.1 Required Input Data

- Processed BTM topographical data files (output of 3.1).
- HSDPlus data:
  - Chemical composition (Sulphur content: weight percent).
  - Surface and Bulk Material Yield Strength and UTS [ksi] from HSD testing.

3.2.2 Key Output Features for ML Model

The individual features included in Data Analytics are provided with the report. Any changes in algorithms to measure them are listed in the release notes.

3.2.3 Control and Validation

- All algorithms, models (StrainModel – physical model), parameters, and routines are subject to MMT's internal software validation, version control, and quality management.
- Intermediate calculations and quality checks are documented per internal procedures.

3.3 Data Analytics (ML Workflow)

MMT utilizes a systematic, multi-stage Machine Learning (ML) workflow for developing, validating, and deploying models to estimate material properties from NDT data, ensuring reliable and consistent predictions.

3.3.1 Overview of the ML Workflow Stages

The workflow consists of three primary stages:

1. **Model Development and Training:** Building robust models using high-quality data.
2. **System Integration and Validation:** Ensuring reliable model performance within operational systems.
3. **Production Deployment and Monitoring:** Managing rollout and periodic performance tracking.

3.3.2 Stage 1: Model Development and Training

- **Data Foundation:**
  - *Data Acquisition:* Models use comprehensive datasets combining NDT measurements (BTM, HSDPlus) with reference data from destructive testing (e.g., fracture toughness, tensile properties, composition) sourced from internal tests, JIPs, and customer projects.
  - *Data Integrity:* QA processes are applied. Reference destructive test data should meet relevant industry standards. Merging data from multiple labs presents challenges due to variations, but can enhance robustness. Reference data has inherent variability (number of tests per sample or bias between different labs); statistical methods (e.g., confidence intervals for K95) may handle this. Certain datapoints may be disqualified or corrected.
- **Feature Engineering:**
  - Predictive features (inputs for the model, e.g., those listed in Section 3.2) are engineered from NDT data, often leveraging physical understanding.

Examples include specific BTM ligament measures or HSD surface strength.

- **Model Training and Evaluation:**
    - *Features vs. Parameters:* It's crucial to distinguish Features (inputs derived from data, see 3.3.2.b) from model Parameters (internal values like weights learned during training to map features to predictions). MMT uses validated training methods for reliable parameter learning.
    - *Model Selection:* Appropriate ML algorithms are selected and trained for the target property (e.g., K95 fracture toughness).
    - *Performance Evaluation:* Performance is evaluated using standard metrics (MAE, RMSE, R2 Score) and compared against statistical results and target performance levels (e.g., a typical target tolerance for K is +/- 20 ksi√in).
- **Model Serialization:**
    - Validated models are saved (e.g., ONNX format) in a secure, version-controlled repository with metadata and documentation.

3.3.3 Stage 2: System Integration and Validation

- **Integration:** Validated models are integrated into operational software (e.g., MMTCentral), with data pipelines established.
- **Validation:**
    - *Validation Testing:* Models undergo pre-deployment validation using methods suitable for the data size (e.g., blind testing against unknown samples or k-fold cross-validation on the development dataset).
    - *Performance Assessment:* Performance is assessed using standard metrics and visualizations (e.g., Unity Plots).
    - *Performance Review:* Results are reviewed across different materials and conditions. Key metrics and statistical evaluations are documented and provided in customer reports for comparison against target performance or application requirements.
- **Deriving Conservative Estimates (using Tolerance Intervals):**
    - *Purpose:* To provide a reliably conservative estimate for critical applications, MMT uses a statistical approach, often applying a "conservative shift" based on tolerance intervals. Tolerance intervals estimate the range expected to contain a specified proportion of the population with a given confidence, aligning well with establishing conservative lower bounds.
    - *Method:* A 1-Sided Tolerance Interval (e.g., using Hanson-Koopmans) determines a lower bound based on chosen confidence (e.g., 50%) and certainty/proportion (e.g., 95%) parameters. The resulting tolerance value represents the shift.
    - *Application:* MMT's standard reported conservative value is typically the model's point prediction minus this tolerance value (e.g., Conservative K = Predicted K - Tolerance Value @ 90% Certainty / 90% Confidence). End-users can utilize this, or the point prediction and uncertainty metrics, according to their own risk management procedures.

3.3.4 Stage 3: Production Deployment and Monitoring

- **Controlled Deployment and Reporting:**
  - Successfully validated models are deployed.
  - **Release Process**
    - Decision is made**.**
    - Release notes are prepared and approved by the Subject Matter Expert (SME). These include Model Application, Release Overview, Validation Summary, Usage Guidance, and Version Information.
    - Accuracy statement updated on report template.
  - Reports using ML predictions clearly state the model release number and the resulting conservative estimate (derived per 3.3.3.c).
- **Periodic Monitoring:**
  - *Performance Tracking:* Deployed models are periodically monitored for degradation and input data drift.
  - *Retraining:* Models are periodically retrained with new validated data or if monitoring indicates performance degradation below acceptance thresholds.
  - *Model Improvement Decisions:* Increased database size or insights from monitoring often trigger the development of improved model versions following the Stage 1 process (3.3.2).

4. Technique Competency and Reviewed Status

Many instrument uses and data analysis aspects cannot be fully automated. To be reliable, the execution of these tasks and procedures requires personnel competency to be dependable and consistent.

4.1 Level of Competency

From a general standpoint, competency

- Level 1 means that the personnel has been trained to apply a specification, procedure, or technique and has shown the ability to do so independently and effectively.
- Level 2 means the personnel is a Level 1 that has been tested on their ability to identify and rectify nonstandard cases.
- Level 3 means a personnel is a Level 2 that has been deemed competent by the SME to manage the knowledge and processes within the company.
- Subject Matter Expert (SME) means a person has the highest topic-specific knowledge. For certain areas there may be more than one SME.

The level of competency of personnel shall be determined either:

- Directly by the Subject Matter Expert (SME) for specific specification, procedure, or technique.
- By Level 3 personnel using training and competency verification requirements provided by that SME.

Technique control parameters:

- A personnel log shall be maintained periodically to track the competency of Level 2, Level 3, and SMEs.
- A certificate may be issued, especially for outside personnel to document competency. These may only be issued when the activities to determine the level of competency include training and verification of the results.

4.2 Reviewed Status

For any activity with an assigned reviewer, it is specified that work performed by Level 1 personnel could directly affect the accuracy and reliability of the result and be reviewed by Level 2 personnel.

Acceptable reviewing methods for the Level 2 personnel shall include:

- Spot-checking measurements and interpretation.
- Verification of testing logs, process logs, and any other documentation required by the specifications for the task.

Reviewers may rely on other reviewers for sub-tasks pending appropriate documentation of who reviewed the work.

Review control parameter: Identification of personnel included with the deliverables.

5. Reference to this Specification

Referring to this specification at MMT E-250 with the current revision shall mean that the requirements from this document are met.

Attachment 5 – BTM Mock Sample Report

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Nondestructive Material Verification - BTM Detailed Report

General Testing Information

Customer	PHMSA MMT R&D PROJECT	**Job ID**	MMT BTM25001	**Report No.**	20250402
Sample ID	CGM-04			**Test Date**	1/22/25
Pipe Size	8.675	**Line ID**	NA	**Test Time**	16:35
GPS Coordinates	42.281342, -71.354950	**Dig ID**	NA		
Test Name	CGM23028				
Sample Description	Seamless pipe sample with WT 0.24 in.				
Testing Location	MMT facility				

Nondestructive Testing:
The following method, instruments, procedures, and techniques have been validated by subject matter experts based on comparison with destructive test results on materials

1. Method: Planing-Induced Microfracture

Nominal Cut Depth 0.03 in. Nominal Island Length 0.19 in. Nominal Island Center Width 0.13 in.

2. Instrument: Blade Toughness Meter (BTM)

Unit Serial Number	BTM003	Blade Parameters	Side A	Side B
Calibration Log	20250530	Width	0.02 in.	0.02 in.
		Calibration Log	00259	00260

3. Procedure

4.1 Field Procedure	Release 1.0
4.2 Laboratory Procedure	Release 1.1
4.3 Engineering Procedure	Release 1.2

4. Technique Verification

Level II Technician:	BF
Level II Personnel:	AH
Level II Analyst:	DC

5. Data Evaluation

3.1 Laser-Scanned Data Processing

(A) Ligament Height (um)

	Count	Avg	StDev
Quadrant 1	297	196	9
Quadrant 2	306	200	7

(B) Flat Width (um)

	Count	Avg	StDev
Quadrant 1	582	138	16
Quadrant 2	609	118	4

3.2 Inputs from HSD Plus Process

HSD Surface Values

Flow1	Flow2
56	81

Other Parameters

Sulfur 0.02

3.3 Physical Model

	Strain*Stress (KJ/m2)
Average	151

3.4 Data Analytics

Release 2025B

	Toughness (ksi*in^.5)
K95	103

Findings

Laboratory-Equivalent Compact Tension (CT) Specimen Fracture Toughness

K (Min of 3 samples equivalent) 105 ksi √in.

Data Engineering

Checked by: IRH

Approved by: SCB

Process log notes:

None applicable (Specifications Met)

Reference information:

See additional documents in report package for more information.