# Public Quarterly Report

**Date of Report:** 4th *Quarterly Report, September 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*
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**For quarterly period ending:** *September 30, 2025*

## 1: Items Completed During this Quarterly Period:

Three tasks have been completed this quarter. Task 1.3 has been concluded successfully with the end of an initial testing for sharper blade geometries which enable reduced cut depths. Findings from this task have been detailed in the final report deliverable for the task in Attachment 1. Task 2.1 has concluded with the completion of several initial field pilot works, associated tool improvements, and the rollout of version 1.1 of the instrument platform. Attachment 2 outlines the learnings and tool improvements associated with Task 2.1. Task 2.3 has been completed with the development and release of supporting documentation for the previously released F250, L250, and E250 procedures. These supporting documents can be found in Attachment 3.

Item #13 from Task 2.2 is completed in correspondence with improvements to the processing software which enable more automation in the delivery of measurements from the tool into machine learning models for final predictions. Additional automation of some quality control metrics is also included. These work tasks are overviewed in the TAP panel update found in Attachment 4.

**Table 1 – Tasks completed and invoiced this quarterly period**

| *Item #* | *Task #* | *Activity/Deliverable* | *Title* | *Federal Cost* | *Cost Share* |
|---|---|---|---|---|---|
| ***14*** | ***N/A*** | ***4th Quarterly Report*** | ***Submit 4th quarterly report*** | ***0.00*** | ***0.00*** |
| ***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*** |
| ***12*** | ***2.1*** | ***Conduct field trials and modify the tool according to trial feedbacks*** | ***A summary of findings and results from field trials submitted*** | ***$36,452.62*** | ***$36,452.67*** |
| ***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*** | ***$16,307.67*** |
| ***15*** | ***2.1*** | ***Conduct field trials and modify the tool according to trial feedbacks*** | ***A summary of findings and results from field trials submitted*** | ***$36,452.62*** | ***$36,452.67*** |
| ***19*** | ***2.1*** | ***Conduct field trials and modify the tool according to trial feedbacks*** | ***A summary of findings and results from field trials submitted*** | ***$24,301.75*** | ***$24,301.78*** |
| ***20*** | ***2.3*** | ***Optimize the field procedure*** | ***Developed field procedure submitted*** | ***$31,410.28*** | ***$31,410.28*** |

## 2: Items Not-Completed During this Quarterly Period:

The tasks related to finite element analysis and related portions of the blade design optimization are still outstanding, although work has been completed to outline a path forward. Work is expected to remain on pause and take two quarters to conclude once it is resumed. Details of this development are outlined in Appendix C. Item #16 corresponds to analytics improvement work currently under way and expected to be completed next 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 process* | *Progress report with completed Task 1 and Task 2 progress from scope of work.* | *$22,698.50* | *$22,698.75* |
| *16* | *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.* | *16307.526* | *16307.666* |
| | | | | | |

## 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 plans to submit their third invoice for the project this quarter. Expenses correspond to all completed tasks reported on to date. The total invoiced to PHMSA will be $166,460.46 in keeping with applicable cost share. Invoiced items this quarter progress ahead of projections due to early completion of Task 2 items. These represent $92,165.11 of invoiced items which would otherwise have been completed in Quarter #5 and Quarter #6.

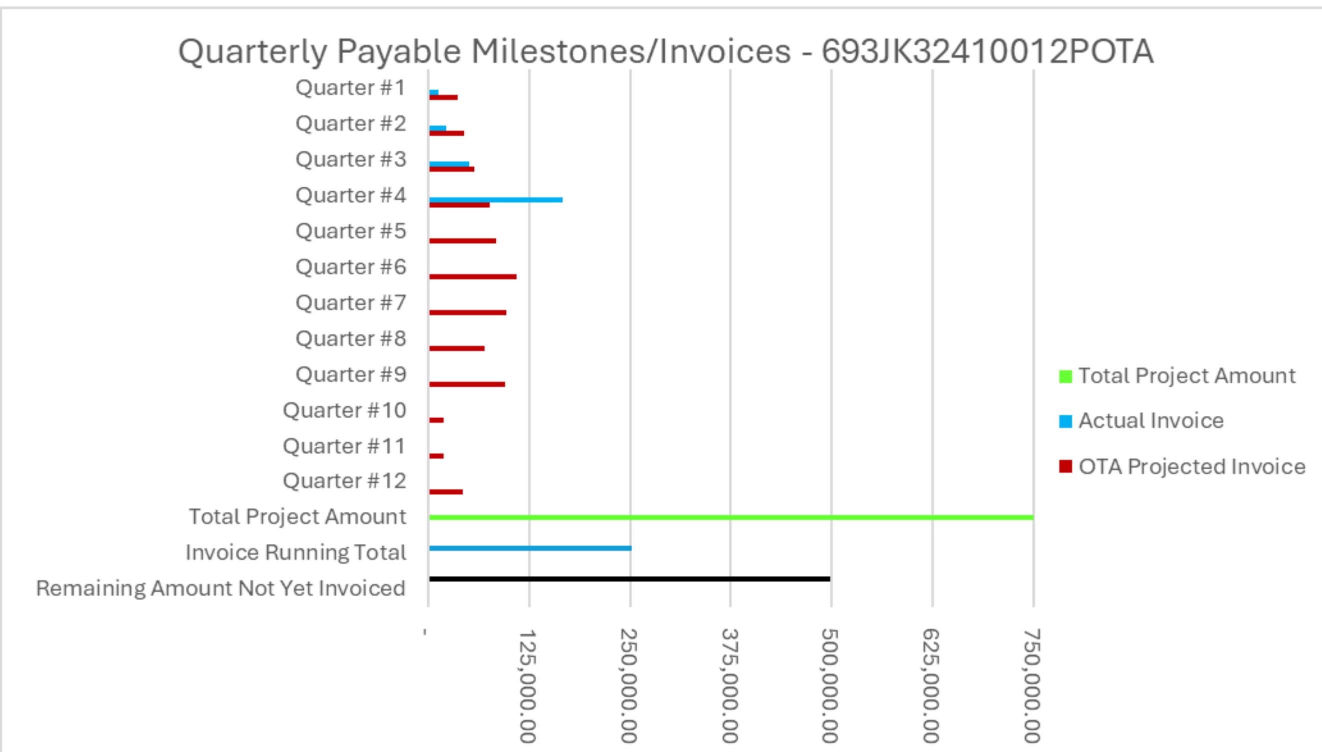


**Figure 1 – MMT quarterly payable milestones and invoices**

## 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.

geometries to reduce test depth. Task 2.1 made significant progress with the validation of v1.1 of the BTM tool, alongside continued in-field utilization of the tool. It is has now concluded following assembly of the final report. Coinciding with the focus on supporting early field utilization of the tool, improvements have been made to the automation and improvement of the post processing tools for test measurement in Task 2.2. This task is expected to reach conclusion at the end of the next quarter alongside completion of the analytics improvements currently under way.

Task 2.3 has concluded this quarter with the production of supporting documentation for the previously circulated laboratory and field procedures. This documentation consists of inspection sheets for consumables such as blades or surface preparation bits, as well as the handling of test specimen produced during testing as they come back into the facility for measurement. Coinciding with this, documentation for components which do not meet inspection criteria have been generated. In combination with the previously circulated materials, these constitute a consistent baseline for the reliable delivery of accurate BTM testing.

Expected work for next quarter includes improvements under Task 2.2 to the toughness prediction model based upon further availability of tested samples. Work toward the completion of the Task 2.4 Third-Party Validation will also be proceeding. Finally, preparation will begin for Milestone 3 tasks which will be starting in earnest in 2026.

**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 | 100 | 100 |
| **Milestone 2:** Field Trials and Evaluation | Hardware | 2.1 Field Device Development | 100 | 100 |
| | Software | 2.2 Data Process and Analytics Optimization | 66 | 66 |
| | Procedure | 2.3 Field Procedure Optimization | 100 | 100 |
| | Deliverable | 2.4 Third-Party Validation | 25 | 25 |
| **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 | 5 | 5 |
| | 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 |

## 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. Overall, the project is continuing along on its expected schedule. Milestone 1 tasks, with the exception of Task 1.2, are complete as of this quarter in accordance with the original submission project timeline. Milestone 2 items are concluding within the original anticipated timeline. It is possible that Milestone 2 will conclude one quarter ahead of schedule at the end of Q4. This will depend on the progress of Task 2.4: Third-Party Validation which has an expected conclusion at the end of Q1 2026. Preparation will begin next quarter to lay the groundwork for Milestone 3 items which are scheduled for work throughout 2026. Milestone 4 is still anticipated to begin in the second half of 2026.

**Attachment 1 – Task 1.3 Final Report**

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PHMSA Task 1.3 Final Deliverable Report

09/30/2025

## Executive Summary

Task 1.3 set out to analyze multiple aspects of the blade design in order to:

1. Optimize material response for consistency and dependence on fracture toughness
2. Reduce cut depth to minimize the invasiveness of the test
3. Optimize blade life to reduce testing cost and save time

Of these objectives, the following was successfully accomplished:

1. Multiple stretch passage widths were evaluated. Analysis concluded that there was a tradeoff between increased stretch passage width and limitations imposed by the nature of the test. A stretch passage width of 0.020'' was selected to balance these limitations, while improving the correlation (r^2 value) between test measurements and material fracture toughness by up to 128% for key metrics.
2. Alterations to various aspects of blade geometry, blade holding interfaces, and coatings to the blade were evaluated to improve blade life. The implementation of a Diamond-Like Carbon (DLC) coating over the tungsten carbide blade material significantly improved wear life, increasing the number of tests per blade by over ten times, drastically reducing consumable costs.
3. Various means of reducing cut depth were investigated. A viable pathway to reducing cut depth by ~25% was identified using a sharper blade geometry. Validation testing confirmed the feasibility of this approach, with the outcome of this task being a sharper blade to be included in ongoing testing of Task 2.4.

## Background

There were several key technical objectives associated with improvements to the blade-like stylus required to perform blade toughness meter (BTM) testing. The first of these objectives included improvement to both the accuracy and consistency of toughness prediction which were known to stem from geometry of the blade. Improvements of this type would assist the technology in becoming a competitive alternative to traditional destructive laboratory toughness testing of all types. Specifically, MMT sought to improve the accuracy of the prediction to be equivalent or better than +/- 20 ksi*sqrt(in).

The final key objective was to improve the ability of the tool to test on a greater volume of pipeline assets. The primary limiting factor is the amount of material which is removed by surface preparation to run a test. At the start of the project a surface must be prepared to a depth of 0.030'' in order ensure a successful test. On a large volume of pipeline assets this depth exceeds the nominal 10% wall thickness loss tolerated by most operators for non-destructive evaluation. The more that required depth is reduced, the larger the population of pipeline assets which may be tested.

## Technical Discussion

### Objective 1: Optimize material response for highest consistency and dependence on fracture toughness

Work on this objective primarily focused on exploring the effects of varying stretch passage widths on resulting material prediction ability, or material response consistency.

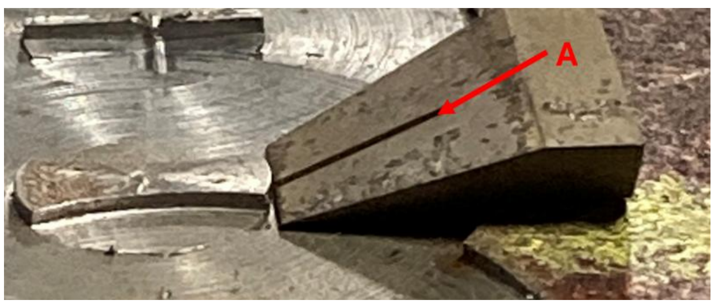


*Figure 1: Blade with Labelled Stretch Passage (A)*

Two primary stretch passage sizes were tested, 0.015'' and 0.020''. A variety of measurements of the fracture surface resulting from these tests were collected and compared. The common criteria utilized to judge these measurements was whether or not they correlated with the K fracture toughness properties of the various steels in the testing program. One metric which reflect how well a group of measurements on various materials correlates with the toughness of those materials, is the coefficient of determination or "r^2" value. Table 1 below shows the relative performance of the measurements produced by the 0.020'' blades and those produced by 0.015'' blades.

| | % increase of r^2<br>20sp vs 15sp blade data |
|---|---|
| Flat Width Measure v1.0 | 34% |
| Flat Width Measure v2.0 | 128% |
| Combined Zone Height | 2% |
| Combined 15% Height | 10% |

*Table 1: 15sp and 20sp measurement vs K - r^2 comparison*

All comparisons between material response measurements showed a stronger correlation between the 20sp tests and the destructive K values for the selected dataset. The improved flat width measurement showed a particularly notable difference in performance. Some thought has been given to why this may be the case.

Generally, a wider flat fracture region is associated with a more brittle response. The brittle vs ductile nature of a fracture test is known to be influenced by the ratio of plastic zone size to specimen thickness. It is hypothesized that the flat width measurement is improved here due to a wider stretch passage being akin to a thicker specimen in an E1820 CT geometry test. Placing the test condition more squarely into the brittle response region by increasing specimen thickness – independent of the varying plastic zone size as yield strength of materials differ – may assist in keeping measurements across samples more comparable. The result is a cleaner measurement which correlates more strongly with underlying toughness properties.

It was briefly considered that investigating even larger stretch passages might yield further improvements. This path was not pursued because of a determined relationship between stretch passage width and required test depth. This relationship is a result of maintaining successful conditions for testing. If a 0.020'' stretch passage is utilized, the test depth will have to exceed 0.025'' to be consistently successful. Larger stretch passages would require test depths in excess of 0.030'' which would directly conflict with objective 2. In general, it has been found that a successful test requires a stretch passage to be slightly less than the test depth.

### Objective 2: Reduce cut depth to minimize the invasiveness of the test without sacrificing accuracy

The main path for exploring reductions to cut depth was based upon two key prior learnings:

1. The larger the stretch passage, the deeper the cut depth required for a successful test.

   Cut depth and stretch passage width must correspond at roughly a 1:1 ratio. As a stretch passage approaches a magnitude equal or greater than the depth of cut, the separated portion of material will deform, then ultimately separate without forming a fracture ligament. The failure to generate a fracture ligament constitutes a failed test. It is also very likely that a condition introducing significant deformation in the separated portion of material (known as the “chip”) will negatively impact measurement accuracy. Figure 2 depicts the typical successful test condition, the deformed result which still produces a fracture ligament, and finally the ‘split’ condition which forms no fracture ligament.

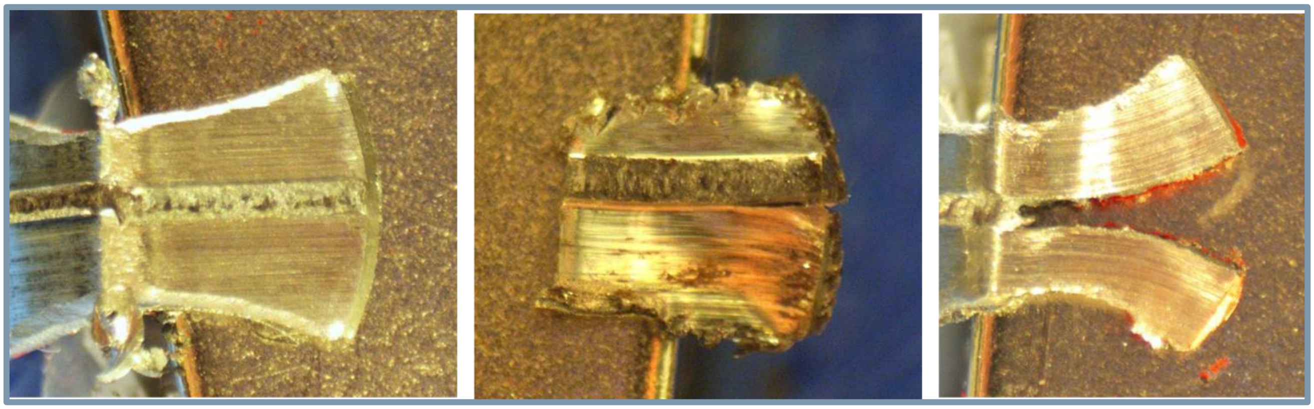

*Figure 2: Effect of decreasing 'stretch passage width' : 'test depth' ratio. Normal (left, Deformed (middle), Split (right)*

Efforts to reduce the cut depth of the tool must therefore avoid split chips or deformation to ensure measurement integrity.

2. Key differences between "prepared cut depth" and "effective cut depth"

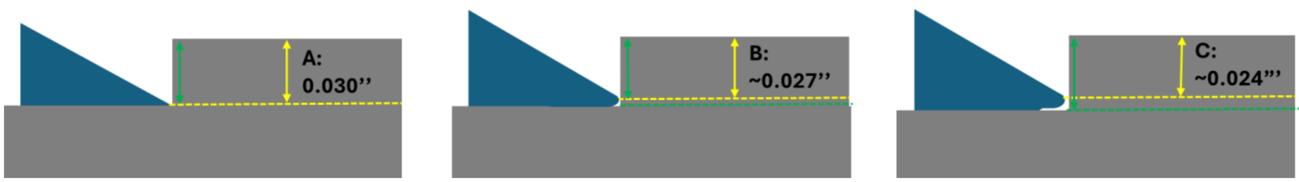


*Figure 3: Ideal Depth (left), Sharpness Consideration (middle), Test Depth Consideration (right), "prepared cut depth" (green), "effective cut depth" (yellow)*

The idealized form of the test consists of a perfectly sharp stylus which will remove the entirety of the prepared island of material. In reality, the blade is not perfectly sharp and the blade is unable to rest perfectly along the machined surface of the prepared material. These non-idealities are depicted in Figure 3. The prepared cut-depth is depicted in green and is equivalent to the entire relieved face of material. The effective cut-depth depicted as the yellow line in Figure 3, is the actual cut plane followed during testing.

Another consideration was the effect of the stylus on the prepared material during initial contact leading up to the formation of the fracture. The deformation zone resulting from the blade tip is known to be directly related to the size of the blade tip. This deformation zone may significantly influence the formation of the fracture surface and whether or not the material responds by splitting, deforming, or generating a raised fracture surface as seen in Figure 2.

From this baseline understanding, MMT set out to improve upon the "effective cut-depth" by reducing the depth lost to the blade tip radius of curvature and by utilizing more of the prepared cut depth when setting up the test. Improvements to the test depth utilization are outside the scope of this document as it is more intimately related to blade holder design considerations explored in 'Task 2.1 – Optimization of Field Tool for Third Party Validation'. The remaining direction for improvement was in investigating an increase in the sharpness of the blade (IE: decreasing radius of curvature of the blade tip). This change would allow the tool to make the most possible use of the prepared cut depth. It would also minimize the deformation zone ahead of the blade tip.

### *Effect of Sharper Blades and Shallower Depth on Material Response*

A set of blades ranging from three-quarters to one-quarter the radius of curvature of the existing blade design were manufactured and tested. The first task was to determine if these blades would be able to survive the high stress conditions of the test to produce valid results. The sharpest blade which was able to survive the test condition was at half the original radius.

Ultimately, any change to the blade geometry interacting with the test specimen may affect the material response which the toughness measurement prediction is built upon. Should changes to the geometry meaningfully impact these measurement results, then the impact on toughness prediction must be investigated. A validation effort aimed at understanding the impact of changing the sharpness was pursued with the blade of half the original radius.

This investigation was relatively limited in scope, aiming only to determine if a steady state response could be reached with the sharper blades, and to develop an initial understanding of how significant the change in material response would be. A small subset of six samples were tested. Figure 4 shows the observed steady state response of one of these tests.

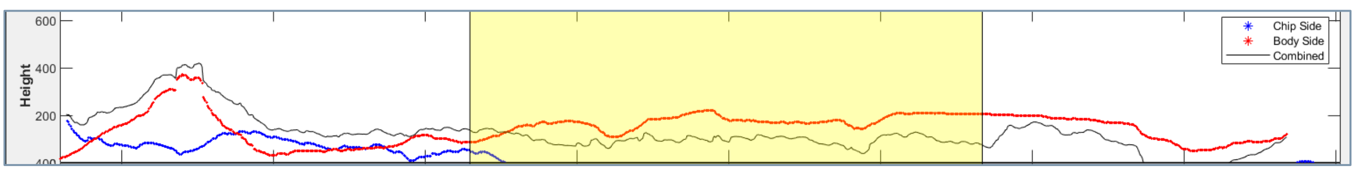


*Figure 4: Steady State Response (shaded yellow) of Sharp Blade test*

With the steady state response successfully produced by the sharper blades, measurements were able to be collected for comparison with historical blade results. Comparison of the material response on two critical measurements utilized in toughness prediction models between the sharper blades and the original blades are seen in Table 2 below.

| % Difference Blunt vs Sharp | Sample ID | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
|---|---|---|---|---|---|---|---|
| | **Flat Region Width** | -39% | -39% | -39% | -15% | -18% | -8% |
| | **Ligament Height** | 30% | -15% | 14% | 57% | 19% | 25% |

*Table 2: Blunt Blade vs Sharp Blade Comparison*

The changes resulting from a sharper blade geometry were found to be significant. A current hypothesis for the cause of material response differences is that a sharper blade radius reduces the pre-deformation before entering the stretch passage, both leading to a greater shear response of the material and a greater stretch before break in the tensile fracture region. The test program confirms that sharp blades are able to successfully test at reduced depth, reaching steady state and producing valid results. Given the magnitude of impact on measured material response, further validation to develop and confirm blind testing capabilities of toughness prediction models utilizing sharp blades is required.

### Objective 3: Optimize blade life to reduce testing cost

The investigation of the blade life was understood to be primarily concerned with two factors:

1. Blade material selection
    a. Initial testing with a variety of tool steels, specialty blade steels, tungsten carbide (WC)
        i. This effort took place prior to the start of the program and is not outlined here. H6WC was the most successful material tested heading into the start of the program. It was therefore the baseline or 'normal' WC for improvement to be compared against.
    b. Specific testing with two WC variants
        i. H10F WC material
        ii. H12F WC material

Testing conducted with the alternate tungsten carbide compositions revealed no improvements to the blade life. Five blades of the same geometry in each material were utilized to test the same material. H10F and H12F did not outperform the original H6 Tungsten carbide material. The decision was made to continue to the next task with the original material.

2. Blade coating
    a. Implement a coating to further improve blade life from prior investigation

Initial research pointed toward various titanium coatings typically utilized for machine tools. After further research and discussion with a variety of vendors, an alternative DLC coating with higher hardness, wear resistance and utilization in applications with high contact pressure was selected.

| | Tests Done | Blades Broken | Tests/Blade |
|---|---|---|---|
| uncoated set 1 | 105 | 36 | 2.92 |
| uncoated set 2 | 92 | 33 | 2.79 |
| coated set 1 | 163 | 5 | 32.60 |

*Table 3: Normal vs Coated Blade Use Rate*

A significant body of data were produced with coated and uncoated blades, the results of which can be seen in Table 3. The impact of the coating was a significant improvement in the blade life.

### *Effects to Material Response Caused by Coating*

While the addition of a coating shows a significant improvement to blade life, similar to sharpness, consideration must to be made for its effect on material response.  Changes to the friction between the blade stylus and the tested material could result in changes to the stress condition which impact the measured response.

Testing with both coated and uncoated H6WC blades were performed in parallel for a significant number of samples. Comparisons were made to determine whether a consistent change could be observed between the measured responses of the material. The results on ligament height generated by the test are shown in Figure 5 below. Measurement results from uncoated blades are in green, while coated blade data are in blue.

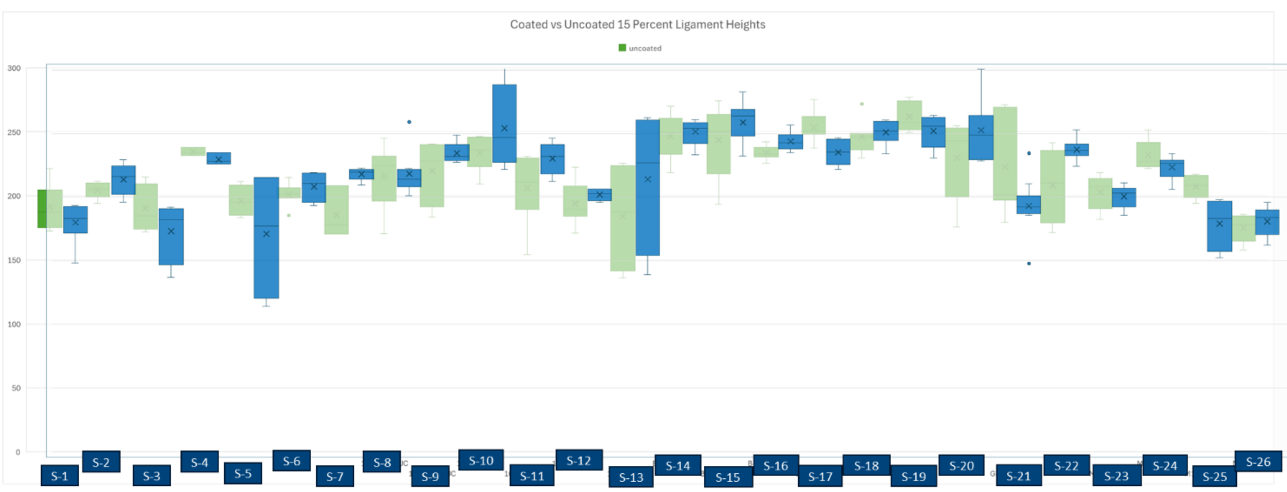


*Figure 5: Box and Whisker Plots of Ligament Height Data for Coated and Uncoated Blades*

While there are some notable exceptions, the majority of samples show a tighter spread of data when produced by the coated blades. It is currently believed that the highest variability samples are a result of difficulties in the test setup which introduced additional test to test variation. Retesting is planned for these samples to better understand the cause of high test to test variation in certain sample materials.

The comparison of coated and uncoated blade testing on flat region width are shown in Figure 6 below.

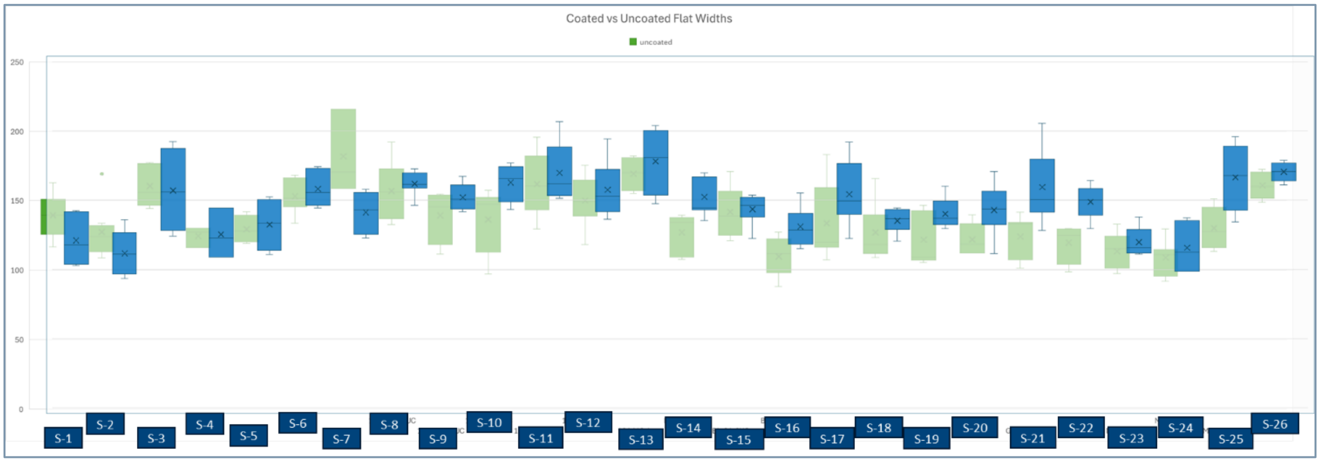


*Figure 6: Box and Whisker Plots of Flat Width Data for Coated and Uncoated Blades*

Impact of blade coating on the total magnitude of flat width is more consistent than that of the ligament height data. Figure 6 shows the distribution of results for all tests conducted on each sample. Each sample has testing conducted in two locations, which are referred to quadrants. When the same comparison of results is performed on a quadrant-by-quadrant basis, the trend in flat region width data is slightly more consistent, and a ~10% increase in the flat region width can be observed. The more consistent quadrant to quadrant finding is considered to result from material property variation due to testing location.

The difference in average measurement for all samples can be seen in Table 4 below.

| % Dif Coated vs Uncoated | SampleID | S-1 | S-2 | S-3 | S-4 | S-5 | S-6 | S-7 | S-8 | S-9 | S-10 | S-11 | S-12 | S-13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ligament Height | 6% | -5% | | 9% | 2% | 13% | -4% | -18% | -1% | -7% | -9% | -12% | -4% |
| | Flat Width | 13% | 12% | | 2% | -1% | -2% | -3% | 22% | -3% | -9% | -19% | -5% | -5% |

| % Dif Coated vs Uncoated | SampleID | S-14 | S-15 | S-16 | S-17 | S-18 | S-19 | S-20 | S-21 | S-22 | S-23 | S-24 | S-25 | S-26 | S-27 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ligament Height | -16% | -2% | -6% | -5% | 7% | -2% | 4% | -10% | 13% | -14% | 1% | 4% | 14% | -3% |
| | Flat Width | -5% | -20% | -1% | -19% | -15% | -6% | -15% | -17% | -28% | -24% | -6% | -6% | -28% | -6% |

*Table 4: % Difference of Average Measurement Results for Coated and Uncoated Blades*

It is important to note that there can be meaningful variation in both measurements. The results show a systematic bias, with the coated blades producing flat widths that are, on average, 8% lower. The mean absolute percent error (MAPE) between the two methods is 11%, indicating the typical magnitude of this difference, regardless of direction. This is similar to the 10% increase in the ligament height revealed by the quadrant to quadrant analysis of the test data mentioned after Figure 4.

To summarize the learnings, the coating increases the magnitude of the flat width measurement but does not consistently effect the magnitude of ligament height measurements.

## Conclusions

This investigation successfully resulted in a finalized blade geometry and material selection ready for blind testing under Task 2.4 and initial commercial deployment. The selected design incorporates two key findings from this work:

1. The selection of a 0.020” stretch passage width, which was validated to improve the correlation between test measurements and material fracture toughness compared to the 0.015" alternative.
2. The application of a Diamond-Like Carbon (DLC) coating to the tungsten carbide blade was proven to deliver a significant improvement in blade life, directly addressing cost and usability objectives.

Furthermore, this task identified a clear pathway to reduce the required test depth by 20-30% through the use of sharper blade geometries. While these sharper blades were proven to be effective, they require additional validation before implementation.

Therefore, the tool will proceed to commercialization with the standard, coated 0.020” stretch passage blade, while the sharper blade geometry is recommended for future validation work.

**Attachment 2 – Task 2.1 Final Deliverables**

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PHMSA Task 2.1 Final Deliverable Report

09/30/2025

## Executive Summary

At the outset of Task 2.1 an initial prototype of the tool was in use for warehouse testing of pipe cut-outs. Initially identified areas for improvement concerned improved attachment to varying pipe geometries, consideration of weather proofing, and minimization of pipe vibration. Learnings from this period of utilization were combined with outcomes from the blade optimization tasks in Milestone 1 and incorporated into v1.0 of the BTM field tool. This version of the tool was utilized for in-ditch mock trials and the very first commercial pilot project work. As findings from initial field trials came to the design team, additional challenges were identified and remediated into design v1.1. Key design challenges included high requirements for structural stiffness, load capacity, and alignment. In some ways, the test being conducted can be thought of as a milling operation. With this viewpoint, high requirements for tool stiffness, alignment, and load carrying capacity are more understandable.

This document will outline key findings from all phases of utilization and testing, as well as the implemented design solutions which addressed them. The final outcome of this task has been the development and deployment of the v1.1 of the tool for utilization throughout early blind validation and adoption efforts. With the foundation provided by the v1.1 platform, the engineering team will be able to take the next step to perform the necessary development for commercial iteration of the tool.

## Instrument Overview

The original prototype iteration of the tool consisted of 5 key subsystems depicted in Figure 1. The pipe feet are responsible for joining the overall instrument rigidly to the pipe sample. The Frame encompasses and connects all the sub systems of the tool. The milling assembly is responsible for preparation of the testing surface. The drive plate holds, orients and translates the blade stylus during the test. The drive motor actuates the drive plate in order to perform the testing operation. These systems in their original prototype implementation are seen in Figure 1 below.

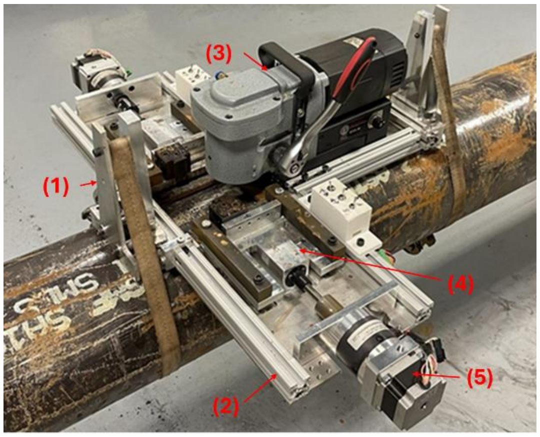



*Figure 1: Prototype BTM: Pipe Feet (1), Frame (2), Milling Assembley (3), Drive Plate (4), Drive Motor (5)*

The drive plate subsystem can be further broken down into several key pieces depicted in Figure 2. The blade is the stylus with key geometry responsible for generating a material response in the sample material. The blade holder is responsible for holding the blade, allowing it to translate closer and further from the pipe during setup, and then locking into a rigid position during testing. The tool post is responsible for allowing the blade holder assembly to translate longitudinally along the pipe, such that the blade can be oriented to the start position of several tests without moving the entire instrument. It must also lock rigidly in place during testing. The T-Slot is responsible for allowing the translation and locking of the tool post to the various prepared testing locations along the longitudinal axis of the pipe. The drive plate joins the blade holder and tool post assembly to the drive block. Finally, the drive block translates the actuation of the drive motor into the linear motion required for the test.

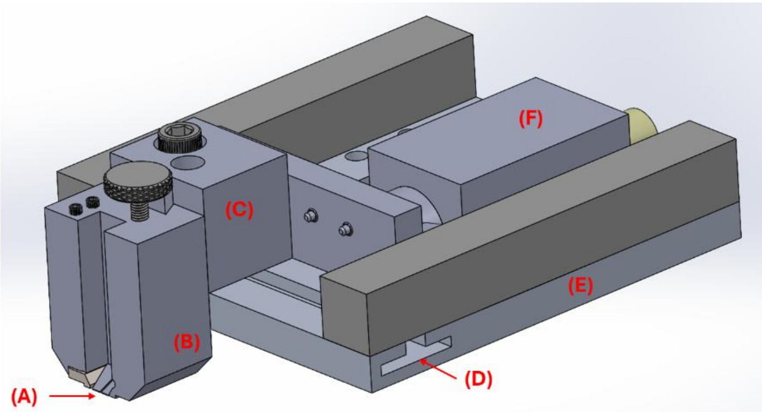



*Figure 2: Drive Plate - Blade (A), Blade Holder (B), Tool Post (C), T-Slot (D), Drive Plate (E), Drive Block (F)*

## Key Findings During Prototype and BTM Rev 1.0 Testing

Utilization of the tool during warehouse testing programs, in laboratory testing, and field mock-ups revealed various shortcomings which needed to be addressed.

A. The initial specification for required motor strength did not prove to be sufficient for all sample materials which were brought in for testing. In the case of sufficiently high strength steel (~75ksi yield strength or greater), the stepper motors would stall and be unable to perform the test.

B. In mock field conditions the electronics controls would overheat if left under direct exposure to sunlight on a warm day (80°F or greater). Follow up testing was performed in laboratory conditions with a temperature control chamber. This testing confirmed that ambient temperatures as low as 75° were able to produce problematic motor controller temperatures, especially if the strength of steel being tested required current draw close to or exceeding 2.5 amps.

C. Linear actuation of the drive plate could result in an operator damaging the blade holder. In the configuration where blade holders are lowered to the test start position, if the drive plate is reversed away from the test start position, the blade holder will interfere with the frame and deform. This will cause the dovetail interface to no longer operate, and misalign the blade during any testing, effectively scrapping the tool post and requiring replacement.

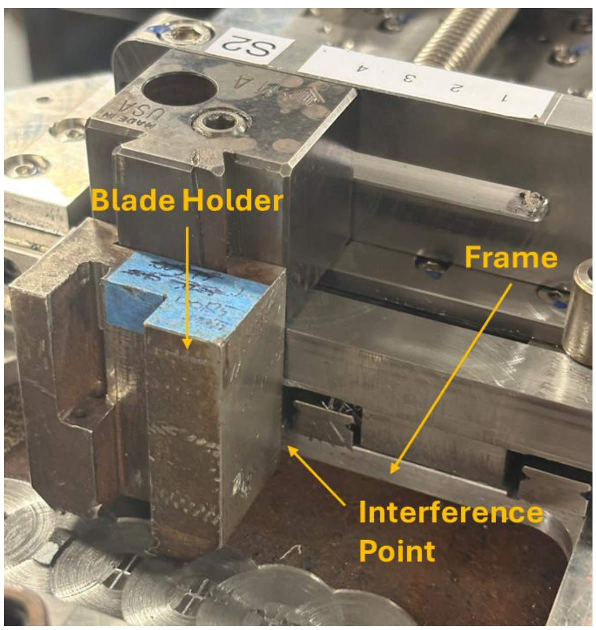



*Figure 3: Blade Holder and Frame Interference*

D. The entire instrument can be forced to rotate around the outside of the pipe, instead of successfully planeing off the prepared island of material. During test configurations where the blades performing testing are not equal in depth within a small margin (~0.005") the imbalance in loads will generate a tangential load to the pipe. The current attachment system (IE: pipe feet) are insufficient to resist this tangent load and will slip, allowing the instrument to translate instead of correctly testing.

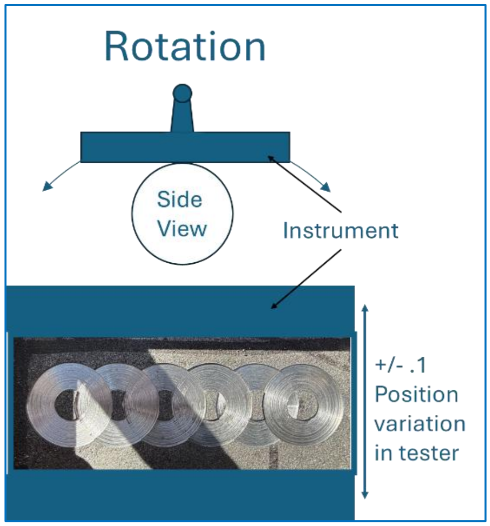



*Figure 4: Diagram of Rotation Around Pipe*

E. Prepared sample islands vary in depth along both the longitudinal direction, as well as the circumferential direction in sufficient amount to cause some tests to fail to generate a successful fracture feature.

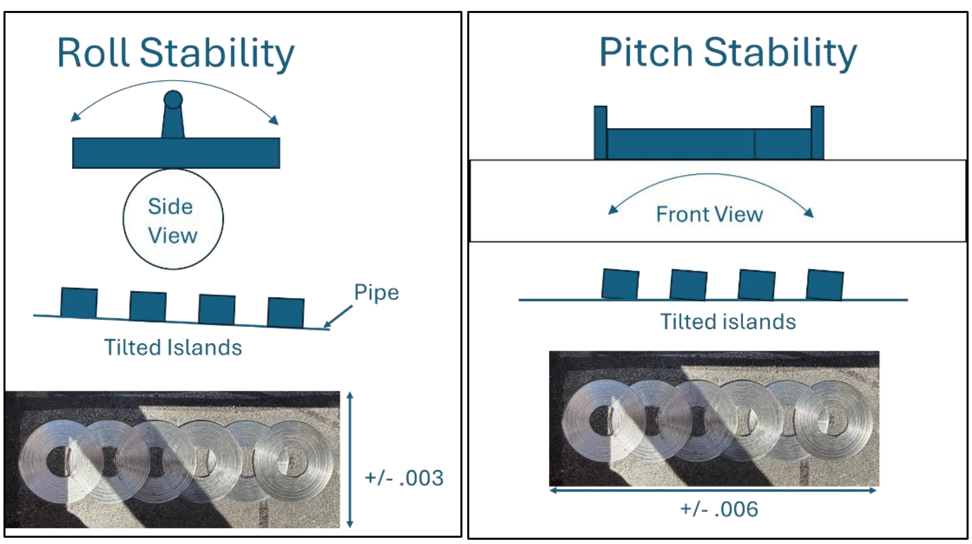



*Figure 5: Pitch and Roll Stability Diagrams*

F. Inconsistency in prepared island surfaces can lead to a raised portion of the machine surface adjacent to the test island which will break the blade utilized for the test.

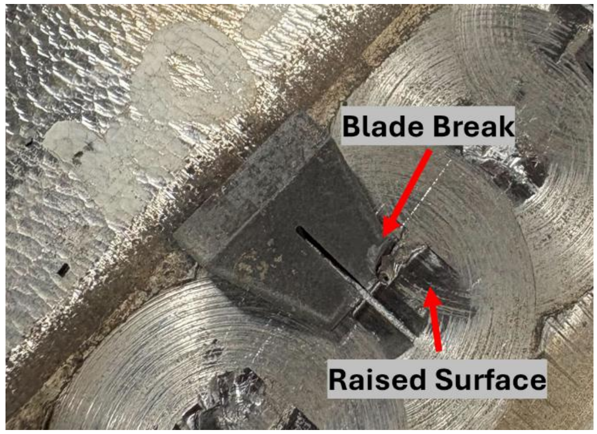



*Figure 6: Raised Prepared Surface and Blade Failure*

G. Misalignment between the orientation of the prepared test surface and the direction of travel of the blade can lead to blades breaking, as well as failed tests.

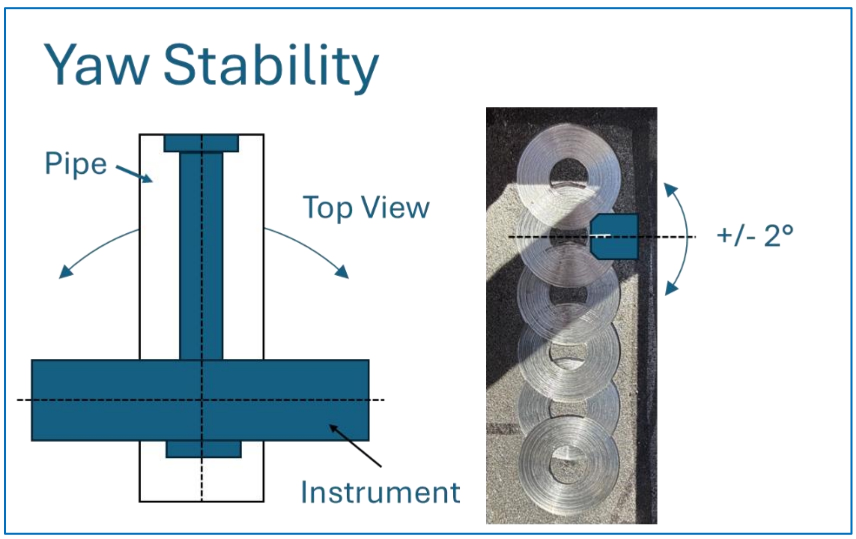



*Figure 7: Yaw Stability Diagram*

H. Loading generated during testing can cause deformation which forces the approaching blades out of alignment. Ultimately, this causes tests to end without the prepared surface being fully removed by the blades. Removing the generated fracture surface by other means can present a significant challenge at this point, frequently damaging tests which would otherwise be usable.

I. Alignment of the blades to the start position of the test was time prohibitive and difficult to execute properly in field conditions.

## Discussion on Design Improvements

Specific steps were taken to address each of the findings identified previously. In some cases the root causes and associated solutions were complex to diagnose or address. In other cases, the approaches taken were straight-forward solutions performed quickly with the intent of eliminating confounding variables in order to address the more complicated issues.

### Issues A. and B.

The most straightforward issues addressed were A. and B. To address A, a larger gearbox which interfaced with the existing stepper motor was specified and implemented.

Similarly, item B was addressed by implementing an active cooling system into the control box with the incorporation of a fan.

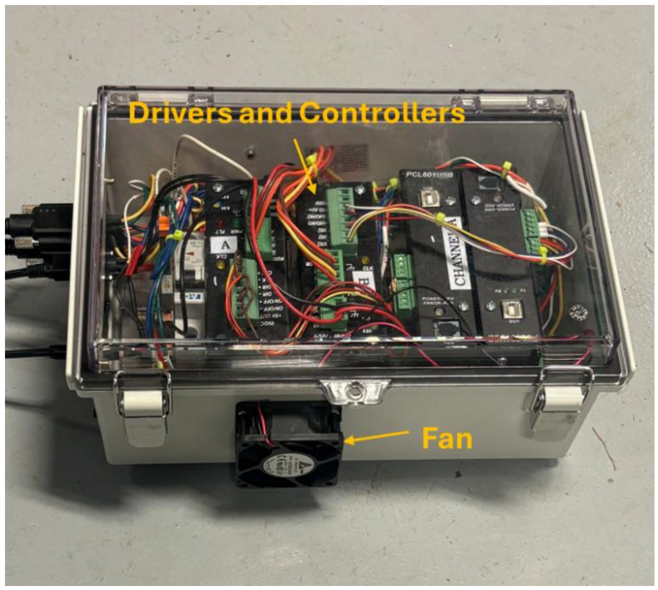



*Figure 8: Improved Electronics Box with Fan*

### Item C.

Item C had two potential paths to a solution. The first would be to improve the strength of the deforming part, such that interference with the frame during incorrect operation would not result in permanent damage. The other solution would be to modify the controls such that incorrect operation leading to deformation of the tool would not be possible. After evaluation, the fault was addressed through the incorporation of limit switches into the control scheme. These limit switches would trigger when the tool was at the edges of the safe operating range and kill power to the motors. An operator can then manually reset the control through a bypass, or manually move the tool into a safe operating condition.

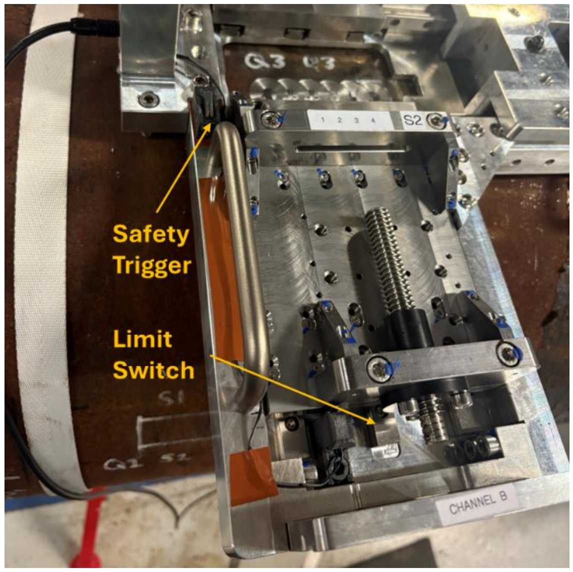


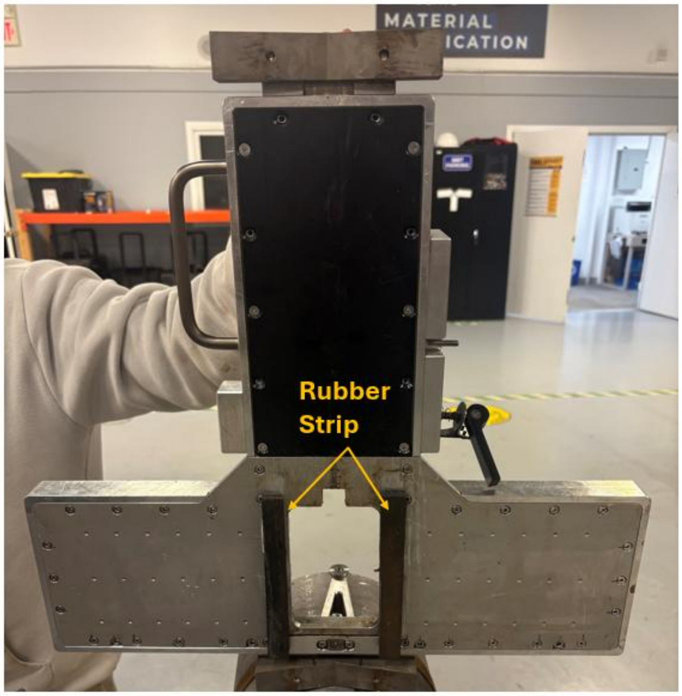

*Figure 9: Limit Switch Implementation*

### Item D

Item D took several iterations to successfully address. The original v1.0 design included a metal interface which would be intended to mechanically contact an additional prepared surface, resisting rotation around the pipe.


*Figure 10: Mechanical Interface for Anti-Rotation*

This approach saw some success but had two major draw backs: the preparation of the additional surface increased total wall thickness removal for the tool, and difficulty securing the frame onto the surface after preparing it. Due to these draw backs, alternative solutions were pursued.



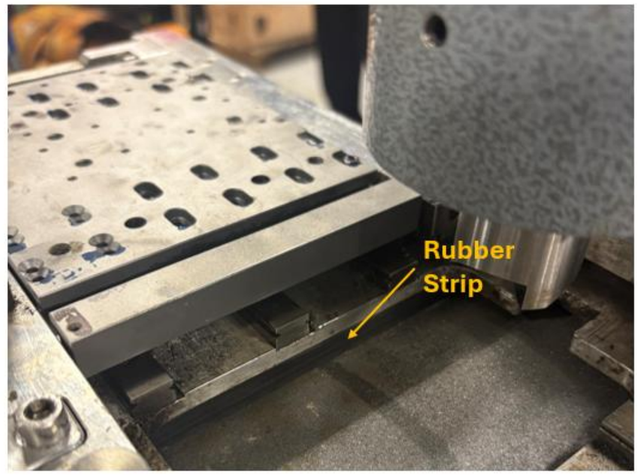




*Figure 11: Rubber Strip Implementation on tester bottom (left) and after attachment to pipe (right)*

The second approach to this problem aimed to increase the friction between the unit and the pipe surface to prevent rotation. A rubber strip was incorporated adjacent to the test area which would be pinched between the frame and the pipe surface when the unit is attached to the pipe. This solution was an improvement over the prior approach, but required the rubber strip to be changed depending on the outer diameter of the pipe being tested. If it was not changed, the proximity of the tester to the pipe in combination with the thickness of the rubber strip would lead to deformation of the frame of the tester.

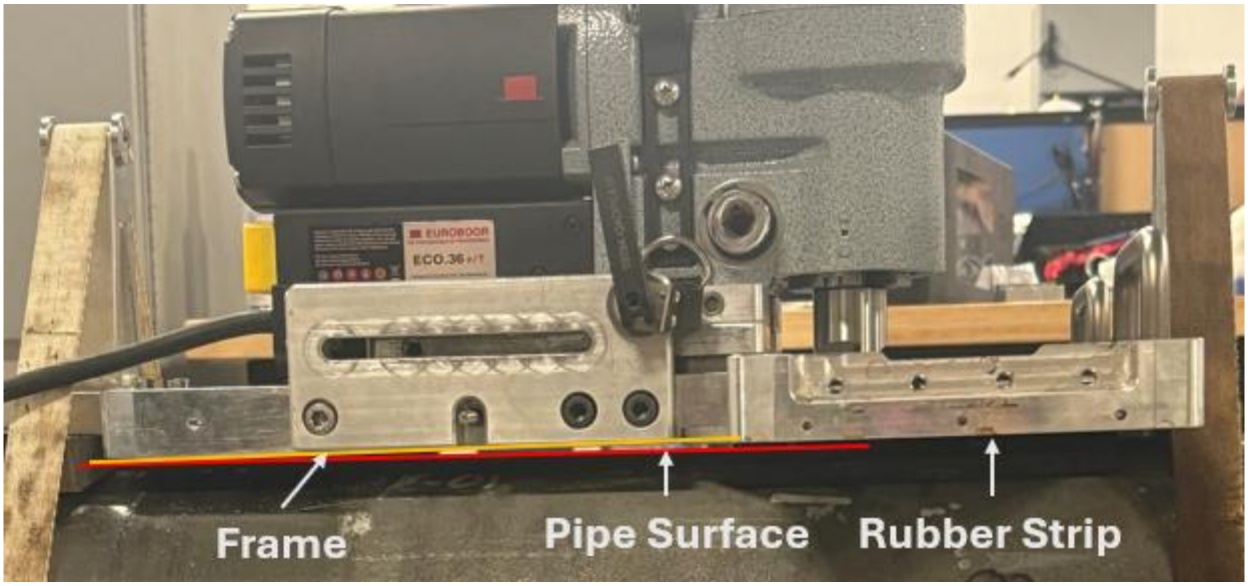



*Figure 12: Deflection of Frame away from Pipe Surface due to Rubber Strip*

As understanding of the various interactions of the tool design became more clear, it became apparent that the varying deflection of the frame was not acceptable. These findings are discussed in more detail during the discussion on Item E. With this understanding a new solution needed to be found to solve rotation around the pipe surface.

The best path forward was still believed to rely upon increasing friction between the tester and the pipe surface to a sufficient level to prevent rotation. Increasing friction at the pipe feet would be ideal, as it is an already existing contact point between the frame and the pipe surface. Modifications to the pipe feet to increase friction would only need to consider the total displacement of the tester away from the pipe and mitigate it through adjustment of the standoff height.

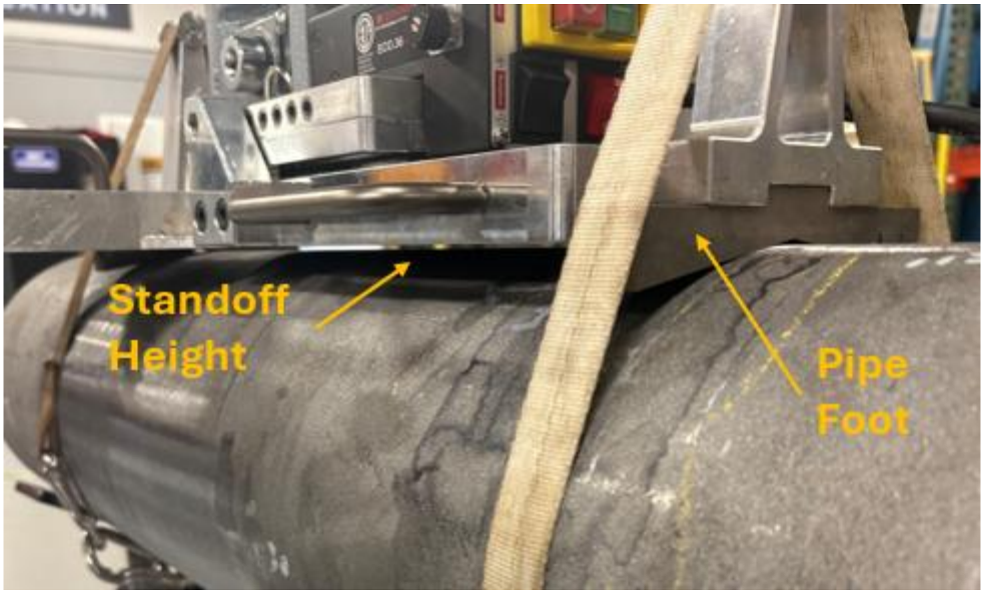



*Figure 13: Standoff between Pipe Surface and Tester*

A diamond coating process designed for high friction and durability was selected for the pipe feet, which can also be seen in Figure 13. After validation it was found that the coating significantly improved the holding force of the tester, sufficiently resisting rotation around the outside of the pipe. A notable consideration is the build up of metal and debris on the coating. This can be successfully removed through a cleaning process in order to avoid premature wearing of the coated feet.

### Item E – Pitch and Roll Stability.

In the initial prototype, there was a measured difference in depth of the prepared surface from side 1 to side 2 in Figure **X**. This can lead to insufficient test depth on the shallower side. Upon investigation there were two potential sources; the entire frame was not sitting tangential to the pipe surface, the surface preparation sled was not sitting tangential to the pipe surface. In various cases either or both of these factors were causing the problem. In either case the fundamental issue was the datum of the surface preparation device had rolled or pitched out of alignment with the pipe surface.


*Figure 14: Prepared Surface with Side 1 and Side 2 callout*

The inclusion of a rubber strip, implemented to avoid rotation around the outside of the pipe, introduced inconsistency in the orientation of the tester on the pipe. Depending on the pipe outer diameter and the thickness of rubber inserted between the frame and the pipe, the frame would deflect from the pipe surface. This became a driving influence in moving away from the rubber strip as a solution to rotation around the pipe. The orientation of the surface preparation sled was also investigated and found to be out of alignment with the rest of the test frame in some assemblies. Upon review of the manufacturing tolerance stack, it was observed that there was room during assembly for the sled to not be parallel to the frame. Process improvements, as well as the utilization of a dedicated assembly table with an engineered flatness grade, were able to mitigate this problem.

Even with these improvements, some misalignment of the prepared surface and the frame of the tester could still be observed. At this point, deflection of the surface preparation assembly during the milling of the prepared surface was investigated. It was found that the utilization of the 'hand brake' which locks the position of the surface preparation sled was introducing slight rotation into the milling assembly. This brake was removed, and the locating pin was improved to no longer require it, completing the 'Pitch and Roll Stability' improvements.

### Item F -

The 'Pitch Stability' still had some inconsistencies. Improvements up to this point had minimized the runout of the prepared sample surface by about 0.005'' – bringing the runout to 0.002’’-0.003’’. The remaining runout issues were now observed to vary inconsistently from position to position during surface preparation. Raised portions of material were still causing failures in blades during testing. Additionally, total depth of the prepared surface varied from position to position.

In order to eliminate this frame deflection, reinforcement of the inside corner of the ‘T’ interface were made. These can be seen in Figure **15**.

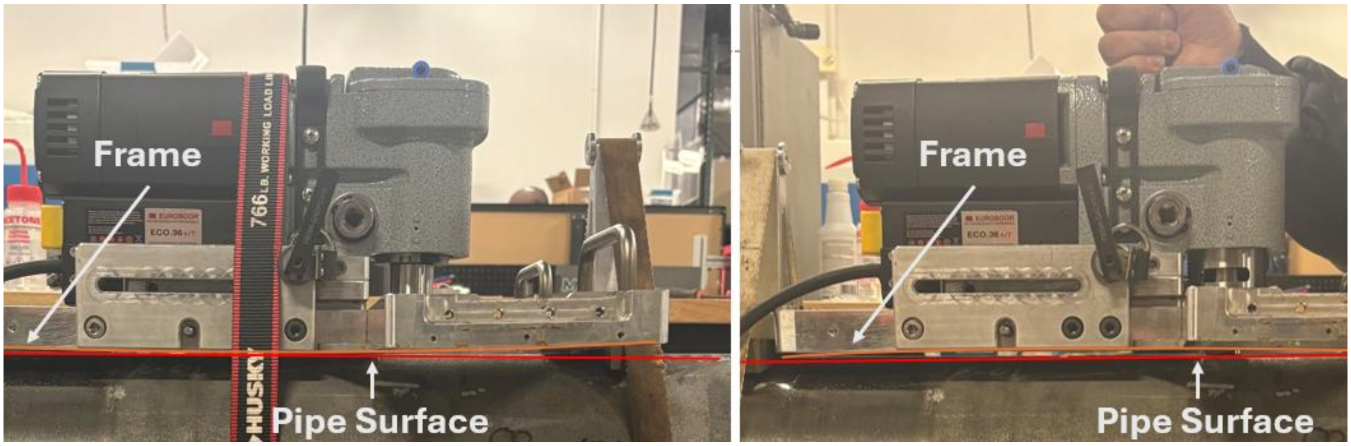



*Figure 15: Frame Deflection Due to Strapping (left) and Milling (right)*

Further investigation revealed that elements introduced into the design to mitigate chatter of the milling assembly utilized to prepare the surface were also contributing to deflections in the frame. These deflections could be mitigated by eliminating the two elements; a ratchet strap around the milling assembly, as well as monitoring the force applied to the quill during milling operations. In order to mitigate chatter during surface preparation in the absence of these features, the locating and locking pin needed to be further improved. A more robust pin was selected, and procedural improvements to maintain a strong interface of the locking feature were implemented.

The final element which addressed the inconsistent heights of prepared surfaces had two main components. The first was a straightforward process improvement. The bit utilized for the milling needed to be cleaned in between the preparation of each milling location. Compressed air alongside a cleaning solution was introduced to perform this task.

### Item G

Item G was an issue caused by misalignment between the longitudinal axis of the pipe and the longitudinal axis of the instrument. It was also exacerbated by any non-perpendicularity between the datum of the surface preparation sled and the blade drive sled. In a manner similar to the prior two items, the elimination of the rubber strip improved the misalignment. Additionally, the diamond coated feet assisted in identifying the correct anchor point for the tester along the longitudinal axis of the pipe. A procedural improvement corresponding to this was also devised. The instrument would be anchored at the foot closest to the testing quadrant first. Then the opposite side would be pivoted back and forth until the tester could be felt to “drop” into position along the longitudinal axis. Once this was done the second strap would secure the other foot.

A complimentary update to the tolerancing of the frame was made for the v1.1 of the unit. These tolerancing considerations were aimed at the perpendicularity of the testing datum and the surface prep datum. With both of these changes made, perpendicularity of the blade and the prepared test island was ensured within 1 degree.

### Item H

This problem was addressed by designing a complimentary U-Channel guide with an incorporated OTS rotoscoping camera solution. The U-channel is responsible for moving the blade holders on either side of the test area at the same time as each other. The improved viewport also assists with placement and orientation of the blades to the test island.

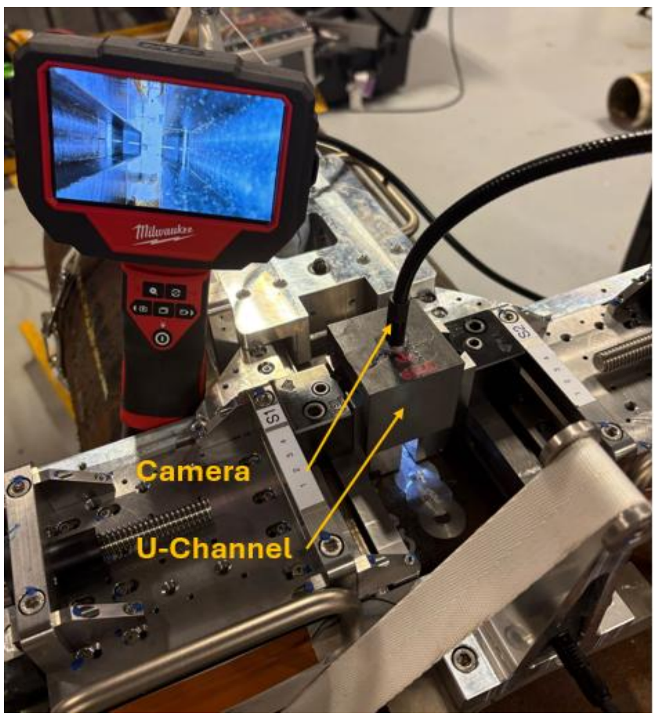



*Figure 16: U-Channel Device and Camera*

## Final Design and Conclusions

The final version of the tool produced for task 2.1 can be seen in Figure X below.

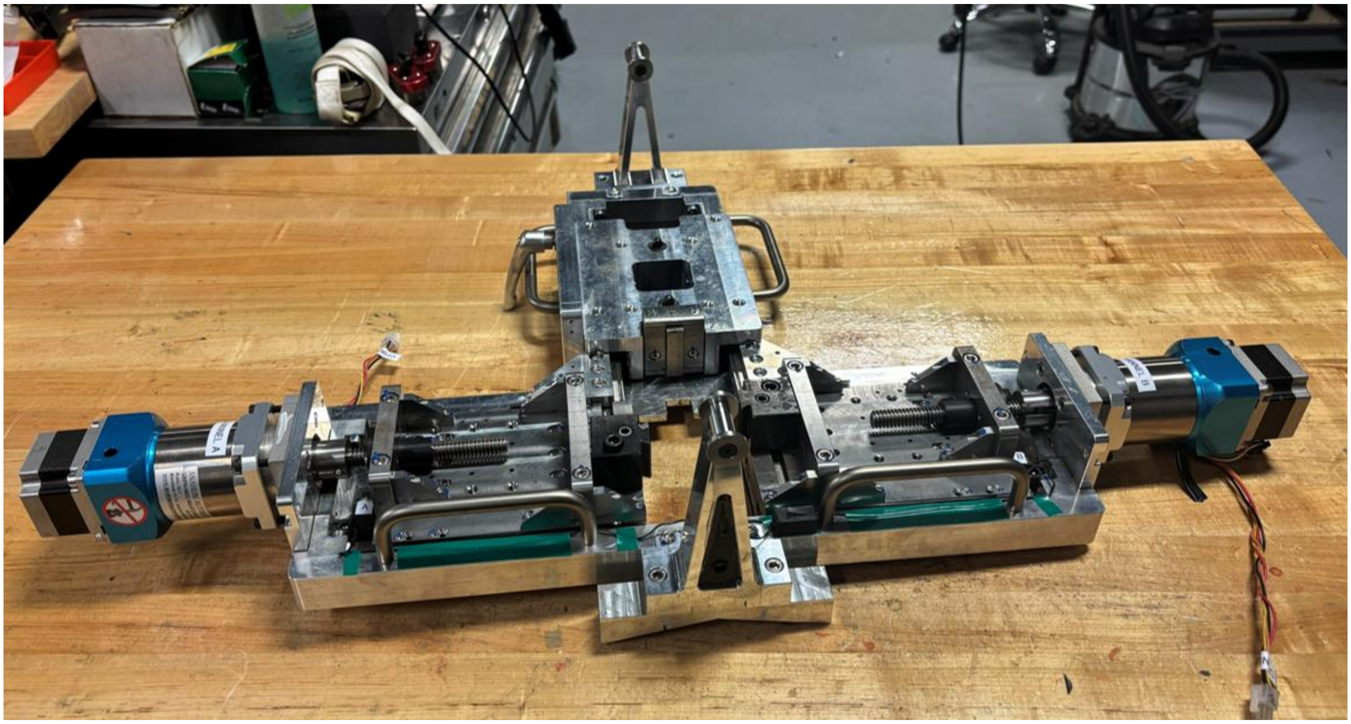


*Figure 17: v1.1 BTM Tester*

This design incorporates all of the learnings and addresses all of the highlighted issues. Many of the findings from the tool design iteration became important process documentation items. These items are incorporated into manufacturing and testing procedure documentation.

## Future Work

As the current instrument is utilized to support initial commercialization efforts of the technology, further notes will be collected. These notes will highlight remaining areas for improvement, as well as pain points in the user experience. Pain points which are concerned with reliability, repeatability, and durability will be highly scrutinized. Another area of scrutiny will be parts of the tool utilization which are considered to require considerable care or skill to execute correctly. The design team will utilize these findings to identify the direction of the fully commercial tool developed under Task 3.1.

**Attachment 3 – Task 2.3 Final Deliverables**

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# L261 BTM Milling Bit [CC] – Inspection Sheet

Cutting Bit Lot [AA]-[ZZ] : ___________________

Technician : ___________________Date (MMDDYYYY) : __________________________

| **Bit ID** **[bit]-[date]-[lot]-[#]** | Non-Plunging Center Flat? | Plunge Depth 0.029-0.031” | Plunge Depth in spec? | Plate Depth 0.029-0.031” | Cut Depth in spec? | Non-Plunging Corner? |
|---|---|---|---|---|---|---|
| CC-[ ]-[ ]-01 | ● | | ● | | ● | ● |
| CC-[ ]-[ ]-02 | ● | | ● | | ● | ● |
| CC-[ ]-[ ]-03 | ● | | ● | | ● | ● |
| CC-[ ]-[ ]-04 | ● | | ● | | ● | ● |
| CC-[ ]-[ ]-05 | ● | | ● | | ● | ● |
| CC-[ ]-[ ]-06 | ● | | ● | | ● | ● |
| CC-[ ]-[ ]-07 | ● | | ● | | ● | ● |
| CC-[ ]-[ ]-08 | ● | | ● | | ● | ● |
| CC-[ ]-[ ]-09 | ● | | ● | | ● | ● |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CC-[ ]-[ ]-10 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-11 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-12 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-13 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-14 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-15 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-16 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-17 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-18 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-19 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-20 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-21 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-22 | ● | | ● | | ● | ● | |
| CC-[ ]-[ ]-23 | ● | | ● | | ● | ● | |

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# L262 BTM Cleanup Bit [CU] – Inspection Sheet

Cutting Bit Lot [AA]-[ZZ] : ____________________

Technician : ____________________Date (MMDDYYYY) : ____________________________

| **Bit ID [bit]-[date]-[lot]-[#]** | Pre-Cleanup Depth #0.000 | Non-Plunging Center Flat | Cleanup Successful? | Post Cleanup Depth #0.000 | Cut depth within spec | Non-Plunging Corner? |
|---|---|---|---|---|---|---|
| CU-[ ]-[ ]-01 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-02 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-03 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-04 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-05 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-06 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-07 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-08 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-09 | | ● | ● | | ● | ● |

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| | | | | | | |
|---|---|---|---|---|---|---|
| CU-[ ]-[ ]-10 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-11 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-12 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-13 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-14 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-15 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-16 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-17 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-18 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-19 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-20 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-21 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-22 | | ● | ● | | ● | ● |
| CU-[ ]-[ ]-23 | | ● | ● | | ● | ● |

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# L263 BTM Blunt Blade [BB] – Inspection Sheet

Blade Lot [AA]-[ZZ] : ____________________

Technician : ____________________Date (MMDDYYYY) : ____________________________

| **Blade ID [blade]-[date]-[lot]-[#]** | Stretch Passage | Entering Stretch Passage Radius #0.0000 | Front Radius #0.0000 | Blade Angle 21°-23° | Width 0.50”-0.54” | Thickness 0.13”-0.15” |
|---|---|---|---|---|---|---|
| BB-[ ]-[ ]-01 | ● | | | | | |
| BB-[ ]-[ ]-02 | ● | | | | | |
| BB-[ ]-[ ]-03 | ● | | | | | |
| BB-[ ]-[ ]-04 | ● | | | | | |
| BB-[ ]-[ ]-05 | ● | | | | | |
| BB-[ ]-[ ]-06 | ● | | | | | |
| BB-[ ]-[ ]-07 | ● | | | | | |
| BB-[ ]-[ ]-08 | ● | | | | | |
| BB-[ ]-[ ]-09 | ● | | | | | |
| BB-[ ]-[ ]-10 | ● | | | | | |

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|---|---|---|---|---|---|---|
| BB-[ ]-[ ]-11 | ● | | | | | |
| BB-[ ]-[ ]-12 | ● | | | | | |
| BB-[ ]-[ ]-13 | ● | | | | | |
| BB-[ ]-[ ]-14 | ● | | | | | |
| BB-[ ]-[ ]-15 | ● | | | | | |
| BB-[ ]-[ ]-16 | ● | | | | | |
| BB-[ ]-[ ]-17 | ● | | | | | |
| BB-[ ]-[ ]-18 | ● | | | | | |
| BB-[ ]-[ ]-19 | ● | | | | | |
| BB-[ ]-[ ]-20 | ● | | | | | |
| BB-[ ]-[ ]-21 | ● | | | | | |
| BB-[ ]-[ ]-22 | ● | | | | | |
| BB-[ ]-[ ]-23 | ● | | | | | |
| BB-[ ]-[ ]-24 | ● | | | | | |

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# Q250 - BTM Red Tag Form

Item : ____________________ Item ID : ____________________

Technician : ____________________ Date (MMDDYYYY) : ____________________________

Reason for Red Tag:

- Failed to meet criteria for critical feature(s): ________________________
- Apparent Visual Nonconformance:

____________________________________________________________

____________________________________________________________

____________________________________________________________

____________________________________________________________

______________________________________________

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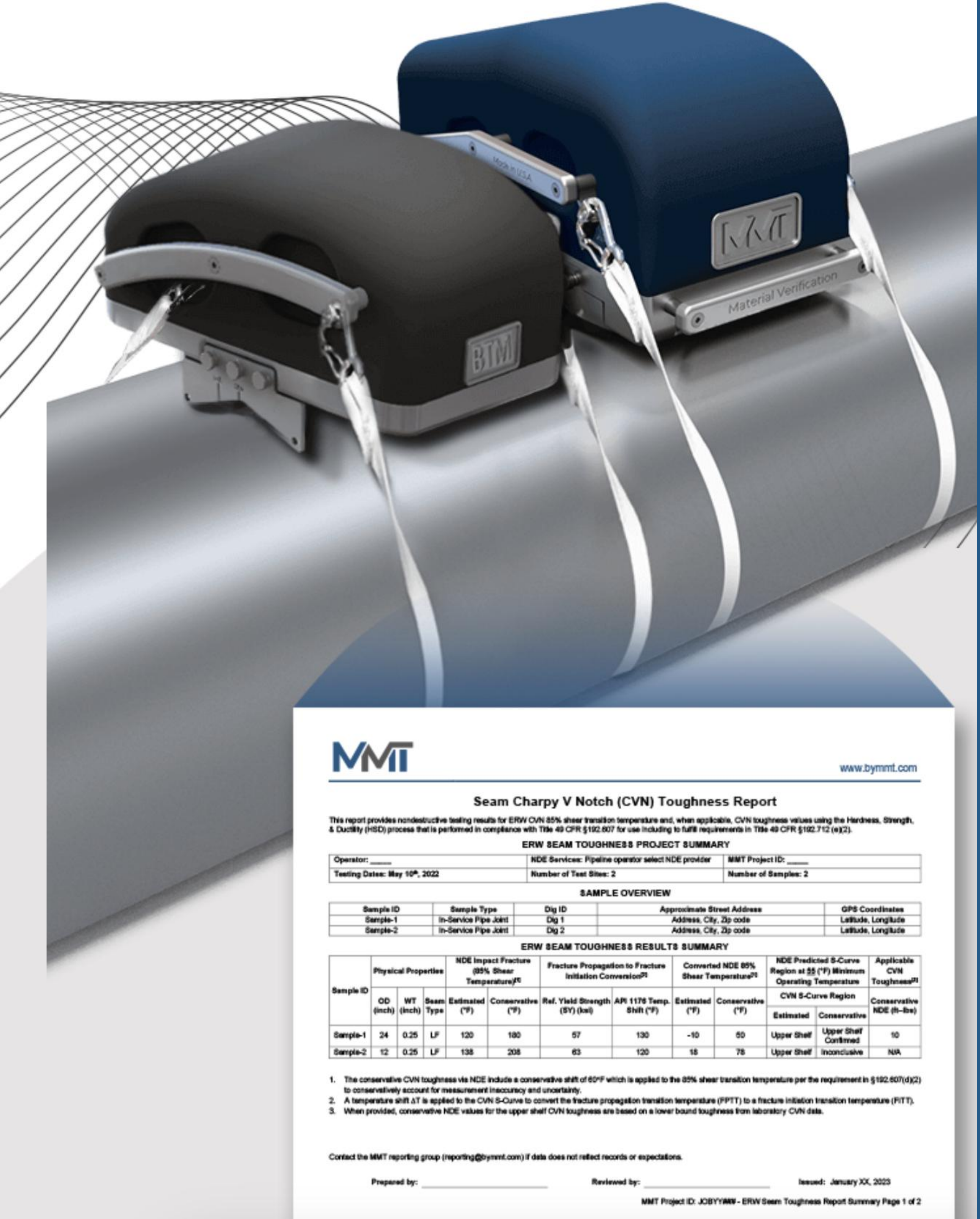
# Q251 - BTM Non Conformity Report

Item : ____________________ Lot # : ____________________

Technician : ____________________ Date (MMDDYYYY) : ____________________________

| Item ID | Red Tag? | Issue | Item ID | Red Tag? | Issue |
|---|---|---|---|---|---|
| | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC | | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC |
| | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC | | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC |
| | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC | | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC |
| | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC | | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC |
| | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC | | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC |
| | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC | | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC |
| | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC | | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC |
| | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC | | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC |
| | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC | | ❑Performed<br>❑Not Performed | ❑Criteria Failure<br>❑Visual NC |

**Attachment 4 – September 30th Progress Report**




MMT www.bymmt.com

## Seam Charpy V Notch (CVN) Toughness Report

This report provides nondestructive testing results for ERW CVN 85% shear transition temperature and, when applicable, CVN toughness values using the Hardness, Strength, & Ductility (HSD) process that is performed in compliance with Title 49 CFR §192.607 for use including to fulfill requirements in Title 49 CFR §192.712 (e)(2).

**ERW SEAM TOUGHNESS PROJECT SUMMARY**

| | | |
|---|---|---|
| Operator: ____ | NDE Services: Pipeline operator select NDE provider | MMT Project ID: ____ |
| Testing Dates: May 10th, 2022 | Number of Test Sites: 2 | Number of Samples: 2 |

**SAMPLE OVERVIEW**

| Sample ID | Sample Type | Dig ID | Approximate Street Address | GPS Coordinates |
|---|---|---|---|---|
| Sample-1 | In-Service Pipe Joint | Dig 1 | Address, City, Zip code | Latitude, Longitude |
| Sample-2 | In-Service Pipe Joint | Dig 2 | Address, City, Zip code | Latitude, Longitude |

**ERW SEAM TOUGHNESS RESULTS SUMMARY**

| Sample ID | Physical Properties | | | NDE Impact Fracture (85% Shear Temperature)[1] | | Fracture Propagation to Fracture Initiation Conversion[2] | | Converted NDE 85% Shear Temperature[2] | | NDE Predicted S-Curve Region at 55 (°F) Minimum Operating Temperature | | Applicable CVN Toughness[3] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | CVN S-Curve Region | | |
| | OD (inch) | WT (inch) | Seam Type | Estimated (°F) | Conservative (°F) | Ref. Yield Strength (SY) (ksi) | API 1176 Temp. Shift (°F) | Estimated (°F) | Conservative (°F) | Estimated | Conservative | Conservative NDE (ft–lbs) |
| Sample-1 | 24 | 0.25 | LF | 120 | 180 | 57 | 130 | -10 | 50 | Upper Shelf | Upper Shelf Confirmed | 10 |
| Sample-2 | 12 | 0.25 | LF | 138 | 208 | 63 | 120 | 18 | 78 | Upper Shelf | Inconclusive | N/A |

1. The conservative CVN toughness via NDE include a conservative shift of 60°F which is applied to the 85% shear transition temperature per the requirement in §192.607(d)(2) to conservatively account for measurement inaccuracy and uncertainty.
2. A temperature shift ΔT is applied to the CVN S-Curve to convert the fracture propagation transition temperature (FPTT) to a fracture initiation transition temperature (FITT).
3. When provided, conservative NDE values for the upper shelf CVN toughness are based on a lower bound toughness from laboratory CVN data.

Contact the MMT reporting group (reporting@bymmt.com) if data does not reflect records or expectations.

Prepared by: ____ Reviewed by: ____ Issued: January XX, 2023

MMT Project ID: JOBYYMM - ERW Seam Toughness Report Summary Page 1 of 2

MMT

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

Co-sponsored By PHMSA
(Project # 1043)

## Q3 2025 – Progress Report
## 09/30/2025

# Agenda

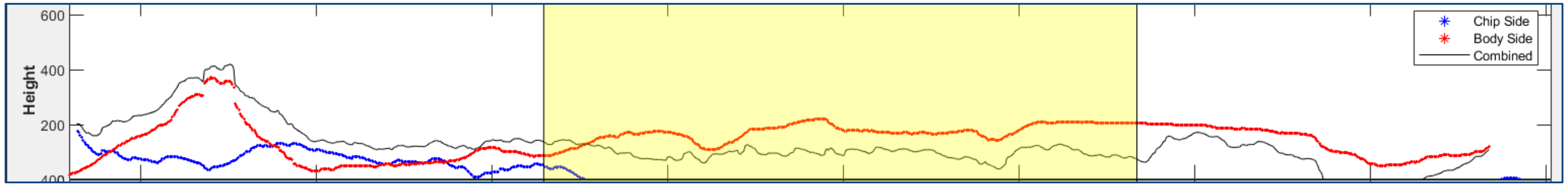
- Task 1.2 updates (FEA)
- Task 1.3 updates & conclusion (Blade Optimization)
- Task 2.1 updates & conclusion (Field Device Development)
- Task 2.2 updates (Analytics Optimization)
- Task 2.3 updates & conclusion (Field Procedures)
- Through end of year update

# Task 1.2 Updates (FEA)

- Updated Vendor
  - An MMT collaborator has received $0.5 million from another agency for scientific research related to the BTM
  - MMT is planning to monitor progress of this team with the intent to retain the same group to successfully accomplish the task including parametric study
  - As discussed in prior TAP a six month completion time should be expected when the work is reinitiated
  - We propose to re-visit the options at the June 2026 TAP meeting

# Task 1.3 Updates (Blade Optimization)

- Sharp Blade Testing Completed
  - Initial effort to confirm steady state behavior and determine necessity of full validation effort before roll out completed
    - Steady State behavior of ligament height during sharp blade test:




  - Measurement comparison indicates impact of sharper blades sufficient to justify dedicated validation effort:

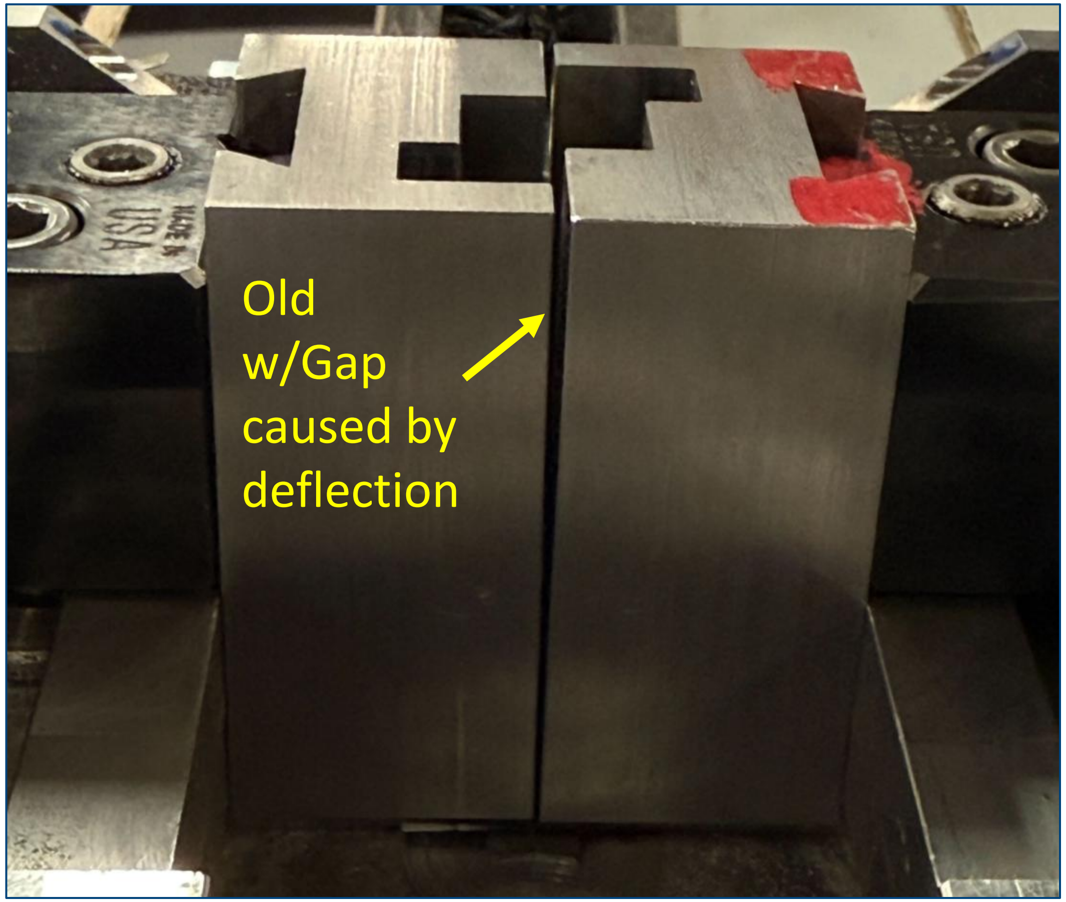
| & Difference Blunt vs Sharp | Sample ID | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
|---|---|---|---|---|---|---|---|
| | Flat Region Width | -39% | -39% | -39% | -15% | -18% | -8% |
| | Ligament Height | 30% | -15% | 14% | 57% | 19% | 25% |

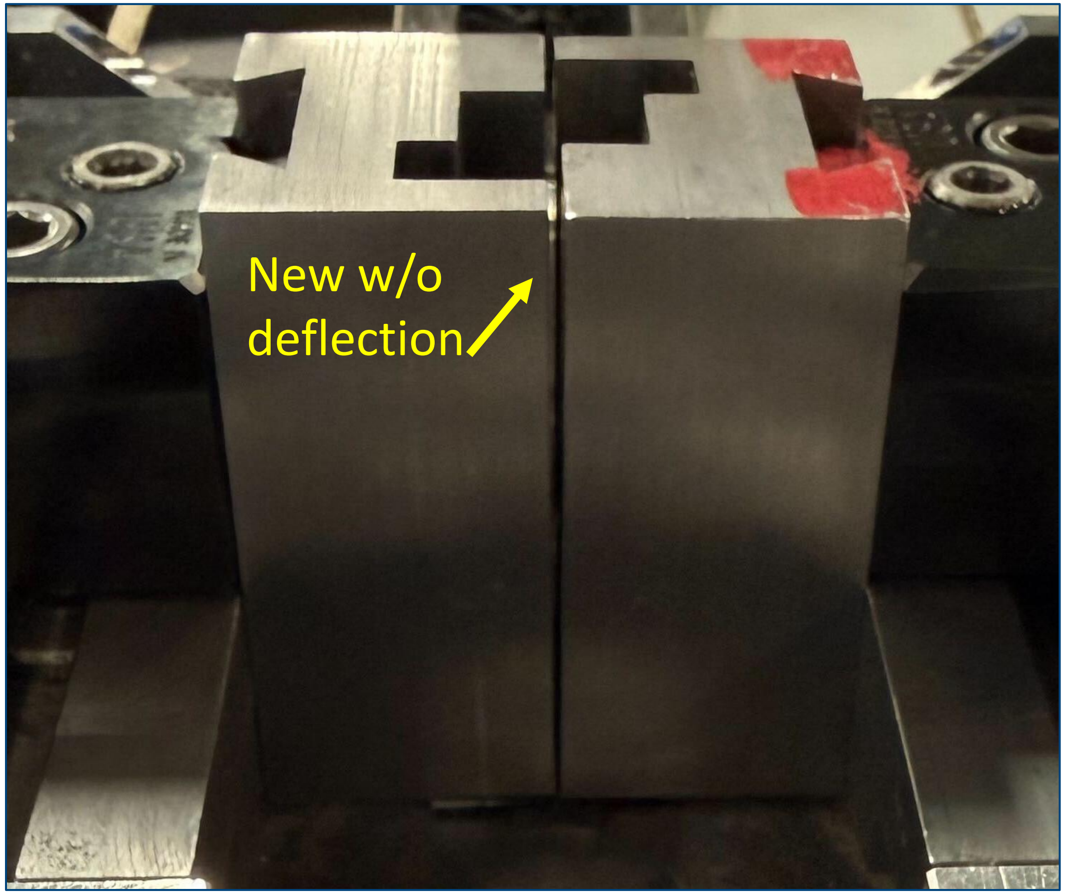
# Task 1.3 Updates (Blade Optimization)

- Overall findings from task have been compiled into the final report for this task
- With delivery of final report this quarter, the task is considered complete.

# Task 2.1 Updates (Field Device Development)

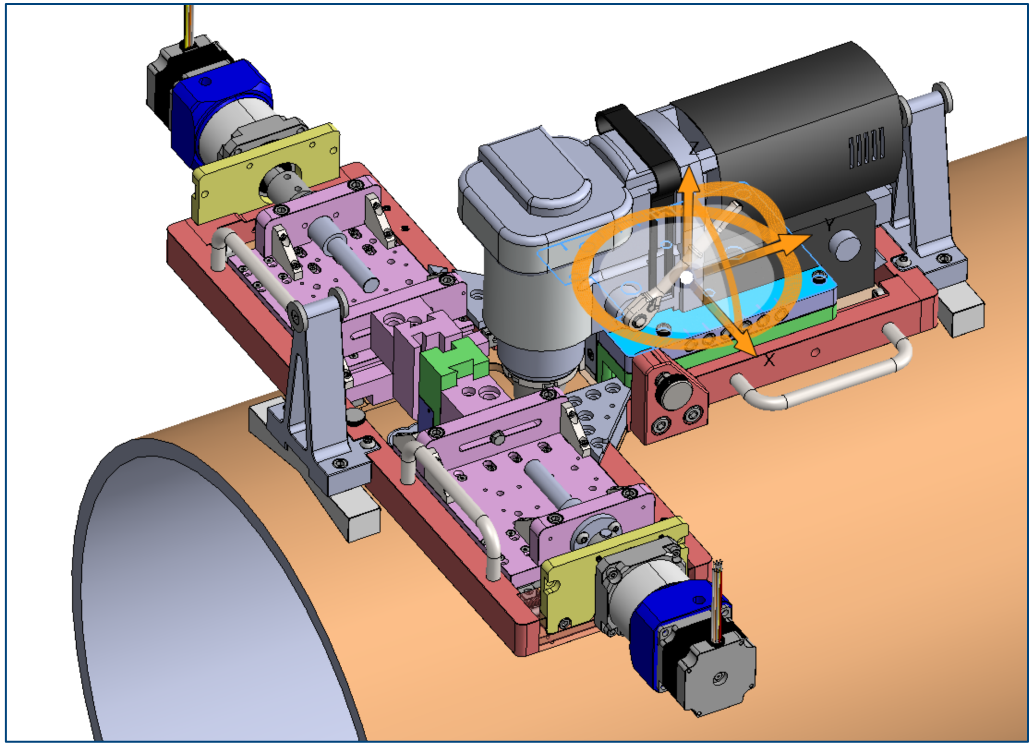
- V1.1 Implementation
  - Addressing Stiffness of Tool Holders

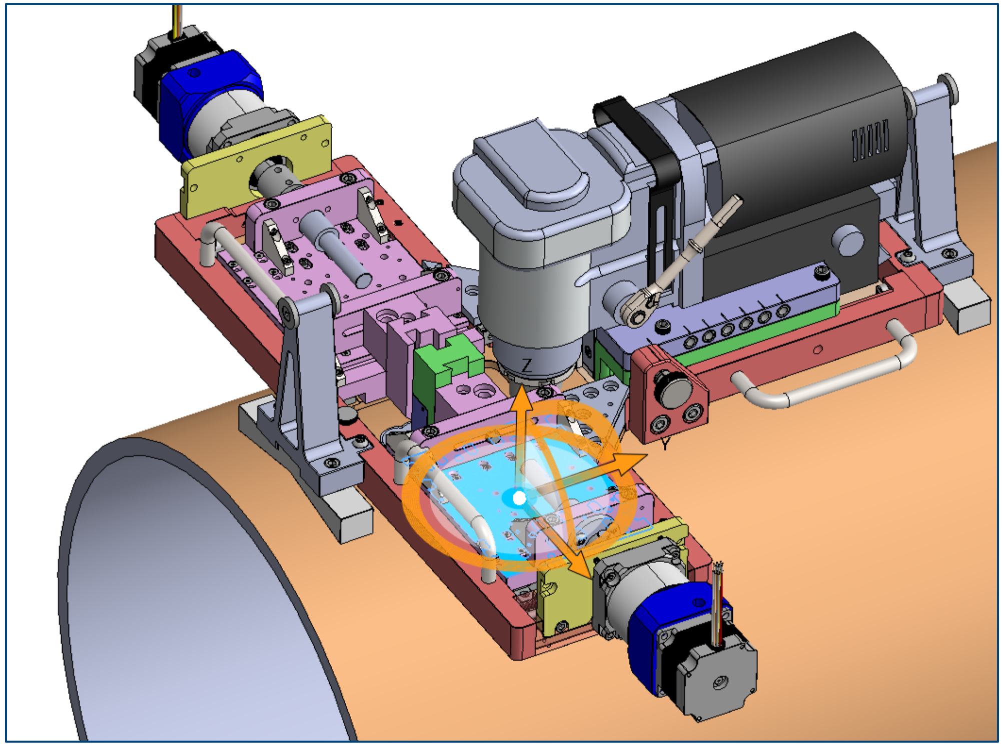


# Task 2.1 Updates (Field Device Development)

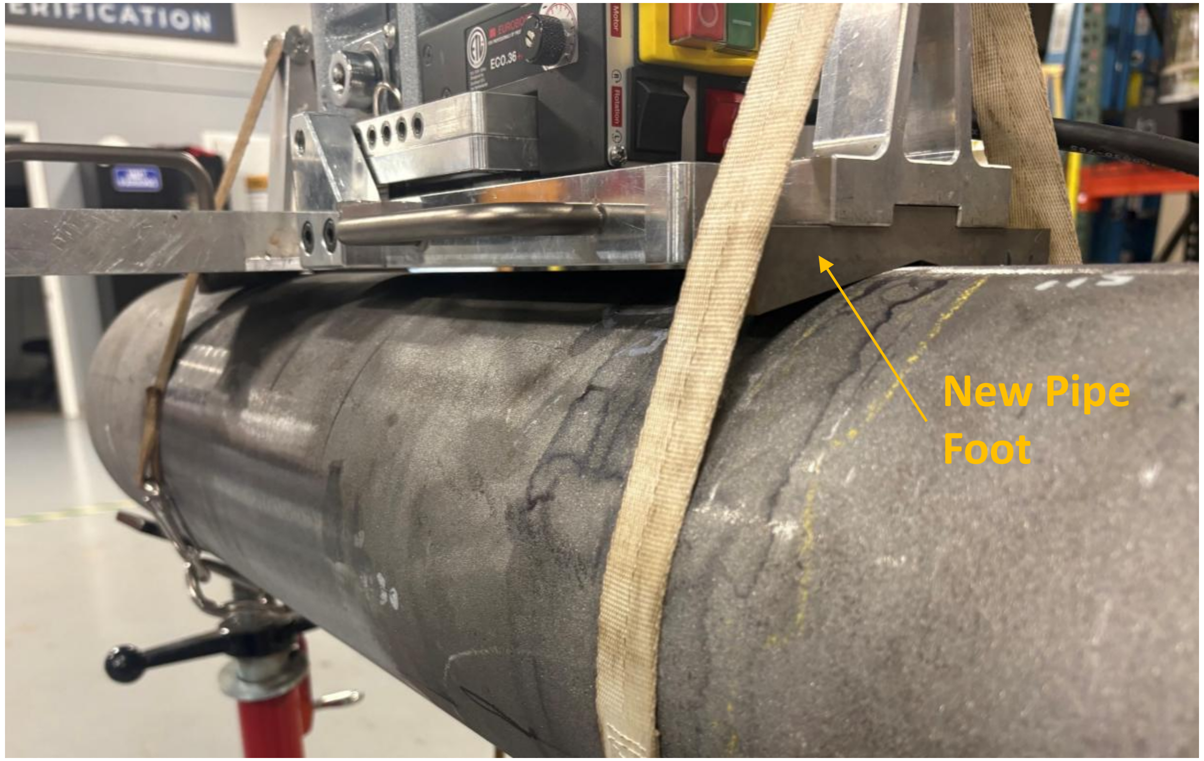
- Improved stiffness has highlighted direction of commercial unit improvment
  - Pitch, yaw, roll, xyz displacement of mag drill greater than expected
  - Different datums for mag drill (left) and drive plate (right)





# Task 2.1 Updates (Field Device Development)

- Foot attachment improvement with diamond coating

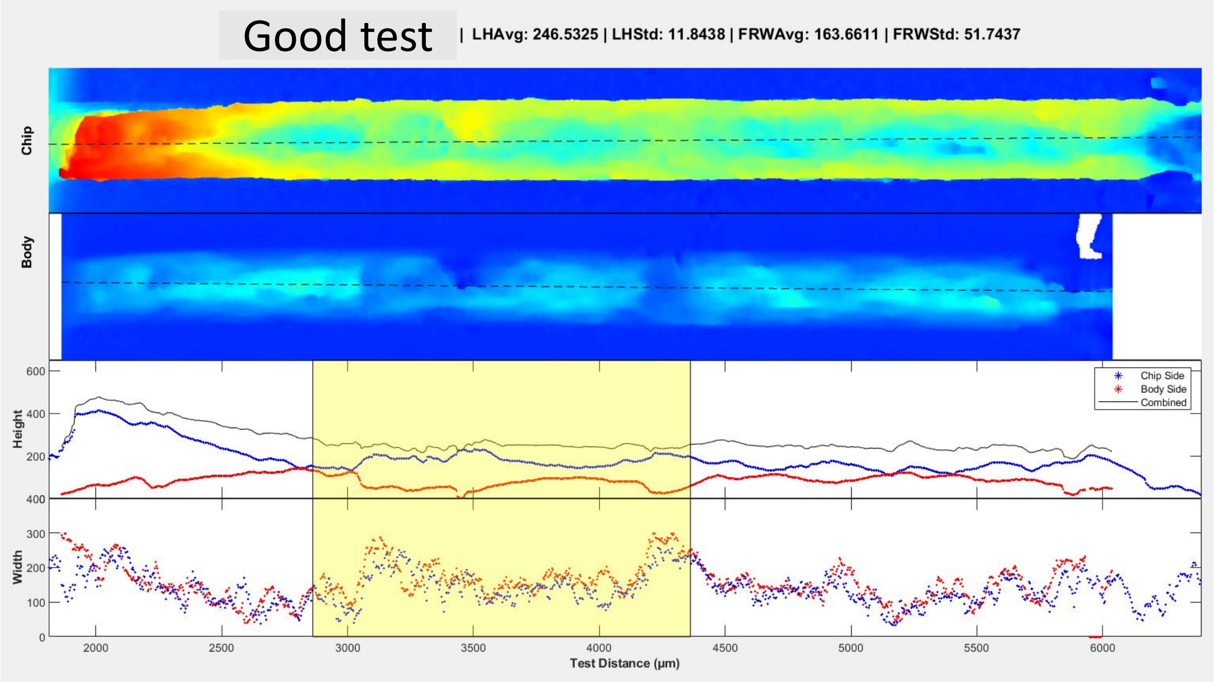


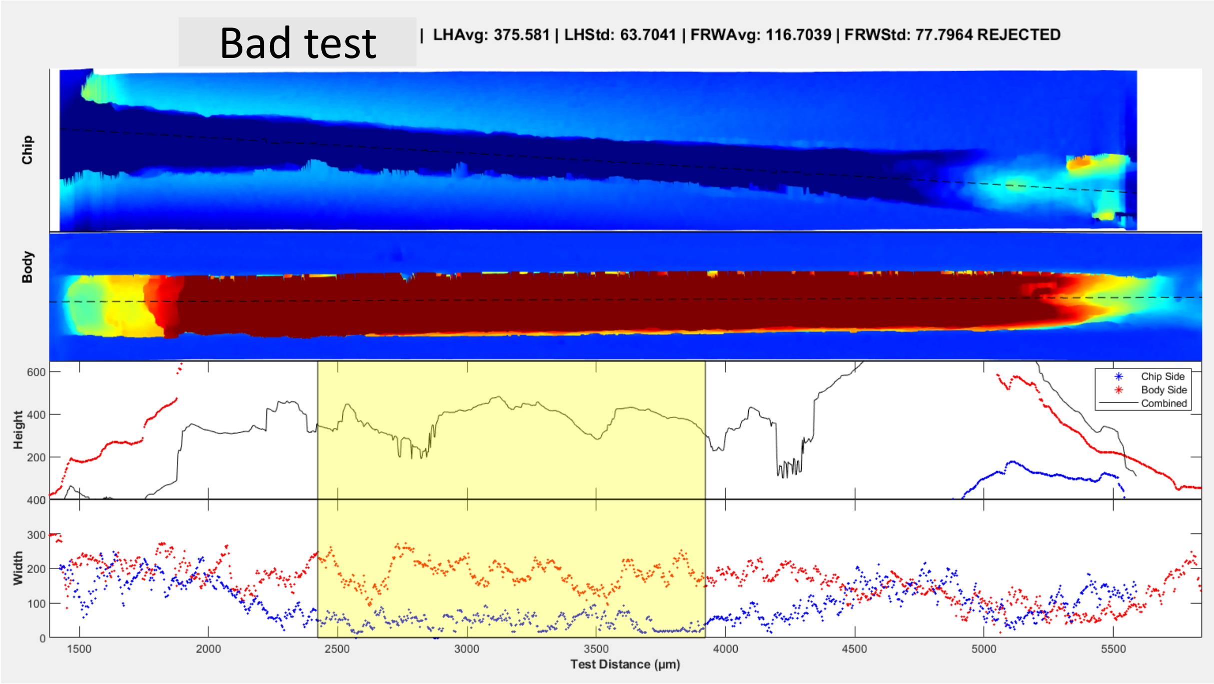
# Task 2.1 Conclusion (Field Device Development)

- With rollout of v1.1 of the field device, the task will be considered complete
- This unit will be utilized throughout initial commercialization efforts, including any third party blind validation
- Task will be officially closed with the delivery of the final report

# Task 2.2 Updates (Processing & Analytics)

- Improvements to auto-generated QA/QC outputs:
  - Single page summary overviewing all key metrics as well as visual representation of the aligned height map

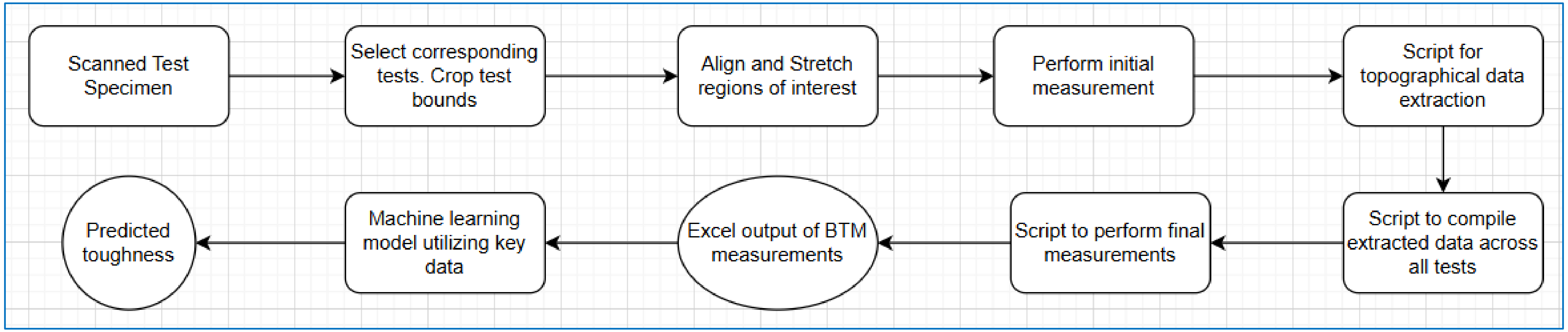


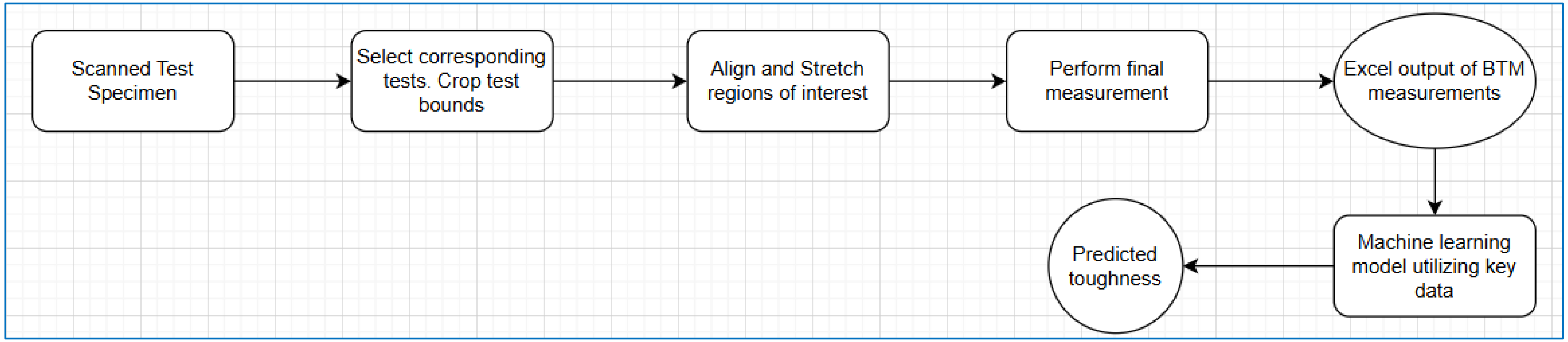
# Task 2.2 Updates (Processing & Analytics)

- Update to post processing software to streamline workflow to produce measurements for final toughness prediction

**Before Improvement:**




**After Improvement:**



# Task 2.3 Updates (Field Procedures)

- L-261 BTM Depth Limiting Milling Bit Inspection Sheet
  - First Release
- L-262 BTM Cleanup Bit Inspection Sheet
  - First Release
- L-263 Blunt Blade QC
  - First Release
- Q250 – BTM Red Tag Form
  - First Release
- Q251 – BTM Non Conformity Report
  - First Release

# Task 2.3 Conclusion

- This Task is being considered complete according to the accomplishment of the following key criteria
  - Completion of: F250, L250, E250
  - Completion of supporting laboratory procedures for L250: L261, L262, L263
  - Completion of quality documentation which support above laboratory procedures: Q250, Q251

# Expected at Year End Q4 Update

- Task 2.2 (Data Processing & Analytics Optimization)
  - Update to TAP on Analytics Improvements
  - Formal closeout with delivery of final report

- Task 2.4 (Third Party Validation)
  - Update to TAP on current status

- Preview of Task 3 Items moving into 2026