Improving Metal Tube Reliability and Useful Life with Advanced Waterjet Technologies and Processes

Final Report

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National Center for Manufacturing Sciences
3025 Boardwalk
Ann Arbor, Michigan 48108

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Acronyms and Abbreviations

Term	Definition
AC	Armaments Center
ARL	Army Research Laboratory
CCD	Charge-Coupled Device
CTMA	Commercial Technologies for Maintenance Activities
DOD	Department of Defense
DEVCOM	U.S Army Combat Capabilities Development Command
NCMS	National Center for Manufacturing Sciences
ODASD-MR	Office of the Deputy Assistant Secretary of Defense, Materiel Readiness

1. Executive Summary

New wear resistant materials of interest to the government are often difficult or impossible to machine by conventional methods. Of particular concern are new coatings that can be applied to the inside of long tubes. These tubes often require features to be machined into the coated parts so machine processes are required that can reach down inside tubes and machine tight tolerance features. These processes also include inspection methods, so that the precision features can be accurately mapped to demonstrate compliance with design requirements.

Ormond used it's unique controlled-depth machining processes to machine the inside of large diameter tubes. These techniques involve multi-step processes whereby material is removed layer-by-layer with optical scanning between passes. The results of the optical scanning are fed back into Ormond's machining model which outputs the machining instructions to achieve final dimensions. Final optical scans demonstrated that the desired geometry and features were achieved to the tolerances required by the government.

All work to date has been on truncated tubes and future work will extend the technology to full-length tubes. Machines are being built at Ormond under separate funding to transition the process to full-length parts at government facilities. Implementation of the technology will enable the use of new high-performance materials that will enhance life and functionality of existing product lines.

Funding was secured for the collaborative initiative through the National Center for Manufacturing Sciences (NCMS) Commercial Technologies for Maintenance Activities (CTMA) Program and the Office of the Deputy Assistant Secretary of Defense, Materiel Readiness (ODASD-MR).

1.1 Results

During this project, development continued in two principle areas - optical mapping or scanning of internal bore features, and waterjet machining of those features.

Optical mapping: Accurate mapping of internal features is critical because the machining process uses the data from the mapping to write the programming for the waterjet machining. This is automated by running the mapping data through Ormond's machining model. The model is sophisticated software that compares the mapped features to desired finished profiles and generates machining parameters which must be used to achieve the final dimensions. Because the features to be mapped were larger than the range of currently used spectral interference sensors, an alternative type of sensor was investigated and used in conjunction with a third kind of sensor – a line sensor. Testing and analysis showed that two triangulation sensors used in conjunction with a line sensor could map all features with a high degree of accuracy. Ormond's software combines the data from all three sensors, and outputs the data in a format that can be read by Ormond's modeling software.

Waterjet machining: Waterjets have been used to machine internal features in other tube sizes and this project extended that capability to the tube size and features that were of interest to the government partner. These features are controlled information and cannot be disclosed in this report.

1.2 Benefits

Extending the capability to optically scan and machine the internal features of interest to the government enabled the use of new wear resistant materials that have the potential to enhance tube life. In addition, the unique capabilities of the waterjet machining process enabled the consideration of novel feature geometry that may enhance the performance of the tubes, increasing their functionality and performance as well as improved life.

The technology is also applicable outside of the DOD, for instance to machine the inside of tubular goods used in the production of oil and gas, as well as heat transfer features for the energy industry.

1.3 Recommendations

The technology development is not complete and must be further advanced to be implemented in the applications of interest to the government. In particular, longer tubes must be machined, and improvements must be demonstrated to the surface finish of the machined features. Improvements may also be necessary as government requirements evolve to more complicated geometry. Improvements to machining processing time should also be developed and demonstrated.

1.4 Technology Transition

The intention is to transition the technology to a government facility when it is sufficiently mature to be operated in a robust manner by shop personnel.

1.5 Invention Disclosure

☐ Yes Inventions ☒ No Inventions

DD882 Invention Report sent to NCMS ☒

1.6 Project Partners

- U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL)
- U.S. Army DEVCOM Armaments Center
- Ormond, LLC
- National Center for Manufacturing Sciences (NCMS)

2. Introduction

2.1 Background

New wear resistant materials of interest to the government are often difficult or impossible to machine by conventional methods. Of particular concern are new coatings that can be applied to the inside of long tubes. These tubes often require features to be machined into the coated parts so machine processes are required that can reach down inside tubes and machine tight tolerance features. These processes also include inspection methods, so that the precision features can be accurately mapped to demonstrate compliance with design requirements.

Ormond has developed waterjet processes that have demonstrated the capability to machine precision features in small tubes, in a wide variety of materials including the materials of interest in this government project. This project extended that capability to larger and longer tubes, demonstrating the ability to machine geometry and tolerances required in materials that are difficult or impossible to machine by any other method.

2.2 Purpose

The purpose of this project was to develop and demonstrate the ability of abrasive waterjets to machine internal features in large bores and to accurately map such features. This demonstration was successfully accomplished and provided the justification to extend the technology to full-length tubes.

2.3 Scope/Approach

The scope of this phase of the project was to make mock-ups of the as-coated truncated tubes and to machine them to finished dimensions as specified by the government. By producing samples of machined and scanned truncated tubes, Ormond has demonstrated the capability to produce the required geometry. By developing the optical scanning techniques to characterize the machined geometry and feeding this data back into the waterjet machining model, it was possible to go from a variable starting geometry to a finished target profile. The optical scanning was able to confirm that the desired geometry had been achieved.

3. Project Narrative

3.1 Task 1 – Determine Starting Geometry of Internal Tube Features

The first task involved working closely with the government to determine the range of likely geometries to be machined. Discussions were held to determine required tolerances and how the features could be dimensioned to take maximum advantage of the new manufacturing processes. The new processes allow variable geometry along the length of the tube and tighter tolerances on certain features that could be of value for product performance. (This approach was taken with the manufacturing of rocket nozzles and hypersonic scram jets with considerable success, allowing the machining of features that were not possible with legacy methods. Altering designs to take advantage of the new manufacturing process enabled improved performance rocket nozzles and scramjets).

Final geometry will not be fully defined until coating processes are fully assessed but the demonstrated flexibility of the waterjet process allow for a wide range of possibilities.

3.2 Task 2 – Measure Coating Thickness

Ormond has been using induction sensors to measure coating thickness on constant diameter tubes (Figures 1 and 2). These sensors are unsuitable for certain types of coatings and for complex geometry because of distortions to the magnetic field caused by neighboring features (Figure 3).

After initial tests, it was decided to alter the overall approach and to map the tubes with optical scanners prior to coating and then map them again after coating. The difference between the two sets of data will provide the most complete map of coating thickness.

Circumferential alignment between the pre-coated data set and the coated tube will be established through a pre-machined indexing mark on the end of the tube.

Figure 1. Induction Probe for Measuring Coating Thickness

Figure 2. Probe Disassembled with 0.125" Sensor to the Right
Used to test functionality of the probe in restricted geometry such as inside features in the tube

Figure 3. Testing of Sensor in Feature Mock-Up Showed Interference of Sidewalls Leading to Inconsistent Results

3.3 Task 3 – Machine Mock-Up Tubes

Tasks 3 and 4 were accomplished concurrently. Task 3 consisted of waterjet machining the geometry of mock-up coated parts, since actual coated parts are not yet available. This task consisted of machining and measuring short sections of internal tube details as the machining process parameters were varied. The scanning data was fed into Ormond's controlled depth machining model to predict the machining steps required to get to finished geometry. Where the target geometry was achieved in the short test sections, the full circumference of features were machined in a longer test piece to demonstrate that the process was repeatable and controllable. This demonstration was successful although the feature dimensions took up the whole tolerance range, suggesting that improvements should be sought to ensure the process would be consistent over time. Nevertheless, the machined mock-up features were likely more consistent than the coated tubes are expected to be.

3.4 Task 4 – Develop Scanning Method

For almost all tubes machined before this project, Ormond had been using optical sensors that are based on Keyence spectral interference systems that are extremely accurate and work well on both smooth/shiny surfaces and waterjet machined surfaces (Figures 4 and 5). Their output is easily integrated into Ormond modeling software, so it is possible to have a closed loop of inspection-machine-inspection that enables the machining of complicated geometry precisely and reliably (Figure 6). These sensors however, were designed for forward-looking semiconductor applications and the 1-mm range was insufficient to scan the proposed final tube geometry. Ormond found similar sensors by Keyence, based on wavelength refractive index variations, that have suitable working ranges but were highly inaccurate for the coating materials of interest and surface finishes of the coating process. Alternatives were sought.

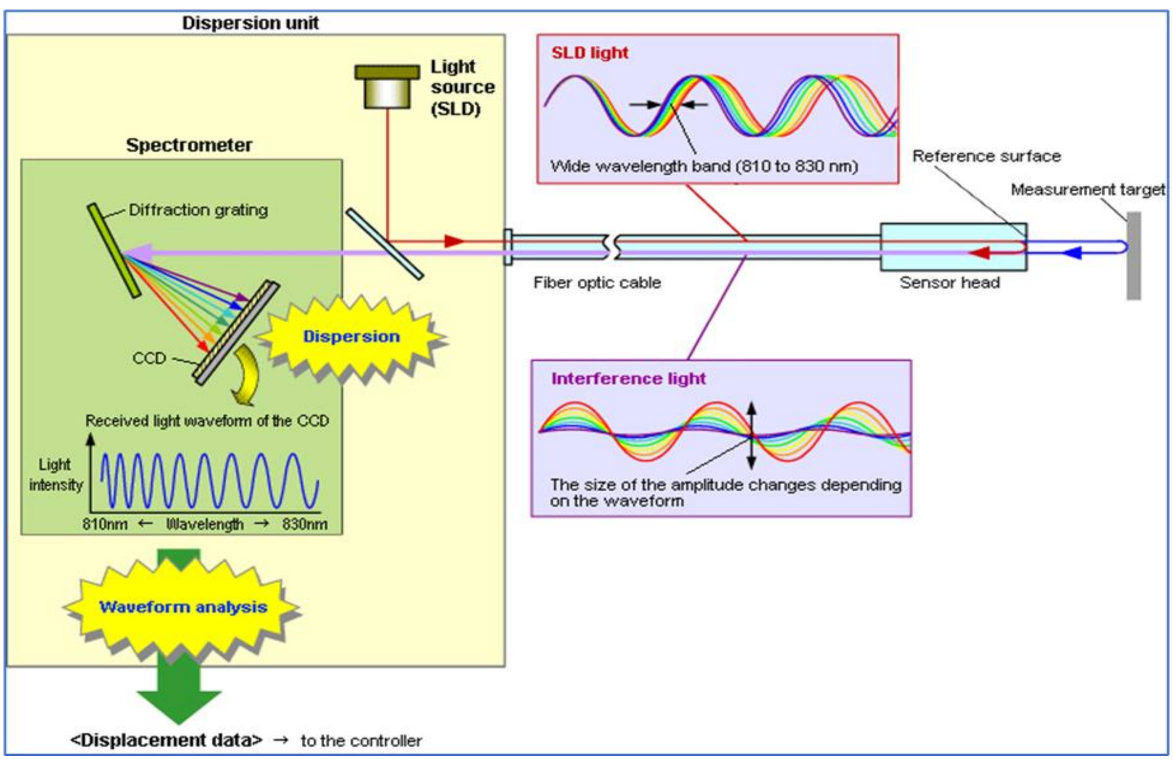

Figure 4. Principal of Spectral Interference Sensing
Note: sensor head is optical only, no electronics. Spectral unit contains light source, spectrometer, and waveform analysis (Image from Keyence)

Figure 5. Line Sensor Scanning Extrusion and Output Graphics
Data is transmitted through robust electrical cable, not optical fiber. Sensor is small enough to fit inside large tubes. Sensor is better for reading side walls than spectral sensors (Image from Keyence).

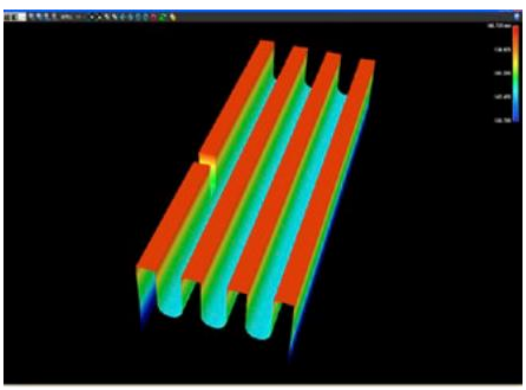

Figure 6. Output Graphics

Ormond identified a vendor who designs custom sensors for spectral interference units and got quotes for building such sensors, along with a quote from a third party for spectral units, but the cost for the hardware would be on the order of $100,000, with the additional expense of engineering time to write the software to convert the output to a useful format for the Ormond model. This was more than Ormond had budgeted ($36K) so a better solution was sought.

Ormond has successfully used line sensors in the past for rocket nozzle applications These sensors raster a laser over a 20-mm length returning the reflection to a charge-coupled device (CCD) chip and analyzing the data to generate a profile. They are a fast and efficient way to accurately measure the geometry of a 20-mm long feature and seemed ideal for this application except that they needed to be combined with other sensors to measure the diameter of the tube (or rotate the head and suffer the reliability and accuracy issues of this arrangement).

Ormond identified triangulation sensors that could be used in conjunction with the line sensor to fully map the bores with high precision (Figure 7). These sensors were low cost and readily available from multiple sources and the output data could be integrated with the Ormond software for adaptive machining of the bore.

Triangulation sensors are usually specified with a repeatability of 0.05%, which would not be good enough for this application because that would result in a 0.025-mm (0.001”) error in diameter measurement. Ormond however, used a precision stage to map the linearity and repeatability of individual sensors and found them to be much better than specifications, provided the very limits of the range was avoided. Because the sensors have digitally readable serial numbers, the software could call-up mapped tables of linear response and compensate for actual measurements. In theory, this makes it possible for the sensor accuracy to be better

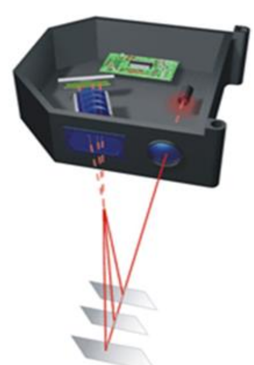

Figure 7. Triangulation Sensor

than 0.0002" which was sufficient for this application (Figure 8). However, continued testing on machined parts showed that the triangulation sensors were better used for circumferential measurements where the noise could be successfully filtered, and the line sensor was better for measuring details such as steps and corner radii. The plan therefore was to use a line sensor to scan the feature of interest and two co-planar triangulation sensors to map diameters. This fit within the overall budget and would result in a robust measurement system that would work for mock-ups, as-coated tubes, in-process tubes and finish machined tubes (Figure 9).

These sensors and measurement strategy were successfully used in Tasks 3, 5, and 6 to characterize the waterjet machined surfaces on the inside of truncated tubes.

3.5 Task 5 – Machine Final Geometry in Mock-Up Tubes

This task required machining the final geometry into truncated steel tubes that already had the as-geometry machined in place. The same waterjet machining processes used to generate the as-coated geometry were used to produce the finished geometry. Similarly, the same optical scanning equipment was used on this stage of the project also.

Follow-on work will extend this demonstration to long-length tubes. Efforts will continue to refine surface finish, geometry control and inspection protocol.

3.6 Task 6 – Optical Scan of Final Geometry

This task involved using the equipment and processes from Task 4 to scan the parts machined in Task 5. Because the preferred solution involved the use of two different kinds of sensors – a line scanner for the machined profile and a triangulation sensor for the absolute diameters – both of these sensors were used to characterize the machined geometry (Figures 10 and 11). Because the preferred method to calibrate the Triangulation Sensor involved averaging of multiple readings by moving the sensor relative to the part, the absolute diameter measurements were made separately from the profile mapping.

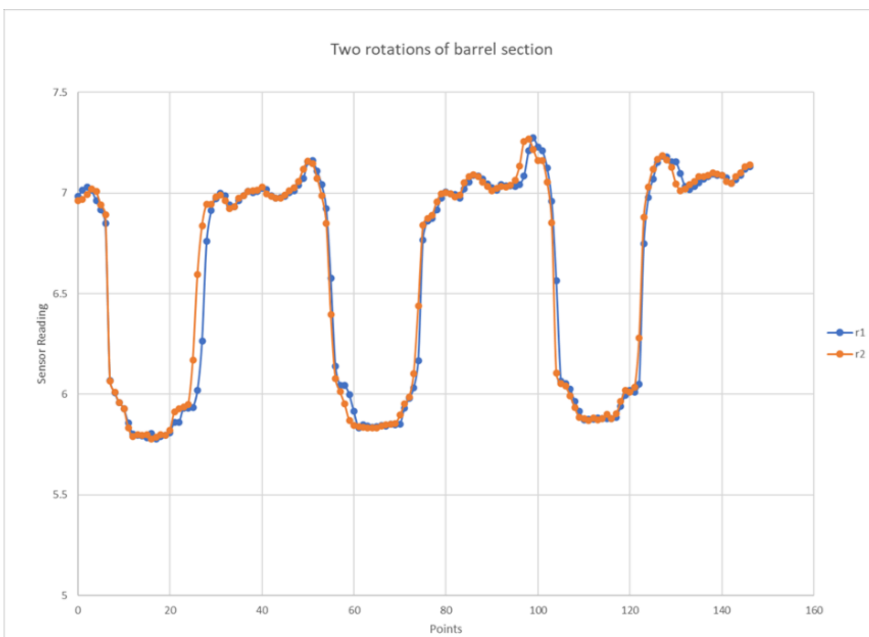

Figure 8. Triangulation Sensor Scan of Waterjetted Tube ID Profile
Repeatability is better than 0.0002.

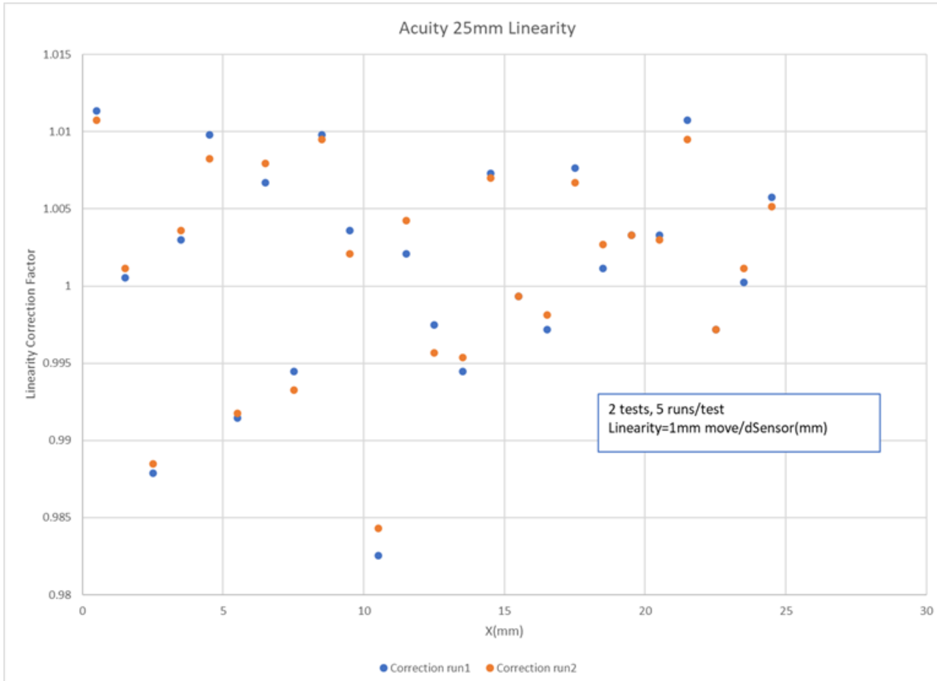

Figure 9. Linearity and Repeatability Test Results Using Nanometer Resolution Stage Allowed Individual Sensor Mapping

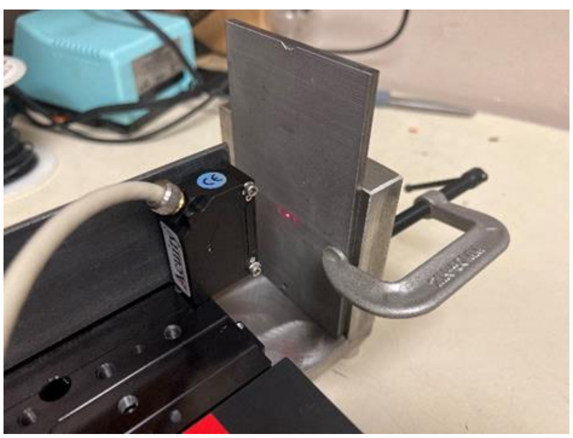

Figure 10. Right-Angled Plate Mapping of Sensor on Precision Stage

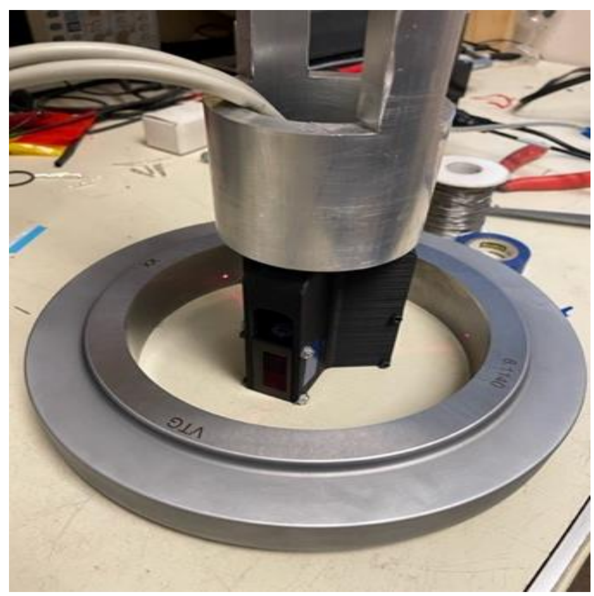

Figure 11. Triangulation Sensors Bench Top Testing in Gauge Ring

4. Conclusions

Advanced waterjet machining techniques coupled with laser mapping while machining can produce complex internal geometry on the inside of tubes for a wide variety of materials. The process demonstrated involved machining, measuring, feeding the resulting data into the machining model, and then having the model output the machining data to complete the part per the final design requirements.

Mock-up tubes and final tubes were machined using the same process and inspection equipment. Other manufacturing processes such as weld build-up or masked milled were considered and rejected as impractical or too complicated and expensive.

The scanning strategy used a combination of triangulation sensors and a line sensor to map the machined features and determine absolute diameters. Other methods, such as spectral interference sensors, were too costly and unsuited to the rapid processing of data.

A strategy was devised that makes coating thickness measurements largely irrelevant for machining purposes. By optically scanning the tubes before and after coating and after waterjet machining, all on Ormond's waterjet machine, the exact location of feature edges can be determined and used to generate machining instructions. However, mapping coating thickness after finish machining may be desirable for quality assurance purposes.

The geometry of interest can be achieved using the machining and measurement techniques demonstrated in this project, at least on truncated lengths of tubes. Further work will be required to implement the technology on full-length tubes.

5. Project Benefits

5.1 Benefits for the General Public

The project advanced waterjet machining methods for internal structures in long tubular parts. Such capability can be useful for a wide variety of applications, such as oilfield tools and tubing, wind turbine components, heat exchangers for electricity generation, gas pipe-lines, aerospace structures, extrusion barrels and gas turbine internals. The processes demonstrated are flexible, robust, economic, environmentally friendly and compatible with other emerging technologies such as large-scale 3D printing.

5.2 Benefits for DOD

The immediate benefit to the DOD is the capability to machine internal structures in large tubes. The tube can be made of wear resistant materials that are difficult or impossible to machine by conventional methods and the technology allows internal geometry to be achieved that is impossible by other methods. These improvements can result in enhanced overall performance and part life of the end-product. For instance, rocket nozzles made by this method could withstand higher tempera-tures and result in improved payload and range. Heat exchangers could be lighter weight and more efficient and compact. Munitions with internal features can be quickly and efficiently machined, creating beneficial geometry that is not possible with current methods. The processes can also be adapted to non-tubular geometry, further extending the benefits of the technology.