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Design and Development of a Fixtureless, Pass-through Machine Tool for Extrusion Machining

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CRADA Final Report
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Manufacturing Science Division
Energy Science and Technology Directorate

DESIGN AND DEVELOPMENT OF A FIXTURELESS, PASS-THROUGH MACHINE TOOL FOR EXTRUSION MACHINING

PHASE 1 FINAL CRADA REPORT

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ABBREVIATIONS AND ACRONYMS

CMM	Coordinate measuring machine
CRADA	Cooperative Research and Development Agreement
FRF	Frequency response function
FT	Fairmount Technologies LLC
ORNL	Oak Ridge National Laboratory
UFF	Universal feeding fixture
XM	XtruMach-3

ABSTRACT

The aerospace, construction/architecture, and transportation manufacturing industries rely heavily on the mass production of near-net shape metallic and composite extrusions. While the production of raw extrusions is a relatively fast process, adding functional features such as holes and slots require additional time, cost, and energy to produce. To compensate for the inherent flexibility of extrusions, conventional machining requires rigid purpose-built fixtures for operations such as trimming, drilling and thinning. This approach requires that the machine tools be as large or larger than the parts themselves. This results in the need for excess shop floor space, energy for auxiliary equipment and motion systems, and significant capital expenditure. Considerable engineering expense and time involved in the designing, building, and proving out of part-specific fixtures for holding the components in specific configurations while machining add to the overall manufacturing cost.

The primary objective of the technical collaboration between Oak Ridge National Laboratory and Fairmount Technologies (FT) is to improve the XM-3, a fixtureless CNC milling machine designed by FT. The machine was developed to trim, drill, and thin extrusions without part specific fixturing to make the manufacturing process more efficient and flexible. Dynamic measurements of the existing structure were collected, and modeling efforts were made to evaluate optimal machining parameters for the current system. Areas of improvement to increase the system stiffness, manufacturability, and machining efficiency were evaluated and highlighted for the next generation design. The impact of this effort may enable agile manufacturing across the commercial and defense aerospace industries, and other industries where extrusions are utilized like in the construction, architecture, and transportation industries.

1. SUMMARY

Phase I of this project evaluated the existing XM-3 machining platform by structural measurement testing and cutting process simulation. The measurements and simulations of the current system provided the team with an understanding of weaknesses in the design of the current system and allowed for identification of target improvements for future design iterations.

The following tasks were completed during Phase 1 of the technical collaboration with Fairmount Technologies:

Task 1: Tap Testing

- The team from ORNL traveled to the Fairmount Technologies facility to perform dynamic tap testing and quantify the structural performance of the XM-3 machine.

Task 2: Machine Metrology and Modeling

- Fairmount Technologies performed some machine tool metrology of the existing machine under static loading cases to understand the deflection of the system.
- Fairmount Technologies shared the design CAD files for XM-3 and create models of the machine (finite element models and machine dynamics models).

Task 3: Design Review

- ORNL assessed the performance of the current machine design and the future design and made suggestions for improvements for ease of manufacturing and dynamic stiffness. This document is considered business proprietary and will not be contained within this report.

Task 4: Final Report

- This report serves as the ORNL summary of the baseline measurements of the current system, results identifying target areas for improvement, and identification of modifications which may be made to the current machine design as well as a design review of the next iteration machine tool design produced by Fairmount Technologies.

2. INTRODUCTION

Fairmount Technologies (FT) has developed the XTRU suite of metal forming and machining technologies capable of rapid manufacturing of structural components from extrusions without tooling or heat treatment. XtruMach (XM), a key technology of the XTRU suite, utilizes a universal feeding fixture (UFF) to securely fixture the parts in all degrees of freedom except one that is used to feed parts through a processing volume within the machine. This allows elongated, curved, flexible structural sections made by extrusion or roll forming, that are much longer than the machine envelope, to be machined without part-specific tooling. Figure 1 below shows airframe components manufactured for customers using the XM technology. While this technology is currently targeted at aluminum parts used in aviation, it can also be used to produce parts for other transportation and construction industries.

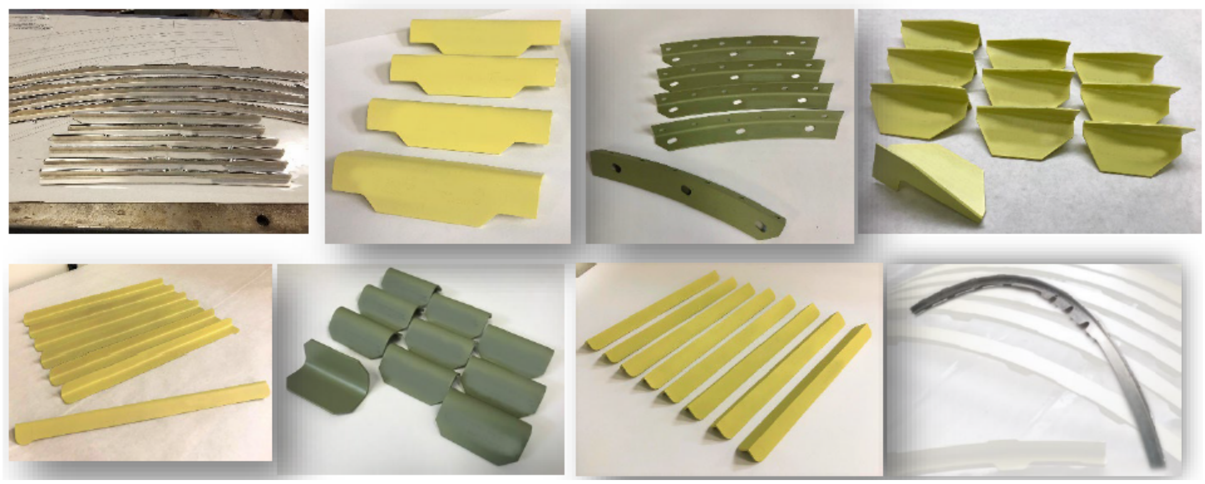

Figure 1. Examples of components machined by XtruMach.

Fairmount Technologies' XtruMach-3 (XM-3) is a small format, four-axis CNC milling machine for rapid machining of extrusions up to a 4" x 4" cross section without the need for dedicated fixturing or manual part repositioning. In this generation of machine design, the tool tip accessed the parts from above the UFF as well as from the front. This design resulted in an increased extension length of the tool, increasing the moment arm and decreasing the tool tip stiffness.

The low machine stiffness for this design made the machining operations more prone to chatter. Chatter also causes significant problems for the machine to track the length of the part accurately.

The intent of this CRADA was to assess the design deficiencies with the current machine tool to identify paths for design improvement or optimal machining parameters for this iteration and provide design feedback on the next version. Together, ORNL and FT performed structural testing, machining simulation, and finite element analysis of the existing machine to guide the development of a new machine with improved stiffness and cutting performance.

3. XTRUMACH-3 MEASUREMENT

Members of the ORNL Advanced Machining and Machine Tool Research group traveled to FT's production facility to observe a cutting demonstration on the existing XM-3 and collect dynamic measurements of the structure. Figure 2 shows the XM-3 machine tool configuration, the universal feeding fixture (UFF), the workpiece, and the cutting tool. Measurements of the machine tool were collected for various spindle poses (changes in orientation of the cutting tool) and at different points on the UFF with both stationary and moving workpieces to identify the most flexible parts of the system.

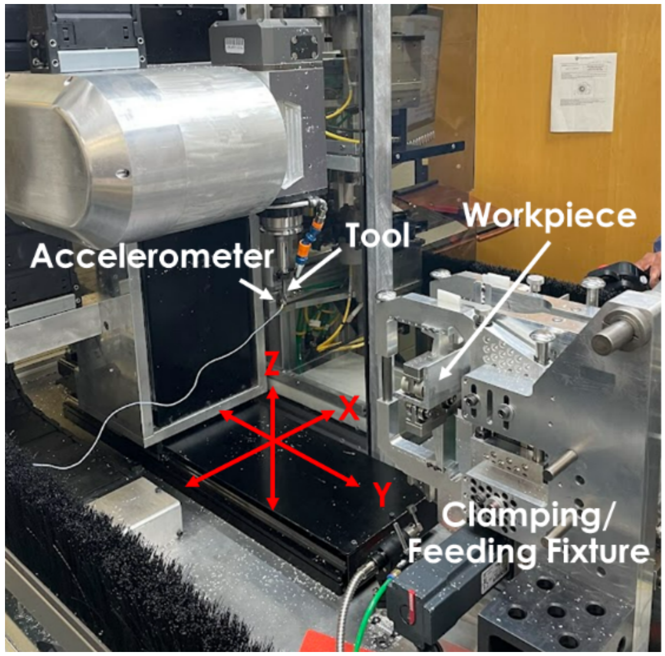

Figure 2. Orientation and nomenclature for XM-3.

3.1 EVALUATION OF SPINDLE DYNAMICS

In many machine tools, the most flexible portion of the system is at the tool tip. The XM-3 tool tip frequency response function was measured in both the X and Y directions for both the 0° and 90° spindle orientations as shown in Figure 3. The magnitude frequency response for each of these four measurements is shown in Figure 4, where in both the X and Y direction, the 0° orientation dominates the flexibility as indicated by the higher peak. The magnitudes of these responses were comparable in both directions, however the natural frequency for the in the X direction is significantly lower than that in the Y direction.

While the tests conducted would allow prediction of optimal stable cutting parameters for this tool-holder-spindle combination, the current data does not allow for identification of spindle and Z axis assembly compliance independent of the cutting tool.

Figure 3. The tool tip frequency response function was collected for two different spindle orientations. Measurements were collected in both the X and Y axis.

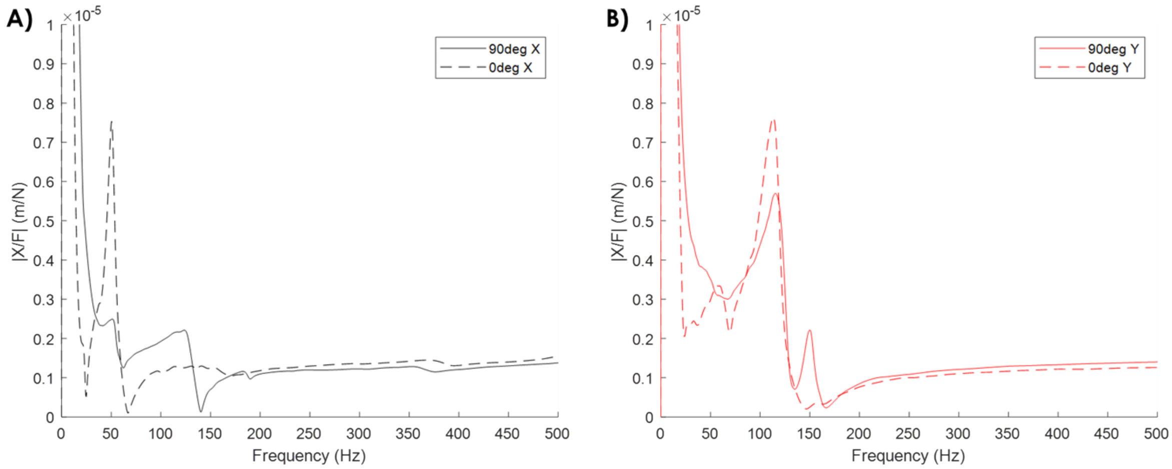

Figure 4. The magnitude of the frequency response function for the cutting tool in the spindle is shown for the 0° and 90° orientations in A) the X axis and B) the Y axis.

3.2 EVALUATION OF WORKHOLDING SYSTEM

The workholding/fixturing and workpiece also contribute to the stability of the system during cutting. For all tests of the workholding system, a 2” x 2” aluminum L extrusion was loaded in the universal feeding fixture (UFF). The clamping/ feeding rollers were engaged with the test workpiece as shown in Figure 5.

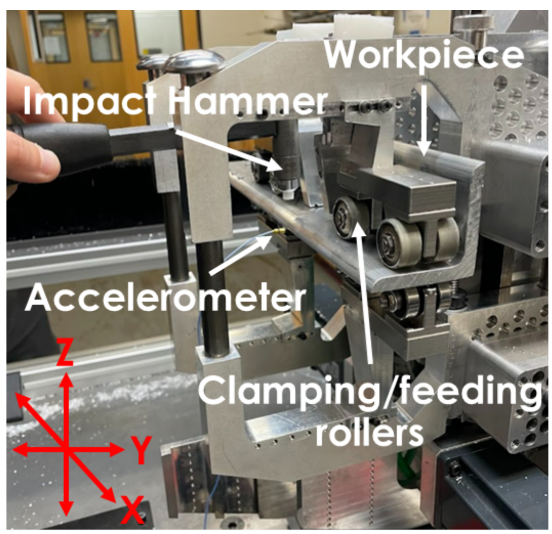

Figure 5. Setup for impact testing of workpiece held in universal feeding fixture. Impact testing is illustrated in the Z direction.

3.2.1 Static Workpiece in Universal Feeding Fixture

The workpiece FRF was collected in the X, Y, and Z directions to evaluate which parts of the structure had the greatest contribution to the flexibility of the system. As shown in Figure 6, the higher peak in the X axis direction indicates that this flexibility of this mode dominates the system dynamics. The most flexible mode in the X direction occurs at 106 Hz and is 4.5 times more flexible than the most flexible modes in the Y and Z directions (both of which occur at 66 Hz). Improvements in the system stiffness should first be aimed at increasing stiffness in this direction.

Additionally, the lack of stiffness in the X direction, which is also the feed direction of workpieces through the fixture for this machine, may be responsible for slipping of workpieces during machining operations. Additional testing of the workpiece dynamics for different bearing preloads would be warranted.

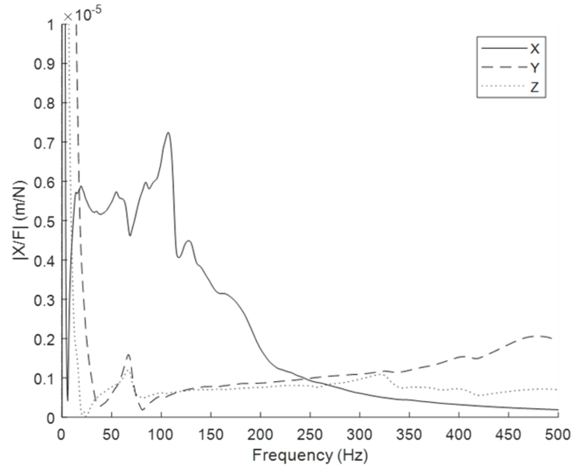

Figure 6. The magnitude frequency response function for the workpiece/ fixture in the X, Y, and Z directions.

3.2.2 Moving Workpiece in Universal Feeding Fixture

The workpiece is fed through the machine by rollers along the X direction. To further investigate the X direction flexibility and the potential for feed rate dependent stiffness changes, the X direction frequency response function was measured as shown in Figure 7.

Figure 7. Impact testing in the workpiece feed direction.

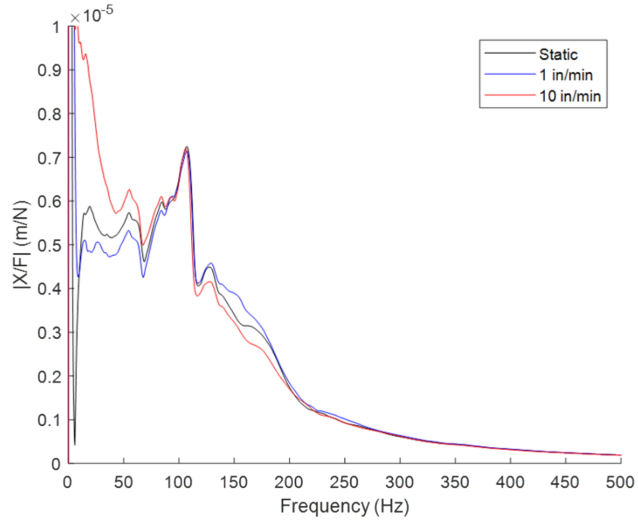

Figure 8. The magnitude frequency response function for the workpiece in the X/feed direction at three different feed rates.

The response was measured under three different conditions: static, 1in/min, and 10 in/min. The similarities in the dominant peak at ~106Hz indicate that the greatest contributor to the flexibility of the system is feedrate-independent.

4. MACHINE METROLOGY AND MODELING

4.1 DEFLECTION TESTING AND FEA MODELING

Fairmount Technologies conducted deflection testing using a portable CMM to record the displacement at several locations across the machine with a series of loads. Traditionally a portable CMM is used by recording coordinates where a predefined ball tip touches the model. To consistently measure deflection the standard tip was replaced with an M6 thread to semi-permanently affix the measurement point to the machine. A location was chosen from every ‘beam’ of the machine to gather enough data to create an analytical model to approximate the machine stiffness. This would be compared to a finite element model and further physical testing.

The portable CMM used was a Quantum Max Faro Arm M Model 7 axis. The arm required zeroing to be used to and to set the reference coordinate system, however once that tip was removed the measured points would not be positionally accurate and can only be used for deflection. Each point was tested under five different X loads and four Y loads with five measurements under each loading condition. With the positions recorded the deflection was calculated and plotted.

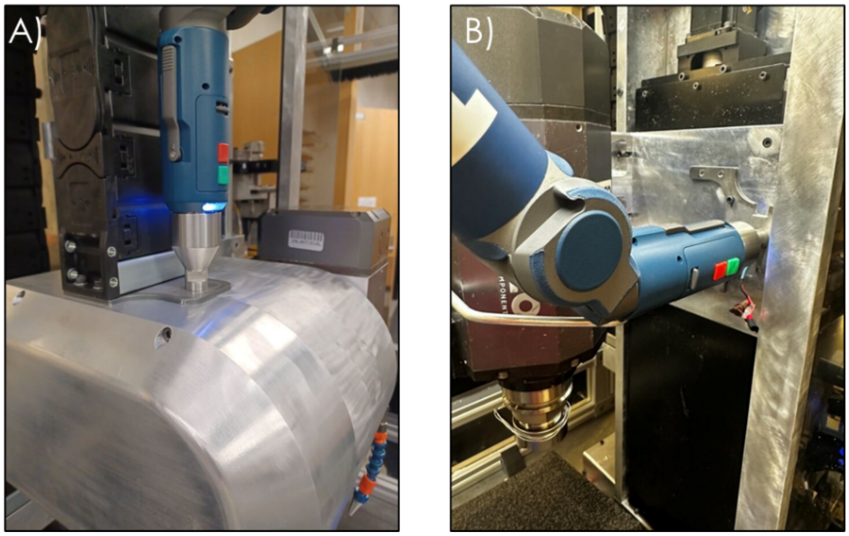

Figure 9. Attachment of the FaroArm at different locations on the XtruMach-3.

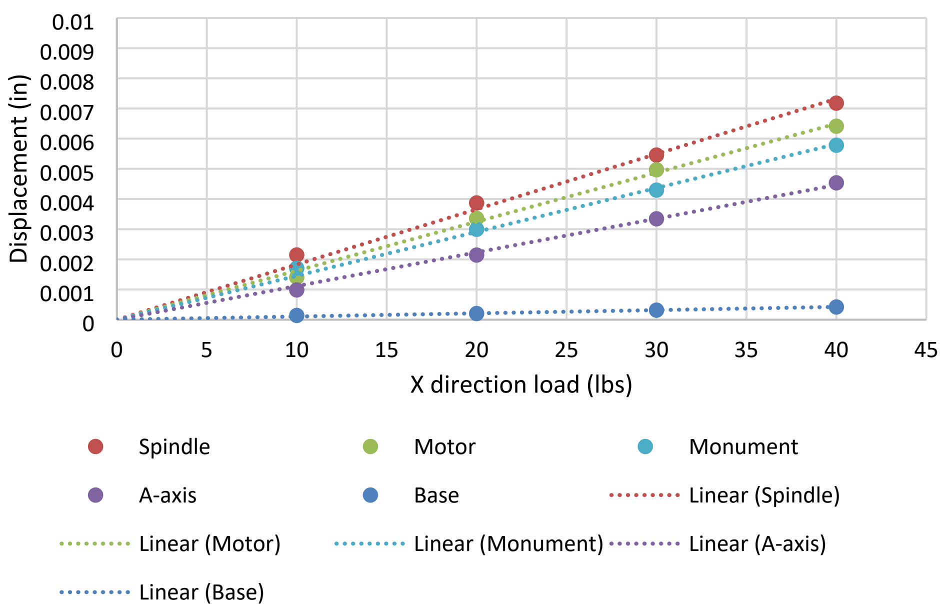

Figure 10. Displacement as a function of applied load as measured by the Faro Arm in the X direction.

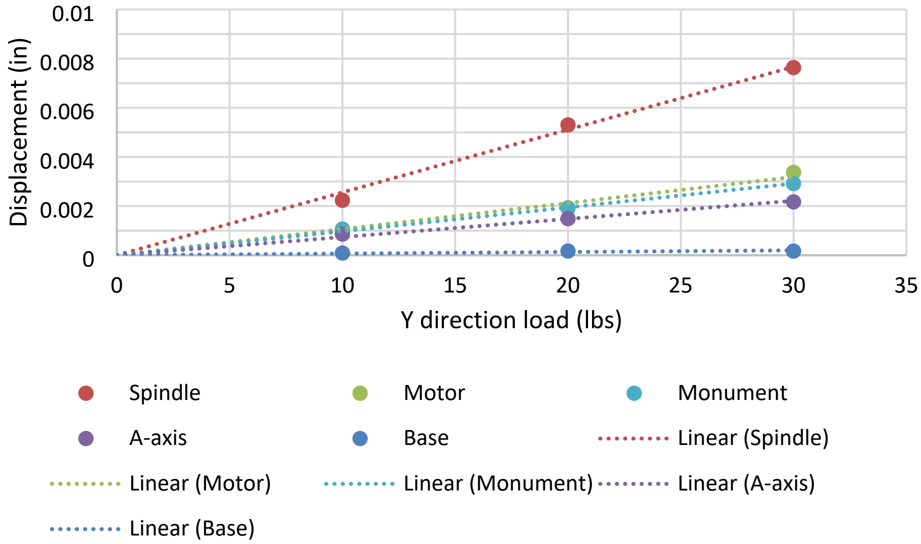

Figure 11. Displacement as a function of applied load as measured by the Faro Arm in the Y direction.

Initial calculations were done with the assumption of perfectly rigid beams with flexure at the joints to find the joint stiffness. Maple was selected as the numeric computing environment to be used for the three-dimensional analysis as it allows for quick processing of equations and automatically simplifies results. FEA was conducted using 3DExperience with both a simplified model of the full machine and a detailed model of the Z axis tombstone. Comparisons between the three models showed that some of the assumptions made within the FEA configuration were faulty and led to inaccurate results, predominately relating to the stiffness of the base and many of the connection stiffnesses. Additional fidelity in future FEA model is needed to more accurately predict machine tool deflections.

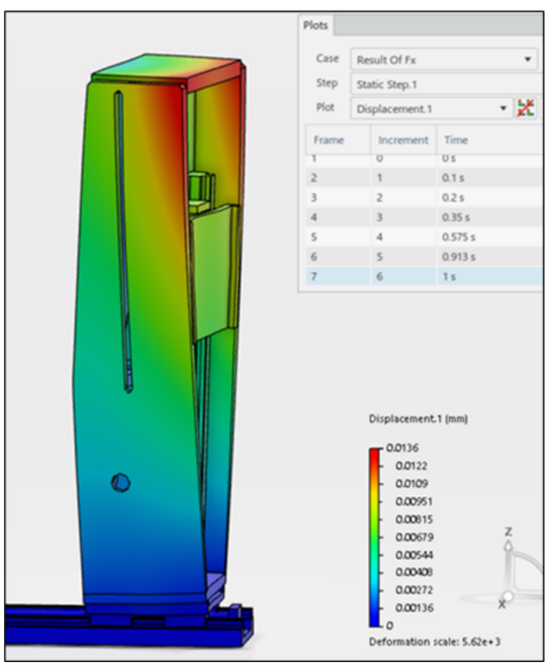

Figure 12. Detailed finite element model of Z axis structure.

5. FUTURE WORK

The work conducted in Phase 1 of this technical collaboration with Fairmount Technologies presents valuable design insights into the current XM-3 machine tool design. Following discussions between ORNL and FT, the team will not be pursuing phase two of this project.