EXPLORATORY MILLING OF MUONIONALUSTA IRON METEORITE USING CrN-, AlTiN-, AND TiAlN-COATED SOLID-CARBIDE END MILLS: PRELIMINARY CUTTING-FORCE ANALYSIS

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ABSTRACT

This paper presents the results of an exploratory milling study conducted on Muonionalusta iron meteorite samples at Michigan State University in collaboration with EMUGE-Franken. Three cutter families—Aero 5 (CrN), TiNoxNF (AlTiN), and Topcut (TiAlN)—were evaluated at multiple feed conditions using cutting force signals. The signals show a clear monotonic rise of signal RMS with feed for every tool family, and one condition (the 6-flute cutter at the highest feed) exhibits a force spike 5–10× larger than all other tests, consistent with a tool-failure event observed during the experiment. The dataset provides a systematic basis for comparing tool performance on a compositionally heterogeneous extraterrestrial workpiece and supports ongoing research into advanced manufacturing processes relevant to in-space resource utilization.

Keywords: meteorite machining, end milling, cutting forces, EMUGE-Franken, machinability, heterogeneous materials

1. INTRODUCTION

Manufacturing science has traditionally focused on engineering alloys whose composition and microstructure are tightly controlled. Iron meteorites represent a fundamentally different class of workpiece: their composition and phase distribution reflect billions of years of natural processing in space, resulting in Widmanstätten iron–nickel banding, silicate inclusions, and localized carbide or sulfide phases that can produce abrupt changes in hardness at the cutting edge [Buchwald, 1975]. These features make meteorite machining an extreme case study in heterogeneous material removal.

Beyond fundamental scientific interest, the ability to manufacture asteroidal or meteoritic material is relevant to long-term in-space manufacturing and resource utilization concepts [Meurisse et al., 2018]. Understanding how commercial cutting tools respond to these materials is a necessary first step toward developing process guidelines for future In-Situ Resource Utilization (ISRU) scenarios. The immediate contribution of the present work is to characterize the terrestrial machinability of a highly heterogeneous Fe–Ni workpiece; ISRU relevance is a longer-term motivation, since ISRU feedstock would ultimately be asteroidal metal or regolith rather than a curated terrestrial specimen.

The Muonionalusta meteorite, an IVA iron meteorite recovered in northern Sweden, was selected as the test material because it is metallurgically well-characterized and available in laboratory-scale quantities. The collaboration between Michigan State University (MSU) and EMUGE-

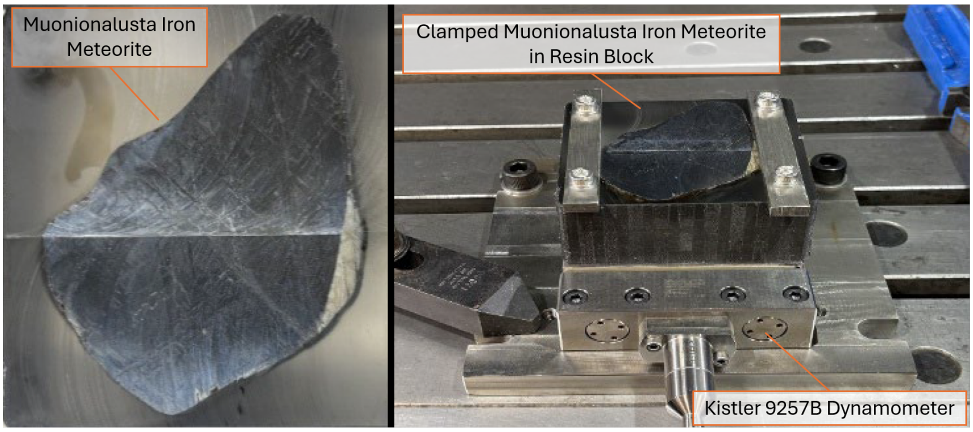

Figure 1. Experimental Setup.

Franken was established to leverage industrial tooling expertise and to rapidly screen multiple cutter designs in a realistic machining setup. This paper reports the experimental design, data acquisition approach, and preliminary observations from the study.

2. BACKGROUND

Iron meteorites of the IVA classification, such as Muonionalusta, are composed predominantly of kamacite (body-centered cubic Fe–Ni, ∼6 wt% Ni) and taenite (face-centered cubic Fe–Ni, ∼30–50 wt% Ni) arranged in the characteristic Widmanstätten pattern. This banded microstructure creates periodic hardness variation at the sub-millimeter scale (kamacite band width ∼0.3 mm; Muonionalusta is a fine octahedrite [Buchwald, 1975]), which directly influences the cutting force signals experienced by a milling tool [Krot et al., 2014].

Previous work on machining of high-nickel iron alloys suggests that tool wear, cutting force stability, and surface finish are highly sensitive to both tool geometry and cutting parameters [Ezugwu & Wang, 1997]. Although meteoritic iron has long been worked into artisanal products such as jewellery and knives [Aerolite Meteorites, n.d.; Oppenheimer, n.d.], no systematic, instrumented (force-measured) study of end milling applied specifically to iron meteorite material using modern coated carbide tools has been reported in the open literature. This study is designed to begin to address that gap at a preliminary level and to generate a dataset that supports future systematic experiments.

EMUGE-Franken tooling was selected because of the company's established expertise in aerospace-grade milling applications, particularly in difficult-to-cut materials such as titanium and nickel-based superalloys. The Aero 5, TiNoxNF, and Topcut cutter families represent distinct geometrical and coating strategies that can be expected to respond differently to the hard, heterogeneous meteorite matrix.

3. EXPERIMENTAL SETUP

Workpiece Material. The workpiece material was a block of Muonionalusta meteorite (IVA iron, ∼7.8 wt% Ni, Widmanstätten structure with kamacite bandwidth ∼0.3 mm (fine octahedrite)). The sample was prepared with a flat milled reference surface prior to the experiment to ensure consistent initial conditions as seen in Figure 1

Figure 2. Representative EMUGE-Franken Topcut solid-carbide end mill.

Cutting Tools. Three families of solid carbide end mills supplied by EMUGE-Franken were evaluated:

- Aero 5 (5-flute, designed for aerospace aluminum and titanium alloys; CrN coating)
- TiNoxNF (4-flute, optimized for titanium and nickel-based alloys with AlTiN-based coating)
- Topcut (4-flute and 6-flute configurations, general-purpose high-performance end mill; TiAlN coating)

All tools had a nominal diameter of 1/4 in. A representative cutter is shown in Figure 2.

Machine Tool and Conditions. Experiments were carried out at the MSU Engineering Research Center on a HAAS VF4 vertical CNC machining center. All cutting was performed under end-milling conditions with down-milling orientation and in dry milling conditions.

Force Measurement and Data Acquisition. Cutting forces were measured using a Kistler 9257B table-type dynamometer. Four measurement channels (Fx, Fy, Fz, and moment) were recorded simultaneously in LabVIEW at a sampling rate of 6,000 samples/s per channel (6 kHz; $\Delta t = 0.000167$ s).

4. TEST MATRIX

A total of 21 milling conditions were tested across the three cutter families. The test matrix was designed to capture the effect of feed rate within each tool family and to explore two larger step-over conditions with TiNoxNF and Topcut tools. Table 1 summarizes all tested conditions.

Table 1. Experimental Test Matrix—EMUGE-Franken Tools on Muonionalusta Meteorite

Tool Family	Flutes	Spindle Speed	Ax. Depth	Feed rate [mm/min]	Notes
Aero 5	5	S688	1 mm	F61 / F122 / F244	3 feed levels
TiNoxNF	4	S688	1 mm	F50 / F100 / F200	3 feed levels
TiNoxNF	4	S917	3 mm	F280	40% step-over
TiNoxNF	4	S917	6 mm	F280	20% step-over
Topcut	4	S688	1 mm	F50 / F100 / F200	3 feed levels
Topcut	4	S917	1 mm	F100	2 repeat runs
Topcut	4	S917	1.2 mm	F100	Extended depth
Topcut	4	S917	6 mm	F280	20% step-over
Topcut	6	S688	1 mm	F74 / F148 / F200 / F296	4 feed levels

Table 2. Data Acquisition Parameters

Parameter	**Value / Notes**
Force measurement	Kistler 9257B table-type dynamometer
Data acquisition software	LabVIEW (National Instruments)
Number of channels	4 (Fx, Fy, Fz, and moment)
Sampling rate	6 kHz
Sampling interval	0.000167 s
Signal units	Newton
File format	Tab-delimited, LabVIEW .lvm format

5. DATA STRUCTURE AND QUALITY

Each test was saved as a tab-delimited LabVIEW Measurement file (.lvm) containing four synchronized voltage channels. The acquisition parameters are summarized in Table 2.

An initial review of the dataset revealed that all files have a consistent structure that enables automated batch processing. Cutting forces vary visibly across feed conditions in preliminary inspections, suggesting a detectable force–feed relationship even before calibration. One record, however, is not a steady-state cut—the 6-flute Topcut at the highest feed (Topcut6fl-S688-1mm-F296) shows amplitudes 5–10× larger than every other test, with the failure onset near 24–25 s consistent with a tool-failure event observed during the experiment (Section 7; Figure 5). This record should be treated as a failure signature rather than a process measurement. Entry and exit transients are present in the time-domain records and should be windowed out before steady-state metrics are computed. A representative steady-state record (Aero 5, F61) is shown in Figure 3.

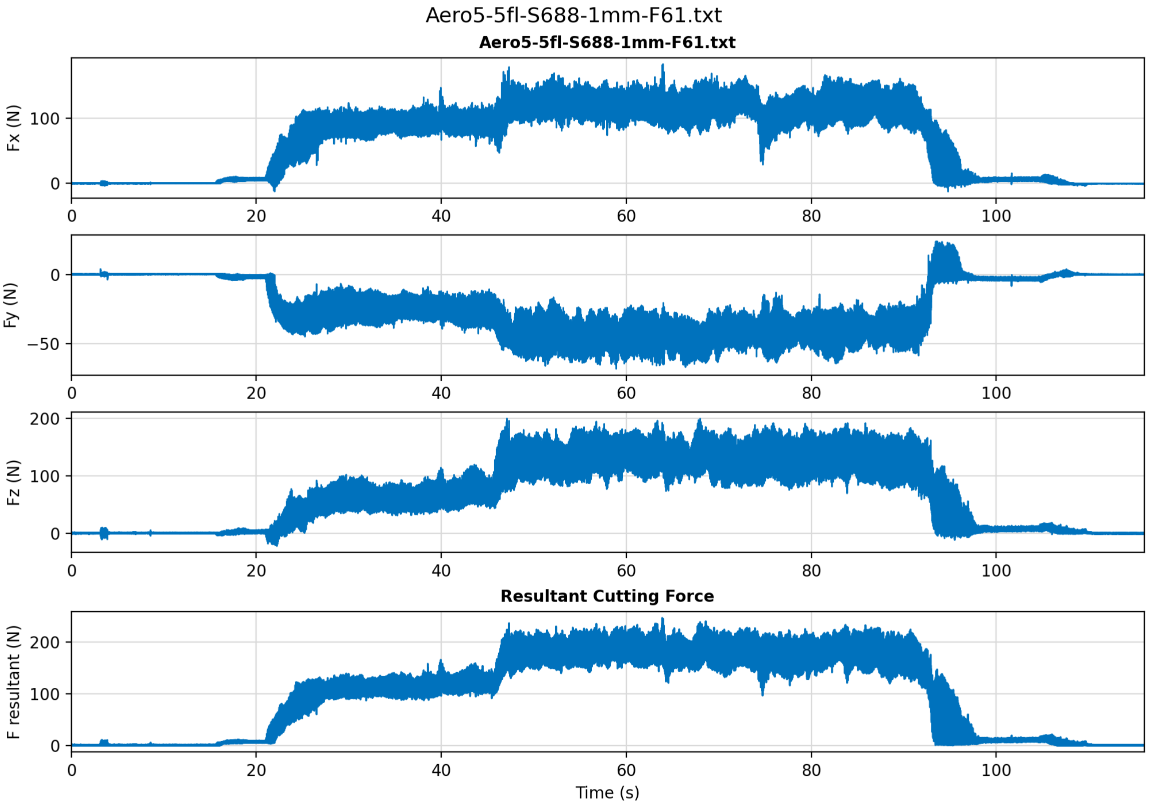

Figure 3. Representative cutting-force record (Aero 5, 5-flute, S688, 1 mm, F61).

Table 3. RMS resultant cutting force, $F_R = \sqrt{F_x^2 + F_y^2 + F_z^2}$, versus feed-per-tooth level (speed code S688, 1 mm axial depth).

Tool (flutes)	**Low** f_z	**Med** f_z	**High** f_z
Aero 5 (5)	125 N (F61)	171 N (F122)	220 N (F244)
TiNoxNF (4)	56 N (F50)	85 N (F100)	122 N (F200)
Topcut (4)	59 N (F50)	82 N (F100)	114 N (F200)
Topcut (6)	93 N (F74)	111 N (F148)	731 N† (F296)

†Contaminated by the tool-failure event (Section 7); not a valid steady-state point.

Preliminary Force–Feed Trend. The cutting force signals show a clear, monotonic increase with feed for every tool family (Table 3). When the feed codes are grouped by approximately constant feed per tooth (feed code divided by flute count), the families fall in a relatively narrow band at matched feed per tooth, with Aero 5 consistently highest.

Figure 4 overlays all records on a common time axis: the F296 record (tool failure) is the clear outlier, which otherwise share a common envelope.

6. ANALYSIS METHODOLOGY

The following step-by-step workflow is proposed for processing the complete dataset:

1. Import all files automatically; parse metadata (tool family, flute count, speed code, feed value, step-over) from file names.
2. Plot raw channel voltages for each test; visually inspect for anomalies, entry/exit transients, and signal saturation.
3. Window the steady-state cutting region, excluding ramp-in and ramp-out segments.
4. Compute descriptive metrics per channel: mean, RMS, standard deviation, and peak-to-peak

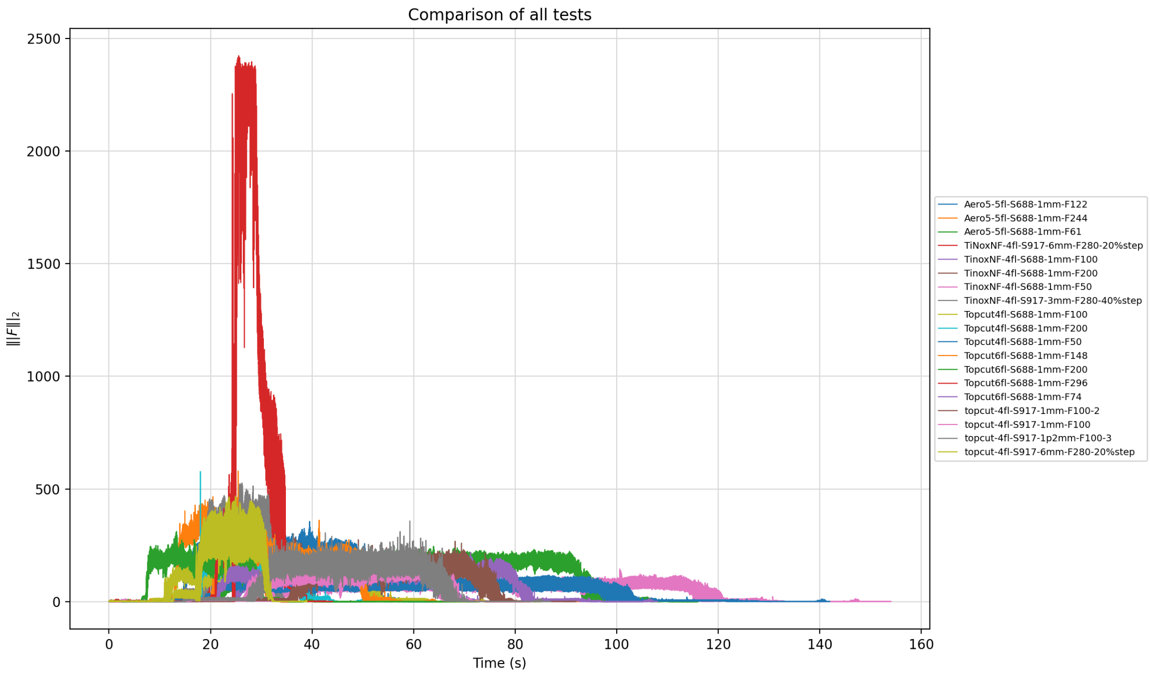

Figure 4. Combined magnitudes for all test records on a common time axis.

amplitude.

5. Apply the dynamometer calibration matrix to convert voltages to force components (Fx, Fy, Fz, and moment if applicable).
6. Compare average cutting force and force oscillation content across tool families and feed levels.
7. Perform frequency-domain analysis (FFT/PSD) to identify potential chatter frequencies or harmonic excitation related to tooth-pass frequency.
8. Identify which tool produced the most stable cutting response and which conditions generated large transients or instability signatures.
9. Correlate force behavior with observed surface quality, chip morphology, tool wear, and operator notes from the test day.

7. DISCUSSION

This study represents an important first step toward understanding how modern commercial milling tools behave when cutting meteorite material. The Muonionalusta meteorite's Widmanstätten microstructure with kamacite and taenite bands creates a periodically varying cutting resistance that has no direct analogue in conventional aerospace alloy machining. Because the band width is sub-millimeter, the cutting edge traverses several bands per revolution at the feeds used here, so any band-induced force modulation may be partly averaged out. This heterogeneity is expected to produce force oscillations that are not synchronized with the tooth-pass frequency, making frequency-domain analysis particularly informative for identifying instability.

The three tool families tested represent distinct design philosophies. The Aero 5 (5-flute) is optimized for high material removal rates in lighter aerospace alloys and offers high stiffness through its flute count. The TiNoxNF is designed for difficult-to-cut materials with high chemical affinity for the tool, suggesting that its coating may perform differently against the iron-nickel matrix of the meteorite than against conventional titanium workpieces. The Topcut in 6-flute configuration is expected to distribute cutting forces more evenly, potentially offering an advantage in terms of surface finish on the heterogeneous material.

The feed sweep within each tool family (three to four feed levels) will allow fitting of a force-feed relationship of the form $F_c = C \cdot f_z^k$, where F_c is the resultant cutting force, f_z is the feed per tooth, and k is an empirically determined exponent. Comparison of the exponent k across tool families may reveal differences in the force-generation mechanism related to tool geometry and coating.

The collaboration with Evan Duncanson from EMUGE-Franken contributed significant practical value: real-time qualitative assessment of chip color, morphology, cutting sound, and surface appearance during the experiments cannot be captured in force data alone. These observations, once formally recorded and incorporated into the dataset, will be essential for a complete interpretation of the force signals.

The larger step-over conditions (3 mm and 6 mm axial depth with 20–40% radial step-over) tested with TiNoxNF and Topcut tools offer a first look at force levels under more aggressive

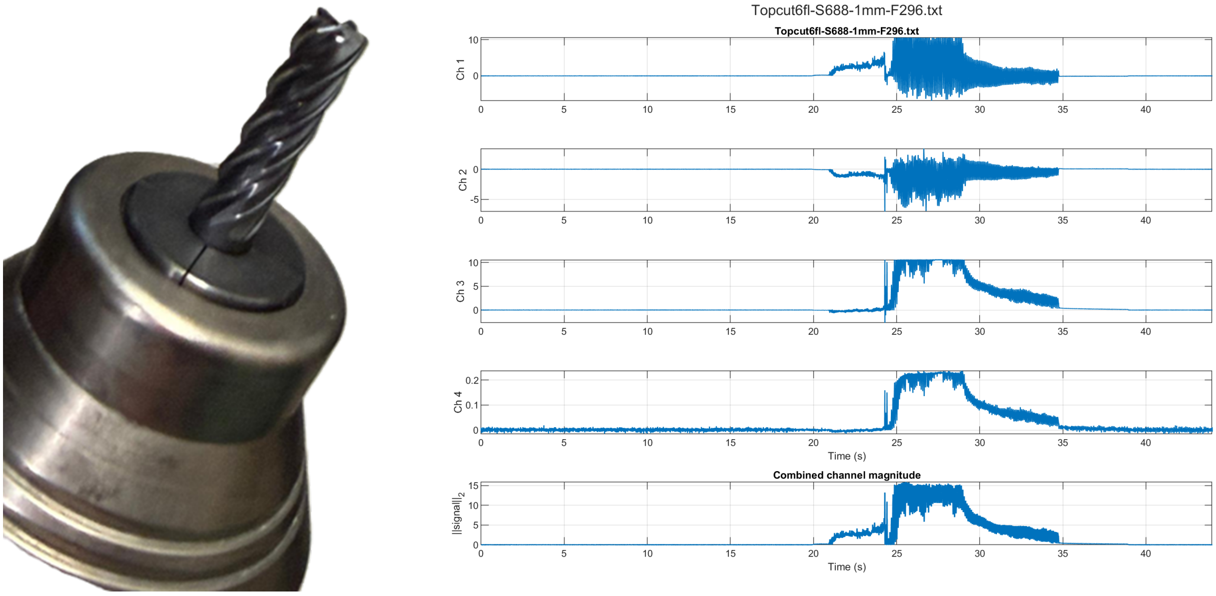

Figure 5. Tool-failure event (Topcut, 6-flute, S688, 1 mm, F296): (left) fractured end-mill tip; (right) the corresponding force record.

material removal scenarios. These conditions are particularly relevant for evaluating whether the tools can sustain stable cutting when the effective engagement area increases and the probability of encountering phase boundaries per unit time rises.

Several design limitations bound the strength of any cross-tool conclusion. (i) The matrix is exploratory rather than balanced: spindle speed changes with axial depth (S688 at 1 mm, S917 at 3/6 mm), and the 3 mm/40% and 6 mm/20% cases differ in both depth and step-over, so these effects are confounded. (ii) The aggressive (large step-over) conditions were run only with TiNoxNF and Topcut, so Aero 5 cannot be compared at those conditions. (iii) All cuts were taken on a single block in one session, so tool wear and cut location are confounded with tool family, and with essentially one run per condition (a single repeated point) repeatability is not yet quantified. (iv) The tool-failure record (Figure 5) indicates that the most aggressive 6-flute condition exceeded a process limit. These points motivate a balanced, replicated follow-up campaign that includes a reference workpiece (e.g. a conventional steel or Ti alloy) to place the meteorite forces in context.

8. CONCLUSIONS

A collaborative milling experiment was successfully completed on Muonionalusta iron meteorite material at Michigan State University with EMUGE-Franken support. The following conclusions are drawn from the preliminary analysis:

- A total of 21 milling conditions covering three cutter families (Aero 5, TiNoxNF, Topcut), multiple flute counts (4, 5, 6), and feed rates spanning F50 to F296 mm/min were successfully completed and recorded.
- Cutting force data acquired at 6 kHz via a Kistler dynamometer have a clean, consistent structure suitable for automated batch processing and both time-domain and frequency-domain analysis.

- Cutting force signals rise monotonically with feed for every tool family (Table 3), and at matched feed per tooth the families differ only modestly (Aero 5 highest).
- The 6-flute Topcut at the highest feed (F296) produced a force signature 5–10× larger than all other tests, consistent with a tool-failure event recorded during the experiment—a concrete machinability limit for the most aggressive condition tested.
- The one-day screening format was effective in generating a broad comparative dataset; targeted follow-up experiments can now be designed around the most promising tool–condition combinations identified from this data.
- These results lay the groundwork for a systematic machinability study of extraterrestrial materials and may contribute to process development for in-space manufacturing applications.

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