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Procedia Manufacturing 10 (2017) 159 – 170

Procedia MANUFACTURING

45th SME North American Manufacturing Research Conference, NAMRC 45, LA, USA

A Fundamental Investigation of Modulated Tool Path Turning Mechanics

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Abstract

This paper describes an experimental machining platform that provides metrology during tube turning (orthogonal cutting) for force, global temperature, feed motion, tool wear, and chip formation during continuous feed and modulated tool path, or MTP, turning. MTP is a technique which produces discontinuous chips by superimposing tool oscillations in the tool feed direction on the nominal feed rate to repeatedly interrupt the cutting process. AISI 1026 cold-drawn steel machining experiments are performed and data is presented for: 1) feed motion and modeling; 2) force measurement and modeling; 3) temperature measurement; and 4) chip formation for constant and MTP tool paths. Shear-localized chip formation that begins and ends during a single MTP chip is demonstrated.

Keywords: *Machining; modulated tool path; cutting force; temperature; chip formation*

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1. Introduction

Unlike milling where the tool constantly engages and disengages the workpiece, conventional turning, boring, and threading operations typically exhibit continuous cutting. Once the cutting edge is engaged with the workpiece, it remains in contact at a specified feed rate until the cut concludes. This tends to produce a continuous chip that can wrap and collect near the cutting edge when machining ductile materials; see Fig. 1. The local buildup of this

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doi:10.1016/j.promfg.2017.07.043

continuous chip can result in one or more of several undesirable outcomes: workpiece scratching, tool damage, machinist injury, and increased cycle time to clear the chip from the tool/workpiece.

Chip management strategies include the use of specialized rake face geometries (i.e., chip breakers) and high pressure coolant directed at the rake face-chip interface to intentionally fracture the otherwise continuous chip. The performance of these strategies depends on the chip thickness, chip radius of curvature, and workpiece material [1], as well as the coolant pressure, direction, and location when high pressure coolant is applied. An alternative approach to these techniques is modulated tool path (MTP) turning, where individual chips are formed by repeatedly interrupting the continuous chip formation via the superposition of tool oscillations on the nominal tool feed motion. In this case, successful chip separation is based on the tool oscillation frequency relative to the spindle speed and the oscillation amplitude relative to the global feed per revolution.

Prior MTP efforts have demonstrated its effectiveness for controlling broken chip length in both turning [2-5] and threading [6]. In this paper, an experimental platform is described that provides metrology during tube turning (which approximates orthogonal cutting conditions) for cutting force, global temperature, feed motion, tool wear, and chip formation during MTP turning. Example data is presented with a focus on: 1) feed motion and modeling; 2) force measurement and modeling; and 3) chip formation for MTP tool paths.

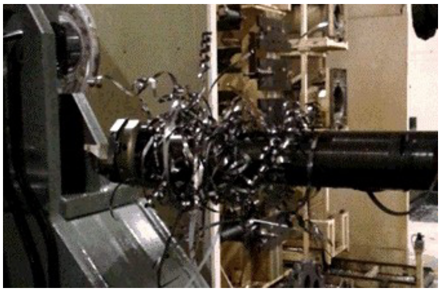

Fig. 1. Chip buildup observed in a boring operation.

Nomenclature

MTP	modulated tool path
OPR	tool oscillation frequency relative to the spindle speed
RAF	oscillation amplitude relative to the global feed per revolution
f	tool oscillation frequency (Hz)
Ω	spindle speed (rpm)
A	tool oscillation amplitude
f_r	global feed per revolution
z	feed motion including the nominal feed and sinusoidal MTP oscillation
F_c	force in the cutting direction
F_t	force in the thrust direction
b	chip width
h	chip thickness
k_c	force coefficient in the cutting direction
k_t	force coefficient in the thrust direction

2. MTP Description

As noted, MTP is a turning technique which produces discontinuous chips by superimposing oscillations in the tool feed direction to repeatedly interrupt the cutting process [5]. An exaggerated depiction of an MTP turning operation is displayed in Fig. 2. The broken chip length is dependent on two, user-defined MTP parameters: 1) the tool oscillation frequency relative to the spindle speed, *OPR*; and 2) the oscillation amplitude relative to the global feed per revolution, *RAF*. The parameters are defined as:

$$OPR = \frac{60 \cdot f}{\Omega} \tag{1}$$

$$RAF = \frac{A}{f_r} \tag{2}$$

where f is the tool oscillation frequency (Hz) in the feed direction, Ω is the spindle speed (rpm), A is the tool oscillation amplitude, and f_r is the global feed per revolution for a traditional, constant feed turning operation.

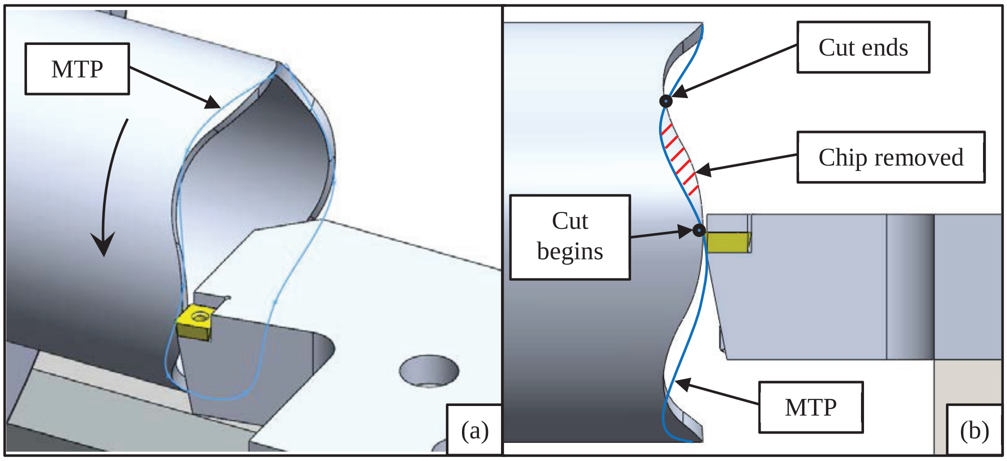

Fig. 2. (a) The tool feed motion along the tube axis is varied sinusoidally to produce a wavy surface in the feed direction. (b) By selecting appropriate *OPR* and *RAF* values, broken chips are periodically produced.

3. Experimental Setup

The testbed for the experiments was a Haas TL-1 computer numerically-controlled (CNC) lathe (8.9 kW, 2000 rpm spindle). Tubular workpieces were machined from AISI 1026 cold-drawn steel. The outside diameter of the workpieces was 72 mm and the wall thickness was 1 mm. Concentricity and cylindricity of the outside and inside diameters with the rotational axis of the lathe spindle was assured by performing a finishing cut immediately prior to conducting the experiments. Orthogonal tube turning was selected, rather than disc or flange turning [7], so that the cutting speed, v_c, would not vary with a fixed spindle speed. Experiments were conducted at cutting speeds of {37.5, 75, and 112.5} m/min with nominal feed rates of {0.051, 0.102, 0.152, and 0.203} mm/rev. The commanded *OPR* and *RAF* values for all tests were 0.5 and 0.8, respectively. Type C, 80° parallelogram carbide inserts with a zero rake angle, 7° relief angle, and a flat rake face were used (ANSI catalog number CCMW3252, Kennametal part number 3757916).

Dynamic cutting forces were measured using a three-axis dynamometer (Kistler 9257B) mounted to the lathe's cross slide. A high speed camera (Fastec IL-3) with a maximum frame rate of 1250 frames/sec was mounted to a tripod which was fixed to the shop floor. An infrared camera (FLIR E40) was attached to the cross slide to establish temperature trends with changes in machining conditions. A laser vibrometer (Polytec OFV-534/OFV-5000) was used to measure the feed direction motion (z). A digital microscope was also attached to the lathe bed to measure insert flank wear at a fixed location between cutting tests. A photograph of the setup is provided in Fig. 3 and additional views are provided in Fig. 4.

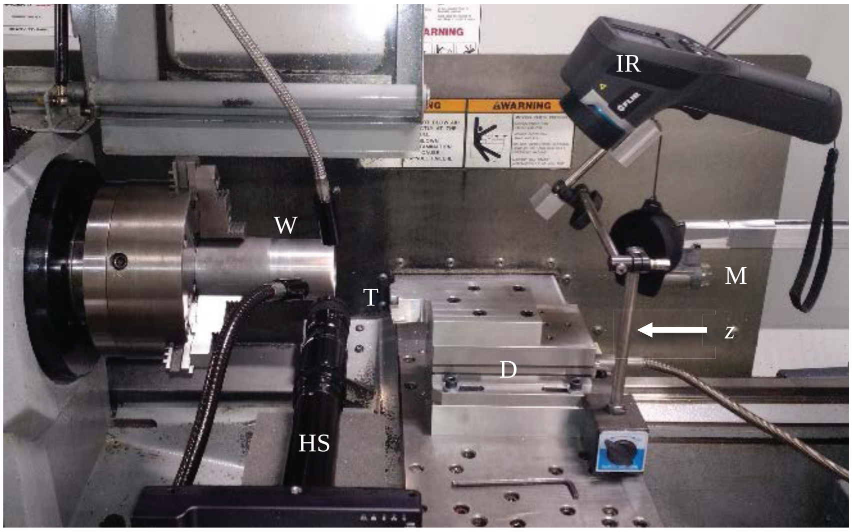

Fig. 3. (a) Photograph of orthogonal tube turning setup including: workpiece (W), tool (T), high speed camera, (HS), infrared camera (IR), digital microscope (M), and dynamometer (D). The laser vibrometer is not shown.

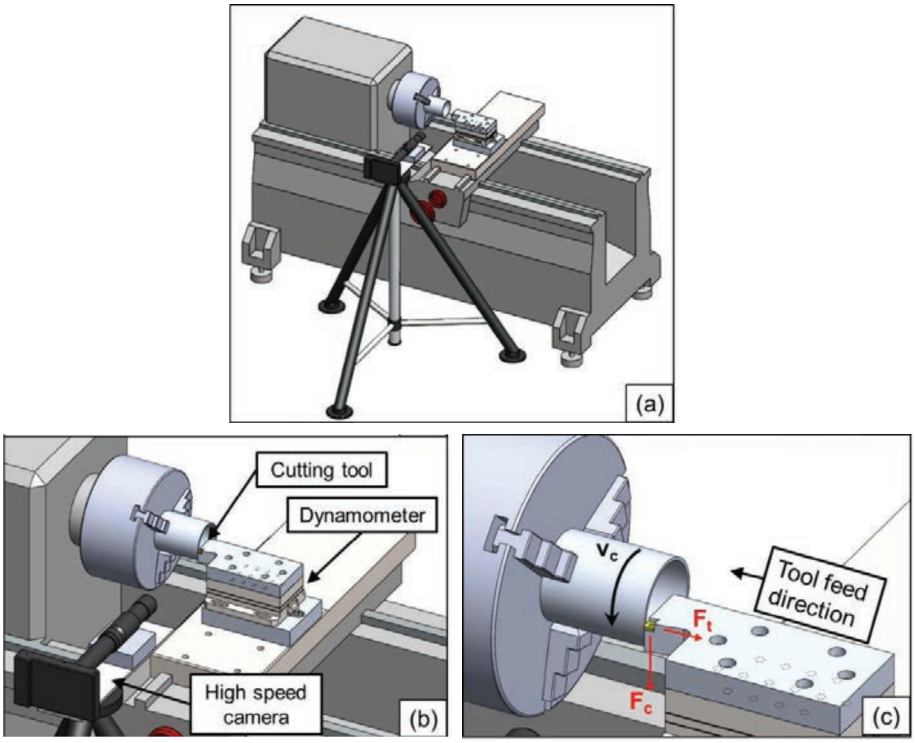

Fig. 4. (a) Tube turning setup: (a) shop floor perspective; (b) detail perspective; and (c) cutting force component directions (thrust, *t*, and cutting speed, *c*).

4. Experimental Results

Experiments were performed for both constant and MTP cutting conditions. Results are presented for MTP feed motion, cutting force, temperature, and chip formation. No appreciable tool wear was observed during testing, so no data is presented for brevity.

4.1. Feed Motion

The feed motion for MTP is modeled as the sum of the nominal feed and sinusoidal MTP oscillation:

$$z = \left(\frac{\Omega}{60} \cdot f_r\right) t + (RAF \cdot f_r) sin\left(\left(2\pi \frac{\Omega}{60} OPR\right) t\right). \tag{3}$$

Laser vibrometer measurements were completed and the velocity was numerically integrated to obtain the *z* displacement versus time. The modeled displacement from Equation 3 was then compared to the measured signal. Example results are provided in Fig. 5 for a spindle speed of 168 rpm and feed per revolution of 0.203 mm/rev. To interpret Fig. 5, the global (linear) slope depends on the nominal feed per revolution and the local oscillation amplitude and frequency depends on the MTP parameters. The *OPR* and *RAF* values to best match the data were 0.497 and 0.8, respectively (0.5 and 0.8 were commanded).

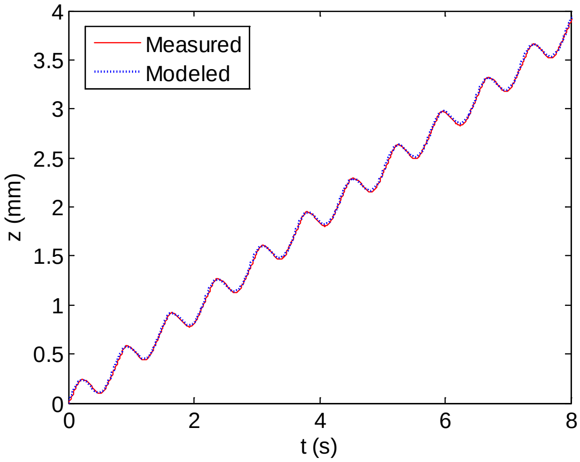

Fig. 5. Measured and modeled feed motion for: Ω = 168 rpm (v_c = 37.5 m/min), f_r = 0.203 mm/rev, and commanded MTP values of *OPR* = 0.5 and *RAF* = 0.8.

4.2. Cutting Force

Once the feed motion was defined, a mechanistic model for the cutting force components in the thrust (*t*) and cutting (*c*) force directions was developed. Figure 6 shows the *z* motion plotted revolution-by-revolution. Note that the *OPR* = 0.5 selection gives a period of two revolutions for a single *z* oscillation. The instantaneous chip thickness due to the MTP motion was then determined using the difference between the current motion and the existing surface defined by the previous revolutions. The chip thickness progression is visualized during the second and third revolutions in Fig. 7. Note that: 1) the length of a single chip is determined from the sum of the three hatched sections (i.e., the product of total time and the cutting speed) shown in the left and right panels of Fig. 7; and 2) the time-dependent vertical height of the hatched sections defines the instantanous chip thickness. The chip thickness, *h*, is displayed in Fig. 8 for a nominal feed rate of 0.203 mm/rev. Note that the maximum chip thickness is sustantially larger than the nominal value.

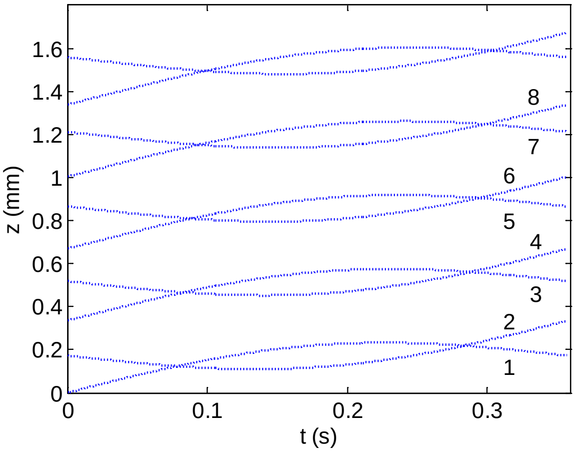

Fig. 6. Revolution-by-revolution feed motion for: Ω = 168 rpm (v_c = 37.5 m/min), f_r = 0.203 mm/rev, and commanded MTP values of *OPR* = 0.5 and *RAF* = 0.8. The revolution number is labeled.

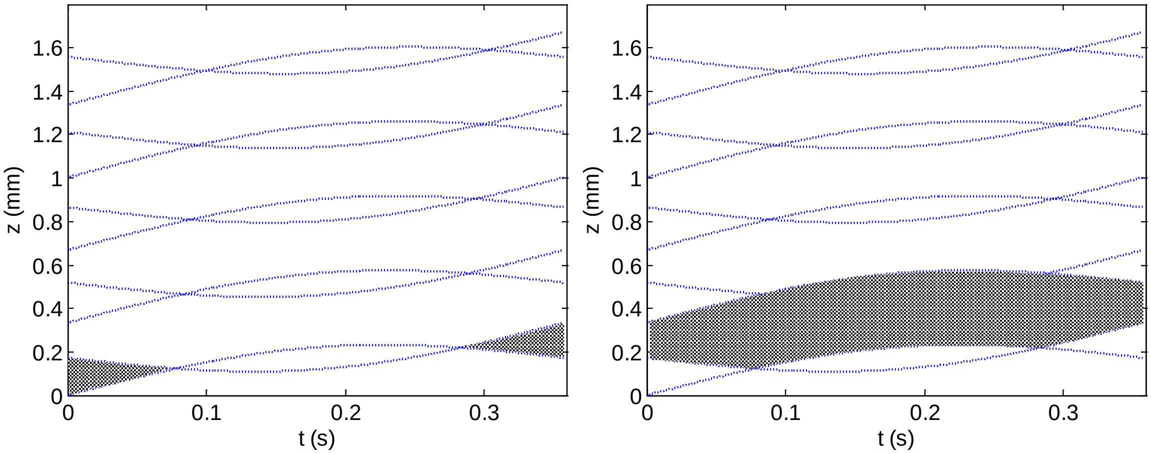

Fig. 7. Revolution-by-revolution chip thickness (shaded region) visualization for: Ω = 168 rpm (v_c = 37.5 m/min), f_r = 0.203 mm/rev, and commanded MTP values of *OPR* = 0.5 and *RAF* = 0.8. (Left) chip thickness during second revolution; (right) chip thickness during third revolution.

Given the time-varying chip thickness and constant chip width (i.e., the difference between the inner and outer tube radii), b, the mechanistic force model was defined as:

$$F_c(t) = k_c(h)bh(t) \tag{4}$$

$$F_t(t) = k_t(h)bh(t) \tag{5}$$

where k_c and k_t are the chip thickness-dependent empirical force coefficients for the cutting and thrust directions, respectively [8]. To determine these coefficients and predict the MTP cutting force, force measurements were completed at four constant feed rates: {0.051, 0.102, 0.152, and 0.203} mm/rev. Using the mean steady-state force value from each test, the coefficients were calculated by rearranging Equations 4 and 5 and substituting the known chip thickness and width. The results are presented in Fig. 9.

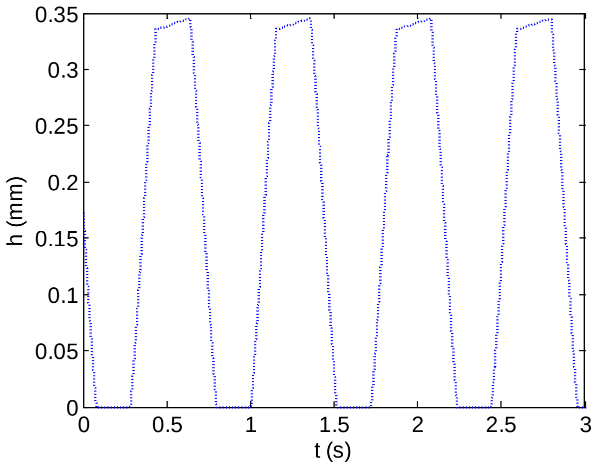

Fig. 8. Chip thickness for: Ω = 168 rpm (v_c = 37.5 m/min), f_r = 0.203 mm/rev, and commanded MTP values of *OPR* = 0.5 and *RAF* = 0.8.

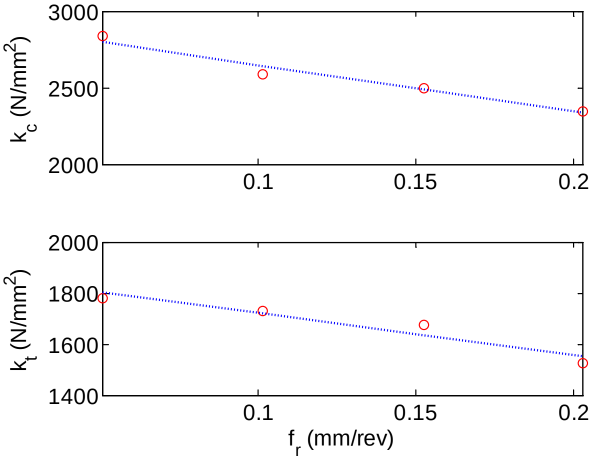

Fig. 9. Cutting force coefficients determined from constant feed tests (b = 1 mm). (Top) The k_c linear fit slope and intercept are: -3051.1 N-rev/mm^3 and 2953.7 N/mm^2. (Bottom) The k_t linear fit slope and intercept are: -1624.9 N-rev/mm^3 and 1883.3 N/mm^2.

Combining the time-dependent chip thickness (Fig. 8), mechanistic force model (Equations 4 and 5), and chip thickness-dependent cutting force coefficients (linear trends in Fig. 9), the MTP force components were predicted. A comparison between the measured and predicted forces for Ω = 168 rpm, f_r = 0.203 mm/rev, *OPR* = 0.5, and *RAF* = 0.8 is provided in Fig. 10. Results for f_r = 0.051 mm/rev are provided in Fig. 11. Good agreement is observed. This level of agreement is representative of other Ω and f_r combinations as well.

4.3. Temperature

Temperature trends were recorded for both constant feed and MTP tests using the IR camera. As shown in Fig. 3, the IR camera was directed toward to tool rake face from a location behind the chip formation. This did not allow the shear plane temperature to be recorded (this was the high speed camera view), but did enable global temperature profiles to be evaluated while cutting. An example scaled temperature map for a constant feed test is displayed in Fig. 12; the curled chip with elevated temperature is observed. The sampling rate was approximately 1 Hz for the temperature videos.

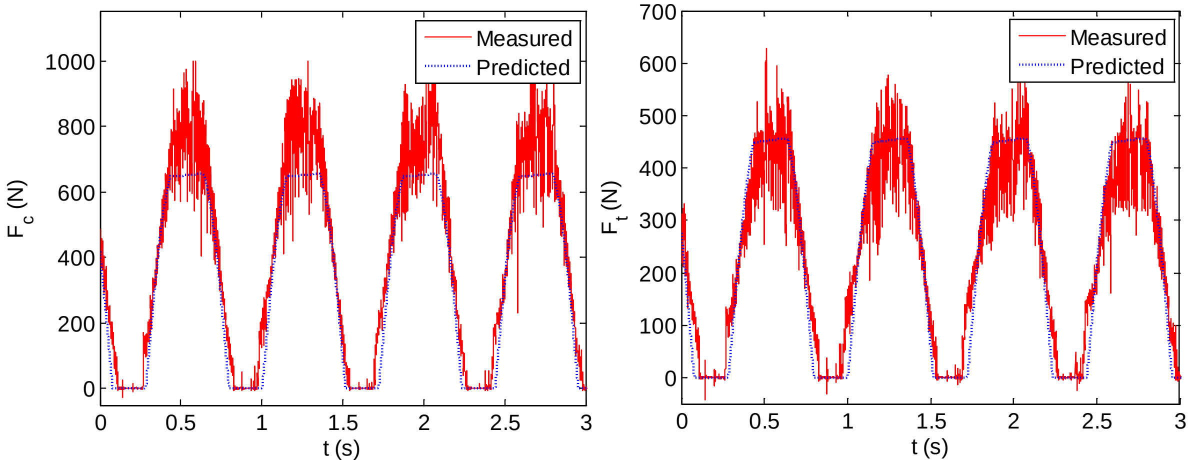

Fig. 10. Force components for: Ω = 168 rpm (v_c = 37.5 m/min), f_r = 0.203 mm/rev, *OPR* = 0.5, and *RAF* = 0.8. (Left) Cutting and (right) thrust directions.

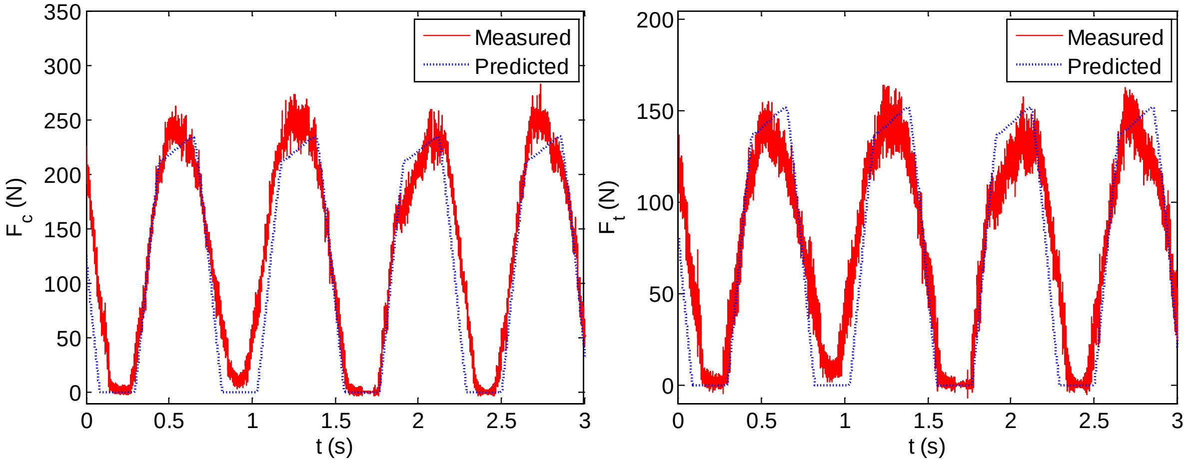

Fig. 11. Force components for: Ω = 168 rpm (v_c = 37.5 m/min), f_r = 0.051 mm/rev, *OPR* = 0.5, and *RAF* = 0.8. (Left) Cutting and (right) thrust directions.

To compare the cutting temperatures between constant feed and MTP tests, the maximum temperature in each video frame was identified and tabulated (approximately 10 points per test). The mean and standard deviation were then calculated. Results for Ω = 336 rpm (v_c = 74.9 m/min) are presented in Fig. 13, where the horizontal axis is the nominal feed per revolution value. Note that the MTP results had continuously varying chip thickness about the nominal feed per revolution. Linear regressions are also included in Fig. 13 as a visual aid. It is observed that the MTP tests resulted in lower overall temperatures and a smaller increase with feed for the same nominal feed value. However, it should be noted that the error bars overlap at all four feed per revolution values.

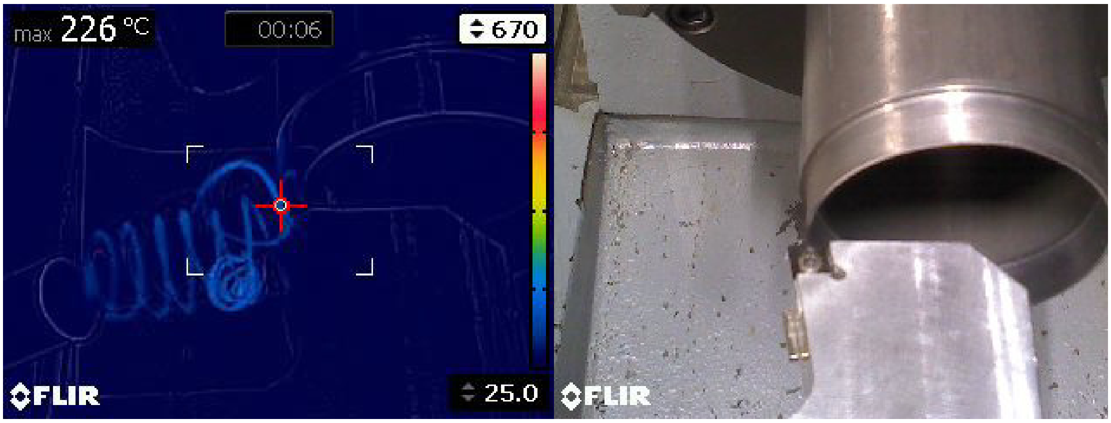

Fig. 12. (Left) Example temperature map obtained using IR camera. (Right) Photograph from IR camera.

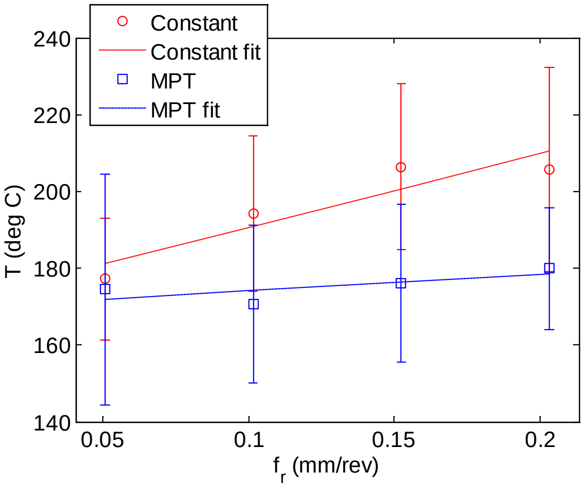

Fig. 13. Mean temperature values and one standard deviation error bars for constant feed and MTP tests at Ω = 336 rpm (v_c = 74.9 m/min).

4.4. Chip Formation

Video of the chip formation process was recorded at 1250 Hz. As displayed in Figs. 3 and 4, the location of the high speed camera enabled a side view of the chip. An example image for constant feed turning is provided in Fig. 14. As expected, a continuous chip is seen.

A sequence of images is presented in Fig. 15 to demonstrate MTP discontinuous chip formation. The cutting conditions were Ω = 168 rpm, f_r = 0.203 mm/rev, *OPR* = 0.5, and *RAF* = 0.8. These images show the increase and decrease in chip thickness that was modeled in Fig. 8. Additionally, panel 3 exhibits what appears to be shear-localized chip formation. Previous authors have described the presence of the serrated chip profile as a competition between strain hardening and thermal softening with a spacing that increases with cutting speed [9-10]. In Fig. 15, the cutting speed is constant, but the chip thickness varies continuously. During the formation of a single chip, the images demonstrate a sequence of: no visible shear-localization, followed by disordered behavior, and finally regular spacing, before the order is reversed. This behavior may be related to both the rate of change (slope) and the value of the instantaneous chip thickness. The chip thickness values for the six images in Fig. 15 are identified in Fig. 16.

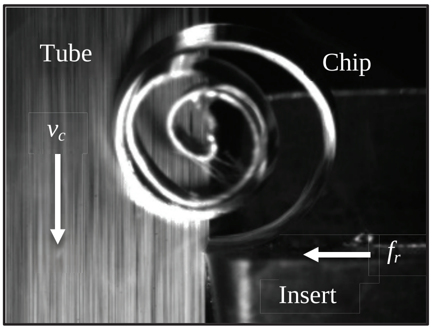

Fig. 14. Image of chip formation from high speed video.

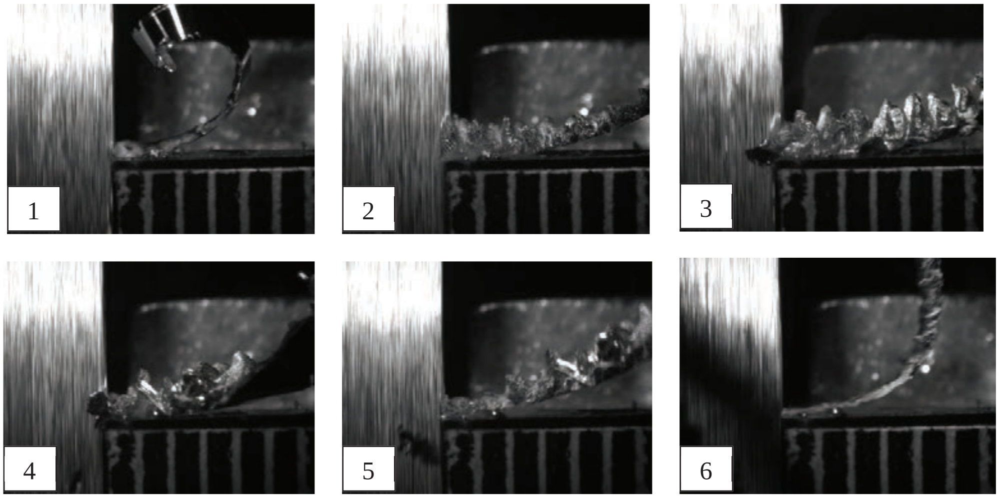

Fig. 15. Images from high speed video for Ω = 168 rpm (v_c = 37.5 m/min), f_r = 0.203 mm/rev, *OPR* = 0.5, and *RAF* = 0.8. The behavior proceeds from initial chip generation (1), to initiation of shear-localization (2), to regular shear-localized behavior (3), to disordered behavior (4), to the end of shear-localization (5), and finally to the chip end (6). For scale, the vertical lines on the insert are spaced at 1 mm intervals.

Shear-localized chip formation was also observed in the constant feed cutting tests. Chips were collected and the peak spacing, Δ, was measured using a digital microscope. Microscope images are displayed in Fig. 17 for v_c = 37.5 m/min (Ω = 168 rpm). The measured spacing values are presented in Fig. 18.

4. Conclusions

This paper provided feed motion, force, temperature, and chip formation data for orthogonal cutting (realized using a tube turning setup) using both constant feed and modulated tool path, or MTP, cutting conditions. MTP refers to a technique which produces discontinuous chips by superimposing tool oscillations in the tool feed direction to repeatedly interrupt the cutting process. Results were presented for AISI 1026 cold-drawn steel machining experiments. A mechanistic force model for the variable cutting force obtained during MTP was presented and validated. Temperature data was shown that suggests reduced global cutting temperatures during MTP. Shear-localized chip formation was observed and shear band spacing values were presented as a function of chip thickness for three cutting speeds. Future work will add tool flexibility to the setup to study the relationship between MTP and chatter, or self-excited vibration during machining. Modeling efforts will also be completed to better understand the initiation and extinction of shear-localized behavior during MTP.

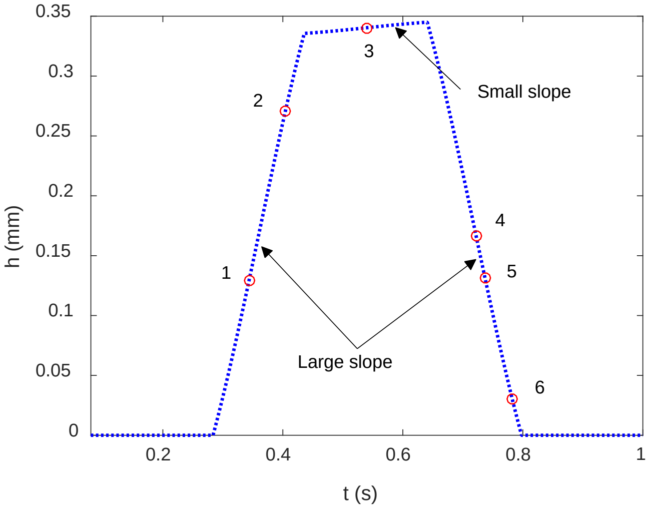

Fig. 16. Chip thickness values for the six images (labeled 1-6) in Figure 15 are identified.

Fig. 17. Microscope images (50x) for constant feed rate tests (Ω = 168 rpm, v_c = 37.5 m/min): (left) f_r = 0.102 mm/rev; (middle) f_r = 0.152 mm/rev; and (right) f_r = 0.203 mm/rev.

Acknowledgements

The authors gratefully acknowledge financial support from the UNC Charlotte Center for Precision Metrology Affiliates program and the donation of turning inserts from Kennametal.

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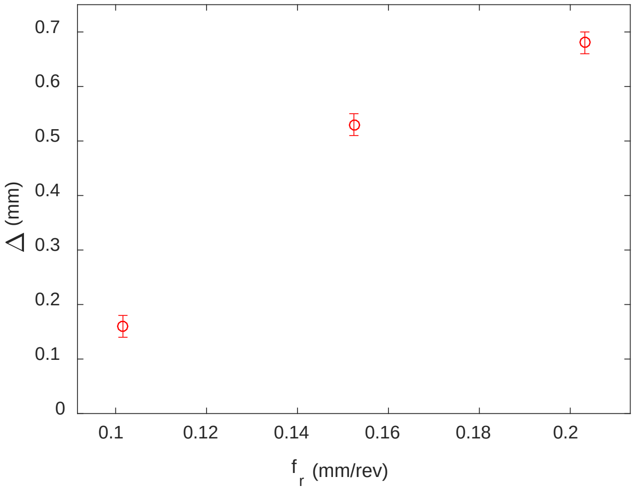

Fig. 18. Shear-localized chip spacing, Δ, for constant feed per revolution tests (Ω = 168 rpm, v_c = 37.5 m/min). The error bars indicate one standard deviation from multiple spacing measurements within a single microscope image (Fig. 17).