EXPERIMENTAL PLATFORM FOR IN-PROCESS METROLOGY DURING ORTHOGONAL TURNING

Mark A. Rubeo, Ryan Copenhaver, Saurabh Landge, and Tony L. Schmitz
Mechanical Engineering and Engineering Science
University of North Carolina at Charlotte
Charlotte, NC

INTRODUCTION

Chip formation mechanics in machining operations have been studied for several decades. These efforts aim to reduce tool wear, improve workpiece surface quality, and facilitate machining automation by reliably predicting and controlling chip segmentation length and frequency. It has been determined that the three main factors which impact chip formation mechanics are: 1) the chip thickness; 2) the radius of curvature of the chip; and 3) the mechanical properties of the workpiece material [1]. Because the chip thickness and radius of curvature are strongly influenced by the geometry of the cutting tool, carbide insert manufacturers provide a myriad of chip breaking geometries to suit specific machining applications. Additionally, researchers have implemented with the modulated tool path (MTP) approach to control chip segmentation length and frequency [2].

The aim of this study is to evaluate the chip formation characteristics for various cutting edge geometries and machining strategies in orthogonal cutting. Orthogonal cutting is approximated using a tube turning setup where a thin-walled, axisymmetric workpiece is machined along its axis. In-process metrology includes high-speed micro-videography, cutting force, tool-chip temperature, and tool wear measurements.

In this paper the experimental platform for studying chip formation in orthogonal turning, including the in-process metrology, is described. Representative high-speed video images, cutting forces, and cutting temperatures are presented to show typical results for an orthogonal turning experiment. Data are included for both traditional turning toolpaths, where the feed remains constant throughout the cut, and for modulated toolpaths (MTP), where the nominal tool motion is modulated using a low frequency/amplitude sine wave in the direction tangent to the machined surface. Finally, future work is proposed where flexibility is added to the cutting tool to facilitate unstable machining operations (i.e., chatter). This novel approach will allow for the observation of chip formation processes during chatter at high magnification and frame rate.

EXPERIMENT SETUP

The test bed for the experiments was a Haas TL-1 CNC lathe (8.9 kW, 2000 rpm). Tubular workpieces were machined from AISI 1026 cold-drawn steel and 6061-T6 aluminum tubing. For brevity, only results from the AISI 1026 steel are reported here. The outside diameter of the workpieces was 72 mm and the wall thickness was 1 mm. Concentricity and cylindricity of the workpiece's outside and inside diameters with the rotational axis of the lathe spindle was assured by performing a finish turning operation immediately prior to conducting the experiments. Orthogonal tube turning was selected, rather than disc or flange turning [3-4], so that cutting speed, v_c, would not vary with a fixed spindle speed. Experiments were conducted with a cutting speed of 75 m/min at feedrates of {0.051, 0.102, 0.152, and 0.203} mm/rev.

The carbide inserts (Type C, 80° parallelogram) were provided by Kennametal. They are summarized in TABLE 1.

TABLE 1. Insert descriptions.

Insert image	ANSI catalog number (Kennametal part no.)	Description
	CCMW3252 (3757916)	7° relief angle, no chip breaker
	CCMT3252LF (3758169) CPMT3252LF (3755485)	7° and 11° relief angle, chip breaker
	CCMT3252MP (3744955) CPMT3252MP (3744958)	7° and 11° relief angle, chip breaker

Dynamic cutting forces were measured using a three-axis dynamometer (Kistler 9257B) rigidly mounted to the lathe's cross slide. A high-speed camera (Fastec IL-3) with a maximum frame rate of 1250 frames/sec and 5 mm field of view was mounted to a tripod which was fixed to the shop floor. An infrared camera (FLIR E40) was used to establish temperature trends with changes in machining conditions. A digital microscope was also attached to the lathe to measure flank wear between cutting tests. A photograph of the setup is provided in FIGURE 1 and additional details are provided in FIGURE 2.

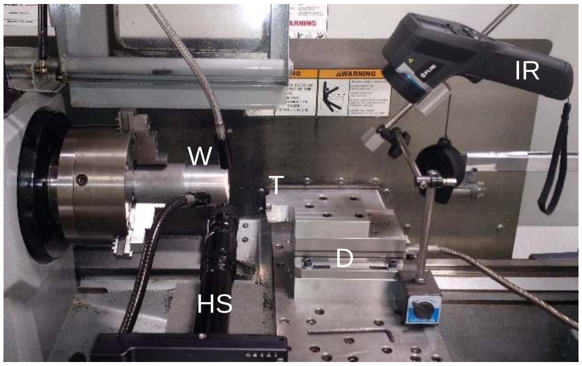

FIGURE 1. Orthogonal tube turning setup including: workpiece (W), tool (T), high-speed camera, (HS), infrared camera (IR), and dynamometer (D).

Cutting forces which occur during orthogonal turning can be described in a two dimensional coordinate frame. The force components are defined in the thrust, F_t, and cutting speed, F_c, directions as:

$$F_t = k_t b h \tag{1}$$

$$F_c = k_c b h \tag{2}$$

where b is the chip width (i.e., tube wall thickness) and h is the chip thickness (i.e., feed per revolution). The cutting force coefficients, k_t and k_c, are empirical constants which relate cutting forces to uncut chip geometry. The cutting force coefficients are primarily dependent on the workpiece material-cutting tool combination.

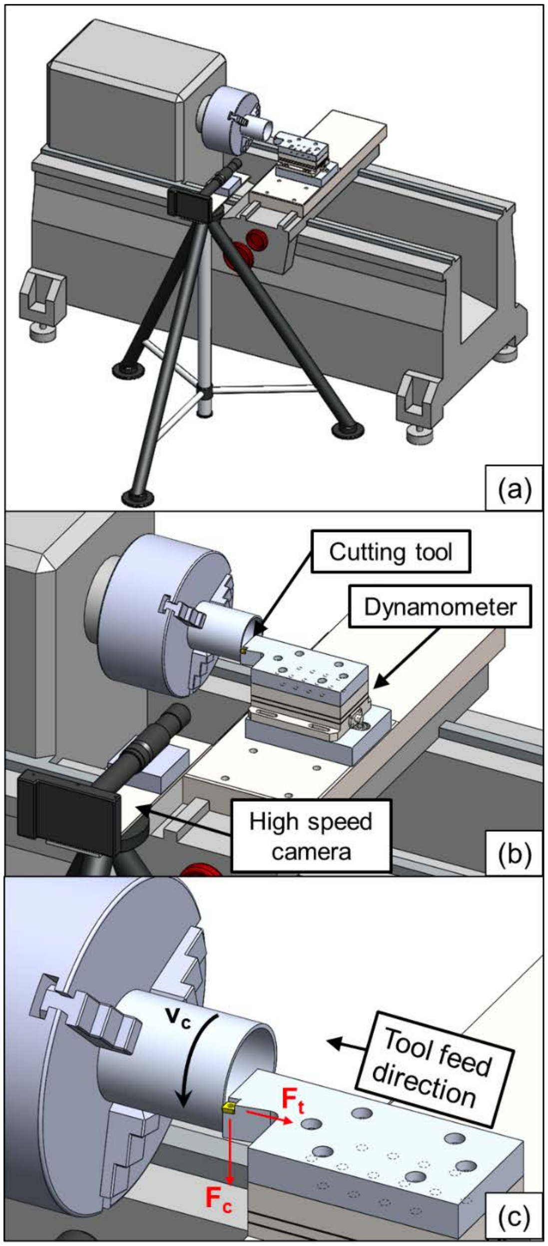

FIGURE 2. Tube turning setup: (a) shop floor perspective, (b) detail perspective, and (c) cutting force component directions (thrust, t, and cutting speed, c).

CONSTANT FEED EXPERIMENTS

As a representative example of the results from constant feed rate experiments, high-speed video images, dynamic cutting forces, and cutting temperatures are presented. The selected constant feed experiment was conducted at a cutting speed of 75 m/min with a feedrate of 0.203 mm/rev with a CCMW3252 type insert (i.e., no chip breaker). The workpiece material was 1026 steel. FIGURE 3 shows the formation of a continuous chip for the orthogonal cutting operation.

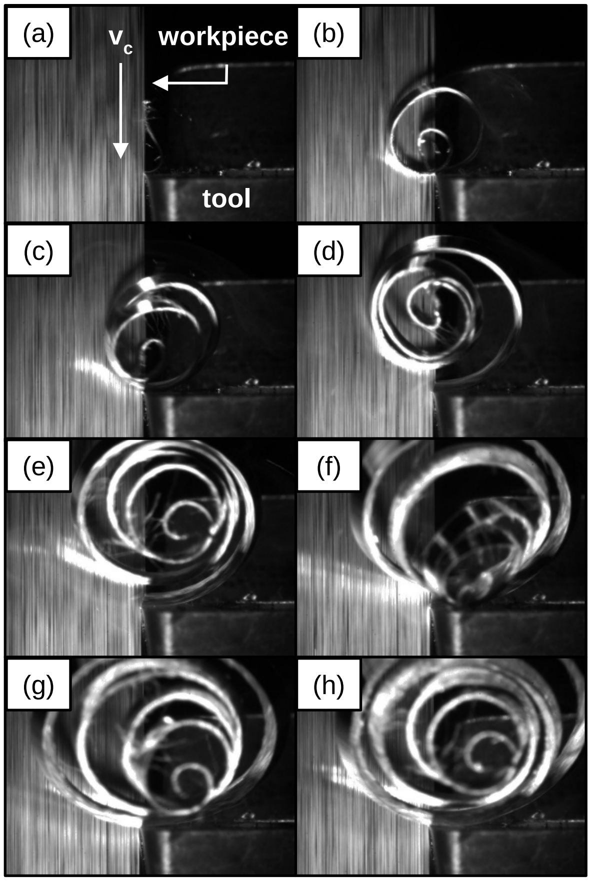

FIGURE 3. Progression of continuous chip formation in orthogonal cutting of 1026 steel.

The dynamic cutting forces for the operation are displayed in FIGURE 4. As the tool progresses through the cut, the force components increase rapidly until a quasi-steady state is reached. Because the chip geometry remains constant throughout the cut, the cutting force also remains constant. The thermal image, shown in FIGURE 5, indicates the maximum temperature for the constant feed operation.

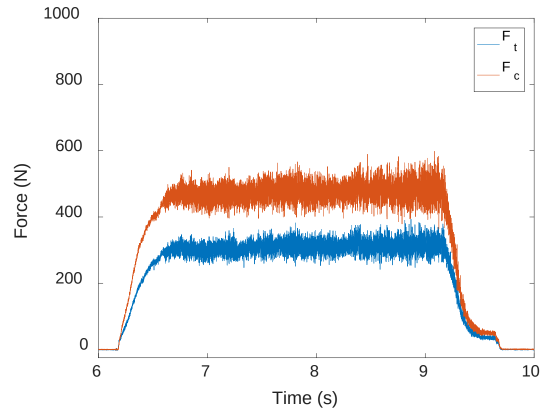

FIGURE 4. Cutting force components in the thrust and cutting speed directions for the constant feed turning operation.

FIGURE 5. Thermal image showing maximum cutting temperature for the constant feed turning operation.

For each insert geometry, the cutting force coefficients were calculated. The resulting thrust direction force coefficients, k_t, and cutting speed direction force coefficients, k_c, are shown in FIGURE 6 and FIGURE 7, respectively.

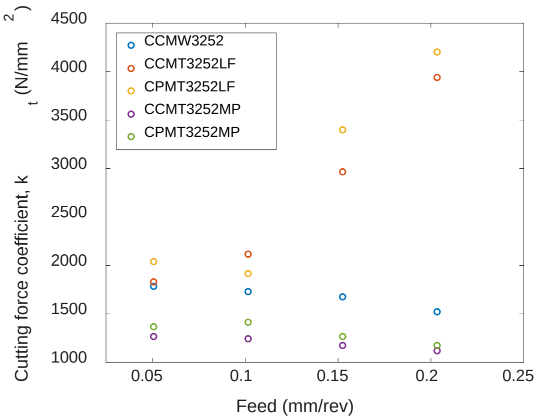

FIGURE 6. Thrust direction force coefficients for all insert geometries.

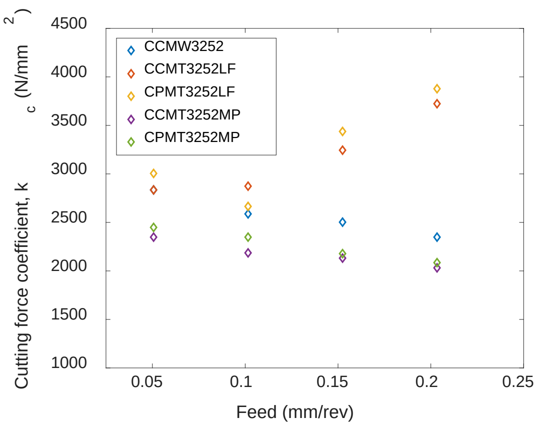

FIGURE 7. Cutting speed direction force coefficients for all insert geometries.

MTP EXPERIMENTS

Modulated tool path (MTP) is a turning technique which produces discontinuous chips by superimposing tool oscillations in the tool feed direction to repeatedly interrupt the cutting process [5]. An exaggerated example of an MTP turning operation is displayed in FIGURE 8 for illustrative purposes. The chip segmentation 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:

$$RAF = \frac{A}{f_r} \quad (3)$$

$$OPR = 60 \cdot \frac{f}{\Omega} \quad (4)$$

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

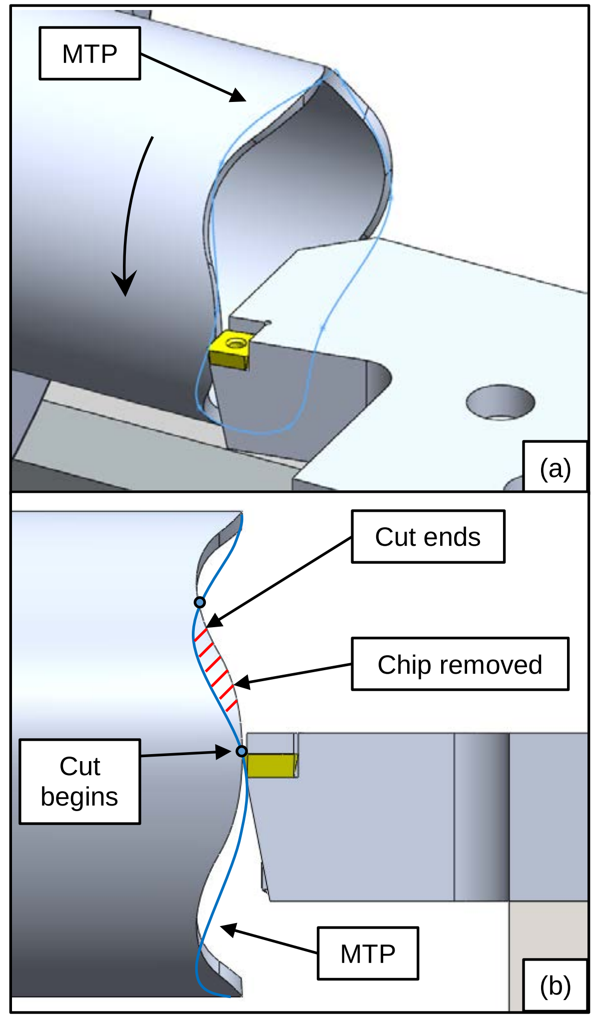

FIGURE 8. Illustrative example of: (a) an MTP turning operation; and (b) MTP chip formation.

As a representative example of the results for an MTP turning operation, high-speed video images, dynamic cutting forces, and cutting temperatures are presented. The machining parameters for the selected MTP experiment are summarized in TABLE 2. The workpiece material was 1026 steel.

TABLE 2. Machining parameters for the selected MTP turning operation.

Cutting speed, v_c	75 m/min
Global feedrate, f	0.203 mm/rev
RAF	0.8
OPR	0.5

FIGURE 9 shows the formation of a discontinuous chip during an MTP orthogonal turning operation. Adiabatic shear banding is observed in images (c)-(g). Because the tool oscillates in the feed direction (i.e., it enters and exits the cut), the instantaneous feedrate varies throughout the cut producing a chip of varying thickness. Similarly, the variation in chip thickness causes a subsequent variation in the dynamic cutting forces as shown in FIGURE 10.

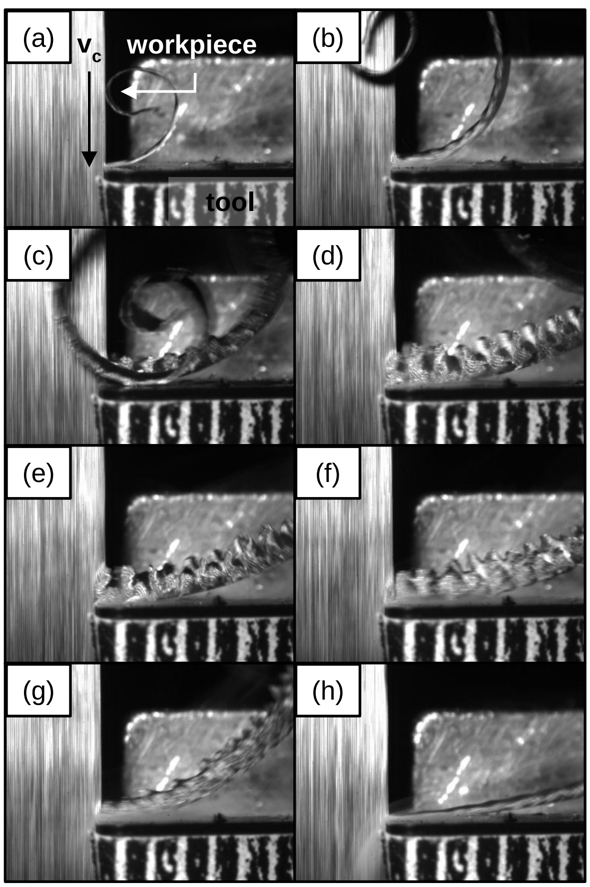

FIGURE 9. Progression of chip formation for an MTP orthogonal cutting operation.

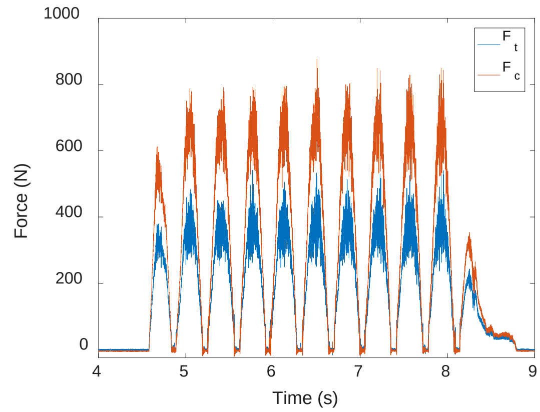

FIGURE 10. Cutting force components in the thrust and cutting speed direction for the MTP turning operation.

The thermal image shown in FIGURE 11 indicates the maximum cutting temperature for the MTP turning operation.

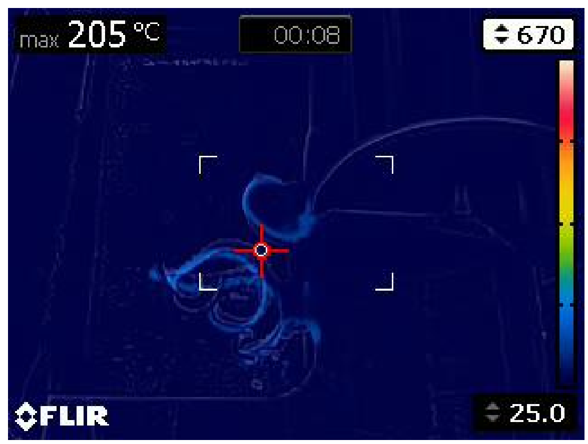

FIGURE 11. Thermal image showing maximum cutting temperature for the MTP feed turning operation.

TABLE 3. Maximum cutting force in the thrust and cutting speed directions.

	Constant feed	MTP
F_t (N)	330	396
F_c (N)	502	705

COMPARISON

To facilitate ease of comparison between the constant feed and MTP experiments, cutting forces, cutting temperatures, and chip formations are presented in TABLE 3, FIGURE 12, and FIGURE 13, respectively.

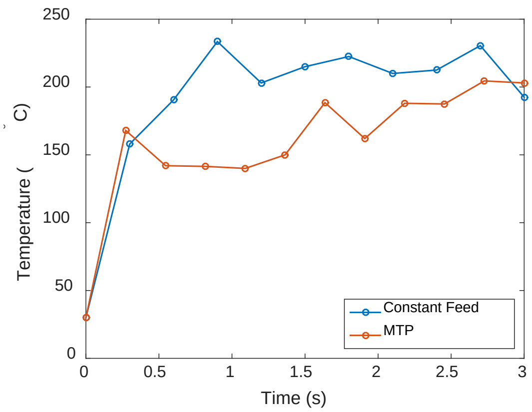

FIGURE 12. Cutting temperature increase during the constant feed and MTP turning operations.

SUMMARY AND FUTURE WORK

In this paper, an experimental platform for studying chip formation in orthogonal turning including in-process metrology was described. The metrology includes high-speed micro-videography, cutting force, tool-chip temperature, and tool wear measurements.

As an extension of the work presented here, high-speed videography of the chip formation process during unstable machining operations (i.e., chatter), will be investigated by adding flexibility to the tool in the feed and cutting speed directions. Further investigation of the adiabatic shear banding observed during the MTP experiments is also proposed.

REFERENCES

[1] Zhang YZ. Chip Curl, Chip Breaking, and Chip Control of Difficult-to-Cut Materials. Annals of the CIRP. 1980; 29(1): p. 79-83.

[2] Adams D. Chip Breaking in Turning Operations Using CNC Toolpaths. Charlotte, NC; 2008.

[3] Ivester R, Whitenton E, Heigel J, Marusich T, Arthur C. 10th CIRP International Workshop on Modeling of Machining Operations. In: 2007; Reggio Calabria, IT.

[4] Whitenton E. High-Speed & Dual-Spectrum Videos of Machining Processes. [Online].; 2015. Available from: http://www.nist.gov/el/isd/sbm/hsds-machining-videos.cfm.

[5] Berglind L, Zeigert J. Chip Breaking Parameter Selection for Constant Surface Speed Machining. In: 2013; San Diego: ASME.

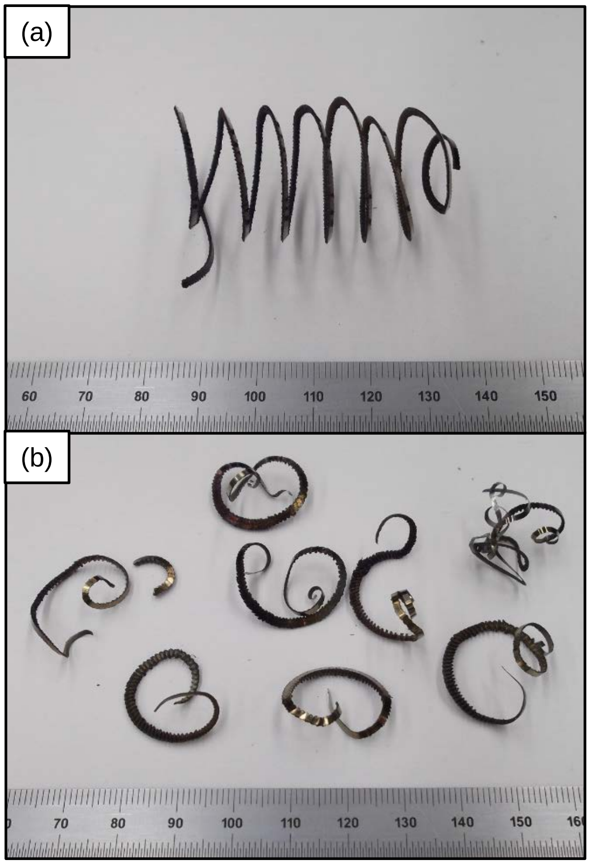

FIGURE 13. (a) Continuous chip for constant feed; and (b) discontinuous chips for MTP.