DEVELOPING A MACHINING MODEL DATABASE FOR HARD-TO-MACHINE MATERIALS

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INTRODUCTION

The analytical stability lobe diagram offers a predictive capability for selecting stable chip width-spindle speed combinations in machining operations. However, the increase in allowable chip width provided at spindle speeds near integer fractions of the system's dominant natural frequency is diminished substantially at low spindle speeds where the stability lobes are closely spaced. Fortunately, the process damping effect can serve to increase the chatter-free chip widths at these low speeds. This increased stability at low spindle speeds is particularly important for hard-to-machine materials that cannot take advantage of the higher speed stability zones due to prohibitive tool wear at high cutting speeds.

The objective of this study is to develop a practical method to identify and model process damping, including a representative database of the process coefficients for hard-to-machine materials in order to accurately predict regenerative chatter in machining operations. This database will include not only process damping coefficients, but also specific cutting force coefficients used to model the forces in milling. The machinability of the materials investigated in this study is generally poor. Therefore, in addition to the process damping and force coefficient database, Taylor-type tool life models are developed for each material.

CUTTING FORCE MODELLING

In metal cutting operations, regenerative chatter is known to be directly influenced by the instantaneous cutting forces during chip generation. The dynamic cutting force, F, may modeled as:

$$F = K_s\, b\{n(t-\tau) \;+\; n(t)\}, \tag{1}$$

where K_s is the specific cutting force, which depends on the tool-workpiece combination; *b* is the chip width; $n(t-\tau)$ is the vibration amplitude in the surface normal direction from the previous cutting path; and $n(t)$ is the current surface normal vibration amplitude [1].

In addition, the process exhibits additional damping when the cutting speed is low. This is due to interference between the cutting tool's relief face and the undulations left behind on the cut surface. This is known as process damping and it serves as an energy dissipation mechanism which increases stability at low cutting speeds. The dynamic force may be combined with the process damping force, F_d:

$$F_d = -C\frac{b}{V}\dot{n}. \tag{2}$$

The process damping force in the surface normal direction is expressed as a function of cutter velocity, $\dot{n}$, chip width, cutting speed, *V*, and a process damping coefficient, *C* [2].

This process damping force, which depends on both the spindle speed-dependent limiting chip width and the cutting speed, is not included in classic regenerative chatter analytical solutions. Therefore, an analytical solution that includes process damping effects was developed [3]. The process damping coefficient is the only value required to define the process damping model. The following sections describe the procedure for obtaining the process constants, K_s and *C*, for difficult-to-machine materials. Preliminary results for AISI 1018 steel, Ti-6Al-4V, and AISI 304 stainless steel are provided.

EXPERIMENTAL PROCEDURE FOR PROCESS COEFFICIENTS IDENTIFICATION

Tool Life

Tool life is the time required to obtain a predetermined wear level. Depending on the dominant wear mode, options include the flank wear width (FWW), crater depth (CD), and/or notch depth (ND). The Taylor-type tool life equation used in this study relates the tool life to the cutting speed using a power law model [4]:

$$VT^{n_T} = C_T \tag{3}$$

The argument for obtaining tool life parameters for each material in this study is to establish an appropriate cutting velocity range to examine the process damping effect. Even though the tool life parameters are tool/workpiece specific, the tool life models could prove useful in establishing a benchmark range of cutting speeds in other cutting operations.

The workpiece materials were AISI 1018 steel, Ti-6Al-4V, and AISI 304 stainless steel. Down milling wear tests were completed using a 18.54 mm diameter single-tooth indexable square endmill (Kennametal: KICR-0.73-SD3-033.3C). A Kennametal (SDCW090308) TiN coated insert with a 15-deg relief angle, zero rake angle, and zero helix angle was used.

The chip load was 0.05 mm/tooth and the axial and radial depths of cut were 2 mm and 4.6 mm (25% radial immersion), respectively. All tests were performed using a water miscible mist coolant with a flow rate of approximately 15-20 ml/min. The primary mode of tool wear in all tests was flank wear; see Fig. 1. To avoid removing the tool and insert from the spindle, a portable digital microscope was used to record the FWW at regular intervals as shown in Fig. 2.

The tool life, T, was defined as the time required to reach a maximum FWW of 0.3 mm. Tests were completed at cutting speeds of {V = 29.1, 58.2, and 174.7} m/min, which correspond to spindle speeds of {Ω = 500, 1000, and 3000} rpm. The values for n_T and C_T were identified by curve fitting the (V, T) data points.

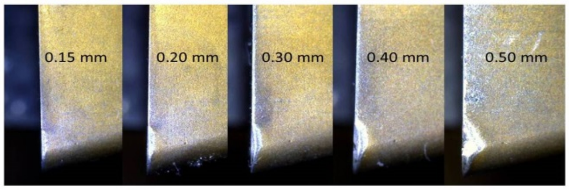

FIGURE 1: Sample measurements of the FWW progression during cutting tests.

Specific Cutting Force

The specific cutting force coefficient, K_s, and average cutting force direction, β, were identified from stable milling tests. The tests were performed on a cutting force dynamometer using a single-tooth indexable square endmill; see Fig. 3. Both 11 deg and 15 deg relief angle insert geometries were chosen in order to observe the dependence on tool geometry. The process damping coefficient was sensitive to flank wear. Therefore, cutting coefficients were measured at specific flank wear widths. A linear regression to the mean cutting force over a series of tests at ascending feed per tooth values was used to identify the cutting force model values [1].

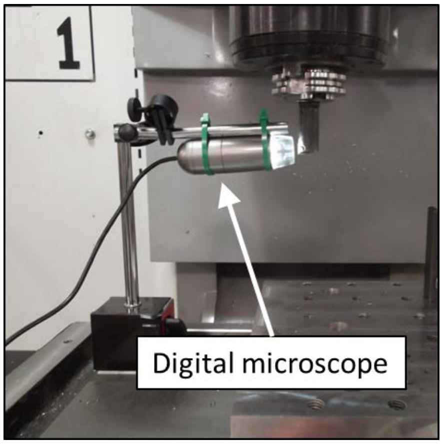

FIGURE 2: Setup for interrupted FWW measurements.

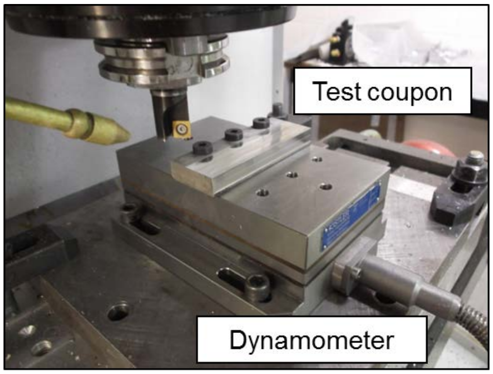

FIGURE 3: Dynamometer setup for cutting specific cutting force coefficient measurements.

Process Damping Coefficient

The process damping coefficient was identified using the flexure method described in ref. [3]. An accelerometer was used to measure the vibration during cutting; see Fig. 4. The frequency content of the accelerometer signal was used in combination with the machined surface finish to establish stable/unstable performance.

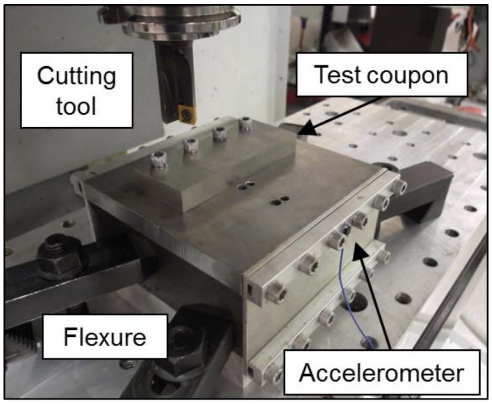

FIGURE 4: Flexure-based machining setup for process damping coefficient measurements.

A grid of stable/unstable test points at low spindle speeds was used to identify the process damping coefficient (via the experimental stability boundary) for each testing condition; see Fig. 5. The coefficient was determined from a least squares fit through the test points.

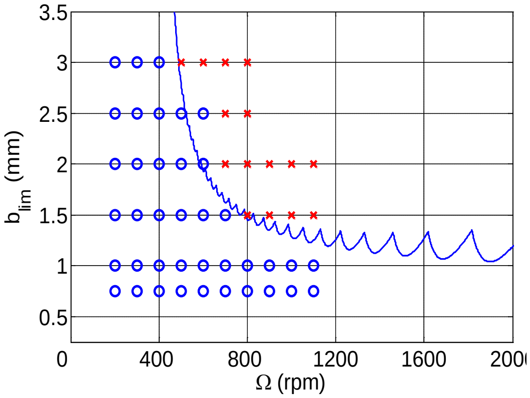

FIGURE 5: Test grid of stable/unstable cutting conditions.

RESULTS

Tool Life

Tool life testing was performed for each material under stable cutting conditions. Figure 6 displays the FWW progression versus cutting time for the specified cutting velocities for titanium. The 'o' symbols represent the intervals at which the FWW was recorded. As expected, the wear rate was found to increase as cutting velocity was increased.

The tool life was then plotted versus the cutting velocity and a power law curve was fit to the data. Figure 7 shows the curve fit through the three data points for Ti-6Al-4V (R^2 = 0.97). It is observed that cutting operations are limited to spindle speeds less than 1000 rpm if a tool life greater than approximately 30 minutes is desired. This range of spindle speeds is used to dictate the operating speeds for process damping characterization. The $\{n_T, C_T\}$ values for the other materials tested are provided in Table-1.

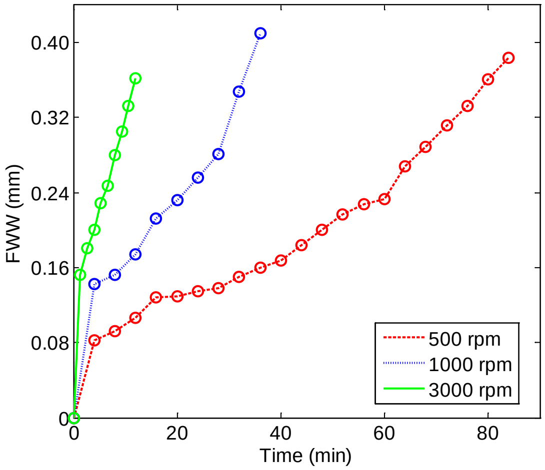

FIGURE 6: Increase in FWW with cutting time at three spindle speeds for Ti-6Al-4V.

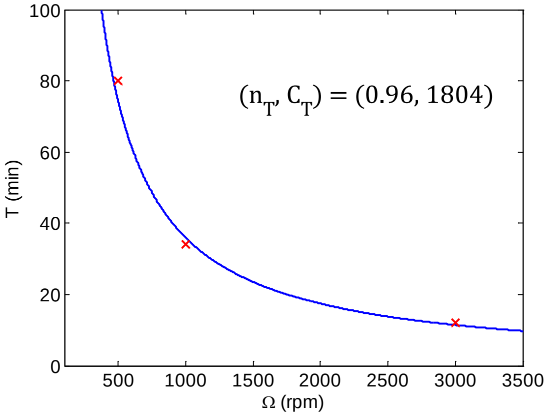

FIGURE 7: Increase in FWW with cutting time at three spindle speeds for Ti-6Al-4V.

TABLE 1: Values for n_T and C_T.

Material	n_T	C_T	R^2
1018 steel*	0.34	649	0.95
Ti 6Al-4V	0.96	1804	0.97
304 SS	0.67	1484	0.98

* Values obtained from testing performed by Karandikar *et al*. [5] using same tool geometry, but uncoated insert.

TABLE 2: Comparison of process coefficients for the 11 deg relief angle tool geometry.

	Low insert wear (FWW < 0.100)			Moderate insert wear (0.150 < FWW < 0.250)		
Material	*K_s (N/mm^2)*	*β (deg)*	*C (N/m)*	*K_s (N/mm^2)*	*β (deg)*	*C(N/m)*
1018 Steel	2531.0	62.0	3.3 x10^5	2550.2	62.0	4.0 x10^5
Ti 6Al-4V	2107.0	66.0	1.7 x10^5	2131.2	60.1	1.8 x10^5
304SS	3318.0	62.5	5.2 x10^5	3517.0	61.0	5.8 x10^5

TABLE 3: Comparison of process coefficients for the 15 deg relief angle tool geometry.

	Low insert wear (FWW < 0.100)			Moderate insert wear (0.150 < FWW < 0.250)		
Material	*K_s (N/mm^2)*	*β (deg)*	*C (N/m)*	*K_s (N/mm^2)*	*β (deg)*	*C(N/m)*
1018 Steel	2359.1	63.5	2.5x10^5	2441.0	63.5	3.0 x10^5
Ti 6Al-4V	2076.3	66.7	1.2 x10^5	2247.2	56.3	1.4 x10^5
304SS	3427.2	63.1	4.1 x10^5	3503.2	61.5	4.5 x10^5

Process Coefficients

The process coefficients for steel (AISI 1018), titanium (Ti 6Al-4V), and stainless steel (AISI-304SS) are provided in Tables 2 and 3. For the tool geometry selected, i.e., zero rake helix angles, there was a moderate increase in specific cutting force coefficient from the new to moderately worn cutting conditions.

In general, there was an observable increase in the process damping coefficient with a relief angle reduction and FWW increase. This serves as an indication that there is an increase in the amount of interference between the cutting edge and the undulations left on the workpiece surface when the tool is worn and/or has a smaller relief angle. Figure 8 illustrates the increase in the stability boundary as the process damping coefficient is increased in the case of 1018 steel.

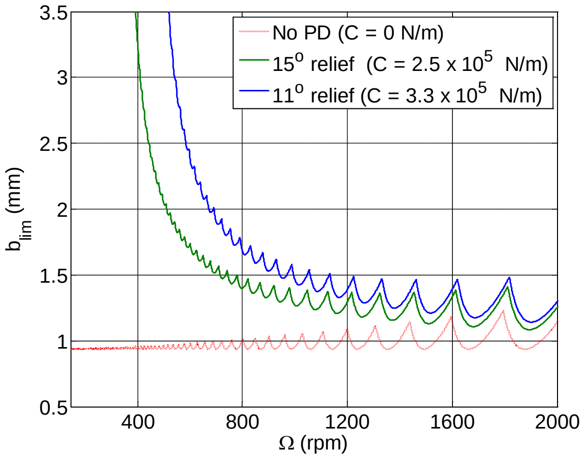

Figure 8: Stability lobe boundary for low wear AISI 1018 steel tests.

CONCLUSIONS

An analytical solution for machining stability while considering process damping was used to obtain process coefficients for hard-to-machine metals. The coefficients, including specific cutting force, process damping, and Taylor-type tool life, were determined experimentally and tabulated for low-speed milling of AISI 1018 steel, Ti 6Al-4V, and AISI 304 stainless steel under various conditions. It was demonstrated that a reduction in the relief angle and an increase in flank wear increased the process damping effect for all materials tested.

Utilizing the effects of process damping can have a significant impact on productivity in machining applications. The effort of cataloging process coefficients could prove to be a practical benefit in today's manufacturing setting.

REFERENCES

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