The Effects of Spindle Dynamics on Precision Flycutting

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Abstract

In this article we examine the effects of structural dynamics on the surface figure of flycut parts. A model is presented that incorporates the machine tool structural loop dynamics and the loading that results from intermittent contact of a rotating diamond cutting tool with the workpiece. The model output is shown to accurately predict the workpiece flatness obtained in a series of cutting trials carried out with a high-speed flycutting spindle. The model is then used to predict workpiece flatness under a variety of cutting conditions. The results indicate that workpiece flatness is highly dependent on the relationship between the spindle speed, the dominant resonant frequency within the structure, and the swept angle of the interrupted cut. The results provide insight into how a flycutting operation may be designed for best results.

Keywords: Precision flycutting, workpiece flatness, machine dynamics

Introduction

Diamond flycutting, a single point cutting process that generates optical quality surface finishes on flat (plano) workpieces, is characterized by depths of cut ranging from roughing cuts of 25 or 50 micrometers to one micrometer or less for finishing cuts. Unlike turning operations, which use a stationary cutting tool that is slowly fed past a rotating workpiece, flycutting operations use a rotating tool that is slowly fed past a stationary workpiece. This arrangement allows flat surfaces to be machined on oddly shaped workpieces without the associated problems of balancing and fixturing that would occur in conventional turning (Chaloux, 1984). An excellent example of ultra-precision flycutting is the production of KDP (potassium dihydrogen phosphate) crystals for the National Ignition Facility laser fusion experiments (Lahaye, 1999).

Workpiece flatness is worst when the dominant structural resonance occurs at any integer multiple of the spindle speed. This result is based on an experimentally verified model drawn from the rich literature on regenerative chatter. The input to the system is the intermittent cutting force, which is readily predicted by the same linear model that is used in much of the vast literature on milling and turning (Tlusty, 1985).

Experimental Setup

Figure 1 shows the two-axis machine tool with a 15 kRPM air bearing spindle used to experimentally validate the model (Professional Instruments model 9590 flycutting machine and Dover track writing spindle). The depth of cut used in all testing is two micrometers and the feed per spindle revolution was kept constant for all spindle speeds at 50 micrometers. With the 3 mm radius diamond tool used in this testing (single crystal, zero rake tool from Edge Technologies), the theoretical surface finish is 100 nm peak-to-valley and 30 nm R\textsubscript{a}.

Figure 1 also shows a close-up view of a 6061-T aluminum workpiece and diamond tool. As can be seen in the figure, the arc-shaped path of the rotating tool matches the radii of the workpiece so that the loading on the tool is constant for the entire test. This simplifies the interpretation of the metrology results by ensuring that the cutting force-induced deflection is constant over the entire workpiece. Figure 1 also shows a cross-sectional view of the workpiece, including the shaded area of the material removed in the current pass of the tool over the workpiece. This area, when multiplied by a material-dependent cutting coefficient, gives a good prediction of the cutting force on the tool. The structural loop of this machine is dominated by a single
structural resonance and the relevant modal parameters were determined from an experimentally measured frequency response. The dominant mode has a natural frequency of 300 Hz and a damping factor of 1% as calculated by polynomial curve fit. The static stiffness is 20 MN/m.

![Al coupon on cross feed axis](image1)

![Flycutter head and tool](image2)

Figure 3 Machine hardware used in the flycutting model validation.

**Workpiece Evaluation**

The flycut samples were measured for flatness using a phase shifting interferometric technique with a transmission flat set up to form a Fizeau measurement cavity with the surface of the test coupon (Zygo VeriFire AT interferometer). The illumination wavelength was 632.8 nm and 1k x 1k spatial sampling resolution was used. Each sample was manually aligned using an accessory mount in 2 axes of tilt to the test cavity. The surface error of both transmission flats was specified as λ/20. Only tip, tilt, and piston were removed from the measured data. Figure 2 shows the measured and predicted workpiece waviness at a flycutting spindle speed of 690 RPM.

![Measured](image3)

![Predicted](image4)

Figure 2 Measured and predicted workpiece flatness at 690 RPM.


**Discussion**

Preparing, cutting, and analyzing the flycutting samples is a time-consuming process. However, the verified model may be used to efficiently explore a variety of issues that may be encountered in practical precision flycutting applications. In this section, the role of structural loop stiffness, damping, and material properties will first be discussed. The relationship between workpiece size, spindle speed, and resonant frequency is then studied so that practitioners may identify the machining parameters that will result in workpieces with reduced out-of-flatness. A change in spindle speed can have a significant effect on the workpiece flatness.

The flycutting model provides a comprehensive picture of the relationship between the spindle speed, the dominant resonant frequency, and the arc of contact with the workpiece. Figure 3 shows the RMS flatness obtained by workpieces of various sizes when cut at various speeds. The results indicate that, in general, it is highly undesirable to set up a flycutting process such that the dominant resonant frequency is an integer multiple of the spindle speed (the opposite is not true; the spindle speed may in fact be chosen at a multiple of the natural frequency although this is an unlikely to be realizable in practice). If we consider the RMS flatness results shown in Figure 3 for the specific spindle speed that is one-third of the resonant frequency, we find two maxima at 60 and 180 degrees of contact arc. For workpieces of this size the tool is vibrating such that it leaves the workpiece out of phase and therefore with the greatest net excitation, as shown in Figure 11. Between these two maxima is a minimum in the workpiece out of flatness when the arc of contact is 120 degrees. For workpieces of this size, the tool is vibrating such that the tool leaves the workpiece in phase with its entrance and with the least net energy imparted to the tool. In this best-case situation, $n$ waves are generated in the workpiece.

![Figure 3 Effect of workpiece size on flatness.](image-url)
Conclusion

This paper has described a model showing how structural loop dynamics and periodic loading resulting from intermittent contact between a flycutting tool and workpiece interact to effect workpiece flatness. This model is a useful tool to improve the resulting flatness of a flycutting operation based on knowledge of the machine tool’s structural dynamics and details of the workpiece geometry. The results provide insight into important considerations for the selection of machining parameters and for the selection of the most appropriate spindle speeds for a given workpiece.

The results show that the preferred spindle speed should be chosen such that the dominant structural resonance does not occur at an integer multiple of the spindle speed. Furthermore, the spindle speed can be fine-tuned such that the vibrating tool will make an integer number of oscillations when the tool is in contact with the workpiece.

References

