THE EFFECT OF PARALLEL MODULATION ON SUB-SURFACE DAMAGE

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1 Introduction

Precision ceramic components are being used today in an increasing variety of engineering applications. Compared to metals, however, ceramics are much harder and more susceptible to brittle fracture. Ceramic components, in most cases, require finishing operations to achieve surfaces of required geometry, tolerance, and finish. Grinding is an enabling technology in the manufacture of ceramic components because it produces accurate shapes deterministically. However, grinding generally induces surface and sub-surface damage in the finished part, which can severely degrade its strength and life under service conditions.

Several other researchers have introduced high frequency vibrations into the machining process. Compared to traditional machining, modulation assisted machining has several benefits. It can reduce the critical depth of cut (for ductile removal), reduce friction at the tool-chip interface and the cutting force, permit better coolant penetration, and inhibit the build up of debris [1-4]. Our previous work [5] focused on the effect of vertical modulation on sub-surface damage. In this paper, we focus on the effect of parallel modulation on sub-surface damage.

2 Theoretical Motivation

Crack shielding can reduce the depth of subsurface damage in brittle materials [5-6]. The shielding effect can be achieved by intermittant unloading. The intermittant unloading does the following:

1. Initiates the material removal mechanism of lateral damage early in the process, before normal damage is fully developed.
2. Utilizes the shielding effects of lateral damage to retard and potentially eliminate normal damage from the finished product.

Vertical modulation results [5] indicate that sub-surface damage may be reduced in single point scratch tests since the acting force between nib and workpiece is unloaded and reloaded intermittently. To further investigate this shielding effect, we considered scratch tests under parallel modulation.

With parallel modulation, the cutting grit moves relative to the workpiece in the form:

$$u(t) = Vt - a\cos(\omega t)$$

where

$u(t)$ is the displament of the cutting grit;

V is the nominal cutting velocity;

a and ω are the amplitude and the angular velocity of the vibration modulation.

Therefore, the relative cutting grit velocity is:

$$u'(t) = V + a\omega\sin(\omega t) = V + V_m \sin(\omega t)$$

where $V_m = a\omega$ is the maximum modulation velocity.

When $V \geq V_m$, $u'(t) \geq 0$, the cutting grit is always in contact with the workpiece. Therefore, the unloading and reloading phenomenon in this cutting situation doesn't occur, and the shielding effect is not expected.

When $V < V_m$, $u'(t)$, the velocity of the cutting grit relative to the workpiece, is not always positive. When $u'(t) > 0$, the cutting grit extends and tends to cut the workpiece; when $u'(t) < 0$, the cutting grit retracts and does not cut the workpiece. When $u'(t) > 0$ and the cutting grit begins to be in contact with the workpiece, the cutting force on the workpiece is loaded; when $u'(t) < 0$, the cutting grit retracts and the cutting force on the workpiece is unloaded. Therefore, the unloading and reloading phenomenon in this cutting situation does occur.

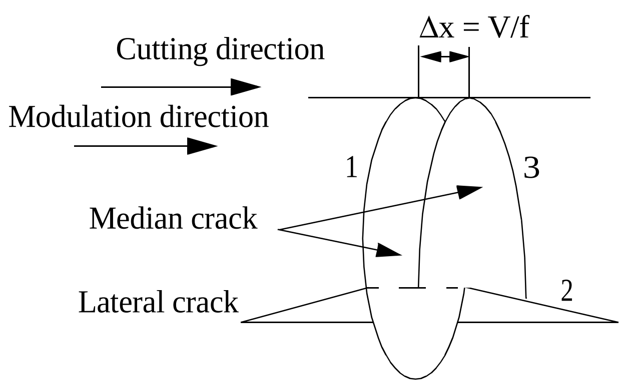

Figure 1: Shielding effect in single point modulation cutting

The unloading and reloading phenomenon in a cutting situation where cutting is modulated in the direction of the cutting is shown in Fig. 1. Loading produces the median crack 1. Subsequent unloading produces the lateral crack 2. Reloading then produces median crack 3. The distance $\Delta x = V/f$ is the displacement of the cutting grit in one cycle, where V is the cutting speed and f the modulation frequency. If Δx is small enough, the lateral crack 2 can act as an effective barrier against further depthwise penetration of the median crack 3. To see any beneficial effect, Δx must be smaller than the length of the lateral crack. Further reducing Δx (by decreasing V or increasing *f*) should increase the shielding effect. The minimum damage depth that could be realized would be the depth at which the lateral crack is initiated upon unloading.

3 Experimental Investigation of the Effects of Intermittent Unloading on Single Point Scratches Under Vertical Modulation

Figure 2 shows a schematic representation of the experimental setup. Pyrex glass, because of its transparency, is chosen as the work material. As shown in Figure 2, the workpiece is vibrated in the Y direction by a magnetostrictive actuator. A diamond cutting nib is mounted on the spindle. The cutting and modulation are in the same direction (Y). A force sensor is placed underneath the cutting nib. To establish initial contact, the table is moved in the Z direction until the force sensor reads 0.1 N. To make a scratch with intermittent unloading, the workpiece extends and retracts within one spindle rotation in Z direction while the actuator is modulating.

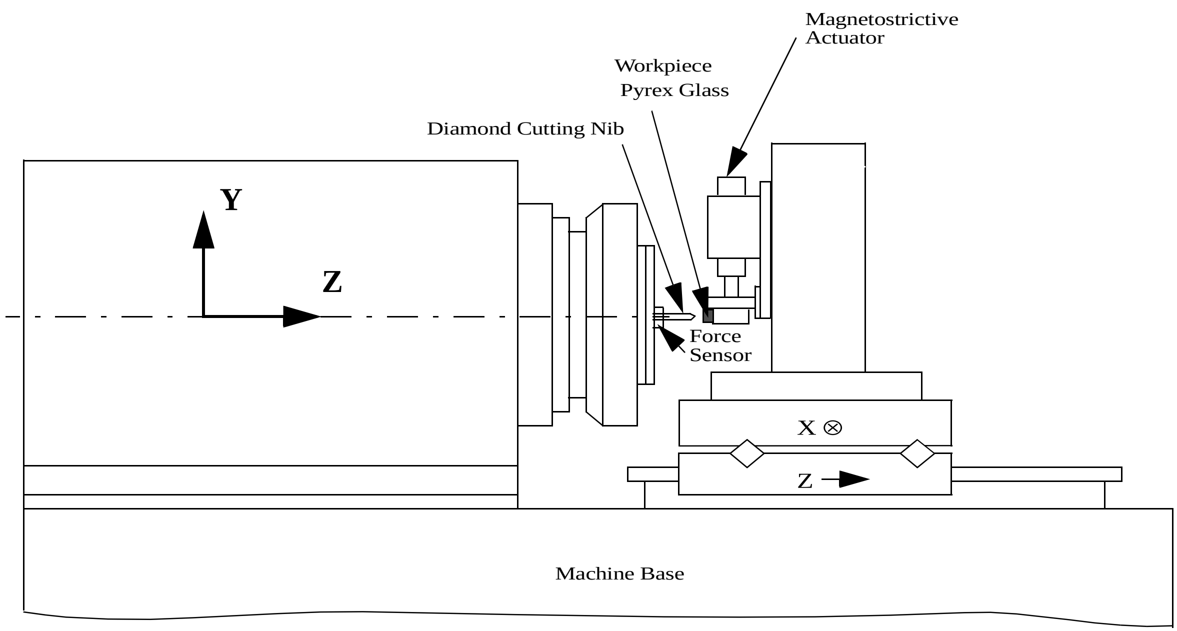

Figure 2: Experimental setup for scratch tests under parallel modulation

Single point scratch experiments were carried out with and without parallel modulation at two cutting speeds -- 40 and 120 mm/sec. Maximum modulation frequency attainable with reasonable amplitude for our magnetostrictive actuator was 4.5 kHz. Accordingly, modulation tests were carried out below this frequency at 3 kHz. The modulation amplitude is 20 μm (peak to valley). Because of the limitation in the maximum actuator frequency, the scratch tests described in this paper were performed at cutting speeds much lower than typical grinding speeds. Table 1 summarizes the results. The damage depth values represent the average of 5 tests. Modulation reduces the damage depth by 33% at 40 mm/s and by 20% at 120 mm/s. As expected, the modulation had less effect at higher cutting speed (higher Δx). When Δx increases relative to the lateral crack zone width, the shielding effect diminishes.

Table 1: Effect of V/f = Δx on damage depth for parallel modulation with depth of cut = 25 μm, peak-to-valley modulation amplitude = 10 μm

Velocity (mm/s)	Modulation Frequency (kHz)	Δx (μm)	Median Damage Depth (μm)
40	0	∞	125.5
120	0	∞	124.8
40	3	13.3	83.2
120	3	40	99.2

4 Conclusions

We performed scratch experiments in which the workpiece was modulated parallel to the cutting direction. The conclusions are as follows:

a. Parallel modulation can achieve the shielding effect. The smaller Δx is, the bigger the shielding effect is.
b. The reduction in subsurface damage for parallel modulation is comparable to the results for vertical modulation. For the same Δx = 40 μm, parallel modulation reduced damage depth by 20% while vertical modulation reduced damage depth by 21%.

References

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