Model development for the beveling of quartz crystal blanks

C. Dong a

aDepartment of Mechanical Engineering, Curtin University, GPO Box U1987, Perth, WA 6845, Australia
Email: c.dong@curtin.edu.au

Abstract: A quartz crystal unit is a quartz wafer (also referred to as blank or crystal plate) to which electrodes have been applied, and which is hermetically sealed in a holder structure. In order to achieve highly stable and reliable quartz crystal resonators without spurious response, quartz crystal blanks are finished into spherically contoured shape. The process of generating a spherical surface on a quartz plate is called beveling or contouring. Crystal manufacturers currently employ a trial-and-error approach because of the insufficient knowledge on the influences of process parameters. This limits the development of new generation crystal resonators. Thus, it is desirable to develop a process model, which can provide the process parameter settings based on the beveled blank design information. A process model for the beveling of quartz crystal blanks is presented in this paper. For a given crystal blank design, the shape of bevel and beveling time can be predicted from process factors, e.g. powder type, machine rpm and barrel diameter.

The inputs of the beveling model are: blank dimensions: \( L, W \); blank frequency: \( f \); bevel width: \( w_b \); bevel depth: \( h_b \); barrel combination: e.g. \( \phi 80, \phi 130, \phi 80 \); average diameter of beveling powder: \( d_p \); machine rpm: \( \omega \).

First, the model for material removal rate, \( mrr_{\text{max}} \), was developed. It is shown from our previous experimental study that the maximum material removal rate is dependent on a number of process parameters e.g. barrel diameter, machine rpm, etc. In order to develop a model, the mechanism of material removal was analyzed. The \( mrr_{\text{max}} \) data of various blanks being beveled using \( \phi 130 \) and \( \phi 80 \) barrels were obtained from experiments. \( mrr_{\text{max}} \) for any machine rpm and barrel diameter is given by

\[
mrr_{\text{max}} = 5.7455(LH)^{1.2}(\omega/120)^2(D/130)^{0.45} \theta^{0.45} \]

where \( \theta \) is the contact angle introduced.

Second, the initial bevel depth due to corner rounding was modeled. This is given by

\[
h_{b1} = 4.2351(LH)^{1.2} \theta^{0.45} (D_1/80)(\omega/120)^2 t_1 - (2.2308 + 0.1 \delta_c) \]

where \( \theta_i = L/D_1 \), \( t_1 = 12 \) and \( \delta_c \) is the centerline-corner difference.

Third, the concept of critical gap height, \( h_{\text{crit}} \), was introduced. This is a factor that determines the shape of bevel. This is because that the gap between a crystal blank and the beveling barrel’s internal surface is non-uniform. Material removal increases with decreasing gap height. It is shown from our previous experimental study that \( h_{\text{crit}} \) decreases with average diameter of beveling powder, decreases with increasing machine rpm, and decreases with increasing barrel diameter. A model for \( h_{\text{crit}} \) was developed based on the experimental data, which is given by

\[
h_{\text{crit}} = 5.8 \times 10^{-3} d_p^{1.2} h_{\text{max}}^{0.5} / H \]

where the unit of \( d_p \) is \( \mu \text{m} \).

This model has been validated using various blanks and good agreement with experiments is found. Given the required bevel profile, the optimal process factors can be chosen with the aid of this process model. Thus, this model provides an efficient and cost-effective way to the design of quartz crystal resonators.

Keywords: Quartz crystal, bevel, model
1. INTRODUCTION

A quartz crystal unit is a quartz wafer (also referred to as blank or crystal plate) to which electrodes have been applied, and which is hermetically sealed in a holder structure. It is the main component of a crystal oscillator, which is an electronic oscillator circuit that uses the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with a very precise frequency.

Quartz crystal blanks can be cut from the source crystal in many different ways. AT-cut rectangular quartz crystal resonators are widely used for the high-precision applications such as mobile communication and GPS (global positioning system) equipment, because of their high temperature-frequency stability, and compatibility for mass production and miniaturization (Koyama et al., 1996 and Sekimoto et al., 1997).

The most common cut is called AT-cut, which was developed in 1934. In AT-cut, the plate contains the crystal’s x axis and is inclined by 35°15’ from the z (optic) axis. The frequency-temperature curve is a sine-shaped curve with inflection point at around 25-35°C. The frequency constant of AT-cut is 1.661 MHz·mm.

In order to achieve highly stable and reliable quartz crystal resonators without spurious response, quartz crystal blanks are finished into spherically contoured shape. A beveled blank is shown in Figure 1. The process of generating a spherical surface on a quartz plate is called beveling or contouring (Virgil, 1982). It is called beveling when one or both faces of a resonator plate are altered to have a partially spherical configuration, and contouring when one or both faces of a resonator plate are altered to have a completely spherical configuration. It is easy to see that there is no flatness in the center after contouring, and there is flatness in the center after beveling.

Beveling or contouring has a drastic effect on the decoupling of modes by restricting the vibrating area of the plate to its central region by energy trapping effect. The frequency separation between the main and overtone modes is inversely proportional to the area of the vibrating region. Therefore, reducing the size of the vibrating area should cause the troublesome inharmonic modes to move to higher frequencies. Additionally, beveling or contouring offers the advantages of ease of mounting and reduced coupling to unwanted modes at the edge of the blank by restricting the blank’s vibrating area to its central region (Salt, 1987).

Two issues in the beveling of quartz crystal blanks are material removal rate and bevel profile. The material removal of lapping and polishing processes has been extensively studied (Evans et al., 2003). In lapping, abrasive powders are mixed with a fluid carrier to form a slurry. The basic model of polishing was investigated by Preston (Preston, 1927) in 1927. He proposed the polishing rate of material to be proportional to a load and relative velocity. A critical size ratio for the characteristic particle size to film thickness was found by Williams and Hyncica (Williams and Hyncica, 1992).

In beveling, no fluid is used. Blanks move with regard to beveling barrels and material is removed by abrasive powders. The gaps between blanks and a barrel’s internal surface are not uniform and play an important role in the shape of bevel.

There is no reported study on the beveling process design for quartz crystal blanks. Crystal manufacturers currently employ a trial-and-error approach because of the insufficient knowledge on the influences of process parameters. This limits the development of new generation crystal resonators. Thus, it is desirable to develop a process model, which can provide the process parameter settings based on the beveled blank design information. In our previous study (Dong, 2010), the beveling process of quartz crystal blanks was studied experimentally and the significant factors affecting the material removal rate and bevel profile were identified. A process model for the beveling of quartz crystal blanks is presented in this paper. For a given crystal blank design, the shape of bevel and beveling time can be predicted from process factors, e.g. powder type, machine rpm and barrel diameter. This model has been validated using various blanks and good agreement with experiments is found. Given the required bevel profile, the optimal process factors can be chosen with the aid of this process model. Thus, this model provides an efficient and cost-effective way to the design of quartz crystal resonators.
As shown in Figure 2, a centrifugal beveling machine consists of a drum and four cylinders. Each cylinder can receive a number of beveling barrels. A beveling barrel consists of a number of inter-connected internal spheres. The diameter ranges from 60 to 200 mm.

Prior to a beveling process, a number of crystal blanks are prepared and weighed. The prepared blanks are mixed with abrasive powder at a certain weight ratio, and charged into beveling barrels. The charged beveling barrels are loaded into the four cylinders of the beveling machine. During the beveling process, the main drum rotates at a speed between 0 and 150 rpm, and the direction of rotation reverses intermittently. Because of the drum’s rotation, each cylinder also self-rotates about its own axis. As a result of the drum’s rotation, the crystal blanks are pressed against the beveling barrel’s internal surface by the centrifugal forces. The cylinders’ self-rotation causes the relative movement between the crystal blanks and the beveling barrel’s internal surface. Because of the friction, material is removed from the crystal blanks and bevel profiles are formed.

The abrasive powders used in this beveling process are commercially available GC (Green Carborundum) powders of grit sizes from GC800 to GC3000. A thin layer of abrasion powders forms on the beveling barrel’s internal surface during beveling.

A three-stage beveling was employed in our production. A fixed blank/powder ratio 1:1.2 by weight was used. The powder was changed every twelve hours, which was called a beveling cycle. During the first stage, the blanks are beveled in φ60 or φ80 barrels for rounding the corners of blanks. The blanks are beveled in φ130 barrels for several cycles to achieve the target bevel width in the second stage. During the third stage, the blanks are beveled in φ80 barrels to deepen the bevel.

2. MODEL DEVELOPMENT

2.1. Material Removal

For the purpose of beveling time estimation, material removal rate needs to be predicted from process parameters. Because a fixed 12-hour powder changing time was used, material removal could only be determined from measuring the bevel profile change after each 12-hour cycle. In our experiments, bevel profiles were measured along the centerline of a crystal blank. Thus, material removal was evaluated in 2-D at the cross-section along the centerline. The maximum material removal occurs at the blank edge, and for cycle $i$, the maximum material removal rate is given by

$$mrr_{max,i} = \frac{h_{b,i} - h_{b,i-1}}{12}$$

(1)
where \( mrr_{\text{max}} \) is the maximum material removal rate in cycle \( i \), and \( h_{b,i} \) and \( h_{b,i-1} \) are the bevel depths after cycles \( i \) and \( i-1 \), respectively.

It is shown from the experiments that maximum material removal rate decreases with time. This is because as beveling progresses, the contact area between the blank and the barrel increases, and the pressure and crack depth decreases, which results in a decreased material removal rate. In order to account for this decrease of \( mrr_{\text{max}} \) with beveling cycle, a decay coefficient with time \( \delta \) was introduced. It should also be noted that if the beveling continues, the gap height will approach zero throughout the blank surface area, i.e. the bevel profile matches that of the internal surface of the beveling barrels. Thus, \( mrr_{\text{max}} \) becomes zero. The material removal within a period of time \( t \) is given by

\[
mrr = \delta(t)mrr_{\text{max}}t
\]

(2)

The following regression model was fitted to our experimental data.

\[
\delta(t) = 0.56 + 0.70\exp(-t/25.91)
\]

(3)

In order to develop a model for \( mrr_{\text{max}} \), the \( mrr_{\text{max}} \) data of various blanks being beveled using \( \phi130 \) and \( \phi80 \) barrels were obtained from experiments. For example, the bevel profile development of a 16 MHz 4.408 mm \( \times \) 1.768 mm blank is shown in Figure 3. The diameter of the beveling barrel was 130 mm. \( mrr_{\text{max}} \) was determined to be 0.466 \( \mu m/h \).

\[\begin{align*}
\text{Figure 3. Beveling profile development of a 16 MHz} \\
\text{4.408 mm} \times \text{1.768 mm blank}
\end{align*}\]

It is shown from our previous experimental study that the maximum material removal rate is dependent on a number of process parameters e.g. barrel diameter, machine rpm, etc. Before a model can be fitted, the mechanism of material removal needs to be analyzed. With reference to general lapping processes, material removal rate is governed by Preston’s equation, i.e.

\[
mrr = Cpv
\]

(4)

where \( p \) is pressure and \( v \) is the velocity of movement. For a beveling process, \( p \) is due to the centrifugal force and \( v \) is the velocity of blanks moving with respect to the barrel’s internal surface. In the 2-D cross-section along the centerline, \( p \) is the combined effect of \( LH \) and \( \alpha \) and \( v \) is the combined effect of \( \omega \) and \( R \). In addition, since blanks contact the barrel’s internal surface at an angle, the concept of contact angle \( \theta \) is introduced. \( mrr_{\text{max}} \) increases with \( \theta \). Since the length of a blank is much less than the diameter of a beveling barrel, the contact angles are \( \theta_2 = L/D_2 \) for beveling stage 2 and \( \theta_3 = L/D_3 - L/D_2 \) for beveling stage 3.

Eqn. 5 is rewritten by taking into account the above mentioned factors as

\[
mrr_{\text{max}} = a_0(LH)^{a_1}\omega^{a_2}D^a_3
\]

(5)

where \( a_0, a_1, a_2 \) and \( a_3 \) are constants to be determined. These constants were determined using the experimental data. The actual regression model is given by
Dong, Model development for the beveling of quartz crystal blanks

\[ mrr_{\text{max}} = 5.7455 (LH)^{1.2} (\omega/120)^{2} (D/130)\theta^{0.45} \]  

(6)

The \( mrr_{\text{max}} \) for \( \phi 130 \) and \( \phi 80 \) barrels from the experiments and model are shown in Figure 4. It is seen good agreement is found.

2.2. Initial Bevel Depth

When the material removal is studied in the 2-D cross-section along the centerline, the initial bevel depth due to corner rounding needs to be predicted. In the beginning of beveling, crystal blanks are beveled for 12 hours to round the corners. After this 12-hour corner rounding, the centerline of a blank may or may not contact the barrel’s internal surface, depending on the centerline-corner difference and material removal rate. The bevel depth after stage 1 is defined as initial bevel depth, and it is negative when the centerline does not contact the barrel’s internal surface, as shown in Figure 5.

The centerline-corner difference is given by

\[ \delta_{\text{cc}} = 1000 \left( \sqrt{R^2 - \left(\frac{L}{2}\right)^2} - \sqrt{R^2 - \left(\frac{L_{\text{diag}}}{2}\right)^2} \right) \]

\[ = 1000 \left( \sqrt{R^2 - \left(\frac{L}{2}\right)^2} - \sqrt{R^2 - \left(\frac{L}{2}\right)^2 - \left(\frac{W}{2}\right)^2} \right) \]

(7)

where 1000 is for converting mm to \( \mu \)m. It is also assumed that the material removal rate causing the initial bevel depth is proportional to \( (LH)^{1.2} (\omega/120)^{2} (D/130)\theta^{0.45} \). The total material removal starts at the corners and moves to the centerline. Since the removal of corners is much faster than material removal in the centerline, the total material removal is given by

\[ m_{t1} = h_{b1} + (c_0 + c_1\delta_{\text{cc}}) \]

where \( c_0 \) and \( c_1 \) are constants to be determined. The regression model for \( h_{b1} \) is given by

\[ h_{b1} = 4.235 \left( LH \right)^{1.2} \theta^{0.45} \left( D/80 \right) \left( \omega/120 \right)^{2} t_1 - (2.2308 + 0.1\delta_{\text{cc}}) \]

(8)

where \( \theta_1 = L/D_1 \) and \( t_1 = 12 \).

The initial bevel depths from the experiments and model are shown in Figure 6. It is seen good agreement is found.

2.3. Critical Gap Height

Critical gap height is introduced as a factor that determines the shape of bevel. This is because that the gap between a crystal blank and the beveling barrel’s internal surface is non-uniform. Material removal increases with decreasing gap height. It is shown from our previous experimental study that \( h_{\text{crit}} \) decreases with average diameter of beveling powder, decreases with increasing machine rpm, and decreases with increasing
Dong, Model development for the beveling of quartz crystal blanks

Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>4.4</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>1.682</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>16.754</td>
</tr>
<tr>
<td>Bevel width (mm)</td>
<td>0.6</td>
</tr>
<tr>
<td>Machine rpm</td>
<td>120</td>
</tr>
<tr>
<td>Barrel diameter 1 (mm)</td>
<td>80</td>
</tr>
<tr>
<td>Barrel diameter 2 (mm)</td>
<td>130</td>
</tr>
<tr>
<td>Barrel diameter 3 (mm)</td>
<td>80</td>
</tr>
</tbody>
</table>

Figure 7. Critical gap height from experiments and model

3. MODEL VALIDATION

The developed model was validated against the experimental data. The blank design information is given in Table 1. Firstly, $h_{b1}$ was calculated to be 2 $\mu$m. Secondly, from the bevel width and GC1200 powder being used, it was calculated that $h_{b2} = 15.9$ $\mu$m and $h_{crit} = 5.3$ $\mu$m. Thus, the resulting bevel depth was calculated to be $h_{b2} = 8.6$ $\mu$m. The material removal rate was determined to be $mrr_{max2} = 0.462$ $\mu$m/h. Thus, the time needed for bevel width development was calculated to be 21.4 hours. The actual time was determined to be
24 hours. \( h_{b2} \) was calculated to be 9.3 \( \mu m \). The predicted bevel profile curve and the actual curve after \( \phi 130 \) beveling are shown in Figure 8a. Finally, the blanks were beveled for another 24 hours using D80 barrels for deeper bevel. \( mrr_{\text{max}3} \) and \( h_{b3} \) were calculated to be 0.230 \( \mu m/h \) and 4.6 \( \mu m \), respectively. The final bevel depth was calculated to be 15.9 \( \mu m \). The predicted final bevel profile curve and the actual curve from measurement are shown in Figure 8b. It is seen that there is a good agreement between the model and the measurement.

4. CONCLUSIONS

A process model for the beveling of quartz crystal blanks is presented in this paper. For a given crystal blank design, the shape of bevel and beveling time can be predicted from process factors, e.g. powder type, machine rpm and barrel diameter. This model has been validated using various blanks and good agreement with experiments is found. Given the required bevel profile, the optimal process factors can be chosen with the aid of this process model. Thus, this model provides an efficient and cost-effective way to the design of quartz crystal resonators.

REFERENCES