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Model development for the beveling of quartz crystal blanks

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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. ϕ80, ϕ130, ϕ80; average diameter of beveling powder: d_p; machine rpm: ω.

First, the model for material removal rate, $mrr_{\max}$, 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 $mrr_{\max}$ data of various blanks being beveled using ϕ130 and ϕ80 barrels were obtained from experiments. $mrr_{\max}$ for any machine rpm and barrel diameter is given by

$$mrr_{\max} = 5.7455(LH)^{1.2}(\omega/120)^2(D/130)\theta^{0.45} \quad (1)$$

where θ is the contact angle introduced.

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

$$h_{b1} = 4.2351(LH)^{1.2}\theta_1^{0.45}(D_1/80)(\omega/120)^2 t_1 - (2.2308 + 0.1\delta_{cc}) \quad (2)$$

where $\theta_1 = L/D_1$, $t_1 = 12$ and δ_{cc} is the centerline-corner difference.

Third, the concept of critical gap height, h_{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_{crit} decreases with average diameter of beveling powder, decreases with increasing machine rpm, and decreases with increasing barrel diameter. A model for h_{crit} was developed based on the experimental data, which is given by

$$h_{crit} = 5.8\times10^{-3} d_p^{1.2} h_{\max}^{0.5}/H \quad (3)$$

where the unit of d_p is μm.

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.

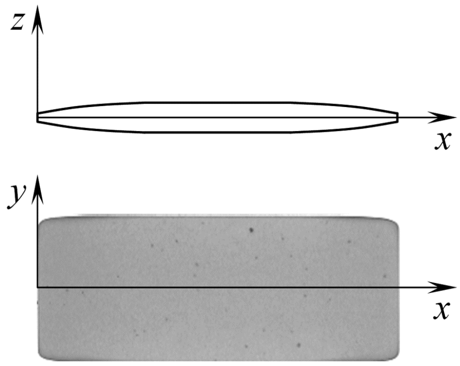


Figure 1. A beveled quartz crystal blank

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.

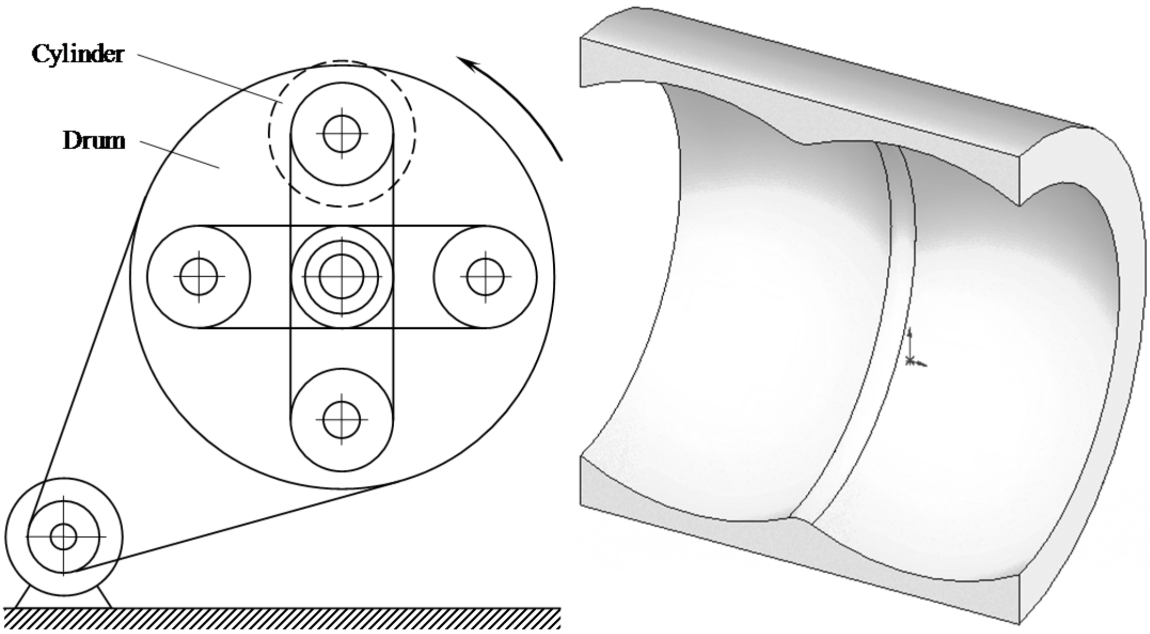


Figure 2. Left: centrifugal beveling machine; right: two-sphere beveling barrel

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' 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

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

where $mrr_{\max,i}$ 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 $mrr_{\max}$ with beveling cycle, a decay coefficient with time δ 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, $mrr_{\max}$ becomes zero. The material removal within a period of time t is given by

$$mr = \delta(t) mrr_{\max} t \tag{2}$$

The following regression model was fitted to our experimental data.

$$\delta(t) = 0.56 + 0.70 \exp(-t/25.91) \tag{3}$$

In order to develop a model for $mrr_{\max}$, the $mrr_{\max}$ data of various blanks being beveled using ϕ130 and ϕ80 barrels were obtained from experiments. For example, the bevel profile development of a 16 MHz 4.408 mm × 1.768 mm blank is shown in Figure 3. The diameter of the beveling barrel was 130 mm. $mrr_{\max}$ was determined to be 0.466 μm/h.

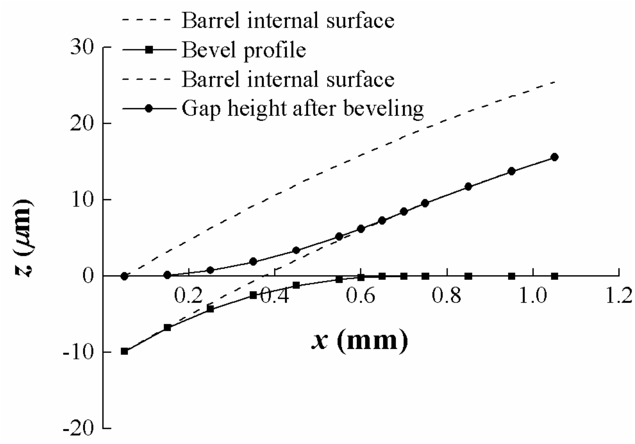


Figure 3. Beveling profile development of a 16 MHz 4.408 mm × 1.768 mm blank

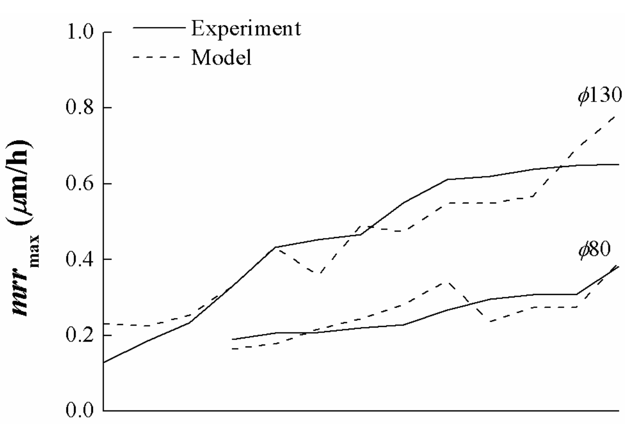


Figure 4. $mrr_{\max}$ for ϕ130 and ϕ80 barrels from experiments and model

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.

$$mrr = Cpv \tag{4}$$

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 ω, and v is the combined effect of ω and R. In addition, since blanks contact the barrel's internal surface at an angle, the concept of contact angle θ is introduced. $mrr_{\max}$ increases with θ. 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

$$mrr_{\max} = a_0 (LH)^{a_1} \omega^{a_2} D \theta^{a_3} \tag{5}$$

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

$$mrr_{\max} = 5.7455(LH)^{1.2}(\omega/120)^2(D/130)\theta^{0.45} \tag{6}$$

The $mrr_{\max}$ for ϕ130 and ϕ80 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

$$\begin{aligned}\delta_{cc} &= 1000\left(\sqrt{R^2-(L/2)^2}-\sqrt{R^2-(L_{diag}/2)^2}\right)\\ &= 1000\left(\sqrt{R^2-(L/2)^2}-\sqrt{R^2-(L/2)^2-(W/2)^2}\right)\end{aligned} \tag{7}$$

where 1000 is for converting mm to μm. It is also assumed that the material removal rate causing the initial bevel depth is proportional to $(LH)^{1.2}(\omega/120)^2(D_1/130)\theta_1^{0.45}$. 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

$$mr_1 = h_{b1} + (c_0 + c_1\delta_{cc})$$

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

$$h_{b1} = 4.2351(LH)^{1.2}\theta_1^{0.45}(D_1/80)(\omega/120)^2 t_1 - (2.2308 + 0.1\delta_{cc}) \tag{8}$$

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.

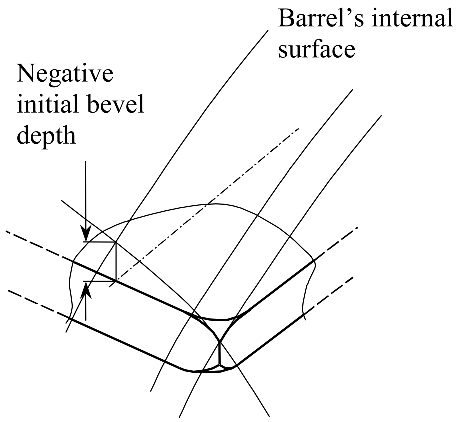


Figure 5. Negative initial bevel depth

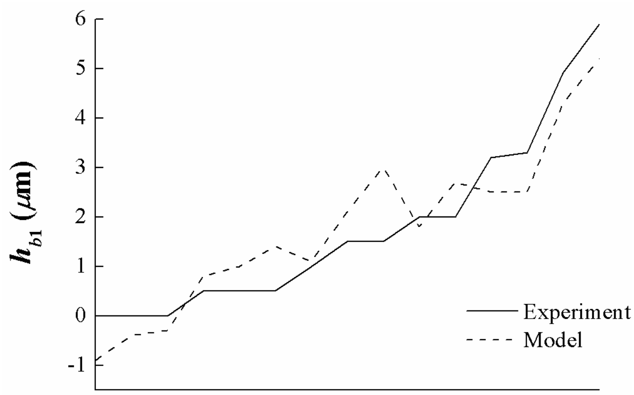


Figure 6. Initial bevel depth from experiments and model

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_{crit} decreases with average diameter of beveling powder, decreases with increasing machine rpm, and decreases with increasing barrel diameter. It is assumed that at the beginning of a beveling process, the beveling barrel is in contact with the blank edge. At the bevel width, the initial gap height, h_0 is given by

$$h_0 = 1000\left[\sqrt{(D/2)^2 - (L/2 - w_b)^2} - \sqrt{(D/2)^2 - (L/2 - 0.05)^2}\right] \tag{9}$$

With the progress of the beveling process, the blank-barrel gap height decreases. When the designed bevel width is achieved, the gap height is the critical gap height, h_{crit}.

h_{crit} can be found by comparing the bevel profile against the beveling barrel surface, i.e.

$$h_{crit} = h_0 - h_b \tag{10}$$

Critical gap height is dependent on the crack depth distribution on the blank surface. When the frequency increases, i.e. the blank is thinner, the difference in the crack depth decreases, and thus the critical gap height increases; when barrel diameter increases, the gap between the blank and the barrel's internal surface decreases, and thus the critical gap height decreases. Thus, the process parameters chosen for the critical gap height model development are: the thickness of the blank H, the diameter of bevel particles d_p, and the maximum gap height $h_{\max}$.

The maximum gap height (μm) between the blank surface and the barrel's internal surface is given by

$$h_{\max} = 1000\left(D/2 - \sqrt{(D/2)^2 - (L/2)^2}\right) \tag{11}$$

The aforementioned analysis postulates that the regression model for h_{crit} is

$$h_{crit} = b_0 d_p^{b_1} h_{\max}^{b_2} H^{b_3} \tag{12}$$

b_0, b_1, b_2 and b_3 were determined using the experimental data. The regression model for h_{crit} is given by

$$h_{crit} = 5.8\times10^{-3} d_p^{1.2} h_{\max}^{0.5} / H \tag{13}$$

where the unit of d_p is μm.

The initial bevel depths from the experiments and model are shown in Figure 7. It is seen good agreement is found.

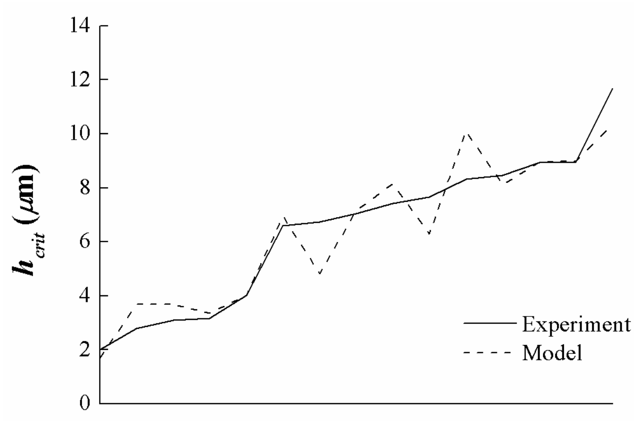


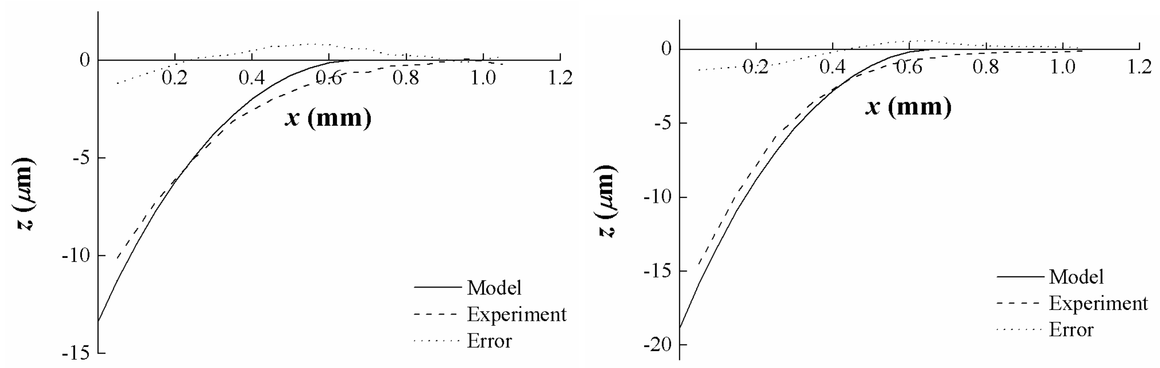
Figure 7. Critical gap height from experiments and model

Table 1. 16.754 MHz 4.4 mm × 1.682 mm blank

Length (mm)		4.4
Width (mm)		1.682
Frequency (MHz)		16.754
Bevel width (mm)		0.6
Machine rpm		120
Barrel diameter (mm)	1	80
	2	130
	3	80

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 μm. Secondly, from the bevel width and GC1200 powder being used, it was calculated that h_0 = 15.9 μm and h_{crit} = 5.3 μm. Thus, the resulting bevel depth was calculated to be h_{b2} = 8.6 μm. The material removal rate was determined to be $mrr_{\max2}$ = 0.462 μm/h. Thus, the time needed for bevel width development was calculated to be 21.4 hours. The actual time was determined to be



(a) (b)

Figure 8. Predicted and measured bevel profiles of the 16.754 MHz 4.4 mm × 1.682 mm blank

24 hours. h_{b2} was calculated to be 9.3 μm. The predicted bevel profile curve and the actual curve after ϕ130 beveling are shown in Figure 8a. Finally, the blanks were beveled for another 24 hours using D80 barrels for deeper bevel. $mrr_{\max 3}$ and h_{b3} were calculated to be 0.230 μm/h and 4.6 μm, respectively. The final bevel depth was calculated to be 15.9 μm. 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

Bechman, R. (1958). Elastic and piezoelectric constants of alpha-quartz. *Physical Review* 110(5): 1060-1061.

Dong, C. S. (2010). Mechanism analysis and experimental study for the bevelling of quartz crystal blanks. Proceedings of the 6th Australasian Congress on Applied Mechanics, Perth, Australia, Engineers Australia.

Evans, C. J., E. Paul, et al. (2003). Material removal mechanisms in lapping and polishing. *Annals of the CIRP* 52(2): 611-633.

Koyama, M., Y. Watanabe, et al. (1996). An experimental study of frequency jumps during the aging of quartz oscillators. *IEEE Transactions on Ultrasonic, Ferroelectrics, and Frequency Control* 43(5): 907-910.

Mason, W. P. (1950). Piezoelectric Crystals and Their Applications to Ultrasonics. New York, USA, Van Nostrand.

Preston, F. W. (1927). The theory and design of plate glass polishing machine. *J. Soc. Glass Tech.* 11(44): 214-256.

Salt, D. (1987). Hy-Q Handbook of Quartz Crystal Devices. Berkshire, England, Van Nostrand Reinhold (UK) Co. Ltd.

Sekimoto, H., S. Goka, et al. (1997). Frequency-temperature behavior of spurious vibrations of rectangular AT-cut quartz plates. IEEE International Frequency Control Symposium: 710-714.

Virgil, E. B. (1982). Introduction to Quartz Crystal Unit Design. New York, Van Nostrand Reinhold Ltd.

Williams, J. A. and A. M. Hyncica (1992). Mechanisms of abrasive wear in lubricated contacts. *Wear* 152: 57-74.