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Grinding Force Control of polishing Cubic Zirconia Gem by an Automatic Faceting Machine

Chanainat Kaothong[a] and Viboon Sangveraphunsiri[b]

Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University

254 Phayathai Road, Pathumwan, Bangkok 10330, Thailand

Tel. +66 2218 6585, Fax. +66 2218 6583

[a]mkaothong@hotmail.com and [b]viboon.s@eng.chula.ac.th

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Abstract. This research work is to develop a controller that combines the position and indirect force control for the gemstone polishing process. The polished gemstones are attached to the end of drop-stick of the Chula Automatic Faceting Machine. The Chula Automatic Faceting Machine has 4-axis high precision motion control and the other 2-axis for spindle and crank motion. Many gemstones (number of gemstones will depends on the size of the gemstone) can be grinded and polished simultaneously with the result of uniform size and quality.

In this research work, the controller is developed based on PID motion control. The reference position of the controller for the grinding process is obtained based on the compliance force control technique with known compliance model. This reference position will specified the pressing force for the grinding process indirectly. The controller developed in-house is used for testing with Cubic Zirconia gemstone which the hardness is 8.5 Mohs. The compliance model and appropriate parameters including the minimum and maximum boundary of polishing process can be obtained experimentally. Then all parameters obtained from the experiment can be used in the controller. The uniform size and quality of the multi-stone grinding and polishing process can be obtained with this controller.

Introduction

Thailand Gems-Industry has been the primary top classified as the highest profitable successfulness for the synthetic made gems (CZ) nowadays. Especially CZ gem on the large market need for large amounts but skill labour of human-being could not able enough produce for the requirement of market because they can't produce CZ gems for uniform size through all manufacturing. Thus, The Advance Manufacturing Research Lab would highly response in research designs and built the CU Automatic Faceting Machine to use in-house. And the controller has been continuously improved for grinding and polishing process so that uniform size and quality for multi-stone operation which the manual process cannot achieve, especially for complicated shapes. This work will cover the research of compliance indirect force control for CZ gem grinding and polishing process without any force sensor installed. It is not wise to use force sensor due to its high price and difficult to maintain.

In this paper, we cover the control strategy to combine both position and force control. The necessary parameters, for a compliance model, and appropriate parameters, for the maximum grinding position and the minimum and maximum boundary for polishing process, are obtained experimentally.

Overview

System Architecture. The system overview of the Chula Automatic Faceting Machine is shown in Fig. 1. It has 4-axis (X Y Z and A axis) high precision motion control which is developed based on PID motion control and the other 2-axis for spindle and crank motion without position control. The motion of X and Z axis have limit-switch as shown in Fig. 2 to limit the travelling distance.

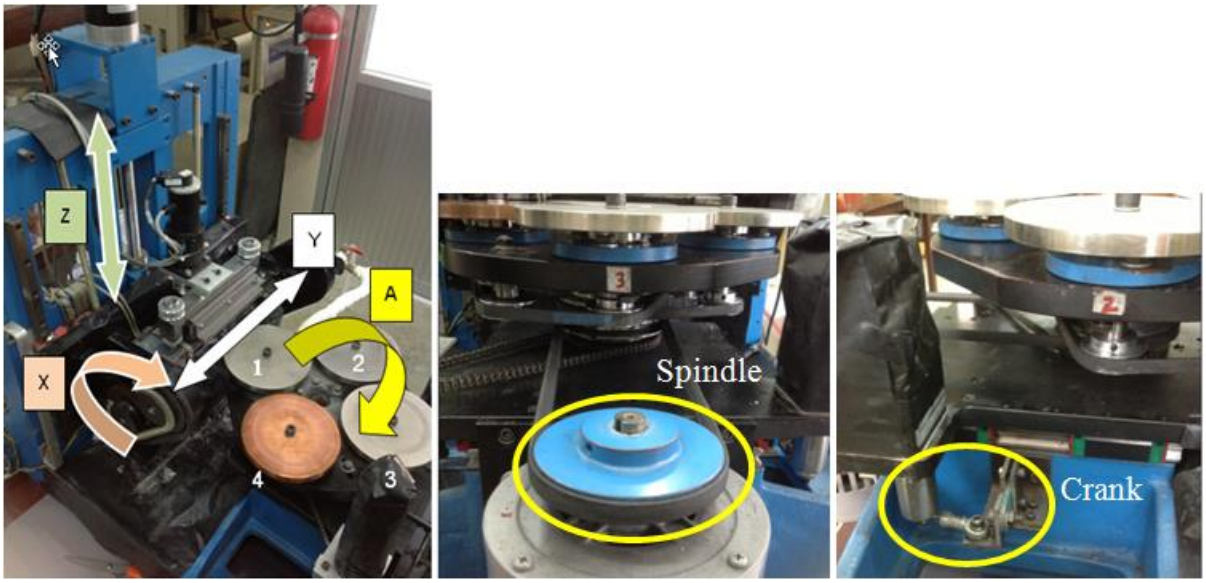

Fig. 1 System overview [1]

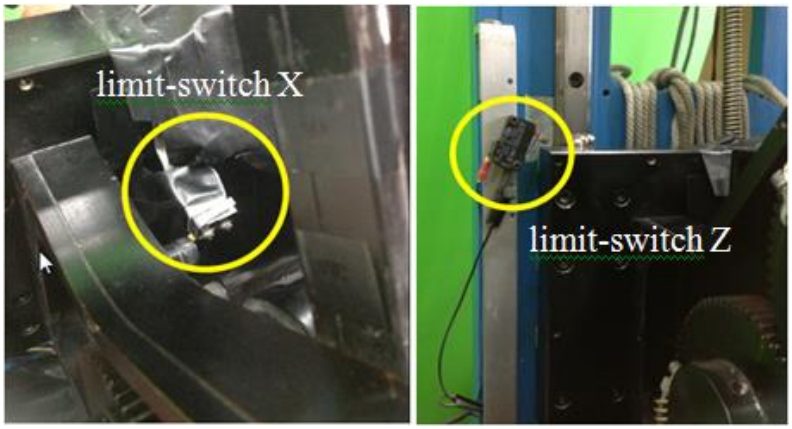

Fig. 2 Limit switch installation [1]

Control parameters. Structure of Automatic Faceting Machine was designed by considering all the control parameter that effect on the shapes, facets and sizes of gem. In gem grinding process, it has only 3 parameter values that want to control as shown in Fig 3.

Index Angle (i). This parameter value is specified how many faces of a gemstone by divide index angle. More index angle mean as the greater resolution of gem grinding process and this parameter is controlled by Y-axis of Automatic Faceting Machine.

Elevation Angle (e). This parameter value is specified the facet of a gemstone which indicate how many angle in a grinding cycle. Elevation angle is measured from the center line of drop-stick to the vertical line and this parameter is controlled by X-axis of the Automatic Faceting Machine.

Depth of cut (h). This parameter value is used to specify size of a gemstone and this parameter is controlled by Z-axis of the Automatic Faceting Machine.

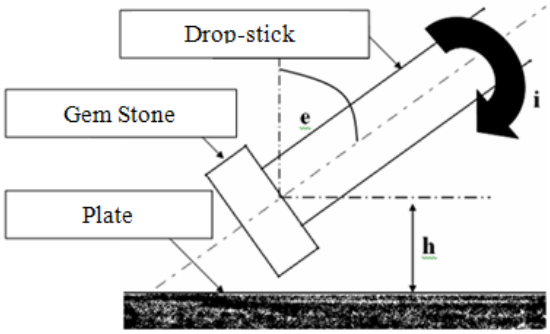

Fig. 3 The parameters need to specify the shape of a gemstone [2].

Kinematics model [4]

Forward Kinematics. Forward Kinematics equation can be obtained from the DH-Parameter where obtained from frame assignment shown in Fig. 4 in our previous works [2]**.**

$$Z = h + \left(L_3 + W/2 \right) C\theta_2 - L_2 S\theta_2 \tag{1}$$

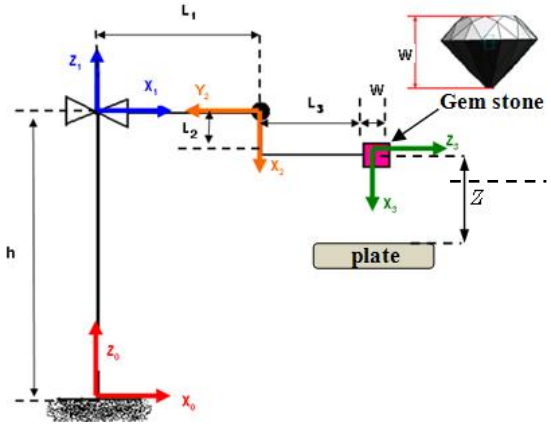

Fig. 4 Automatic Faceting Machine with frame assignments [2].

From Eq. (1) where

Z is the distance measured from a center of a gemstone to the grinding wheel surface (plate) in the vertical direction,

h is the motion along Z-axis,

L_2 is the offset distance between the X-axis (see Fig. 1) and the center line of a drop stick (see Fig. 3) measured along the vertical direction,

L_3 is the offset distance between the X-axis (see Fig. 1) and the tip of a drop-stick measured along the vertical direction,

W is the height of a gemstone as shown in Fig. 4,

$C\theta_2 = \cos\theta_2$, $S\theta_2 = \sin\theta_2$.

The distance h is obtained from the encoder attached in Z-direction. And the distance Z is the distance based on the shape of the gemstone.

Inverse Kinematics. For the gemstone grinding process, we normally know the Z value (according to shape of the gemstone) from Eq. (1), it is used to determine the error between the Z value and depth of cut for the additional distance calculation from Eq. (2). The reference distance h (the sum of additional distance and measured distance) is used as the controlled variable in the feedback control loop.

$$h = Z - \left(L_3 + W/2 \right) C\theta_2 + L_2 S\theta_2 \quad (2)$$

Indirect force control

Compliance control [3]. Indirect force control with a purposed compliance method as shown in Fig. 5 is an analysis of interaction between the manipulator and environment when contact force was arise. Consider the equation $F = K\Delta Z$ when contact force occur meanwhile the gemstone was pressed down on polishing plate. This behavior is considered as active compliance when $K_e >> K_m$.The stiffness K can be estimated at $K = K_m$ and the displacement ΔZ of deformation between manipulator and environment is $\left\| Z_d - Z_e \right|$ whereas the term passive compliance used where $K_m >> K_e$ for the stiffness K can be estimated at $K = K_e$ and the displacement ΔZ of deformation between manipulator and environment is $\left| Z_e - Z_r \right|$. Due to the Automatic Faceting Machine is designed with very high stiffness compare to the stiffness of deformation between a gemstone and the polishing plate. Therefore displacement ΔZ of the gemstone in the polishing process can be estimated as $\left| Z_e - Z_r \right|$.

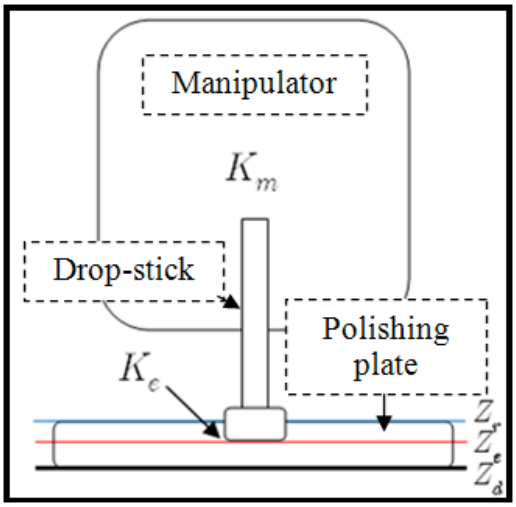

Fig. 5 Compliance control model [1].

Where

K_m is a stiffness of manipulator (faceting machine with drop-stick),

K_e is a stiffness of contact between a gemstone and the polishing plate,

Z_r is a position that no deformation between a gemstone and the polishing plate,

Z_e is a final position that a gemstone reached when pressing on the polishing plate,

Z_d is a desire position that the controller used as a reference position.

Controller. The controller of the Automatic Faceting Machine as shown in Fig. 6 was developed based on PID motion control (Gray block) by adding force sense technique (White block). The reference position of the controller for the grinding process is obtained based on the compliance force control technique with known compliance model. This reference position will specified

the pressing force for the grinding process indirectly through the equation below in our previous works [1]**.** Where I is current of the Z-axis motor. L is the pitch of Z-axis ball screw.

$$F = \frac{K_{motor} I}{0.177 \times L} = \frac{0.215 \times I}{0.177 \times L} \quad (3)$$

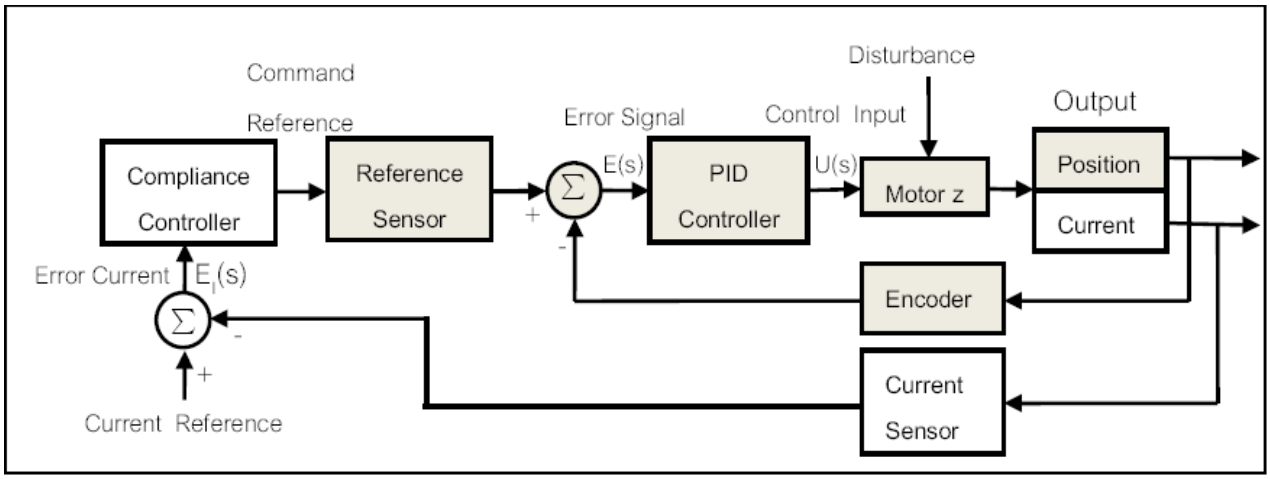

Fig. 6 Block scheme of position and compliance control [1].

Experiments

In experiment, we use Cubic Zirconia gemstones with cylinder shape which the hardness is 8.5 Mohs and the cylinder's diameter 4 mm and 4.5 mm in length as shown in Fig. 7. In our previous works [1], for this kind of the gemstone, we can obtain compliance model and appropriate parameters including the minimum and maximum boundary of polishing process through the experiment**.**

Compliance model stiffness $K = K_e \approx 3 \times 10^5$ N/m
(Stiffness of contact face between gem surface and polishing plate surface)

Minimum boundary of polishing process 435 N
(Indirect force control was activated when measured current was below Minimum value)

Maximum boundary of polishing process 598 N
(Indirect force control was deactivated when measured current was over Maximum value)

Limit the increment of the reference position grinding 0.06mm
(This limit value is the boundary of the additional reference position from the pressing gemstone)

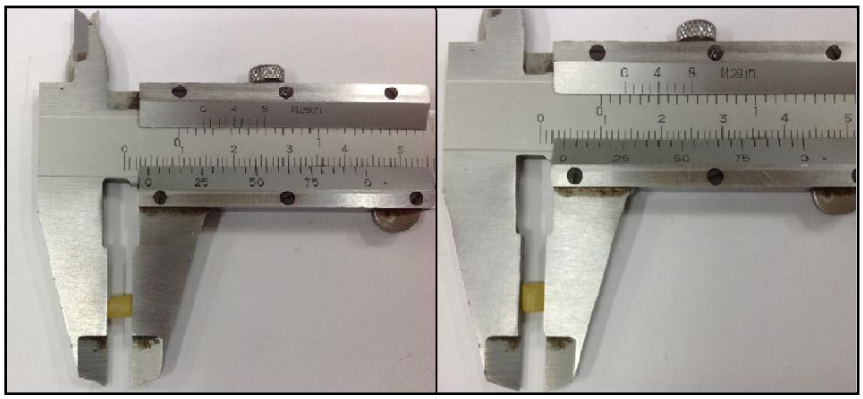

Fig. 7 Dimension of Cubic Zirconia gemstone [1].

Experimental procedure:

1) Open program then setting home position of X and Z-axis.
2) Input all parameters into the developed software as shown in Fig. 8 including the grinding steps are shown in Fig. 9.

3) Use pre-shaped gemstones, set the appropriate parameters as above for gem polishing process.

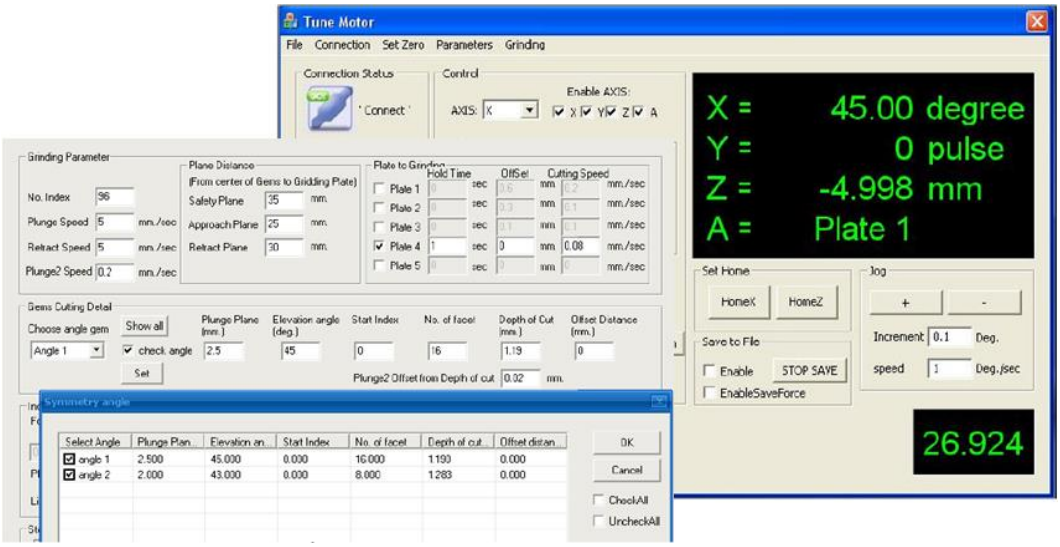

Fig. 8 CUGrinding program.

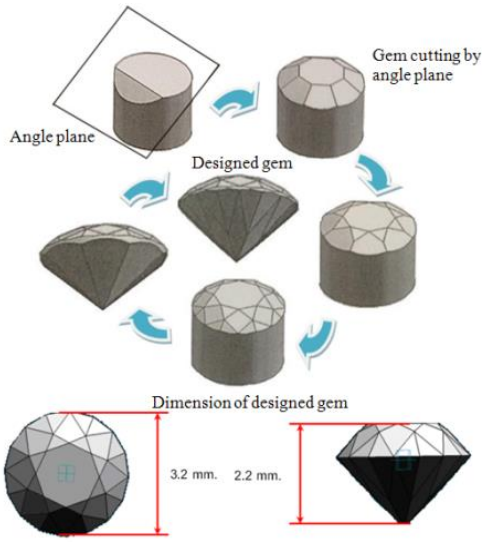

Fig. 9 The steps of gem grinding.

Experimental result

After gem polishing step, we get the experimental result as shown in Table 1 and Table 2.

Table. 1 Indirect force Status, average and maximum increment of reference position of gem polishing on crown side.

Elevation angle	Avg additional position	Max additional position	Status	Elevation angle	Avg additional position	Max additional position	Status
degree	millimeter	millimeter	On/Off	degree	millimeter	millimeter	On/Off
Crown side				42	0.00	0.00	Off
47	0.00	0.00	Off	42	0.00	0.00	Off
47	0.03	0.04	On	42	0.02	0.03	On
47	0.03	0.04	On	42	0.03	0.04	On
47	0.02	0.03	On	42	0.03	0.04	On
47	0.03	0.04	On	42	0.03	0.04	On
47	0.02	0.03	On	42	0.03	0.04	On
47	0.02	0.03	On	42	0.02	0.03	On
47	0.03	0.04	On	27	0.05	0.06	On
47	0.03	0.04	On	27	0.05	0.06	On
47	0.03	0.04	On	27	0.06	0.06	On
47	0.02	0.03	On	27	0.06	0.06	On
47	0.02	0.03	On	27	0.05	0.06	On
47	0.02	0.03	On	27	0.06	0.06	On
47	0.03	0.04	On	27	0.05	0.06	On
47	0.02	0.03	On	27	0.06	0.06	On
47	0.02	0.03	On	0	0.00	0.00	Off

Table. 2 Indirect force Status, average and maximum increment of reference position of gem polishing on pavilion side.

Elevation angle	Avg additional position	Max additional position	Status	Elevation angle	Avg additional position	Max additional position	Status
degree	millimeter	millimeter	On/Off	degree	millimeter	millimeter	On/Off
Pavilion side							
45	0.00	0.00	Off	45	0.00	0.00	Off
45	0.00	0.00	Off	45	0.00	0.00	Off
45	0.00	0.00	Off	45	0.00	0.00	Off
45	0.00	0.00	Off	45	0.00	0.00	Off
45	0.00	0.00	Off	43	0.00	0.00	Off
45	0.00	0.00	Off	43	0.00	0.00	Off
45	0.00	0.00	Off	43	0.00	0.00	Off
45	0.00	0.00	Off	43	0.00	0.00	Off
45	0.00	0.00	Off	43	0.00	0.00	Off
45	0.00	0.00	Off	43	0.00	0.00	Off
45	0.00	0.00	Off	43	0.00	0.00	Off
45	0.00	0.00	Off	43	0.00	0.00	Off

From the table 1 and 2, the average of the additional reference position is approximately 0.02 mm and the average of the maximum additional position is approximate equal to the average of the additional reference position which is 0.02 mm.

Summary

This paper is a development of the Automatic Faceting Machine for indirect force control with compliance method based on PID motion control. Then all appropriate parameters, obtain from experiment, are used input in the gem polishing process. The average error, from the desired reference position, is 0.02 mm can be obtained. This error is acceptable in the real grinding and polishing process of gemstone application as shown in Fig. 10. The experiment results confirm validity and effectiveness of the developed framework.

Fig. 10 Experimental gems.

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