Surface Finish Improvement of Medium-Sized Mold Steel Using an Innovative Sphere-Like Polishing Tool with Force Control

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ABSTRACT

The aim of this study is to develop an innovative sphere-like polishing tool, which applied on a machining center, to improve the surface finish of medium sized STAVAX plastic mould stainless steel. A polishing wheel as the polishing tool was driven in two rotational axes to generate movement like spherical polishing. The STAVAX specimen was burnished using ball burnishing process as a pre-surface finish improvement. Then, the polishing process using the innovative sphere-like polishing tool was conducted as the further improvement. The polishing processes with force control and without force control were investigated. A sliding control methodology was applied to the force control of the polishing process. Based on the comparison of both of polishing processes, it was shown that the polishing process with force control had better surface finish uniformity. It was proved not only by the visual inspection but also by the statistical analysis because the polishing process with force control had smaller variance value than without force control.

Keywords: innovative sphere-like polishing tool, sliding control methodology.
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1 INTRODUCTION

In recent decades, plastic has increasingly been used to replace metallic components due to its good properties such as resistance to corrosion and chemicals, low density, low cost, good insulator and easy to manufacture. Most of plastic components are manufactured through forming and shaping processes such as extrusion, injection molding, blowing, casting, and thermoforming processes. Hence, moulds play an important role in the plastic components manufacture. A mould must have some properties such as corrosion resistance, wear resistance, high toughness, high hardness, and good surface finish. STAVAX plastic mould stainless steel is one of the mould materials that can meet the requirements. To improve the surface finish of the plastic mould stainless steel, some processes such as grinding, lapping, burnishing and polishing are usually applied.

Some studies have been carried out about surface finish improvement of mould. Some researches have proposed the optimal parameters of the ball burnishing process using a tungsten carbide ball or a roller [4], [6], [7], [9]. The improvements of the surface roughness using these burnishing processes were in between 40% and 90%. Furthermore, the surface finish of moulds made from steel or glass were successfully improved between 66% and 98% by polishing process [2], [14]. Moreover, sequential ball grinding, ball burnishing and ball polishing processes have been successfully accomplished to improve mould surface finish [10]. Some main polishing parameters such as polishing time, spindle speed, feed rate, stepover, depth of penetration, slurry concentration, and abrasive size have been identified to optimize the mould surface quality [5], [10]. Like these main polishing parameters, the polishing force also plays an important role in the surface improvement [5], [3], [8].

Although some research is available on the polishing process, no research has been done in multi rotational axis of polishing tool. Therefore, the aim of this study is mainly to develop an innovative sphere-like polishing tool that can provide multi rotational axis to meet the requirement of multi directional flow of abrasive slurry since it is required to optimize the surface finish improvement [12]. Moreover, a comparison between with and without force controls of polishing process using this innovative tool will be presented. A sliding control methodology will be applied in this study to obtain a robust controller [11].

2 DESIGN OF AN INNOVATIVE SPHERE-LIKE POLISHING TOOL

To provide multi directional abrasive material flow between polishing tool and workpiece, a polishing wheel instead of a polishing ball is used for design of an innovative sphere-like polishing tool. The polishing wheel is driven in two rotational axes. The first rotation denoted procession is driven by the spindle rotation of a machining center, and another one denoted spinning is driven by an additional motor using toothed belts and bevel gears transmissions. Fig. 1(a). and Fig. 1(b). show the setup of the innovative sphere-like polishing tool on the machining center.

3 EXPERIMENTAL SETUP

The experiment of polishing process using the innovative sphere-like polishing tool was conducted on the machining center MV-3A. The polishing tool was mounted on the spindle of machining center, while the additional motor was hung near the spindle. The additional motor speed was adjusted using motor control. To measure the polishing force subjected by the polishing tool, a single axis load cell was clamp on the table of machining center. Using an assumption that the workpiece placed above the load cell is very rigid, the polishing force subjected on the workpiece can be measured by the load cell without any losses. As in general polishing-process, aluminum oxide (Al_2O_3) was used in this study as abrasive slurry material. It is very corrosive material. As a result, in order to protect the machining center from corrosion, an abrasive slurry container was used and placed between workpiece and the load cell. Moreover, the abrasive slurry was circulated from a slurry reservoir to the slurry container using submersible pump.

A computer was used to control tool path of the polishing tool. It sent x, y, and z axes data to the machining center. The x and y axes of the polishing processes with and without force control were generated by CAM software. The z axis of the polishing process without force control was also generated by CAM software, while the z axis of the polishing process with force control was generated

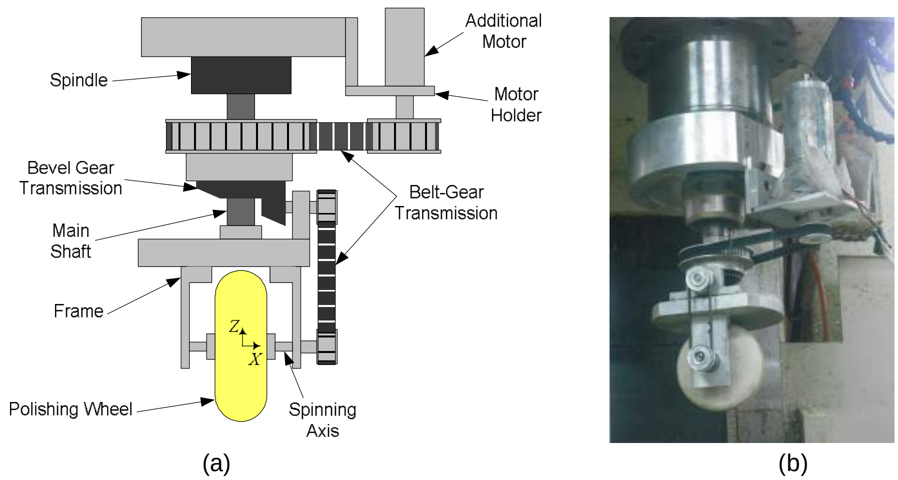


Fig. 1: The innovative sphere-like polishing tool setup: (a) schematic illustration, (b) polishing tool fabrication on the machining center.

based on the measured polishing force by the controller program in the computer. This controller had feedback from the load cell signal through interfacing system such as amplifier and Analog to Digital Converter (ADC). Fig. 2 shows the experimental setup of the polishing process using the innovative sphere-like polishing tool.

4 CONTROL METHODOLOGY

4.1 Model of the Polishing Process

The polishing process using the innovative sphere-like polishing tool is modeled as a single degree of freedom of mass-spring-damping system shown in Fig. 3.

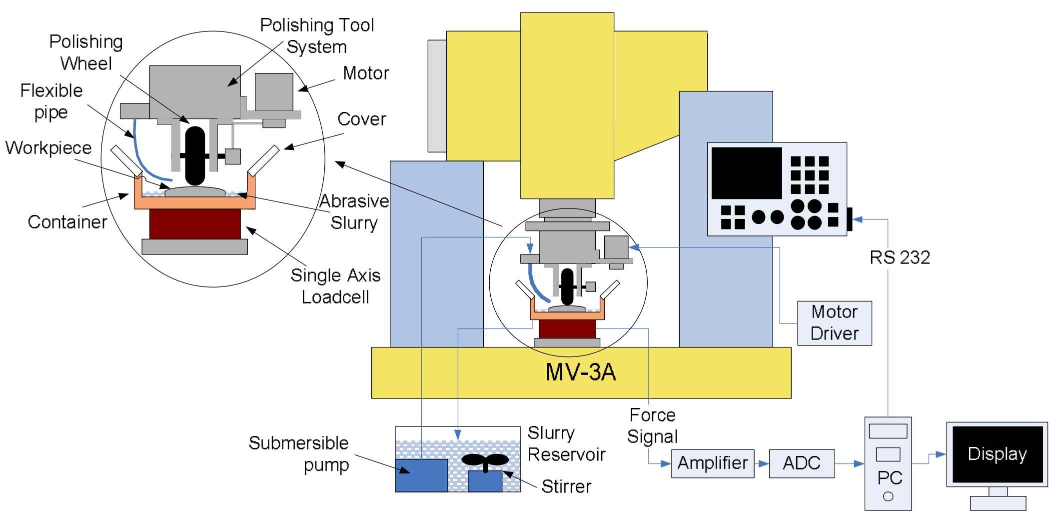


Fig. 2: The experimental setup of the polishing process using the innovative sphere-like polishing tool.

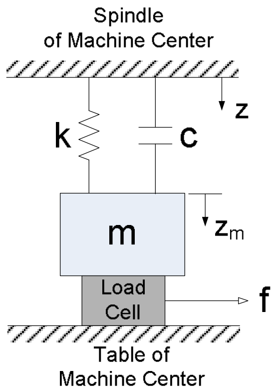


Fig. 3: The model of the polishing process.

The variables shown in Fig. 3 are described as follows:

- k: the stiffness of the polishing tool system,
- c: the damping of the polishing tool system,
- m: the mass of the workpiece, the container, and some abrasive slurry,
- z_m: the displacement of the workpiece,
- z: the z-axis input of machine center,
- f: the load cell output as the polishing force representative.

Based on the model, the polishing process is written as equations below:

$$\begin{aligned} m\ddot{z}_m &= -c(\dot{z}_m - \dot{z}) - k(z_m - z) \\ f &= Az_m \end{aligned} \tag{4.1}$$

Because z axis was used as control variable, the z variable in Eqn. (4.1) was considered as a control law, u. Then Eqn. (4.1) is transformed to the x variable shown below:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\frac{c}{m}x_2 + A\frac{c}{m}f_r - \frac{k}{m}x_1 + A\frac{k}{m}u \end{aligned} \tag{4.2}$$

where $x_1 = f = Az_m$, f_r is feed rate of the polishing process, and A is load cell transfer function. The complete derivation of Eqn. (4.2) has been reported in [15].

4.2 Design of Controller

Based on the Eqn. (4.2)., the control law was obtained. A sliding control methodology was applied in this study. The aim of the sliding control is to make the dependent variable, x(t), achieve the desired value, $x_d(t)$, through a sliding surface. The sliding surface for second order system is written in Eqn. (4.3)..

$$s = \dot{e} + \lambda e = 0 \tag{4.3}$$

where $e = x - x_d$ and λ is a positive constant. To obtain the control law equation, Eqn. (4.3). is derived as follows:

$$\dot{s} = \ddot{e} + \lambda\dot{e} = 0 \tag{4.4}$$

$$(\ddot{x}_1 - \ddot{x}_d) + \lambda\dot{e} = 0 \tag{4.5}$$

$$(\dot{x}_2 - \ddot{x}_d) + \lambda\dot{e} = 0 \tag{4.6}$$

$$\left[\left(-\frac{c}{m}x_2 + A\frac{c}{m}f_r - \frac{k}{m}x_1 + A\frac{k}{m}u\right) - \ddot{x}_d\right] + \lambda\dot{e} = 0 \tag{4.7}$$

$$u = \frac{c}{Ak}x_2 + \frac{1}{A}x_1 + \frac{m}{Ak}\ddot{x}_d - \frac{m}{Ak}\lambda\dot{e} - \frac{c}{k}f_r \tag{4.8}$$

To make this controller more robust to disturbances, Eqn. (4.8). is augmented as follows:

$$u = \frac{c}{Ak}x_2 + \frac{1}{A}x_1 + \frac{m}{Ak}\ddot{x}_d - \frac{m}{Ak}\lambda\dot{e} - \frac{c}{k}f_r - \eta\,\mathrm{sgn}(s) \tag{4.9}$$

where η is positive constant and sgn is signum function. The stability analysis and the simulations of this controller have been reported in [15].

5 EXPERIMENTAL WORK AND RESULT

5.1 Material of the Workpiece

In this study, STAVAX stainless mould steel, which has good properties such as corrosive resistance, good polishability, wear resistance, good machinability, and good stability in hardening, was used. It can be applied to all types of moulds, is especially suited for larger tools where corrosion in production is unacceptable and where high surface finish is required. Tab. 1. shows the chemical composition of the STAVAX stainless mould steel [13]. The hardness of this material is about HRC 52 after hardened and tempered. The ground surface roughness of the workpiece was about Ra 0.345 μm. The surface roughness measuring equipment was put in the metrology laboratory with temperature control at 20 ± 0.3ºC. Then the optimal ball burnishing process was applied on the workpiece as a pre-surface finish improvement. The parameters of the optimal ball burnishing process are shown in Tab. 2.. The ball burnishing process was applied on two zones. Every zone had dimension of 30 mm x 70 mm. The surface roughness after ball burnishing process was about Ra 0.282 μm.

5.2 Polishing Process on the STAVAX Stainless Mould Steel

After conducting ball burnishing process, one of burnished zone would be subjected to the polishing process without force control and another one would be subjected to the polishing process with force control. Every polishing process had same parameters. The dimension of every polishing zone was 30 mm x 60 mm. Tab. 3 shows the parameters applied to the polishing process.

The zigzag tool path was generated by CAM software. The 3D drawing of workpiece with two polishing zones shown in Fig. 4(a) was firstly developed. Then machining process using zigzag tool path was designed and simulated on every polishing zone. Every polishing process using the innovative sphere-like polishing tool was simulated as facing process using end mill cutting tool shown in Fig. 4(b).. After the simulations were run, the zigzag tool path NC code on both polishing zones was generated.

Component	Percentage
C	0.38 %
Si	0.9 %
Mn	0.5 %
Cr	13.6 %
V	0.3 %

Tab. 1: The chemical composition of the STAVAX stainless mould steel.

Parameters	Levels
Ball material	Tungsten carbide
Lubricant	Grease
Burnishing force	400 N
Feed rate	400 mm/min
Feed step	60 μm

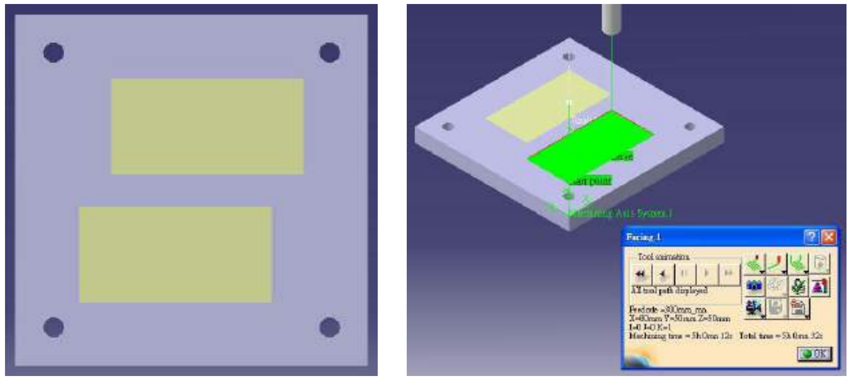
Tab. 2: The parameters of ball burnishing process.

Parameters	Values
Tool path	Zigzag
Procession speed	400 rpm
Spinning speed	700 rpm
Feed rate	300 mm/min
Feed step	0.02 mm
Depth of penetration	20 μm
Abrasive size	0.3 μm
Slurry concentration	1:30

Tab. 3: The parameters of polishing process.

5.3 Setpoint of the Polishing Force

For conducting the polishing process with force control, a force setpoint was required. To obtain the force setpoint, a polishing experiment using parameters shown in Tab. 3 was conducted. Then, its polishing force was measured and recorded. The measurement result of this experiment is shown in Fig. 5.. It can be shown in Fig. 5 that the polishing force measurement was fluctuated. This fluctuation was caused by roundness and eccentricity error of the polishing wheel. It cannot be avoided because the precision polishing wheel is very difficult to be fabricated. Therefore, the polishing force setpoint was determined by the average value of measured force under the parameters shown in Tab. 3.. It was about 0.952 N.



(a) (b)

Fig. 4: Generation of the polishing tool path: (a) development of 3D workpiece drawing, (b) the machining process simulation.

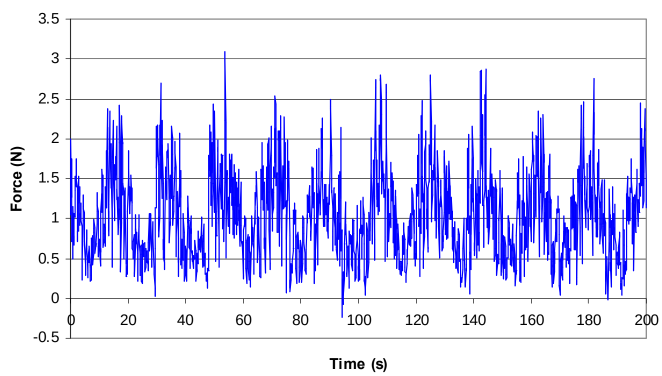


Fig. 5: Measurement of the polishing force.

5.4 Experimental Result

Fig. 6 shows the polishing result with and without force controls. It is seen in Fig. 6(a). that the surface roughness of the polishing process without force control was not uniform. Some places were under-polishing. Therefore, the surfaces in those places were not shinny enough. Otherwise, the result of the polishing process with force control shown in Fig. 6(b). was uniform on the entire zone. Tab. 4. shows the surface roughness comparison of the polishing results between with and without force controls.

Based on statistical analysis, it is also shown that the surface roughness results have been obtained from different uniformity of zones because they have different variance values. To check whether both of variance values have a significant difference or not, the variance test for two samples described by [1] was used. The hypotheses used in this analysis were

- H_0: $\sigma_1^2 = \sigma_2^2$ as null hypothesis
- H_1: $\sigma_1^2 > \sigma_2^2$ as alternative hypothesis

The null hypothesis will be rejected if the F value is larger that $F(\alpha,\nu_1,\nu_2)$. It was used 95% confidence level. Hence, the significant level, α, was equal to 0.05. The degree of freedoms, ν_1 and ν_2, obtained from sample size minus one were equal to 11 because the same sample sizes were used. The $F(\alpha,\nu_1,\nu_2)$ was obtained form F distribution table while the F value of this analysis was:

$$F = \frac{s_1^2}{s_2^2} \tag{5.1}$$

$$F = \frac{0.003}{0.001} = 3 \tag{5.2}$$

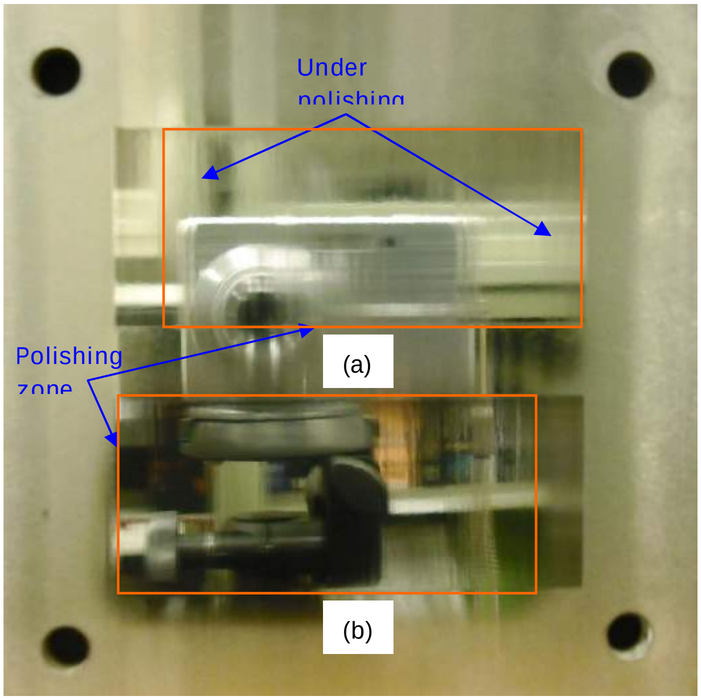


Fig. 6: The polishing result: (a) without force control, (b) with force control.

Without Force Control [Ra]	With Force Control [Ra]
0.19 μm	0.16 μm
0.17 μm	0.14 μm
0.18 μm	0.18 μm
0.18 μm	0.16 μm
0.16 μm	0.20 μm
0.26 μm	0.20 μm
0.20 μm	0.16 μm
0.14 μm	0.14 μm
0.16 μm	0.18 μm
0.32 μm	0.22 μm
0.18 μm	0.18 μm

0.27 μm	0.16 μm
Average: $\bar{x}_1$ = 0.201 μm	Average: $\bar{x}_2$ = 0.173 μm
Variance: s_1^2 = 0.003 μm²	Variance: s_2^2 = 0.001 μm²

Tab. 4: The polishing result comparison.

Because F value in Eqn. (5.2) was larger than F(0.05,11,11) = 2.82, the null hypothesis was rejected. Therefore, it was stated that the variance of the polishing process without force control was significantly larger than the variance of the polishing process with force control. Furthermore, it was stated that the uniformity of the polishing process with force control was significantly better.

6 CONCLUSION

An innovative sphere-like polishing tool, applied on a machining center, has been developed to improve the medium-sized surface finish of the hardened and tempered STAVAX plastic mold stainless steel. To perform the polishing process, the x and the y positions of polishing tool can be generated by CAM software. Moreover, its z position has to be adjusted using a control system consist of a load cell, an interfacing system, and a computer as a controller to provide uniform polishing force subjected on the workpiece. Furthermore, the uniformity of surface roughness can be achieved.

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