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Development of precision polishing machine based on parallel-kinematic system.

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Abstract

Increasing demand on mass production of high precision functional surfaces (curved or freeform) has pushed the development of relatively low cost and high precision surface finishing processes for mould manufacturing. For some applications such as small optical lenses, the existing bonnet polishing (BP) process has limitation in polishing the inner surfaces of moulds due to tool head size and generation of mid-spatial frequency errors.

In this paper, a novel precision polishing machine suitable for polishing inner surface of mould was developed based on a parallel-kinematic precision positioning system (PI Hexapod H840.D2). The hexapod was held in a machine frame, which allows precision movement in 6 degrees of freedom. An air bearing, electrically driven spindle (speed range from 500 rpm to 8000 rpm) was mounted to the Hexapod to drive the polishing tool. A rubber bonnet tool with a polyurethane pad was used to engage the part surface. In order to test the performance of this prototype machine, the machine was used to polish flat surfaces of P20 steel alloy which is widely used to manufacture plastic injection moulds. All polishing processes were carried out using diamond paste with particle size of 3 µm. Pre-polishing results showed that the feed rate of the hexapod, spindle rotating speed, tool offset and number of polishing passes are the main factors affecting the polished surface quality. A Taguchi approach was used to study the influence of these four main polishing parameters on the machined surface. After optimisation of the processing parameters, the polishing machine can consistently achieve ≤ 10 nm surface roughness Ra.

Keywords: Bonnet polishing, Hexapod, Taguchi approach, mould polishing

1. Introduction

Precision polished parts are often evaluated by two capabilities which are surface roughness and form accuracy. Both of them have a direct relation to parts life duration and performance. There are several precision manufacturing methods available on market. They all have their own advantages and disadvantages in terms of precision, machinability, production time and tool accessibility. The BP process is a well-established precision polishing process. It has the ability to obtain sub-nanometre surface roughness on hard and brittle materials and it can correct form errors in microns range. Moreover it can reduce mid-spatial frequency errors created by machining process which are undesirable on surfaces where the light is scattered due to these errors. However available BP machines and processes are expensive, time consuming and not adapted for parts with small curved/freeform surfaces. Therefore a new concept of precision BP machine is developed with emphasis on the issues identified above. In the present paper only the surface roughness capacity of the developed machine is reported. P20 high hard tool steel is polished to evaluate the designed machine capacity to produce precision surface roughness. Further a Taguchi method is used to identify the optimum polishing conditions to consistently obtain nano-scale surface roughness.

2. Machine Design

Based on precision machine design methodology a new bonnet polishing machine (Figure 1) has been developed [1]. The design is simple, low cost and easy to assemble. Further, it has free access for machine cleaning to avoid different particle size contaminations. Each element of the machine is chosen to fulfil a specific function. The hexapod provides the precision movement in 6 degrees of freedom. A hexapod was chosen over serial kinematic stages mainly for its stiffness. The minimum incremental movement is within 3 µm in all axes. The Nakanishi EMR-3008K spindle produces controlled rotational speed with less than 1 µm run out. It has an air bearing system which allows a long cycle run with minimal thermal expansion. The tool is made out of a 6 mm diameter steel rod of 80 mm length. It has a 10 mm diameter disc of 5 mm thick on the end (Figure 2). On the top of the disc, a 10 mm radius soft rubber pad is glued with a polyurethane pad glued on the top of it. Other parts are designed and manufactured to obtain full functionality of the machine. The overall machine has been designed to be stiff enough to overcome the internal and external vibration and distortion. Additional room is left above the hexapod holding plate for controllers (hexapod and spindle). Places below the machine base plate are used to implement a slurry tank.

Furthermore the framework has been subjected to an FEA analysis to identify any unwanted stresses or displacement. In order to simplify the simulation only the frame with hexapod holding plate is designed. To assimilate the reality initial conditions are applied. The bottom of the model is selected to be a fixed geometry and a pressure of 50 N/m^2 is applied on the hexapod mounting plate. The applied load is largely higher than expected force of polishing. The stress analysis shows a maximum stress of 257 N/m^2, however the overall structure is subject to minimal distortion stresses (Figure 3). The displacement results show the maximum displacement to be in the middle of the cross frame. The extent of the displacement is less than 0.5 µm. Based on this analysis it could be concluded that the designed structure frame is stiff enough for purpose.

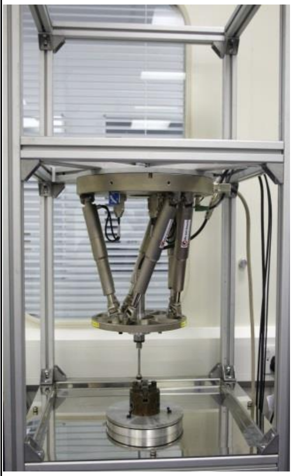

Figure 1: Hexapod based BP machine.

Figure 2: Polishing tool.

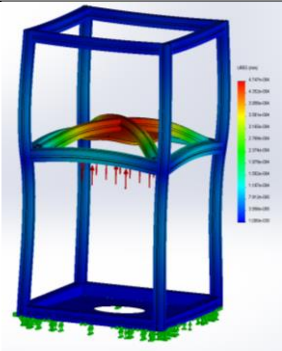

Figure 3: Machine frame structure FEA Analysis.

3. Experimental setup

The prototype machine needs testing to identify its capacity as a polishing machine. This experiment focuses on its capability to achieve precision optimum surface roughness. P20 high hard tool steel is a commonly used material in plastic injection moulds and die-casting due to its good material stability. The material was delivered in the pre-hardened condition at around 300 HB. It has good machinability and homogeneous microstructure. P20 steel of 30 mm diameter is cut and ground to similar lengths. Further they are hand polished using SiC abrasive papers grit up to 400 to give a base line roughness. The surface roughness Ra is around 30 nm at this stage.

On the designed machine four parameters are identified which have an impact on surface finish. These are feed rate (mm/min) of the hexapod, rotational speed (rpm) of the spindle, tool offset (mm) and the number of passes. To identify the optimised condition of these parameters, a Taguchi approach is used. Zeng, Blunt et al, have used this approach to optimise BP polishing of artificial CoCr knee implants and routinely obtained surface roughness of 7 nm Sa [2]. The parameters evaluated using Taguchi are chosen from those which have high influences on the polishing process. A standard orthogonal array L9 (3^4) was chosen for the experiment table 2. The levels of each parameter are chosen from literature review on the achievement of precision surface roughness using BP processes. All other parameters are fixed and given in table 1. A raster scanning approach is used to polish these samples. Each sample is measured before and after polishing using a Dektak XT stylus profiler. Five measures are taken over the surface with one in the middle and four others around the edges. Approximately the same location is used during measurement to increase the validity of the experiment. The measurement length is 4.8 mm long using a Gaussian regression filter with standard cut-off (0.8 mm); in order to show mid spatial frequencies.

Table 1: Fixed polishing parameters

Tool angle	0 degrees
Step change	0.5 mm
Bonnet type	Hy57 polyurethane polishing pad
Bonnet radius	10 mm
Slurry	1 µm diamond paste

Table 2: Taguchi experimental setup

	Feed Rate (mm/min)	Speed (rpm)	Offset (mm)	No of Passes
Sample 1	15	500	0.2	8
Sample 2	15	700	0.25	12
Sample 3	15	1000	0.3	16
Sample 4	20	500	0.25	16
Sample 5	20	700	0.3	8
Sample 6	20	1000	0.2	12
Sample 7	25	500	0.3	12
Sample 8	25	700	0.2	16
Sample 9	25	1000	0.25	8

4. Result Analysis

The software Minitab is used on the analysis of the experimental results. Experimental parameters and the results are input in the software. The output is given on a chart in the form of signal to noise ratio (S/N). Figure 4 shows the impact of each factor with their given parameters. Higher S/N ratio indicates the optimum condition and also provides information on the factor level of influence on the polishing processes. The rotational speed of the spindle has the highest impact on the improvement of the surface roughness followed by the tool offset. This is then followed by number of passes and finally the feed rate. The chart also shows the level which has the higher S/N ratio. Table 3 indicates the optimum polishing conditions based on their S/N ratio. Samples polished with the optimum polishing conditions and their results are given in table 3.

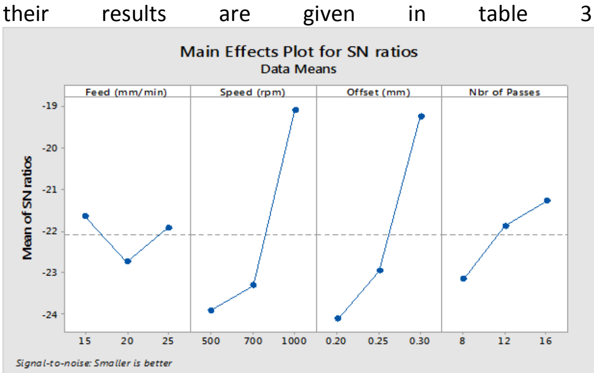

Figure 4: Main effects plot for S/N ratio.

Table 3: Optimum polishing condition

Feed Rate	Speed	Offset	No of Passes
15	1000	0.3	16
Ra from 25.5 nm to 5.6 nm: 78% Improvement			
Ra from 40.4 nm to 7.8 nm: 81% Improvement			

5. Conclusion

A surface roughness Ra of 5.6 nm from 25.5 nm or 7.8 nm from 40.4 nm is obtained over a 30 mm^2 areas. This shows the ability of the designed hexapod polisher to achieve precision surface roughness on hard steel. Both samples have different result for same parameters due to the initial condition of the surfaces. Therefore a prolonged number of passes i.e. polishing time could further improve the surface roughness.

References

[1] Slocum, A. H. (1992). Precision machine design. Society of Manufacturing Engineers

[2] Zeng, S. Y., Blunt, L., & Jiang, X. Q. (2012). The application of Taguchi approach to optimise the processing conditions on bonnet polishing of CoCr. In Key Engineering Materials (Vol. 496, pp. 235-240). Trans Tech Publications.