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## Development of precision polishing machine based on hexapod.

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### Abstract

Increasing demand on mass production of high precision parts, has pushed the precision manufacturing industry to develop relatively low cost, reliable precision finishing processes to meet market requirements. A gap within the provision of low cost polishing processes has been identified; namely parts with a radius of curvature less than 10mm will be increasingly present in new mass produced products, yet such parts cannot be efficiently polished with existing bonnet polishing (BP) process due to tool head size and the tool holder being bigger than the part radius. Moreover in some applications such as optical lenses the mid-spacial frequencies errors present in the surface severely affects the optical performance of the lenses. Therefore, bonnet polishing with physical contact is more appropriate process for these types of surfaces.

A novel low cost precision polishing machine is presented in the present paper. The machine is a form of bonnet polishing. The machine is composed of a Hexapod H840.D2 (PhysikInstruments) which allows precision movement in 6 degrees of freedom held in a machine frame. An air bearing, electrically driven spindle (speed range from 500rpm to 8000rpm) is mounted to the Hexapod to drive the polishing tool. A rubber bonnet tool with polyurethane pad is used to engage the part surface. In order to test the performance of this prototyped 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 sizes of 3 $\mu$ m. 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. Moreover, the Taguchi approach was used to investigate the four polishing parameters. The optimisation of the parameters allows the polishing machine to consistently achieve  $\geq 10$  nm surface roughness Sa.

Keywords: Bonnet polishing, Hexapod, Taguchi approach, P20 mold steel 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 with the parts life duration and its 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- spacial frequency errors created by machining process which are undesirable on optical 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.

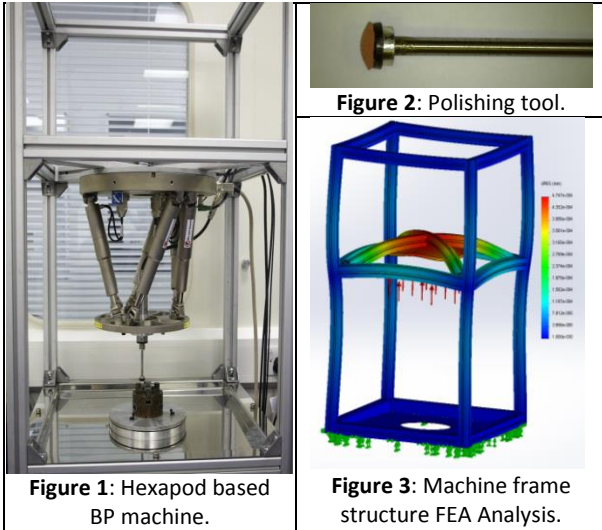
### 2. Machine Design

Based on precision machine design methodology [1], a new bonnet polishing machine has been developed (Figure 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 elements of the machine

is chosen to fulfil a specific function. The hexapod provides the precision movement in 6degrees of freedom. A hexapod was chosen over serial kinematic stages mainly for its stiffness. The minimum incremental movement is within 3 $\mu$ m in all axes. The Nakanishi EMR-3008K spindle produces controlled rotational speed with less than 1 $\mu$ m runout. It has an air bearing system which allows a long cycle run with minimal thermal expansion. The tool is made out of a 6mm diameter rod of 80mm length. It has a 10mm diameter disc of 5mm thick on the end (Figure 2). On the top of the disc, a 10mm 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 will be used to implement the slurry tank.

Furthermore the framework has been subjected to an FEA analysis to identify any unwanted stresses or displacement on the model. 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 50N/m<sup>2</sup> 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 257N/m<sup>2</sup>, however the overall structure is subject to minimal distortion stresses (Figure 3). The displacement results shows the maximum displacement to be in the middle of the cross frame. The amount of the displacement is less than 0.5 $\mu$ m. Based on these analyses it could be

concluded that the designed structure frame is stiff enough for purpose.



### 3. Experimental setup

The prototyped 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 for 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 30mm 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 30nm 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. Shengyue, Blunt et al, have used this approach to optimise BP polishing of artificial CoCr knee implants and routinely obtained surface roughness of 7nm Sa [2]. The parameters evaluated using Taguchi are chosen from those which has high influences on the polishing process. Standard orthogonal array L9 (3<sup>4</sup>) was chosen for the experiment table1. 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 2. A raster scanning approach is used to polish these samples. Each sample is measured before and after polishing using the 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 measures to increase the validity of the experiment. The measurement length is 4.8mm long using Gaussian regression filter with standard cut-off (0.8mm); to show mid spatial frequencies.

**Table 1:** Fixed polishing parameters

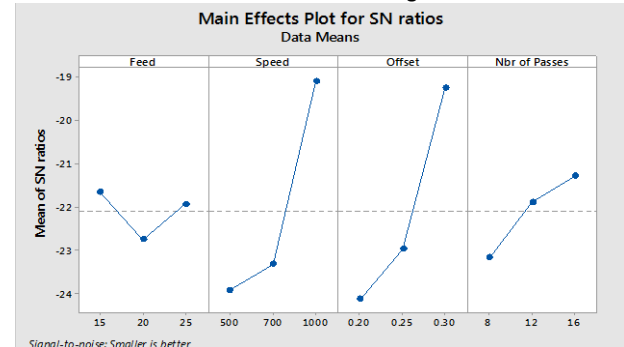
Tool angle	0 degrees
Step change	0.5mm
Bonnet type	Hy57 polyurethane polishing pad
Bonnet radius	10mm
Slurry	1 µm diamond paste

**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 condition 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
Surface Roughness Ra from 25.5 to 5.6nm: 78% Improvement			
Surface Roughness Ra from 40.4 to 7.8nm: 81% Improvement			

### 5. Conclusion

A surface roughness Ra of 5.6nm from 25.5nm or 7.8nm from 40.4nm is obtained over a 30mm<sup>2</sup> 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

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- [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.