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Corrective Abrasive Finishing Processes for Freeform Surface

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Abstract. Traditionally, abrasive finishing process focus on producing excellent surface finish on regular form shapes. Ever increasing demands in freeform features in aerospace, energy and medicine industry requires abrasive finishing technology not only provides excellent surface finish but also is capable to correct the errors on freeform surfaces. The paper presents current development of corrective finishing technology for freeform surface.

Introduction

A decade ago, R. Komanduri [1] and his colleague published a paper in summarise the technical development in fine abrasive processing. By convention, polishing was meant to imply best finish without regard for shape or form accuracy, e.g., in the preparation of metallurgical samples where the objective is to remove the scratches so that microstructure can be observed after etching. It is also used for removing the damage, such as microcracks, voids, etc., caused by the previous manufacturing operation, such as grinding. Conventional lapping in contrast is used not for finish but for form accuracy, such as flatness in the case of flat objects or sphericity in the case of balls. The term honing is used, similar to lapping, for form and shape accuracy and for generating the topography to 'trap' the lubricant. Finishing is a general term used to describe any or all of these processes. Traditionally, for a precision component, grinding will provide good size and form accuracy and polishing will improve the surface finish to the highest standard. However due to the tools used in polish have relatively low stiffness and a long polish process may loss the form and size accuracy. Therefore a manual corrective polishing is sometimes required.

As the advances of abrasive technology, the form accuracy becomes increasingly important to the ever demanding market. Technique advances in CNC machine tools enable a polishing process to become a good choice for form error correction, particularly for the components with tight tolerance of from accuracy and surface roughness. This means a surface with excellent form accuracy and surface finish can be achieved simultaneously on just one finishing machine. This paper presents recent development in abrasive finishing technology with particularly focus on the corrective polishing for freeform surfaces.

Concept of Corrective Polishing for Freeform Surface

Components with a freeform shape can be found in a wide range of applications in aerospace, medicine and energy industry, exemplified by prothetic joints and turbine blades. Currently, a freeform component can be manufactured through machining directly or a mould insert used in a replication process such as injection moulding or pressing respectively. The machining process is considered as a critical element in a freeform generation. A simple example of direct machining for a freeform surface [2] is robotic grinding and polishing for turbine vane airfoil. It requires in situ measurement, profile mapping and tool path planning. More commonly, machining processes for freeform surface include the diamond turning with Fast Tool Servo (FTS) systems, the raster milling or grinding with a series of subsequent polishing steps. Usually free form surface is machined with a ball end milling cutter or grinding wheel in a machining centre. Conventional polishing is to produce a smooth, deformation-free, and scratch-free surface, which is bright, shiny, and mirror-like in appearance. Polishing minimizes all fine surface irregularities left over during the milling or grinding operation. As the tolerance getting tighter, sometimes a manual polishing can be the only choice. To avoid such

time and cost intensive process, many efforts were made in developing new polishing technology – namely corrective polishing. Due to high demands on the geometrical precision in corrective polishing, the form accuracy is usually achieved by iterative correction loops consisting of a machining step, a surface measurement and the generation of an adapted NC machining programme in order to compensate for the form deviation identified. As a consequence, a series of new challenges has to be addressed.

Besides the requirements on the form accuracy and surface roughness, the integrity of surface regarding the material property is of equally importance. In view of the peculiarities of the work materials (advanced ceramics, optical glasses, semiconductor materials, aerospace alloys etc.), the stringent requirements of these materials in practice, the need to remove very small amounts of material (atomic bits) to minimize or eliminate brittle fracture, the very high surface finish and form accuracy requirements, and the required surface integrity (i.e., minimal or no surface or near surface damage including metallurgical changes, residual stresses, defects such as micro-cracks and material re-deposits), it is necessary to consider the corrective abrasive finishing process as a system. Komanduri et al [1] listed 9 points of consideration for ultraprecision machining system, most of which are applicable to corrective abrasive finishing process. Here the key elements are iterated.

1. High precision, vibration-free, rigid machine tool;
2. High resolution motion control;
3. Thermal stability;
4. Feedback control;
5. High loop stiffness between the tool and the workpiece;
6. Submicron abrasives of uniform grain size bonded into a wheel or in the form of a coated abrasive or as free abrasive;
7. Suitable dressing techniques for different bonded abrasive tools;
8. Ultraprecision metrology system integrated into the machine tool but isolated from the response of the machine tool during machining;
9. High level of clean environment including temperature, vibration, humidity, and dust control.

The first 4 points are related to machine tools performance and the following three points are associated to tool preparation, albeit the point 5 is debatable for polishing, where soft polishing pads are often used.

Machine Tool Dynamics

To achieve a freeform surface error correction, the minimum control axes should be 5 axes assuming the datum of component can be aligned on the machine precisely. Due to the locating error is unavoidable, more degrees of freedom have to be controlled by introducing more control axes. Another challenge of freeform polishing is the changing mismatch between machining surface of the polishing tool and required surface of the workpiece. For easy process control, control systems with 6 or more controllable axes are commonly used to provide extra movement for the mismatch correction. Brecher et al [3] developed a double-V-parallel kinematic module with four degrees of freedom for their freeform machining research. As shown in Fig. 1 the module can run in force control mode and is capable of superimposing eccentric movements to the rotating polishing tools so as to control tool orientation correctly to the local surface normal. The unit is designed as a closed system that can be mounted on various machine tools. The base machine guides the adaptive polishing unit over the workpiece surface using three axes only; the polishing module itself provides the local movements including the angular alignment for ensuring constant process parameters.

As a part of research on the Euro50 telescope development, a Zeeko polishing machine centres was designed and manufactured for aspheric lens polishing [4,5]. The CNC control system provides synchronized control and power amplifiers for the X, Y, Z, A, B axes and the turntable rotation (C). It also provides control of the tool rotation (H axis) speed. A schematic machine structure is illustrated in figure 2. The machine is particularly suitable rotational aspheric surface polishing. It is also capable to polishing any type of freeform as long as the curvature radius of concave surface is larger than that of polishing tool. At Huddersfield, an excellent surface finish of Sa 2.8 nm was achieved in

a knee condyle section polishing automatically on a Zeeko IPR 200 machine [6]. Fig 3 is the photograph of the polished knee joint component. A unique feature of the Zeeko polishing machine is that the polish bonnet is supported by a pressurized air; so that the stiffness of the polish pad becomes controllable through air pressure.

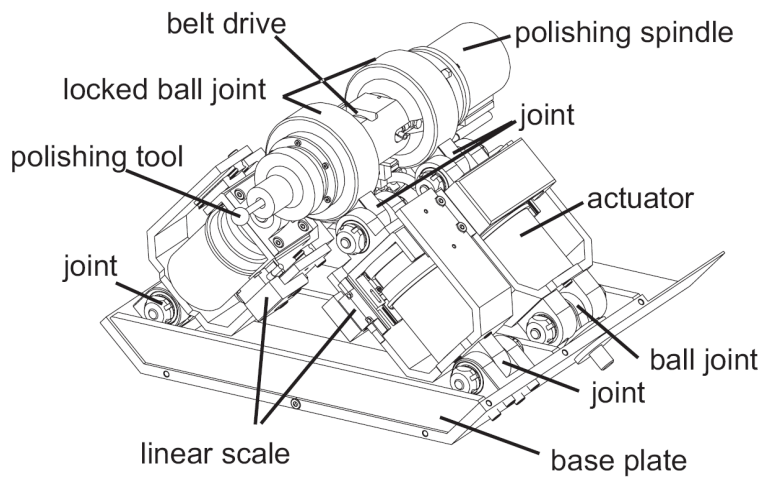


Figure 1. Four-degree-of-freedom double-V-parallel polishing unit [3]

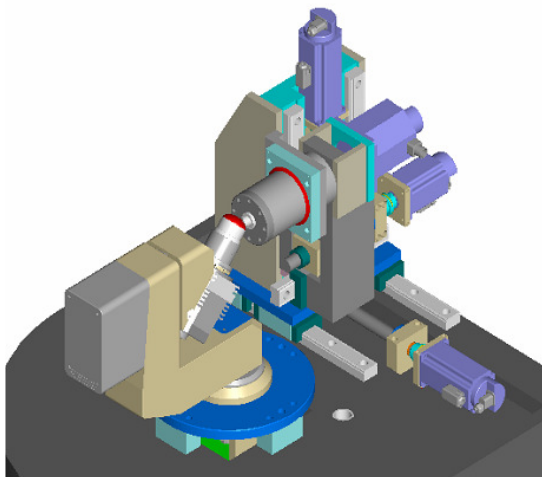


Figure 2. Zeeko machine structure [4, 5]



Figure 3. A polished knee joint component [6]

Robotic grinding and polishing is a common chamfering, deburring and finishing method for complex components [7-11]. Since a robot is capable to facilitate over 6 degrees of freedom, it is also used for freeform correction. Huang et al [2] reported their researches on turbine-vane overhaul application. The system applies a sand belt wheel as grinding and polishing media. Therefore the setup is a linear contact mechanism, which means their system is actually a 2D error compensation system. Through the path planning enabled a 3D freeform surface to be machined, many restrictions would remain. Because the abrasive grits are bonded on the sand belt, the effects of tool wear on material removal rate should be compensated. The suggested compensation methods are increasing belt speed and decreasing federate, which were found satisfactory with a certain limit within the tool life. A force feedback system was employed for the surface profile control through tool path design.

Models for Error Correction Finishing

A successful corrective polishing system should be capable to remove materials precisely according to the errors at the different positions of the component. Knowledge of material removal in finishing process is essential for error correction. Early developed models for the analysis of material removal in finishing process are Preston equation and Archard equation. According to Preston equation [12]

$$\frac{dz}{dt} = C_p p v_r \quad (1)$$

The equation presents the material removal rate dz/dt is determined by the relative velocity v_r , the polishing pressure p . The constant C_p represents the effects of other influential process parameters that are not taken into account. So, the Preston coefficient has to be determined experimentally for each single polishing system consisting of polishing tool, workpiece and polishing slurry. From tribological point of view, Archard equation predicts the abraded wear volume V_w [13].

$$V_w = K \frac{F_n s}{H} \quad (2)$$

Where F_n is the normal load, s is the sliding distance and H is the abraded workpiece surface. From Preston and Archard models, it can be seen that the material removal can be related to the normal load or pressure acting on the workpiece surface.

A true 3D polishing method being capable to correct errors was studied by Wu, Kita and Iko [14]. In this method, the polishing tool is an elastic spherical grinding wheel. Considering the micro feature correction, the real depth of cut is of significance in corrective polishing. Wu et al illustrated a good linear relationship (as shown in Fig. 4) between actual depth of cut δ and polishing parameter S_p , which defined as

$$S_p = \frac{(V + f)p}{f H_v} \quad (3)$$

Where V is polishing speed, f is feed speed, p is contacting pressure and H_v is workpiece hardness. This relationship indicates that the polishing materials removal can be controlled by contact pressure, polishing speed and feed speed. They also indicated that the pressure distribution between the tool and workpiece should be considered for form correction. For a true 3D surface error correction, pressure distribution control will be an important issue. Wu et al [14] also noticed the effects of tool orientation on the materials removal. This provides an extra route for form error correction.

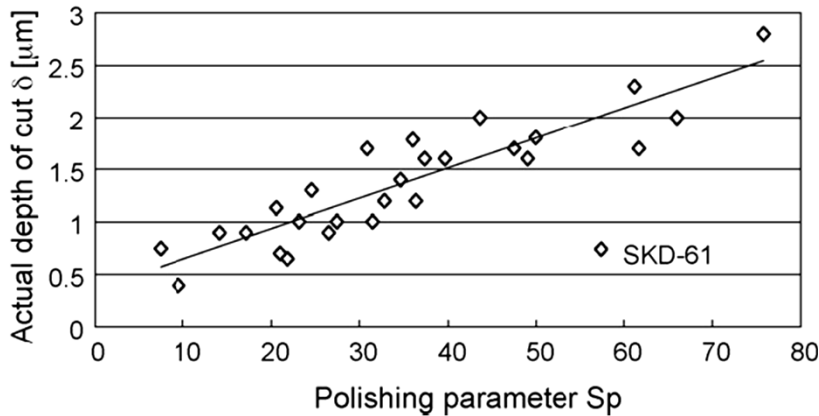


Figure 4. Polishing materials removal [14]

The pressure distribution plays an important role in the corrective finishing process. Roswell et al [15] investigated into contact stress in a polishing process. They classified the contact stress distribution into non-Hertzian circular contact and Hertzian elliptic contact, from which the relationship between polishing forces and polish pressure can be established. Based on the Hertzian contact theory, the pressure distribution will follow an elliptic distribution, where the maximum contact pressure is at the centre of the contact. The mean pressure is two thirds of the maximum pressure. The contact force F can be calculated as:

$$F = \frac{2\pi E^2 (k') \Delta^2 P_0^3}{3k} \quad (4)$$

Where k is semi-minor to semi-major axis of contact ellipse, Δ is contact parameters determined by contact geometrical features and material properties, $E(k') = \int_0^{\pi/2} \sqrt{1 - k'^2 \sin^2 \theta} d\theta$ and $k' = \sqrt{1 - k^2}$. By considering the kinetic friction coefficient μ_k , the friction torque of contact T_f is:

$$T_f = \frac{2}{9} \mu_k \pi (1 + 1/k) \left(\frac{3kF}{2\pi} \right)^{4/3} (E(k')\Delta)^{1/3} \quad (5)$$

As demonstrated in Eqs. 4 and 5, the contact stress distribution depends on the contact geometry. The constant force did not generate constant removal rate when the surface curvature changed.

For machining of precision freeform components, different data formats may be used in design, machining and metrology on their own merits. Transforming data formats from a conventional matrix based definition of single surface points into a closed polynomial description (e.g. splines) or from one polynomial description into another is accompanied with losses in precision and time intensive calculations. The machining of ultra-precision freeform components with form tolerances in the sub-micron range requires a close interaction between the machine tool, the process and the procedure for the NC tool path generation. Especially for the optical freeform machining the choice of a data-format for the surface description as well as the calculation of the tool path is crucial for the overall achievable quality of the workpiece. Thus, the consistency of the data format in describing a freeform surface geometry is essential and critical in handling metrology data, in planning the best suited tool path trajectory as well as in actively controlling the machine tool during operation. This is highly important issue for ensuring the required form accuracy as well as in enabling a highly effective and deterministic machining.

A data format based on NURBS (Non-Uniform-Rotational-B-Spline) was introduced [16, 17] in order to use it for the highly precise description of freeforms during the design, for the calculation of complex tool trajectories, for the calculation of corrective re-machining steps and for the handling in a machine control system. Some reasons for using NURBS are that they:

- offer one common mathematical form for both, standard analytical shapes (e.g. conics) and free form shapes;
- provide the flexibility to design a large variety of shapes;
- can be evaluated reasonably fast by numerically stable and accurate algorithms;
- are invariant under affine as well as perspective transformations;
- are generalizations of non-rational B-splines and non-rational and rational Bezier curves and surfaces.

A NURBS based surface is defined as follows:

$$\mathbf{S}(u, v) = \sum_{i=0}^n \sum_{j=0}^m R_{i,j}(u, v) \mathbf{P}_{i,j} \quad (6)$$

The rational basis functions

$$R_{i,j}(u, v) = \frac{N_{i,p}(u)N_{i,q}(v)w_{i,j}}{\sum_{k=0}^n \sum_{l=0}^m N_{k,p}(u)N_{l,q}(v)w_{k,l}} \quad (7)$$

are weighted p -th and q -th degree B-Spline basis functions $N_{i,p}$ with the parameters u and v . The basis functions are activated by the knot vectors

$$\mathbf{U} = \left\{ \underbrace{0, \dots, 0}_{p+1}, u_{p+1}, \dots, u_n, \underbrace{1, \dots, 1}_{p+1} \right\} \quad (8)$$

and equivalently \mathbf{V} according to u and v . There is a fixed number of active basis functions in one knot span. Hence surface modifications have only local affects. The surface lies in the convex hull of the control net consisting of the control points $\mathbf{P} = \{\mathbf{P}_{i,j}\}$. Each control point has a weight $\mathbf{w} = \{w_{i,j}\}$ representing a proportional attraction or rejection of the surface from this point.

Brecher et al [3] investigated the method for a tool path calculation based on the NURBS data format. By using the data format NURBS, the data in the data chain can be easily exchange. Furthermore, NURBS allow local tool path manipulations for the correction of local form deviations. The key issue in their methods is to minimise the distance vector between desired surface and machined surface within a limited time span. An online data processing during the trajectory calculation can reduce pre-processing time, because no data transformation is required during the process chain from start to finish with the measurement. However, due to the required high number of real time data calculations, an online machine control with NURBS is still not possible for multi axis control with a 650 MHz CPU (Central Processing Unit) system. Therefore the trajectories are stored in G-Code format for the machine and in a series of splines for the adaptive polishing module. A multi-axis movement control was realised by combining the usages of NURBS and conventional G-code. The corrective polishing process is controlled by feed rate and dwelling time calculated from error maps.

With the surface model available for error analysis, the capability of error measurement becomes next line of consideration for the freeform error corrective finishing.

Metrology requirement

The errors to be corrected in a corrective polishing are normally at the level of submicron to micron range. The prosthetic components are good examples of precision freeform surface with tight tolerances. As an example, dimensional tolerance of medical implant components can be less than 0.2 μm and surface finish requirement can be 0.05 μm for hip joints [18, 19]. For such high standard requirement, the measurement is usually carried out in situ. If the measurement has to be carried out off-line, the machine has to have a facility to enable the component to be relocated at the same position.

The requirements for medical implants can be found in the BS and ISO specifications: BS 7251-14:1998, ISO 7207-2:1998 [18, 19]. It can be noted that there are no current guidelines for the tolerances of freeform shape. The dimensional tolerances for freeform component are not stipulated in the standards. Therefore where this is the case the tolerances guidelines for hips are used or the tolerances are driven by company standards. In practice the surface metrology requirements are routinely bettered in normal manufacture i.e. the current achievable surface finish is within 5-10 nm compared to the stated 50 nm in the standards. This is due to the fact that standards are not reviewed as often as companies advance their manufacturing practises.

As the polished surface finish fall into nanometre range, local surface features have significant influence to the component performance. Traditional 2D surface measurement cannot provide sufficient information to the component manufacturers and end-users. Three-dimensional surface measurement becomes increasingly important, particularly for orthopaedic component manufacturing. Blunt and Jiang [20] compared numerous surface topographical measurement techniques and conclude:

1. In the 2D mode stylus instruments can be employed for monitoring and controlling the manufacturing process of the femoral heads though good environmental control and instrument maintenance is required. These instruments can be used for 3D measurement of the surface of the heads and acetabular cups only when the table errors can be corrected for by new digital techniques or improved translation devices.
2. The focus detection instruments can be used in manufacturing process of the femoral heads and acetabular cups when the slopes of scattering region on the bearing surface are less than standard critical angle limited by the objective numerical aperture.
3. The phase-shifting interferometers can offer the best method for 3D measurement of femoral heads due to large measurement range and nano-meter resolution.
4. AFM is ideal for description of the detail of surface structure of the femoral heads though for full characterization many measurements need to be carried out.

They recommend that contacting and non-contacting measurement should be implemented according to different analyzing requirements of the orthopaedic joint prostheses. Another important

development in surface metrology is surface characterization identification and evaluation. Jiang and Blunt [21] provide a wavelet method for the feature extraction from 3D surface measurement. These technique developments are important support to the quality improvement of corrective finishing processes.

Controllable Finishing Process and Its Control

Similar to conventional finishing process, a corrective finishing process can be influenced by a series of controllable or uncontrollable parameters. The type of abrasive, polishing cloth or pads, polishing fluid, the pressure acting between the workpiece and tools and kinematical movement are all important for the process quality and efficiency. In research of material removal mechanism, Evans et al [22] defined four components involved in a finishing process. They are the workpiece, abrasive granule, fluid and lap. The mechanism of interactions between these components is still not clear. Understanding these interactions seems critical in dealing with the changes in process input variables to productivity and part quality. This is particularly true for the development of corrective abrasive finishing technology.

Workpiece. The object of finishing is to modify the workpiece in size, shape and surface texture. Nowadays, the materials subject to finishing process are of wide spectrums, from brittle materials to ductile materials, from homogeneous single materials to composite multiphase materials. The material physical property and machinability are important influential factors to the finished surface integrity.

Abrasive Granule. The function of abrasive granules in the slurry is to mechanically remove materials from the surface of the workpiece. The granules themselves can be distinguished by a number of factors, including chemical composition, size, size distribution, shape and concentration, while the effect of each of these factors may be important or insignificant. Commonly used polishing abrasives are diamond, aluminium oxide and silicon carbide. Diamond abrasives usually produce less surface relief than other abrasives. The abrasives used for grinding are normally down to the size around 5 μm . Polishing abrasives are usually smaller than that used in grinding. For precision polishing, abrasive grit size can be submicron. Under some conditions, agglomeration of smaller particles becomes important, affecting the average size and the size distribution. In some cases, the granules fracture, changing the average particle size and shape during the polishing process. These changes will certainly influence the stability and predictability of the finishing processes, since the granule size and its distribution have great effects on material removal rate [22-26].

Fluid. The abrasives used in polishing are usually in forms of paste or abrasive powders in colloidal suspension or polishing oil, water or organic solvent (ethylene glycol, alcohol, kerosene, glycerol). The fluid phase of the slurry may be characterized by its chemical composition and by its physical properties. Chemical compositions of fluids include water and nonaqueous fluids like hydrocarbons and alcohols. The pH of the fluid may be controlled by addition of acids or bases, or by the use of a buffer system. The fluid in finishing may promote material removal by chemical reactions. Physical properties of the fluids affect both fluid dynamics and material transport in polishing. These properties include viscosity, density and thermal conductivity, all of which are pressure and temperature dependent. These properties can also be varied by changes in the chemical composition of the fluid.

Lap. In the context of material removal mechanisms, the lap imposes relative motion between the granules and the workpiece and affects slurry and swarf transport through the contact. The lap can be a plate, pad, cloth or thin film with different stiffness. The materials of lap can be metal, composite or organic materials. Stiffness, porosity, wear rate, thermal and elastic properties of the lap are of functional importance. As a general rule, a good polishing lap should: (a) hold the abrasive media; (b) have a long life; (c) not contain any foreign material, which may cause scratches; (d) have appropriate hardness/softness; and (e) be clean of any processing chemicals, which may react with workpiece.

Material removal in a finishing process is the result of interaction of these four components. Evans et al [22] summarized four hypotheses of material removal mechanism, namely, brittle crack, plastic flow, chemical dissolution and friction wear. The first two hypotheses are commonly recognized in

grinding, which are evidenced by removed chips. The friction wear hypothesis was developed in response to the lack of information provided by the chemical hypothesis regarding the influence exerted by the polishing medium. Actual polishing will proceed through a combination of material removal mechanisms, depending on the conditions in the system. To date, no one has succeeded in developing a quantifiable material removal model. Many works remains to be done. In order to guide corrective finishing control, many researchers [14, 27-29] are experimentally investigating the relationship between material removal rate and influential process parameters. The commonly considered parameters include polishing speed, feed rate, pressure between tool and workpiece, and tool type, shape and orientation.

In theory the error correction will be a straightforward job if a finishing process is deterministic. In practice, successful error correction relies on carefully planned strategy and tool path design. While investigating the hydrodynamic polishing process, Su et al [29] explained a machining principle – if the curvature effect of error profile is negligible, to obtain an arbitrary shape, the machining time distribution at the machining area should be a linear function of the desired profile. As a consequence, two machining strategies were described as machining corollaries.

(1) If the curvature effect of a desired profile is negligible and the machining zone area is infinitely small, to obtain this profile, the time distribution of tool motion should be a linear function of the profile. This corollary means to machine an arbitrary shape is simply to control the tool motion to have a time distribution similar to the desired profile.

(2) To obtain an arbitrary profile, the layer-by-layer removing strategy can be used. In each layer, the removed thickness is uniform. To do so, the tool is controlled to have a uniform machining time distribution at each grid of machining area of the layer, where the grid size is much smaller than the dimension of machining zone. Particularly, the boundary of each layer with a specific depth should be equal to the contour of the desired profile at the corresponding depth.

To satisfy the premise of the machining principle – the curvature effect of error profile is negligible, the machining spot should be very small. For most polish process, this premise is not easy to match. For time-dwell strategy, there may be two difficulties: over cutting on the boundary of machining area and overlap in tool path design. The over cutting may be moderated by reducing the diameter of tool, increasing the elastic modulus of tool, or reducing the applied load. Another possible way to reduce the depth of over-cut is to rearrange properly the machining time near the boundary. Regarding the tool path overlap design, it is important to make sure the ripples created by tool path are within the tolerance limit.

Commonly used of corrective strategies are dwelling time depending on the position of the workpiece [22, 30, 31]. This is because the material removal rate is relatively constant with increasing polishing time [27]. The longer the tool dwells, the more materials are removed. A dwell time map will established to match the error measured and then translated into federate for the process control. With such strategy, Walker et al [30] demonstrated a successful arbitrary form peak-to-valley error correction from 20.4 to 6.2 microns. The limitations polishing a free-form part are currently due to the quality of the metrology as delivered by a CMM. By applying a limited load (2 N) on polishing tool, Su et al [29] demonstrated that the hydrodynamic polishing can create both uniform depth and parabolic shape pockets with root mean square waviness less than 30 nm by layer-by-layer strategy. The layer-by-layer strategy still has over-cut and under-cut problem when the surface profile falls between the layers. Su et al [31] developed a modified layer-by-layer method to cope such problem.

In order to correct spot error on freeform surface, Walker et al [28] developed a corrective polishing method named as “precessions” process. The polishing tool used comprises an inflated, bulged rubber membrane of spherical form, covered with nonpitch flexible polishing surfaces. The membrane moulds itself around the local asphere, retaining good contact everywhere. Such a membrane has the property that the polishing tool stiffness and the contact area can be controlled independently by air pressure and axis offset when it is used on a Zeeko machine. When the polishing tool feeds toward the workpiece surface perpendicularly (pole-down spinning), the tool exhibits zero surface-speed at centre, rising linearly to a maximum at the periphery. According to Preston equation and Hertzian contact pressure distribution, the material removal in the contact spot presents a

spinning “W” shape. Such material removal pattern is difficult to be used for form correction. For this reason, the rotation-axis of the tool is inclined to the surface’s local normal, at an angle of typically 10-25 degrees. The tool polishes on the side of the bulged membrane, and the zero-point of surface-speed is shifted outside the contact spot. In this way the materials removal pattern become an asymmetrical “V” shape. The “Precessions” method precesses the tool-axis (see Fig. 5(a)) in discrete steps (typically four) about the local-normal to the surface of the workpiece. In this way, the material removal will possess a symmetrical V shape, which is idea for a spot error correction. As an example, Fig. 5(b) presents a set of material remove pattern by the “Precession” method. The material removal functions are near-Gaussian, and effectively edgeless, with no sharp discontinuities. Even for polishing a curved lens, the material removal functions are usually measured on flat-stock. The tool-advance and dwell-times are adjusted to give the desired width and depth respectively on the curved surface. The results [32] indicated that the errors of a freeform surface could be reduced down to less than 1 micron level.

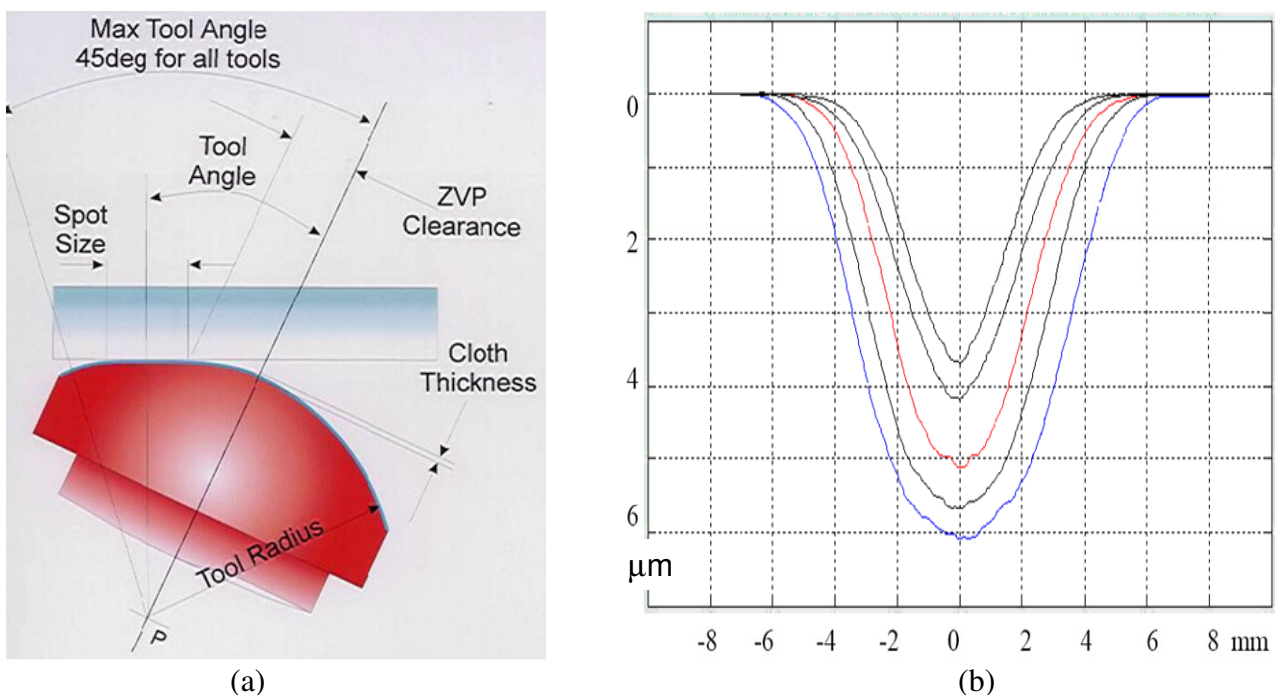


Figure 5. Precessing tool position and material removal function of “Precessions” method [28]

Currently there are not many reports on polishing process monitoring. This may be due to the process material removal is so small that there is no suitable sensor to provide meaningful signals. As discussed previous, the capability of metrology is a critical factor that limits the further improvement of accuracy of corrective polishing. Currently most corrective polishing operations rely on in situ or off line measurement to provide error information. With the development of acoustic emission gap elimination technique that could detect submicron contact [], online process monitoring may be possible.

Summary

Development of corrective polishing technology enabled the errors on freeform surface to be corrected. Successful corrective polishing relies on the capability of the machine tools been used. Normally these machines should have 6 or more degree of freedoms to allow freeform to be machined. The basic models for corrective polishing are still based on Preston and Archard equations. New models consider the effects of tool feed rate and local deformation in the polishing zone. A NURBS based surface modelling method is widely adopted in corrective polishing for its speed for process control. The main strategies for the corrective polishing are time dwelling and layer-by-layer

methods. Further improvement of corrective polishing technology depends on the application of better metrological facilities and online process monitoring.

References

- [1] R. Komanduri, D.A. Lucca, and Y. Tani, Technological Advances in Fine Abrasive Processes, *Annals of the CIRP*, Vol.46, No. 2, (1997), pp. 545-596.
 - [2] Robotice grinding and Polishing for turbine-vane overhaul, *J. of materials Processing Technology*, Vol. 127(2002) pp.140-145
 - [3] C. Brecher, S. Lange, M. Merz, F. Niehaus, C. Wenzel, M. Winterschladen, NURBS Based Ultra-Precision Free-Form Machining, *Annals of the CIRP*, Vol.55, No. 1, (2006), pp. 547-550.
 - [4] D. D. Walker, , R. Freeman, G. McCavana, R. Morton, D. Riley, J. Simms, D. Brooks, E. D. Kim, A. King, The Zeeko/UCL Process for Polishing Large Lenses and Prisms, *Proc. of SPIE*, Vol. SPIE-4411 (2002) pp.106-111.
- The Euro50 Extremely Large Telescope”, Torben Andersen, Arne L Ardeberg, Jacques Beckers, *Proceedings SPIE Apr 2002 Vol. 4840 pp 214-225.*
- [5] R. G. Bingham, D. D. Walker, D-H. Kim, D. Brooks, R. Freeman, D. Riley, A novel automated process for aspheric surfaces, *Proc. of SPIE*, Vol. SPIE-4093 (2000) pp.445-450.
 - [6] P. Charlton, L. Blunt, Surface and form metrology of polished “freeform” biological surfaces, *Wear*, Vol. 264 (2008) pp.394–399.
 - [7] T. M. Stephen, L. M. Sweet, M. C. Good, M. Tomizuka, Control of tool/workpiece contact force with application to Robotic deburring, *IEEE J. Robot. Autom.* RA-3(1) (1987) pp. 7-18.
 - [8] G. M. Bone, M. A. Elbestawi, R. Lingarkar, L. Liu, Force control for robotic deburring, *ASME J. Dyn. Syst. Meas. Cont.* Vol.113 (1991) pp.395-400.
 - [9] R. Hollowell, R. Guile, An analysis of robotic chamfering and deburring, *ASME DSC-6* (1987) pp.73-79.
 - [10] D. F. Ge, Y. Takeuchi, N. Asakawa, Dexterous polishing of overhanging sculptured surface with 6-axis control robot, *Proceedings of the IEEE International Conference on Robotics Automation*, (1995) pp.2090-2095.
 - [11] F. Ozaki, M. Jinno, T. Yoshimi, K. Tatsuno, M. Takahashi, M. Kanda, Y. Yamada, S. Nagataki, A force controlled finishing robot system with a task-directed robot Language, *J. Robot. Mechatronics*, Vol.7, No. 5 (1995) pp.383-388.
 - [12] F. W. Preston, The theory and design of plate glass polishing machines. *J Soc Glass Technol* Vol.11 (1927) pp. 214–256.
 - [13] J. F. Archard, Contact and rubbing of flat surfaces. *J Appl Phys.* Vol.24, (1953) pp. 981–988.
 - [14] X. Wu, Y. Kita, K. Ikoku, New polishing technology of free form surface by GC, *Journal of Materials Processing Technology*, Vol. 187–188 (2007) pp. 81–84.
 - [15] A. Roswell, F. Xi, G. Liu, Modelling and analysis of contact stress for automated polishing, *Int. J. of Mach. Tools & Manuf.* Vol.46, (2006), pp.424-435.
 - [16] David F. Rogers, Rae A. Earnshaw (editors), "State of the Art in Computer Graphics - Visualization and Modeling", 1991, New York, Springer-Verlag, pp. 225 - 269
 - [17] Les Piegl, "On NURBS: A Survey", Jan 01, 1991, *IEEE Computer Graphics and Applications*, Vol. 11, No. 1, pp. 55 – 71.

- [18] BSI 7251-4: 1997; Orthopaedic joint prosthesis – Part 4: Specification for articulating surfaces made of metallic, ceramic and plastic materials of hip joint prosthesis. <http://www.bsi-global.com/index.xalter>
- [19] BS 7251-14:1998, ISO 7207-2:1998 Orthopaedic joint prostheses. Components for partial and total knee-joint prostheses. <http://www.bsi-global.com/index.xalter>
- [20] L. Blunt, X. Q. Jiang . Three dimensional measurement of the surface topography of ceramic and metallic orthopaedic joint prostheses. *Journal of Materials Science: Materials in Medicine*, Volume 11, Number 4 (April 2000), pp. 235-246.
- [21] X. Q. Jiang, L. Blunt, Third generation wavelet for the extraction of morphological features from micro and nano scalar surfaces, *Wear*, Vol. 257 (2004) pp.1235–1240.
- [22] C.J. Evans, E. Paul, D. Dornfeld, D.A. Lucca, G. Byrne, M. Tricard, F. Klocke, O. Dambon, B.A. Mullany, *Material Removal Mechanisms in Lapping and Polishing*, Vol. 52, No. 2, (2003) pp. 611-633.
- [23] D.D. Walker, A.T.H. Beaucamp, D. Brooks , R. Freeman, A. King, G. McCavana, R. Morton, D. Riley, J. Simms, Novel CNC polishing process for control of form and texture on aspheric surfaces, *Proceedings of SPIE – The Int. Soc. for Opt. Eng.*, Vol. 4767 (2002) pp.99-105.
- [24] *Material Removal Mechanisms in Lapping and Polishing*, *CIRP Annals - Manufacturing Technology*, Vol. 47, No. 1, (1998) pp. 239-244.
- [25] R. S. Dwyer-Joyce, R. S. Sayles and E. Ioannides, An investigation into the mechanisms of closed three-body abrasive wear, *Wear*, Vol 175 (1994) pp. 133-142.
- [26] Aghan R. L. and Samuels L. E. Mechanisms of abrasive polishing, *Wear*, Vol.16 (1970), pp. 293-301.
- [27] E. Brinksmeier, O. Riemer, A. Gessenharter, Finishing of structured surfaces by abrasive polishing, *Precision Engineering* Vol.30 (2006) pp. 325–336.
- [28] D. D. Walker, D. Brooks, A. King, S. w. Kim, The ‘Precessions’ tooling for polishing and figuring flat, spherical and aspheric surfaces, Vol.11, No. 8, (2003) pp.958-964.
- [29] Y. T. Su, C. C. Horng, S. Y. Wang, S. H. Jang, Ultra-precision machining by the hydrodynamic Polishing process, *Int. J. Mach. Tools Manuf.*, Vol. 36, No. 2, (1996) pp. 275-291.
- [30] D.D. Walker, A.T.H. Beaucamp, V. Doubrovski, C. Dunn, R. Freeman, G. Hobbs, G. McCavana, R. Morton, D. Riley, J. Simms, X. Wei, New results extending the Precessions process to smoothing ground aspheres and producing freeform parts, *Proc. of SPIE*, Vol. SPIE-5965 (2005) pp. 249-255.
- [31] Y. T. Su, C. C. Horng, J. Y. Sheen, H. JAR-Sian, A Process Planning Strategy for Removing an Arbitrary Profile by Hydrodynamic Polishing Process, *Int. J. Mach. Tools Manuf.*, Vol. 36, No. 11, (1996) pp. 1227-1245.
- [32] D. D. Walker, A. T. H. Beaucamp, D. Brooks, V. Doubrovski, M. Cassie, C. Dunn, R. Freeman, A. King, M. Libert, G. McCavana, R. Morton, D. Riley, J. Simms, New Results from the Precessions Polishing Process Scaled to Larger Sizes, *Proc. of SPIE*, Vol. SPIE-5494 (2004) pp.71-80.

If a polishing process has a deterministic machining nature and is capable of removing an arbitrary profile to a desired precision, it has two main advantages in performing the error correction task as compared to the trajectory controlled machining methods. One advantage is that the precision requirement of the servo-mechanisms for a polishing machine is much lower than the machining precision which can be achieved through error compensation by the polishing process. This is because the high positioning precision requirement in the z-direction for the trajectory decided machining processes is unnecessary for a polishing process. It is replaced by the need for an accurate machining rate control. In other words, by attaining a proper machining rate control of the polishing process, the machining precision of work surface can be greater than the positioning precision of the machine tool (see discussion in Appendix A). The other advantage is that the high structure rigidity requirement (needed for the trajectory controlled machining methods) is relieved for a polishing process. This is because the structure deflection or vibration has a negligible effect on the machining performance of a polishing process [23]. As a result, for the error compensation purpose a deterministic polishing process is a better choice.

AE

Machine tool kinematics

Error measurement

More research is required to guide the selection of suitable process parameters.

1. D.D. Walker, A.T. Beaucamp, R.G. Bingham, D. Brooks, R. Freeman, S.W. Kim, A.M. King, G. McCavana, R. Morton, D. Riley, J. Simms, "Precessions process for efficient production of aspheric optics for large telescopes and their instrumentation," in Specialized Optical Developments in Astronomy, eds. E. Atad-Ettdgui, S. D'Odorico, Proc. SPIE 4842, 73-84, 2002

2. D. Walker, D. Brooks, R. Freeman, A.M. King, G. McCavana, R. Morton, D. Riley, J. Simms, "First aspheric form and texture results from a production machine embodying the Precessions process," in Optical manufacturing and Testing IV, Proc. SPIE, **4451**, 267-276, 2000

3. 'The 'Precessions' Tooling for Polishing and Figuring Flat, Spherical and Aspheric Surfaces', D.D. Walker, D. Brooks, A. King, R. Freeman, R. Morton, G. McCavana, S-W Kim, Optics Express, Published by Optical Society of America on <http://www.opticsexpress.org/>, Vol. 11, issue 8, April 21st, pp958-964

Dipayan Jana, SAMPLE PREPARATION TECHNIQUES IN PETROGRAPHIC EXAMINATIONS OF CONSTRUCTION MATERIALS:

A STATE-OF-THE-ART REVIEW; PROCEEDINGS OF THE TWENTY-EIGHTH CONFERENCE ON CEMENT MICROSCOPY, DENVER, COLORADO, U.S.A., APRIL 30 – MAY 4, 2006

Jana, D., Sample Preparation Techniques in Petrographic Examinations of Construction Materials: A State-of-the-art Review, Proceedings of the 28th Conference on Cement microscopy, ICMA, Denver, Colorado, 2006, pp. 23-70.

Process monitoring

It has been reported that difference lap materials would make significant difference in surface finish.

The compliance of polishing system is an important common feature for corrective polishing processes in achieving high accuracy. It allows the surface finish to be improved without losing form

accuracy. To enable corrective polishing tool path planning is essential element for the error correction. This depends on the method of freeform surface modelling and error measurement.

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$$c^2 = a^2 + b^2 \tag{1}$$

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- [1] Dj.M. Maric, P.F. Meier and S.K. Estreicher: Mater. Sci. Forum Vol. 83-87 (1992), p. 119
- [2] M.A. Green: *High Efficiency Silicon Solar Cells* (Trans Tech Publications, Switzerland 1987).
- [3] Y. Mishin, in: *Diffusion Processes in Advanced Technological Materials*, edited by D Gupta Noyes Publications/William Andrew Publishing, Norwich, NY (2004), in press.
- [4] G. Henkelman, G. Johansson and H. Jónsson, in: *Theoretical Methods in Condensed Phase Chemistry*, edited by S.D. Schwartz, volume 5 of *Progress in Theoretical Chemistry and Physics*, chapter, 10, Kluwer Academic Publishers (2000).
- [5] R.J. Ong, J.T. Dawley and P.G. Clem: submitted to *Journal of Materials Research* (2003)
- [6] P.G. Clem, M. Rodriguez, J.A. Voigt and C.S. Ashley, U.S. Patent 6,231,666. (2001)
- [7] Information on <http://www.weld.labs.gov.cn>