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Analysis of tool-mass-acceleration effects onto sub-aperture computer controlled polishing (CCP)

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ABSTRACT

Although computer controlled polishing (CCP) of aspheres and freeforms is one of the best understood state-of-the-art fab processes today, there are yet some unsolved issues: e.g. compared to bonnet polishing, fluid jet polishing is taking less iteration steps reaching the same form accuracy and ion beam figuring eventually is reaching much higher shape accuracies. This paper is a first move into solving this matter by introducing a novel footprint recording approach for CCP. To that aim, a new method for measuring the impact of a single tool mass acceleration value onto footprint shape is presented, the second derivative footprint recording (SECondo) method. First experimental evidence of the SECondo effect is presented, demonstrating that for bonnet polishing, acceleration of tool mass significantly alters the pressure distribution within the footprint and consequently affects its cross section.

Keywords: *computer controlled polishing CCP, CCOS, aspheres generation, bonnet polishing*

1. computer controlled polishing (CCP)

Thanks to their point symmetry, spherical optical surfaces have been polished by full-aperture, load controlled fresh feed polishing ever since the mid-17th century when Baruch Spinoza was one of the first to polish lenses made of glass to optical qualities in Voorburg, The Netherlands[1]. Unfortunately, this simple but ingenious self-correcting process which is based on random tool movements can neither be applied to generate aspherical surfaces due to their axis symmetry nor for freeforms which often have no symmetry at all. Consequently, todays state-of-the-art in aspheres and freeforms finishing is computer controlled polishing (CCP)[2] where a small sub-aperture tool is locally polishing every point within the clear aperture of the optical surface under computer control.

CCP is an iterative process alternating shape measurements and corrective polishing. A well recorded sub-aperture tool influence function, based on the shape of the local footprint (FP) of the applied polishing process, is fed into the machine running software together with the measured form error profile of the optical surface being processed. From this, a dwell time map is calculated, containing information about how long at what point within the clear aperture polishing must be carried out. After each corrective polishing run along the dwell time map, the surface shape is measured again and CCP is repeated iteratively until the desired shape accuracy has been generated and the surface has been polished to optical qualities.

Within CCP, various polishing processes are applicable, a.o. bonnet polishing by using an inflated tool[2], ion beam figuring (IBF)[3], wheel or belt polishing[4], fluid jet polishing (FJP)[5] and magnetorheological finishing (MRF)[6]. The right choice of the applied polishing process depends on the workpiece material, and the dimension and shape of its FP: FP's diameter must be smaller than the smallest lateral shape deviation to be removed and, as a rule of thumb, should not exceed half of the smallest local radius of curvature of the surface to be polished[7].

One of the essential steps of CCP is the recording of the tool influence function which is usually done by recording a static FP (indicated by "A" in Fig.1) without relative lateral movement between tool and

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workpiece and by recording a dynamic FP (indicated by “B” in Fig.1) where the tool is traveling by constant speed along a straight path across the resting workpiece generating a linear groove. Out of the cross sections of static and dynamic FPs the tool influence function is generated (indicated by “I” in Fig.1) and used to calculate the dwell time map.

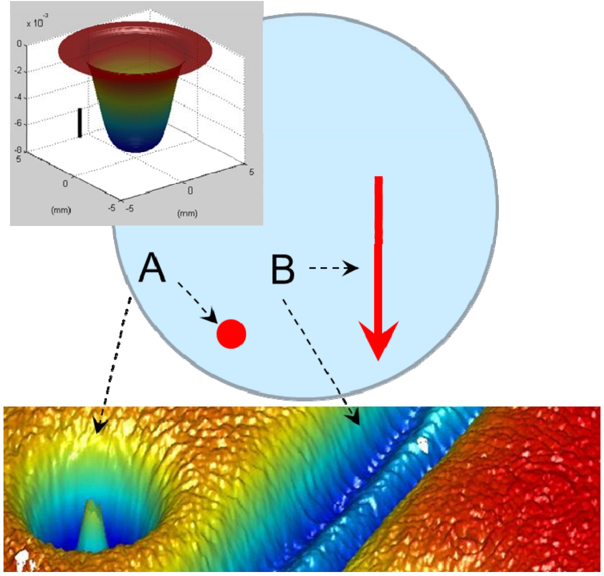

Fig.1 Footprint (FP) recording in CCP: a local FP “A” without any lateral tool movement and a linear FP grove “B” with tool moving at constant relative speed. Both are used to determine the influence function "I" needed to determine the dwell time map.

2. tool mass acceleration (TMA) effects in CCP

Each CCP method consists of a certain combination of polishing method, shape testing method, algorithm applied to calculate the dwell time map and type of machine engaged. For a given shape, the quality of a specific CCP method is determined

a) by the number of iteration steps needed to reach a certain shape accuracy and
b) by the eventually reachable ultimate shape accuracy.

In general, CCP quality depends on

- the accuracy of the applied shape measurement method,
- mounting and remounting accuracy of workpiece between CCP machine and testing set-up,
- the quality of the algorithm applied to calculate the dwell time map,
- the accuracy of polishing machine positioning the footprint along the dwell time map,
- tool wear

and on the FP shape being stable during one iterative polishing run.

Although CCP is one of the best understood state-of-the-art fabrication processes today achieving ultimate shape accuracies on aspheres and freeforms, there are some not yet well understood issues: e.g. Fluid Jet Polishing taking less iteration steps than bonnet polishing reaching the same form accuracy, or Ion Beam Figuring outperforming bonnet, wheel and belt polishing in terms of achievable highest shape accuracies.

This paper presents a first step into solving this matter: a report on an experimental study where for bonnet polishing, the influence of Tool Mass Acceleration (TMA) effects onto FP shape stability and consequently on CCP quality has been analyzed.

2.1 SECondo: testing method for TMA effects in CCP

In the following, a novel testing method to record the influence of a single tool mass acceleration (TMA) value onto the footprint FP shape is presented. The so-called SECondo (second derivative footprint recording) method is based on the fact that a mass that is traveling with constant angular speed v along a circular path (featuring a radius R) is experiencing an acceleration value of $a = v^2/R$.

Two circular grooves featuring the same diameter are polished into a previously polished, flat workpiece surface applying two different kinematic approaches using the same CCP machine.

The first groove is being polished in a lathe-like situation (see Fig.2.a): the sample is being rotated with constant angular speed ω. At a distance R from the workpiece rotary axis, the bonnet polishing tool is fixed in space and in local contact with the workpiece surface. Consequently, a circular groove is being polished without any TMA present applying a lateral relative speed between tool and workpiece of $v = \omega R$.

Subsequently, a second circular groove (again with a diameter of $2R$) is generated at a different position on the sample surface by applying the same values of polishing parameters (slurry, bonnet pressure, polishing pad etc.) as during the generation of the first groove. The only difference to the generation of the first groove is that this time, the workpiece is not rotating but fixed in space while the bonnet tool is traveling with constant ground speed v along the circular path (see Fig.2b). Consequently, again a circular groove with a diameter of 2R is generated but this time with TMA effects being present.

After interferometric measurements of both circular grooves and comparison of their cross sections, the TMA effect for a single TMA value a onto the FP shape is extracted and the second derivative FP has been recorded applying SECondo method.

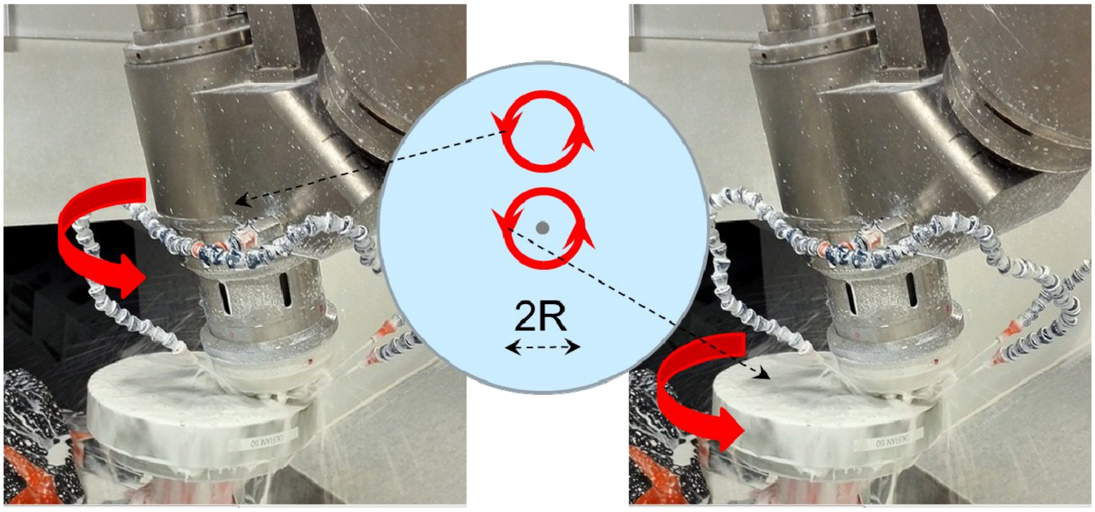

Fig.2 The SECondo method for measuring the influence of a specific tool mass acceleration (TMA) value ($a = v^2/R$) onto footprint shape in computer controlled polishing: **(a)** on the right hand side the relative speed v is generated in a lathe-like situation where the workpiece is rotating with constant angular speed and the bonnet tool is fixed in space; **(b)** on the left hand side the workpiece is not rotating but the bonnet tool is traveling along the circular path generating again the relative speed v. Comparing the cross sections of these two circular grooves, the effect of a single TMA value onto the FP shape can be determined.

2.2 Applying SECondo

For experimental verification of TMA affecting FP shape in CCP, the following SEcondo test has been carried out applying bonnet polishing on a state-of-the-art Zeeko IRP200 machine[8]: for a relative speed between tool and workpiece of v = 1000 mm/min two circular grooves featuring the same diameter $2R$ = 10 mm (see Fig.2) were generated recording the influence of a TMA value of a = 27 mm/sec^2 by comparing the two different kinematic approaches as described in section 2.1. The cross sections of the two generated grooves are significantly different as presented in Fig.3 differing in maximum depth approximately about 11%. In contrary to that, there were no differences in cross sections for tool ground speeds at e.g. v = 300 mm/min detected, indicating a correlation between TMA value and its influence on FP shape.

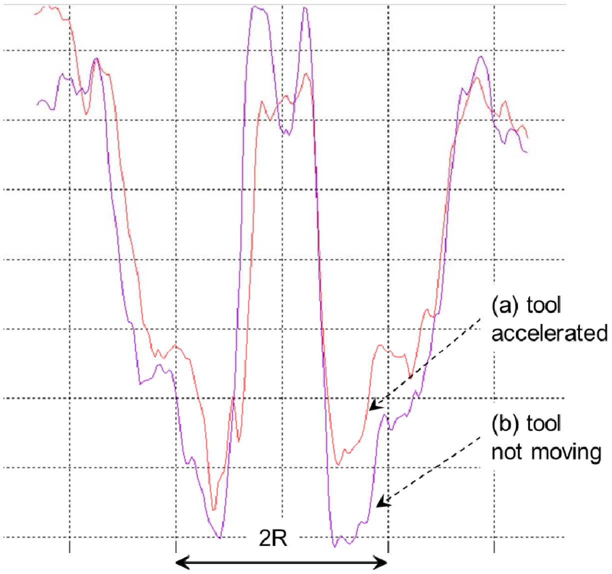

Fig.3 Comparison of interferometric measurements of the cross sections of two circular grooves (R = 5 mm) generated by the SECondo method at the same relative speed between bonnet tool and workpiece surface (v = 1000 mm/min): **(a)** by accelerated tool mass movements and **(b)** without any tool mass acceleration being present.

2.3 proposal for new FP recording method

Based on the experimental results, we propose a new approach to CCP taking TMA effects onto FP shape into account (see Fig.1 and Fig.4):

1. Following the standard procedure, the static and dynamic FP are recorded and the dwell time map is determined (see Fig.1).
2. Subsequently, from the given dwell time map, the maximum TMA value, a_{max}, is being extracted. Applying the SECondo method, the impact onto FP shape of 25% a_{max}, 50% a_{max}, 75% a_{max} and a_{max} are measured and saved into a look-up table.
3. Finally, this look-up table is used to locally adjust the tool influence function optimizing the dwell time function and ultimately improving CCP quality.

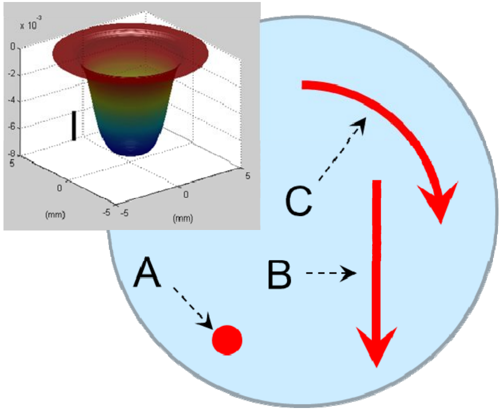

Fig.4 Proposed footprint recording using the SECondo method locally adjusting the tool influence function “I” along the dwell time map taking TMA effects into account: a local FP “A” without any lateral tool movement, a linear FP grove “B” with tool moving at constant relative speed along a linear path and, additionally, circular grooves “C” with tool mass traveling at constant angular speeds along a circular path recording the impact of TMA values onto FP shape.

3. Conclusions

This paper presents a first step for CCP to take local changes of footprint shape caused by tool mass acceleration (TMA) effects into account. To that aim, the second derivative footprint recording (SECondo) method for measuring the influence of individual TMA values onto footprint shape has been presented. First experimental evidence of the SECondo effect has been presented, demonstrating that for bonnet polishing, acceleration of tool mass significantly alters the pressure distribution within the footprint and consequently affects its cross section. Finally, a new approach to CCP has been proposed where footprint shape changes based on local TMA values along the dwell time map are recorded and taken into account optimizing CCP quality. Based on the “First Light” experiments reported in this paper, currently the implementation of the proposed CCP approach using the SECondo method has been started optimizing CCP algorithms to increase the quality of bonnet polishing.

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