Robot based sub-aperture polishing for the rapid production of metre-scale optics

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Abstract

Advances in technology are driving the requirement for metre-scale optics. Traditional optical process chains have used grinding for aspherisation, followed by sub-aperture CNC polishing, with the final form figure correction carried out with energy beam processes. With the trend for larger optics, this approach is slow thereby restricting capacity and increasing costs. The recent technological advances in grinding and final figure correction using Reactive Atom Plasma (RAP) technology have demonstrated significantly reduced cycle times. These reductions have yet to be matched by advances in polishing technology; therefore currently, multiple high performance sub-aperture polishing machines are required alongside a grinding and energy beam machine to achieve full utilisation in optical manufacturing process chains.

To address this challenge, an industrial robot based polishing system has been developed using a standard Fanuc six axis robotic arm, aimed at bridging the aspherisation and final figure correction processes. The use of conventional industrial robots is a low capital cost alternative compared to conventional high cost sub-aperture polishing systems, offering the potential to employ higher numbers of low cost units within manufacturing cells. The robot based polishing system has been developed to remove subsurface damage and mid-spatials from the incoming surface, providing an optical quality finish suitable for interferometric measurement and subsequent RAP figure correction. A final neutral polish is employed using the robot system. The reported results demonstrate that this approach, in conjunction with BoX grinding and RAP figuring, provides a viable, faster and lower cost alternative to other current process chains.

1 Introduction

Advances in technology are driving a requirement for higher precision optics. Today, applications include ground based telescopes such as the European Extremely Large Telescope (E-ELT), fusion energy system components and next generation lithography machines. Segmented mirror technology, as employed for the E-ELT (figure 1), enables the scaling up of ground based telescopes [1, 2]. This in turn has lead to a requirement for many hundreds of metre-scale off-axis mirrors, with a target completion date of 2018. Conservative estimates place the required production rate for segments at 1 per day. Suitable materials for these classes of optics include low expansion glass or glass ceramics such as ULE®, Zerodur®, and fused silica. Successful fabrication demands high form accuracy, low subsurface damage and roughness and, critically, fast processing times.


Source ESO website

Figure 1: Illustration of proposed E-ELT telescope

Currently optical process chains employ grinding for asphérisation, followed by sub-aperture CNC polishing, with the final form figure correction carried out with energy beam processes, see figure 2. Recent technological advances in grinding [3] and final figure correction using Reactive Atom Plasma (RAP) technology [4] have demonstrated significantly reduced processing times. These reductions have yet to be matched by advances in polishing technology; therefore currently, multiple high performance sub-aperture polishing machines are required, alongside a grinding and energy beam machine to achieve full utilisation in optical manufacturing process chains.

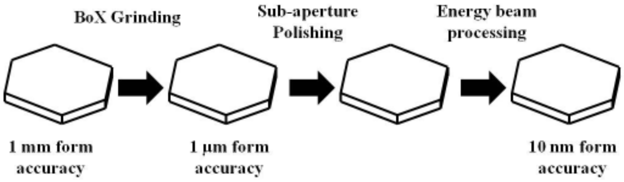


Figure 2: Current process chain for large optics

Therefore, this restricts the potential of the process chain to manufacture high volumes whilst reducing costs. The challenge faced is to reduce the polishing cycle time or unit machine cost thus lowering the overall system cost. To address this challenge, an industrial robot based polishing system has been developed at Cranfield, using a standard industrial robotic arm. The system fulfils a dual role, initially processing the ground aspherised surface in preparation for RAP processing and then applying a neutral polish to the RAP processed surface. Figure 3 illustrates the process chain.

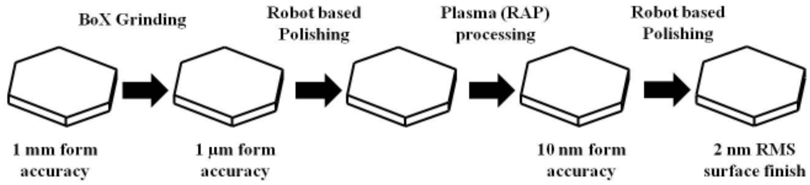


Figure 3: High production process chain for large optics

This paper describes the design and development of the robot based polishing system using an industrial Fanuc six axis robotic arm.

1.1 Polishing process

Polishing is an iterative “force controlled” process, in comparison with grinding and milling processes which are deterministic “position controlled” processes [5]. For a given combination of polishing tool, abrasive slurry and tool pressure, the amount of material removed increases with the amount of time spent over a given contact area. Preston’s equation, based on contact pressure, velocity and contact area, is used to predict material removal rates [6]. For a specific polishing process, a Preston coefficient is calculated which varies with different type of material substrate. However, this approach is based on a consistent controlled polishing process.

Evans et al. [7] defined the four components for polishing processes as the tool, abrasive, carrier fluid and workpiece. The tool or polishing pad is generally made of pitch, polyurethane or cloth. Mechanical characteristics (viscosity, elastic/plastic behaviour, hardness), porosity, wear and shape govern abrasive penetration, surface finish and slurry transport respectively. Abrasives used include diamond grit, aluminium oxide, silicon carbide and cerium oxide, dependant on removal rate and surface finish required. In glass manufacturing, cerium oxide is generally used. Average size and size distribution, as well as concentration are important factors. Concentration (weight per volume), temperature and pH have to be kept constant throughout the process to maintain a material removal rate which is as consistent as possible. Research, targeting the polishing of laser optics, has shown that particle sized distribution is very important in terms of process induced surface damage. This is highlighted when small particles agglomerate during the process leading to larger rogue particles and deep polishing damage [8].

There are different approaches to the polishing of complex freeform surfaces. For low slope surfaces, one option is to modify the part by “stressing” its shape into a spherical form, allowing a conformal polishing approach to be employed. There are mechanical and size limits to this approach [9, 10, 11]. Sub-aperture polishing, using smaller compliant tools, is another approach which is currently used for large metre scale freeform optics [12, 13]. Different process kinematics have been used, such as, eccentric tool movement, tilted tool axis and precession tool movement [14]. Different techniques have been tested and commercialised such as Optotech correction technology [15], Zeeko precession [16], Schneider CCP Swift [17], Optipro ultraform finishing [18] and MRF polishing [19]. Sub-aperture robot based polishing techniques have also been used by Zeiss and Sagem using ABB industrial robots [20, 21]. With contact processes such as polishing, one of the challenges faced is the handling of edges.

The strategy proposed in this research was to remove subsurface damage and mid-spatials producing an optical quality surface with robot based polishing. Figure correction would then be carried out with a non-contacting plasma process.

2 Robot based polishing platform

The robot based polishing system was developed to process the ground aspherised surface. The aim was to remove subsurface damage and mid-spatials from the ground surface and provide an optical quality finish suitable for interferometric measurement. Figure correction would then be carried out with RAP technology, which, with its higher removal rates, provides a faster cycle time than current figure correction sub-aperture polishing processes. A final neutral polish is employed using the robot system to address any surface roughness degradation resulting from the plasma process.

A standard industrial robot was selected and basic geometrical and thermal testing carried out to establish the robot performance. The robot was then integrated into a polishing platform and a series of tests carried out to demonstrate that a low cost robot based polishing platform can be used to improve optical surface roughness with limited surface accuracy degradation.

2.1 Industrial robot

A Fanuc M710ic/50 six axis robot was selected. The unit is a low cost unit typical of systems extensively used within the automotive industry. With a working envelope suitable for optics up to 1.5 metres, the positional repeatability was specified to be in the order of 70 microns dependant on speed, loading and motion selection. To assess the robot performance for application within a polishing platform, series of geometrical tests were performed. These were carried out in a laboratory environment (20˚C±1˚C) operating with representative loads (50kg) and speeds (100mm/s). Initially, a thermal map was taken after spiral XY plane motion, a thermal gradient of 2.5°C was observed after 1.3 hours running. Additional prolonged running produced a 5°C gradient after 6 hours. Figure 4 illustrates the thermal loading with the central joint housing containing four motors showing highest load, followed by the lower joint at the robot base containing two motors.

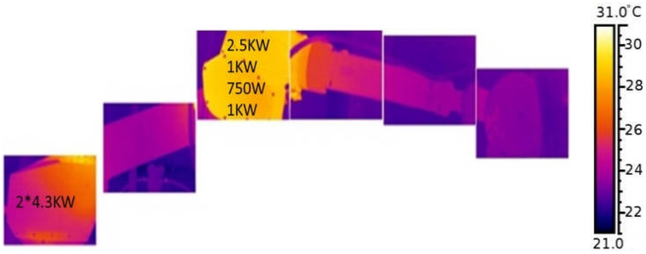


Figure 4: Robot thermal distribution

Geometrical measurements taken in the XY plane using a laser interferometer showed repeatable error motions of up to 150 microns with applied compensation. These tests confirmed the suitability of the selected robot and the error magnitudes measured were used to help specify the polishing head compliance.

2.2 Polishing platform

The robot was equipped with a high precision air bearing spindle and a commercial lapping slurry system was assembled to provide a low cost platform. Figure 5 shows a photograph of the platform. The system design enabled polishing speeds up to 10,000 rpm and a maximum normal polishing force of 100N to be utilised.

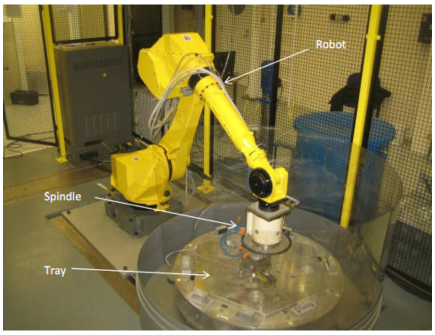


Figure 5: Industrial robot based polishing system

The polishing tool configuration selected was a flexible solid rubber base with a polyurethane pad. This combination provided a higher level of compliance in line with the positioning repeatability of the industrial robot platform. Polishing pressure was controlled through the vertical motion of the robot.

The slurry system was designed to handle cerium oxide and diamond slurries with continuous recirculation. For the glass and glass ceramics, a water based cerium oxide slurry with 1-5 micron particle sizes was selected. Large particle sizes filters (>50 microns) were employed to avoid general contamination of the slurry.

Tool path programming for complex geometric surfaces was carried out using Matlab, for simpler surfaces the Fanuc Roboguide software could be used in CAM configuration. Error compensation was applied to the tool path motions to remove coarse robot linear motion errors. In this mode robot velocities up to 100mm/s were used. An integrated displacement probing system was employed to provide the alignment of the component and robot co-ordinate systems.

3 Experimental Procedure

Experiments were conducted on specimens of 100 mm x 100 mm x 20 mm. Each surface was ground to same specification to remove subsurface damage induced by previous processes.

The material selected was Corning Fused Silica 7980 HPFS® standard grade [21]. Its mechanical properties are close to other low thermal expansion materials such as Zerodur and ULE. Material properties are given in Table 1. Extensive grinding subsurface damage data has been collected for these materials when processed using the BoX® machine.

Table1: Materials characteristics

Material	Density (ρ) g/cm^3	Elastic modulus (E) GPa	Micro Hardness (H) GPa	Fracture toughness (KIc) $MPa.m^{1/2}$
Fused silica	2.2	72.7	5.2	0.7
ULE	2.2	70	4.6	1.8
Zerodur	2.5	91	6.2	0.9

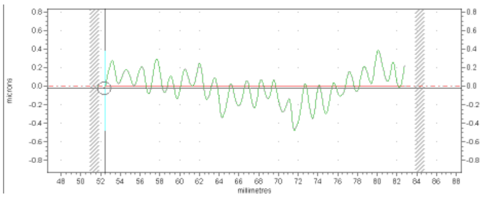
The ground samples were ground using the BoX ultra-precision grinding machine with a D46 wheel using standard finishing parameters [22]. The prepared surfaces had a PV form of < 2 microns and subsurface damage < 10 microns.

The polishing parameters used in this test are representative of a finishing process. Material removal rate measured based on trench polishing is $1.15mm^3/min$. After 5 runs of 52 minutes over each specimen, 15 microns were removed. The surface texture and profile were measured using a Form Talysurf profilometer 120L with 2 micron radius diamond stylus, and surface roughness with a CCI.

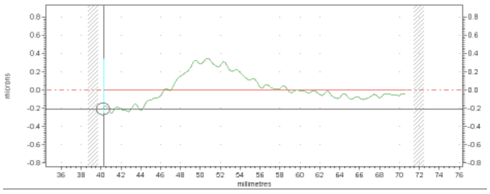
4 Results and discussions

The surface showed a significant improvement in optical quality after the third of the five polishing runs. The input surface roughness was $R_a < 120$ nm and $R_t < 3$ µm. The output surface roughness after three polishing runs was reduced to $R_a < 8$ nm and $R_t < 66$ µm.

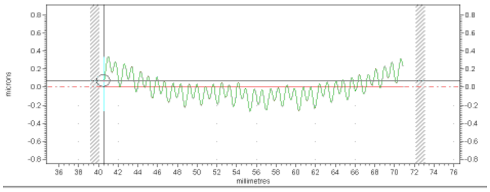
The two additional polishing runs were completed to ensure total removal of the grind "cusping" and any subsurface damage. Comparison of the surface texture before and after polishing is shown in figure 6, the data taken using a Form Talysurf Profilometer. Figures 6a and 6b show the surface profile evolution pre-polish and post-polish across the grinding cusps. Figures 6c and 6d show the evolution along the grinding direction.



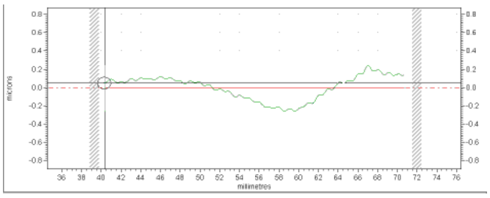
a) Pre-polish (5 runs) – Grinding "cusp" direction



b) Post polish (5 runs) – Grinding "cusp" direction



c) Pre-polish (5 runs) – Grinding direction



d) Post polish (5 runs) – Grinding direction

Figure 6: Surface profile evolution during polishing process

These results demonstrate that the general surface form was maintained within one micron with a reduction in mid-spatials and without the addition of any high frequency errors.

The surface roughness of the sample was finally characterised using the Rank Taylor CCI with measurements taken at five different positions on the sample. Figure 7 shows two typical measurements plots.

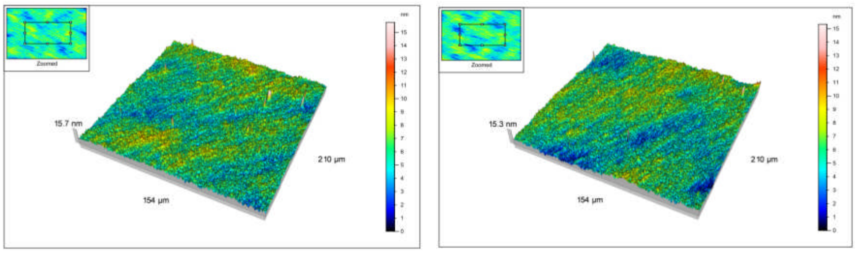


Figure 7: Surface roughness after polishing process

Surface roughness measured below 2 nm S_a and 10 nm S_t. These values show that adequate polishing slurry particles sizes were selected to obtain reflective surfaces. Using softer pads and a higher filtration level after RAP figuring, the surface roughness is expected to improve further for fused silica. For different substrate materials, further experiments will be necessary to confirm surface roughness and subsurface damage depths.

In relation to cycle times, the surface roughness target was reached after 2.6 hours and after 4.4 hours all evidence of grinding cusps and subsurface damage was eliminated. For a 1.45m hexagonal mirror, these process times would correspond to 355hrs and 600hrs respectively. These early results are showing a potential reduction factor of twenty in capital cost investment. Further improvements in removal rate are expected with an increase of cerium oxide particles sizes. In addition, due to limited cost and implementation times, multiple polishing robotic stations can be employed in parallel to reduce production time. Therefore, a possible process chain, after BoX grinding, is to use a robotic polishing to obtain interferometric measurements. Bulk removal of subsurface damage can be achieved efficiently combining sub-aperture polishing and RAP neutral processing. After RAP figuring process, final polishing can be performed using robot based polishing.

5 Conclusions

A sub-aperture polishing system has been developed using an industrial robot arm, a standard polishing slurry system and flexible tools. This has the potential to reduce the investment cost by a factor of twenty compared to existing commercial solutions.

The results demonstrate that a robot based polishing system can remove mid-spatials and subsurface damage from fused silica without form degradation. Optical surface quality is obtained, enabling interferometric data to be acquired and subsequent figure correction of the surface using RAP technology.

Cycle times for polishing are complementary to the established BoX grinding and RAP processes, thus offering the potential for vastly reduced cycle times over the current manufacturing processing chain.

Further work is required to improve surface roughness after RAP processing. A higher level of filtration combined with softer polishing cloths will be tested while subsurface damage will be controlled through systematic HF etching of the produced samples.

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