CIRP Annals - Manufacturing Technology 62 (2013) 315–318

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Super-smooth finishing of diamond turned hard X-ray molding dies by combined fluid jet and bonnet polishing

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ARTICLE INFO

Keywords:
Ultra-precision
Finishing
X-ray optics

ABSTRACT

Fabricating super-smooth aspheric optics for future hard X-ray telescopes will require a new process chain. Whilst diamond turning of electroless nickel plating can generate ~100 nm P-V aspheric molding dies, associated turning marks must be removed before replication. An innovative two-step freeform finishing method is presented, that combines fluid jet and precessed bonnet polishing on a common 7-axis CNC platform. The removal rate and surface texture relationship of fluid jet with abrasive type and pressure is documented, and form correction demonstrated down to 27 nm P-V. A novel bonnet tool-pathing method called "continuous precessing" is then applied, which delivers super-smooth anisotropic surface texture of 0.28 nm rms.

1. Introduction

X-ray radiations are created in space by extremely high energy celestial events. Such events include supernova explosions, destruction of positrons, creation of black holes, as well as the decay of radioactive matter in space. However, such high energy rays cannot be reflected or refracted with conventional optics like other electro-magnetic radiations. Instead, the total reflection of X-rays over flat and smooth surfaces at very shallow angle of incidence was first reported by Compton in 1923 [1]. The discovery of this phenomenon called "grazing incidence" reflection led to the suggestion by Wolter in 1952 [2] of a number of optical configurations using confocal paraboloid and hyperboloid sections to focus X-ray radiations. The most practical, for the purpose of building of an X-ray space telescope, is known as the Wolter type-1 configuration and shown in Fig. 1.

The challenge thenceforth has been to come up with a manufacturing process chain capable of forming and finishing the thin aspheric mirrors needed for the Wolter Type-1 nested configuration. From the early 1980s onward, technology progressively became available to fabricate space telescopes capable of focusing soft X-ray radiations. The process chains involved either direct fabrication of thin glass shells by precision grinding, or the diamond turning of electroless nickel plated molding dies for replication by coating with a material such as gold or iridium. In both cases, finishing of the shells or molding dies was required to smooth down the surface roughness. This involved either manual or semi-automated polishing.

When dealing with high energy radiations there exists a relationship between form accuracy and surface roughness of the optical surface on one hand, and the upper limit of radiation energy that it can reflect (measured in keV) and resolution of the images it can produce (measured in arcs) on the other hand. State-of-the-art finishing of molding dies has enabled the fabrication of X-ray imaging telescopes by replication, such as ASCA, XMM-Newton, Suzaku and ASTRO-H shown in Fig. 2. But in future years, the goal

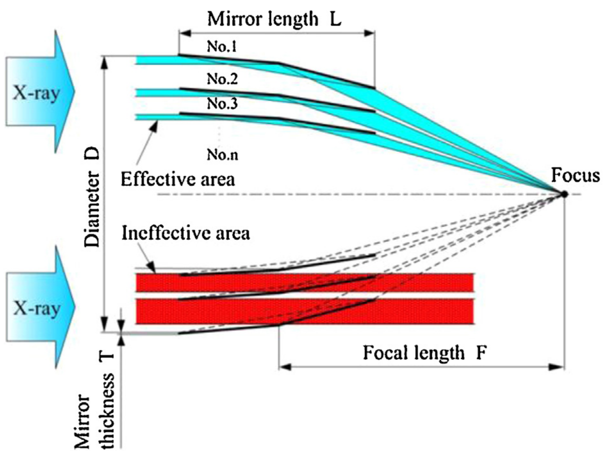

Fig. 1. Wolter type-1 configuration for grazing incidence X-ray mirrors.

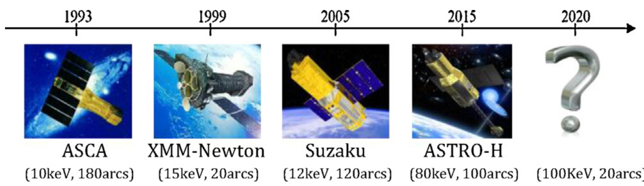

Fig. 2. Past and future specifications of replicated X-ray telescopes.

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0007-8506/$ – see front matter © 2013 CIRP.
http://dx.doi.org/10.1016/j.cirp.2013.03.010

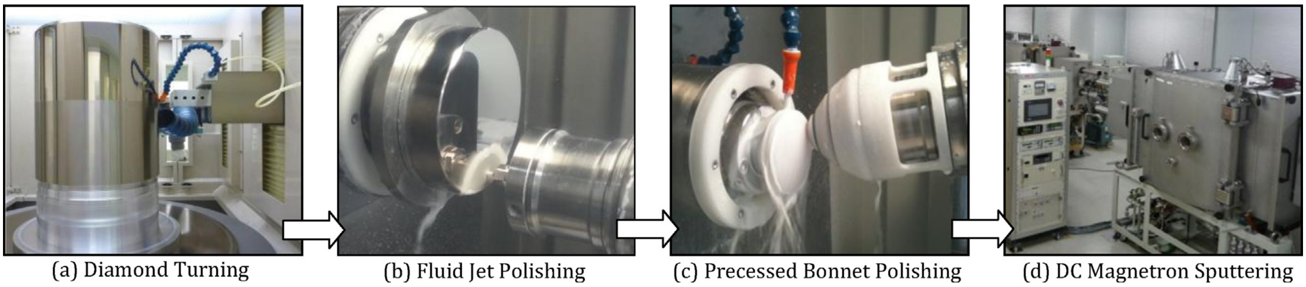

Fig. 3. Proposed process chain for fabricating aspheric hard X-ray shells, including (a) molding die generation by single point diamond turning, two-step finishing by (b) fluid jet polishing and (c) precessed bonnet polishing, (d) deposition of multi-layer coating using DC magnetron sputtering.

of building high resolution aspheric hard X-ray telescopes will require stringent specification, such as roughness less than 0.3 nm rms and deviation from aspheric shape less than 50 nm P-V on the molding dies.

A process chain has been proposed [3] that relies on diamond turning of electroless nickel plated molding dies, for thin aspheric mirror replication by DC magnetron sputtering. The diamond turning of large aspheric electroless nickel plated molding dies [4] and replication by multilayer Pt/C deposition [5] have been demonstrated in previous publications. This paper focuses on the intermediate finishing steps, the missing elements in realizing the process chain shown in Fig. 3.

In this paper, a novel concept is presented of combining the fluid jet and precessed bonnet polishing processes using a common 7-axis CNC platform shown in Fig. 4. This combination can produce super-smooth and ultra-accurate optical surfaces on electroless nickel plated dies. In particular, the characteristics of fluid jet removal rate and surface texture as functions of abrasive size and fluid pressure are documented. For final finishing, the surface is then polished with a novel bonnet tool pathing method named "continuous precessing", which can deliver super-smooth anisotropic surface texture when used with nano-particles slurry.

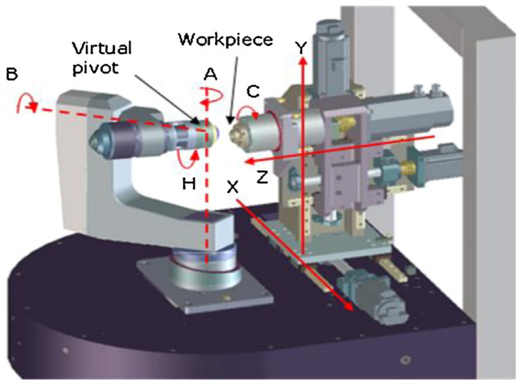

Fig. 4. 7-axis CNC platform used for fluid jet and bonnet polishing.

2. Experimental procedure

2.1. Single point diamond turning

A7075 aluminum alloy was cut into 50 mm diameter and 150 mm diameter plano, concave and convex samples, and turned by a single-point diamond turning machine [4]. A layer of nickel–phosphorus alloy 0.1 mm thick was deposited on the diamond-turned aluminum alloy samples by electroless nickel plating in industry. The hardness of the electroless nickel and aluminum alloy was 568 and 183 Hv respectively. All samples were single-point diamond-turned again within of few hundred nanometers form accuracy.

2.2. Corrective polishing by fluid jet

Fluid Jet Polishing (FJP) has been studied in recent years as a potential finishing method for optical lenses and molds with a number of materials, such a glass and nickel. In the FJP process, a mixture of water and abrasive particles is delivered by a pump to a converging nozzle of outlet diameter usually between 0.1 and 2.0 mm. The jet impinges the work-piece, thus generating an influence spot which is moved across the surface to follow a tool path programmed in to the 7-axis CNC machine.

Improvements to the stability of the process, by computational fluid dynamics modeling and optimization of the slurry management and delivery system to the nozzle, were recently reported [6]. This work has led to a significant reduction in surface waviness induced by the process, and the ability to deterministically polish surface down to less than 50 nm P-V.

In this paper, a series of experiments were conducted on the electroless nickel plated samples, to assess removal rate and surface texture dependency on certain process parameters such as abrasives size and fluid pressure. The optimal depth of removal for complete suppression of diamond turning marks was also determined using a stitching white light interferometer. The parameters of these experiments are summarized in Table 1.

Table 1
Parameters of fluid jet process characterization experiments.

Workpiece	50 mm diameter electroless nickel plated and diamond turned
Nozzle type	Sapphire insert
Nozzle diameter	1.5 mm
Pressure range	4–16 bar
Tool path mode	Raster
Track spacing	0.2 mm
Attack angle	0 deg
Surface feed range	10–200 mm/min
Abrasives	Alumina
Grain size Range	2–4 μm
Weight concentration	40 g/L

Corrective polishing was then attempted on a 150 mm diameter sample, by iteratively measuring form on a Fizeau interferometer and feeding the error to a feed moderation algorithm [6].

2.3. Super-smoothing by "continuously precessed" bonnet

Precessed bonnet polishing is a sub-aperture finishing process which has been described in the literature at various stages during its development [7–9]. The operation of the process in shown in Fig. 5 (left): The position and orientation (precession angle) of a

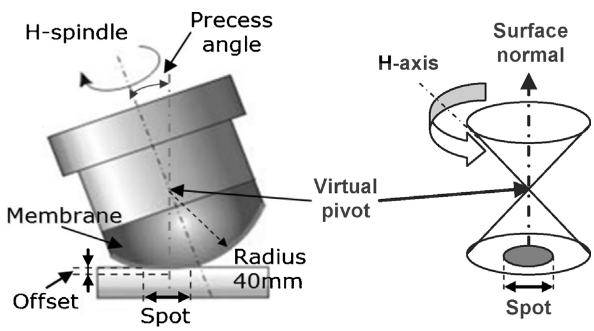

Fig. 5. Precessed bonnet (left) and "continuous precessing" (right).