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Local figure correction of diamond turned aluminum substrates by Magnetorheological Finishing (MRF)

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Abstract

As demonstrated in the present work, the surface irregularity of diamond turned aluminum surfaces can be improved by a magnetorheological finishing process (MRF). The removal behavior of rapidly solidified Al6061 (RSA Al6061) based on standard MR fluids and adapted finishing parameters is investigated. Typical polishing functions (spots) and resulting removal rates are described. The material removal for an iterative figure correction is discussed versus the surface micro-roughness characteristics. The given micro-roughness values (rms) are related to the spatial frequency range: f ~ (10-2500) 1/mm which are relevant in terms of stray light requirements for the mentioned optical applications. Results are given for representative components. The effectivity of the approach is shown on mirrors for a cryogenic application.

Keywords: aluminum Al6061, Magnetorheological Finishing, diamond turning

1. Introduction

Aluminum is the most conventional material for diamond turning of reflective optics in the field of astronomy and space. In particular, the cutting behavior and the machining of Al6061 as preferred alloy for mirror applications in the infrared spectral range (IR) have been in the focus of research for decades. Technological progresses due to the rapidly solidification of the Al6061 alloy with a micro-grained and homogeneous structure enable significant lower micro-roughness values (rms) in comparison to standard Al6061. Furthermore, polishing processes are under development to smooth the diamond turned optical surface statistically in order to avoid diffraction effects caused by the diamond turning marks [1] and thus, creating the basis for the usage of Al6061 as a substrate material for challenging mirror systems acting in the near infrared spectral range (NIR). Relevant instrument designs that are diffraction limited oftentimes require both, small surface figure deviation (typically 40 nm rms @ 100 mm x 100 mm) and a low surface micro-roughness (~ 3 nm rms) on complex shaped geometries, e.g. optical freeforms. To establish a closed manufacturing chain for sub-aperture figured aluminum mirrors and to close the gap towards high quality nickel plated optics for the visual spectral range (VIS) [2], the investigation of potential local figuring techniques for Al6061 are mandatory.

2. Method: Magnetorheological Finishing

MRF is known as a well-established finishing technique for optical glass and other optical materials like glass ceramics, ceramics, and crystals. The polishing function is built by the magnetorheological fluid that becomes rigid under the influence of an electromagnetic field. By applying a controlled fluid volume on a rotating wheel, a so called "ribbon" is formed by the magnetic flux density, generating an abrasive zone at the outer diameter of the polishing wheel. A controlled plunging of the ribbon towards the optical surface leads to a local pressure distribution and finally to an abrasion function (MRF spot). The overall spot size and characteristics are influenced by process parameters, material properties, and fluid composition. The material removal is dominated by a shearing mechanism and permits a deterministic figure correction while smoothing the surface simultaneously. The smoothing effect affects lateral structures that are small with respect to the polishing spot. The MRF process leaves an own frequency signature due to the flow direction of the fluid. Both MRF capabilities, deterministic figuring and micro-roughness reduction, are in the focus of research. The MRF removal process, primarily investigated for optical glass like fused silica, BK7, or crystalline calcium fluoride, can also be adapted to non-ferrous metals. The ability of MRF on electroless nickel is favourable verified by multiple metal optical systems for VIS applications [3].

3. MRF of aluminum Al6061

Based on the knowledge of a proven MRF process for electroless nickel, a parametric study on RSA Al6061 was carried out. The investigation was done on plano diamond turned samples with a diameter of 48 mm, with a surface figure deviation < 1 µm PV and a surface micro-roughness of about 3.5 nm rms @ 140 µm x 110 µm (white light interferometer, WLI, 50x magnification). Key parameters like fluid viscosity, magnetic flux density, wheel rotation velocity, and ribbon height were varied to develop a constant abrasion process for two commercial MR fluids. Targeting a reasonable peak removal rate (PRR) for figuring purposes, a diamond based fluid and a second fluid containing cerium oxide particles were used. As a result of the study, a stable removal function could be obtained for both MRF fluids. For the two commercial fluids, the developed MRF process shows a peak removal rate of 0.5 µm/min to 0.7 µm/min (cf. figure 1).

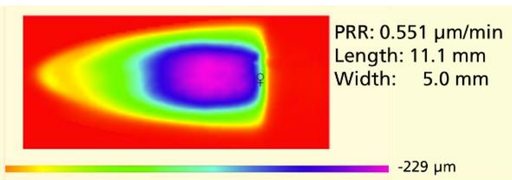

Figure 1. Polishing spot and peak removal rate (PRR) for a diamond based fluid on RSA Al6061.

In comparison to electroless nickel and optical glass, typical PRR are in the range of 2 µm/min to 5 µm/min in case of diamond based fluids. The reduced removal rate and the insensitivity regarding the abrasive fluid particles is presumably caused by the specific material properties (e.g. hardness, Young's modulus, fracture toughness) and the different chemical interaction between substrate material and polishing fluid.

3.1. Figure and micro-roughness of MRF processed Al6061

Figure 2 illustrates a typical deterministic figure correction of a diamond turned RSA Al6061 optical surface (plano, diameter 66 mm). An initial figure deviation of 41 nm rms could be improved in one MRF cycle by the factor of 3.

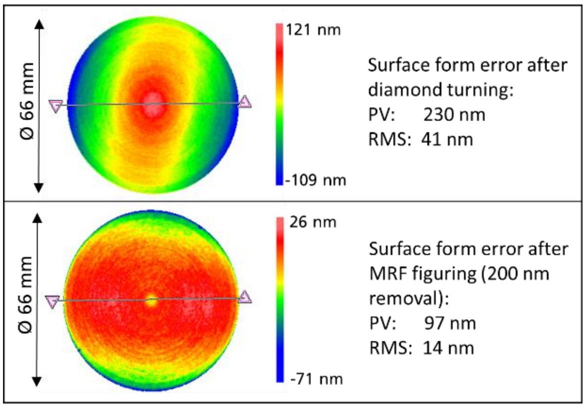

Figure 2. Surface figure before and after MRF: deterministic MRF figuring for three times lower rms values.

The total material removal for the figuring process was 200 nm and eliminates the diamond turning marks from the Al6061 surface completely. The abrasion process generates a specific MRF surface "signature", which has been investigated in more detail by processing diamond turned samples with an incremental MRF removal of 25 nm, 50 nm, 100 nm, and 500 nm, while monitoring the micro-roughness. It has been shown that the MRF process attacks the high frequency turning groove structure already after 25 nm material removal. The crystalline, micro-grained structure of aluminum and its alloying components causes an inhomogeneous abrasion on micro-scale that leads to gradually higher roughness values for increasing material removal.

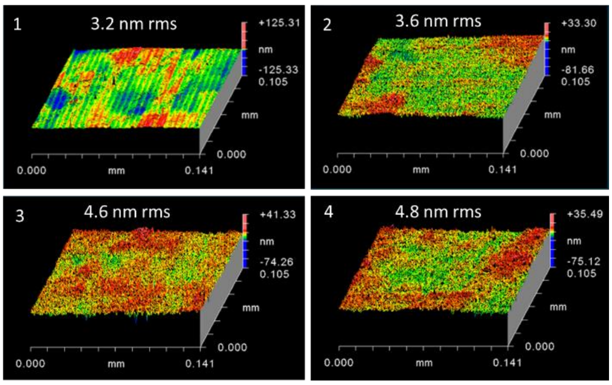

Figure 3. Micro-roughness initially after diamond turning (1) and after MRF removal, 2 = 25 nm, 3 = 100 nm, 4 = 500 nm (WLI, 50x magnification).

Figure 3 proves the rising preparation of material structure depending on the amount of material removal by white light interferometric investigations at a measurement area of 140 µm x 100 µm. A similar tendency is to be noted at lower spatial frequencies at a measurement area of 0.7 mm x 0.5 mm. In both cases, MRF changes the spatial frequency characteristics. The initial diamond turned micro-roughness degrades from 2 nm to 3 nm rms to approximately 4 nm to 5 nm rms. The major part of the increase occurred while removing the first 100 nm of material while generating the MRF specific signature.

3.2 Fabrication of Al6061 mirrors for cryogenic applications

The CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES) at the Very Large Telescope is realized as an all metal athermal system made of Al6061. An updated CRIRES instrument (CRIRES$^+$) is working in a spectral range from 0.92 µm to 5.2 µm and requires for increased mirror accuracy to improve the measurement capabilities. A batch of seven different CRIRES$^+$ mirrors using a fabrication chain consisting of diamond turning, MRF figuring and smoothing by a chemical-mechanical polishing (CMP) step is realized [4]. The developed MRF process was used to improve the diamond turned surface figure deviation well below the irregularity design requirement of 315 nm PV. Figure 4 depicts the final surface figure deviations, reached on bare RSA Al6061 of the Slit Viewer Mirror 1 (parabolic, off-axis) and the Collimator Mirror (parabolic, off-axis). The final micro-roughness after MRF, CMP, and optical coating was measured to 2.9 nm rms and 3.2 nm rms, respectively, at a measurement area of 140 µm x 100 µm (WLI, 50x magnification).

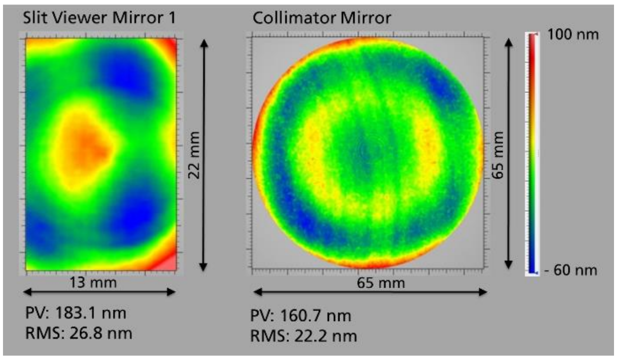

Figure 4. Final form deviation of the CRIRES$^+$ Slit Viewer Mirror (left) and Collimator Mirror (right). Piston, tilt, and optical power removed.

4. Conclusion

The developed magnetorheological finishing process is a potential option for the sub-aperture figuring of diamond turned aluminum surfaces. It provides a powerful tool to reduce remaining surface figure errors after diamond turning. The deterministic figuring characteristics have been demonstrated on bare aluminum (RSA Al6061) mirrors with plano and aspherical shapes. Limiting factors are the relatively low material removal rate and a progressive roughening that requires for a further smoothing by CMP for NIR optics. The developed process chain was applied on cryogenic mirrors and demonstrates the ability for mirror applications with enhanced figure requirements for the near infrared spectral range.

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