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Ion beam figuring of RSA aluminium surfaces

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Abstract

Ion beam figuring (IBF) is attributed a great potential to overcome the present limitations in direct ultra-precision machining of optical elements made of standard aluminium alloy material. Low energy (≤1.5 keV) ion beams consisting of inert ions like argon and reactive ions like oxygen are capable to suppress the etching selectivity of the individual crystallites preserving roughness at material removals up to 1 µm. Ion irradiation has been performed on RSA6061 and RSA905 diamond turned surfaces. The physical and chemical ion-surface interactions have been investigated by optical microscopy, atomic-force microscopy (AFM), and energy dispersive X-ray (EDX) measurements. Eventually, a novel deterministic ion beam machining process has been developed for figure error correction of pure standard aluminium alloy surfaces with focus on superior optical surface quality.

ultra-precision metal mirrors, aluminium, ion beam figuring

1. Introduction

Ultra-precision metal mirrors made of optical RSA aluminium alloys are widely used in space and ground-based optical applications. In most cases the aluminium surface is coated by an amorphous nickel-phosphorous (NiP) layer that can be diamond turned and polished, e.g. by magneto-rheological finishing or ion beam figuring. In order to avoid bending of the mirror due to the bi-metal effect it is desirable to manufacture ultra-precision surfaces out of pure aluminium. Direct machining of RSA standard alloy aluminium surfaces by diamond turning and mechanical polishing has recently been proven to be feasible while achieving sufficient surface roughness of <3 nm. However, residual figure error correction of pure aluminium surfaces by ion beam technology has yet been obstructed due to a significant increase of micro-roughness during ion irradiation. This effect is mainly attributed to selective etching of the surface depending on crystallite orientation, composite and local defect structure, as well as sub-surface damage. Our investigations aim at a novel ion beam related technology suitable for direct machining of aluminium surfaces. Using a chemical reactive gas process it is now possible to keep the micro-roughness in its initially low state, which is typically about 5 nm root-mean square (rms).

2. Experimental

Ion beam machining experiments were performed on 47 mm aluminium disc samples made from the standard alloy materials Al6061 and Al905 (RSP Technology). The diamond-turned surface revealed an rms roughness of about 5 nm.

For IBF an ultra-high vacuum vessel with a base pressure of 2×10^{-7} mbar was used. A Gaussian-shaped ion beam was provided by a radio frequency-driven ion source with focussing triple extraction-grid system at 1.5 kV beam-voltage. We used Ar and O_2 as well as Ar:O_2 gas mixtures for ion generation, respectively. Beam current measurements revealed an ion beam full-width half maximum (FWHM) of about 5.2 mm at working position.

3. Results and discussion

3.1. Al6061 material

Process development investigations were carried out within testing fields by homogeneous ion beam scanning over a graphite hard mask with 13 mm opening (Fig. 1).

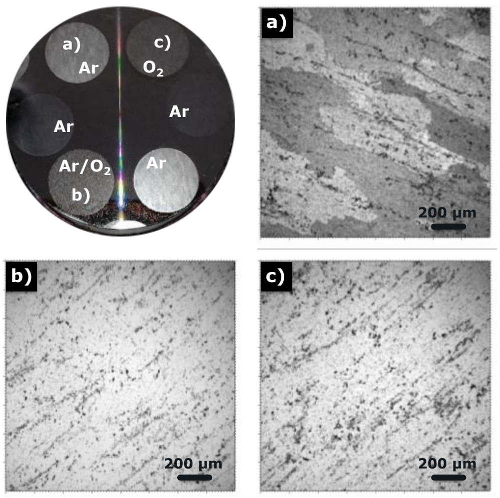

Figure 1. IBF machined Al6061 sample with 6 testing fields. The optical microscopy images reveal the surface change from a domain-like morphology in inert processes with a) pure Ar to a flat morphology with a directed defect structure in reactive gas processes with b) a 6:1 Ar:O_2 mixture, and c) pure O_2.

The surface morphology changes significantly with addition of O_2 to the Ar process gas (Fig. 1). Already small amounts of O_2 (Ar:O_2 = 15:1) strongly reduce the surface roughness dominated by domain-patterns (Fig. 1a) towards smooth surfaces, which, however, exhibit a strong defect structure being also present at higher O_2 fractions or with pure O_2 processing (Fig. 1b/c). After 400 nm etching with pure O_2 the roughness is about 11 nm rms compared to 40 nm rms for Ar.

The origin of defect formation was analysed in detail by SEM-EDX mapping (Fig. 2).

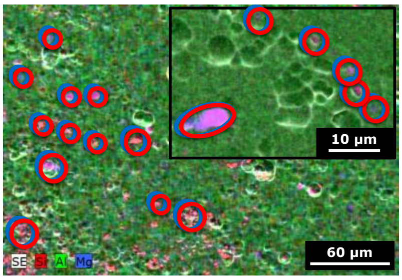

Figure 2. SEM-EDX analysis (550x) of an Al6061 sample after 2 µm ion beam processing with an Ar:O_2 mixture of 6:1. inset: 3300x

As a result, high amounts of Si and Mg were found inside the defect pits. Since the etching depth of 2 µm is far from the near-surface region, the Si- and Mg-signals are attributed to precipitates being present within the aluminium matrix. Indeed, the precipitation in the form of a quaternary alloy phase with composition $Al_5Cu_2Mg_8Si_6$ is known for Al6061 [2]. Ion beam processing with Ar and O_2 seems to preferably erode the precipitate particles resulting in etch pits. With further etch progress the formed pits are found to increase mainly laterally indicating a more isotropic etch characteristics during aluminium ion beam machining with O_2 gas.

3.2. Al905 material

The alloy composition of Al905 contains Fe, Cu and Mn, but no Si and Mg. Thus, the formation of the quaternary alloy precipitates is not expected for Al905 making this aluminium alloy interesting for IBF experiments. AFM and white light interferometry (WLI) results confirm this assumption (Fig. 3). The surface after Ar ion beam processing shows a high-frequent roughness (Fig. 3a/4).

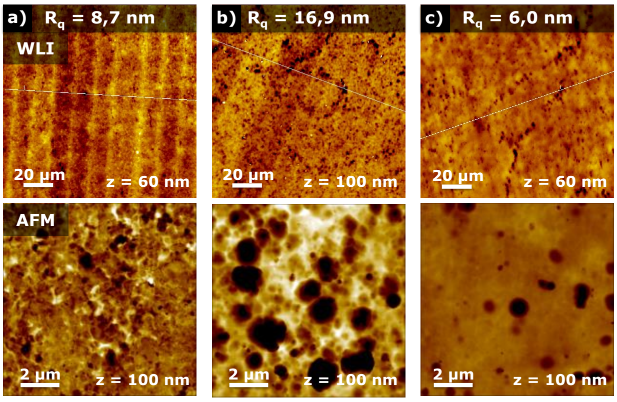

Figure 3. Al905 surface morphology (upper: WLI / lower: AFM) at etching depth of 380 nm with a) pure Ar, b) Ar:O_2 mixture, and c) pure O_2 process gas. The z-value corresponds to the height scale.

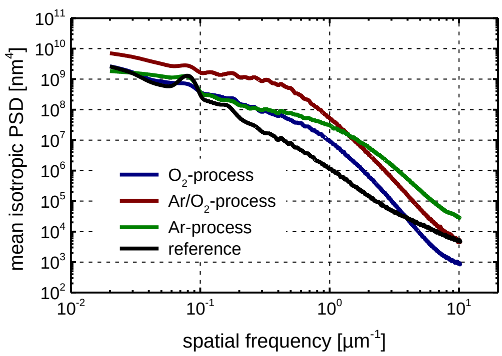

Figure 4. Power spectral densities derived from AFM measurements of untreated Al905 (reference) and after ion beam processing.

The addition of O_2 to the process gas additionally results in etch pit formation (Fig. 3b). Applying pure O_2 process gas (Fig. 3c) the surface becomes smooth (about 6 nm rms). However, submicron etch pits are apparent, which are mainly contributing to the surface roughness (Fig. 4). Individual and coalescing etch pits result in certain deviations in the power spectral density (PSD) between O_2 process and reference in the range of 0.1 – 4 μm^{-1}.

3.3. Direct ion beam machining

Ion beam figuring experiments were performed on Al6061 and Al905 samples via deterministic machining applying the dwell time approach. Firstly, the footprint profile of an oxygen ion beam with 5.0 mm FWHM estimated from Faraday measurements was analysed. The footprint is reproduced well within the etching profile revealing a Gaussian shape with only a slight FWHM increase below 10%. Based on the footprint profile, the initial surface and the target surface profile, the dwell time profile is calculated. This standard IBF approach is feasible also for reactive processing providing a uniform shape transfer into the aluminium surface (Fig. 5). Slight deviations in the border region result from trenching and scattering effects from the graphite hard mask. Within the used etch depth scale the surface retained specular (≈6 nm rms). However, further efforts are necessary to enhance the machining depth to the desired region up to 1 µm.

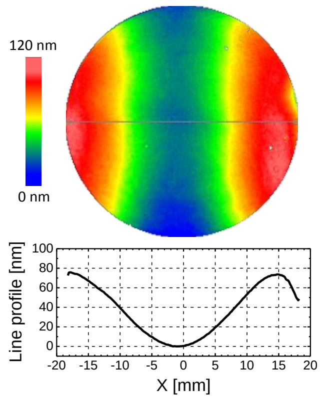

Figure 5. Sinusoidal surface profile on Al905 and the corresponding line profile plot: mean profile of the 160 mm center region (straight) and the sinusoidal reference (dotted).

4. Summary

The ion beam machining experiments showed that the surface morphology of Al6061 and Al905 can be significantly improved by reactive processing with O_2. In Al6061 the roughness is limited by precipitates incorporated into the aluminium matrix, which are preferably eroded resulting in etch pits. Al905 exhibits more favourable structural properties retaining a smooth surface during ion beam processing.
Due to a better pre-process polishing and development of more customized reactive process pathways we are confident of further advancements in direct IBF machining of aluminium surfaces with view on highest optical surface quality.

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References

[1] Chakrabarti D J and Laughlin D E 2004 *Progress in Materials Science* **49** 389–410