

ABSTRACT

Surface integrity influences several functional parameters such as friction, wear and tear, ability of distributing and holding lubricant, thin film coating etc. It is not uncommon that aerospace inertial sensor technology demands 'zero' surface and subsurface defects up to atomic level, on sensing element microstructures. These microstructures are mostly non-metallic brittle materials such as glass, fused silica, silica etc. and are machined and polished such that the surface integrity is maintained. Non-contact type unconventional nanofinishing techniques are being developed to augment or replace chemo-mechanical polishing (CMP) techniques for finishing such microstructures.

To understand and appreciate the challenges in nanofinishing of these glass microstructures, it is essential to understand the brittle damages, such as surface cracks and plastic deformation that can occur on the surface of hard brittle materials like glass ceramics fused silica etc. when the surfaces are precision ground, lapped and polished. If the amount of material removal is controlled and reduced to a certain level, only ductile damages such as plastic deformation, densification, chemical and structural changes remain. With non-contact finishing process, if the material removal amount can be further controlled at the molecular or atomic level, both structural and chemical damage free surface and subsurface can be achieved on these components. Significant gap in literature is observed for non-contact finishing of 3D freeform surfaces without precision tool positioning requirements. Novelty of the present medium pressure plasma process is that it combines the isotropic material removal capability of low pressure plasma and atomistic material removal capability of atmospheric pressure plasma. This process is capable of simultaneously polishing entire complex 3D surfaces including cavities where no tool or beam can reach.

Plasma polishing chamber is designed and built with zerodur material with an optical window to enable optical emission spectroscopy. Components up to 40 mm diameter can be processed in this chamber. Stable plasma with processing gases such as He and Ne and reactive gases such as O₂ and SF₆ up to 30 mbar pressure is achieved by using dielectric barrier capacitive coupled RF discharge. Optical emission spectroscopy is used to identify the relative density of the excited species in the plasma and monitor the various oxidation states of silica and established correlation with respect to material removal rate and ratio of oxidation states of silica Si II and Si III and the same is used as a tool to monitor the polishing process.

With He as a processing gas and oxygen as a reactive gas, surface modification is possible by medium pressure plasma. On machined fused silica surface, the achieved improvement in surface roughness is up to 68% with He-O₂ plasma while there is 85% improvement in surface

waviness. However, reactive radicals such as Fluorine is required for sustained material removal. SF_6 as reactive gas is identified with multiple experiments. Further surface finish improvement is achieved with He- SF_6 - O_2 gas mixture plasma with a material removal rate of $0.008 \text{ mm}^3/\text{min}$. He as plasma processing gas and O_2 and Teflon as a source of fluorine also was studied but discontinued due to carbon contamination. However, SF_6 as fluorine sources is observed to be more practical and useful. Atomistic material removal has also enabled reduction in surface residual stresses and surface cracks thereby enhancing the surface integrity.

A finite element based software i.e. Comsol[®] is adopted to simulate plasma processing and it is used to analyse the distribution of the radicals inside the plasma chamber with and without specimens. It also utilized to find out the ratio of free volume to the total available volume of the chamber for uniform distribution of radicals. The position of planar specimens, hemispherical shell and prisms inside plasma chamber are optimized for effective distribution of radicals which are adopted in subsequent experimentations. The shape and size of the electrodes outside plasma chamber are varied to get homogenous distribution of reactive species and ions. In the presence of hemispherical shell component, the four sided electrode provides higher density of radicals. The simulated results are validated with electron temperature measurement using experimental optical emission spectroscopy data and analytical model. The temperature calculated by simulation is approximately 550 K which can be considered as 'cold plasma' process.

The developed process is used to uniformly polish the complex shaped gyro component, a hemispherical resonator shell, which is fabricated with fused silica by a rotary ultrasonic milling process. A combination of plasma polishing and cleaning process is arrived to achieve sustained polishing of the hemispherical shell. Sustained material removal rate of $0.026 \text{ mm}^3/\text{min}$ is achieved during this process. The uniformity of material removal is confirmed by measuring the reduction in frequency mismatch and surface integrity by enhanced Q factor after each plasma processing using Laser Doppler Vibrometer. Uniform and isotropic plasma machining is ascertained by 18% reduction in frequency mismatch between two orthogonal modes. After multiple level of plasma processing the surface roughness of 22 nm is achieved. Raman spectroscopy analysis provides clear evidence of reduction in strain bonds after plasma processing. There is significant reduction of puckered four-member and three-member rings structures indicating the reduction of surface strain caused by machining process resulting in significant improvement in Q factor of hemispherical shell.

The plasma processing method developed has been successfully applied as super finishing process post chemo-mechanical polished optical prisms. The surface chemical network analyses by Raman Spectroscopy clearly indicate reduction of distorted network structure of fused silica post plasma polishing. The increase in ratio of area under 440 to 605 cm^{-1} confirms that the chemical bond structure of the surface is becoming more like bulk material and atomic level surface and sub-surface defects are reduced distinctly. Also, the surface figure is improved as indicated by reduction of power spectral density (PSD) of higher wave length even though there is marginal degradation of surface finish from 2 to 3 Å units (Ra) as achieved by chemo-mechanical polishing (CMP) process. The Plasma treated prisms when used in Gyro device, has shown increased life span without reduction of laser intensity when compared to CMP finished prisms.

A non-contact atomistic medium plasma polishing method is conceived, polishing set up is designed and developed and is capable of polishing complex shaped glass or fused silica components. The process is fine-tuned and implemented as super finishing process to remove molecular or atomic level defects in already fine finished surfaces by finishing process such as Chemo-mechanical polishing.