Stress Compensation by Deposition of a Nonuniform Corrective Coating

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Thin-film stresses distort the surface flatness of a coated optic in a convex or concave manner for compressive or tensile films, respectively. While traditional evaporated optical coatings typically lead to the formation of low-magnitude tensile stresses, more-energetic processes such as ion-beam sputtering,[1] magnetron sputtering,[2] and plasma-ion–assisted deposition[3] generally form highly compressive films with significant distortion of the optical surface. Such stress-induced curvature can be mitigated by using thicker substrates, coating the back surface of the optic to yield an equivalent deformation in the opposite direction,[4] or by prefiguring the optic surface to counteract the effects of the film stress.[5] These modifications can be costly, while process modifications to alleviate highly compressive stresses often lead to porous, environmentally unstable films.

A unique approach was developed to prefigure the optic surface by depositing a radially nonuniform film using the same deposition process as the optical coating. The corrective coating is deposited beneath the functional optical coating, on the same surface of the substrate, with a thickness profile designed using finite-element analysis to correct for the anticipated surface-flatness deformation resulting from the eventual optical coating deposition from the as-fabricated flat substrate surface. This approach is depicted in Fig. 1.

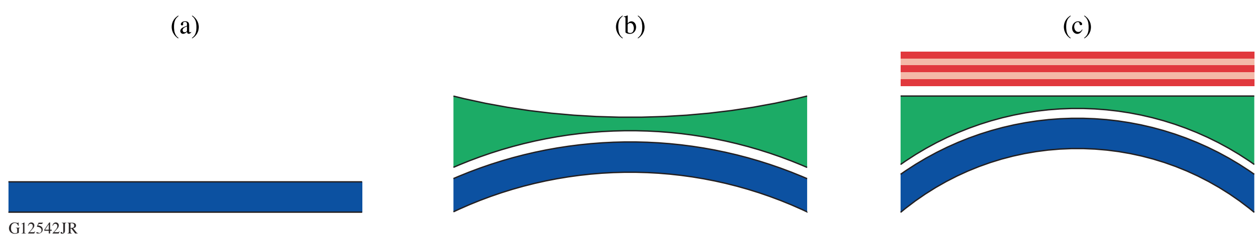

Figure 1
Mitigation of a high compressive film stress by deposition of a gradient compensation layer is illustrated, with (a) the as-fabricated flat substrate; (b) the addition of a compressive, radially graded layer leading to a concave surface, even though the substrate has been deflected in a convex manner; and (c) the combination of the gradient compensation layer and the optical coating leading to a nominally flat coated surface.

This method was used to compensate the stress-induced deformation of a 3.3-μm-thick optical coating on a 100-mm-diam × 3-mm-thick fused-silica substrate. The coating was deposited using plasma-ion–assisted electron-beam evaporation, with alternating layers of hafnium dioxide and silicon dioxide. The calculated compensation layer consisted of a gradient-thickness silica layer with zero physical thickness at the optic center and increasing in a cubic manner to a thickness of approximately 6.7 μm at the edge. The graded coating was fabricated by depositing the corrective layer directly on the substrate through a mask centered on the rotating optic. The mask blocked all deposition flux from reaching the center of the optic, then gradually increased the open space and corresponding thickness, in a cubic manner, until the full thickness was reached at the optic edge. For the purposes of this proof-of-concept demonstration, the chamber was then vented, the mask removed, and the system evacuated once again in order to deposit the multilayer (non-graded) optical coating. Surface-flatness measurements were taken at each stage of the deposition process to quantify the changes from the individual process steps. To implement this in a production process, the mask insertion/removal would be automated while the chamber remains under vacuum.

Surface-flatness measurements were performed using a Zygo Verifire 633-nm interferometer of the uncoated substrate, the substrate with the gradient compensation layer, and the finished component after deposition of both the compensation layer and the multilayer mirror. To improve surface-flatness measurement accuracy, the non-graded mirror coating was designed and fabricated with a center wavelength of 633 nm to reduce errors resulting from nonuniformity of the reflected phase of the coating. After process qualification and the development of a suitable compensation profile to yield a flat coated surface, the deformation from any uniform coating deposition could be compensated. The measurement of the uncoated substrate was removed from that of the stress-compensation layer and the overall component to evaluate only the impact of this stress-compensation approach. An additional control substrate was also included in the multilayer deposition to evaluate the anticipated deformation without the use of the compensating layer. The results are shown in Fig. 2.

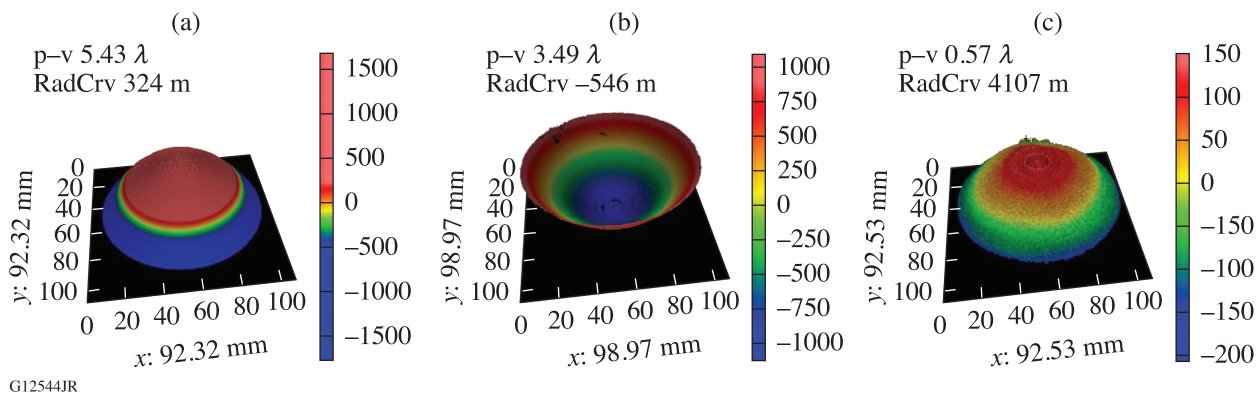

Figure 2
Change in the surface figure of a 100-mm-diam, 3-mm-thick fused-silica substrate as a result of coating with an all-dielectric mirror coating with or without a silica stress-compensation layer (as-fabricated surface flatness subtracted from all subsequent measurements). (a) The control (mirror coating only) surface figure, at 5.4 waves of deviation from flat (λ = 633 nm). (b) After coating with the silica compensation layer, the surface is 3.5 waves concave. (c) Once the high reflector coating is deposited, the combination of the two coatings results in a nominally flat optic, with the change in surface flatness ~10% of that resulting from the high reflector alone. A slightly thicker compensation layer could further improve the surface flatness. p–v: peak to valley.

The surface deformation of the coated optic with the corrective layer is reduced by nearly 90% relative to that of the coated control substrate without the graded corrective layer [Fig. 2(a) at 5.43 waves versus Fig. 2(c) at 0.57 waves at 633 nm]. It is also clear that a slight increase in the thickness of the corrective layer would further improve the surface flatness, since Fig. 2(c) is still dominated by a spherical-like term with a low edge and a high center (as would result from a compressive film stress, which is the compensation the gradient layer would provide). This stress-mitigation approach significantly reduces the deformation of an optic coated with a compressively stressed film while allowing deposition on a single substrate surface. As demonstrated, a cubic-thickness gradient silica layer can reduce the surface deformation of a compressively stressed optical coating by an order of magnitude.

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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