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The two topics discussed in this issue of Coating Materials News are durable coating engineering and layer deposition tolerances. The first topic is concerned with the design and production of coatings that can tolerate harsh mechanical environments without suffering a serious loss in performance. The second topic illustrates the importance of index and thickness values as related to production factors such as yield and producibility.

Engineering Hard, Durable Coatings

Many articles concerned with the mechanical abrasion and wear properties of thin film have appeared over the years in the CERAC Coating Materials News [1]. We assemble here the various pieces to construct a more complete picture, but the reader might refer to the earlier articles for greater detail. The design and deposition of mechanically durable optical thin film coatings must consider wear and abrasive, and often impact, forces in addition to optical performance. Such coatings are structurally engineered of hard, strong, lubricious, and energy dissipating / absorbing components.

The essential components of a durable coating structure, consisting of the adhesive Interface to the substrate, the Intermediate Layer System, and the low friction Surface, are illustrated in Figure 1. The deterministic properties of each component that contribute to coating durability are listed for each component.

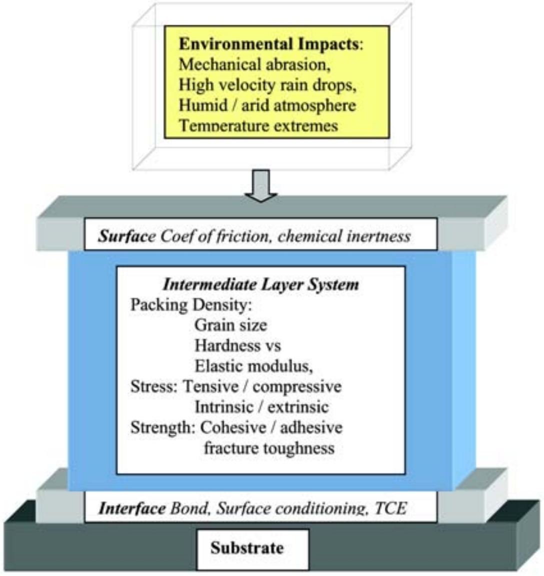

Figure 1. The surface, intermediate, and substrate- interface components that determine the durability of a coated film structure .

Engineering a mechanically hard and durable coating begins at the substrate surface and involves the phenomenon of nucleation and the characteristics of the film nano-structure that lead to dense adherent growth. Nucleation density and the establishment of interfacial bond strength are functions of surface energy. The kinetic and chemical energies of the arriving adatoms influence mobility on the surface and the initiation of surface bonds. High surface kinetic energy promotes 2-D coverage of the surface in advance of 3-D growth, thereby insuring a dense compact nanostructure as opposed to columnar growth with its characteristic large void volume. Often a surface conditioning layer must be added to prepare the surface for chemical bonding. When applying coatings to materials of dissimilar chemistry, specific metal oxides can be applied in thin layers to the substrate to form a chemically reactive interface bond. Alternatively, some fluoride compounds or mixtures such as IRX™ provide strong interface bonds. Surface contamination that might interfere with strong physiochemical bonding must be removed. Oil-free cryopumps are efficient at removing water from the coating atmosphere; low water content promotes chemical bonding. In addition to chemical considerations, thermal expansion differences impose extrinsic stresses, and together with the internal stress of the multi-layer structure, need to be included in the total system stress analysis.

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The Intermediate Layer System provides the mechanical and optical properties required. The Intermediate Layer System will be composed of sub-layers that, as a system, provide sufficient hardness and fracture toughness, and appropriate elastic modulus to provide compliance for distributing and damping the Rayleigh shock loading caused by an impacting particle. This system will consist of multi-layers of alternating hard and elastic material components chosen to produce the durability required. Coatings materials that are hard often display high cohesion, but low adhesion. Similarly, they might possess a high degree of hardness, but be brittle or have high internal stress. Strong adhesive bonding between all layers of the AR coating is critical to achieving durability. If sliding or impacting forces against the coating exceed the adhesive strength at layer interfaces, the film can fracture or detach. If the impacting force exceeds film cohesive strength, the film can be damaged. Ductile coatings are more likely than brittle coatings to maintain integrity (crack-free) and maintain adhesive bonds; therefore, layers with the appropriate elasticity modulus are integral components of our design. We know from published studies that to be mechanically resistant to high-velocity impact events, the protective coating design must include both hard and elastic layers [2]. Layers that possess high elastic moduli absorb and distribute the energy of the reflected Rayleigh waves that, if concentrated can cause structural damage. The structural design of the coating will therefore include hard layers interspersed with layers of high moduli. Film modulus is determined to a large degree by film micro- and nano-structure. The deposition process and material composition are variables that require engineering to alter the film elastic modulus as required. The important properties: adherence, hardness, strength, and elasticity would be balanced to produce the most durable coating.

Film thickness and substrate shape need to be considered for the protective coating of non-flat surfaces such as exposed lenses and domes. Durable films have thicknesses between 5 and 20 µm, dependant on modulus and hardness balance and well as on adhesive strength. Deposition chamber configuration will determine the angle of impingement of the materials on curved substrates, a parameter that influences the density and thickness uniformity of the film.

Finally, high resistance to wear resistance abrasive wear requires an outerface with low coefficient of sliding friction. Abrasive wear resistance decreases rapidly with minor (microscopic) surface defects that are either inherent in the coating or that might be caused externally by micro-scratches or micro-particulate impact. The coating must be microscopically smooth and physically hard to resist micro-scratching during handling procedures and field operation. Surface defects will increase the coeff. of sliding friction, thereby permitting impacting objects to couple energetically and abrade or scratch the surface promoting coating fracture. Here again, a dense, hard, smooth film layer microstructure such as produced by high-energy deposition processes and advanced materials is essential.

When high resistance to abrasive wear forces is required, several inter-related ingredients are necessary beyond the requirement for a strong bond between substrate and coating. The coating layers must be physically dense to prevent the diffusion of moisture to the interface where it can weaken the adhesive bond strength or alter internal stresses. This generally requires that the film layers be amorphous in structure and without grain boundaries instead of polycrystalline, i.e., it must possess a packing density near that of the bulk form. Special materials such as IRX™, possess these properties. The high kinetic energies present in the sputtering plasma and bombarding ions (IAD) increase the packing density of the layer and promote amorphous microstructure by discouraging crystalline microstructure. High surface energy is present by high substrate temperature; for temperature-sensitive substrates, high adatom energies provided by energetic ions promote dense microstructure.

Combining these essential components is the key to producing durable coatings with maximum abrasion and wear resistance and high damage threshold to impacting forces.

Thickness and Index Tolerances

This topic is addressed in the production area: To what accuracy should we know the refractive indices and physical thickness of our coating materials and deposition processes? The coating designer and production engineer need to know the limits of their processes to obtain and maintain high yield. The answer to this general question is actually application-specific. The tolerances in thickness and index values are different for a high-efficiency AR coating than for a narrow bandpass filter or a high-reflector, for example.

The quantity that determines the optical properties of each layer of a coating is the optical path of the layer, OP = n x t, where *n* is the refractive index at wavelength λ, and *t* is the physical thickness. In the first approximation, the quantities are interchangeable, but for AR coatings requiring the lowest possible reflectance, the value of the index weighs in more heavily. Consequently, in spite of precise and accurate physical thickness monitoring and control, the lowest reflectance value might not be attained. Many high-performance coatings, especially those that operate over wide bandwidths, include layers whose thickness is less an integral multiple of a wavelength accessible by the optical monitoring system. A corollary to this requirement is deposition process stability to insure that the *n* and *t* values are reproducible over time. Process stability requires coating material batch consistency and reproducibility in the coating equipment mechanical and process parameters (temperature, rate, spacing, background pressure, composition, and deposition energy). Any question about process temporal stability requires a current repetition of the calibration of the optical and mechanical properties of the coating layers before optical parts can be introduced into the production phase.

Examples of typical AR design will illustrate the importance of index and thickness knowledge. First we present in Figure 2 the predicted performances of three designs for an AR that is required to reflect <0.5% avg in the visible region and < 0.2% at 1064 nm for 30° incidence (mean polarization) on BK-7 glass. The designs differ in layer number. The layer materials are silicon dioxide, SiO_2, and tantalum pent-oxide, Ta_2O_5. We see that the 14-layer design (green curve) provides broader average coverage in the visible and has a better centered, but narrower reflectance at 1064 nm. The orange curve for the 10-layer design, however, permits large error tolerance because it is broader near 1064 nm than the 14-layer design (green curve), but at the expense of higher average R in the visible region. The 14-layer design has two layers <4 nm thick; the 10-layer design has one such thickness. The thinnest layer in the 6-layer design is 17 nm.

Now let's look at the effect of changing the index of the last layer from 1.46 at 520 nm (SiO_2) to 1.38 (MgF_2) and re-optimizing the designs to fit the target values. In Figure 3, we see significant reductions in average reflectance when MgF_2 is substituted for SiO_2 in the last layer of the design. There is only one layer of thickness < 4nm in the 14-layer design now, but there are now two such layers in the 10-layer design. Further design refinement might improve the performance slightly.

The design exercise has illustrated two points: that the lower the index of the last layer is, the lower will the average reflectance be; a change of 5% index value is significant. Secondly, that designs for highest the performance can require very thin layers. Thin layers demand tighter control (lower error) on absolute physical thickness, and this requirement has an impact on production yield.

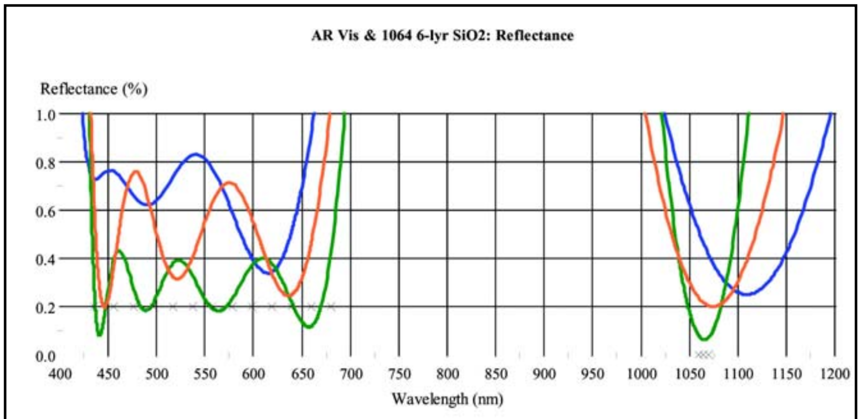

Figure 2. Computed performances of three designs: orange curve: 10-layers; blue; 6-layers, and green: 14 layers. Last layer is SiO_2.

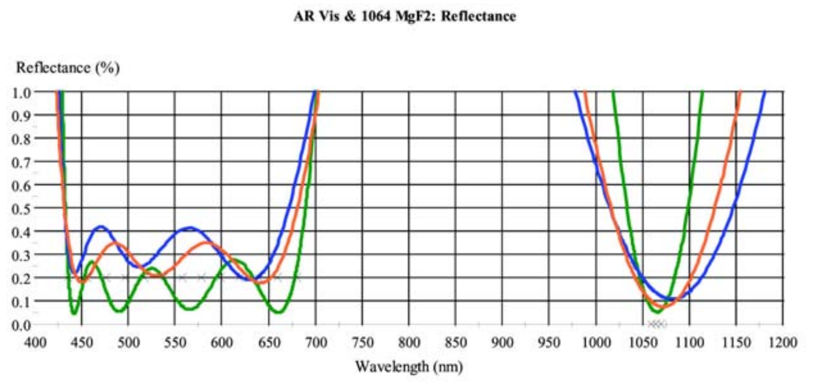

Figure 3. Computed performances of three designs with the last layer changed to MgF_2. As with Figure 2, Orange curve: 10-layers; blue; 6-layers, and green: 14 layers.

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