ARRI FSND Filters

Technology and Comparison Charts

WHITE PAPER

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ARRI FSND Filters – Technology and Comparison Charts

New anti-reflective optical thin-film coatings are offering exciting opportunities in the development of MPTV neutral density (ND) filters. These state-of-the-art tools offer unprecedented optical precision, and provide a whole new range of options for optical engineers, cinematographers and camera operators.

ARRI introduced camera-internal absorbing anti-reflective multilayer thin-film filters for ALEXA's and AMIRA's in 2013. Placed immediately in front of the imaging sensor, they deliver maximum optical quality. Our new MPTV filters optimized for use in matte boxes are based on this experience, coupled with further detailed research and exhaustive testing.

Optical performance is of course paramount, but the ability to withstand the rigors of life on set, and robustness in extreme environmental conditions are also high priorities. And, to support logistics, ARRI's new MPTV filters come complete with barcoded labels.

Technology Review: From Dye to Thin Film Neutral Density Filters

ND filters reduce the amount of light entering the lens, homogenously and neutrally colored across the whole image scene. A typical application for them would be to allow shallower depth-of-field with a larger aperture stop - i.e. a lower T-Stop number (see Figure 1). For optical engineers, the challenge is to make filters that achieve this without the risk of adding unwanted visual side effects or compromising image quality.

Figure 1. Upper image: No filter. Middle image: ARRI FSND 1.2 filter. Lower image: Typical classic dye based ND 1.2 filter (not IRND). A neutral density filter enables smaller T-stop settings while keeping exposure constant, to blur the fore- and background due to a decreased depth of field. For example, a scene that is exposed with a T-stop of 5.6 (upper image) can be exposed at 1.4 (+4 stops); when a ND 1.2 filter (-4 stops) is implemented (middle and lower images); when using digital cameras, attenuation of near-infrared light becomes essential to avoid false color issues (bottom image).

Lens: 65mm, T-stop variable, focus distance approx. 1.1m; Camera: Alexa XT, EI 3200, 25 FPS, SA 358°, WB 3200K matched to light source, open gate (image cropped for illustration), rendered to Rec 709; Matte box: ARRI SMB-1

The twentieth century was dominated by absorbing ND filters made from dyed glass or dyed polymer/adhesive films sandwiched between two glass sheets. With the introduction of digital cameras filters designated "IRND" were developed that had an increased attenuation around 800nm (see Figure 2). This was necessary because common imaging sensors pick up near infrared light, which contaminates the image with false color information, giving some black tones a reddish hue, for example (see Figure 1).

However, the local spectral dimming can also affect the red channel appearance, and color neutrality can suffer compared with earlier standard dye-based filters for film-based acquisition. A constant transmittance over the sensor's full spectral range is desired (see Figure 2 for a comparison of typical IRND and idealized ND filters).

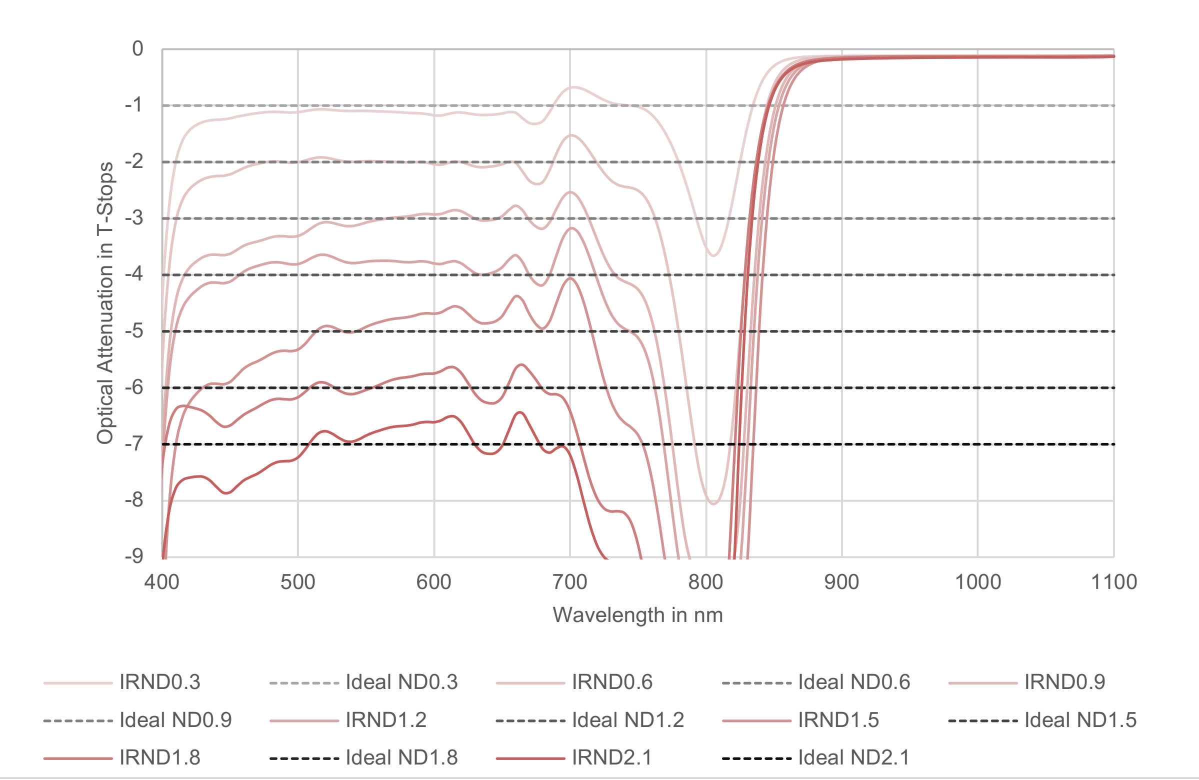

Figure 2. Spectral attenuation of an exemplary set of dye-based IRND filters compared with idealized neutral density filter curves from ND0.3* (-1 stop) to ND2.1 (-7 stops). Deviations from these idealized constant spectra means that the filter will change color appearance and if large enough, this color difference is perceptible.

Dye-based filters have many inherent limitations, and multilayer thin-film coatings were identified as a possible alternative to them decades ago. But it has taken until now for the technology to come up to scratch for cinematographic applications.

Early attempts, in the 1950s produced coatings that acted as a partial metallic reflector. [1]. This was improved by shading the reflector [2]. Because of their low reflecting but smooth optical appearance, such filters were named "dark mirrors". Their coatings were made up of silicon monoxide layers, and an aluminium film overcoated with a germanium film – the germanium's absorbance masks the reflective aluminium film in the visible spectral range. The key optical design feature was to lessen the coupling between spectral transmittance and reflectance to enable low reflecting absorbing thin film coatings.

In the early 1970s a metallic ND filter with further reduced spectral reflectance was patented [3], but the coating's reflectance was still dependent on its frontside orientation with respect to the object space/the scene. This asymmetry creates problems while filming as pronounced "ghosting" can occur - especially with several consecutive filters in a matte box, or if a single filter is incorrectly positioned.

There were many technological advances during the 1970s and 1980s, for instance in the understanding of how to combine color neutral absorbing ultrathin metal films (<10nm thickness) with impedance matching

* ND 0.3 attenuates by a factor of $10^{-0.301} = 0.50$, ND 0.6 by $10^{-0.602} = 0.25$, etc.

dielectric multilayer coatings. By the early 1990s the key design principles of today's optical thin-film neutral density filters had been established, [4] and [5].

Products aimed at the photography industry were patented shortly after in Japan [6]. Many more patents and patent applications followed, and continue to come. A recent application [7] gives an overview on more contemporary designs and cites many relevant patents.

Optical thin-film coatings implementing ultrathin metal films are also common in modern architectural, automotive and aerospace applications, as well as in the semiconductor industry.

How Thin are Thin Film Coatings?

The complete multilayer thin-film coating on one clear glass substrate side is roughly a ten thousandth of the substrate's thickness, comprising several layers or complex mixtures of dielectrics, semiconductors and metals (see Figure 3).

The absorbing layers embedded inside the coating stack have a thickness of only a few nanometers – that is approximately ten atomic layers, and thickness must be controlled with a precision in the range of 0.3nm or 0.000 000 000 3 meters. To give an idea of the scale we're talking about, grass grows about 20 to 40 nanometers per second in the summer months.

Optical coating design presents big challenges, and, unsurprisingly, only a few selected optics manufacturers master the ultrathin metal film coating process to deliver high quality and highly repeatable performing filters.

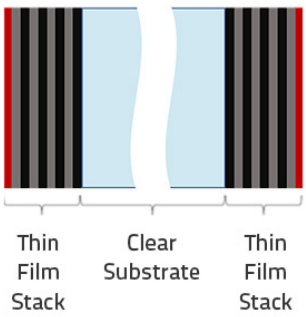

Figure 3

Color Neutrality

At first, neutral density filters should attenuate the incoming light’s spectrum neutrally over the field of view to maintain wide color gamut, and minimum color difference compared with shooting without filters (see Figure 4).

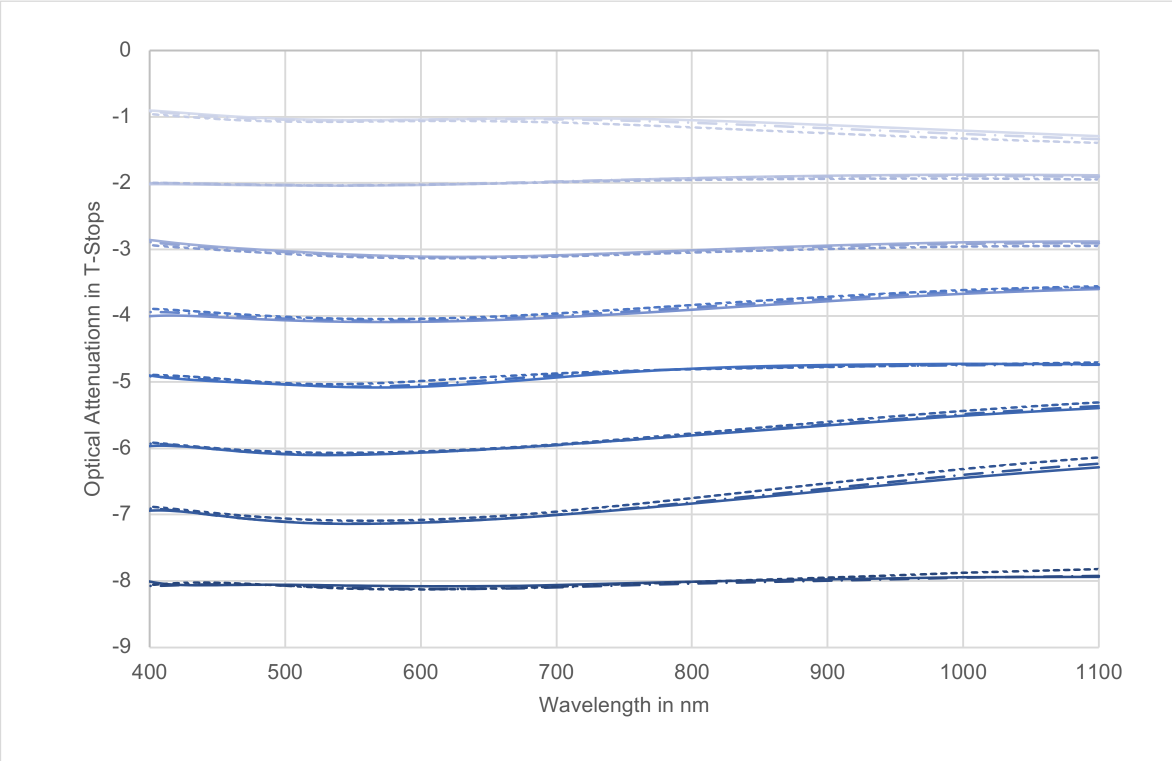

Figure 4. Spectral attenuation of ARRI FSND filters from ND0.3 to ND2.4. Transmittance is highly neutral in the visible spectral range (mainly 400nm to 750nm) and does not depend significantly on angular field of view (AFoV) position - for each filter density, the horizontal field of view positions 0° (on optical axis), 60° cone (e.g. max. AFoV for ARRI Zeiss Master Prime 21mm on Super 35 format) and 90° cone (e.g. max. AFoV for ARRI Zeiss Master Prime 12mm on Super 35 format) are depicted.

Such spectrally smooth and almost angle-independent attenuation characteristics became available through multilayer thin-film ND filters and are not possible with classic dye-based absorbers. This becomes more obvious when we compare color differences by both technology approaches with a test chart, cf. Figure 5.

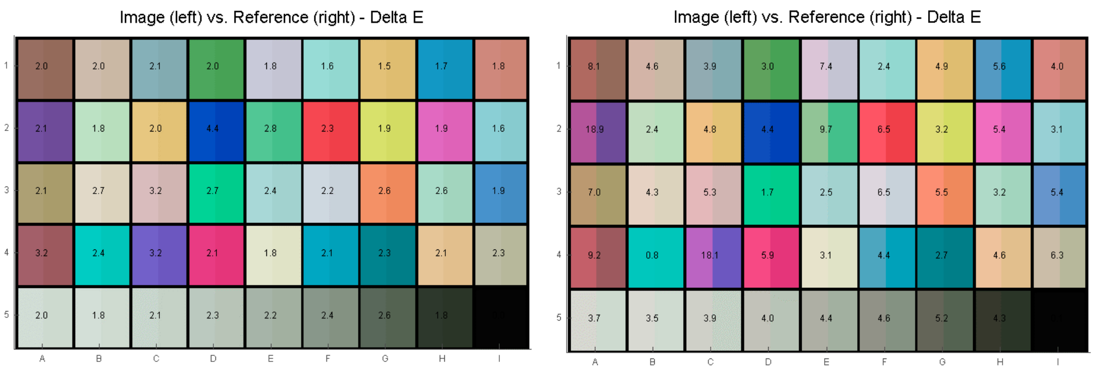

Figure 5. Results of color difference in transmittance for an ARRI FSND 1.2 filter (left example) and a typical classic dye based ND 1.2 filter (right example). The inset numbers are CIE2000(1:1:1) ΔE values, that give a hint on perceivable color difference. For instance, ΔE ≤ 1.5: slight, 1.5 < ΔE ≤ 3: noticeable, 3 < ΔE ≤ 6: appreciable color difference.

Stray Light

For ease of access and replacement, MPTV filters are positioned in a matte box in front of a lens. While this position is convenient, it is optically delicate, and can result in flare-like ghost reflections being focused onto the imaging sensor. The severity of visibility of this stray light is proportional to spectral radiance*, which usually increases with focal length**. But it is also highly dependent on the specific optical design of the deployed lens, and the associated stray light paths.

Whether this stray light is regarded as problematic, or artistically valuable, lies in the eye of the beholder, and their specific imaging requirements. To facilitate a choice to the DP and to avoid distraction from the objective lens' flare, ARRI FSND filters are equipped with low reflective coatings on the smooth optical surfaces, and blackening of the edge surfaces (see Figures 6 and Figure 7).

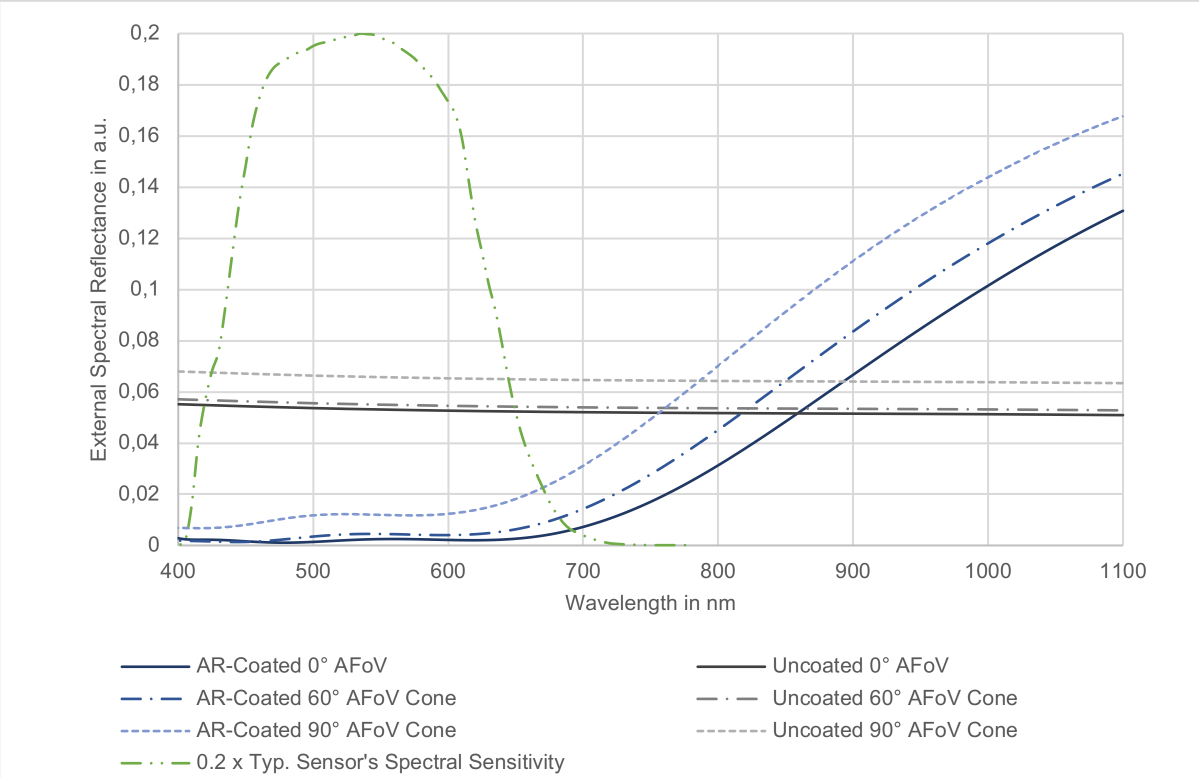

Figure 6. Typical reflectance of ARRI FSND filters compared with uncoated glass. With anti- reflective coatings, the reflectance is reduced by nearly one order of magnitude in the visible spectral region (here indicated by a typical sensor's spectral sensitivity). A higher reflectance in the near infrared region is acceptable, and does not deteriorate imaging performance (cf. Figure 4, Figure 5 and Figure 7).

* Simplified, spectral radiance is the spectral optical power over the irradiated area.
** Concerning entocentric imaging with decreasing angular field of view for increasing focal length.

In normal cinematographic situations with increasingly sensitive imaging macro contrast (HDR), micro contrast (4K/8K) and color gamut (Rec 2020), the flare of ARRI FSND filters is designed to be minimal (see Figure 7).

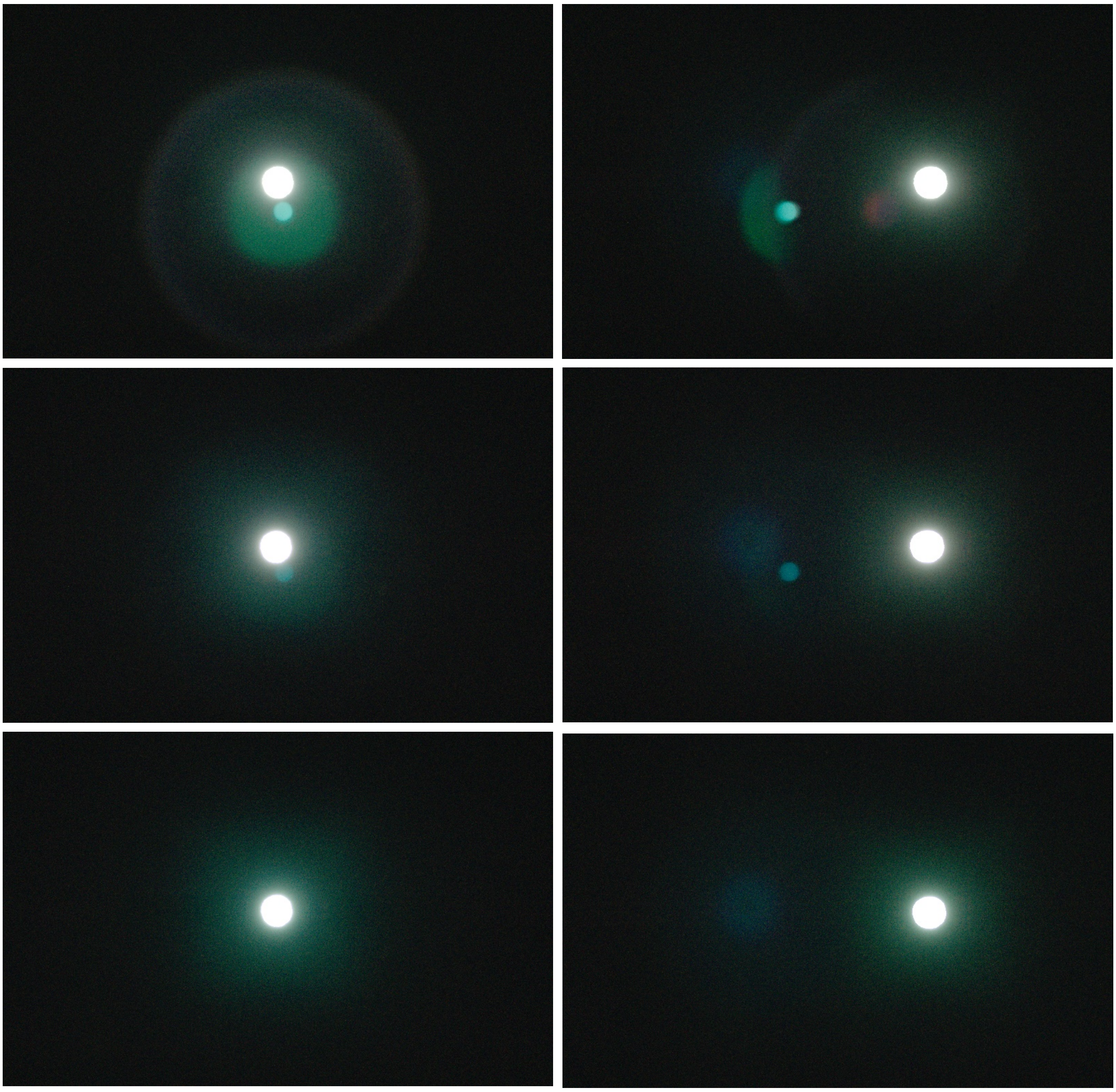

Figure 7. Stray light performance comparison of a typical classic dye-based ND 1.2 filter without anti-reflective coating (upper row examples) to ARRI FSND 1.2 (middle row examples) filter. The uncoated dye based ND 1.2 filter shows strongly saturated ghosting colors, and a significant reduction of macro contrast for illumination near the optical axis – an issue for HDR imaging. The lower row examples show the situation without filters inside the matte box. The light source's illuminance was adjusted for constant exposure and camera settings. Lens: 65mm, T1.3, focus distance approx. 0.9m; Camera: Alexa XT, EI 3200, 25 FPS, SA 358°, WB 6500 matched to light source, open gate, rendered to Rec 709; Matte box: ARRI SMB-1

Another topic related to flare are surface defects, such as scratches, particulate contamination of the surfaces, the surface's roughness and inclusions, bubbles, and striations inside the glass substrates. These defects usually become visible inside homogeneously bright bokeh areas, for instance in out-of-focus highlights. This is tackled by strict tolerancing of the surface's and the glass' quality, state-of-the-art manufacturing processes, and meticulous quality control. Another counter-acting measure is a special protective coating that, combined with a dedicated multilayer thin film design and material selection, enables easy cleaning, and improves robustness against wear (see Figure 8).

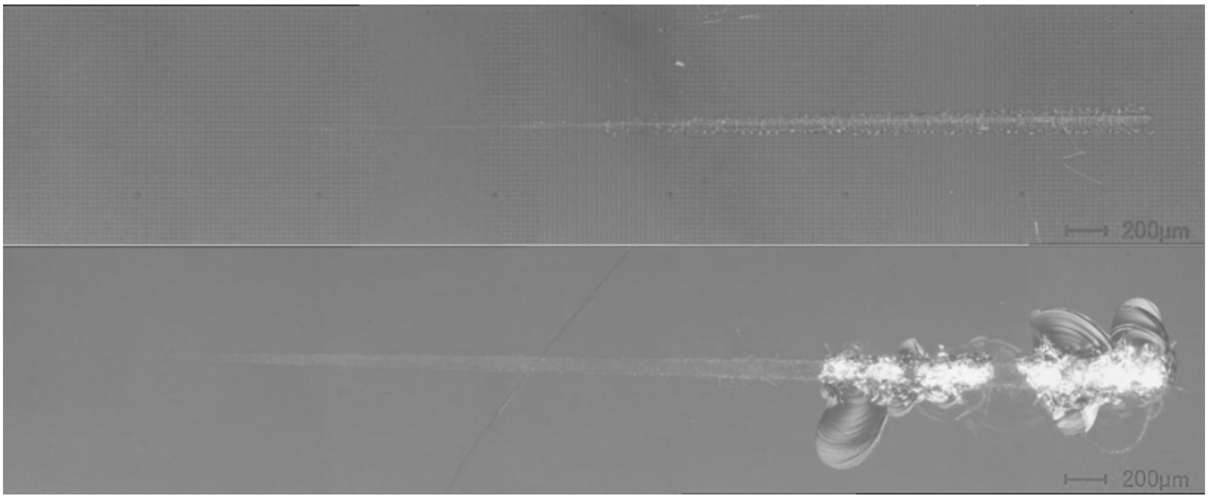

Figure 8. Scratch resistance testing per ISO 20502 standard to quantitatively measure adhesion and scratch resistance of thin film coatings. Depicted are scratch marks, for which the load on a diamond tip with 200µm radius was progressively increased up to 50N (proportional to approx. 5kg load), while sliding on the specimen's surface from left to right. The top image shows an ARRI FSND sample; the lower a reference competitor's thin film ND filter, for which even the substrate shows spallation under the applied pressure. The wider the scratch mark, the softer is the corresponding multilayer coating.

Matte box filters are used in harsh environments and need to fulfil the camera team's expectations on handling robustness, reliability and optical performance over an extended period. MPTV filters also need to withstand global climatic conditions, UV radiation, and contact with chemical substances like dedicated optics cleaning agents, cosmetics and hand sweat. To improve mechanical shock resistance and handling comfort, ARRI FSND filters have a rounded circumferential geometry.

When high dynamic range image acquisition and clean out-of-focus highlight effects are required, efforts to maintain high surface cleanliness become increasingly important – for example when shooting inside with lit candles or bright daylight through windows. ARRI FSND filters' water and oil repellent surfaces support easy cleaning and reduce the likelihood of optical surface contamination in the first place.

However, non-volatile residuals from unfavourable cleaning agents[*] may still deteriorate the optical performance of the filters, and care should be taken to avoid them. The cleaning and handling of precision optics in every imaginable situation can be a delicate matter and cannot be fully covered in this short paper. For a more thorough understanding of the topic, we advise comprehensive literature [8]. With cinematography and thin-film ND filters in mind, ARRI also provides a short cleaning reference with each MPTV filter.

Imaging Performance

Finally, let's address imaging aberrations by MPTV filters. The highest imaging performance allows for many creative options. It simplifies implementation of CGI content, and in case less crisp pictures are preferred, it is always possible to intentionally and creatively deteriorate the image.

Hence, ARRI FSND filters are designed for superior imaging performance. To limit asymmetric distortion, especially critical when using tele lenses, the optical surfaces must be fully parallel to the filter's area. Slight spherical bending usually is not a big issue, but irregular surface form, or glass volume deviations, can decrease imaging resolution. To avoid aberrations by such irregularities (which can worsen when several filters are inserted into the matte box), the average[**] disturbance limit by one ARRI FSND filter allows for physically limited, and thus best possible imaging performance (to give some idea of how thin this layer is: if the width of the filter were scaled up to 4000 km - the distance between Los Angeles and New York City - the thickness would scale up to just 75 cm).

[*] For instance, unfavourable might be household window cleaner with perfume and intentionally non-volatile residual substances for "longer lasting cleanliness".
[**] RMSt transmitted wavefront error according to standard ISO 10110-14.

Admittedly, plane parallel windows in front of or behind a lens would unavoidably introduce intrinsic aberrations, even if the filter substrate was a perfectly plane parallel glass sheet without any irregularities. As function-of-lens parameters (for instance, a decreasing T-stop and an increasing angular field of view), as well as filter parameters (for example, substrate thickness and dispersion of the materials), lateral and longitudinal chromatic, spherical, coma, astigmatism/field curvature, and distortion occur. In many cases, those intrinsic aberrations do not become noticeable and are negligible compared with the objective lens' aberrations.

But if they do become apparent (which conceivably might happen when shooting with an ultra-wide-angle lens at moderately closed aperture stops), there are several options:

- Minimize the number of filters in the matte box. A maximum of three consecutive filters is recommended. It's worth noting that three consecutive filters without anti-reflective coatings make an additional light loss of approximately -0.4 stops.
- Consider using camera-internal filters instead of, or additional to, matte box filters. At the filter position between lens and detector, as the intrinsic aberrations will usually be lower because of the smaller angular field and thinner filters. ARRI Signature Prime lenses even account for the intrinsic aberrations caused by camera-internal filters in ARRI cameras. And, at this position, there is the additional benefit that no focusing of veiling glare or flare appears for first order scatter from the filter when using entocentric or telecentric lenses – this is the case for most motion picture or photographic lenses.

Further Reading

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