Considerations for dimensional sizing of imperfections using magnification imaging with a digital camera

In this Annex, we consider some practical aspects of sizing optical imperfections according to the dimensional method of Section 3.5, but not covered in Annex B. This extends the discussion of Annex C. While the considerations here are relevant for any imperfection dimension, the issues become severe for imperfections equal to or smaller than size A, and especially so for narrow scratches. For these imperfections a magnifying imaging system will often be required, both for documentation and consistency. For concreteness, we consider a typical dark-field laboratory microscope with various magnifying objectives which forms an image recorded by an industrial-grade CCD camera.

The measurement parameters we consider are: the image field-of-view, F, the resolving power, R, the minimum sizeable imperfection, S_5, and the collection efficiency C. The microscope parameters that determine the measurement parameters are: the objective magnification, M_o, the (de)magnification to the camera, M_c, the objective numerical aperture, NA, the camera pixel spacing, D_p, the camera sensor size, D_s, and the approximate illumination wavelength, λ. Below we define the measurement parameters and explain how they impact one another. We then present a table of measurement parameters using a typical set of fixed instrument parameters for several values of objective magnification, which is typically the most flexible instrument parameter.

The microscope objective forms an image, which is projected onto the camera. The field of view seen of the source plane at the camera is

$$F = D_s/M_p/M_{c.}$$

Field of view decreases with magnification. The resolving power of the objective is

$$R = 1.22\ \lambda\ /2/\text{NA}.$$

Typically, the NA gets larger as the objective magnification gets larger, so the resolving power improves with magnification. For the minimum sizeable imperfection, we use the rule-of-thumb that states that to reliably size an object, that object should span roughly 5 camera pixels:

$$S_5 = 5 \text{ x } D_p/M_p/M_c.$$

Note that if R is larger than S_5, R must take the role as the minimum sizeable imperfection. S_5 is a conservative quantity for sizing. The collection efficiency is

$$C \sim ½\ (1\text{-sqrt}(1\text{-NA}^2)) \text{ x } 100.$$

The collection efficiency is best used as a relative indicator of instrument sensitivity. If it is known that an imperfection achieves a certain signal to noise at high magnification (high NA), then C can be used to determine if less magnification (even if within acceptable resolving limits) will have adequate signal-to-noise.

Typically, the key tradeoff is between S_5 and F. As smaller imperfections must be measured, there is a corresponding drop in field of view. As we will see below, this can have serious consequences.

The table below shows some typical values.

	microscope objectives-------------------------------------				
objective magnification M_o	**2.5**	**5**	**10**	**20**	**50**
objective numerical aperture NA	0.06	0.13	0.2	0.4	0.7
objective resolving power R [um]	5.59	2.58	1.68	0.84	0.48
minimum sizeable imperfection S_5 [um]	20.48	10.24	5.12	2.56	1.02
field-of-view F [mm]	5.84	2.92	1.46	0.73	0.29
optimal collection efficiency C [%]	0.09	0.42	1.01	4.17	14.29

camera magnification M_c	0.63	matches 1" microscope tube to 2/3" sensor
sensor size D_s [mm]	9.2	horiz width of 2/3" sensor
pixel size D_p [um]	6.45	1.2 megapixel CCD
wavelength λ [um]	0.550	center wavelength of typical bulb

Consider now a size-A scratch callout on a 1” clear-aperture optic. The largest allowable scratch width is 5 um; we must consider scratches as narrow as 1 um for accumulation purposes. The first requirement would allow us to operate at 10x objective, with an S_5 of roughly 5 um. Since smaller scratches do not really need to be sized, we will only require that a 1 um scratch be resolvable, not necessarily sizeable. This latter requirement necessitates a 20x objective. To cover a 1” CA with the field-of-view of the 20x objective (and even the 10x) requires hundreds of images. In most cases this will be impractical, so care should be taken how narrow scratches are specified and inspected, if an imaging system/camera is to be used.

There are additional tradeoffs to consider. Camera pixel size can be reduced in order to decrease S_5, but only at the expense of decreased well depth (dynamic range). Larger sensors can possibly be used (at a high cost), but most common microscopes can only handle up to 1” sensors. Higher NA objectives may be possible, but working distances decrease and cost increases. We have assumed throughout that the imaging system has acceptable signal-to-noise for the imperfections of interest. This may not be true for narrow scratches at lower magnifications, with their lower collection efficiency. So advantages with field-of-view may come at the expense of poor signal-to-noise for imperfections of interest.

Once the appropriate imaging/camera system is chosen, a decision must still be made on how to interpret the imperfection images. Consider an intensity profile across a narrow imperfection. As opposed to the steep, well-defined imperfection boundaries typical of larger imperfections (well away from sizing or resolving limits), the profile of the narrow imperfection will show gradual, sloping edges. In this case, an appropriate measurement technique must be used for the imperfection width. For example, a full-width-half-maximum approach may be appropriate, or a 90% integrated intensity may be preferred. Usually, these details will not have a significant impact on the performance of the optic, but they could be important in determining conformance to the specification. So again, care is warranted when specifying and inspecting narrow/small imperfections at or below size A.