Meaningful Surface Roughness and Quality Tolerances

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For surface quality and surface roughness, there are few guidelines or tools for calculating appropriate tolerances. Typically, we simply use a legacy specification (e.g. 60-40 and 3 A RMS) with little thought for either the cost of achieving the specification or the penalty for failing to achieve it. Often these legacy specifications are often unnecessarily costly and in some cases completely meaningless. This paper provides some basic rules and equations for calculation of the real or perceived impact of these specifications, and some guidelines for the initiate (and for some of us veterans as well) as to how to compose a meaningful tolerance.
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1. Introduction – changing times, and changing drawings

In the late 70's and early 80's, there was very little to choose from in the way of optical drawing formats. MIL-STD-34, published in 1960, a notes-based format was used in the US and much of the world. It survives today in spirit, if not in practice in much of the optics community. In a MIL-STD-34 drawing, surface quality was specified according to MIL-O-13830 (1954) and surface roughness according to MIL-STD-10 (1949).

Times have changed. Today we know a lot more about surface quality and surface roughness, and how these parameters affect performance, or don't, in most optical systems. Dozens of new drawing standards have been released, many of which use the same notation, but interpret the notation differently. Optics manufacturing has progressed from pitch and slurry to diamond machining and CNC systems. Metrology has moved from visual check to megapixel interferometers. And yet we are still writing our specifications the same way. We can, and should, do better.

2. Scratch and dig is a cosmetic standard [1].

The surface quality test of MIL-PRF-13830B (the successor to MIL-O-13830) is based on a visual comparison, under specific darkfield lighting conditions, of a subject surface imperfection and a comparison standard set to determine the visibility or "grade" of the imperfection. The specification references a drawing for surface quality standards, C7641866. This approach to surface imperfections was first proposed by McLeod and Sherwood in 1945 [2]. They offered up comparison standards numbered from 10 to 120, to be used in this comparison method. As early as 1945 they recorded that "there is little correlation between the appearance or visibility of a scratch and its measured width." Frankford Arsenal documents dating to the same period declare that "these numbers are arbitrary, and are not to be assumed as denoting the width of the scratch." Scratch morphology is a better predictor of scratch visibility or brightness, than width [3]. The master scratch set is at Picatinny Arsenal, and has remained intact and virtually unchanged in 50 years.

Because of a series of unfortunate events, however, the scratch and dig standard has become the most mis-used, ambiguous, and mis-interpreted specification. Most of these problems can be sorted out, however, by changing the way we call out our surface quality specification.

3. Choosing a meaningful surface quality specification - cosmetic

If you are still trying to specify the cosmetic quality of your optics, then the scratch-dig number system works for you. I don't recommend using anything tighter than 60-40, unless you want to spend money on a cosmetic specification. Certainly one should never go below 40-20 for a cosmetic specification. Even the #40 scratch is barely visible in normal conditions.

Rather than use the MIL-PRF-13830B, however, it is wiser and safer to use the voluntary equivalent, ANSI/OEOSC OP1.002 [4]. This new standard is still being maintained, is less ambiguous, is not at risk of being withdrawn, and has far less confusion associated with it than the MIL standard. Since it uses the same comparison standards as the MIL, the meaning of the numbers is the same. The language to invoke this standard is "Surface quality 60-40 per ANSI/OEOSC OP1.002." You will want to also specify the comparison standard to be used.

Discounting the ones claiming to offer width-based standards (which is just plain wrong) and chrome on glass reticles (which don't look like scratches), there are three commercial manufacturers; FLIR/Brysen, Davidson Optronics, and Jenoptik. This last is the plastic paddle sold by both Edmund Optics and Thor Labs. I'm not sure how repeatable any of these standards are, but I suspect each company does a decent job of certifying them to whatever internal masters they have. In some cases, these sets are not mutually compatible. The #10 artifact of one brand could be brighter than the #60 artifact of another [5]. So

the meaning of the visibility of a scratch is dependent on the comparison samples being used. For all commercial procurements, the brand of the comparison standard should be referenced on the drawing. For example, "Surface quality 80-50 per ANSI/OEOSC OP1.002 using brand x comparison standard," is a reasonably unambiguous approach.

4. Choosing a meaningful surface quality specification - dimensional.

Some applications require a width specification, or are sensitive to scratches too small to see. In 1985, there were no practical alternatives to scratch and dig. Lots of people have tried to extend the usefulness of the scratch-dig standard by adding higher brightness light sources and magnification, which has caused more confusion. In 1996, with the publication of ISO 10110, there was an alternative. Based on the German DIN 3140 standard, part 7 describes all surface imperfections in terms of a "root area", and not only allows but practically requires direct measurement of every scratch and dig. Lately this approach has been gaining momentum, but aside from a few stalwarts, it has not become common practice in the US.

The newest revision of the American National Standard for surface imperfections, OP1.002, retains the visibility method from MIL-PRF-13830B, but adds the dimensional method from MIL-C-48497A, which is familiar, easy to use, and effective for people who really require a functional specification. To invoke the dimensional method, a pair of letters is used, such as A-A or E-E, to reference a specific size of imperfections.

Table 1. Translating scratch width and dig diameter to correct specifications per OP1.002. Note that if you need to specify a specific specification that isn't on the table, e.g. 2um scratches and 20um digs, you can write it using A and then the value required (A2-A20)

Maximum scratch width in microns	Scratch specification letter	Maximum dig diameter in microns	Dig specification letter
120	G	700	G
80	F	500	F
60	E	400	E
40	D	300	D
20	C	200	C
10	B	100	B
5	A	50	A
n	An	n	An

5. Surface texture.

Surface texture, or roughness, is another area where new specifications improve our options. MIL-STD-10A, which was a very good standard for the time, was not for polished surfaces *per se*, and focused primarily on average roughness, a parameter that is uncommon in the optics community. Today, the successor document is ASME B46.1-2002, and the standard has grown to some 110 pages, and now includes notations for more than 40 parameters, including RMS, slope, skew, kurtosis, and my personal favorite, PSD. The latest revision adds the areal versions of all these specifications, which is a huge breakthrough for power users who need to specify the 2D PSD and RMS amplitudes by spatial frequency for (for example) diamond turned surfaces. But for most applications, all you need is an RMS surface texture specification.

6. Choosing a meaningful surface texture specification- scale lengths.

There as several good papers on the effects of roughness and waviness[6,7]. Unfortunately not all of them are still in print, such as Bennett and Mattson's excellent book. But the equations required to determine a meaningful roughness specification are fairly simple. High spatial frequency surface texture, or roughness, scatters light. The amount of light scattered is proportional to the square of the RMS roughness (assuming a lot of stuff not worth getting into here), and the angles the light is scattered into is determined by the spatial bandwidth of the roughness.

Most people are unaware of the importance of spatial bandwidth (or trace length or window size, on unfiltered data) in evaluating roughness. Simply put, a roughness without a spatial bandwidth is meaningless. For almost all smooth surfaces, if you measure a larger area, the RMS surface error is higher; if you measure a smaller area, the RMS error will be lower.

In reading MIL-STD-10A, it is clear this was well understood by the authors. So if the user did not specify scale lengths, it was assumed that the roughness was measured with a stylus, and that the scan length was 0.03 inches, or about 0.8 mm. This works for applications where we are not so concerned about where the light goes after it scatters from the surface, due to our surface roughness. Unfortunately, the newer standards such as ASME B46.1-2002 and ISO 10110 Part 8 do not have defaults or if they do, they are not the same as they were for MIL-STD-10A. The result is significant ambiguity, and in some cases, gamesmanship on the part of suppliers. So to have a meaningful roughness specification, we must now indicate the spatial scale length explicitly on the drawing. To invoke the old MIL-STD-10A limit, we need to write "Surface roughness per B46.1-2002 Rq < 1 nm for spatial scale lengths shorter than 0.8 mm." This can be shown pictographically in an ISO 10110 drawing or using the symbology of ASME Y14.36M-1996.

In the cases where we do care where the scattered light goes, we need to consider selecting our cutoff spatial scale length. It has been shown elsewhere [8] that the scattered light follows the grating equation. That is,

$$\theta_s = sin^{-1}\left(\frac{\lambda}{L}\right) \quad (1)$$

Where L is the spatial period of interest and λ is the wavelength of light. The shorter the spatial period, the higher the scattering angle. So our roughness can be assumed to scatter light into a host of angles related to the spatial periods covered by the roughness specification. For visible light (say λ = 0.56 um), the default spatial bandwidth from MIL-STD-10A equates to roughness which scatters light at angles greater than 0.04 degrees. For some applications, this is perfectly appropriate.

7. Choosing a meaningful surface texture specification - amplitude.

For a well-behaved polished surface of a lens, the fraction of light scattered (S) is given by equation (2), where n is the index of the material, σ is the RMS roughness, and λ is the wavelength of light. (For mirror surfaces, set n equal to -1).

$$S = \left(\frac{2(n-1)\pi\sigma}{\lambda}\right)^2 \quad (2)$$

From this we can see a direct meaning to our roughness value. For example, assuming we have ten surfaces in a typical visible lens (n = 1.7, λ = .56 um) we can tabulate a meaningful roughness tolerance for allowable levels of scatter in a lens system. In practice, specifying anything below about 1nm RMS is clearly unnecessary except for extreme circumstances.

Table 2. The RMS roughness amplitude corresponding to the allowable level of scatter, assuming a visible band lens, n = 1.7, l = 0.56, and ten surfaces (a typical double Gauss, for example).

total loss	per sfc	RMS, nm
0.001%	0.0001%	0.1
0.015%	0.0015%	0.5
0.05%	0.005%	0.9
0.25%	0.025%	2
1.0%	0.10%	4
1.5%	0.15%	5
3.0%	0.30%	7
5.0%	0.50%	9

8. Summary.

For some applications, very careful attention needs to be applied to determine the appropriate surface quality or roughness specification. But for most applications, these specifications are intended more to control workmanship and prevent unwanted artifacts than to serve as functional tolerances. Nevertheless, it is irresponsible of us to simply write down an incomplete or ambiguous specification in the 21st century. I have provided here the basic rules and mathematics that will allow the casual user to write a meaningful tolerance on surface quality and roughness, with just a few minutes of thought.

7. References and notes.

[1] This history of scratch and dig is drawn from M. Young, "The scratch standard is only a cosmetic standard," Proc. SPIE Vol 1164, pp185-190 (1989).

[2] J.H. McLeod and W.T. Sherwood, "A proposed method of specifying appearance defects on optical parts," J. Opt. Soc. Am. Vol 35, pp 136-138 (1945).

[3] G. White and J. Marchiando, "Scattering from a V-shaped groove in the resonance domain", Appl. Opt. Vol 22, No 15, pp 2308-2312 (1983).

[4] ANSI/OEOSC OP1.002-2009, "American National Standard For Optics and Electro-Optical Instruments-Optical Elements and Assemblies-Appearance Imperfections." American National Standards Institute, Inc. (2009).

[5] For the details, see: D. Aikens, "The truth about scratch and dig", OF&T technical digest, Optical Society of America (2010).

[6] For example, D. Aikens et. al., "Specification and control of mid-spatial frequency wavefront errors in optical systems", OF&T technical digest, Optical Society of America (2008).

[7] J. M. Bennett and L. Mattsson, *Introduction to Surface Roughness and Scattering,* Optical Society of America, (1989).

[8] J. R. Harvey, A. Kotha, "Scattering effects from residual optical fabrication errors", Proc. SPIE Vol. 2576, pp.155-174 (1995).