Advanced Wear Analysis with OmniSurf and OmniSurf3D

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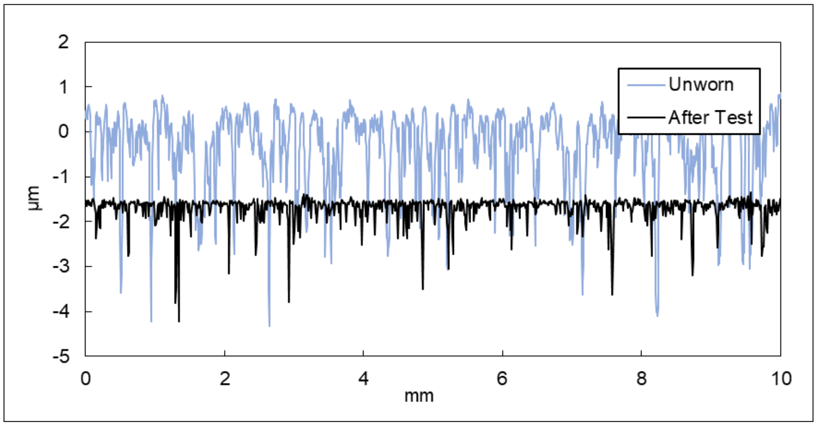


Figure 1. How much has this surface worn? The answer can be much more complicated than it might seem.

Accurately assessing wear is critical for designing surfaces in contact. Factors such as coatings. materials and lubricants can significantly influence the durability of an interface and reliable wear analysis is essential in designing and selecting these factors. Unfortunately, mistakes are commonly made when it comes to assessing the actual wear depth for an interface. Often the attributes that we measure and report are not actually related to the amount of wear.

In this article we will present fundamentals and practical tools for exploring and assessing surfaces at various stages of wear. Armed with these accurate assessments we can make comparisons of coatings, materials and lubricants – and ultimately make decisions to ensure reliable, functioning surfaces.

Macro vs Micro Wear

Let's start by considering two types of wear. "Micro" wear occurs at depths similar in scale to that of the overall roughness. It is often due to the ongoing wear typical of a system operating within designed parameters, such as in well-lubricated engine components.

The two profiles shown here are typical of what one might find in a "micro" wear scenario. The unworn surface on the left is eventually worn to become the surface on the right. High peaks are removed, while the valleys remain.

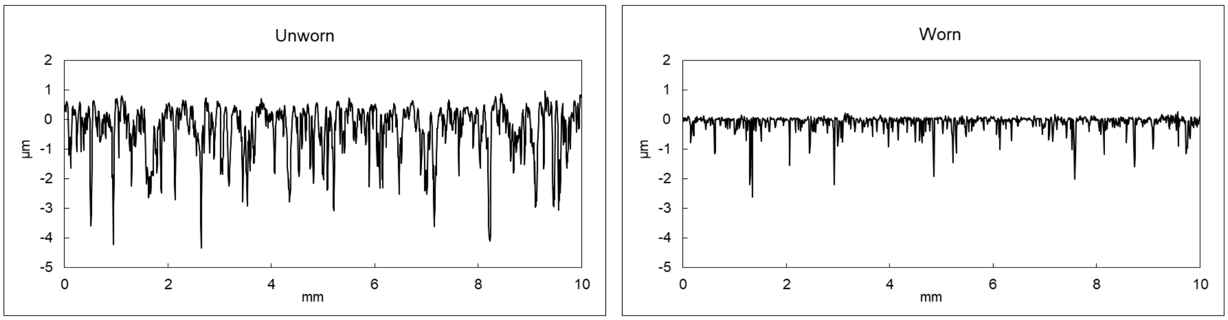


Figure 2. "Micro wear" occurs at a similar scale to the overall roughness of a surface.

"Macro" wear is typically comprised of a worn region that is deeper than the original surface texture. Ideally, this wear might occur in a small region bounded by one or two unworn region(s). In these particular macro wear scenarios we can quickly and easily use tools such as OmniSurf3D's profile wear analysis tool for determining the depth and cross-sectional area of a wear scar:

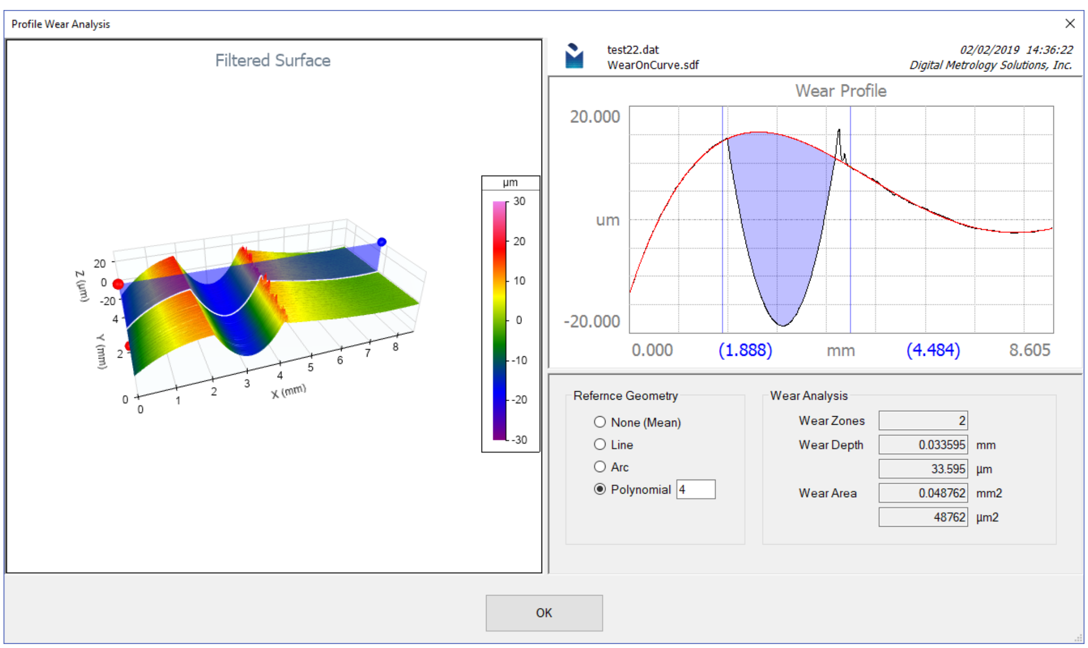


Figure 3. "Macro wear" is a change in geometry rather than a shift in surface texture. This image from OmniSurf3D software shows that the cross-sectional area of removed material is a good indicator of the amount of macro wear.

The Pitfalls of Accelerated Testing

Many tribological tests (e.g., pin-on-disc, ball-on-disc, etc.) attempt to simulate wear at a vastly accelerated pace. This typically results in making a macro wear scar, as the testing conditions are amplified to shorten test times and reduce testing costs. This approach has certain limitations:

1. The wear is not necessarily indicative of actual operating conditions
2. More important for this discussion, the wear scar becomes a “macro” feature whereas in actual function, the wear may be more at a micro scale
3. These tests are not always sensitive to surface texture and lubrication influences.

In many cases, understanding the subtle changes in micro-wear generated within the actual operating parameters is preferable. The good news is that, with modern analysis tools such as OmniSurf and OmniSurf3D, we can measure both macro and micro wear accurately in order to explore the effects of design options and decisions.

Analyzing Macro vs Micro Wear

The general rule we will follow is this: once you have wear areas deeper than the surrounding texture, you need to use macro wear analysis. Comparing roughness in virgin material with the roughness at the bottom of the scar offers no information as to the depth of the scar. It’s like digging a hole in your yard, then comparing the height of the grass at the top to the size of the rocks at the bottom, in order to somehow estimate the depth of the hole!

For “macro” wear analysis we need to consider the overall volume of material removed (or the area of material removed, in profile measurements). Macro wear is a change in shape and geometry rather than a change in the shape of the texture.

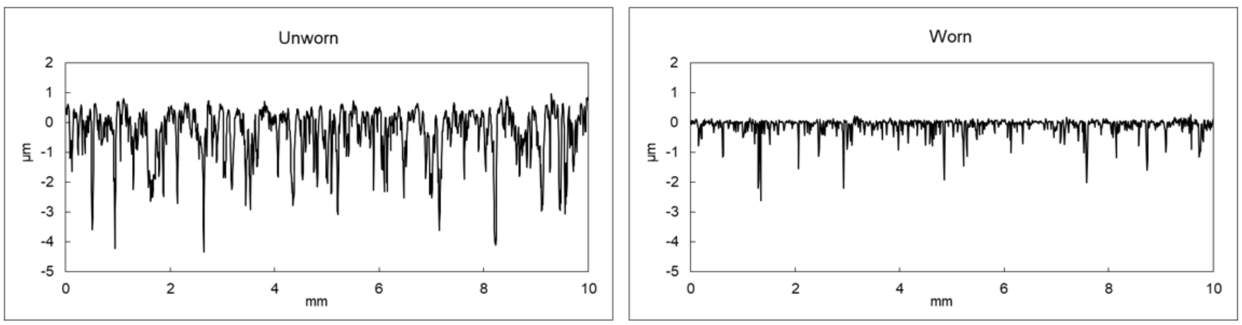
As the OmniSurf3D image in Figure 3 shows, we can fit a reference geometry through the unworn areas to bridge across the worn area. This fitted geometry can be of any form (line, arc, polynomial, etc.) and it approximates the original, unworn surface. On the right side of Figure 3 we see a red reference line that was created based on a 4^{th} order polynomial. This reference was chosen based on the curved nature of the virgin surface areas. The wear depth and cross-sectional area are reported based on the shaded, blue region on the right side of the graphic above.

When dealing with "micro" wear, parameters can lie!

All too often, people will measure a roughness parameter before and after some period of wear, and then use the reduction in the roughness parameter as a measure of the amount of wear. For example, they may simply look at the change in average roughness (Ra) and call that the wear amount.

Consider the two surfaces we showed earlier (and again in Figure 4 below). The unworn surface has an Ra value of 0.61 µm. The worn surface has an Ra value of 0.16 µm. This could lead one to assume that the surface experienced 0.45 µm of wear.

This would be a very <u>wrong</u> assumption!



Ra Before Wear = 0.61 µm **Ra After Wear = 0.16 µm**

Wear Depth: 0.61 – 0.16 = 0.45 µm??

Figure 4. A change in a surface texture parameter such as Average Roughness is often (wrongly) taken as a measure of the amount of wear. If that approach was applied in this example, we would consider that the surface has experienced 0.45 µm of wear—where in reality it has worn well over 2 µm!

The problem with most traditional parameters like Ra, Rz, Rpm, etc. is that they are based on the surface's meanline. And, when a surface wears, the meanline moves as well. Thus, there is a new reference line and results are not comparable. If we plot the worn profile on top of the unworn profile, we get the graph in Figure 5:

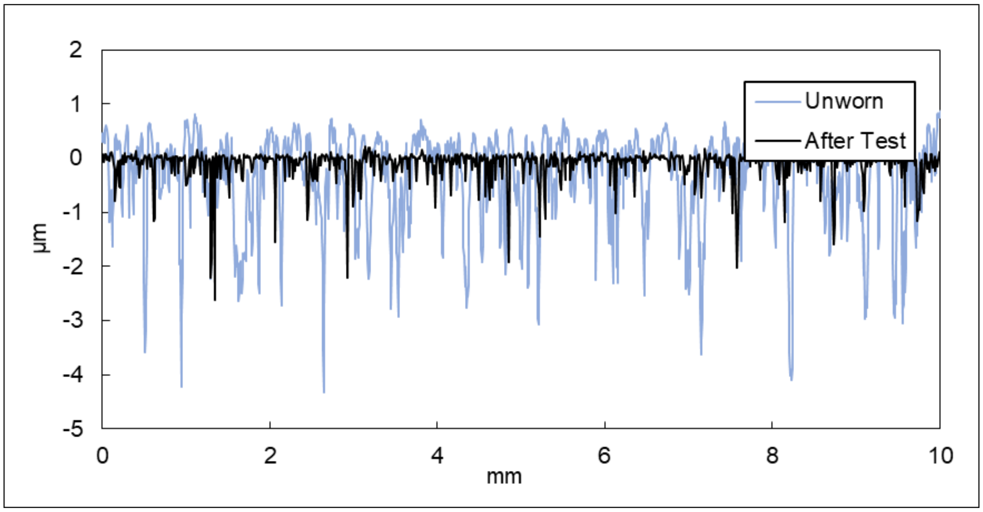


Figure 5. Simply overlaying the Before and After profiles does not take into account that the surface's meanline has moved due to wear.

Looking closely at the above figure reveals a problem: the bottoms of the valleys appear to have moved up after testing. This isn't the case in the physical world. In the physical world, the valley bottoms should have remained the same while the peaks moved downward.

The wear of the surface in the physical world should look more like Figure 6:

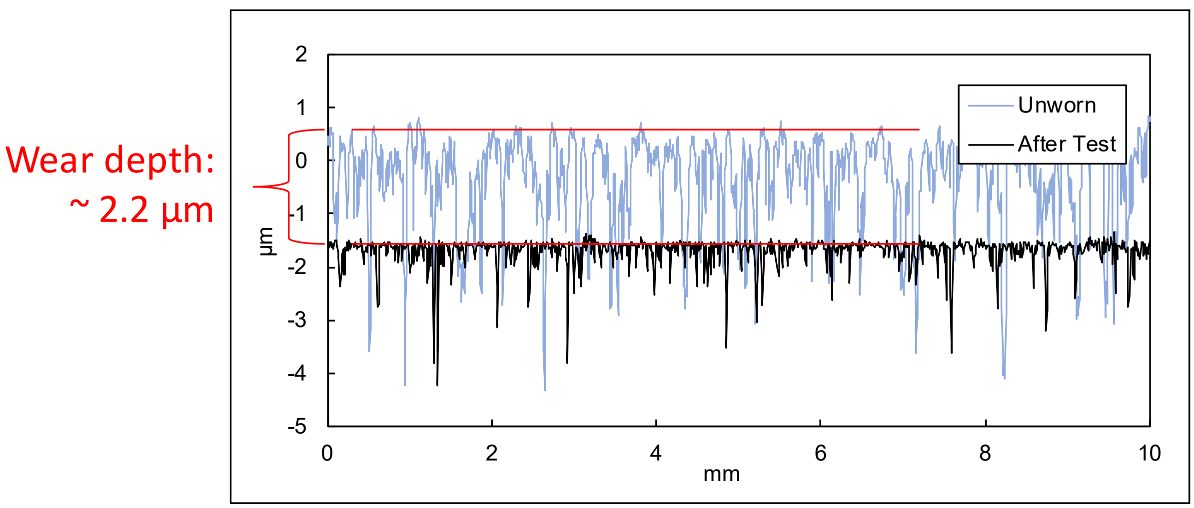


Figure 6. By adjusting the profiles to match the valley structure we get a much more accurate depiction of the actual wear.

Here we have adjusted the unworn and worn profiles to match up the nominal valley structures. In doing, so we have a very powerful graphic. We can clearly see the worn surface has peaks sitting much lower than the original peaks. In fact, we could look at these superimposed profiles and get an estimate of the wear depth of 2.2 µm—**very** different than the (wrongly) estimated value based on the 0.45 µm change in Ra!

Beware of the Rk family!

The Rk parameter family is commonly used to describe surfaces in sliding/loading/wearing applications. This parameter family includes Rk, Rpk, Rvk, Rmr1 and Rmr2. In many cases a "valley volume" (also called "oil holding volume" or "crevice volume") parameter "Rvo" is also included.

These parameters are based on establishing the "kernel" region of the roughness profile and subsequently determining peaks and valleys relative to this kernel. (See also "Plateau Honing: Which Parameters Should I Use?"

In a wear scenario, the peaks of the surface are modified. This changes the "kernel," and thus the other parameters in the Rk family are influenced. Moreover, there can be scenarios in which, according to the Rk parameter family, the valleys can appear to *grow* after a surface's peaks are worn. This is not logical in the physical world, but it is the result of the Rk parameter mathematics.

Consider the two profiles in Figure 7:

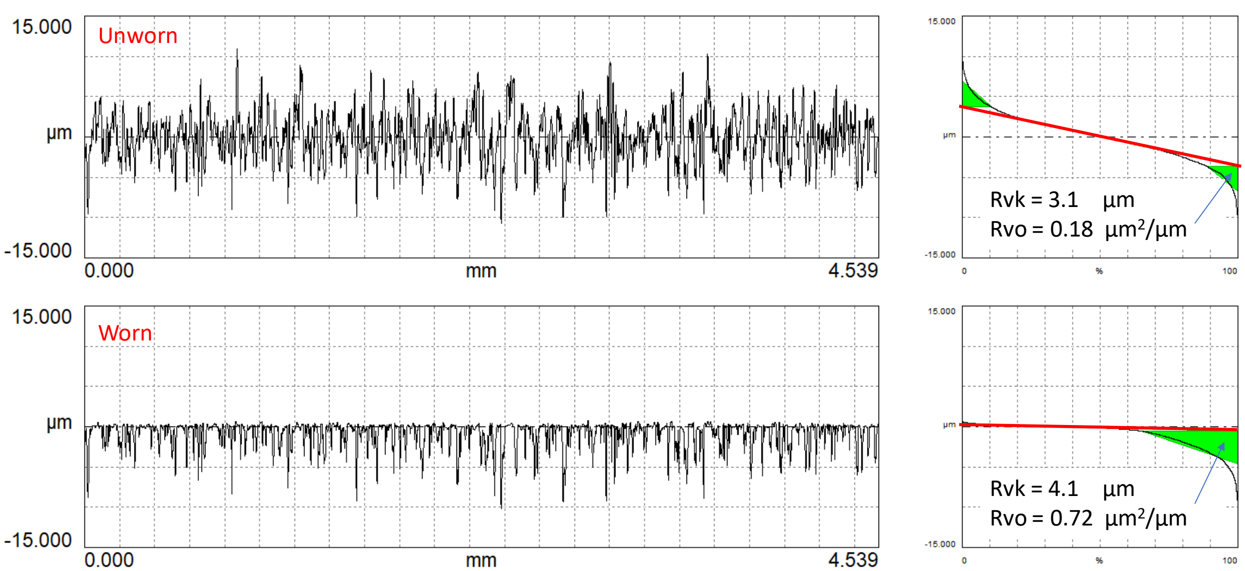


Figure 7. Relying on the Rk parameter family to analyze wear can lead to inaccurate—and even illogical—conclusions.

In the unworn profile above, the Rk line (shown in red) is somewhat sloped. This leaves a relatively small triangle on the right side for the valley volume (Rvo). After wearing (bottom profile), we see that the red line is more horizontally oriented, and a completely different region of the profile becomes associated with the valleys. The valley depths appear to have increased by 33% and the valley volume now appears to be 4 times larger. This can be very misleading if we look only at parameter values with no consideration of the profile graphs.

A better way of describing micro wear

Ideally, "micro" wear can be best understood through the profile graphs themselves. One of the classic works in this regard is a paper by Williamson from the 1960's. (*Williamson, J. B. P. (1967). Paper 17: Microtopography of Surfaces. Proceedings of the Institution of Mechanical Engineers, Conference Proceedings, 182(11), 21–30)*

In this paper, Williamson presented data from several stages of wear on a given surface. More importantly, care was taken to re-measure the surface in almost exactly the same place at each step. As a result, this graphic was produced:

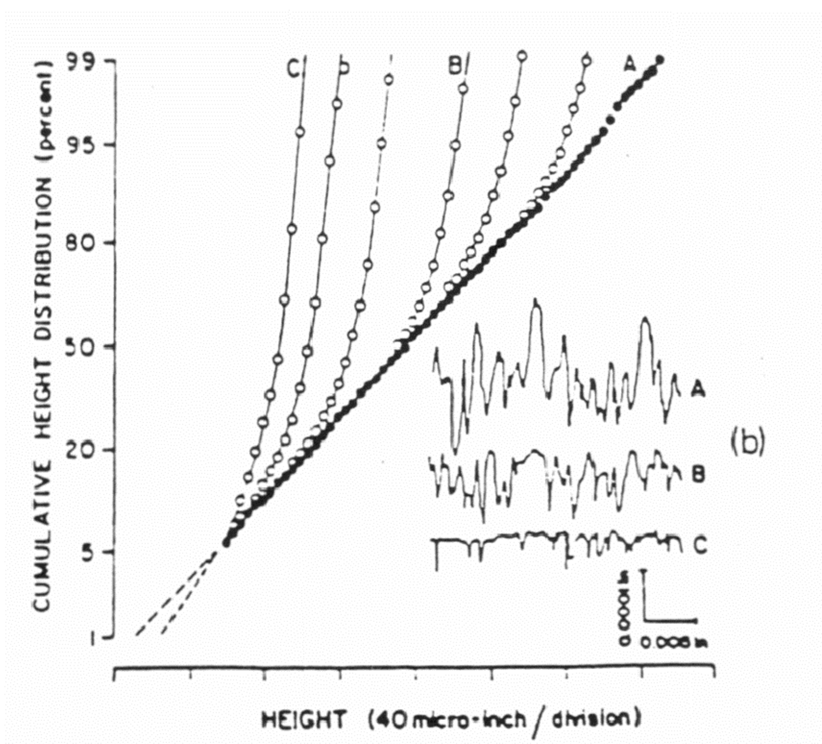


Figure 8. Williamson's classic graph shows the profiles of a surface undergoing wear, and the material probability curves that result.

At first, this graph may be a bit confusing, so let's explore the pieces. In the profile graphs we can see the progression of the unworn surface (A) to the worn (B and C) surfaces. As the surface wears, the peaks are removed.

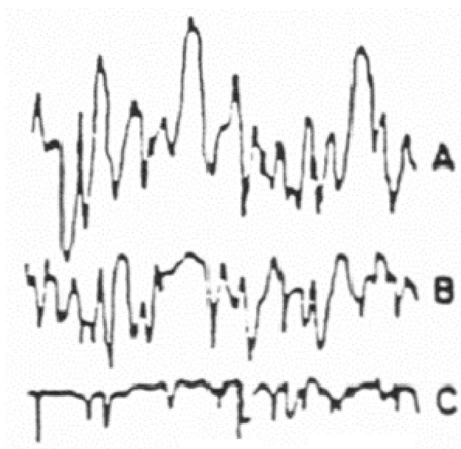


Figure 10. The surface roughness profiles from the Williamson graph.

The three profiles may be understandable, however, at first viewing, the 7 superimposed curves on the original figure are a bit unusual. These curves are the "material probability" curve, which Williamson plotted in a rotated orientation.

A material probability curve is the material ratio curve (a.k.a. "bearing ratio curve" or "Abbot-Firestone Curve") plotted on normal probability paper. In this figure from OmniSurf we see a surface roughness profile followed by the material ratio curve and the material probability curve:

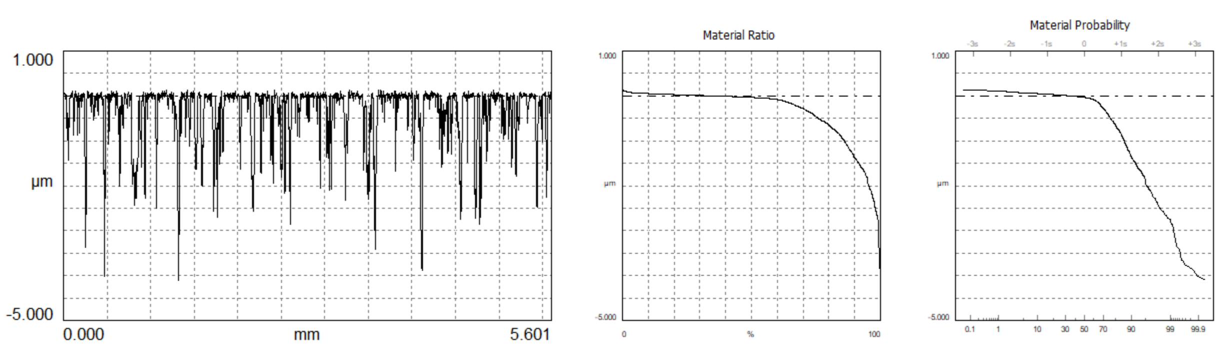
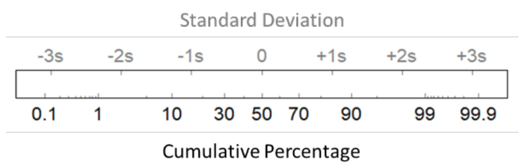


Figure 10. A surface roughness profile and the resulting Material Ratio and Material Probability curves.

The probability graph is a powerful, visual tool for separating two, random distributions. A probability graph is a plot of a cumulative distribution (which in mathematically the same as a material ratio curve) on “normal probability paper.” Normal probability paper is based on the re-scaling of the percentage (X) axis into a linear scale of equivalent standard deviations (σ):



The beauty of the probability graph is that it converts a normally distributed random profile into a straight line. The slope of the line is equal to the standard deviation (Rq) of the original profile. Steeper slopes on the probability graph relate to “rougher” surfaces. With this probability-based visualization, we can model a worn surface as two random components: the peak surface and the valley surface. This is graphically depicted as follows:

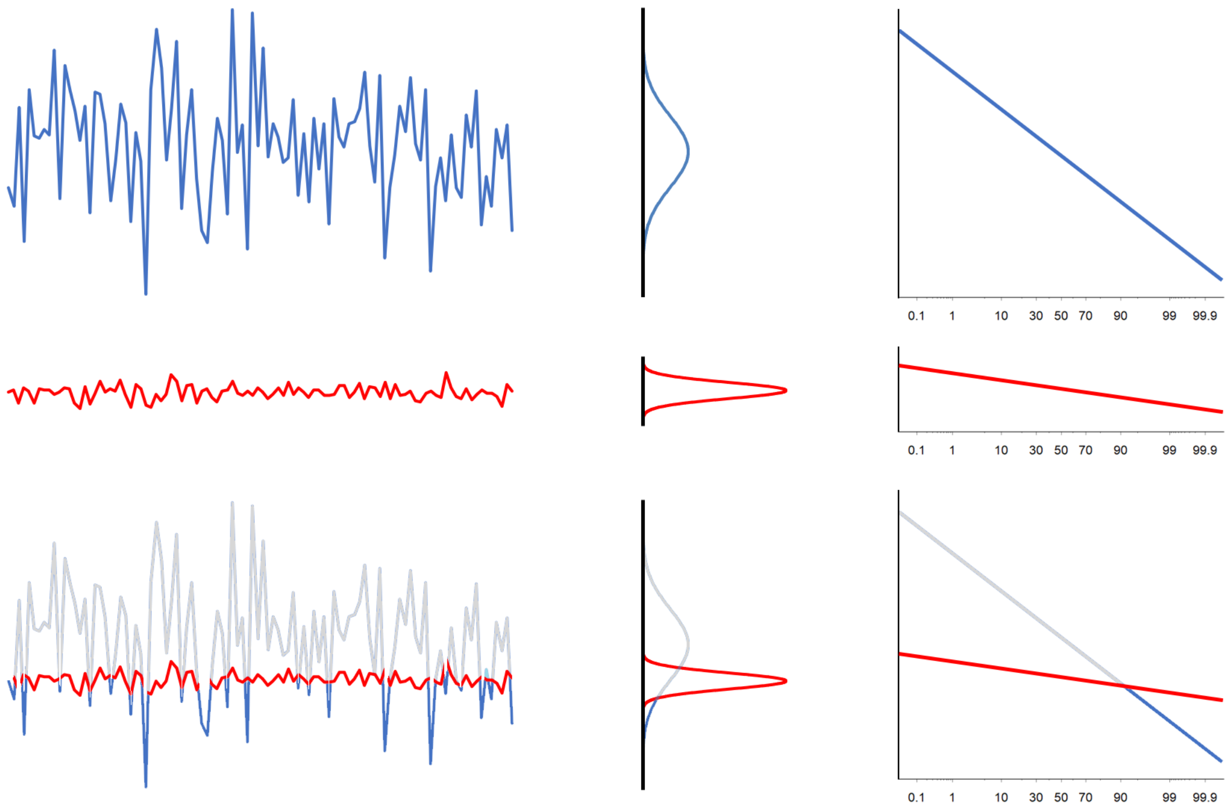


Figure 11. Modelling a worn surface as two random components: the peak surface(blue) and the valley surface (red).

Based on the above, the original (blue) surface is worn away by new (red) surface. The resulting surface (bottom profile) is comprised of peaks from the red (wear) surface and valleys from the blue (original) surface. The material probability curve gives the ability to separate the two.

Based on this visualization of the wear process, we can reformat the Williamson figure in a "depth orientation" to better match the wearing of the profiles. This modified version of the plot shows the change in peak depths of the profiles alongside the changes in the peak regions of the material probability curve:

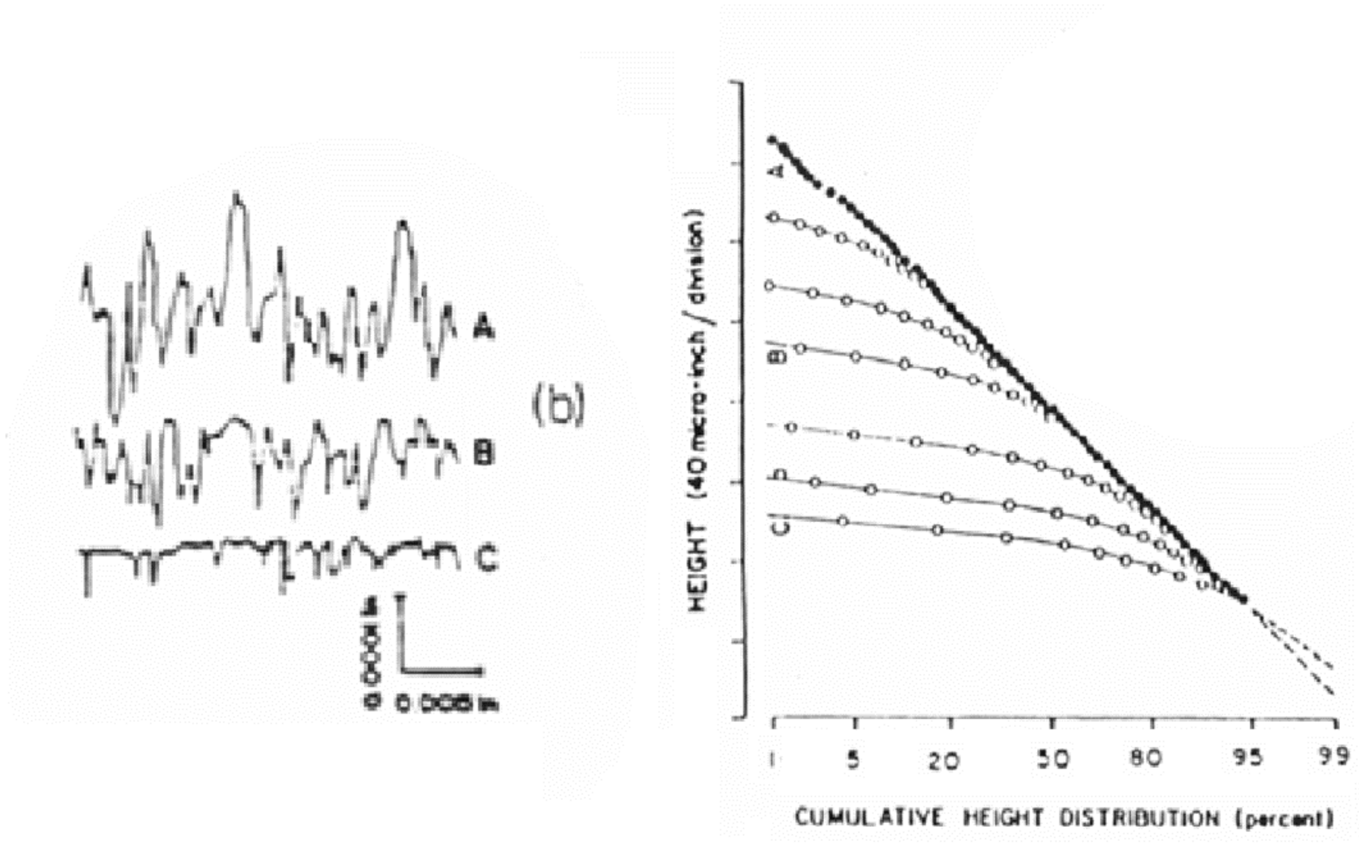


Figure 12. Reformatting the Williamson figure in a "depth orientation" to better match the wearing of the profiles.

Probability plotting as a modern wear analysis tool

Scientists during Williamson's time did not have today's computing power and these curves were manually generated. This must have been a laborious task as we can see the relatively few data points that were used for each curve.

Fortunately, in today's world we have powerful tools such as OmniSurf and OmniSurf3D for surface analysis. These packages can quickly provide material ratio curves comprised of many 1000s of points.

In this OmniSurf screen capture, we see an example of a slightly worn surface. The two linear regions in the material probability curve are readily apparent in OmniSurf's probability plot.

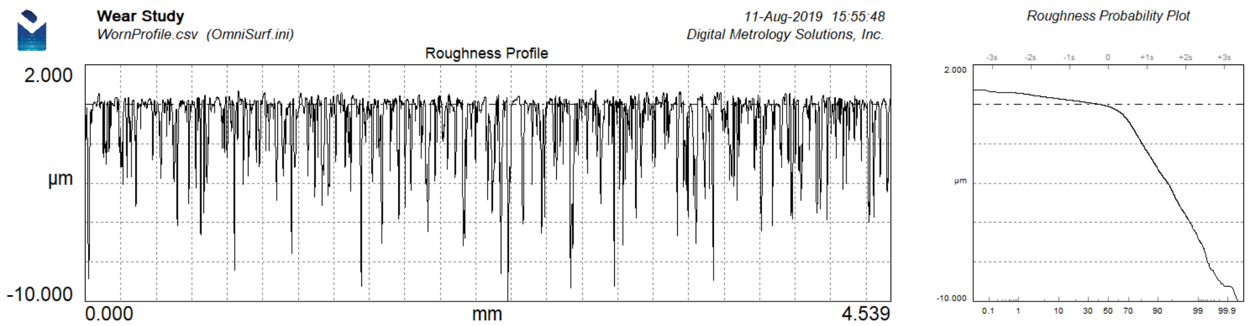


Figure 13. A profile and its matching material probability curve in OmniSurf.

The material probability curve is also available for 3D surface analysis in OmniSurf3D as shown in this screen capture:

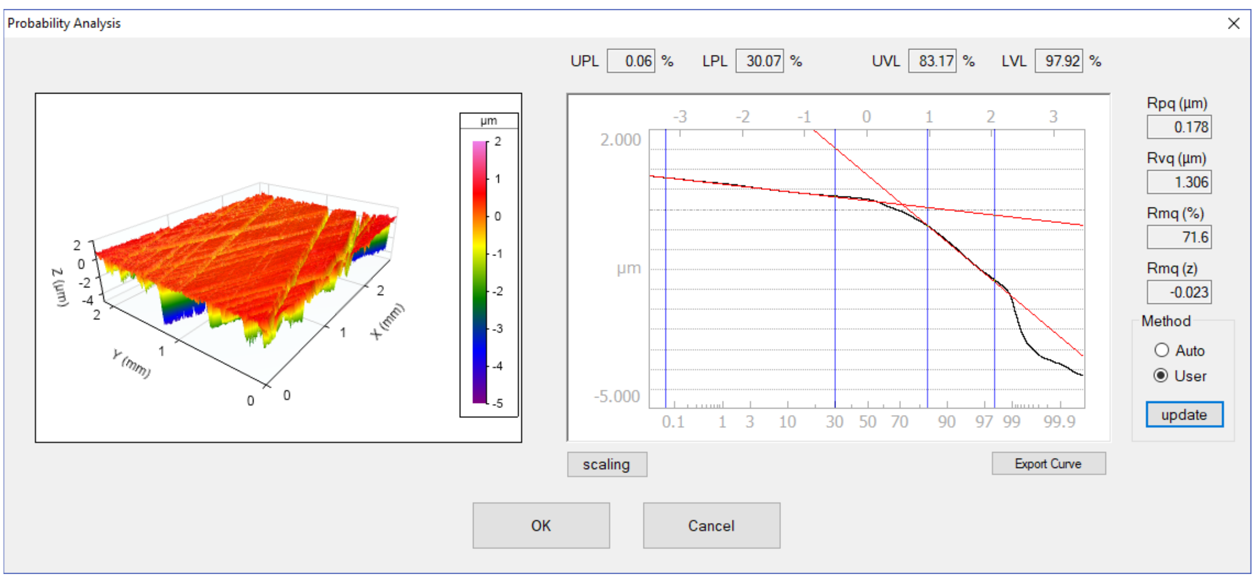


Figure 14. A 3D surface plot and material probability curve in OmniSurf3D.

The OmniSurf (2D) and OmniSurf3D software packages provide the ability to export the material probability curves for further analysis. For example, we can export the material probability curves for worn and unworn surfaces and then align the valley regions.

Once we've aligned the valley regions, a possible measure of wear could be based on the amount of material removed. This is graphically depicted as in Figure 15:

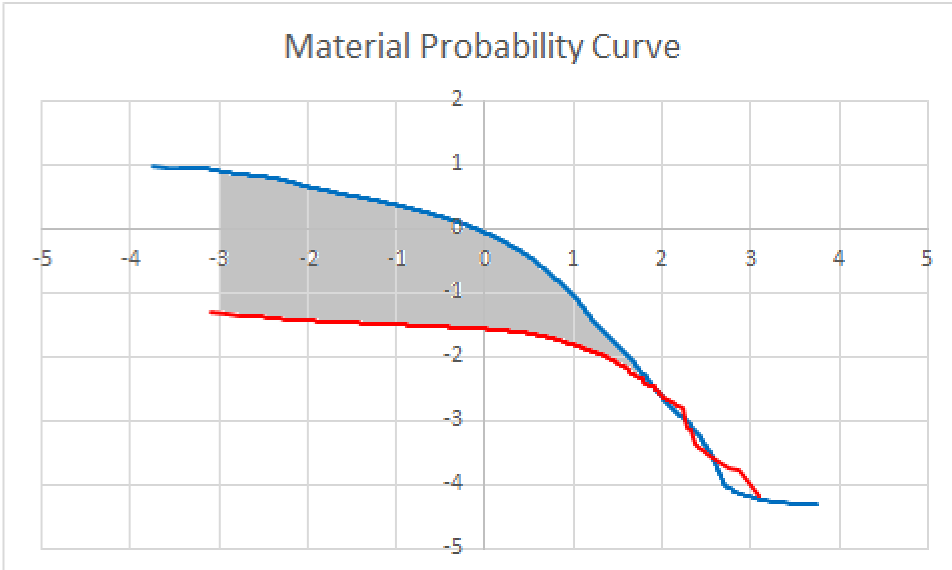


Figure 15. One possible measure of wear can be based on the amount of material removed.

Note: in the above graph, the red and blue curves are different lengths. This is due to a difference in the data density of the two profiles which were measured with different instruments.

Another possible measure of wear depth could be the vertical distance at the σ = 0 position, as in Figurer 16:

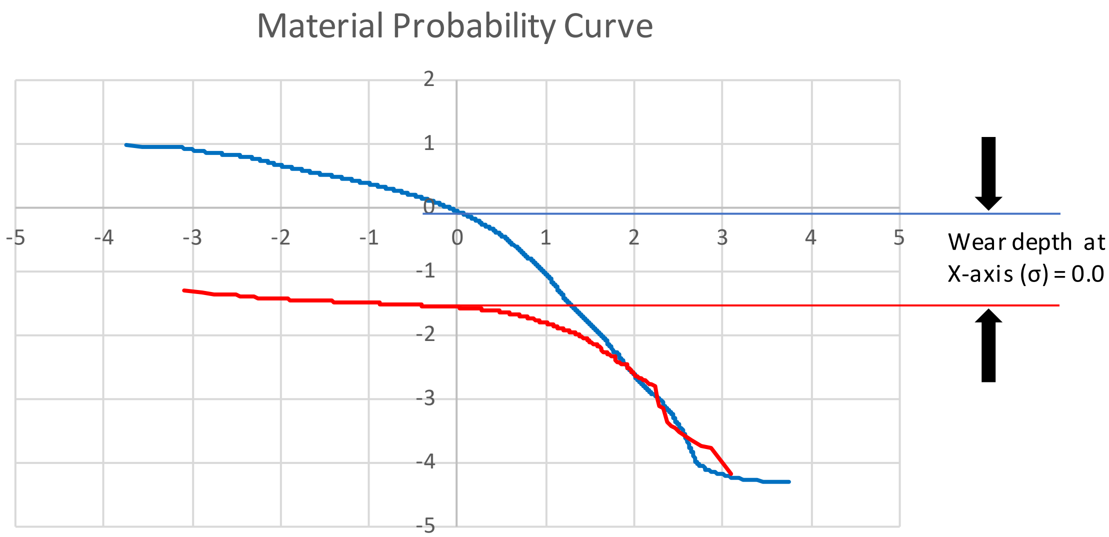


Figure 16. Wear depth could also be measured by the vertical distance at the σ = 0 position.

The material probability curves provide a more robust and reliable assessment of wear depth. Furthermore, this analysis can be more forgiving of changes in measurement locations. The graphical difference between the unworn and worn probability curves can be described by heights or areas – ultimately providing meaningful wear determinations.

More is Better!

A comparison of two profiles is interesting regarding the total amount of wear. However, comparing more profiles can often provide deeper insights into the rate of change due to wear. Perhaps, the wear rate is accelerated during early hours and then slows as the surfaces break-in. This wear process can be study through the simultaneous probability plotting of multiple profiles.

As an interesting exercise, Figure 17 shows a simulated wear progression comprised of six profiles at various stages of wear.

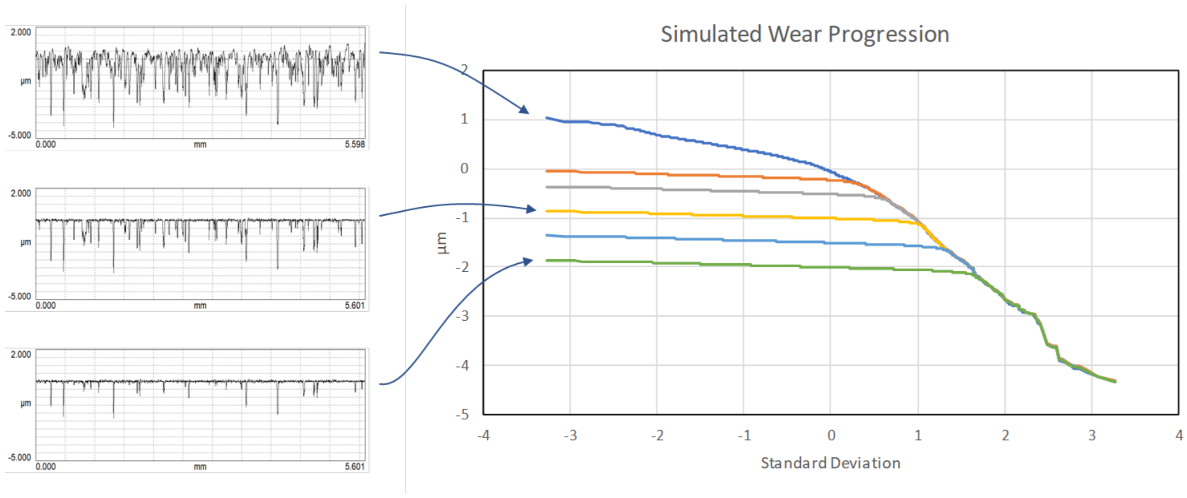


Figure 17. A simulated wear progression comprised of six profiles at various stages of wear.

Wrapping things up…

Hopefully, this sheds a bit of light on the challenges of measuring and understand surface wear and some great tools from Digital Metrology that are available to help you understand your worn surface. If you have questions or would like to talk more about the wear you are seeing on your surfaces – contact Digital Metrology today. We love talking about this stuff!