Over the years, increasingly effective means have been developed for measuring surface topography and for exploiting this data to understand wear. Three-dimensional measurement techniques have led to the development of parameters that allow engineers to correlate wear to particular manufacturing processes and/or wear mechanisms. By further developing these techniques, engineers expect to be able to predict wear and thereby extend component life.

This article discusses wear mechanisms and conventional methods of quantifying wear, then presents optical profiling technology and shows how it can measure the parameters that are critical to predicting component life.

Wear mechanisms
Abrasion, corrosion, erosion, plowing — the list of wear mechanisms could fill a page. Each type of wear results in a different, progressive modification of the surface, from pitting and cracking to deformation or material transfer.

The dominant wear mechanism may also change across the lifespan of a component. Figure 1, for example, shows a sliding contact automotive sensor after accelerated life testing. A worn section of the sensor’s resistor traces (yellow and red) is shown in a false-color, three-dimensional map. During the initial running-in period, material was lost quickly, after which the surface stabilized for a large number of cycles. Improper design could lead to early failures (Fig. 2) in which accumulated wear debris adheres to and bridges the sensor surfaces, generating electrical shorts and thus false readings.

Fig. 1 — The surface of a sliding contact automotive sensor after accelerated life testing. A worn section of the sensor’s resistor traces (yellow and red) is shown in a false-color, three-dimensional map.

Understanding wear and its underlying causes is critical to the manufacture and maintenance of structures, seals, drive trains, medical devices, and many other products.

OPTICAL PROFILING QUANTIFIES WEAR

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With regard to component performance, wear may be bad, good, or indifferent. For example, cylinder walls lose a significant amount of material during the early stages of an engine’s life, yet this wear only marginally degrades engine performance. However, a loss of significant valleys in which lubricant can be retained may lead to increased friction and potential scoring, scuffing, and galling. Therefore, defining and quantifying the wear mechanisms that degrade performance or cause failure are the goals of today’s more precise wear-testing techniques.

**Quantifying wear**

In one long-used wear testing technique, a component is weighed and placed into service, then removed and weighed again, periodically over the life of the part. The weight of material lost is considered a measure of how much the part has “worn.” While this method serves as a general indicator of wear, it unfortunately gives little indication of the wear mechanism or of any change in functionality.

Two-dimensional measurement techniques, such as stylus profiling, characterize wear based on a single trace measurement across the sample surface. The most widely specified surface parameter, average roughness (Ra), was developed based on two-dimensional stylus measurements.

However, Ra makes no distinction between peaks and valleys, neither does it provide information about spatial structure, both of which are critical to understanding surface performance. Other two-dimensional parameters have been developed that are sensitive to these types of surface characteristics, but they are still based on the limited, single slice of the surface.

**Optical profiling**

Most recently, three-dimensional surface measurement instruments have led to sophisticated methods for visualizing and quantifying wear. Chief among these methods is optical profiling, in which the interference of light waves is the basis for measuring surface shape and roughness. This noncontact method can resolve features from nanometer-scale roughness through millimeter-scale step heights, operating at the scales typical of mechanical wear.

Figure 3 shows an optical profiler analysis of a honed cylinder wall. In such an analysis, hundreds of parameters can be calculated to describe surface wear, including the volume of material lost over time, the ratio of peaks to valleys, and the directionality of wear. Recently-developed three-dimensional parameters, such as the S-Parameter set, describe not only surface shape, but also functionality.

**Relating parameters to wear**

This wealth of three-dimensional parameters is a boon for engineers, yet the goal remains to find those parameters that are sensitive to performance-affecting wear. As an example, the shaft shown in Fig. 4 tended to cause loud squeaks in operation after a period of time. The manufacturer specified an average roughness (Ra) value for surface finish. Yet optical profiler analysis revealed that the Ra of new and worn shafts was virtually identical — no prediction of performance could be made based on Ra alone.

On the other hand, another three-dimensional parameter, Normalized Surface Volume (Nvol), was found to have changed by almost 40% over the wear period. Nvol describes the void area beneath a plane placed across the peaks of a surface. It decreases rapidly as spiky, peak material is re-
shafts will perform similarly. Functional parameters such as $S_{bi}$ indicate what the eye cannot: that both of these shafts will perform similarly.

Unworn Worn, 50,000 miles

Fig. 5 — Three-dimensional optical profiler analysis of a new and worn shaft. Functional parameters such as $S_{bi}$ indicate what the eye cannot: that both of these shafts will perform similarly.

moved, which is typical during the running-in phase of a component. The large change in $N_{vol}$ indicated that peak material had been worn away, creating a larger load-bearing surface, which led to the stick/slip mechanism causing the squeak.

Component designers can use information such as this to anticipate wear and to engineer surfaces that perform well both initially and predictably over their lifetimes.

Parameter combinations

In some cases, a combination of parameters may be more meaningful than a single parameter. One such combinational parameter is $S_{bi}$, the Surface Bearing Index. $S_{bi}$ indicates a surface’s overall roughness relative to the surface area that would bear a load. $S_{bi}$ increases as a peak wears down and becomes more like a plateau. It is a stable parameter that tends to change only when a process or surface is altered dramatically, as by a significant defect.

Figure 5 shows an optical profiler analysis of a shaft that has been worn down by a mating component. The shaft’s surface texture changed dramatically during the wear period. This degree of change might lead to the conclusion that performance would be significantly impacted. Yet while $R_a$ decreased by more than 50%, the shaft still continued to function well. $R_a$ alone could not indicate whether the part would or would not function.

On the other hand, $S_{bi}$ was found to change very little over the wear period. Even though peak material had worn away, the percentage of the surface bearing the load did not change dramatically. In fact, in this case, the worn surface was more stable than a new surface: it was smoother, but not so smooth as to squeak, bind, or overheat.

The $S_{bi}$ parameter highlighted a feature of this shaft that was indiscernible by the eye, intuition, or $R_a$. Parameters such as this can indicate component life effectively because they relate to function rather than to a statistical description of texture.

Measurement techniques

Advanced three-dimensional wear measurement techniques can be a significant competitive advantage for component designers. As use of these techniques spreads, it becomes increasingly important for design and quality professionals to understand wear and three-dimensional wear parameters, to avoid expensive design and testing pitfalls.

One engineer for an automotive component manufacturer recounted a customer’s new test requirement, which his company’s sensor design did not pass. However, when an optical profiler compared the test sensors with those removed from high-mileage vehicles, his team noted a buildup of wear debris in the laboratory-tested parts that was not present in actual-use sensors. In normal service, the wear debris was cleared away as it was produced, whereas the laboratory test caused it to accumulate. His team was thereby able to work with the customer to redesign a test that better reflects real-world conditions.

Predicting wear and life

By testing components over their lifetimes, then constructing a model of wear modes versus various surface parameters, it is possible to determine which parameters serve as accurate wear predictors for each given case. The ultimate goal of such studies is to predict — and extend — the life of components and systems.

One of the most exciting outcomes of such testing is the growing number of “engineered surfaces,” in which designers build particular wear-fighting characteristics into component surfaces. Knowing which wear mechanisms lead to performance deterioration, and anticipating how the part will change throughout its life, engineers can combat the effects of wear, making more effective use of lubricants, materials, and processing.

For the foreseeable future, wear mechanisms will remain somewhat unpredictable, challenging component and system designers and limiting the lives of their products. Yet armed with new tools for identifying and monitoring destructive wear, engineers are better able to develop designs that reduce wear — or even to exploit wear to improve component performance. Three-dimensional surface characterization provides the data required to make informed decisions about wear, part performance, and ultimately component life.

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