Large field-of-view scanning white-light interferometers

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1. Introduction

Scanning white-light interference (SWLI) microscopes routinely measure machined parts in industry, using broadband light, electronic detection, precision mechanical scanners and the principles of low-coherence interferometry to characterize surface form and roughness. Benefits of these instruments include their high Gauge Repeatability and Reproducibility (GR&R) capability, the large number of measurement points acquired in a small amount of time and the non-contact nature of the method.

Although there are many forms of SWLI microscope available, the maximum size of the parts they can measure is usually on the order of 5-10 mm (1X objectives). In this paper, we look at different implementations of large field-of-view (FOV) interference microscopes in the context of the measurement of machined surfaces. The extension of white-light interferometry to large objects is straightforward when surface finish is smooth. However, rough surface finishes tend to render the measurement process increasingly difficult as part size increases. We describe these limiting effects, how they can be mitigated and show examples of measurement on production machined parts. An example tool is a par-focal and par-fringe, dual-objective interference microscope used for form and roughness measurements on parts that can be as large as 40 mm. Finally, we briefly describe an experimental interferometer measuring rough parts as wide as 200 mm.

2. Optical profiling of large rough parts – Why is it difficult?

Low magnification optical systems tend to have low numerical aperture (NA), that is, they capture light scattered by the surface in a fairly reduced solid angle compared to higher-magnification systems. The low NA also restricts the lateral resolution of the instrument. In practice, most instrument manufacturers tend to match the lateral resolution to the footprint of a camera pixel at the object surface. However, because the lateral resolution spot is fairly large at low magnifications (30 microns for a 0.02NA objective) the range of random surface heights present within one spot can become comparable to the wavelength of light when measuring rough parts. This is the source of the so-called speckle phenomenon. In practice, each different illumination direction or wavelength generates a slightly different random intensity pattern at the detector, or speckle. Because of the random nature of this phenomenon the phase of the interferogram becomes meaningless and one no longer observes the macroscopic continuous interference fringes seen on smooth objects. However, white-light interferometry still detects regions of high-modulation interference, thus allowing surface profiling based on the presence or absence of interference. This is the domain of the coherence radar. The difference between the smooth and rough regimes is illustrated in Figure 1 where we show the interference signals detected at 9 neighboring pixels using an experimental 30-mm FOV white-light interferometer. We observe loss of fringe contrast,
random lateral displacements of the peak interference signals and distortion of the signal envelope in the rough regime.

These phenomena have been studied extensively at the University of Erlangen both theoretically and experimentally. The key conclusions can be found in the published literature. Among these, an important observation is that the noise of a surface height map generated using the location of peak interference contrast is directly proportional to the local surface height standard deviation, even though the height map itself is not representative of the actual microscopic shape of the surface. This property immediately sets a lower limit on the repeatability of the measurement. This limitation can be overcome by increasing the wavelength of light used for the measurement (i.e. to 5 or 10 µm), but that is not always a practical solution.

Figure 1 Comparison of white-light interference signals measured on a smooth (a) and rough (b) surface, using a 30-mm FOV white-light interferometer.

3. Instrument optimization

Keeping in mind the rather fundamental limitations outlined above, it remains necessary to optimize a white-light interferometer design to maximize the quality of the signal used for the measurement of rough surfaces. In practice, the transition from the smooth regime to coherence radar requires optimization of such system parameters as the source dimension, imaging system lateral resolution, scattered-light collection, source spectral width, reference mirror reflectivity, dispersion correction, etc. We can briefly describe the effect of the most influential factors and suggest optimal settings derived from our experiments on prototype large-FOV systems.

One of the most important parameters is the NA of the optical system. Large NA objectives capture more scattered light, which is an important benefit when measuring parts that scatter light in the entire half-space. Also, higher NA implies higher lateral resolution, which creates a beneficial speckle averaging effect at each pixel. As the number of speckles per pixel increases the contrast drops but the increased object amplitude at the detector compensates for this and the net effect is a relatively constant signal modulation. However, the practical benefit is that speckle averaging causes more pixels to detect a usable signal.

Ideally, the source should be as small as possible since distant source points generate different (also called decorrelated) speckle patterns. However, practical considerations when using broadband sources such as halogen lamps or LED impose finite source dimensions. Fortunately, the effect is not too
rapid and we observe a fairly linear contrast loss with source size, with a maximum 25% loss (for the rough parts used for this study) when the image of the source fills the pupil of the microscope objective.

A wide source spectral width produces a narrow signal envelope, increasing the interferometer resolution, while at the same time increasing the available amount of light. However, widely spaced wavelengths generate decorrelated speckles, resulting again in contrast loss. Experimental compromises are fairly dependent on the actual part roughness. However, a starting point consists in a full-width-at-half-maximum to central-wavelength ratio of about 15%.

Finally, because the amount of light scattered by the object in the instrument’s pupil can be very weak compared to the reflection of the reference mirror, it is useful to decrease the reference surface reflectivity. Because the dynamic range to be covered can be quite large the ideal is an objective having adjustable reflectivity. We observed significant fringe contrast improvements when dropping the reflectivity of reference surfaces down to 4% and even below 1%. However, as the reference reflectivity is better matched to that of the rough surface the total amount of light captured by the instrument can drop dramatically. In practice, the optimum reflectivity is the one that maximizes detected signal modulation when the source is running at its highest output power. A consequence is that the optics need to be properly anti-reflection coated so as not to introduce a strong background intensity at the detector.

As a conclusion to this experimental investigation we ran a GRR on production lapped parts. The Ra roughness of these surfaces is close to 0.3 μm, with a very short roughness correlation length, resulting in a very low apparent reflectivity. The one-standard deviation GR&R for flatness measurement is less than 0.08 μm, a result consistent with meeting 10% gauge on a 4-μm flatness tolerance. These results were obtained after applying a 13 x 13 low-pass filter to the height data in order to emulate the lateral resolution of an infrared interferometer using a 10-μm broadband source.

![Figure 2](image.png)

**Figure 2** (a) 30-mm diameter part within the FOV of the 0.15X objective. (b) Height map of the surface. The part has a slight spherical shape creating an 8-μm sag. (c) Height map of a 0.7 x 0.5 mm subregion captured with the 10X objective for roughness measurement. Ra is about 0.2 μm for this surface.

4. **Example of a tool for the combined measurement of form and roughness**

We have developed an instrument to exploit this new large-FOV capability by integrating form and roughness measurement in a package, combining two objectives on a two-position slide: a medium-magnification objective for local roughness characterization with a very-low-magnification objective for
form measurement. The system uses polarization elements to eliminate the light scattered by optical components in the microscope objectives, a source of contrast reduction when measuring rough parts.

The respective FOV covered are $0.70 \times 0.53$ mm (about 10X system magnification) and $42.7 \times 32.0$ mm (about 0.15X system magnification). So far this tool has been applied to the characterization of machined parts with roughness as large as 1.4 $\mu$m Rz, while it routinely measures on the factory floor ground parts having an Rz roughness on the order of 0.2 $\mu$m. Figure 2a shows a 30-mm diameter part within the FOV of the 0.15X objective. The corresponding measured form is shown in Figure 2b with a PV departure of about 8 $\mu$m. The 10X objective allows capturing a magnified subregion for roughness characterization. The resulting height map is shown in Figure 2c. The Ra roughness is on the order of 0.2 $\mu$m for this particular surface finish.

5. Non-telecentric imaging – Very large aperture white-light interferometer

The interferometers studied so far are all based on telecentric objectives, which can indiscriminately measure smooth and rough surfaces. If one only intends measuring rough objects it becomes possible to use non-telecentric optics and perform measurements using a rough reference surface. This technique has been successfully demonstrated at the University of Erlangen where an aluminum casting about 200-mm wide was measured with scanning white-light interferometry using LED arrays for the illumination. Figure 3 at right shows the measured height map.

6. Concluding remarks

As optical profilers continue to improve they become more attractive metrology solutions for a number of industries, including the machined parts industry where a wide range of surface finishes are the norm. The addition of large FOV capabilities to current and new instruments, based on a better understanding of the physical phenomena encountered in the rough measurement regime, is a step forward in providing flexible, production-line ready tools to these industries for combined and easily automated form and roughness measurement.

7. References and notes

2. Or should we say macroscope?