Interference Microscopy for Clean Air – How Optical Metrology Is Improving Quality Control of Fuel Injection Systems

Robert Sachs and Frank Stanzel

ZygoLOT GmbH, Im Tiefen See 58, 64293 Darmstadt, Germany
sachs@zygolot.de

1 Introduction

The current 50% market share of diesel engines in European passenger cars is attributable to impressive improvements in efficiency and power combined with progressive reductions in nitrous oxides, hydrocarbons, carbon monoxide, and particle emissions. Fuel injection systems are central to diesel engine design, and it is here that significant precision engineering advances have contributed to the success of these systems. In the latest common rail systems, a high-pressure pump stores a reservoir of fuel at 2000 times atmospheric pressure to optimize fuel atomization. These extraordinary pressures place high demands on the precision manufacture of injection pumps and valves. Common rail technology will be the principal means of complying with the Euro VI emission standard, which comes into effect in 2014 [1].

Tightened flatness tolerances on sealing surfaces have made it necessary for manufacturers to continually monitor and adjust their production equipment. Throughput and the need for full area 3D surface topography inspection are the principal drivers for the introduction of optical metrology, typically single-task pushbutton instruments. Here we review the development of optical interferometry for the automotive industry in Europe, with an emphasis on fuel injection systems. The injection nozzle metrology provides a specific example of recent developments addressing challenging metrology tasks in specially targeted ways.

2 From Laser to White Light Interferometers

Early success in optical systems for fuel injector metrology relied on phase-shifting laser Fizeau interferometry, still a standard for super-finished surfaces [2]. These systems have been ruggedized for harsher conditions using factory enclosures and offer true pushbutton function. Fizeau interferometers satisfy gauge R&R for flatness tolerances down to 0.4 um, and have been in continuous use for over 13 years. Fizeau interferometers have been supplemented by geometrically desensitized [3], grazing incidence [4] and infrared technologies to accommodate

W. Osten (ed.), *Fringe 2013*,

DOI: 10.1007/978-3-642-36359-7_96, © Springer-Verlag Berlin Heidelberg 2014

higher-Ra surface textures and provide additional information such as thickness and parallelism [5].

Developments in fuel injection technology have introduced several new metrology requirements as components evolved to smaller sizes. Higher magnification is essential, and surface roughness is now a key result. Sealing surfaces are no longer flat, and form deviation with respect to cones and spheres has become an important measurement. Finally, with an increasing number of production steps, it is necessary to measure parts in many intermediate stages, both optically rough and smooth. These developments require optical metrology methods that are beyond the reach of laser-based phase shifting interferometers.

Where phase-shifting interferometers have reached their limits, coherence scanning interferometry (CSI) is able to meet requirements and has emerged as the preferred metrology solution for critical parts in diesel injection systems [6-8]. CSI microscopes are able to perform flatness, form, roughness and dimensional measurements on a single platform simply by the appropriate choice of objective. A particular strength of interferometric microscopy is the independence of vertical resolution and accuracy from the objective magnification. Flatness measurements are feasible with specially developed low-magnification, wide-field-of-view objectives, able to perform single-shot measurements of parts with diameters up to 22 mm, and much larger dimensions by means of stitching [9]. For form and roughness measurements of recessed surfaces, higher magnification objectives have working distances of 40 mm and above. An interferometric microscope can in many cases replace a flatness, roughness, and coordinate measurement machine with one instrument. Batch measurements are routine, with some instruments loaded by robot. The introduction of metrology enclosures has brought the interferometric microscope out of the metrology room onto the factory floor.

3 Application to Injection Nozzles

The injection nozzle features some of the most sensitive dimensions in fuel injection systems. Being mass-produced parts, only statistical process control is feasible, which in turn demands exceptional gauge capability. We will discuss three critical CSI applications on this part: flatness of the valve body surface, roughness on the valve body surface, and conical form deviation in the valve seat. All measurements pass gauge R&R below 10% at current tolerances.

The nozzle body flatness measurement is illustrated in Fig. 1. The circled interface contains two 15 mm diameter sealing surfaces. The lower surface is measured in a single shot using a low-magnification objective. ISO-standard filters are applied and the flatness is evaluated. In an additional step (not shown,) pattern recognition is used to perform lateral measurements. Lateral results include line widths of laser scribes and positions of the high-pressure bores.

In a second step, a roughness measurement is performed around the high-pressure bore, as illustrated in Fig. 2. Image recognition locates the bore, followed by 3D measurement using a higher-magnification objective. The evaluation is performed over a circular slice using ISO-standard filters. The precise positioning of this slice ensures superior gauge capability.

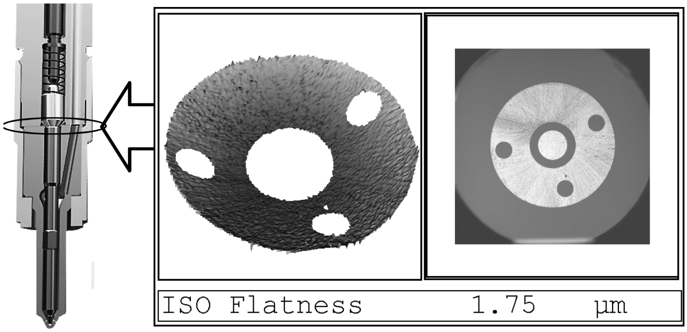

Fig. 1 CSI flatness measurement of the nozzle body sealing surface (circled.) Height map, camera image and flatness result is displayed. Image recognition locates bores.

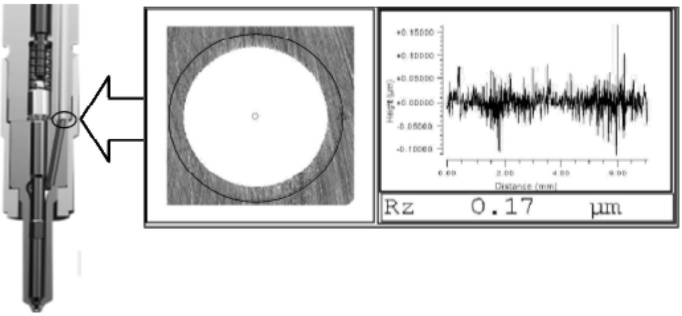

Fig. 2 CSI roughness measurement around high-pressure bore (circled.) ISO-standard roughness measurement is adapted to circular geometry.

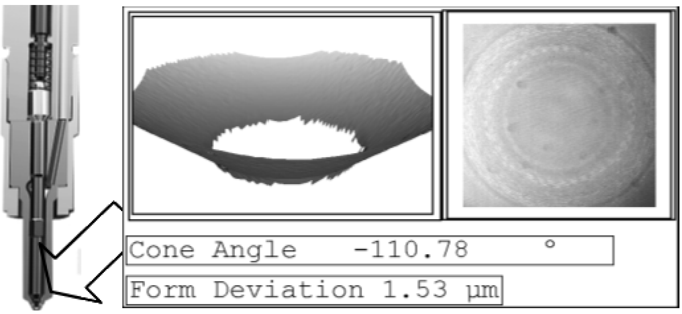

Fig. 3 CSI form and form deviation measurement in the valve seat. Measurement is performed using super-long-distance objective. Height map, camera image and shape results are displayed.

Finally, the valve seat is measured using a super-long-working distance objective, as illustrated in Fig. 3. An extended vertical range is achieved by merging multiple vertically offset scans. The seat angle is evaluated in an annular region, and then the best-fit cone is subtracted from the total dataset. This supplies form deviation results, which can be extended to roundness and straightness.

The three measurements are performed using configurable software. Pushbutton function is emulated by graphical user interfaces in which desired parts and measurements can be selected in catalogue screens. Many applications are set up for tens of parts with numerous measurements each. Custom part holders and ever-faster hardware is continuously improving throughput.

4 Outlook

The next generation of CSI microscopes correlate closely to optical stylus measurements and are robust in the presence of vibration [10]. The unique vibration insensitivity of these systems has motivated a cooperation project between ZygoLOT and the University of Applied Sciences in Magdeburg, with the goal of directly integrating a CSI microscope with a production machine. This will be the next step in bringing precision optical metrology onto the production floor.

References

1. Wiartalla, A., Severin, C.: Wechselwirkungen zwischen Dieselmotortechnik und -emissionen mit dem Schwerpunkt auf Partikeln. In: FAT-Schriftenreihe, vol. 238. VDA-FEV GmbH, Aachen (2012)
2. Mantravadi, M.V., Malacara, D.: Newton, Fizeau, and Haidinger Interferometers. In: Malacara, D. (ed.) Optical Shop Testing, pp. 1–45. Wiley Interscience (2007)
3. de Groot, P., et al.: Geometrically desensitized interferometry for shape measurement of flat surfaces and 3-D structures. Optical Engineering 39, 86 (2000)
4. Briers, J.D.: Interferometric Flatness Testing of Nonoptical Surfaces. Applied Optics 10, 519 (1971)
5. de Groot, P., et al.: Optical Interferometry for Measurement of the Geometric Dimensions of Industrial Parts. Applied Optics 41, 3853–3860 (2002)
6. de Groot, P.: Coherence Scanning Interferometry. In: Leach, R. (ed.) Optical Measurement of Surface Topography, ch. 9, pp. 187–208. Springer, Berlin (2011)
7. ISO, 25178-604: Geometrical product specification (GPS) – Surface texture: Areal – Nominal characteristics of non-contact (coherence scanning interferometric microscopy) instruments. International Organization for Standardization, Geneva (2013)
8. Dresel, T., et al.: Three-dimensional sensing of rough surfaces by coherence radar. Applied Optics 31, 919–925 (1992)
9. Colonna de Lega, X., et al.: Large field-of-view scanning white-light interferometers. In: Proc. ASPE, vol. 1275 (2003)
10. Badami, V.G., et al.: Evaluation of the measurement performance of a coherence scanning microscope using roughness specimens. In: Proc. ASPE (2011)