ADVANCED METROLOGY FOR ENERGY EFFICIENCY

Lightweighting is a priority for automotive OEMs in their quest to adhere to exacting engine efficiency and emission guidelines. More and more, massive iron engines and components are replaced with aluminium and lightweight alloys that match the strength of iron without the negative weight implications. Cutting-edge optical metrology tools can facilitate the manufacture of lightweighted engine components.

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There have been many initiatives in recent years aimed at reducing vehicle emissions and increasing overall efficiency. This has required the automotive sector to focus enormous resources on optimising engine performance. Be it due to concerns over climate change or insulating economies against the vagaries of fuel costs and possible fuel shortages; the race is on to make vehicles considerably more efficient while at the same time maintaining a level of required functionality and attractiveness to stimulate sales and profitability.

Thermal barrier coatings

Focusing on efficiency, automotive OEMs are looking to reduce weight and at the same time, enhance the efficiency of engine performance. One area of focus in line with these goals is the replacement of cast-iron cylinder liners used in aluminium cylinder blocks with more thermally efficient and lighter-weight materials. Various viable alternative materials and solutions exist that must be wear- and scuff-resistant as well as having a low friction coefficient, one such being thermal barrier coatings (TBCs).

TBCs are the choice for many automotive OEMs today, effectively, coating the cast aluminium block bores with a spray of wear-resistant, ceramic or composite material. This material will harden to form a much thinner surface – relative to a liner – in the aluminium cylinder. To date, the most commercially viable of these are being applied through the use of the plasma spray process, which yields superior wear resistance compared to iron, enabling aluminium alloy engines to utilise robust tribological materials within the harsh environments of combustion chambers.

However, there are also some inherent issues with the spray-coating process that require the implementation of rigorous quality management procedures and measuring protocols. For example, at the high velocity with which the coating is applied to the cylinder wall, a splatter morphology occurs, leading to possible inconsistent coating.

Surface metrology

Properties of the coating such as porosity, micro-hardness, thickness, adhesion, and strength are essential metrics in assessing its viability and provide important tools for evaluating which process parameters need to be changed to achieve an optimum coating [1].

The non-deterministic porosity distribution across the surface of the cylinder after spraying requires the use of a metrology technology that is able to reliably, repeatably and accurately measure the three phases required to produce a finished lined cylinder:
- mechanical activation;
- thermal spray application;
- post-spray finishing.

Any metrology solution used to assess the surface characteristics of a spray-lined cylinder must be able to make highly accurate measurements at all three of the phases of the process, each stage transitioning from extremely rough to very smooth. This dynamic range of surface textures requires a metrology solution such as the one developed by Zygo using its coherence scanning interferometry (CSI) technology (see the box). CSI can capture data pertaining to a vast array of surface heights and textures and is used in Zygo's range of 3D optical profilers.

3D optical profilers

CSI extends interferometric techniques to surfaces that are complex in terms of roughness, steps, discontinuities, and structure. Additional benefits include the equivalent of autofocus at every point in the field of view and suppression of spurious interference from scattered light.
CSI technology is at the heart of all Zygo's 3D optical

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CSI: coherence scanning interferometry explained

CSI uses the principle of optical interference to compare a part that needs to be measured to a 'perfect' reference surface; Figure 1 shows a typical set-up. Interferometry divides a light source into two paths and compares the light reflected from a test surface to light reflected from a reference surface. The two reflections combine at a detector where they interfere with each other, and a pattern of light and dark intensities is created. That interference pattern represents the surface topography of the test surface

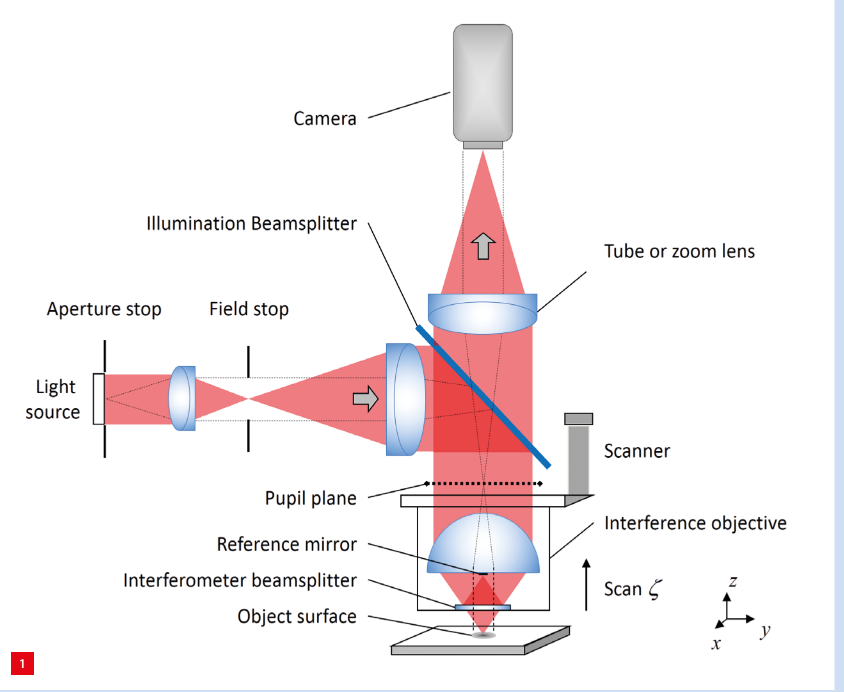
In the system, light comes from an illuminator based on white LEDs. That light travels through illumination optics to the objective. The objectives in Zygo's optical profilers not only provide magnification like a regular light microscope, but they also contain the reference surface. This makes them an interferometer, or an interferometric objective.

The objective has a beam splitter which divides the incoming light into two paths: a test path which goes to the part being measured, and a reference path which goes to the perfect mirror. When the distance between the beam splitter and the reference surface is the same as the distance between the beam splitter and the test surface, the light that is reflected off of these two surfaces will interfere, creating a series of alternating light and dark called an interference signal.

The interference signal only happens when the test and reference legs of the interferometer have the same length, so if one of those lengths is changed, complex topography can be explored. This is called scanning, and it is done by moving the entire objective perpendicular to the test part.

The interference signal is imaged onto a camera and each pixel processes the signal it sees to produce its own height value, and then all the heights for all the pixels are combined to create a map for the surface being tested.

Because CSI uses white light, the interference signal is localised, which means that it only happens when the test and reference legs are the same length. Because of this, surfaces that are rough or structured with steps or other discontinuities can be measured.



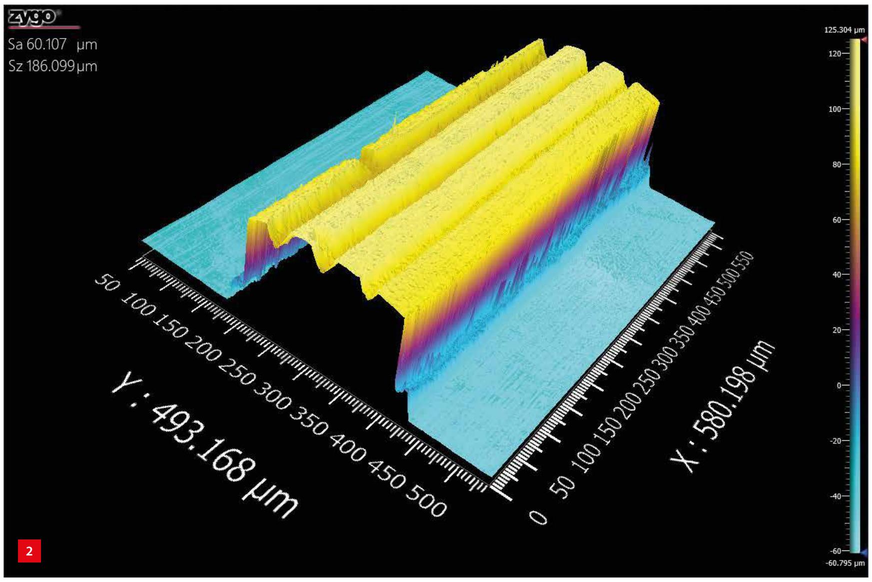
Typical set-up for coherence scanning interferometry; see the text for explanation.

As an all-optical technology, CSI is completely non-contact, and Zygo's CSI instruments can measure virtually any material and texture from rough to smooth, shaped to flat, and opaque to transparent. CSI is also very precise with nanometer or sub-nanometer height precision and a fast, consistent measurement speed (1.9 million pixels in just a few seconds) at all magnifications, unlike other techniques where the height precision and speed depend directly on the magnification.

Comparing confocal scanning microscopy with CSI, both have the ability to stitch multiple images, are characterised by high-magnification, high-resolution imaging, and are suitable for rough and steeply sloped surfaces. However, CSI can in addition be used on super-smooth or optically transparent surfaces, and with CSI measurement speed and instrument precision is independent of objective numerical aperture and magnification. Also, unlike confocal scanning microscopy, CSI is appropriate for low-magnification, large-field-of-view imaging (< 5x).

profilers, delivering sub-nanometer height precision at all magnifications, and analysis of a broader range of surfaces (from rough to super-smooth, including thin films, steep slopes, and large steps) quicker and more precisely than other commercially available technologies. This makes it ideally suited to applications such as the spray-lined cylinder application, which is detailed below.

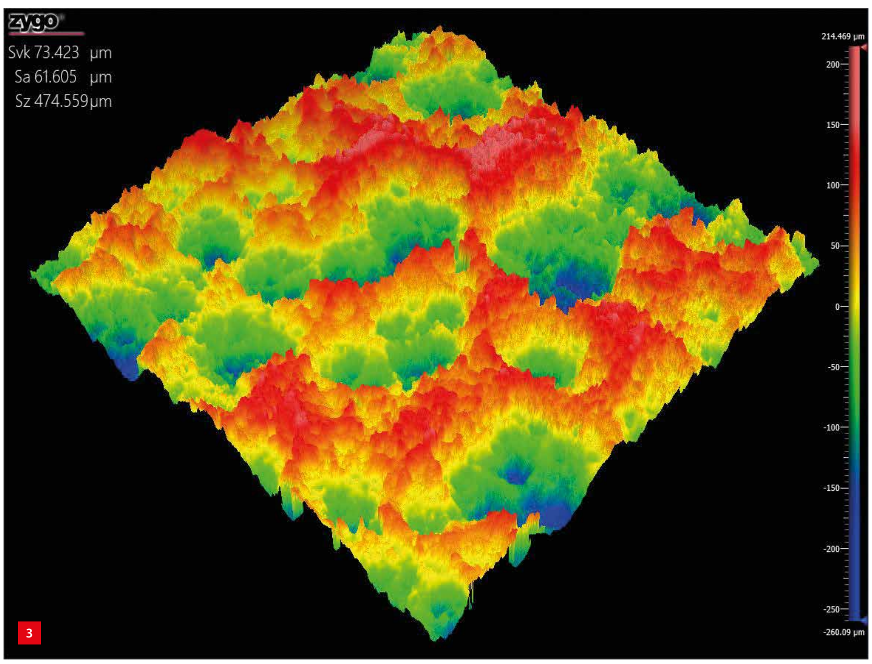
Alternative technologies, such as fax film, rely on affixing a thin sheet of plastic to the cylinder surface and applying a solvent to soften and conform the sheet to the surface. When removed and sufficiently hardened, it is then manually inspected under a microscope. This method,



CSI scan of the mechanically activated surface that will provide the anchor for the thermal barrier coating to adhere to the cylinder wall surface. The height scale runs from –60 to +125 µm.

though used extensively, is messy, and can result in very subjective results. When looking specifically at the metrology demands connected with the analysis of the spray-coating of cylinders, Zygo's CSI 3D optical profilers benefit from being non-contact, thereby eliminating any chance of the inadvertent compromising of surface integrity. In addition, CSI technology enables the highest vertical resolution measurement agnostic of the interferometric objective.

Other optical measurement technologies may perform sub-optimally when the surface texture is considered quite smooth. Focus variation technologies, for example, require some level of texture on the surface to be able to resolve the surface.



Measurements of the dark, rough features after the TBC application can provide process engineers information on the formation and distribution of surface porosity. The height scale runs from –260 to +214 µm, the XY dimensions are approx. 1 mm x 1 mm.

Zygo's Mx™ software powers complete system control and data analysis, including interactive 3D maps, quantitative topography data, intuitive navigation, and built-in statistical process control (SPC), control charting, and pass/fail limits. As a result, hundreds of parameters can be reported when measuring surface structure and texture across varying surface scales, including areal surface roughness to ISO 25178 standards, and 2D profile standard compliance to ISO 4287/4288.

Spray-lined cylinder application

Mechanical activation

For the mechanical activation / pre-coating stage of the process, the cylinder walls need to be scored (Figure 2), which needs to be strictly controlled as this dictates the amount of TBC that will be applied. Too thin, and there's the possibility that the TBC can flake off. Too thick, and the honing process can remove the peaks that contain the TBC, either scenario potentially compromising the quality and efficiency of the cylinder coating process.

For such step-height-type measurements, Zygo's CSI technology enables the company's optical profilers to speedily measure structures higher than 250 µm with their extended scan capabilities accurately and repeatably.

Thermal spray application

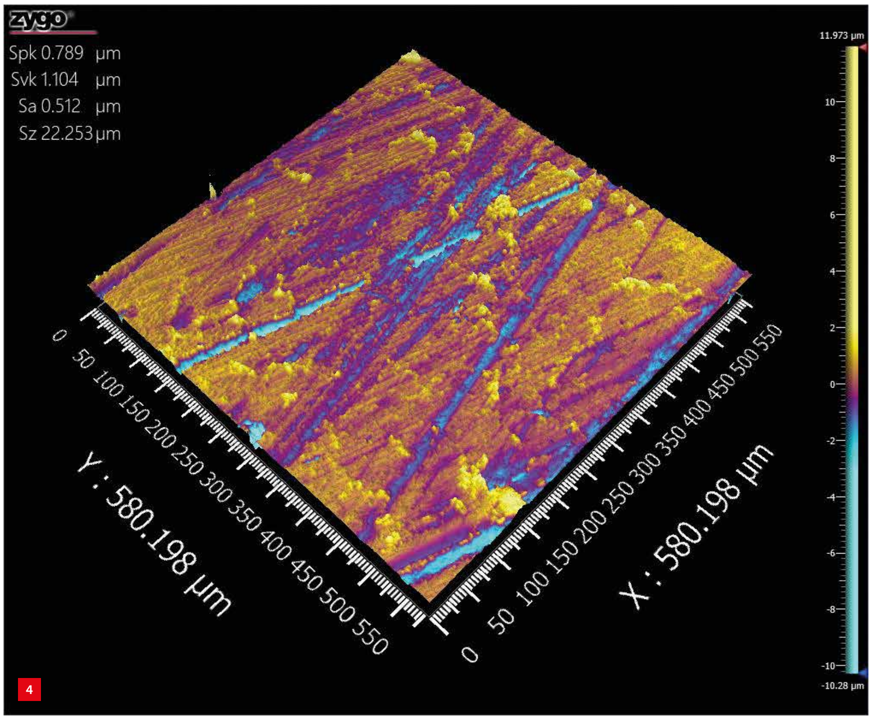
After the TBC application, automotive OEMs need to assess how the pores have developed (Figure 3). The variety of pore sizes – ranging from 50 µm^2 to over 1 mm^2 – will help determine the lubricity retention of this newly sprayed surface. Because these pre-honed coatings are typically very rough and have low reflectivity, typical CSI systems will have difficulty acquiring data from the surface. With Zygo's implementation of CSI, such surfaces are easily measured, producing consistent metrics for process engineers.

Post-spray finishing

Finally, it is necessary to analyse the finished surface texture (Figure 4) of the cylinder post-spraying, checking crosshatch (a textured pattern on a cylinder wall used to retain oil for proper lubrication of the cylinder and piston rings), as well as the final porosity (pore density, pore volume by area, and change of pore size by cylinder depth).

To conclude

Transitioning from the very rough surface measurement pre-honing to the final assessment of extremely smooth



Honing generates the proper stratified surface for the sliding ring/cylinder interface. Quantifying the lubricity by direct measurement of porosity will assist with honing process control. The height scale runs from –10 to +12 µm.

honed surfaces displays the full dynamic range of the Zygo CSI-based optical profiler systems. The development of specialised hardware and software enhancements has significantly improved this capability, enabling measurements of previously inaccessible steep surfaces and super-polished surfaces with one metrology solution.

REFERENCE

[1] Robinson, D., Ramsunder, P., and Samantaray, C., "Analyzing Porosity in Thermal Barrier Coatings: Edge Detection of Images using MATLAB", *121st ASEE Annual Conference and Exposition*, Indianapolis, IN, USA, 2014.