Journal of Microscopy, Vol. 189, Pt 3, March 1998, pp. 188–191.
Received 18 August 1997; accepted 27 November 1997

SHORT COMMUNICATION

Surface profiling of combustion chamber deposits using aperture correlation confocal microscopy

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Key words. Surface analysis.

Summary

The depth discrimination capability of a confocal microscope can be used to generate height-coded maps of surface topography from reflective surfaces. However, this surface profiling ability is severely limited when black surfaces are examined. In this paper we describe how a new form of confocal microscopy, known as self-correlating aperture microscopy, can be used to obtain surface topographies from the black carbonaceous deposits found in the combustion chambers of internal combustion engines. The technique is nondestructive and requires no sample preparation. The stereo pair images presented show the range of different morphologies found in combustion deposits generated by different fuel chemistries.

Introduction

Confocal microscopes differ from wide-field microscopes primarily in their ability to provide depth discrimination. The improved depth discrimination provided by confocal microscopy can be used either to generate three-dimensional stacks of images or height-coded maps of surface topography. In transparent and translucent materials, such as biological tissue, depth discrimination is used to provide an ‘optical sectioning’ capability. The confocal microscope illuminates a thin focal plane within the sample causing either epifluorescent or reflected light to be produced. The light is collected by a spatially restricted collector so that only light from a shallow focal plane is collected. This method therefore allows a two-dimensional cross-sectional image from within the sample to be generated. Using high-numerical aperture oil- or water-immersion lenses this slice can be as thin as 0·3–0·5 μm. If the z stage on the microscope is stepped a known and fixed distance a series of perfectly registered optical sections can be acquired. This type of data can be processed by a computer to give surface- or volume-rendered reconstructions of the 3D structure. Alternatively single optical sections can be captured and used for direct quantification of the 3D structure using stereological methods (e.g. Gundersen *et al.*, 1988a,b). In applications where surface, rather than subsurface, information is of interest the depth discrimination capability of a confocal microscope allows it to be used as a surface profiling tool (Wilson & Sheppard, 1984). In surface profiling mode the focal plane of the microscope is moved down in the z direction towards the surface. As each element of the surface comes into focus the reflected intensity shows a sharp maximum. If the z positions of these maxima are recorded for each pixel in the x–y image plane then a height-coded map of the surface can be generated. The height information can be displayed as a contour map, an orthographic projection or as a stereo pair 3D image. The confocal microscope as surface profiler can be used to resolve depth variations of about 0·5 μm (Hamilton & Wilson, 1982).

When used in surface profiling mode the confocal microscope relies upon light being reflected back from the outermost layers of the surface to the detector. Intuitively one would expect that changes in surface reflectivity would affect the accuracy of this technique. However, this is not the case and even fairly large changes in surface reflectivity can be accommodated (Wilson & Sheppard, 1984). The reflectivity of a surface depends upon many different aspects of the physical make-up of the outermost layers and is also dependent to some extent on the wavelength of the light used. Some surfaces are very efficient absorbers of light, i.e. optically black in colour, and in these circumstances a reflected signal may be too weak or noisy for reliable surface profiling. This problem can be particularly acute with real-time tandem scanning reflected light microscopes (Petran *et al.*, 1968). These microscopes use a spinning disc arrangement and have a low light 'budget' whereby only about 1% of the available light is used.

In this paper we describe how a new, white light source, confocal microscope with a high light budget can be used to obtain surface profile images from a virtually black surface. The new instrument uses a spinning disc aperture mask arrangement to provide a low-crosstalk series of images which are a combination of confocal and conventional images (Wilson *et al.*, 1996; Juškaitis *et al.*, 1996). The technique has become known as self correlating aperture microscopy (SCAM). The surfaces analysed here are black carbonaceous deposits found in the combustion chamber of an internal combustion engine. The deposits have a very low reflectivity and previous attempts to image these deposits with laser scanning confocal microscopy have been unsuccessful. The deposits have been imaged with SCAM without the need for sample coating or other preparation. Typical images of deposits of very different morphology are presented.

2. Materials and methods

2.1. Self-correlating aperture microscopy

The optical principles applied in an SCAM instrument are described in Wilson *et al.* (1996). The basic idea is to use a rotating disc composed of an aperture mask. This mask is a pattern of 'pixels' that are either completely black or completely transparent. The pattern of pixels is designed so that the pattern is uncorrelated with itself; in practice this is achieved by using a random sequence of black and transparent pixels. Each transparent pixel acts as a confocal aperture and the image obtained from this aperture mask is a combined confocal and conventional image. A region on the disk is also completely transparent so that a conventional reflected light image is obtained. A 'pure' confocal image is obtained by subtracting the conventional image from the combined image. The light budget of an SCAM can be as high as 20% (Wilson *et al.*, 1996) which compares very favourably with the 1% light budget found in many tandem scanning confocal microscopes (Petran *et al.*, 1968).

For the imaging experiments described here a second generation prototype SCAM developed at Oxford University was used. The microscope uses a rotating Perspex disc with a photo-lithographically printed set of 80 μm square apertures on an 80 μm pitch. The aperture transmissivity was either zero (i.e. black) or one (transparent) and the pattern of transparent apertures was randomly distributed over a sector of the disc. The disc was rotated at ≈ 1500 revolutions per minute to synchronize with the frame rate of the CCD camera that was used to capture both the composite and the conventional images. The illumination source was a 250-W projector lamp bulb, with a set of neutral density filters to reduce light intensity. Real-time combined confocal and conventional images were displayed on a monitor next to the microscope. Images required for subsequent processing were stored on the PC hard disk. A stepper motor and interface unit suitable for moving the microscope stage in the z-direction was used to acquire z-series of confocal images.

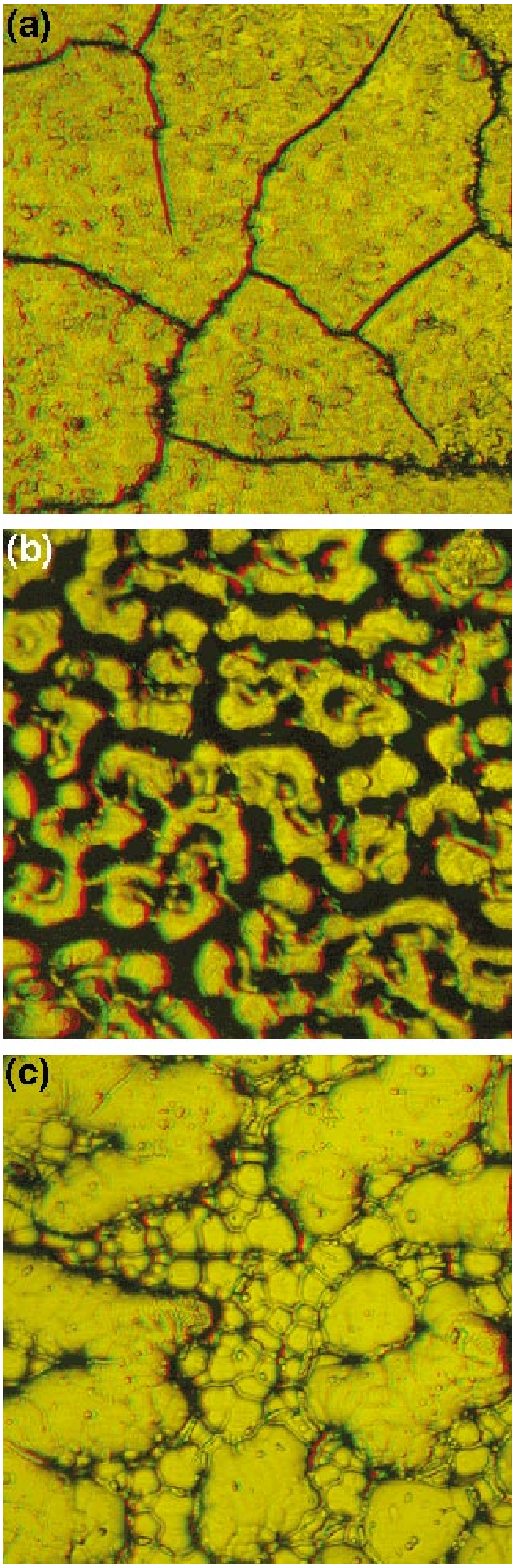
2.2. Combustion deposits

An internal combustion engine, of either petrol or diesel type, burns the fuel at extremely high temperatures. The ignition processes taking place in the combustion chamber are complex and depend upon the 3D shape of the combustion chamber, the fuel chemistry and the engine cycle. The combustion process leads to a build up of carbonaceous deposits of complex morphology and chemical composition. Previous attempts to image these deposits with laser scanning confocal microscopy have required sputter coating of the deposits with a thin layer of metal. Applying this coating effectively destroys the sample and means that further chemical and physical analysis cannot be carried out.

For this study samples of combustion chamber deposits were obtained by inserting cylindrical steel probes into a machined groove in the combustion chamber of a test engine (Kalghatgi *et al.*, 1995). The engine was then run under standard operating conditions on three different fuels, with a fresh probe being fitted for each fuel. Each of the probes in turn was temporarily fixed to the x–y stage of the SCAM and several areas from each probe were examined using a 50× magnification, 0·8 numerical aperture, Olympus objective lens. The combined confocal/wide-field image from the microscope is shown real time. This feature allows an initial, nonconfocal, examination to be carried out before a complete confocal z-series is acquired. Once representative regions for each sample probe had been identified a z-series of 512×512-pixel confocal images for each region was recorded using the automatic z step facility built into the microscope. For each area the z series consisted of between 25 and 40 images spaced 0·5–1·0 μm apart. The stacks of images were used to create stereo pair images by shifting each of the images in the auto-focus images by 0·5 pixels to the left or right, respectively.

3. Results and discussion

Figure 1(a)–(c) shows one stereo pair anaglyphic image for each of the three probes. The images show the topographies of the combustion deposit surfaces obtained without metal coating or other pretreatment. In each case the combined conventional and confocal images were recorded on a cheap CCD video camera and then processed to obtain the



individual confocal images. In all three cases the light intensity provided by the projector lamp was more than sufficient to produce reflectance images of high signal-to-noise ratio. These 3D images show the wide range of microscopic surface morphology found in combustion chamber deposits. The surface morphology of these deposits is influenced by temperature gradients in the combustion chamber, the chemical composition of the fuel and the running conditions of the engine.

The surface shown in Fig. 1(a) is composed of flat plates of carbonaceous material with no visible subsurface structure. The fine details of the surfaces are quite well resolved, showing a lightly pockmarked finish with small lumps of deposit attached. The small range of depths in the *z*-direction accounts for the subtlety of the 3D effect in this image. Figure 1(b) shows a much more striking and complex topography. The surface is composed of bridges and pillars with relatively deep chasms in between. There is some evidence of a complicated subsurface structure and high porosity. The black regions between the pillars indicate areas where the light has not been reflected back to the detector. These regions are perhaps too far outside the range of the *z*-series to be clearly resolved. Figure 2 is a colour-coded height representation of Fig. 1(b). The surface morphology of the deposits shown in Fig. 1(c) is an interesting combination of two types of morphology: a series of bulbous 'cauliflower'-like regions rising up from the surface and regions of 'crazy paving' in between. The surface detail of the cauliflower regions is again clearly resolved and is similar to, though somewhat smoother than, the surface shown in Fig. 1(a). The crazy paved areas are particularly interesting because the vast majority of the ridges meet at an angle of $\approx 120°$. This is the angle found between three liquid lamellae in a liquid foam structure. The fact that these ridges meet at this angle suggests that the deposits may have been formed by the carbonization of a series of liquid bubbles at the surface. The crazy paved regions may well be the precursors of the bulbous cauliflower features.

The range of surface morphology found for the three fuels indicates that the process of combustion deposit build up in an internal combustion engine is not simply due to deposition of amorphous carbon (i.e. soot). The high temperatures and competing chemical reactions in the

Fig. 1. Stereo pair images of the three combustion deposit probes described in the text. Each image has been anaglyphically encoded and the 3D effect can be obtained by viewing with red/green glasses. In each case the images were taken with a 50× magnification, numerical aperture 0·8, Olympus air objective lens. Each of the images is 230 μm square.

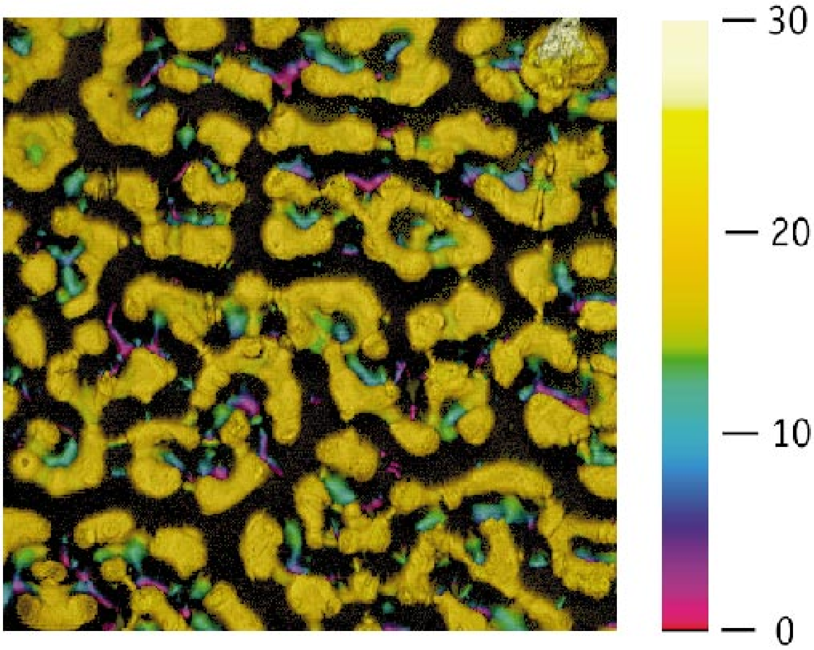


Fig. 2. A colour-coded height representation of Fig. 1(b) The height scale on the right of the image is in micrometres. Both reflectivity and height are encoded in the image as brightness and hue, respectively.

combustion chamber provide conditions where complex and well-characterized morphological features are generated. Further work is underway to assess the repeatability of the morphologies and to quantify the size and morphology of the deposits.

Previous attempts to image uncoated combustion deposits, such as those shown here, with confocal microscopy have been unsuccessful. The highly light-absorbent surfaces provide poor signal-to-noise images that are unsuitable for surface profiling. The images shown here, obtained very quickly and noninvasively, give an indication of the potential of the SCAM instrument for surface profiling on black and unreflective surfaces.

Acknowledgments

We thank Dr Gautam Kalghatgi (Shell Research & Technology Centre-Thornton) for the use of the combustion chamber probes and Shell Research Management for permission to publish this note. Tony Wilson acknowledges the support of the Paul Instrument Fund.

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