Quantitative image analysis of electrophoretic coatings

F. GRILLON, D. FAYEULLE, M. JEANDIN
Ecole des Mines de Paris, Centre des Matériaux P. M. Fourt, BP 87, 91003 Evry Cedex, France

It has recently been shown that thermal-barrier coating (TBC) properties can be improved when the bond coat is cellular (Fig. 1). This coating is obtained by the so-called “CELCO” (CELlular COating) process [1, 2] based on electrophoresis.

Quantitative metallography was applied to the electrophoretic deposits because it showed the most potential in establishing microstructure–thermo-mechanical properties–process relationships. Conventional techniques such as (two- or three-dimensional) roughness profilometry or stereo-imaging could not be used because of the coating morphology which featured overlapped contours. The linear roughness, and thus the extrapolated

Figure 1 Cross-section SEM image of a “CELCO” TBC with an SEM plan view of the bond coat (top left).

Figure 2 Various stages of image processing. (a) Secondary electron 7.2 kV SEM image; (b) digital image after thresholding; (c) image resulting from opening of the grey image; (d) gradient image; (e) digital image after thresholding of the gradient image with single dots and (f) recreation of the missing particles by hole-filling.
surface roughness, was therefore determined by quantitative image analysis (QIA).

Squaregrid Tracor Northern 8500 and 8502 analysers were used. Processing using 256 grey levels was applied to scanning electron microscope (SEM) images acquired in a 512 × 512 pixel format to save time and memory. This format gave sufficiently high resolution although 1024 × 1024 pixel acquisitions could have been performed.

After a previous impregnation by a polymer resin to improve cohesion, three cross-sections of each coating (deposited on to cylinders) were studied. Although the samples were impregnated and carefully polished (from 1200-grit paper to 3 μm diamond paste), some particles were torn from the surface, which made the use of adequate imaging and processing necessary to quantify these missing particles.

Following preliminary imaging tests using (direct as well as skimming) optical light, X-ray signal, absorbed and backscattered electrons, processing was applied to secondary-electron SEM low-tension (7.2 kV) images of metallized specimens. The latter technique revealed all of the significant features, in particular the outline of the missing particle traces as well as the substrate and the coating (Fig. 2a).

The processing software, written in a low-level programming language for flexibility reasons (easy to modify), was divided into three stages: digital imaging of the substrate and the coating; measurements by closing operations applied to the coating; and quantification of the coatings linear roughness.

Previous thresholding of the initial grey image extracted all of the relevant features, free from all background noise produced, for example, by scratches and mounting (Fig. 2b).

The outline of the missing particle traces, revealed by the high contrast of the starting image, was processed by three successive erosions of size 3, which made the black areas propagate followed by a dilatation of the same size (Fig. 2c). A gradient image resulted from substracting the opened image from the starting image (Fig. 2d), which consequently left all high-gradient areas. The particle trace outlines were then extracted by a mere thresholding and cleared from background noise by thinning and removing of the single dots (Fig. 2e). The final stage recreated the missing particles using a hole-fill algorithm (Fig. 2f).

The principle of the extraction of the substrate from the remainder was based on the fact that the substrate corresponded to a large zone of fairly uniform grey levels. The electrophoretic coating, however, exhibited rather high-frequency grey–black alternating areas. The starting image (Fig. 3a) resulted from mixing of the first threshold image (Fig. 2b) with the final dilatated image (Fig. 2f). In the grey image, substrate extraction was therefore obtained by opening, i.e. erosion then dilatation, of a large size, i.e. 7, repeated seven times (Fig. 3b). Subsequent thresholding and intersecting of the complementary image with the starting image of the sample displayed only the coating (Fig. 3c). The remaining defects at the coating–substrate interface were suppressed due to an erosion of size 1 followed by a thinning and a template dilatation before adding to the substrate-only image (Fig. 3d).

In-depth features of the coating (e.g. the porosity)

Figure 3 Various stages of substrate and coating extractions. (a) Digital image resulting from mixing of the images shown in Fig. 2b (darker dots) and Fig. 2f (lighter dots)*; (b) extracted substrate by opening; (c) extracted coating after removal of background noise and (d) intersection with a template.

*More significant colour reprints of figures 2 and 3 can be obtained by writing to the authors.