



Analyzing Porosity in Thermal Barrier Coatings: Edge Detection of Images using MATLAB

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Abstract

Thermal spray has been widely used in aerospace and manufacturing industries for a variety of applications, especially for coating technology. The process-structure-property correlations to the coating technology are very important for achieving lifetime durability and sustainability. An important measure of coating integrity is the porosity of the surface structure. Traditionally porosity of the deposit is obtained by microscopy of the surface and the use of software based on grayscale threshold setting. This paper evaluates the grayscale threshold method using MATLAB for determining porosity on test images of a thermal barrier coating (TBC). Also, it is found that the porosity of test images can be assessed within 0.5% by the above method.

1. Introduction

Surface coatings in the aerospace and manufacturing industries are used to produce thermal barriers, corrosion resistance and wear resistance. Figure 1 illustrates an Yttria-Stabilized-Zirconia (YSZ) coating on a bond coat of NiCoCrAlY applied to a substrate of AISI 316 steel. Thermal spray includes processes such as air plasma spray (APS), high velocity oxy-fuel (HVOF), low pressure plasma spray (LPPS) and electron beam physical vapor deposition (EBPVD). Properties of the coating such as porosity, micro-hardness, thickness, adhesion and strength are important metrics in assessing its viability and also provide important tools for evaluating which process parameters need to be changed to achieve an optimum coating^[1]. The percentage of porosity in a surface coat for example has been related to the onset of future cracks and final delamination from the substrates^{[2][3]}. Generally thermal barrier coatings (TBCs) have a lifetime up to five years and needs more process control mapping and *in-situ* sensing for the analysis of a dozen of variables including temperature, pressure, particle velocity, plasma for a reliable coating on super alloy substrates^[4]. Significant research has been done using digital image processing and interlinks that to the TBC^[5]. For the assessment of porosity, which is the property reviewed in this paper, the conventional methodology is the evaluation of microstructures using optical microscopy and digital image analysis using grayscale thresholding. Unfortunately this technique is subjective, not only due to grayscale threshold setting, but also to variations in the image due to light intensity, surface reflectivity, sample

preparation and impregnation technique. In this report, the accuracy of the grayscale thresholding approach will be investigated using MATLAB.

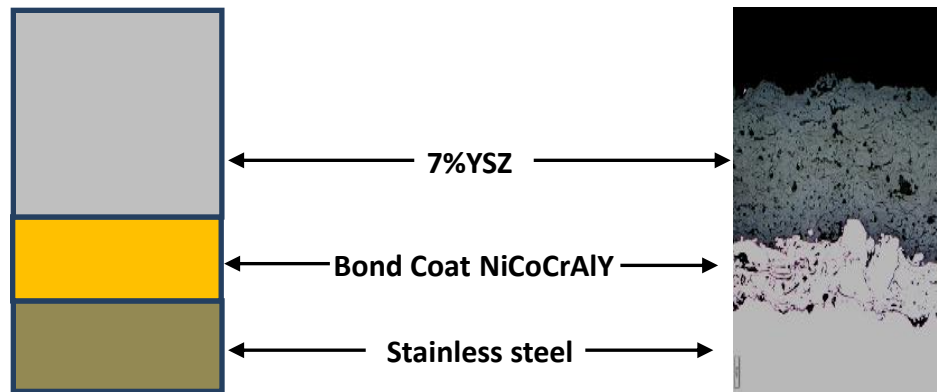


Figure 1. Schematic for thermal barrier coating 7% YSZ

2. Image Processing

Modifying digital images has been made possible in modern technology through what is known as image processing, which is a key tool in analyzing various forms of media. It enables one not only to enhance images by removing unwanted portions of the image signal, but also makes possible the concept of embedding messages, codes, and other features into the same images. Further, it is important in coding and decoding images and in the actual recognition of those images as well. Image processing is how a system, which responds based on certain images, would determine when and what responses are most appropriate if any at all. The process is done through the use of eight basic steps:

- Image acquisition
- Image enhancement
- Image restoration
- Color image wavelets
- Multi-resolution processing
- Compression
- Morphological processing
- Segmentation

The first three steps deal with the actual retrieval of the image. They make the size and rotate the image, alter the contrast, and restore the image, respectively. Steps four and five, which are color image wavelets and multi-resolution processing, pull the portion in the image that is the focal point and adjust its resolution. The compression step ensures the image is of adequate size to be stored or transmitted. Finally, morphological processing and segmentation steps deal with the dissection of the image to determine how it is to be used.

3. The Design

3.1 Method

The creation of this system was executed in five major steps. Those steps are as follows:

- Establishing a control set of images (image database) to be tested against
- Filtering each of the control images
- Establishing a test image or the image needing to be recognized
- Filtering the test image
- Comparing the test image to the images in the database to determine if they are a match

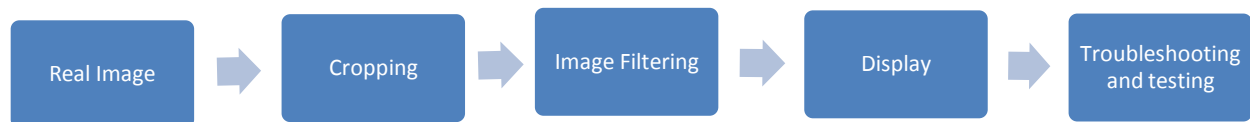


Figure 2. Method of Edge detection using MATLAB

Image processing using MATLAB software as shown in figure 2. The following is the process followed for the last two steps:

Filtering Control Image

- Determine desired means of filtering (grayscale, black and white, edge detection)
- Convert the image to a grayscale image
- Convert the grayscale image to a black and white image

- Perform Edge detection on the black and white image

Compare Images

- Correlate each of the filtered test images with its control counter parts
- Record the correlation results of the test images with each of the control images into a spreadsheet
- Based on the results, determine which of the images are similar and which ones are not

3.2 Flow Chart

The flow chart of the design and method is shown in Figure 3.

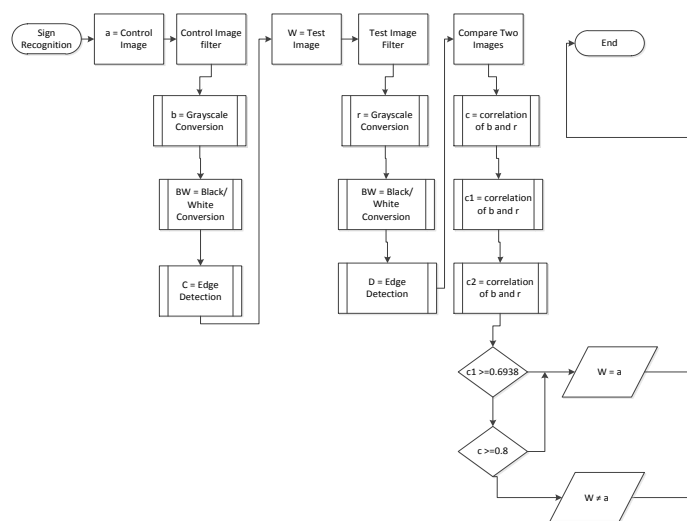


Figure 3. Flow chart of designing and method of edge detection

Explanation on the various items is as follows:

Grayscale - Each pixel, or element in the matrix, has a numerical value representing its intensity, or shade of gray, ranging from 0 to 1 with 0 representing black and 1 representing white.

True color RGB- A true color red-green-blue (RGB) image is represented as a three-dimensional $M \times N \times 3$ double matrix. Each pixel has red, green, and blue components along the third dimension with values in $[0, 1]$, for example, the color components of pixel (m, n) are $\text{My Image}(m, n, 1) = \text{red}$, $\text{My Image}(m, n, 2) = \text{green}$, $\text{My Image}(m, n, 3) = \text{blue}$.

Binary – Much like the grayscale images, the elements of a binary matrix are denoted using 0s and 1s. The difference, however is that the computer recognizes each pixel as either black or white, making the image easier to analyze.

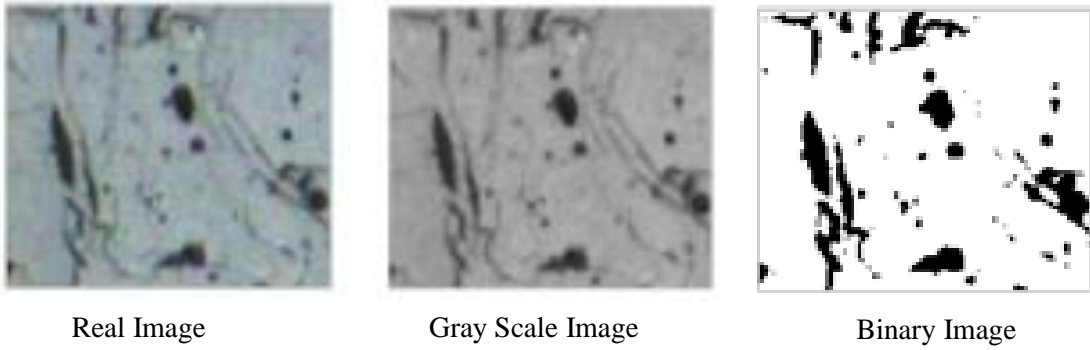


Figure 4. Conversion from the real image – gray scale images – binary images

Filtering – Image filtering is used to filter out certain wavelengths from the signal or image processed. The filtering process has also different functionality such as band pass, color, neutral density (ND), and Infrared (IR). Furthermore, image filters are being used for coating, substrates, or both, to block certain wavelengths or image signals that are prohibited, while allowing the light is being transmitted. This is important because the system must able to recognize the image instead of other noise or unwanted signals that the camera detects.

Edge Detection – The process of classifying and placing sharp discontinuities in an image is called edge detection. The discontinuities are immediate changes in pixel concentration, which distinguish boundaries of objects in a scene. There is a very large number of edge detection techniques available, each technique designed to be perceptive to certain types of edges. Variables concerned in the selection of an edge detection operator consist of edge orientation, edge structure and noise environment. Operators can be optimized to look for vertical, horizontal, or diagonal edges. Edge detection is a difficult task in noisy images, since both the edges and noise hold high- frequency content. Efforts to reduce the noise result in unclear and distorted edges. Techniques used on noisy images are typically larger in scope; therefore, they can gather enough data to discount localized noisy pixels. An example of edge detection methodology is given by the function:

$$BW = \text{Edge}(I) \quad \dots\dots\dots (1)$$

This function takes a gray scale or a binary image I as its input, and returns a binary image BW of the same size as I, with 1's where the function finds edges in I and 0's elsewhere.

- (a) The Sobel method finds edges using the Sobel approximation to the derivative. It returns edges at those points where the gradient of I is maximum
- (b) The Prewitt method finds edges using the Prewitt approximation to the derivative. It returns edges at those points where the gradient of I is maximum.
- (c) The Roberts method finds edges using the Roberts approximation to the derivative. It returns edges at those points where the gradient of I is maximum.
- (d) The Laplacian of Gaussian method finds edges by looking for zero crossings after filtering I with a Laplacian of Gaussian filter.
- (e) The zero-cross method finds edges by looking for zero crossings after filtering I with a filter you specify.
- (f) The Canny method finds edges by looking for local maxima of the gradient of image.

The gradient is calculated using the derivative of a Gaussian filter. The method uses two thresholds, to detect strong and weak edges, and includes the weak edges in the output only if they are connected to strong edges. This method is therefore less likely than the others to be fooled by noise, and more likely to detect true weak edges.

Correlation – Correlation is a mutual relationship or connection between two or more images. There are types of correlations such as cross correlation and correlation coefficient. The two are similar because they both will provide the similarities and differences of the images but the way that it is done by the two types of correlation is different. Cross correlation is when the pictures are divided into smaller rectangular blocks. The blocks are then compared to one another to see the similarity and difference between the two. Correlation coefficient is when two or more random variables are interdependent with one another. The variables are used to explain the similarity and difference between the two images. The correlation outputs a number ranging from -1 to 1; with 1 being an exact match, 0 being no similarity, and -1 being an exact opposite.

Threshold – This is the minimum intensity or value of a signal that will produce a response or specified effect. In this instance, the threshold is the upper and/or lower bounds by which an image is determined to be similar or different. In the case of correlation, the threshold would be the percentage determined as the similarity marker. For example, a threshold can be set such that if the correlation of two images outputs a number greater than 0.75 then the images would be considered the same; if the output is less than -0.75, then the images are opposites.

Gray Scale Analysis – After converting an image to grayscale, the bit values in MATLAB will range from 0 to 256, with each value of gray corresponding to a distinct numerical value. On this scale the color black is represented by the number zero and white is represented by the number one. The grayscale image can then be converted into a contour plot diagram which gives a gray level a color on the RGB scale. The darker grays will be in the blue family and the lighter grays will be in the red color family, as shown in figure 5. From this the images can be tested to establish a threshold value for porosity. Figure 6 shows the calculation for a larger image sample (1000 x 1000 pixels).

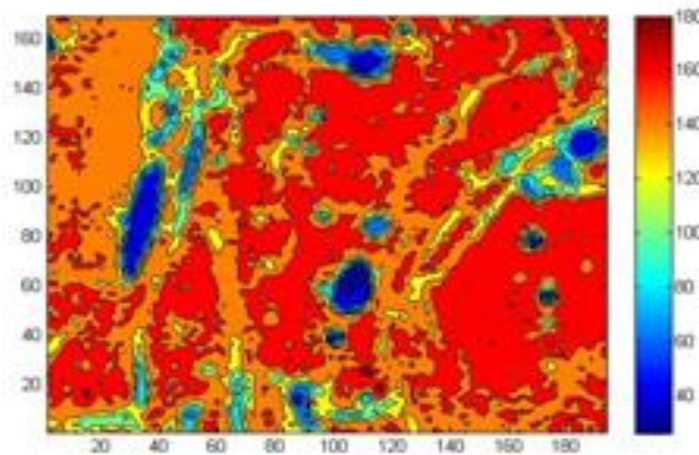


Figure 5. Plotting of the gray scale contours using MATLAB

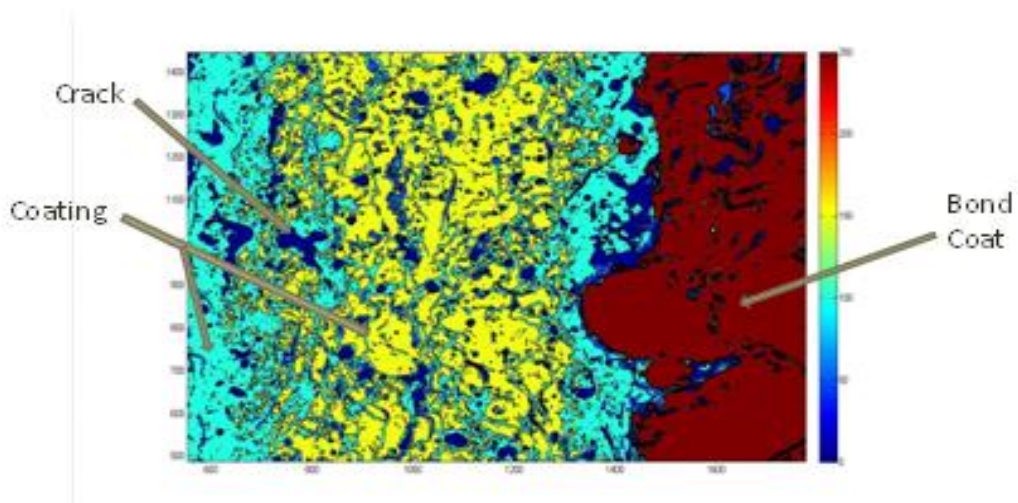


Figure 6. Calculation of Gray scale contours for 1000 x 1000 pixel of image sample

4. Design Verifications and Results

The following graphs are a depiction of the results of the *grayscale methodology*. Figure 7 displays the percentage of porosity that manually calculated for the control images we created. This was done in order to provide a known set of data to compare our findings.

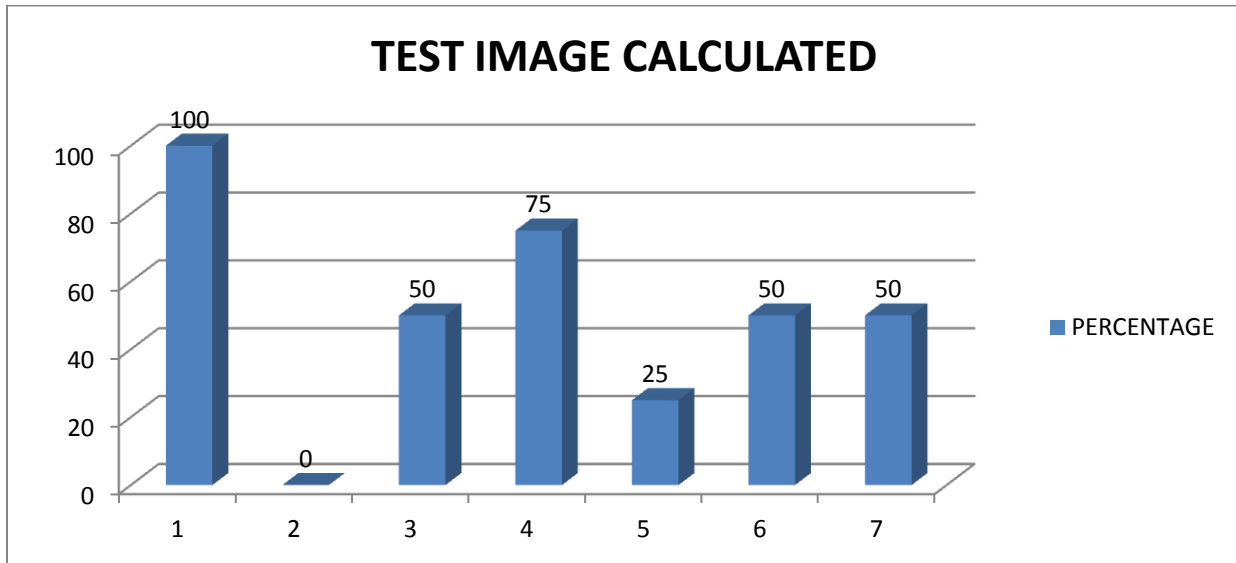


Figure 7. Calculation of % porosity from the control image

The following figure 8 shows the results of the control images after they were processed through the MATLAB software.

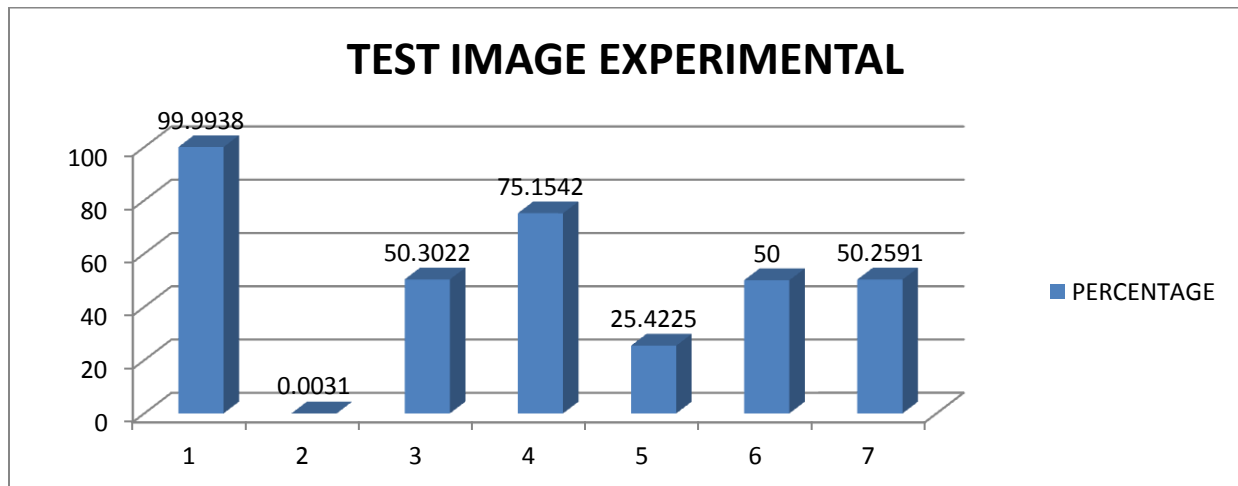


Figure 8. Calculation through the experimental test sample

Figure 9 shows the difference between the actual porosity percentage and the tested results acquired through MATLAB.

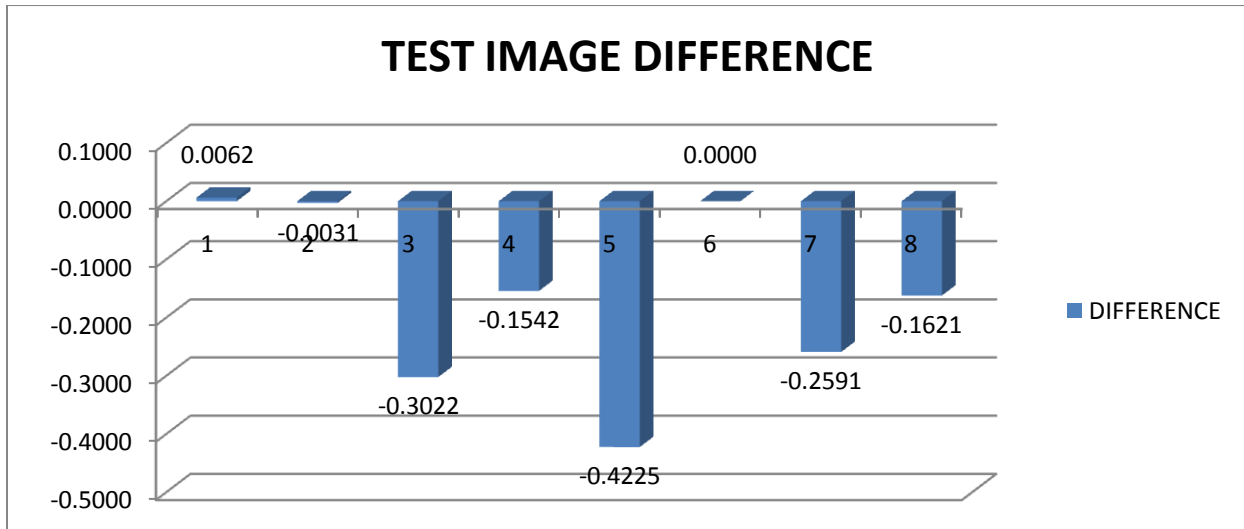


Figure 9. Calculation through the MATLAB software

5. Conclusions

The primary objective of this project was to analyze how well the grayscale thresholding method can evaluate porosity in a thermal barrier coating. It was found that the MATLAB software was able to estimate porosity within about 0.5 %. The knowledge gained from this image process method should be able lead to a greater understanding, and eventually an increase in the life cycle durability of the coating, and how porosity affects that durability too.

6. Future works

A downside to this system is that the program takes significantly longer to analyze large images. The ideal solution to this problem would be to design the system in a way which breaks the larger images down into much smaller images, and then compute the overall porosity. The difficulty can be further resolved by instituting an automation subroutine for larger images.

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Acknowledgment

We would like to give special thanks to Ben Zimmerman at CCAM, and Kendra Parks, & Monique Williams of VSU, without which the completion of this project would not have been possible. They have aided in several areas by providing images and in understanding the processes involved in the software as well as for the thermal barrier coatings.