A computer vision based system for off-line quality control of a chemically coated component of a diesel fuel injection pump

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1 October 2005

Abstract

The quality control is a very important concern in the modern manufacturing industry. In order to serve this purpose, in-line and off-line metodologies can be applied. Off-line methods and destructive anlysis are frequently associated. This is the case of metallographic investigations aimed to evaluate the microstructure of mechanical parts. This methodology is based on the visual inspection of sliced samples of the part under investigation. Computer based image analysis techniques have a great deal in this field. A case study for the automatic measurement of depth, quantity and geometry of the pores in the coating layer over a steel mechanical part is presented in the following pages. At first the image is divided, by means of a statistics based algorithm, in three horizontal bands. The coating layer is, in this way, separated from upper preparation material and underlying steel. This first step lets evaluate the depth of coating layer and depth of pore layer inside coating. Afterwards, by means of a segmentation algorithm and the following morphological processing (skeletonization and binary erosion), single pores in form of lines are extracted from the background. Their number, length and position can be therefore exactly calculated. The gained informations are used as parameters to check the specs conformity of incoming parts.

Keywords: Manufacturing, Segmentation, Digital Morphology, Skeletonization.

1 Introduction

Computer based image analysis has experienced and is experiencing, in the modern manufacturing industry, a very big spread. Possible applications are:

- object shape recognition;
- surface inspection for defects finding;
- evaluation of materials microstructural characteristics.

Some of the above mentioned investigation fields are more suitable for in-line analysis metodologies, some other for off-line analysis metodologies. In most cases off-line and destructive strategies are linked together. In the case study presented in these pages, it has been developed an off-line methodology for the analysis of the fine structure of a chemically coated mechanical component of a diesel fuel injection pump. The images taken from the metallographic samples of the part under investigation are inputs for the developed analysis software (see figure 1).

In figure 2, can be recognized three quite well delimited horizontal bands. The upper and lower bands are respectively the preparation material (bakelite) and the underlying steel base. The band in the middle is

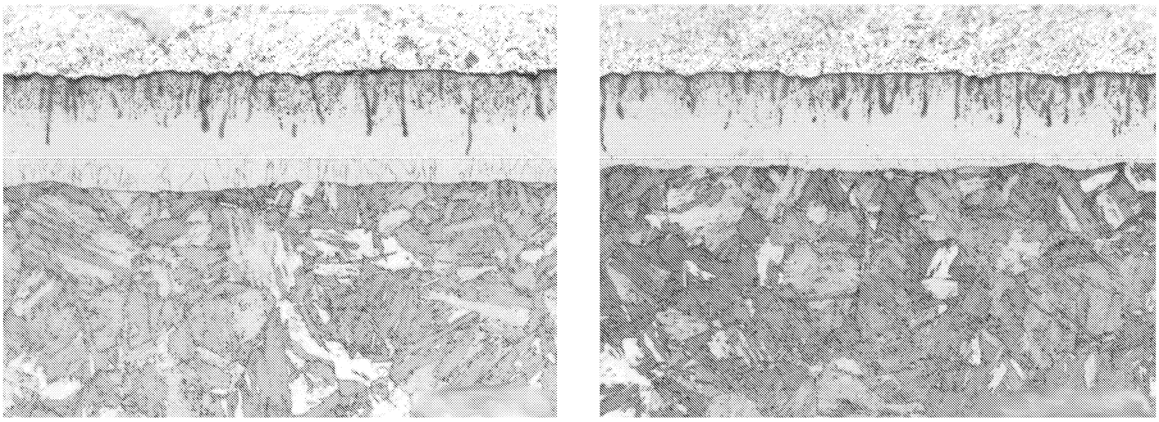


Figure 1: Images taken from metallpgraphic samples of two different parts (magnification 1000×).

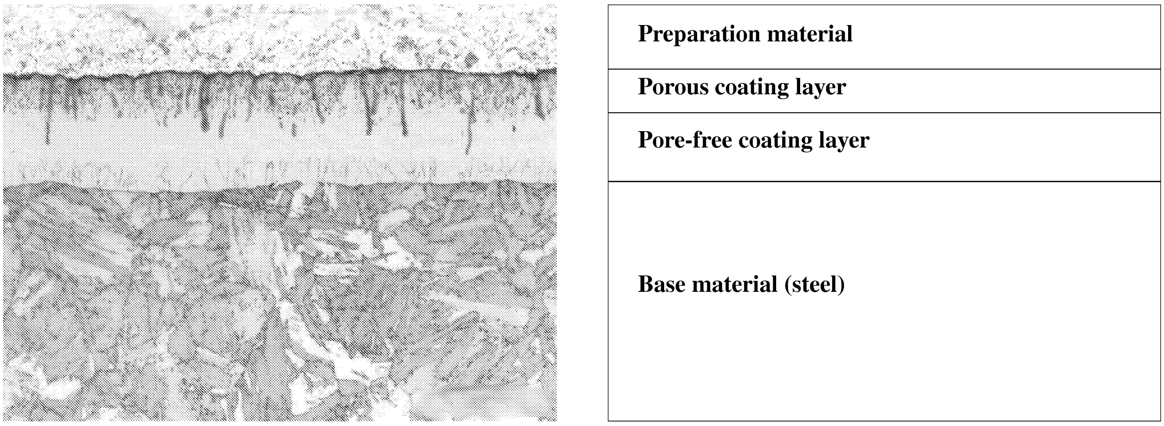


Figure 2: Horizontal subdivition of a metallographic sample.

actually our concern: the chemically built up coating layer. Within the coating layer is possible to recognize a pore and a pore-free sub-layer. In the pore-free band, deep pores cross almost all the coating.

The characteristics to be extracted from presented images that will be used for the incoming quality control are the followings:

- total thickness of coating;
- thickness of upper pore layer inside the coating;
- density of pores in the above mentioned sub-layer;
- maximal length of deep pores;
- number of deep pores whose length is bigger than a fixed value.

In figure 3 are presented two images resulting from the statistical analysis (left image) and from skeletonization after segmentation (right image). From the image on the left is possible to calculate the total depth of coating layer and of pore sub-layer. It is possible to obtain the pore density too. The last evaluation is performed comparing the grey level of pore sub-layer with the one of pore-free sub-layer taken as reference. From the image on the right are extracted all other needed informations.

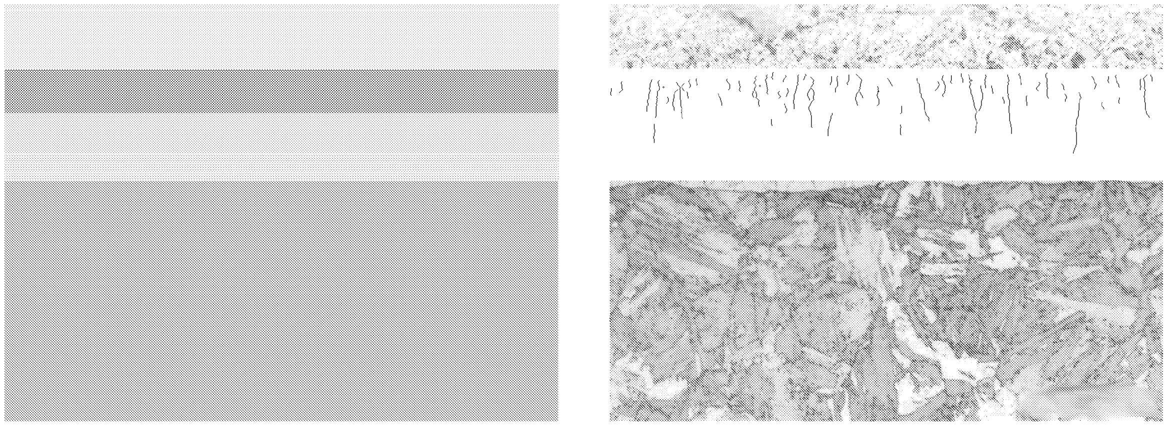


Figure 3: Images of the characteristics calculated from sample image in figure 2. From these images it is possible to extract the necessary informations for the part quality evaluation.

2 Statistical analysis

The basis for the following statistical analysis is the assumption that the image pixels, belonging to the same horizontal band, are occurences of independent random variables with same *probability density function* PDF and therefore with same mean and standard deviation. The presented hypothesis relies on following statements:

- the whole sample, because of its small dimensions ($100[\mu\mathrm{m}]$ long), is equally illuminated;
- the phisical agregation and chemical composition of each band is omogeneous.

Taken as true the previous statements, it could be said that the number and the energy of photons emitted from the surface of each single element of the sample part is similar, in the case they belogs to the same horizontal band.

But the target of our analysis is just to find the band limits. In other words, to find a rule that defines to which band each row belongs to. The used criterion is based on the membership of the row mean to a given confidence interval for the mean of the rows belonging to the same horizontal band.

We assume that the pixels of a row are observed values of g_n indipendent random variables ($n = 1, \ldots, N$ where N is the number of image array columns), with same PDF, mean μ and variance σ^2. From the central limit theorem (§ 24.6 in [6]) follows that the random variable $g'_m = (g_1 + \ldots + g_N)/N$ ($m = 1, \ldots, M$ where M is the number of rows of image array) is asintotically normal ($N \to \infty$) with mean μ and variance σ^2/N. It is then possible to apply to the random variable g'_m the same well known techniques to find a confidence interval for mean of random variables.

The following procedure is used (§ 24.6 in [6]):

1. choose a confidence interval γ (e.g. 95%, 99%, or similar);
2. find out the solution of equation

$$F(c) = \frac{1}{2}(1 + \gamma) \tag{1}$$

   from the coded table of *t Student* distribution with $n - 1$ degrees of freedom (n is the number of known samples);
3. calculate the mean $\overline{x}$ and variance s^2 of samples;
4. calculate $k = sc/\sqrt{n}$ and than the confidence intervall for the mean μ

$$\overline{x} - k \leq \mu \leq \overline{x} + k. \tag{2}$$

In our case study n is a multiple of N. As the number of rows belonging to the band increases, i.e. as the number of samples for the evaluation of mean and variance increases, it reduces the confidence interval amplitude of a factor $\sqrt{l \cdot N}$ (where l is the number of rows already belonging to examinated pump).

For the images of figure 1 has been chosen: $\gamma = 99,8\%$, and therefore, because n is big already at first calculation ($n \approx 900$), then $c = 3,09$. If b is the band to that the 'm-row could belong to, the interval is given by $\overline{x} - k \leq \overline{x}_m \leq \overline{x} + k$, where $\overline{x}$ and k are referred to the pixels to be assined to b and $\overline{x}_m$ (calculated as mean of the pixel already assigned to b and of pixel of a m-row).

3 Segmentation and binary morphology

The step following the band separation of image is the binary segmentation. The role of the object and background is played respectively by the deep pores and by the white coating. The pores will be rendered as black pixels, the background will be white. Segmentation is a required step before the skeletonization and digital morphology processing.

3.1 Hyperbola filter

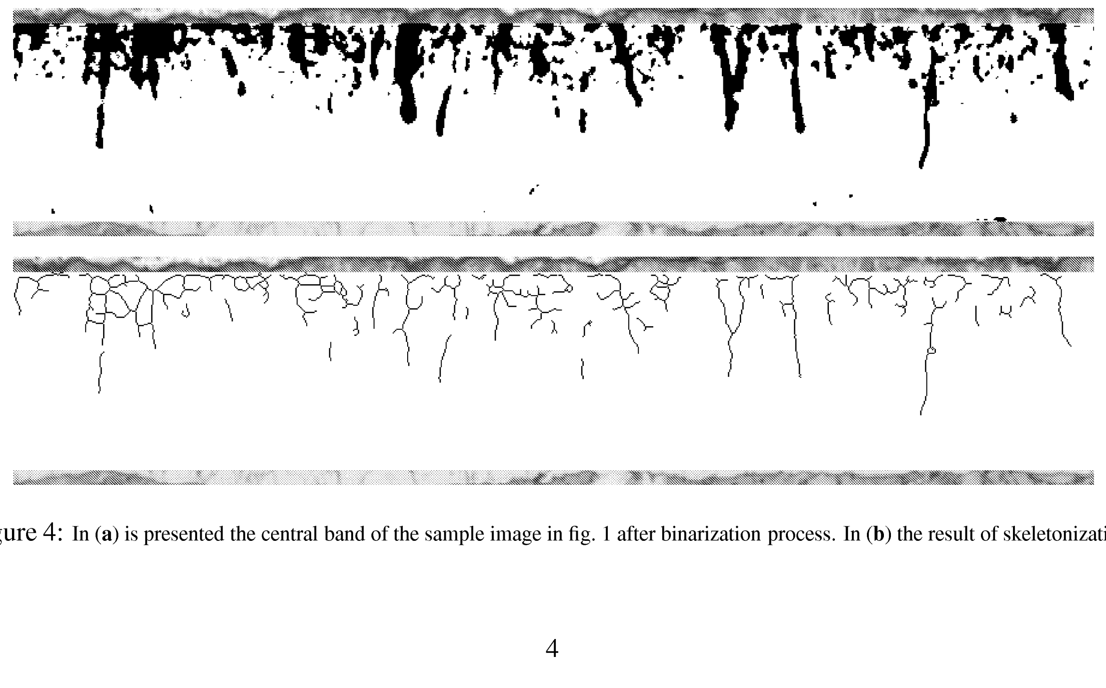
Among different segmentation algorithms, the hyperbola filter has shown to be the better for our images. Let consider the pixel p_0 of a gray level image and the pixel p_0' as the corresponding pixel of resulting binaryzed image. Let $\overline{p}_0$ be the pixel risulted from convolution between original image and a given convolution array. p_0' is defined as:

$$p_0' = \begin{cases} 0 & \text{if } p_0 \leq 2\mu \cdot \dfrac{N}{\overline{p}_0 + 1}, \\ 1 & \text{if } p_0 > 2\mu \cdot \dfrac{N}{\overline{p}_0 + 1} \end{cases} \tag{3}$$

where

- μ is the mean of grey levels of complete image;
- N is the number of possible grey levels 8 [bit/pixel]).

The Roberts' array is the one who gives better results. For our purposis has been used a 5^{th} order Roberts' convolution array.



a

b

Figure 4: In (**a**) is presented the central band of the sample image in fig. 1 after binarization process. In (**b**) the result of skeletonization.

3.2 Zhang-Suen algorithm for skeletonization

The step after the band recognition and binaryzation of coating band is the one for the skeleton (or essential line) production. By means of the skeleton is possible to extract the number of deep pores and their dimensions.

A widely used algorithm ist the one prepared by Zhang-Suen [20]. It has been used as metering algorithm

a

b

c

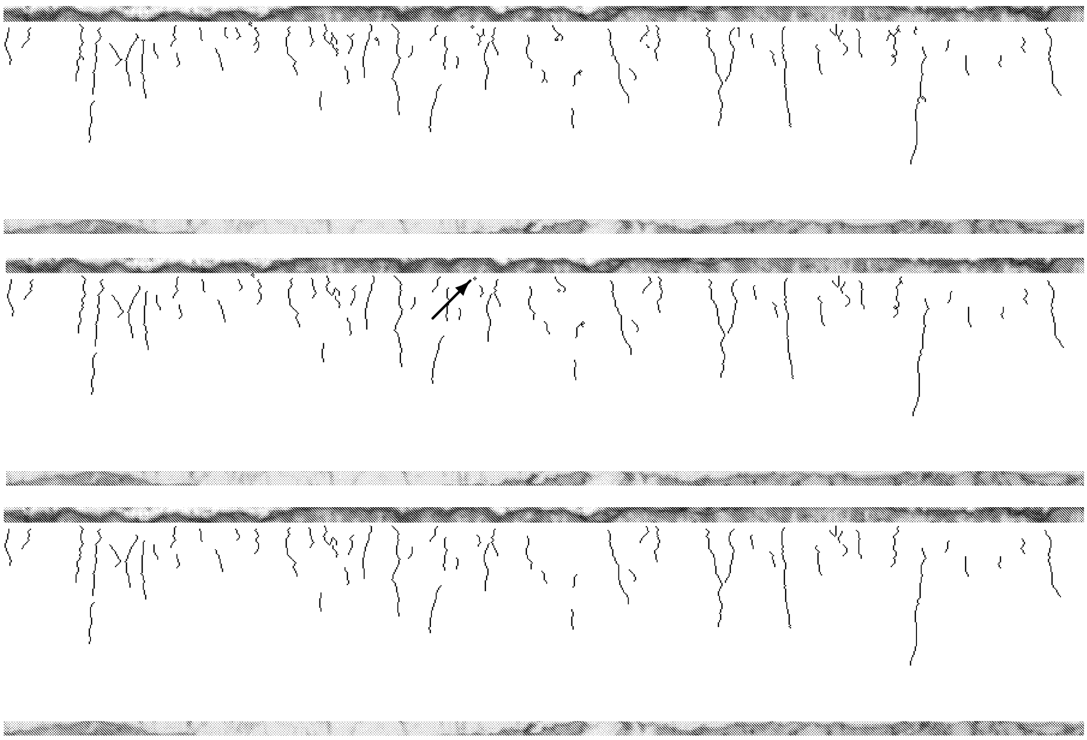


Figure 5: In (**a**) the horizontal parts of the skeleton have been suppressed, in (**b**) the branches of the skelton have been separated. At last in (**c**) the small circles like the one pointed out from the arrow have been removed.

to judge the quality of other algorithms. It is a parallel method, that is, the new value of a pixel can be calculated just starting from the values coming from the previous iteration.

The algorithm is devided in two steps. During the first one, a pixel $\mathrm{I}(i, j)$ is deleted (or marked to be deleted) if the following conditions have been proven:

1. the connectivity number value is OK;
2. has at least 2 near pixel that belongs to background and object;
3. at least one of $\mathrm{I}(i, j+1)$, $\mathrm{I}(i-1, j)$ and $\mathrm{I}(i, j-1)$ is a background pixel (white);
4. at least one between $\mathrm{I}(i-1, j)$, $\mathrm{I}(i+1, j)$ and $\mathrm{I}(i, j-1)$ is a pixel of background.

At the end of this first analysis, the marked pixels are deleted. The following step, checks whether

1. at least one between $\mathrm{I}(i-1, j)$, $\mathrm{I}(i, j+1)$ and $\mathrm{I}(i+1, j)$ is a background pixel;
2. at least one between $\mathrm{I}(i, j+1)$, $\mathrm{I}(i+1, j)$ and $\mathrm{I}(i, j-1)$ is background pixel.

The marked pixels are deleted. If at the end of both iterations there are no more pixels marked to be deletated, the program stops; the skeleton has been completed.

In order to improve the quality of the skeleton, the chain Stentiford [18] preprocessing → Zhang-Suen algorithm → Holt [18] postprocessing has been proven to be very effective.

After skeletonization further improvements of the image under analysis have been realized by means of simple algorithms of digital morphology. All horizontal lines have been deleted, the pore branches have been separated, etc. . The results related to the image in fig. 4 are presented in figure 5.

The fundamental algorithms that have been used in fig. 5 are listed below. The first one, that has been used to delete horizontal lines, outputs a boolean TRUE in the case the examined pixel is the central pixel of one of the masks presented in figure 6, otherwise FALSE. In case of TRUE the examined pixel is marked for deletion.

The second one is a recursive algorithm that separates the pore branches. It is needed to count the single pores. The policy of branch separation is to separate the shorter branch from the longer one.

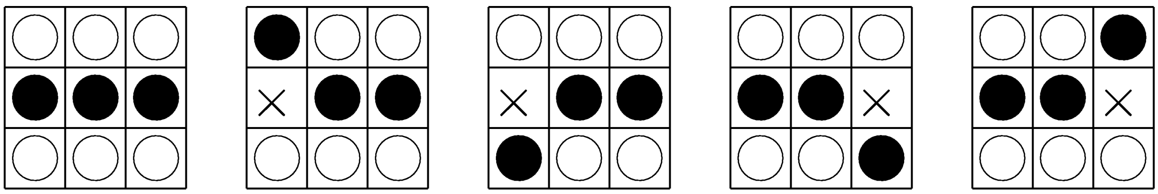


Figure 6: Templates to identify horizontal lines.

The third algorithm is the one that eliminates the short pores. The pores shorter than a user fixed length are deleted. It is recursive algorithm that calculates the length of pores an deletes the shorter ones.

Last processing is the one used in fig. 5**b** in order to deleted the circular artifacts like the one pointed out by the arrow. A binary erosion algorithm is used. The structuring elemnt is presented i fig. 7**a**, it has actually the shape of the artifacts to be deled. The eroded image is combined with not eroded image in order to eliminate the artifacts.

The fig. 5**c** is finally ready to correctly identify the position, the length and the number of deep pores inside the coating layer of the part under analysis.

Figure 7: In (**a**) the mask used for binary erosion. The pixel marked with $\times$ is the origin pixel. In (**b**) the skeleton elemnt to be deleted.

4 Conclusions

The developed procedure has been tested on many (> 10) images of different metallographic samples. With same camera, mycroscope and frame grabber for the image acquisition, the software was able to perform a correct analysis (recognise the horizontal bands and find out pores) in the 99% of the examined cases.

This software based analysis becomes therefore a valid objective methodology for the evaluation in quality classes on incoming parts. The main advantage is the elimination of the operator subjectivity.

A combination of 1^{st} order statistical analysis, segmentation techniques and basic digital morphology algorithms has been efffectively used to face the problem.

The most important step in the development of this software has been the coating layer recognition. Actually the statistical approach as first analysis step could be used thanks to the horizontal image distribution. In order to let the procedure be more robust a step ”0” can be implemented. The role of the step ”0” should be to turn the image to the horizontal position.

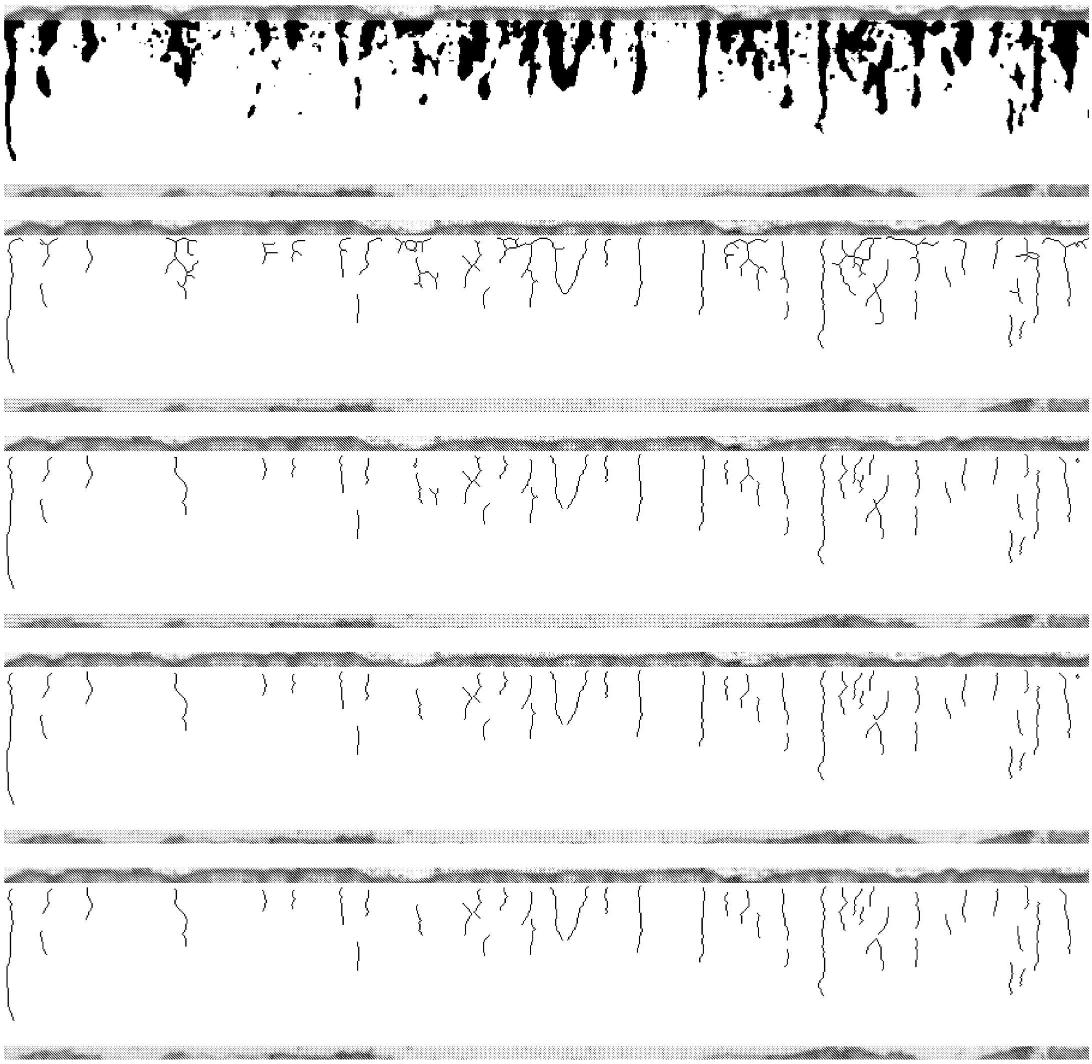


Figure 8: All steps described in the figures 4 and 5 applied to the second sample image of figure 1. In this case, the skeleton of pores shorter than 15 pixels has been deleted.

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