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# Analysis of Microstructure Images Referred to Percolation Theory

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## Abstract

The paper discusses possible applications of the percolation theory in analysis of the microstructure images of polycrystalline materials. Until now, practical use of this theory in metallographic studies has been an almost unprecedented practice. Observation of structures so intricate with the help of this tool is far from the current field of its application. Due to the complexity of the problem itself, modern computer programmes related with the image processing and analysis have been used. To enable practical implementation of the task previously established, an original software has been created. Based on cluster analysis, it is used for the determination of percolation phenomena in the examined materials. For comparative testing, two two-phase materials composed of phases of the same type (ADI matrix and duplex stainless steel) were chosen. Both materials have an austenitic - ferritic structure. The result of metallographic image analysis using a proprietary PERKOLACJA.EXE computer programme was the determination of the content of individual phases within the examined area and of the number of clusters formed by these phases. The outcome of the study is statistical information, which explains and helps in better understanding of the planar images and real spatial arrangement of the examined material structure. The results obtained are expected to assist future determination of the effect that the internal structure of two-phase materials may have on a relationship between the spatial structure and mechanical properties.

**Keywords:** Percolation, Austenitic-ferritic structure, Duplex steel, ADI, Image analysis, Cluster analysis

## 1. Introduction

The term *percolation* was initially used mainly to describe the process of leakage or filtering of fluids in a system of fine channels. Yet, the idea of percolation can also help in explaining a series of the commonly encountered phenomena such as the spread of fire or the flow of liquid through a filter. These are the unstructured systems of stochastic geometry, where random processes play a significant role. The term equally important in the discussion of a percolation problem is the percolation threshold. In theory, this is a limit at which the transition from one system/state to another occurs [3].

The phenomenon of percolation is known in crystallography, but it has never got a precise quantitative method of assessment. The methods used so far have been limited to a description of the observed microstructure and its morphology in the examined polycrystalline material. In the discussion of percolation we also come across the term of percolation path. This is a path (a trajectory) formed by the interconnected individual grains, which make up the spatial structure. Of course, in a structure of this type, the effect of percolation occurs in three dimensions, which significantly complicates the assessment and quantitative determination of its degree (Fig. 1) [ 4].

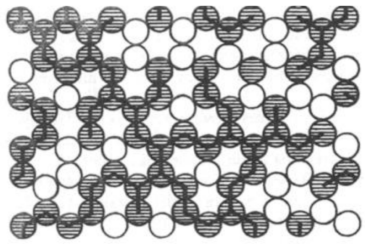

Fig. 1. Example of percolation path for nodes present in a two-dimensional hexagonal grid. Each node is marked as a circle with a radius equal to ½ distance between the nearest neighbouring nodes. Blank circles correspond to the blank nodes, the shaded circles are filled nodes, while clusters of connections are marked with thick lines [4]

Reference literature gives information on the effect of austenite on the mechanical properties of steel alloys, but not always the presence of this phase in the structure of the examined material affects in a linear way changes in the selected property such as e.g. hardness (Fig. 2) [1]. It was once suggested that these properties may depend on the spatial orientation of individual phases relative to each other, meaning in this case the austenite phase. To better explain this phenomenon it was decided to refer to the percolation theory [2,6].

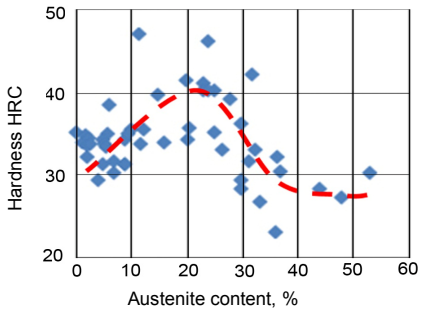


Fig. 2. Ductile iron hardness vs austenite content in the structure of ausferritic matrix

For studies of percolation, the ADI cast iron was selected and austenitic-ferritic duplex steel as a reference material. Studies of the percolation effect assessment are the first step in building a model of the spatial distribution of phases in polycrystalline materials.

## 2. Methodology and results

The first stage in the studies was preparation of metallographic specimens for the examinations of microstructure carried out under an OLIMPUS IX70 optical microscope. Polished cast iron specimens were etched in a 10% solution of potassium pyrosulphite ($K_2S_2O_5$). This etchant was chosen due to a significant improvement it brings to the microstructure image quality. The use of this solution shows austenite in the form of white fields, while graphite and ferrite appear as shaded fields. Duplex steel was etched in a 3% solution of nitric acid and sulphuric acid. Due to specific properties of this material, it was not easy to prepare specimens for examinations.

A series of metallographic images was taken at different magnifications. To make the task of the evaluation of the percolation effect simpler, only images taken at 1000x magnification were selected. In this way, the resulting high-quality pictures with clearly distinguishable fields of individual phases allowed automatic image processing. Graphical image processing was done with an INSCAPE software using properly imposed vector fields. Bright fields that have not been etched by the etching agent form an area occupied by the austenite phase. In contrast, the shaded nodes are the area where ferrite is present (Figs. 3 to 6). Thus prepared images were stored as "pgm" files in an ASCII encoding. Using this software it is possible to load the data into the programme without the additional function of colour recognition.

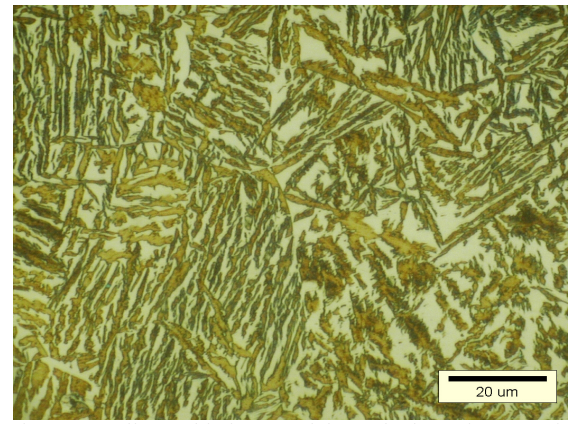


Fig. 3. Metallographic image of the etched cast iron matrix structure

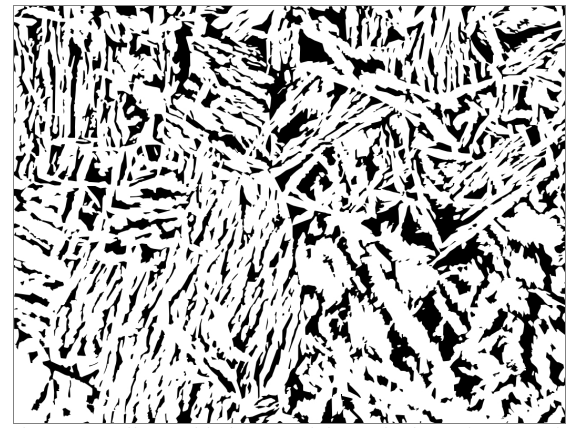

Fig. 4. Metallographic image of the etched cast iron matrix structure after graphical processing by INSCAPE

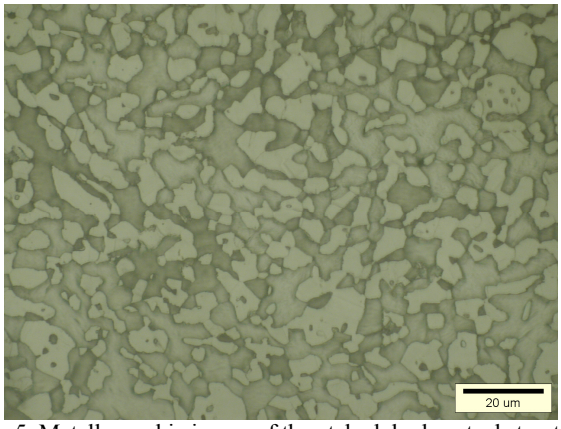

Fig. 5. Metallographic image of the etched duplex steel structure

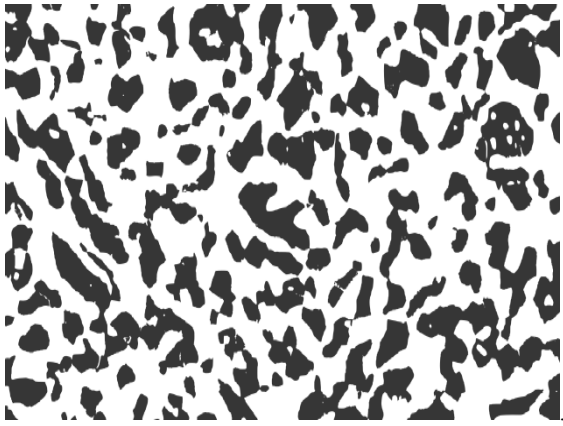
Fig. 6. Metallographic image of the etched duplex steel structure after graphical processing by INSCAPE

Processing of metallographic images is the procedure difficult to standardise. The captured images were characterised by different levels of brightness and colour saturation. Therefore, an appropriate threshold separating the brightness of individual constituents in the examined structure had to be chosen. Poorly chosen threshold separating the white and black areas could result in significant errors, which should be avoided. After development of the procedure and processing of the images it was found that, at this stage of the study, the assumed maximum error in the size of the occupied field relative to the austenite field did not exceed 1% (Fig. 7).

Thus processed image was next analysed by PERKOLACJA.EXE – an original programme written in C++ language. The programme is based on site percolation theory. The elements, of which a grid applied on metallographic image is built, are nodes. A single node can always find connection with another node in the grid - top, bottom, left, or right, and always (when the node is filled) has access to it. A single unified field of interconnected elements forms a cluster. A connection, i.e. a bond, between these elements is always available.

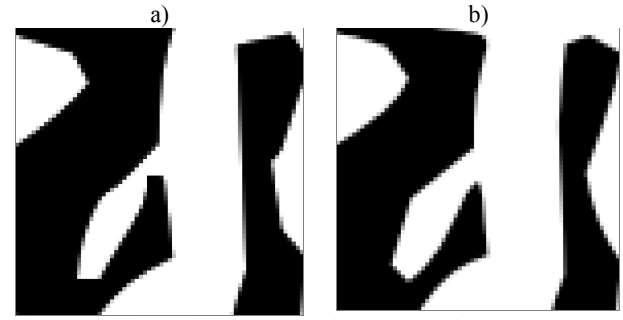

Fig. 7. Visible are differences in thickness of the distinguishable white austenite fields analysed by the software at different brightness thresholds; a) brightness threshold of 0.35; b) brightness threshold of 0.38

Language C++ was chosen because of its high potential and good performance of the resulting applications. Metallographic images stored in digital form are a set of numerous pixels with well defined parameters (e.g. colour). It is assumed that, depending on the pixel hue, it is either filled or not. By observation it has been accepted that the hue above 125 in a 255 element grey scale does not belong to the structure formed by austenite.

After loading the images into the programme, the software saves each pixel in a special table, recognising at the same time its hue. When it is less than 125, the programme sets "1" in its place which means that the node has been filled. When the value obtained is larger than 125, the program sets "0".

The next process performed by the programme is analysis of the resulting zero-one table. At this point, the programme examines if near the specific selected pixel there is a neighbouring pixel with the same colour. If there is one, then a cluster is formed, composed of the detected group of adjacent pixels of the same hue.

After cluster analysis, the statistical analysis begins. At this point, the programme counts the number of clusters that are located in the tables, the number of all filled nodes, the percent content of the phase and space occupied by this phase. Clusters are next grouped according to their size. The first group contains clusters that occupy an area larger than the half-image field. The next group has the lower limit two times smaller, and so on.

The analysis of the examined metallic materials (ADI matrix, duplex steel) gave the results presented in Table 1.

The results obtained by the programme require further interpretation and drawing appropriate conclusions referred to the percolation theory.

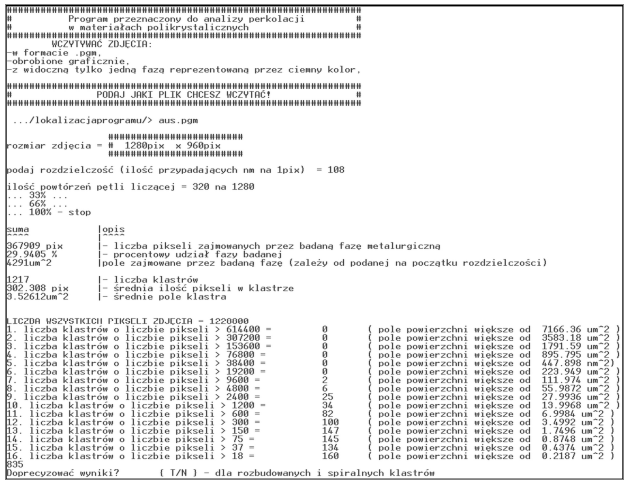


Fig. 8. Programme window after the performed analysis

Table 1.
The results of analysis of a metallographic image examined for the austenite phase content in ADI matrix and duplex steel

| Parameter examined | ADI matrix | Duplex steel |
|---|---|---|
| The number of pixels occupied by the examined metallic phase [pixels] | 367909 | 507144 |
| Percent content of the examined phase [%] | 29,9405 | 41,2715 |
| Field occupied by the examined phase [µm] | 4291 | 5915 |
| The number of clusters | 1217 | 136 |
| Average number of pixels in a cluster | 302 | 3729 |
| Average cluster field [µm] | 3,52 | 43,4951 |

# 3. Conclusions

The main aim of the studies was to create a tool for spatial analysis of two-phase materials, consistent with the theory of percolation. The aim was achieved through creation and application of a proprietory programme called PERKOLACJA.EXE for precise determination of the distribution of the examined phase in a plane of the metallographic section. This is a specialised programme, and as such it can be used to study other materials of complex structure for the determination of percolation level. For example, in the case of pearlitic-ferritic steels, this will be the evaluation of ferrite percolation in the microstructure.

The results of evaluation of the percolation level in ADI and duplex steel are consistent with the general observations of metallographic images. In the case of duplex steel there is an obvious continuity of austenite in the structure, numerically confirmed by the programme. Moreover, in duplex steel, the phases are less refined, which results in the occurrence of a considerably smaller amount of clusters, while the existing clusters are much larger in size compared to ADI matrix.

Based on the studies conducted it can be concluded that in the case of duplex steel, the probability of the occurrence of percolation in the structure is much higher. The percent content of austenite is in this case quite significant (41%). However, a relatively small number of clusters suggests that this phase can be stored in individual islands separated by the ferrite phase. To confirm that austenite phase clusters can get connected with each other, or contact each other, in the future another module will be added to the programme, and its task will be analysis of the structure morphology.

One of the trends in further research will be searching for reference between the two-dimensional structure of a metallographic image and spatial structure of multiphase materials. According to the conducted statistical studies, the assignment of nodes with probabilities higher than $p = 0.3116$ enables exceeding the percolation threshold in a spatial structure for the site percolation, while for the bond percolation, these will be the bonds assigned with a probability higher than $p = 0.2488$ [4]. Investigating the metal behaviour at these points and in their neighbours can bring interesting conclusions. If there are maxima or minima and if there is a change in their tendency, it should be possible to determine which spatial structure will be the optimal one and how it will affect the properties of e.g. ausferritic ductile iron. In addition, the test results can be translated into other areas of scientific research such as the search for more durable composite materials.

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