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P. Camus, W. Soffa, S. Brenner, M. Miller. QUANTIFICATION OF INTERCONNECTED MICROSTRUCTURES BY FIM. Journal de Physique Colloques, 1984, 45 (C9), pp.C9-265-C6-268. 10.1051/jphyscol:1984945 . jpa-00224426

**HAL Id: jpa-00224426**

**<https://hal.science/jpa-00224426>**

Submitted on 4 Feb 2008

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## QUANTIFICATION OF INTERCONNECTED MICROSTRUCTURES BY FIM

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**RESUME** - Les propriétés physiques des matériaux biphasés sont en grande partie déterminées par la morphologie de la microstructure. Pour les matériaux contenant des précipités isolés, la microstructure pourra être entièrement définie par la taille, la forme et la densité des particules. Néanmoins, pour les systèmes dont les deux phases sont interconnectées, la morphologie est beaucoup plus difficile à décrire quantitativement. Cet article fait le point sur quelques approches possibles permettant par microscopie ionique de champ, d'obtenir les paramètres quantitatifs pour décrire des morphologies plus complexes.

**ABSTRACT** - The physical properties of two-phase materials are largely determined by the morphology of the microstructure. With materials containing isolated precipitates, the microstructure can be fully defined by the size, shape, and number density of the particles. However, in systems in which both phases are interconnected, a quantitative description of the morphology is much more difficult to make. This paper points out some possible approaches to obtaining quantitative parameters to describe these more complex morphologies using field ion microscopy.

## I. INTRODUCTION

Previous APFIM studies have clearly demonstrated for the first time that the morphology of the microstructure that forms by spinodal decomposition in the iron-chromium and iron-chromium-cobalt systems is isotropic and highly interconnected or percolated in three dimensions[1,2]. The observed microstructure coarsens very slowly and it has been proposed that this is closely related to the morphology of the highly interconnected two phase microstructure[1]. To determine the effect of morphology on coarsening, it is necessary to have a quantitative parameter of the morphology.

The field-ion microscope may be the ideal instrument to provide the required morphological parameter because of its unique sectioning capability with which a three-dimensional view of the material can be generated. This paper outlines possible approaches to the quantification of the morphology of interconnected microstructures and points out some of the difficulties.

## II. PERCOLATION

Percolation theory predicts that isolated particles will exist in any structure where the volume fraction is less than a critical value[3]. At volume fractions greater than this critical value in isotropic systems, the theory predicts that there will be a finite probability of an infinitely sized cluster. The critical volume fraction, known as the percolation limit, is 50 % in two dimensional systems and only 15 % in three dimensional systems. In a material above the percolation limit, an interconnected microstructure may exist with loops or circuits of one phase enveloping the other phase.

In materials below the percolation limit the microstructure of isolated particles, as shown in the evaporation sequence of field-ion micrographs in figure 1, can be fully described by parameters such as size, shape, and number density. However, in materials above the percolation limit because of the possibility of infinite sized particles, these parameters are not necessarily applicable and do not fully describe the microstructure. The average spacing and mean intercept of one phase, that have been previously used to describe percolated microstructures, are a measure of the scale of the microstructure but they do not describe it fully, in particular the degree of interconnectivity.

### III. TOPOLOGY

The morphology may also be described by the measurement of the topological properties. These type of measurements describe the connectivity of the structure but ignore the details of the size and shape[4]. In this approach the structure is sectioned and reconstructed to produce a reduced network of nodes that are connected by branches as shown in figure 2. The structure is then characterized by the topological invariants given by

$$P_1 = P_0 + b - n$$

where  $P_0$  and  $P_1$  are the zeroth and first Betti number,  $b$  and  $n$  are the number of branches and nodes respectively.  $P_1$  is the number of the branches which may be removed without creating new separate parts and  $P_0$  is the number of separate parts. The genus or the number of closed loops per unit volume may also be calculated from this data.

The most serious problem associated with this type of analysis is the large number of sections that must be recorded so that a significant number of nodes and branches are recorded. This type of analysis is also restricted to the finer structures so that the full extent of the loops is intersected within the lateral field of view.

### IV. FRACTALS

A relatively new approach to describe the geometrical features of complex, irregularly shaped structures is using the concept of fractals developed by Mandelbrot[5]. Fractals represent objects or patterns that appear self-similar independent of scale. Detailed measurement of the patterns leads to a fractal dimension which is a measure of the density with which a curve fills a space. Fractal analysis has been found to be useful in analyzing percolated structures. However, at this stage of development, the fractal analysis of experimental data in general and field-ion micrographs in particular is extremely difficult and time consuming because of the point-wise calculation which must be performed.

### ACKNOWLEDGMENTS

Research sponsored by the National Science Foundation under a Industry/University cooperative grant DMR-8022225. Additional support provided by the Division of Materials Sciences, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

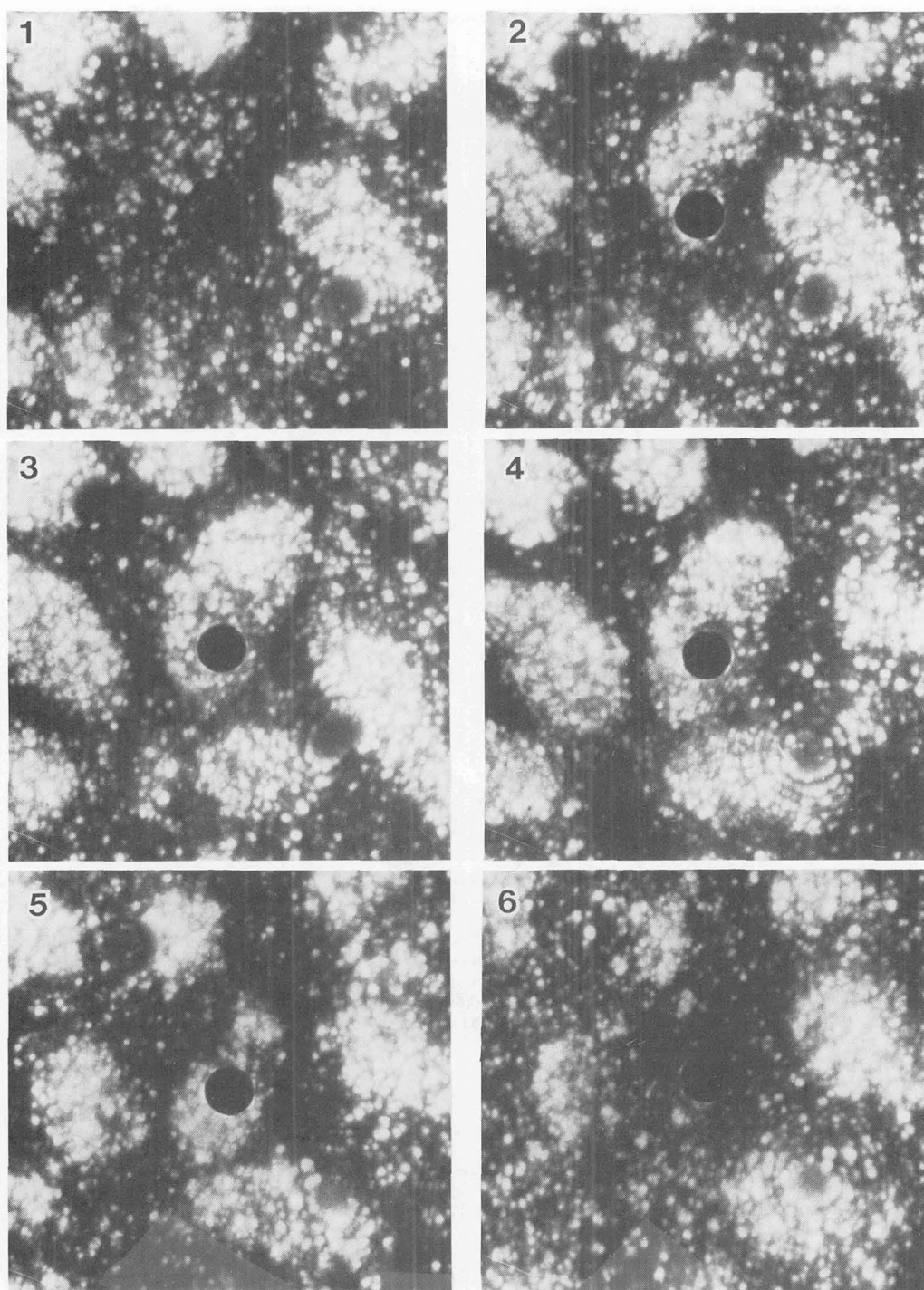


FIGURE 1. Series of field ion micrographs showing the appearance and disappearance of an isolated particle. Amount of material removed between each micrograph is 4.0 nm.

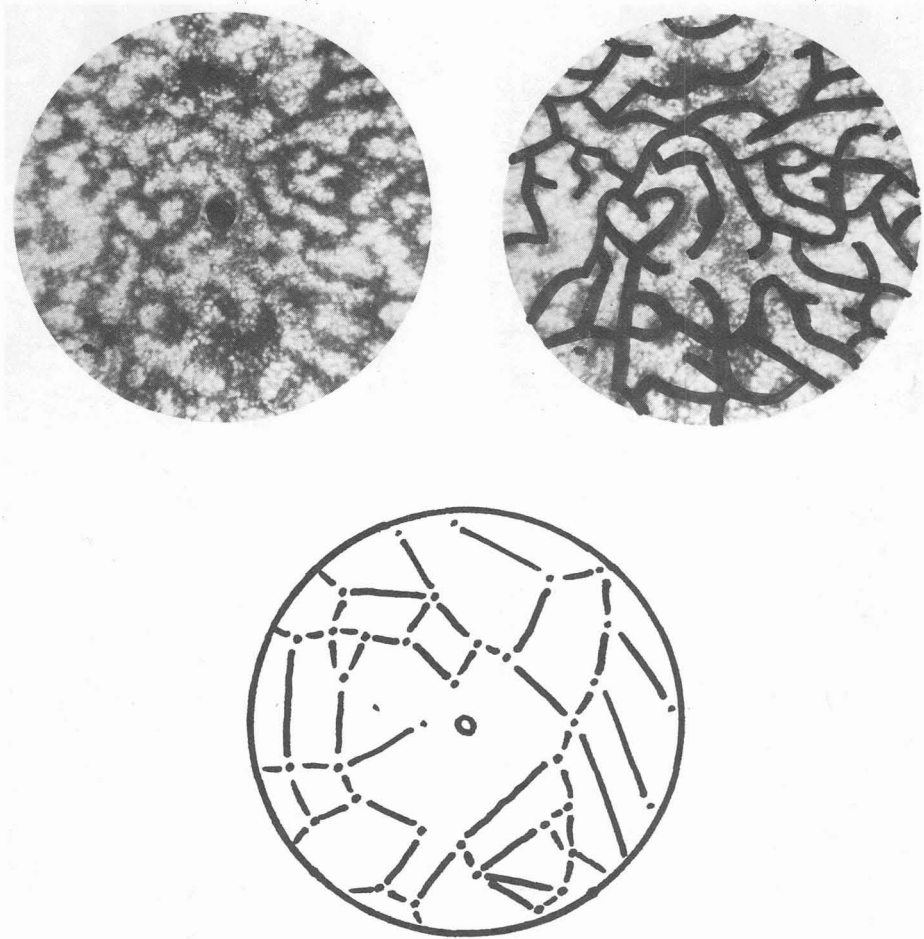


Figure 2. Stages of topological analysis of a field ion micrograph:  
 (a) Field ion micrograph showing brightly imaging and interconnected darkly imaging phases  
 (b) Representative network of darkly imaging phase  
 (c) Reduced node and branch network of the microstructure

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