Computer assisted analysis of transgranular and intergranular micromechanisms of brittle fracture

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Abstract

Automated techniques dealing with the fractography analysis of fractures that occurred in Magnesium Aluminate Spinel ($MgAl_2O_4$) are considered. Fractures were found to develop following the mixed brittle fracture pattern, predominantly by chipping. The main relief elements include chipping facets, which are formed under conditions of transgranular and intergranular fracture. Some informative features that aid in describing micromechanisms of fracture are proposed. An image recognition algorithm was applied, which allows detecting transgranular fracture sections on fractograms and calculating their area. The algorithm includes the edge detection operations using the Sobel method. It also uses a number of filters, which allow detecting the morphological features inherent in the transgranular fracture in the image.

Keywords

Fractogram, scanning electron microscopy, image recognition, edge detection, Sobel algorithm, thresholding.

1. Introduction

Fractography analysis that provides for a high reproducibility of results has now become possible owing to the computer assisted techniques for investigating images obtained by scanning microscopy. To this end, statistically significant arrays of fracture components are considered in order to make the identification of fracture micromechanisms of materials and structures more reliable. In particular, this applies to brittle fractures of materials that are formed under conditions characterized by a low energy intensity of fracture. In addition, the comparative analysis of different areas is important, which is followed by identifying the factors of microstructure embrittlement. In our case, brittle fracture describes a fracture surface without macroplastic deformation, which occurs in the conventionally elastic zone of the material deformation. At the same time, microplastic strains can localize at the microlevel, in particular, at the crack tip. The rate of brittle fracture is much higher than that of ductile fracture. This makes the former particularly dangerous and requirs additional research. Fracture

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occurs along the crystallographic planes (planes of chipping) in case of transgranular failure or along grain boundaries in case of intergranular failure. Brittle fracture is particularly sensitive to structural features that prevent plastic deformation under the loading conditions considered (emission of brittle carbides, embrittlement of grain boundaries, structural and morphological changes, etc.), or under a triaxial stress-strain state.

Therefore, the objective criteria that describe the permissible non-uniformity of the structure based on the quantitative fractography analysis need to be developed. This will provide for a deeper understanding of the material deformation patterns that occur at different scale levels, especially when supported by the modern software for the analysis of images obtained by scanning electron microscopy. Such algorithms are efficient because they consider the hypotheses that suggest a relationship between the morphological features analyzed and the physical-mechanical properties of materials, as well as the correctness of the methods for recognizing and analyzing the morphological formations on the fracture surface.

This article aims at analyzing the morphology of brittle fractures in the images of fracture surfaces of Magnesium Aluminate Spinel ($MgAl_2O_4$) in order to identify the trans granular and intergranular micromechanisms of fracture.

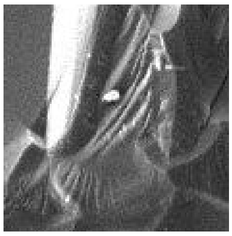
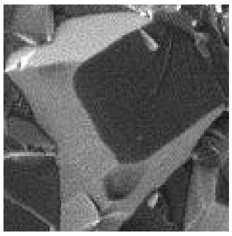
2. The relationship between the morphological features analyzed and the physical-mechanical properties of materials

Deformation caused by shear in the sliding planes or cleavage planes, or on grain boundaries is known to precede fracture of a polycrystalline material. A great many papers describe and streamline the signs of transgranular and intergranular micromechanisms of fracture. Being based predominantly on experimental data, they need to be systematized because of their descriptive nature and morphological diversity. Given the above, a quantitative fractography analysis requires a unified description of signs inherent in the micromechanisms of fracture. In this regard, detecting and considering the non-uniformity of the fracture surface at different scale levels appears critical. In addition, the concept of “multiscale” addresses the need to consider the material deformation and fracture on the fractographic image along with their reflections. And the fractographic image needs to be given a universal physical description that will allow it to be used for investigating a wide class of materials and deformation rates.

Table 1

Micromechanisms of fracture and signs that describe the condition of the fracture surface

Micromechanism of fracture	Description of the micromechanism of fracture	Image of a surface fragment with a certain the micromechanism of fracture

Transgranular fracture - (transcrystalline)	combines the elements of chipping and quasi-chipping, as well as provides for the combination in different ratios of the fracture elements specified and plastic strains localized, which appear in the form of lines on the fracture surface of the grain	
Intergranular fracture - (intercrystalline)	occurs mainly along the grain boundaries due to their lower strength compared to that of the grain body. Fracture is facilitated by impurities segregated at grain boundaries. Fracture has a jet pattern – steps of chipping that occurred due to fracture of bridges between brittle cracks that propagated along crystallographic planes.	

A fractogram of a fracture surface contains important information about the nature of deformation and characteristics of the fracture process, as well as other factors that affect the strength of materials. Therefore, the fractogram analysis makes it possible to obtain valuable information that allows improving the material studied and preventing its further fracture. Samples of initial images are shown in Fig. 1, a, b. They are taken from the database of images depicting fracture surfaces of Magnesium Aluminate Spinel ($MgAl_2O_4$) [7]. As is seen, fracture patterns analyzed are caused by a mixed micromechanism of failure. Most clearly pronounced is the transcrystalline jet fracture type that occurred by the chipping mechanism inherent in brittle fracture. In addition, the fracture surface shows the elements of transgranular fracture, that is, light wavy ridges, indicating a higher energy intensity of crack propagation. Thus, fractograms present with two types of sections distinguished on the fracture surface. The first type is flat and smooth sections that are usually characteristic of intergranular fracture. The second type is wavy sections that correspond to the transgranular fracture of the material. In order to automate the process of recognizing the above sections in the image, an algorithm was developed, which receives a fractogram as an input and, by applying a number of transformations, highlights the sections corresponding to the intergranular and transgranular fracture. Next, the sections found are quantified by calculating their areas. In particular, this allows us to conclude as to which type of fracture prevails for a certain specimen./To detect intergranular and transgranular areas of fracture in images, an algorithm was used, which consists of the stages of edge detection by Sobel method, thresholding, removal of small binary objects, and detection of zones with a texture corresponding to two types of fracture sections.

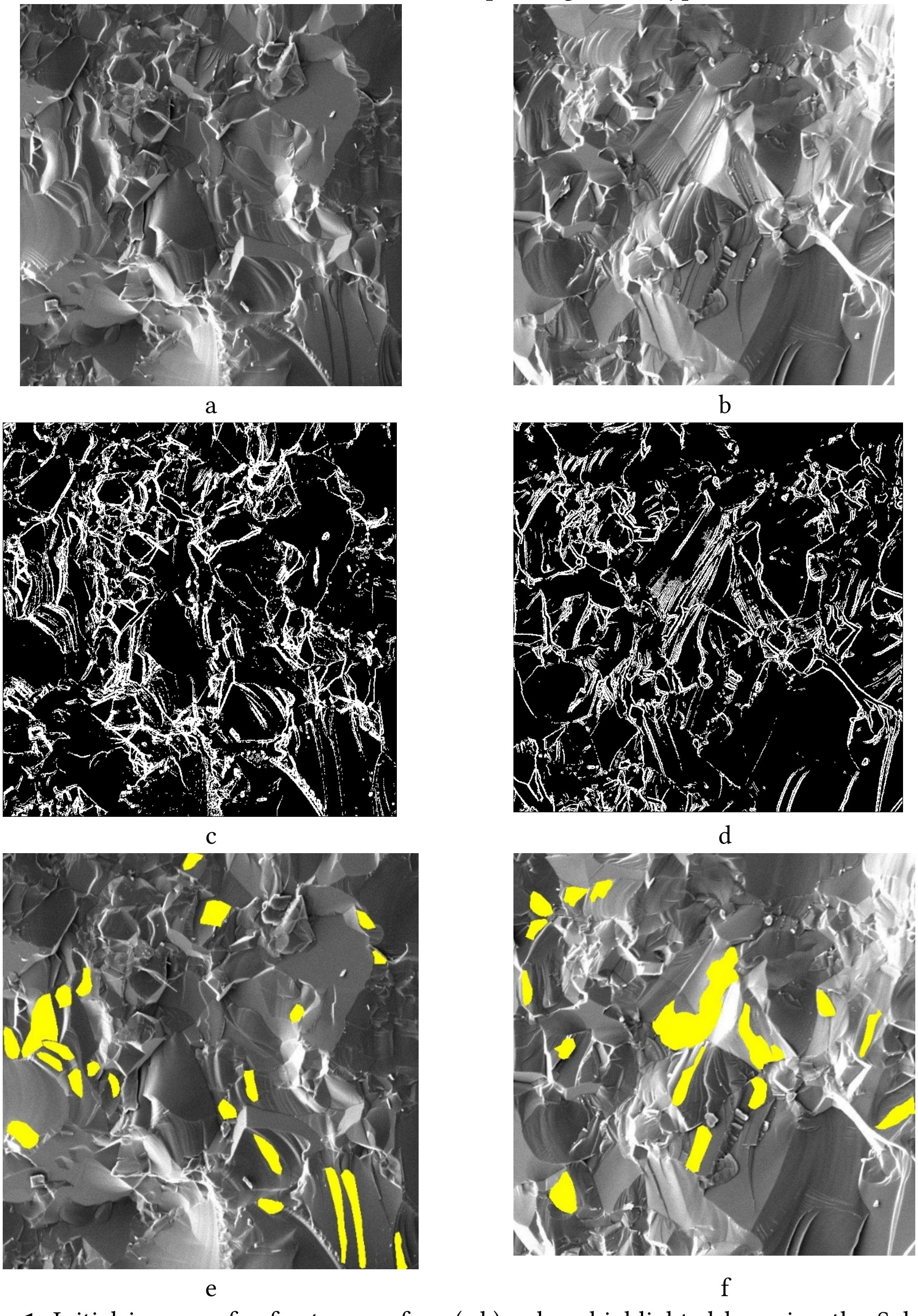


Figure 1. Initial images of a fracture surface (a,b); edges highlighted by using the Sobel operator and filtering (c,d); superimposed masks of areas of intergranular fracture

3. Image processing algorithm

General process of image processing for segmentation of intergranular and transgranular fractures is shown on Fig. 2.

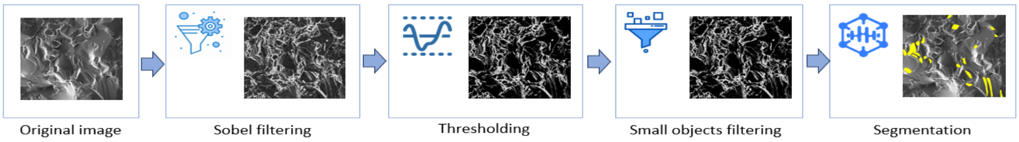


Figure 2: Image processing steps to highline the intergranular fractures

Morphologically, the fracture surface (Fig. 1, a, b) is formed by a complex combination of sections of intergranular and transgranular fracture, which are usually limited by clearly visible edges of fractures or kinks. Moreover, the sections of transgranular fracture are also characterized by a wavy topography, which contains ridges and depressions with a specific texture. Therefore, the Sobel edge detection method was used as the first step of the recognition algorithm [8]. Suppose the original image is represented by two-dimensional pixel array I_0. Then Sobel operator uses a pair of 3×3 convolution kernels:

$$\begin{aligned} G_x &= \begin{bmatrix} +1 & 0 & -1 \\ +2 & 0 & -2 \\ +1 & 0 & -1 \end{bmatrix} * I_0; \\ G_y &= \begin{bmatrix} +1 & +2 & +1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} * I_0, \end{aligned} \tag{1}$$

where G_x and G_y are horizontal and vertical gradients.

The convolution is performed by sliding the kernel over the image starting at the top left corner and allows to highlight parts of the original image with gradients. The Sobel operator performs a spatial gradient measurement on the image and thereby emphasizes areas of high spatial frequency corresponding to the edges. At the same time, the gradient of the intensity function is calculated at each point of the image. The operator uses two 3×3 pixels kernels convolved with the input image to compute approximations of the horizontal G_x and vertical G_y gradients. At each image point, the obtained gradient approximations are combined by calculating gradient G and its direction θ:

$$\begin{aligned} G &= \sqrt{G_x^2 + G_y^2}, \\ \theta &= arctan\left(G_y/G_x\right). \end{aligned} \tag{2}$$

After the edges are selected, the image will contain a significant number of small artifacts, which impede further processing and the search for the sections of interest. This is explained by the complex morphology of the initial fractogram. At the same time, such noises usually have a much lower intensity than those found after applying the Sobel edge operator. To discard them, thresholding was used with a limit that allows preserving all the important components of the image and discarding a significant amount of noises.

Binary object filtering was applied to the image after thresholding. To do this, all connected objects were found and those with a height and width of less than 3 pixels were removed from further consideration. Figure 1, c, d shows the resulting images obtained after pre-processing using the Sobel operator, thresholding and filtering.

The images presented in Fig. 1, c, d visualize large black areas that correspond to smooth sections of intergranular fracture on the initial fractogram; as well as areas formed by quasi-parallel white lines, which correspond to the zones of transgranular fracture in the fractogram. Such sections are characterized by high morphological homogeneity and similarity in different areas of the image.

Sections of transgranular fracture are characterized by a significant morphological non-uniformity. To perform the automated detection of transgranular fracture sites, we applied to the preprocessed images (Fig. 1, c, d) a set of filters with kernels containing parallel components with different angles of inclination (from 0° to 150° with a step of 30°). This made it possible to highlight the sections that contain parallel edges. Other sections in the image were attributed to intergranular fracture. Images presented in Fig. 1, e, f show the sections of intergranular and transgranular fracture detected by the method described above.

4. Analysis of MgAl2O4 fracture fractograms

The area occupied by sections of both types was calculated. Figure 3 shows the distribution histograms of the areas occupied by sections of transgranular fracture on the specimens studied. As seen from the histograms of the specimens, the sections of intergranular fracture are, in general, significantly larger than those of transgranular fracture (the areas up to 2000 pixels prevail).

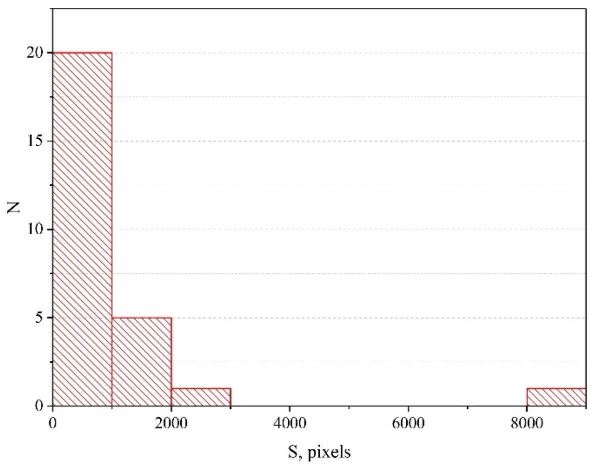


Figure 3: Distribution histogram of areas occupied by sections of transgranular fracture

The quantitative analysis of fracture areas suggests that the surface was formed by a mixed micromechanism of fracture. However, in case of transcrystalline fracture, the terms "ductile" and "brittle" do not always correspond to the micromechanisms considered. This makes it difficult to attribute brittle fracture to either type considered. When investigating the fracture surface, digital analysis was used to detect the signs of plastic deformation, waviness of the fracture surface characteristic of transgranular fracture. Brittle fracture with the smoothed, structureless surfaces is typical of intergranular fracture.

The advantage of the "computer-assisted" classification of crystallographic features is that it allows identifying patterns of the fracture process itself [9]. In most cases, the chipping of metals and alloys occurs as a result of the initiation and propagation of cracks in structurally non-uniform ("weak") places in the metal (grain boundaries weakened by impurities, non-metallic inclusions, etc.) [10, 11]. In the first approximation, the ratio of the areas occupied by the micromechanisms analyzed is a comparative characteristic, which describes the energy intensity of fracture that occurs in polycrystalline bodies. It also characterizes the energy absorbed by the material when the fracture is formed.

5. Conclusions

An algorithm for the image analysis is proposed, which makes it possible to recognize the sections of transgranular fracture on fractograms. The algorithm takes into account the morphological features of such sections and allows highlighting the connected sections and calculating their area.

Fractography analysis of the fracture surfaces of specimens from Magnesium Aluminate Spinel ($MgAl_2O_4$) suggests that its fracture occurred following the mixed brittle fracture pattern, predominantly chipping.

The results of the fractography studies suggest the presence of sections, in which different grains have the same character of fracture. There are also sections of brittle fracture that propagates in a parallel direction, which changes sharply in the adjacent grain. The more frequent are the changes in the direction of fracture, the more ductile the material. Steps of branching on the fractures of the specimens studied also indicate the margin of the material plasticity.

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