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Modelling and characterization of ductile fracture surface in Al-Si alloys by means of Voronoi tessellation

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ABSTRACT

In this study, a new approach to model the system of dimples on the fracture surface of Al-Si alloys using the weighted Voronoi tessellation is proposed. The tessellation model is applied to metallographic images of the eutectic phase to simulate a fracture surface appearance (as projected on a fractograph) that would potentially exhibit this structure if it had been fractured under uniaxial tensile loading. It enables the determination of geometrical features of virtual fracture surface projections, such as the dimple density, the area and equivalent diameter distributions, and topographic features, such as the dimple depth, the surface area and the roughness, by means of geometrical approximations, empirical and analytical relations. A brief review of the fractographic observations on different Al-Si alloys is made to demonstrate preconditions and motivation for using mosaic methods and in particular their weighted version. The simulation results are confirmed by experimental measurements indicating the credibility and usefulness of the model. The routine for generating the weighted Voronoi diagram is implemented as a Java plugin for the Fiji interface and is easy to execute.

1. Introduction

The fracture surface of a material provides important information about the toughness characteristics of the material and the conditions under which it has been fractured. The fracture toughness characterises the ability of a material to resist fracturing. It is conventionally described by the critical value of the stress intensity factor, K_{Ic}, where the subscript I indicates the opening mode of the fracture loading, i.e. the fracture under uniaxial tensile loading [1]. The critical value of the stress intensity factor implies that the material can no longer accommodate more stress by plastically deforming after the critical value has been reached, which results either in a brittle fracture of the material or an unstable crack propagation with subsequent material failure [2].

Al-Si alloys exhibit a ductile fracture pattern when fracturing under the load. A ductile fracture surface is composed of dimples that result from the void coalescence upon material failure. The shape of dimples can differ depending on the loading condition. Under uniaxial tensile loading, the dimples are nearly equiaxed and have defined borders. Under tear or shear loading, the dimples exhibit elongated parabolic shapes with one end being open. Under real circumstances, however, fracture usually occurs under mixed loading modes and propagates along multiple planes, which leads to the asymmetry in dimple shapes within a particular fracture surface and a mismatch between the mating fracture surfaces in general [1].

In materials that consist of isolated elastic particles in a plastic matrix fracture occurs in two ways, i.e. by cracking of particles or by debonding of particles from the matrix. There is a heavily deformed zone at the crack tip of every fractured particle, which reaches the size of the critical crack opening displacement upon the final fracture. When such zones of neighbouring particles overlap encompassing the whole interparticle area, the “void sheet” between the particles is formed [3]. In Al-Si alloys, voids nucleate at the Si particles. As a consequence, the size of the dimples is limited by the voids originating at the surrounding inclusions and corresponds roughly to the interparticle spacing [4]. The strong correlation between the interparticle spacing in the eutectic phase and the spacing of dimples on the fracture surface, as well as between the former and the fracture toughness of the material indicates that the fracture toughness of a material is strongly related to the interparticle spacing [5].

The fracture toughness can also be computed as a function of the local fracture strain expressed by the relation to the depth-to-width ratio of dimples [6]. Since the voids grow in direction perpendicular to

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the tensile loading, they have a relatively shallow profile. Broek, for example, who investigated ductile fracture in aluminium alloys, has therefore proposed the depth-to-width ratio of 1/3 to 1/5 [4]. By approximating the voids with oblate ellipsoids, it has also been shown that the depth-to-width ratio of dimples has the same order as the size-to-distance ratio of Si particles. In general, the dimple depth-to-width ratio reported in earlier studies for different materials varies mostly between 0.4 and 1 [6,7].

Many attempts have been made to link the topographic characteristics of the dimples observed on the fracture surface to the toughness of a material. For instance, a relation between the toughness and the energy needed to form a unit of the fracture surface can be exploited where the latter is expressed as a function of the tensile strength and the depth of dimples. A good correlation between the values of the stress intensity factor computed by this way and experimental ones has been shown [7]. In [8], a further adjustment of this relation has been made in terms of the dimple depth: instead of using an average value of dimple depth for a structure, different size groups of dimples and their volume fractions have been considered to compute the weighted average of the fracture toughness. It is important to note that for two-phase materials, such as Al-Si alloys, the toughness of each phase has to be taken into account. The toughness computed by means of the non-linear rule of mixture has shown a good correlation with the experimental results [9].

In Al-Si alloys, a combination of the strength characteristics and the toughness is still less beneficial than, for example, in steels [10]. Therefore, the relationship between the microstructure and the fracture toughness has to be investigated with respect to different microstructural scenarios in order to develop new casting routes and alloy compositions with improved mechanical performance. Determining the fracture toughness of Al-Si alloys by conventional experimental methods is complicated since it requires large specimen sizes or the application of more sophisticated procedures [11]. Determining the toughness from the fracture surface properties by using the analytical methods described above can, therefore, be a good alternative to the experimental estimations. In order to do so, however, electron fractographs covering a statistically representative field of measurements have first to be acquired, which requires sample preparation and imaging efforts. Moreover, a considerable image pre-treatment effort is needed to be able to segment the dimples on the fracture surface of electron fractographs. The image pre-treatment procedure strongly depends on image quality and resolution and therefore often entails a subjective evaluation. So a quick, simple and reliable method to obtain fractographic information for the toughness estimation would contribute to carrying out investigations in a more effective way.

In this study, a new approach to model the system of dimples on the fracture surface of Al-Si alloys using the weighted Voronoi tessellation is proposed. This method allows the simulation of a fracture surface appearance (as projected on a fractograph) that would potentially exhibit this structure if it had been fractured under uniaxial tensile loading by using metallographic images of the eutectic phase. Simulated fracture surfaces enable the determination of geometrical features of projections, such as the dimple density, the area and equivalent diameter distributions, and topographic features, such as the dimple depth, the surface area and the roughness, by means of geometrical approximations, empirical and analytical relations. The routine for generating the weighted Voronoi diagram is user-friendly: it is implemented as a Java plugin for the Fiji interface.

2. Materials and Methods

2.1. Experimental Data

Fracture surfaces of unmodified (2X) and Sr-modified (3X) eutectic Al-Si alloys in as-cast (AC) and solution-treated (ST) conditions fractured under uniaxial tensile loading have been imaged by Scanning Electron Microscopy (SEM). The fractographs of the alloys are shown in Fig. 1.

The quantitative fractography of the tensile test fractures has been based on SEM images that have provided projections of the fracture surfaces as well as fracture surface profile images combined with stereological methods to extract further topographic information.

2.2. Image Processing

At first, SEM images of fracture surfaces have been treated in such a way as to obtain the dimple borders only. To segment the borders of the dimples, a similar algorithm as for foam reconstruction [12] has been applied with the help of a4i Analysis software [13]: the binarisation of images revealing the borders of the dimples has been followed by the dilation of the segmented phase to obtain a border network which divides an image plane into closed cells. Then, the Euclidean distance transformation has been executed on the system of borders. The obtained distance map has been used as an input for the watershed transformation, which has enabled an extraction of a one-pixel-wide network of borders, bounding closed cells of dimples for further quantitative analysis. The image processing operations are summarised in Fig. 2.

Then, a4i Analysis software has been used to obtain quantitative characteristics of dimples from the segmented images. In particular, information on area, equivalent diameter, aspect ratio and shape factor was obtained. In addition, distributions and areal densities of the computed characteristics have been determined. At least 5 fields have been analysed for every alloy. As a next step, the third dimple dimension – the depth – has been determined by using SEM images of fracture surface profiles.

2.3. Image Analysis

2.3.1. Estimation of the Dimple Depth-to-width Ratio

Cross sections of fracture surfaces have been analysed using SEM images that were acquired during FIB tomography of the tensile test specimens. The FIB cuts do not necessarily pass through the middle part of the dimples, but the depth-to-width ratio of the dimple remains almost the same for any random cut through it [4]. As soon as the ratio is computed in a statistically valid manner, the depth is defined as a product of the dimple's equivalent diameter and the ratio. Segmented fracture surface profiles have been analysed manually so that > 200 measurements have been recorded. Actually, two types of ratios have been estimated, i.e. the average depth-to-width ratio and the ratio of the average depth to the average width. It has been shown on the example of the steel specimens mentioned in [1] that the ratios can differ significantly. Therefore, it has to be clearly stated which ratio will be used for further calculations.

2.3.2. Estimation of the Fracture Surface Area

A fracture surface area can be estimated by applying different methods: from the approximation by triangular elements to the application of stereological equations [1]. In this work, an approximation of the fracture surface by oblate ellipsoids is proposed. The decision is motivated by the fact that the dimples on the fracture surface of Al-Si alloys are mostly shallow holes and that such an approximation has already been used by Broek [4] to show the relation between the depth-to-width ratio of the dimples and the size-to-distance ratio of the Si particles. Though the ellipses are not space-filling, the fracture surface is paved by the ellipses having the same area as the corresponding dimples (see Fig. 3). In so doing, it can be assured that the area equal to the area of the analysed fractograph (i.e. the projection of the fracture surface) is taken into account.

The oblate ellipsoid has two equal semi-axes $a = b$ and a third semi-axis c that is smaller than the other two axes. Thus, the dimple itself can be described as a half of the oblate ellipsoid with the surface area of [14]: