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Inter-particle/void distance for plastics toughening

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Abstract

A new method for measuring two-dimensional inter-particle/void distances was developed. The method was successfully applied to computer-generated 2D models representing polished surfaces of particle/void modified plastics ranging from relatively non-flocculated to flocculated particles/voids dispersions.

Keywords: Toughness; Particle/void distance; Polymer matrix composites; Simulation; Image analysis

1. Introduction

Toughening of plastics can be achieved by the addition of particles/voids [1–5]. One of the important parameters for toughening has been found to be the surface-to-surface inter-particle/void distance (ID) (or ligament length between particles/voids,) because a localized microscopic plane stress–strain transition between particles/voids depends on ID. Wu [6,7] has suggested a relationship between volume fraction, ID and particle size for spherical, mono-sized particles in a cubic lattice array given by

$$\mathrm{ID} = D_\mathrm{p}\left[k\left(\frac{\pi}{6v_\mathrm{f}}\right)^{1/3} - 1\right] \tag{1}$$

where D_p is the particle diameter, k is a geometric constant ($k = 1$ for simple cubic (SC), $k = 2^{1/3}$ for body centered cubic (BCC), $k = 4^{1/3}$ for face centered cubic (FCC)) and v_f is the volume fraction of particles/voids. The applicability of Eq. (1) is limited though to particular particle/void dispersion types and mono-sized particle/void distribution as self-indicated. Eq. (1) is hardly applicable to any other realistic random particle/void dispersions. Also, the ID given by Eq. (1) is sensitive to the type of dispersion. For example, if the particle dispersion type changes from simple cubic (SC) to FCC, ID changes from 0.31 μm to 0.84 μm, i.e., 171% increase for values $D_\mathrm{p} = 0.6$ μm and $v_\mathrm{f} = 0.15$. A further example is that ID increases by 22 times when SC changes to FCC dispersion type for values $D_\mathrm{p} = 0.4$ μm and $v_\mathrm{f} = 0.48$. Moreover, neither SC or FCC represents any statistical characteristics of a realistic random particle dispersion. Nonetheless, Eq. (1) has been used by researchers for real particle dispersions by assuming $k = 1$ to analyze experimental data [8–11]. Thus, some practical method for ID characterization has been desired for meaningful data analysis.

Wu [7] further developed Eq. (1) without regard to the dispersion type but only for the lognormal particle/void size distribution given by

$$\mathrm{ID}_\mathrm{lg} = \mathrm{ID}\exp[(\ln\sigma)^2]$$

or

$$\mathrm{ID}_\mathrm{lg} = D_\mathrm{p}\left[k\left(\frac{\pi}{6v_\mathrm{f}}\right)^{1/3} - 1\right]\exp[(\ln\sigma)^2] \tag{2}$$

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where ID_{lg} is the mean surface-to-surface inter-particle distance and σ is the standard deviation. Eq. (2) is still sensitive to dispersion type although it has been used by other researchers [3].

Hall [12,13] and Hall and Burnstein [14] has developed a method of nearest neighbour distances (NND) for computing IDs for random dispersion of particles, which can be practicable for experimental data. However, IDs based on the algorithm do not reflect the general statistical characteristics of particle dispersion for the plane stress/strain transition.

In this paper, a procedure which can be used as an analytical tool for two-dimensional ID characterizations of particle/void modified plastics is developed. The two-dimensional analysis is useful because three-dimensional analysis is often difficult in a laboratory and microscopic images including polished surfaces are two-dimensional.

2. The proposed procedure for 2D inter-particle/void distance measurements

As discussed above, researchers have adopted particular IDs which might not be relevant, in some cases, to the plane stress/strain transition. A fundamental question can be raised as to what the ID should be. The ID should be the one that represents characteristics of particle/void dispersion in relation to the plane stress/strain transition. The plane stress/strain transition is governed by the ligament thickness between particles/voids, which is represented by ID, when a material is subjected to stress.

The following procedure is established for measuring IDs of 2D image particle/void dispersion.

1. Nominate an arbitrary particle/void for commencement (e.g., particle/void '1' in Fig. 1).
2. Choose a nearest particle/void (e.g., particle/void '2' in Fig. 1) to the first nominated particle/void and then draw a connecting line between two surfaces of the particles/voids.
3. Choose another particle/void (e.g., particle/void '3' in Fig. 1) which is the nearest to the midpoint between the previous two particle/void surfaces.
4. Draw a triangle connecting the previous two particle/void surfaces.
5. Repeat step 3 and step 4 using one of the unused and outermost lines of triangles until all the particles/voids are connected.
6. Remove all the lines affected by the edges of the 2D image outline.
7. Finally measure the inter-particle/void distances.

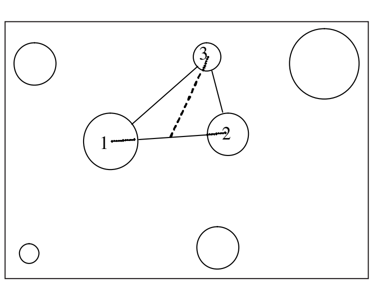

Fig. 1. Schematic particle/void dispersion and line connection; void number indicates order of choice for connection.

3. Sample generation for implementation of the procedure

Three different types of particle/void dispersion were computer-generated and are shown with lines drawn according to the procedure (Fig. 2). The positions of the particles/voids were first randomly generated and then the particles/voids were graphically repositioned to generate examples for different types of dispersion without changing the particle/void sizes. The first type (Type I) is of relatively even dispersion but the third type (Type III) is of relatively flocculated dispersion. The second type (Type II) is one that is of intermediate type between Type I and Type III.

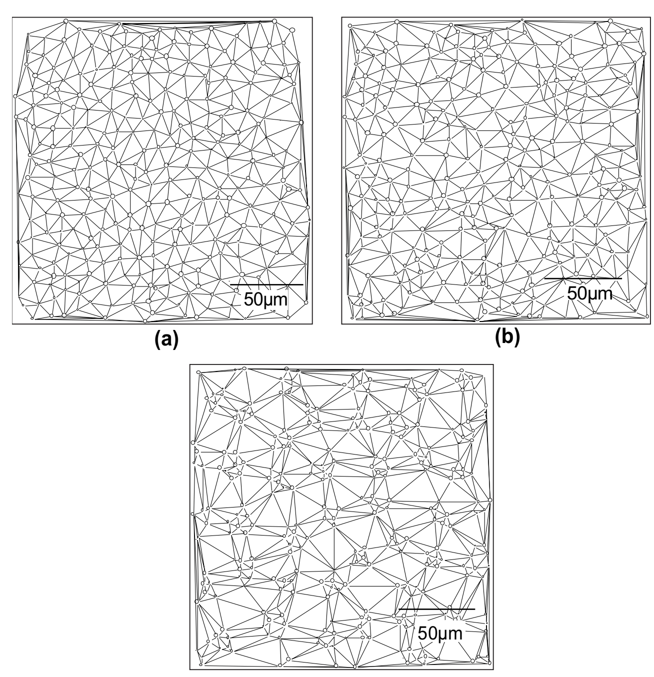

Fig. 2. Computer generated 2D images of particles/voids with connecting lines: (a) relatively even dispersion referred to as 'Type I'; (b) intermediate dispersion referred to as 'Type II' and (c) relatively flocculated dispersion referred to as 'Type III'.