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SPACING PARAMETERS OF NON-DEFORMING PARTICLES

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The Effect of Alloy Deformation on the Average Spacing
Parameters of Non-Deforming Particles

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Abstract

It is shown on the basis of stereological definitions and a few simple experiments that the commonly used average dispersion parameters, area fraction $(A_A)_B$, areal particle density N_{AB} and mean free path λ_a , remain invariant during plastic deformation in the case of non-deforming equiaxed particles. Directional effects on the spacing parameters N_{AB} and λ_a arise during uniaxial deformation by rotation and preferred orientation of non-equiaxed particles. Particle arrangement in stringered or layered structures and the effect of deformation on nearest neighbor distances of particles and voids are briefly discussed in relation to strength and fracture theories.

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Introduction

Recent work⁽¹⁻³⁾ on geometrical contributions to deformation and fracture mechanisms in particle strengthened alloys has led to an examination of the effect of plastic deformation on the average particle spacing parameters. Consideration of questions such as whether the planar particle density is a function of strain in the neck of a tensile specimen, or whether the directional length distribution of the mean free path is anisotropic in uniaxially deformed specimens are relevant to the understanding of the role of particles and inclusions in deformation and fracture. The following discussion of these and other problems is based on the principles of stereology as presented by Underwood.⁽⁴⁾

Theory

The sample cube of volume $V_T = \ell^3$ (figure 1a) contains particles of constituent β embedded in a homogeneous plastic matrix, α . The polydispersed system of β particles is characterized by the following average spatial dispersion parameters⁽⁴⁾:

Average volume fraction

$$(V_v)_\beta = \bar{V}_\beta N_{v\beta} \quad (1)$$

Average areal fraction

$$(A_A)_\beta = \bar{A}_\beta N_{A\beta} \quad (2)$$

Average number of intersections of particles per unit test area

$$N_{A\beta} = \bar{H}_\beta N_{v\beta} \quad (3)$$

Matrix mean free path between non-contiguous particles

$$\lambda_\alpha = \bar{L}_{3\beta} \frac{1 - (V_v)_\beta}{(V_v)_\beta} \quad (4)$$

where $N_{V\beta}$ is the average number of β particles per unit volume of the sample cube, $\bar{V}_\beta$ is the average particle volume, $\bar{A}_\beta$ is the mean particle intercept area, $\bar{H}_\beta$ is the particles' mean projected height or mean caliper diameter, and $\bar{L}_{3\beta}$ is the mean intercept length of the particles. It is noted that the average dispersion parameters $(V_v)_\beta$, $(A_A)_\beta$, $N_{A\beta}$ and λ_α are each a function of $N_{V\beta}$, the average number of particles per unit volume, and one or more of the mean particle size parameters $\bar{V}_\beta$, $\bar{A}_\beta$, $\bar{H}_\beta$ and $\bar{L}_{3\beta}$. The average dispersion parameters are measured on statistically random planar test sections, usually by a systematic point count for $(A_A)_\beta$, or a count of intersections of particles for $N_{A\beta}$, or by an intercept count along test lines for λ_α .⁽⁴⁾

The sample cube of α and β material is now deformed at constant volume to a rectangular parallelepiped (figure 1b) such that $l_x \neq l_y \neq l_z$. The following discussion will present the effect of the deformation on the particle dispersion parameters.

a) Equiaxed non-deforming particles of any spatial arrangement.

Neither the average number of particles per unit volume, $N_{V\beta}$, nor the average particle size parameters $\bar{V}_\beta$, $\bar{A}_\beta$, $\bar{H}_\beta$ and $\bar{L}_{3\beta}$ are changed by the deformation. Consequently, according to equations 1-4, the particle dispersion parameters $(V_v)_\beta$, $(A_A)_\beta$, $N_{A\beta}$ and λ_α remain invariant throughout the deformation. Also, since neither $N_{V\beta}$ nor $\bar{V}_\beta$, $\bar{A}_\beta$, $\bar{H}_\beta$ and $\bar{L}_\beta$ are functions of directionality, the particle dispersion parameters are independent of the orientation of the test planes and test lines and

$$(A_A)_{\beta xy} = (A_A)_{\beta yz} = (A_A)_{\beta xz} = (A_A)_\beta \text{ random} \quad (5)$$

$$N_{A\beta xy} = N_{A\beta yz} = N_{A\beta xz} = N_{A\beta} \text{ random} \quad (6)$$

$$\lambda_{\alpha x} = \lambda_{\alpha y} = \lambda_{\alpha z} = \lambda_\alpha \text{ random} \quad (7)$$

where the subscripts x, y, z refer to test planes or test lines parallel to the axes or the planes defined by the coordinate system x, y, z of figure 1. These conclusions apply to any type of spatial distribution of equiaxed rigid particles in either deformed or non-deformed materials, regardless of whether the spatial distribution is random or non-random, or whether it has directional character or not, or whether the particle size is uniform or non-uniform. In the determination of average spacing parameters a single test (or sampling) plane is sufficient for random particle distributions, but in the case of directional sampling of non-random, and possibly anisotropic, spatial distributions of particles it is required that the number and spacing of the directional and parallel test planes and test lines be such that the measurements provide statistically valid results.

b) Non-deforming particles of non-equiaxed shape.

i) Initially of random orientation. Non-equiaxed or non-spherical particles are subject to rotation during plastic deformation of the aggregate with resulting preferential orientation of their largest axes parallel to the direction of the largest tensile strain. The spatial dispersion parameters affected by the rotation are N_{AB} and λ_α , because the lengths $\bar{H}_B$ and $\bar{L}_{3B}$ acquire directional character. For instance, if, as a result of preferred particle orientation in the deformed state, $\bar{H}_{Bz} > \bar{H}_{Bx}$ and $\bar{L}_{3By} < \bar{L}_{3Bz}$, then $N_{ABxy} > N_{AByz}$ according to equation 3 and $\lambda_{\alpha y} < \lambda_{\alpha z}$ according to equation 4. While N_{AB} and λ_α are now directionally dependent, their average values established over all orientations of test planes and test lines remain equal to the average values (on any plane or in any direction) in the undeformed state.

The area fraction (A_{AB}) remains invariant during the deformation and is equal in all directions. This is seen convincingly if equations 1-3 are combined to give:

$$(A_A)_\beta = \bar{A}_\beta N_{A\beta} = \bar{A}_\beta \cdot \bar{H}_\beta \cdot N_{v\beta} = \bar{V}_\beta N_{v\beta} = (V_v)_\beta \quad (8)$$

Because neither $\bar{V}_\beta$ nor $N_{v\beta}$ is a function of deformation or direction, equation (8) holds independently of the direction of measurement or of deformation history, subject only to the requirement of statistical validity.

ii) Initially of parallel orientation. For the case of elongated particles or discontinuous fibers aligned with their major axes parallel to the direction of uniaxial deformation, it is seen from equations 1-4, and with reference to the geometry of figure 1b, that $N_{ABxy} > N_{AByz}$, $N_{ABxy} > N_{ABxz}$, $\lambda_{ax} < \lambda_{az}$, in the undeformed state. Ideally, if the particles or fibers do not rotate during the uniaxial deformation, the average spacing parameters in each direction remain invariant during the deformation, provided that the directional size parameters remain unchanged, i.e. $\bar{H}_{\beta z}$ and $\bar{L}_{\beta x}$, for instance.

Experiments

For the purpose of experimental verification, the microstructural spacing parameters related to the dispersion of Fe_3C particles were measured in several spheroidized tool steels, with nominally 1.05% C, in the "as-received" and deformed conditions. The deformation consisted of either uniaxial tension, uniaxial compression or rolling. Representative microstructures are shown in Figure 2. It is seen that the structural effect of deformation is most visible in the specimen with particles of pronounced non-equiaxed shape (figure 2c).

The effect of deformation on the microstructural parameters is shown in figures 3 and 4. The area fraction of cementite, $(A_A)_\beta$, and the mean free path of ferrite, λ_α , were measured on the planes and in the direction indicated by the subscripts x,y,z, where z is the direction of the primary deformation. The

particle orientation factor (O.F.) is established by the ratio of the numbers of particle intercepts (N_x , N_y , N_z) with test lines respectively perpendicular and parallel to the deformation direction. The orientation factor is a measure of the average aspect ratio of the planar particle intercepts in the direction of deformation.

Within the limits of the experimental precision, the data of figures 3 and 4 confirm the theoretical conclusions, namely that 1) in spite of considerable scatter, the area fraction measurements are not in disagreement with the expected constancy of area fractions during deformation; 2) the mean free path increases in the direction of elongation and decreases in the direction of compression in correlation with changes of the orientation factor indicating rotation of non-equiaxed particles (figure 3 and figure 4, rolled rod), and 3) the mean free path is approximately invariant during deformation in the steel with approximately constant orientation factor (figure 4, rolled bar). The particles in this steel also appear to be more equiaxed (figures 2b and 2c) than those in the steels with pronounced particle rotation (figure 2a).

Discussion

The average microstructural measures of particle concentration and spacing remain unchanged by deformation if the particles are equiaxed. The most apparent effects of deformation in the photomicrographs of figure 2 are due to the rotation of non-equiaxed particles. In practice, in many alloys the most visible effects of deformation are particle stringing, due, for instance, to geometrical alignment of particles on grain boundaries, or particle fibering, due to particle deformation and fracture. If the particles are equiaxed, the average dispersion parameters $(A_A)_\beta$, $N_{A\beta}$ and λ_β do not reflect observable structural anisotropy, because they are independent of the orientation of test planes

and test lines. A more complete characterization of the microstructure requires additional information about the directional variation of the distribution of spacing parameters, such as the frequency distribution of the intercept length components of the mean free path in various directions, or the frequency distribution of the number of particles in directionally oriented test cells. An application of the analysis of the heterogeneity parameters of fibered or layered microstructures, relevant to mechanical properties, was developed by Underwood and Starke,⁽⁵⁾ and the effect of deformation on the dispersion morphology of deformable particles was described by Durham.⁽⁶⁾

A spacing parameter which merits further consideration is the nearest neighbor distance which, for instance, is of importance when considering particle interactions. The average nearest neighbor distances in a volume ($0.554 N_V^{-1/3}$) or on a plane ($0.500 N_A^{-1/2}$) as calculated for random distributions of point particles,⁽⁴⁾ do not change as a result of deformation as long as the distributions remain random, even though the distance vector between a specific pair of point particles does change in length and direction in accordance with the deformation of the specimen. Also, since the average number density of the intersections of equiaxed particles on test planes remains constant throughout the deformation, any planar measures of average interparticle distance based on N_{AB} (such as $N_{AB}^{-1/2}$) also remain invariant. If the particle placement is idealized by associating it with an imaginary cubic grid, as is often done in particle strengthening theories, the grid point separation would change in accordance with the imposed deformation, but the statistical average planar particle intercept density, N_{AB} , measured on randomly spaced parallel test planes, would remain constant with deformation and change of test plane orientation, for equiaxed particles, even if the particles were regularly and exactly placed at the grid points. As far as particle

spacing in real particle systems is concerned, any inference based only on the deformation of an imaginary grid could be grossly misleading.

The above considerations are particularly relevant to the analysis of ductile fracture processes involving particle-nucleated void growth in the necked portion of tensile specimens. In modeling the fracture process it is often assumed that either the particle spacing or the void spacing or both are a geometrical function of strain^(3,7-9) (for instance, ⁽⁷⁾ $\lambda_{\alpha}(\epsilon) = \lambda_{\alpha}(0) \exp(-\epsilon/2)$, where ϵ is the longitudinal strain and λ_{α} is the mean free path on a transverse planar section). The assumption derives from theoretical models with parallel cylindrical voids of infinite length^(8,9), but it has been shown here that it does not generally apply to measures of the average spacing if the particles or holes are appreciably smaller than the specimen or neck length. In the neck, as well as elsewhere in the specimen, the average planar number density of equiaxed particles and the mean free path remain constant with strain and orientation. The planar number density of void intercepts (and their average center-to-center spacing) on a cross-sectional plane is invariant with deformation for longitudinal voids ($\bar{H}_z \ll \lambda_z$) parallel to the tensile specimen axis, unless the volume number density, N_v , or the longitudinal caliper length, $\bar{H}_z$, of the voids increases with strain, by nucleation of new voids or plastic growth of existing voids, respectively.

In general, the proper evaluation of the role of particles in deformation and fracture requires careful consideration of the spacing parameters and of their presumed dependence on strain.

Conclusions

1. The average spacing parameters $(A_A)_B$, N_{AB} and λ_{α} of non-deforming equiaxed particles are invariant with respect to plastic deformation.

2. In the case of non-deforming, non-equiaxed particles, the average spacing parameters $N_{A\beta}$ and λ_{α} may acquire directional character by rotation of the particles into a preferred orientation during deformation of the alloy.
3. The average directional spacing parameters $(A_A)_{\beta z}$, $N_{A\beta xy}$, and $\lambda_{\alpha x}$ of non-deforming and non-rotating, non-equiaxed particles are invariant during uniaxial deformation.

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Figure Captions

Figure 1. a) Sample cube before deformation

b) After deformation

Figure 2. a) Steel B, after compression (100% strain), longitudinal section (yz plane) 1,800x.

b) Steel D, as received, longitudinal section (yz plane) 2,400x.

c) Steel D, after rolling (187% strain), longitudinal section (yz plane) 2,400x.

Figure 3. Change of areal fraction $(A_A)_\beta$, mean free path λ_α , and orientation factor O.F. in compression and tension.

Figure 4. Change of areal fraction $(A_A)_\beta$, mean free path λ_α , and orientation factor O.F., with reduction of thickness and elongation in rolling.

(a)

Sample Cube Before Deformation

(b)

After Deformation

Figure 1

Figure 2(a)

Steel B, after compression (100% strain), longitudinal section
(xz plane) 1500x. Compression direction is vertical.

Figure 2(b)

Steel D, as received, longitudinal section (yz plane) 1500x.

Figure 2(c)

Steel D, after rolling (187% strain), longitudinal section (yz plane) 1500x. Rolling direction is horizontal.

TENSION AND COMPRESSION

● STEEL A, $\frac{1}{4}$ in. ROUND

○ STEEL B, $\frac{7}{16}$ in. ROUND

z = DIRECTION OF TENSION
AND COMPRESSION

Figure 3

Change of areal fraction $(A_A)_{\beta}$, mean free path λ_{α} , and orientation factor O.F., in tension and compression.

ROLLING

- Δ STEEL C, $\frac{1}{4}$ in. ROUND
- $\square$ STEEL D, $\frac{1}{2} \times \frac{1}{2}$ in. BAR

Figure 4

Change of areal fraction $(A_A)_{\beta}$, mean free path λ_{α} , and orientation factor O.F., with reduction of thickness and elongation in rolling.