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Review
A systematic description of microstructure

ERHARD HORNBOGEN
Institut für Werkstoffe, Ruhr-Universität Bochum, Postfach 102148, 4630 Bochum 1, Federal Republic of Germany

A systematic treatment of microstructure is proposed. This structural level of solid matter comprehends all features which do not belong to bulk structure, or phase structure (crystals, glasses). Zero to three-dimensional discontinuities in the phase structure are defined as microstructural elements. Prototypes of two-phase microstructures are dispersion, net, cell and duplex. There may exist microstructural order, gradients, anisotropy, as well as mixtures and transformations of microstructural elements and types. Microstructural energy is given by the product of the density of a microstructural element and its specific energy. The scale of microstructure must be based on relations to properties. Fractal analysis may become useful for the description of rugged, fissured and branched microstructures.

Nomenclature

a	Amorphous phase
α, β	Crystalline phases
b	Atomic spacing (m)
d	Geometric dimension (integer)
d_β	Particle diameter (m)
D	Fractal dimension (non-integer)
ε	Step or interval scale (m)
f	Volume fraction of particles
F	Force by obstacle on dislocation (N)
G	Shear modulus (Pa)
Γ	Designation of any microstructure
Γ_{cell}, $\Gamma_{\text{dispersion}}$	Type of microstructure
k	Boltzmann constant ($\mathrm{J\,K^{-1}}$)
L	Length of irregular curve (m)
ϱ_i	Density of microstructural elements (see Table II)
$\varrho_{\alpha\alpha}$	Density of grain boundaries ($\mathrm{m^{-1}}$)
$\varrho_{\alpha\beta}$	Density of interfaces ($\mathrm{m^{-1}}$)
s_Γ	Microstructural specific entropy ($\mathrm{J\,K^{-1}\,m^{-3}}$)
S_i	Spacing of microstructural elements, grain diameter (m)
$\Delta\tau$	Increase in yield stress (Pa)
U_i	Specific energy of microstructural elements (see Table II)
ΔU_i	Interaction energy of microstructural elements (see Table II)
u_Γ	Microstructure energy density ($\mathrm{J\,m^{-3}}$)
W	Number of configurations in a structure
x, y, z	Cordinates in geometric space
N_a	Number of atoms per mole ($\mathrm{mol^{-1}}$)
V_m	Molar volume ($\mathrm{m^3\,mol^{-1}}$)

1. Introduction

Microstructure is a structural level of solid matter, which first attracted the attention of mineralogists. An example is the etching experiment with meteorites of the Viennese pharmacist Widmannstätten during the first half of the 19th century. Metallurgists followed towards the end of that century. There has been an enormous volume of specialized work, but less effort to define the essence of microstructure [1, 2]. Ceramicists and polymer scientists followed later on in paying attention to microstructure. The latter favour the term 'morphology" or "superstructure" for the structural level of concern to us. A comprehensive treatment of microstructure of all materials which should include concrete, all composites, and integrated circuitry is not yet available.

An attempt at a systematic treatment of microstructure for metallic and ceramic material was published recently [3]. The present paper represents a continuation of that effort. Some information had to be repeated from an earlier paper to facilitate understanding of the new aspects. These include the following points:

(a) definition of an energy and entropy of microstructure,

(b) definition of microstructural elements as discontinuities in the phase structure [2],

(c) definition of the number of parameters required for a complete description of a certain microstructure,

(d) definition of prototypes of two-phase microstructures using percolation of phases,

(e) extension of the concept of percolation to microstructural elements (lattice defects) and anisotropic structures,

(f) an attempt at a quantitative definition of "fine" and "coarse" microstructures (scale effects),

(g) a quantitative approach to complex microstructures, described as mixtures of different elements and types with fine and coarse components,

(h) the use of fractal geometry for "fragmented" features of microstructure, and

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TABLE I Levels of structure of materials

Level of structure	Structure or specimen	Scale (m)
Macroscopic +5	Plant: power station	
+4	Machine: gas turbine	
+3	Simple function: bearing	
+2	Part: crankshaft	
+1	Semi-finished shape: sheet	
Microscopic −1	Microstructure	5×10^{-9} to 10^{0}
−2	Phase	10^{-9} to 10^{-6}
−3	Molecule	10^{-9} to 10^{-4}
−4	Atom	$< 10^{-9}$
−5	Elementary particle	10^{-15}

(i) the origin of microstructure as a non-equilibrium phenomenon.

Energy and structure are the two principles that govern the behaviour of materials. Among the levels of structure, a first distinction is required between bulk structure (or macrostructure) and microstructure (Table I). An increasing number implies a higher complexity. There are qualitative differences between the levels and there is also a tendency for scale to increase with the number of levels. This, however, cannot be generalized. The grain size in a transformer steel (level −1) may be much larger than a transistor in an integrated circuit (level +3). A semantic problem exists with the term microstructure. It is used for any fine structure (levels < 0), for miniaturized artificial structures such as the CPU (central processing unit) of a computer, or for the particular level −1. German is the only language with a special name for it: das Gefüge*. This level alone is dealt with in the present article.

2. Elements of microstructure

The first step towards a definition of what is microstructure is approached by a double negation: microstructure is everything which is neither phase structure (crystal, glass) nor bulk structure (specimen, semi-finished products) [2, 3]. A particular feature of microstructure is that it is not closely related to thermodynamical equilibrium. For a quantitative description, all discontinuities in the phase structures should be defined as microstructural elements (Table II). These elements have to be distinguished according to their geometric dimension d_i ($i = 0, 1, 2, 3$), and by the nature of the discontinuity: position of atom, type of atom, orientation of electron (Table III and Fig. 1). Table II shows that the units for the densities of elements of different dimension must differ, as well as the units of specific energies. By summing up the products of densities (ϱ_i) and specific energies U_i, the bulk microstructural energy (u_Γ) is obtained, which augments that given by the phases (in stable or metastable equilibrium, or frozen-in) (Fig. 2):

$$u_\Gamma = \sum_i \varrho_i U_i \qquad (1)$$

If densities ϱ_i become so high that the spacings of microstructural elements are only a few atomic spacings b apart (for example, interaction of stress fields of dislocations) the microstructural energy is modified by the interaction energy ΔU:

$$u_\Gamma = \sum_i \varrho_i [U_i - \Delta U(\varrho_i)] \qquad (2)$$

If the spacing of grain boundaries or dislocations approaches atomic dimensions, an amorphous phase originates which sets an upper limit for the energy storable by addition of those elements (Equation below). Microstructural energy provides the driving force for reactions such as recrystallization or particle coarsening. It is an important aspect of microstructural stability [4].

3. Mixtures, disorder, order, gradients

It is implied in Equation 1 that different microstructural elements can be mixed inside one material. Thermomechanical processing of alloys is one way to produce such mixtures of many elements. If the yield strength is of concern, the elements become elementary hardening mechanisms which are combined to obtain high yields strength in alloys [5].

The density of microstructural elements ϱ_i alone does not provide sufficient information for a quantitative description. If a simple grain structure is considered, its average grain size $\bar{S}_{\alpha\alpha}$ is related to the density of boundaries $\varrho_{\alpha\alpha}$. An upper limit exists for $S_{\alpha\alpha} = 3b$:

$$3b < \bar{S}_{\alpha\alpha} \sim \varrho_{\alpha\alpha}^{-1} \qquad (3)$$

In addition, five functions are required for a complete description Table IV [6, 7]:

1. A distribution function of grain size, or grain boundary spacing $S_{\alpha\alpha}$.
2. A distribution function of the sites (centres) of the grains.
3. A distribution function of the orientation of crystallites (ODF) [8].
4. A function for the shape of grains.
5. A distribution function for orientation of non-equiaxed grains (microstructural anisotropy).

TABLE II Geometrical dimension, unit of density, and specific energy of microstructural elements

	Geometrical dimension, d	Example	Units of density, ϱ_i	Units of specific energy, U_i
1	0	Radiation induced vacancy	m^{-3}	J
2	1	Dislocation	m^{-2}	$\mathrm{J\,m}^{-1}$
3	2	Grain boundary	m^{-1}	$\mathrm{J\,m}^{-2}$
4	3	Pore, particle	m^{0}	$\mathrm{J\,m}^{-3}$

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*Gefüge is derived from the verb fügen, to fit together. Gefüge has the meaning of "something which fits together". The Greek letter Γ will be used for the designation of microstructure.

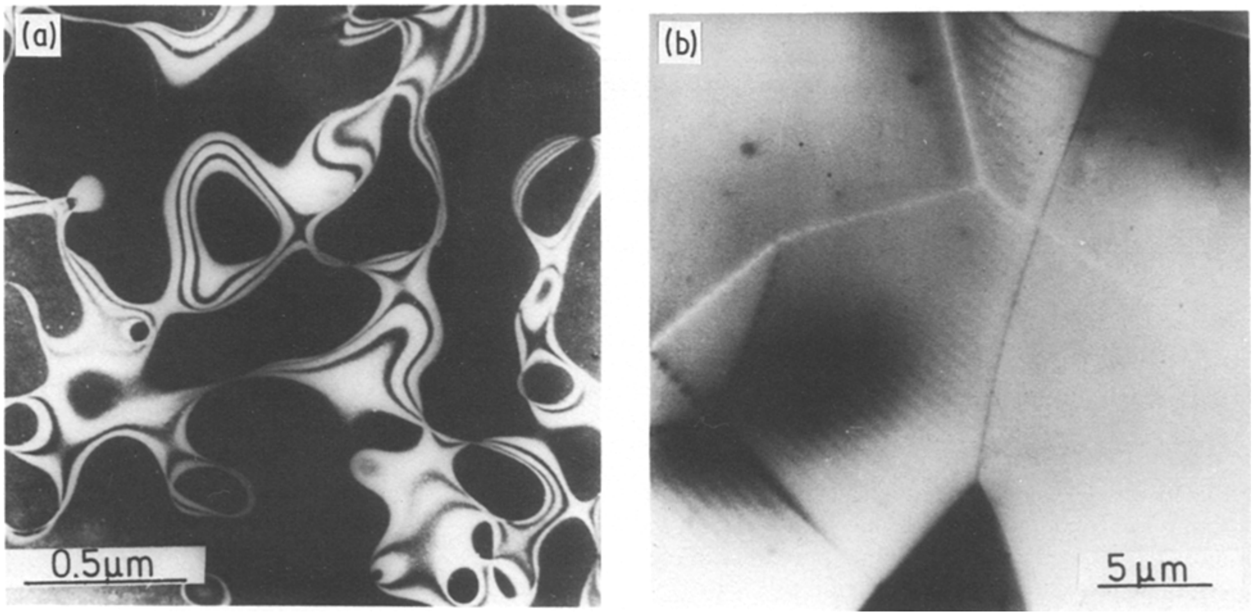


Figure 1 (a) Anti-phase-domain boundaries ($d = 2$) in b c c. Fe_3Al (TEM dark field). (b) Grain boundaries and Bloch walls in α-Fe (TEM, defocusing, bright field).

The site distribution function may vary between random and high-symmetry order (Fig. 3). A microstructural tensor can be used to describe the symmetry of ordered microstructures (Fig. 4) which is comparable to the methods used for the description of crystal structures [9]. An inverse transformation (reciprocal lattice) of the site function of microstructural elements is suitable, especially for the analysis of diffraction effects caused by microstructural order. Microstructural disorder implies an entropy s_Γ which is lowered with increasing symmetry and perfection of the order:

$$s_\Gamma = \frac{kN_a}{V_m} \ln W \qquad (4)$$

where k is the Boltzmann constant and W has the usual meaning of the number of configurations in which microstructural elements or particles can be arranged. Lined-up cube-shaped γ'-particles in nickel alloys provide an example of cubic microstructures, pancake grains are orthorhombic, honeycombs hexagonal. Fibre reinforcement is a way of producing artificially any type of disordered or fully ordered microstructure.

Microstructural gradients are identical with gradients of the density (ϱ_i) of microstructural elements:

$$\frac{d\varrho_i}{dx} = \text{grad}\,\Gamma \qquad (5)$$

The density of dislocation rings shows a gradient close to a surface or grain boundary (Fig. 5). In modern surface treatments, gradient structures (usually two- or multi-phase) are often produced intentionally, to improve the adherence of a surface layer with the substrate. A homogeneous microstructure is defined by grad $\Gamma = 0$. It should be distinguished for a homogeneous phase structure, i.e. one-phase material, and from a homogeneous distribution of atoms in a phase.

4. Two-phase structures, percolation, transformation

A homogeneous grain-boundary structure ($d = 2$) will provide in addition edges ($d = 1$) and corners ($d = 0$). Prototypes of two-phase microstructures can be defined, if it is assumed that a second phase forms (by heterogeneous nucleation) at points, lines or planes to form a dispersion, net or cell (Fig. 6). A fourth type can be thought to form if half of the α grains are replaced by β [10]. Examples for a random and an ordered version of such a duplex structure are also shown in Fig. 6. If our two-phase microstructures consist of individual equiaxed grains, they can be defined by the densities of boundaries and their ratios (Fig. 6):

$$\text{Dispersion:} \quad \varrho_{\beta\beta} = 0 \qquad (6a)$$

$$\text{Net:} \quad \varrho_{\alpha\alpha} \neq 0,\ \varrho_{\beta\beta} \neq 0 \qquad (6b)$$

TABLE III Discontinuities in the phase structure which were defined as microstructural elements

Geometrical dimension, d	Type of discontinuity in the phase structure		
	Atomic position	Type of Atom	State of electron
0	Vacancy, interstitial atom	Substituted atom	Colour centre in ionic crystal
1	Dislocation	Segregated atom at dislocation	Dangling bond at dislocation in semi-conductor
2	Grain boundary, stacking fault	Anti-phase domain boundary	Bloch-wall, Néel-wall
3	Non-coherent particle, pore	Coherent particle	Ferromagnetic particle

TABLE IV Maximum number of geometrical and statistical functions which are required to describe a microstructure ($d = 2$, valid for grain boundaries only)

Geometrical dimension of element	Site	Size	Shape	Orientation of crystal (texture)	Orientation of microstructural element	Total
0	1	0	0	0	0	1
1	1	1	1	0	1	4
2	1	1	1	1	1	5
3	2	2	2	2	2	10

$$\text{Cell:}\quad \varrho_{\alpha\alpha} = 0 \tag{6c}$$

$$\text{Random duplex:}\quad \varrho_{\alpha\alpha} = \varrho_{\beta\beta} = 0.5\varrho_{\alpha\beta} \tag{6d}$$

$$\text{Ordered duplex:}\quad \varrho_{\alpha\alpha} = \varrho_{\beta\beta} = 0 \tag{6e}$$

Ordered duplex is a hypothetical microstructure which is not found in nature. It may, however, not be impossible to produce it to a good approximation as a synthetic microstructure (see Section 6).

Disregarding the details of grain structure, the types of two-phase microstructures (or those consisting of two microstructural components which must not necessarily be phases, for example in composites) can be distinguished by their percolation behaviour (Latin percolare, to flow through) [11–14]. There are four possibilities (Table V and Fig. 7): percolation in α, or β, ($\alpha + \beta$), and no percolation. The last-mentioned case is represented by the ordered duplex structure, which does not exist in present materials (Fig. 6). A dispersion with β particles percolates in the matrix α, while α is isolated by β, which percolates as cell wall in the cell structure. In a net, the original percolation of the α-grain structure is not completely removed by the rods of β. This structure, as well as random duplex, shows percolation of α as well as β, in spite of their different type.

The concept of percolation also applies to the microstructural elements in one-phase materials: a dislocation provides a one-dimensional path and a grain boundary a two-dimensional path for percolation, except when dislocations are exclusively rings and if grains are dispersed in a large single crystal (Fig. 7).

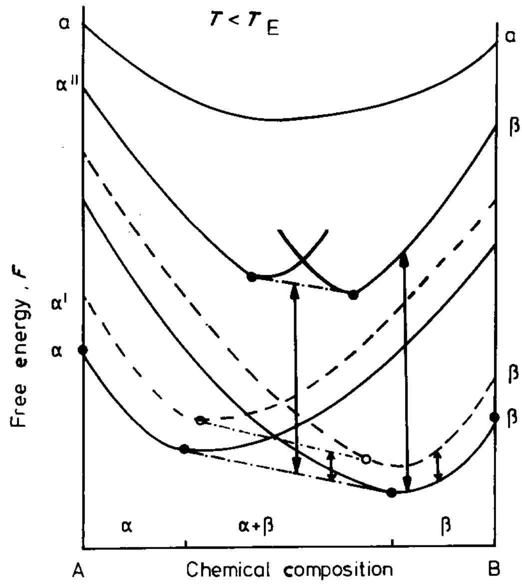


Figure 2 Binary free-energy–chemical composition diagram for a eutectic alloy at $T < T_E$ (T_E = eutectic temperature). a = amorphous phase, (α, β) perfect crystalline phases, (α', β') phases containing microstructural elements at moderate density, (α'', β'') phases containing elements at very high density.

For the relation of microstructure to properties, the dimension of percolation is of great importance (Fig. 7). The path of electrons which provide conductivity, or the path for chemical attack, can be one-dimensional, while plastic strain in a single phase or the passage of a crack require percolation across the total cross-section of a bulk specimen (two-dimensional percolation).

Transformations are known in other levels of structure (Table I), for example, transformation of phase structure, electronic structure or nuclear structure. Microstructural transformations are represented by changes in the type (Figs 6 to 8). They can be defined either by the disappearance or appearance of new microstructural elements (see Equation 6) or by a change in percolation (Table IV, Fig. 7) [3]. This is illustrated for the transformation dispersion → cell:

$$\Gamma_{\text{disp.}} \rightarrow \Gamma_{\text{cell}} \tag{7}$$

$$(\varrho_{\beta\beta} = 0) \rightarrow (\varrho_{\beta\beta} > 0)$$

which implies the formation of β–β contacts, $\varrho_{\beta\beta} > 0$, and consequently the creation of percolation of β. Microstructural transformations are often associated with large discontinuous changes in bulk properties.

Different types of two-phase microstructure can form mixtures inside one material. An important example is a fine (dispersion + cell) structure. It is formed in precipitation-hardened alloys with a particle-free zone along the grain boundaries (Fig. 9).

5. Scale in microstructures

The atomic spacing $b \approx 0.3$ nm is the lower limit for the scale of microstructural dimensions (Table I and Equation 3). The spacing of microstructural elements or the diameter of crystallites S_i must exceed $3b$. No upper limit exists for such spacings, because the densities of all non-equilibrium features (grain boundaries, dislocations. etc.), can become zero.

TABLE V Systematics of percolation in different types of isotropic two-phase microstructures (see Figs 6 and 7b)

Phase	Dispersion	Net	Cell	Random duplex	Ordered duplex
α	2	1	0	1	0
β	0	1	2	1	0
$\alpha + \beta$	0	1	0	1	0

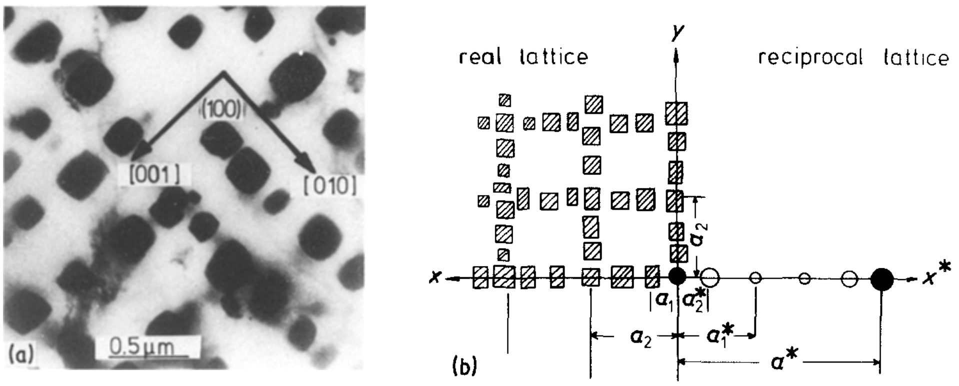


Figure 3 Microstructural order. (a) Ordered arrangement of γ'-particles in Ni–13.8 at % Si alloy, 70 h, 750° C (TEM). (b) Section of microstructure (a) in real and reciprocal space (schematic).

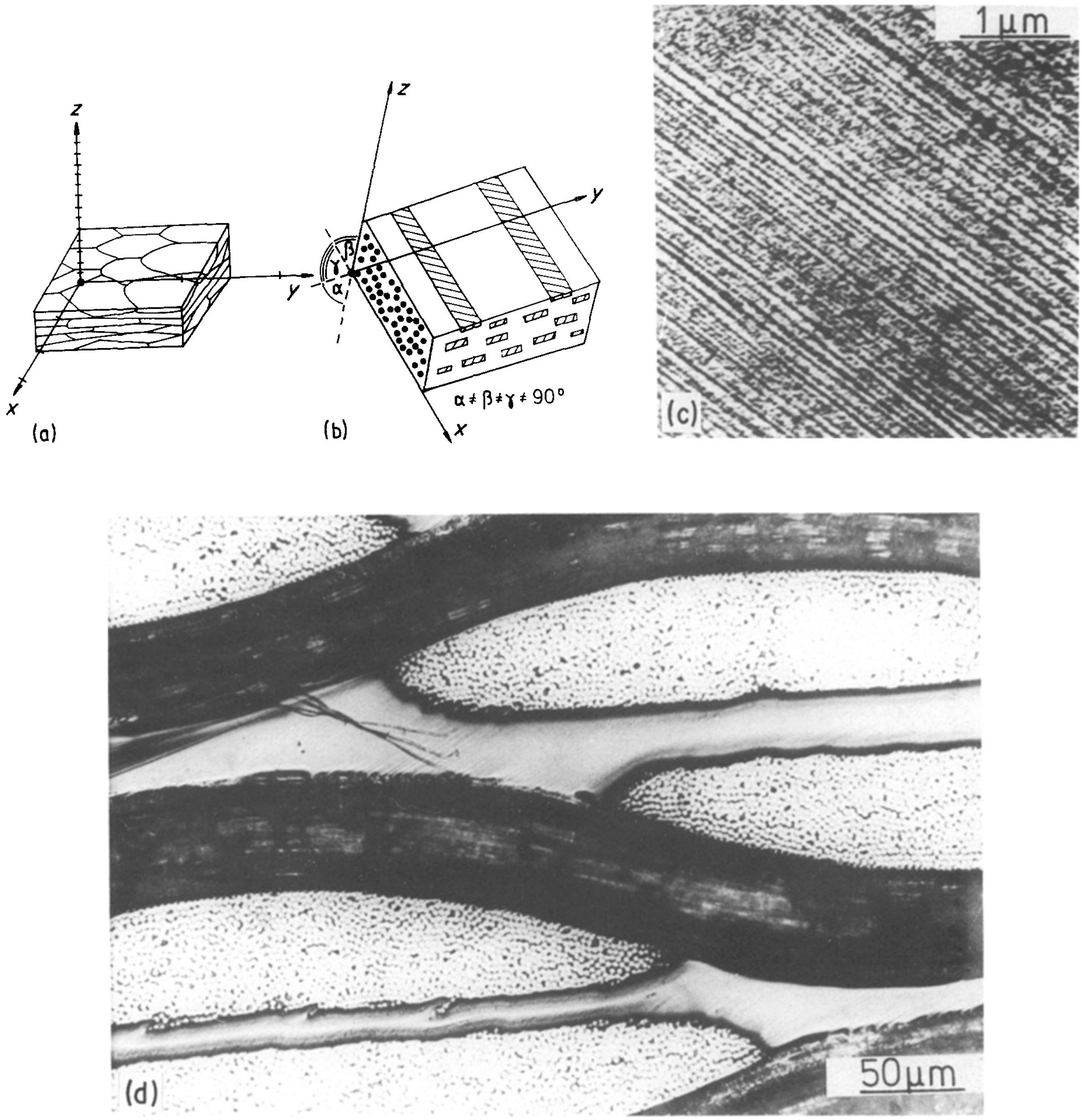


Figure 4 Anisotropic microstructures. (a) Pancake grain structure, as obtained by rolling of a uniaxed microstructure (schematic). (b) Fibre plus ribbon enforced composite, orthorhombic symmetry (schematic). (c) Lined-up rods of cobalt particles in copper which have formed by directional recrystallization in Cu–2.8 at % Co, 10 % c.w. 10 h 550° C; uniaxial anisotropy (SEM). (d) Aramid fibre-reinforced polycarbonate foils; tri-axial anisotropy, aramide cut perpendicular and parallel to fibre axis. (light microscopy).

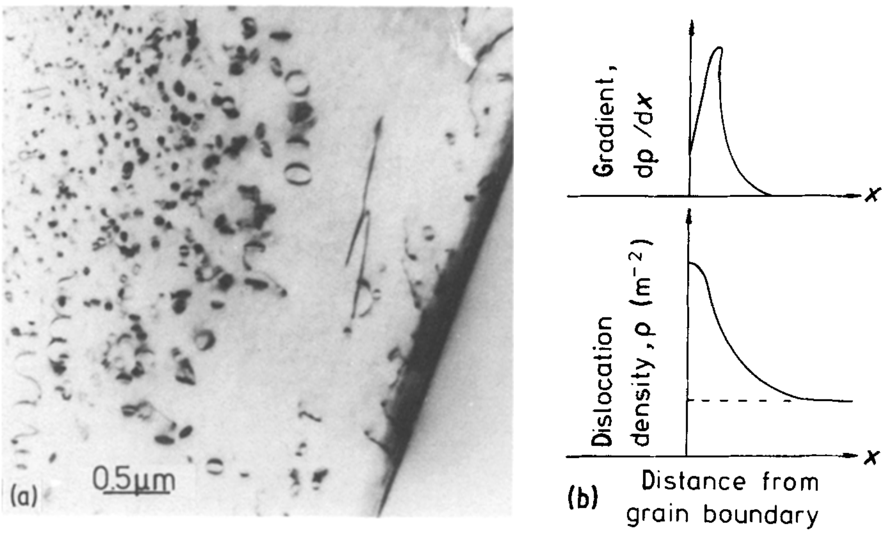


Figure 5 Microstructural gradients. (a) Gradient of dislocation density in the environment of a grain boundary in a quenched Al–2 % Cu alloy (TEM). (b) Schematic representation of a gradient of dislocation density ϱ.

It is sometimes useful to subdivide the wide scale of spacings of microstructural elements, $3b < S_i < \infty$, into sub-levels. This can be based on the interactions of microstructural elements with – for example – mobile dislocations, Bloch walls in ferromagnets, or flux threads in superconductors.

The interaction of dislocations with a dispersion microstructure will be used to illustrate the definition of sublevels in microstructure [15]. The Friedels equation describes the increase in shear stress $\Delta\tau_\beta$ caused by dispersed obstacles (particles β) in a matrix α (Table VI and Fig. 9).

$$\Delta\tau_\beta = \frac{Gb}{S_\alpha}\left(\frac{F}{Gb^2}\right)^{3/2} \tag{8}$$

Three different critical microstructural scales can be obtained from this equation. A "coarse" microstructure does not lead to any considerable dispersion hardening and $\Delta\tau_\beta \approx 0$. The prerequisite for this to occur is a particle spacing S_α much larger than the atomic spacing:

$$\begin{aligned} &\text{Coarse microstructure:} \quad S_\alpha/b > 10^4 \\ &\text{Fine microstructure:} \quad S_\alpha/b < 10^4 \end{aligned} \tag{9}$$

The second sub-level of microstructure is of concern for the particle diameter d_β. For fineness (Equation 9) one can distinguish between particles which are bypassed or sheared by mobile dislocations. The general definition for the critical particle size $d_{\beta c}$ is $F(d_\beta) = Gb^2$. The critical particle diameter can be calculated for any particular case, for example coherent and ordered, or non-coherent. Accordingly, fine microstructures should be subdivided as

$$\begin{aligned} &\text{Hypofine:} \quad d_\beta < d_{\beta c} \\ &\text{Hyperfine:} \quad d_\beta > d_{\beta c} \end{aligned} \tag{10}$$

It is worth mentioning that the scale of

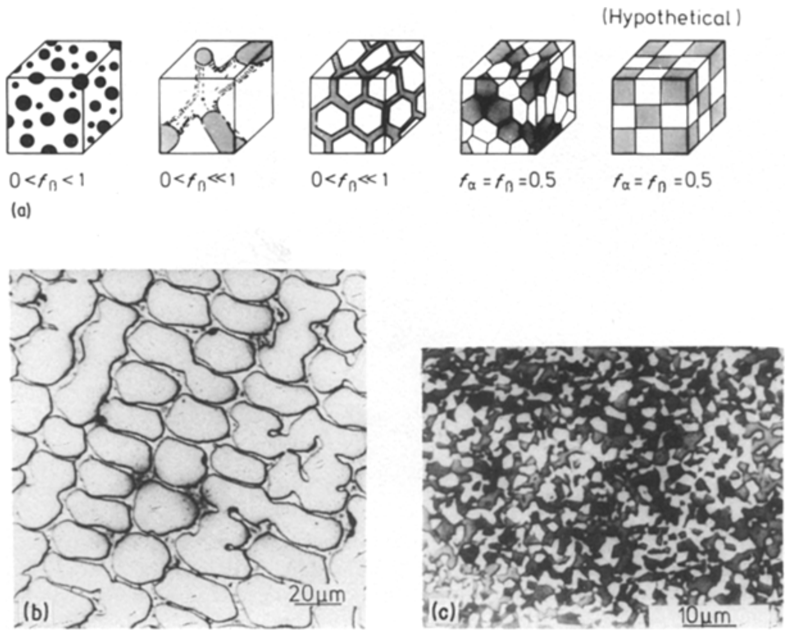


Figure 6 (a) Principle types of two-phase microstructures (schematic). (b) Cell structure, Fe + 12 Mn + 0.5 B + 12 C (wt %) (light microscopy). (c) Duplex structure Fe + 9% Ni, $\alpha + \alpha_M$ (ferrite + martensite) (light microscopy).

TABLE VI Estimated critical particle diameters for aluminum alloys

Particles	d_c (nm)	Structure of interface*	Comments
Diamond	0.2	n-c	
Si, $FeAl_3$, $CuAl_2$	0.5 to 5	n-c	
Zn	15	n-c	
$LiAl_3$	50	c	Passage of single dislocation
	> 500	c	Dislocation pairs
Pore	∞	n-c	Pores are sheared above critical size

*c, coherent; n-c, non-coherent.

microstructures has been defined by qualitative and quantitative relations to bulk properties. Other definitions may be based on the resolution power of microscopy or by the density of interfaces $\varrho_{\alpha\beta}$, i.e. the degree of dispersion $\varrho_{\alpha\beta} = f_\beta d_\beta^{-1}$ (Equations 6) or $(\varrho_{\alpha\alpha} + \varrho_{\beta\beta} + 0.5\varrho_{\alpha\beta})^{-1} = S$ for the grain size of a duplex structure (Equation 6d).

6. Fractal microstructures

There are still some important geometrical aspects of microstructure which resist an adequate description by the principles which have been outlined above: tree structures [16, 17] formed by dendritic growth or crack branching; paths of electrical discharge; irregular dislocation lines or grain boundaries; and the surfaces of powder particles formed by rapid solidification (Fig. 10). These structures have in common a certain type of irregularity which, at a first sight, may resist quantitative description. The problem of finding the true length of a section through a highly branched dendritic structure or through a much more irregular rugged surface can be solved using the following relation between the apparent line length L (or surface A) and the scale of the steps ε by which the contour is approximated [18, 19]

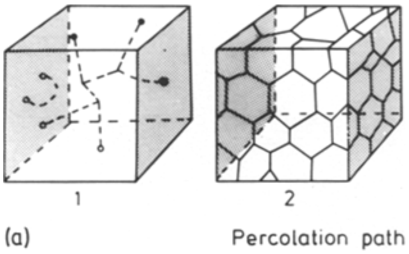
$$L(\varepsilon) \sim \varepsilon^{d-D} \tag{11}$$

where d is the geometrical dimension ($d = 1$ for a line, $d = 2$ for a surface) and D is the fractal dimension. D is a non-integer, and is suitable for characterization of the ruggedness of microstructural elements. When $D > d$ and ε can take any value this implies that $L(\varepsilon \to 0) < \infty$. For the analysis of microstructures there exist physical limits: $\varepsilon > b$, the atomic spacing, i.e. the scale of the phase structure. For experimental methods, $\varepsilon_{\min}$ is defined by the resolving power of the microscopy, and determination of a characteristic D value for a particular microstructural element must be made with a wide range of ε values. A plot of log$L$ against logε is drawn (Fig. 11). Its characteristic shape contains the information on a microstructure which is regarded as a D-dimensional space (compare Table II). The synthesis of a multiple dendritic microstructure is shown in Fig. 11b. The element is represented by $L(\varepsilon) = 4$, $\varepsilon = 3$ from which the fractal dimension of this structure can be calculated as $D = \log 4/\log 3 = 1.262$. L increases by 4/3 for each fragmentation by 3 for creation of a self-similar progression.

Finally, some microstructures show a multiple subdivision into units of different scale: martensite, concrete, semicrystalline spherolitic polymers [20]. At present the question as to whether they show fractal properties, i.e. a self-similar geometry, is being studied. Fractal analysis of microstructure is still in a very early stage of development. It may, however, provide a new tool which brings us closer to a complete and quantitative description of microstructures.

7. Origin of microstructures

Microstructure has been defined here as a non-equilibrium phenomenon. The immense variety which



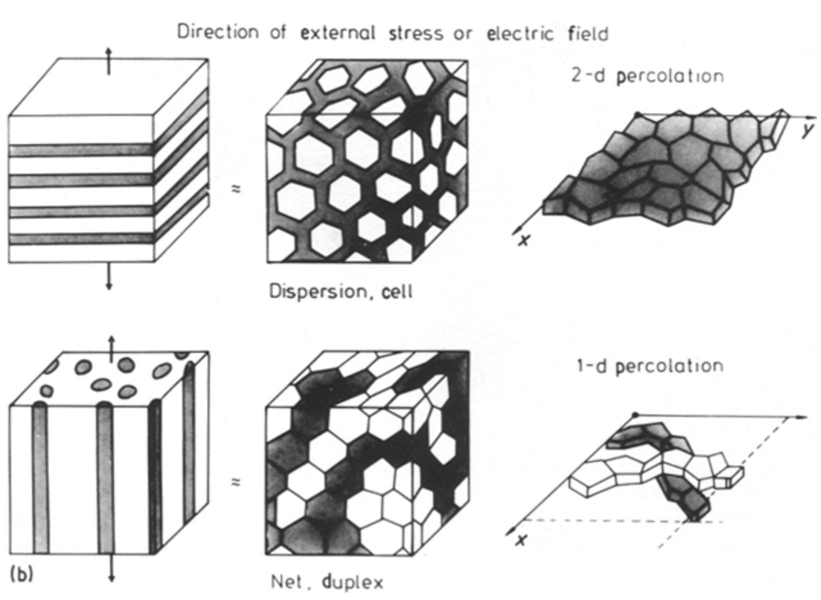


Figure 7 Percolation in microstructures, schematic. (a) Percolation of microstructural elements (dislocations $d = 1$, grain-boundaries $d = 2$ (Table II). (b) Percolation in anisotropic and isotropic heterogeneous microstructures.

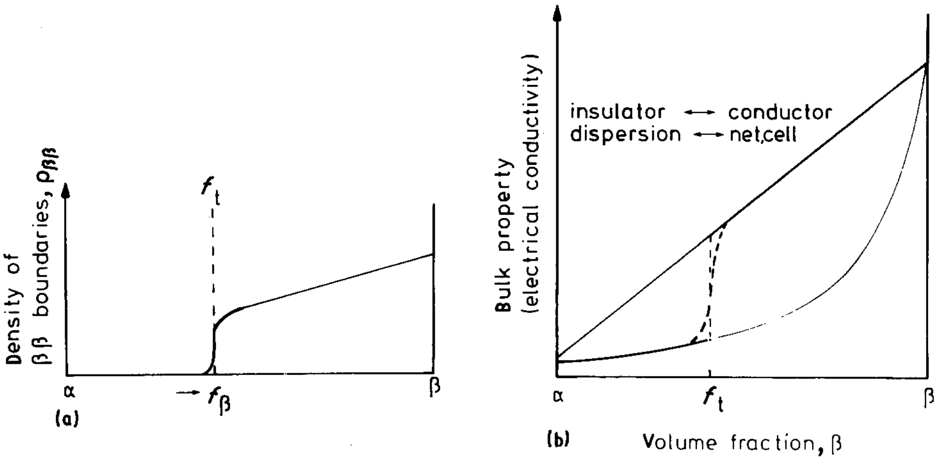


Figure 8 Microstructural transformation in ($\alpha + \beta$) phase mixtures. (a) Characterization by discontinuous change in $\beta\beta$ boundary density $\varrho_{\beta\beta}$ at point of percolation f_T. (b) Discontinuous change of bulk properties at f_T by transition to different rules of mixture (sequential to parallel arrangement of phases).

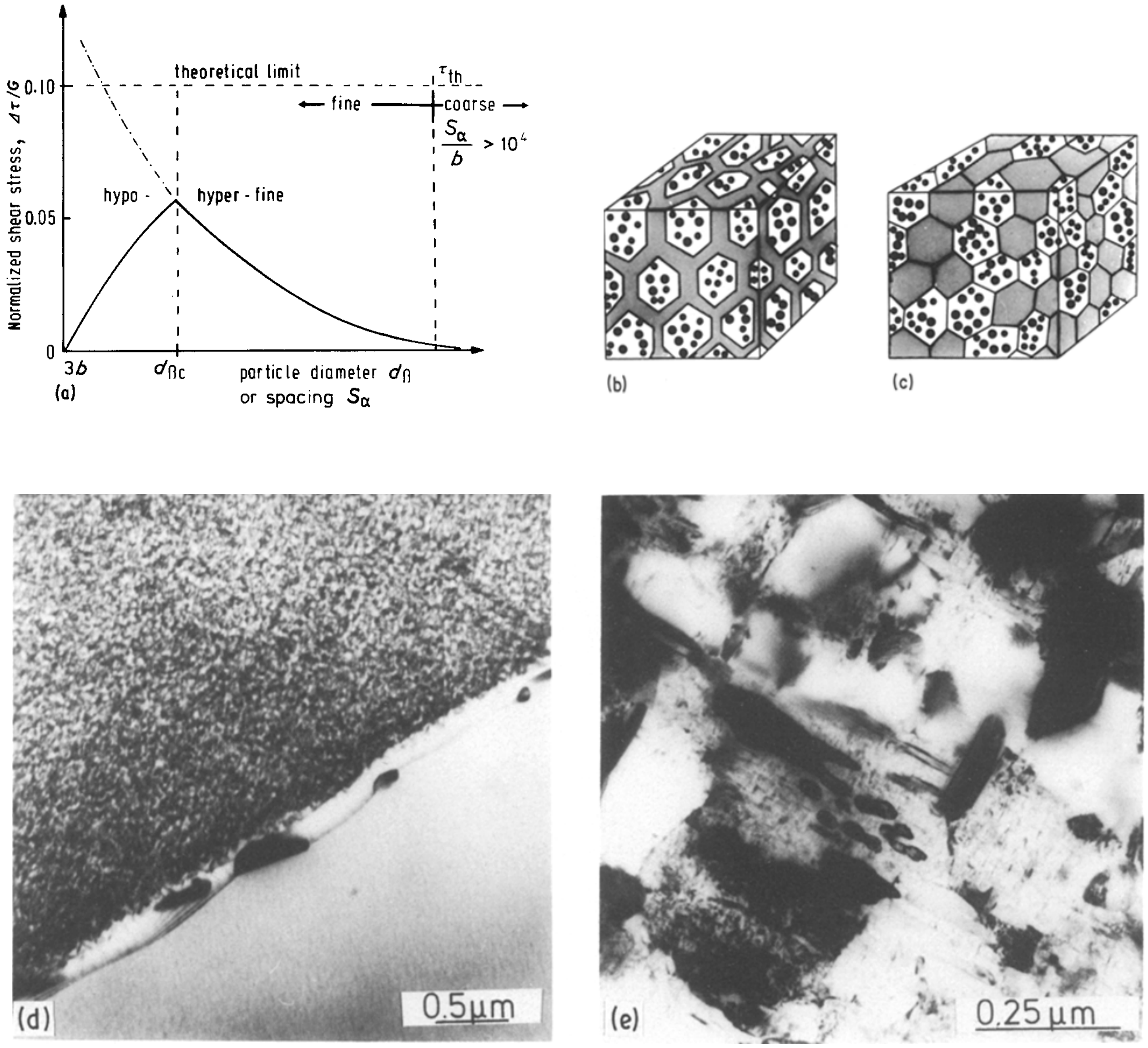


Figure 9 (a) Definition of fine and coarse microstructures using interaction of dislocations with dispersed particles of diameter d_β or spacing S_α. (b, c) Complex microstructures are mixtures of different types and of coarse and fine scale: (b) coarse cell + fine dispersion, (c) duplex + fine dispersion. (d) Particle-free zone at grain boundary (coarse cell + fine dispersion) in Al–2.3 at % Cu, 10 min 200° C. (e) Duplex structure with additional fine dispersion in one phase: Fe + 17.6 Ni, 0.66.V, 12.6 Co, 3.6 Mo, 1.6 Ti, 0.5 Al (wt.%), 95% c.w., 100 h 700° C, 3 h 500° C.

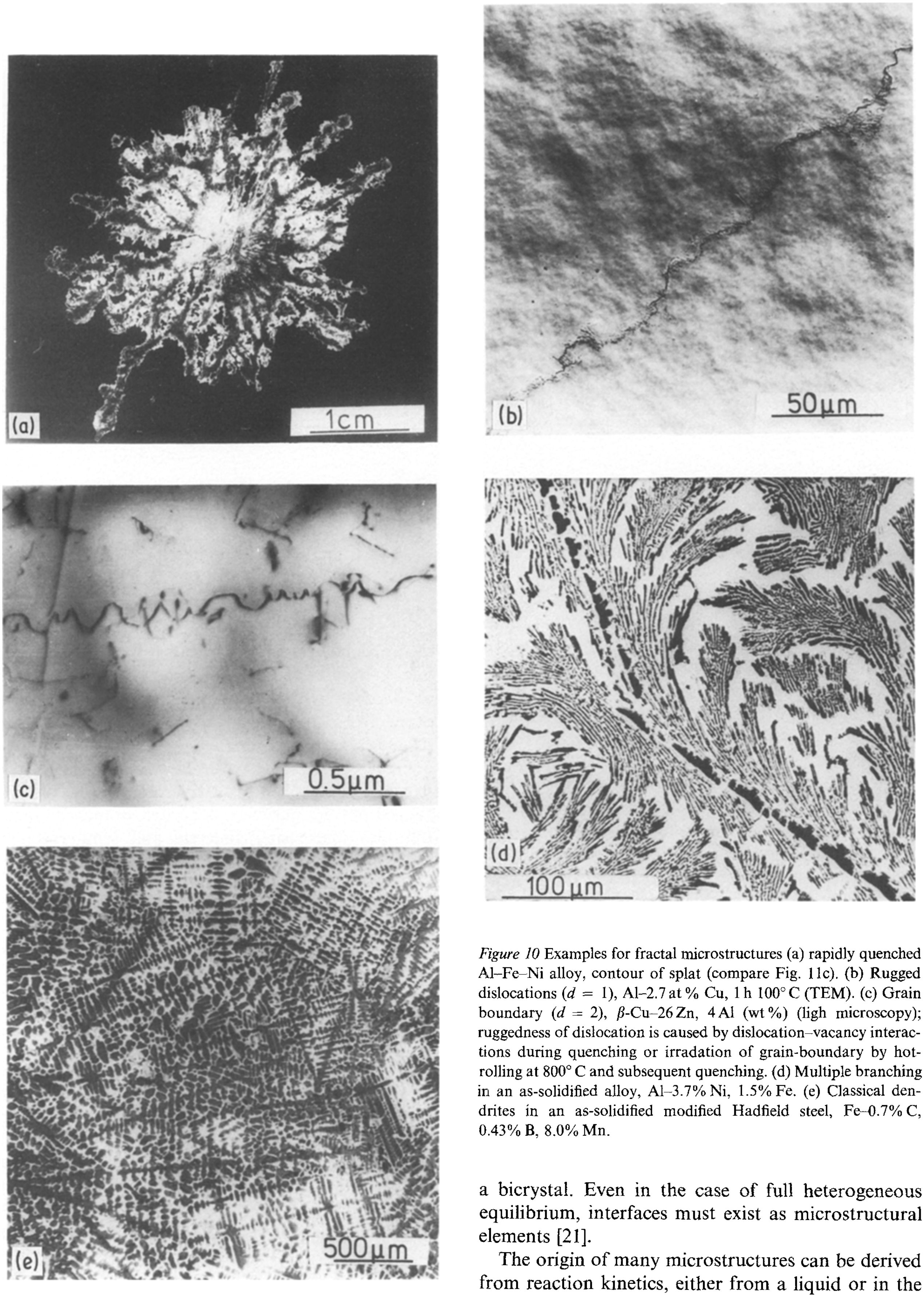


Figure 10 Examples for fractal microstructures (a) rapidly quenched Al–Fe–Ni alloy, contour of splat (compare Fig. 11c). (b) Rugged dislocations ($d = 1$), Al–2.7 at % Cu, 1 h 100° C (TEM). (c) Grain boundary ($d = 2$), β-Cu–26 Zn, 4 Al (wt %) (ligh microscopy); ruggedness of dislocation is caused by dislocation–vacancy interactions during quenching or irradation of grain-boundary by hot-rolling at 800° C and subsequent quenching. (d) Multiple branching in an as-solidified alloy, Al–3.7% Ni, 1.5% Fe. (e) Classical dendrites in an as-solidified modified Hadfield steel, Fe–0.7% C, 0.43% B, 8.0% Mn.

exists in nature and technology originates in many different ways from high free-energy states of matter. Only perfect single crystals and homogeneous glasses possess no microstructure. Closest to full heterogeneous thermodynamic equilibrium comes a stable volume fraction of equilibrium phases which grows to a bicrystal. Even in the case of full heterogeneous equilibrium, interfaces must exist as microstructural elements [21].

The origin of many microstructures can be derived from reaction kinetics, either from a liquid or in the solid state. There are homogeneously and heterogeneously nucleated microstructures. The geometrical parameters of growth structures (lamellae, rods, dendrites) are determined by the thermodynamics of irreversible processes. They are referred to as dissipative microstructures [22, 23]. They include ordered and anisotropic eutectic microstructures, as well as structures which originate by biological growth (wood, bone).

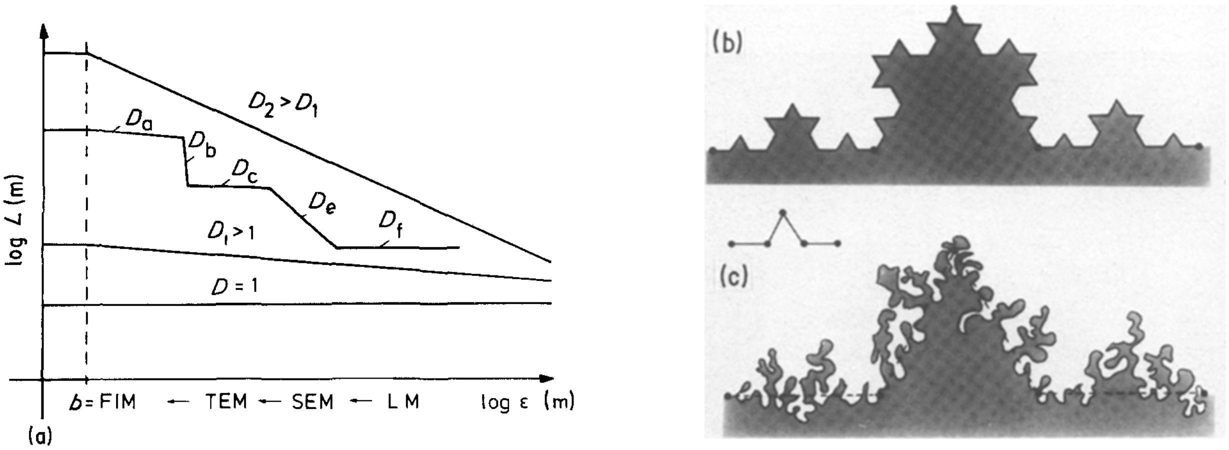


Figure 11 (a) Fractal analysis of microstructures (schematic): effective line length L (or area) as a function of the resolution of details ε (see Equation 11). $D = 1$ is the mathematical line; $D > 1$ represents increased irregular ruggedness; D_a, D_b, . . . represent ruggedness in certain ranges a, b, ... Resolutions of microscopic methods have been indicated in a schematic way. (b) Synthetic fractal structure, representing dendritic growth; three fragmentations of the indicated element, $D = \log 4/\log 3$. (c) Irregular fractal structure, repreenting surface of splat (Fig. 10a); $D > 1.5$.

A large number of microstructures are formed directly by external (for example mechanical) energy: dislocation cell walls, twin boundaries, slip bands, shear bands, persistent bands, etc. [24].

For another large group, the term "artificial" or "synthetic" microstructure is appropriate (which implies that those mentioned earlier are natural microstructures). These comprehend arbitrary phase mixtures agglomerated by pressing and sintering, mechanical alloying, extrusion, impregnation, or bonding by cements as well as all man-made honeycomb and sandwich structures.

The highest degree of sophistication of synthetic microstructures is obtained by vapour deposition techniques. Starting from simple and complex sequences of lamellae of different phases [25], or ultrafine multiphase mixtures, precisely defined shapes of engineering structures can be obtained such as integrated circuits.

8. Summary and conclusions

"Microstructure" is the structural level between phase structure and bulk structures. An appropriate definition should comprehend all its features and be well-suited for relating to the bulk properties of materials.

Three types of discontinuity in phase structures are proposed as microstructural elements: atomic position, type of atom and state of electron. These in turn can have a zero- to three-dimensional geometry. Bulk microstructural energy is determined by the densities of these elements (for example dislocations, grain boundaries, interfaces, Bloch walls). Elements occur as mixtures, disordered, ordered, or in gradients. In case of order different degrees of symmetry exist, as in solid and liquid crystal structures (microstructural anisotropy).

Prototypes of two-phase microstructures represent dispersion, net, cell and duplex. In grain structures, they can be defined by the densities of grain and interface boundaries. A more gneral way is using percolation of two, one or no phase. A change in percolation behaviour (or type) is a microstructural transformation. Types of microstructure can be mixed; for example, dispersion and cell in a precipitation-hardened alloy with particle-free zones at grain boundaries.

There exist scale effects which suggest a subdivision of the level of microstructure. As an example it is shown that a distinction between hypo- and hyperfine, and coarse dispersion structures can be based on dislocation particle interactions. Thus, the scale of microstructure is defined for particular microstructure–property relations.

Fractals may be useful to characterize certain irregular but self-similar microstructures such as rugged powder particles, dendrites, branched cracks, but also martensite, concrete and semi-crystalline polymers. The shapes of lines or surfaces are regarded as D-dimensional spaces, where D is not an integer, but contains information on the irregularity of a microstructure.

Finally, the origin of microstructures is discussed briefly. It is characterized as a non-equilibrium phenomenon.

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References

1. F. N. RHINES, *Met. Trans.* **8A** (1977) 127.
2. E. HORNBOGEN, *Pract. Metall.* **5** (1968) 51.
3. *Idem*, *Acta Metall.* **32** (1984) 615.
4. J. M. MARTIN and R. D. DOHERTY, "Stability of Microstructure in Metallic Systems" (Cambridge University

Press, 1976).

5. E. HORNBOGEN, in Proceedings of ICSMA5, Aachen, Vol. 2 (Pergamon, 1979) p. 1337.
6. E. E. UNDERWOOD, "Quantitative Stereology" (Addison-Wesley, Reading, Pennsylvania, 1970).
7. S. A. SALTYKOV, "Stereo metrische metallographie" (translated from Russian edition) (Verlag für Grundstoffindustrie, Leipzig, 1974).
8. H. BUNGE, "Texture Analysis in Material Science" (Butterworth, London, 1982).
9. T. P. HARRINGTON and T. P. MAAN, *J. Mater. Sci.* **19** (1984) 761.
10. K. LÜCKE, *Z. Metallkde.* **75** (1984) 948.
11. J. GURLAND in Proceedings of 2nd International Congress on Stereology, edited by H. Elia (Springer, Berlin, 1967) p. 250.
12. P. G. DE GENNES, *La Recherche* **7** (1976) 919.
13. R. DeWIT in Proceedings of 4th International Congress on Stereology, (edited by E. E. Underwood and R. DeWit) (National Bureau of Standards, Washington, D.C., 1976) p. 45
14. R. T. DeHOFF and S. M. GEHL, in Proceedings of 4th International Congress on Stereology, edited by E. E. Underwood and R. DeWit (National Bureau of Standards, Washington, D.C., 1976) p. 29.
15. E. HORNBOGEN, in Proceedings of 6th International Symposium on High-Purity Materials in Science and Technology, Dresden, 1985 Vol. I (Academy of Science) p. 24.
16. H. HORN, "Trees" (Princeton University Press, 1971).
17. M. BERRY, in Proceedings of 4th International Congress on Stereology, edited by E. E. Underwood and R. DeWit (National Bureau of Standards, Washington, D.C., 1976) p. 49.
18. B. T. MANDELBROT, "The Fractal Geometry of Nature (Freeman, New York, 1983).
19. B. T. MANDELBROT and D. E. PASSOJA (eds), "Fractal Aspects of Materials" (Materials Research Society, Pittsburgh, 1984).
20. P. G. DE GENNES, "Scaling Concepts in Polymer Physics" (Cornell University Press, Ithaca, 1979).
21. C. S. SMITH, *Metall. Rev.* **9** (1964) 1.
22. E. HORNBOGEN, *Met. Trans.* **10A** (1979) 947.
23. *Idem*, in Proceedings of 5th International Conference on Rapid Quenching and Solidification of Metals (RQ5), Würzburg, 1984 (North Holland) p. 785.
24. M. HEATHERLY, in Proceedings of ICSMA6, Melbourne, (Pergamon, 1982) p. 1184.
25. J. M. GIBSON and L. R. DAVISON (eds) "Layered Structures, Epitaxy, and Interfaces," (Materials Research Society, Pittsburgh, 1984).

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