Fractal Material Science: A New Direction in Materials Science

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To optimize the structure and properties of alloys, it is necessary to take into account the effect of the self-organization of a dissipative structure with fractal properties at load. This requires the development of self-organizing technologies for material production. Fractal material science takes into account the relation between the parameters of fractal structures and the dissipative properties of alloys. It also takes into account the base properties of highly nonequilibrium systems and the self-organizing process of the fractal structure in bifurcation points.

INTRODUCTION

Technological advances in the production of materials with optimal service-condition properties demand new methodologies; the basis of this proposed methodology is synergetics, a theory of self-organizing dissipative structures. According to synergetics, material with required properties can be produced only in nonequilibrium conditions by realizing the effect of a dissipative structure self-organization. Technologies that make use of this effect are called self-organizing technologies. Dissipative structures consist of highly ordered self-organizing formations in systems that are far from thermodynamic equilibrium and have specific forms and typical spatial-time dimensions. The most important characteristics of these structures are their life span (they exist only if energy is continuously supplied), region of localization, and fractal dimension. This fractal dimension makes it necessary to combine synergetics with fractal theory.

SYNERGETICS

Synergetics considers self-organizing processes and decay properties as inherent to any open system of an organic or inorganic nature. Biological, chemical, physical, and other nonequilibrium processes tend to undergo nonequilibrium phase transitions corresponding to bifurcation. Such a fracture is attributed to stepwise changes of a dissipative-structure fractal dimension.

The driving force of self-organization is the tendency of open systems to minimize entropy production. This follows from the Glansdorf-Prigogin and Klimontowich theorem. For the open systems that exchange energy and matter with the environment, a change of entropy consists of two parts

$$dS = d_iS - d_eS \qquad (1)$$

where d_eS takes into account the transfer energy through the boundaries of the system, and d_iS takes into account entropy changing inside. Entropy production is

$$d_iS/dt = p$$

At the bifurcation points, open systems have certain properties. First, the self-organization of dissipative structures with the fractal properties takes place. The subordination principle is also in operation (according to this principle, a set of variables is governed by one or two variables acting as the order parameters). Third, nonequilibrium phase transitions ("stability-instability stability") are accompanied by a spontaneous variation of the medium and the dissipative structure type; controlling the parameters of the functional relationships between the bifurcation points are found. Fourth, the universality and scale invariance of the relationship of the critical parameters controlling the establishment of instability by the system are ensured. Finally, the hierarchic sequence of the change of the mechanisms of energy dissipation in the process of transition from one bifurcation point to another is retained.

The relation between structural and mechanical properties is controlled not only by initial structure (static structure) but also dynamic (dissipative) structure in bifurcation points as well. These structures have fractal properties.

Table I. A Comparison of Traditional and Fractal Material Science Approaches

Parameter	Traditional	Fractal
Technology	Near equilibrium or nonequilibrium	Self-organizing (high nonequilibrium)
Physicochemical Analysis	Maximum entropy ($F \rightarrow F_{min.}$)	Minimum entropy ($P \rightarrow P_{min.}$)
Properties Optimization	Chemical content-initial structure-mechanical properties	Chemical content-initial structure-dynamic (fractal) structure-dissipative properties

FRACTALS

Although the mathematical theory of fractals was developed in the 1920s in physics, these concepts have been put to use only recently. Initial studies were carried out by B. Mandelbrot, who developed the concept of fractals as a self-similar set. The theory of fractals is regarded as a basis for quantitative description by means of the fractal dimension of various structures. B. Mandelbrot referred to fractals as structures consisting of parts that, in some sense, are similar to integers; fractals are of a fine (noninteger) dimension (D) that is always smaller than the topological dimension.

In conventional materials science, microstructure elements are described using the Euclidean dimension (d). For point defects (e.g., vacancies and interstitial atoms), d = 0; for linear defects (dislocations), d = 1; for planar defects (twins), d = 2; and for three-dimensional formations, d = 3. However, the Euclidean dimension cannot be used to describe structural elements differing from standard ones (e.g., points or straight lines). Thus, it is well known that grain boundaries, being the most important elements of the microstructure, are curvilinear, and this form can be described by the fractal dimension (D) corresponding to $1 \le D \le 2$. Surface defects may also be described using the fine dimension, corresponding to the range $2 \le D \le 3$.

Thus, fractal theory introduces a new quantitative parameter-fractal dimension for describing structures, which, because of its universal nature, is suitable for describing structures in systems types. With a system such as a deformed solid, the fractal concept makes it possible to describe quantitatively the elements of the initial microstructure (e.g., phases, grain, boundaries, etc.) and the structures formed during deformation.

A.S. Balakin formulated the principle of the fractal analysis of material micro-