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Review

Considerations of some key concepts in fundamental Materials Science

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For years now Materials Science has been recognized as a specific scientific speciality. Does the Science which consists in preparing materials and in studying their properties possess its own basic foundations or, on the contrary, is its fundamental part only constituted by concepts from other scientific fields such as solid state physics, mechanics, electricity, crystallography, etc. It is the author's opinion that some particular key concepts such as "processing", "non-equilibrium and evolution", for instance, are specific to the Materials Science field and that a better definition of their content and of their mutual action may lead to a "global view" of Materials Science. An attempt is made here to look at and define such concepts and to initiate discussion and, above all, controversies.

1. General considerations

The object of Materials Science is the study of the preparation and properties of materials. So, one of the main purposes of Materials Science is to succeed in preparing materials with well-defined properties in a reproducible way. That is why Materials Science may be considered as a science compared with artistic or craft activities which may also lead to the production of materials. It has long been known that a given material derives its properties directly from its microstructure and it may be said that one of the main purposes of Materials Science is to prepare materials with well-controlled microstructures in a reproducible way. It should be pointed out here that the majority of the studies carried out in the field of Materials Science deal with the setting up of relations between microstructures and properties. The relations between given microstructures and derived properties is a key concept in Materials Science. However, in order to prepare materials it is necessary to handle two matters properly:

(a) Adequate available raw materials or semi-manufactured material, R, should be chosen;

(b) An adequate or carefully studied set of processes should be chosen.

This last consideration may be expressed by

$$\mathscr{F} \rightarrow R \Rightarrow M, \qquad (1)$$

where $\mathscr{F}$ is a set of processes and the application of $\mathscr{F}$ to R is the processing. Equation 1 means that the application of an adequate set of processes $\mathscr{F}$ to R leads to the production of a material M. In order to produce M in a reproducible way it appears that it is necessary to maintain $\mathscr{F}$ and R constant as a function of time, or to modify $\mathscr{F}$ as a function of the variations of R on a real-time basis whenever possible. The "processing" appears to be another key concept in Materials Science; indeed, when a material is prepared, something must have been processed in something else. The concept of "processing" has not been investigated very much in fundamental Materials Science; it is the purpose of the present paper to try to consider it and to draw attention to some of the consequences of the analysis. So far "the relations between microstructures and properties" and "the processing" appear to be

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two key concepts in Materials Science. In the author's opinion at least one other should be given more attention, that is, the concept of "non-equilibrium and evolution" of materials towards equilibrium or towards another non-equilibrium state or another material. Indeed, the great majority of materials are out of equilibrium solids. Moreover as the "processing" is constituted of a series of operations (mentioned below) which are performed out of equilibrium, some fundamental questions have to be posed. Here are some examples. One can wonder, when a material is being processed, whether the different transformations take place "close to" or "far from" equilibrium? When, let us say, N atoms (of similar or different natures) are considered, how many different solids (having different properties, with a detectable life time) can be formed using one particular method or using different processes? How will such materials develop in their course to equilibrium when aging or when undergoing thermal activation for instance? Can they follow different trajectories? If so, how many? Other questions concerning the "evolution" of materials may be considered, especially those relative to the reactivity of materials placed in given environments. It is of course absolutely impossible to give a definitive and decisive answer to all these questions. All that I can say is that in more than ten years having been associated with a number of research projects in Materials Science in subfields such as thin film preparation, splat-cooling, amorphous semiconductors, physical metallurgy, phase diagrams of oxides, refractories, use of natural by-products, powder characterization, biomaterials, clay-based ceramics, physical and special ceramics, etc., my feeling is that the themes of "processing", "relations between microstructures and properties" and "non-equilibrium and evolution" are intimately mixed and that a better understanding of their definition, of their content, of their mutual action and importance may constitute a large part of the basis of fundamental Materials Science. One should also remember that Materials Science as a scientific field is an Applied Science and hence trends in the future in the Materials Science field will be largely dictated by economical and political needs [1] (e.g. the search for re-usable materials, the difficulty of being supplied with a particular raw material because of political uncertainties, etc). Of course Materials Science should remain an Applied Science but more attention should be placed on the definition and the understanding of the key concepts common to all the subfields of Materials Science. This paper which aims to be of fundamental essence is a modest attempt to present, illustrate and sometimes help to clarify, the content of such concepts by taking into account results, personal experiences and ideas collected in the different Materials Science subfields.

2. Processing as a key concept in Materials Science.

In Equation 1, $\mathscr{F}$ has been called the set of processes and the application of $\mathscr{F}$ to R the processing. Clearly speaking the processing can be defined as the series of the operations carried out* one after the other (or simultaneously) on an initial object in order to give a final object. Let us suppose that an initial object R possesses a finite and well-determined set of characteristics and/or properties $(X_1, X_2, X_3 \ldots X_i)$ taking the values† $(x_1^R, x_2^R \ldots x_i^R)$ and that this initial object undergoes a series of successive or simultaneous operations $(\mathscr{A}, \mathscr{B}, \mathscr{C} \ldots \mathscr{D})$ leading to the final object M which may itself present the same set of characteristics and/or properties $(X_1, X_2, X_3 \ldots X_i)$ taking the values $(x_1^M, x_2^M \ldots x_i^M)$. Each of the successive $\mathscr{A}, \mathscr{B}, \mathscr{C} \ldots \mathscr{D}$ operations leads to a given state (or intermediate object) N, O, P, Q which also present the same set of well-defined characteristics and/or properties with of course different values. It appears that the characteristics and/or the properties $(X_1, X_2 \ldots X_i)$ have to be chosen in order to describe any object entirely and in a non-redundant way. All these considerations may be summarized by the following:

$$\begin{array}{l|cccccc}
\text{Characteristics/} & R \xrightarrow{\mathscr{A}} & N \xrightarrow{\mathscr{B}} & O \xrightarrow{\mathscr{C}} & P \rightarrow \cdot\cdot & Q \xrightarrow{\mathscr{D}} & M \\
\text{properties} & & & & & & \\
\hline
X_1 & x_1^R & x_1^N & x_1^O & x_1^P & x_1^Q & x_1^M \\
X_2 & x_2^R & x_2^N & x_2^O & x_2^P & x_2^Q & x_2^M \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
X_i & x_i^R & x_i^N & x_i^O & x_i^P & x_i^Q & x_i^M .
\end{array} \qquad (2)$$

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*The operations are carried out in an order which is fixed and must be left unchanged.

†The term "value" is taken in its most general meaning, it can be a number, a distribution, a set of functions or relations, etc.

Of course any of these x_i^J can be equal to zero or equal to a neutral value. For a material to be processed from an intermediate state to another one implies that some work has to be done. This amount of work must be in direct relation with the quantities of energy $A, B, C \ldots D$ introduced during each operation. So, the operations $\mathscr{A}$, $\mathscr{B}$, $\mathscr{C} \ldots \mathscr{D}$ are in fact particular functions of the quantities of energy $A, B, C \ldots D$, and, of course, a great number of other parameters. In such a case the relations in Equation 3, which may be written, are sometimes theorems of existence; meaning that it is sure that these functions exist but is not sure that they can be set up using the physical tools we shall mention presently.

$$\left.\begin{array}{l} \mathscr{A} = \mathscr{A}\ [\mathrm{A}] \\ \mathscr{B} = \mathscr{B}\ [\mathrm{B}] \\ \mathscr{C} = \mathscr{C}\ [\mathrm{C}] \\ \vdots \quad\ \ \vdots \\ \mathscr{D} = \mathscr{D}\ [\mathrm{D}] \end{array}\right\}. \qquad (3)$$

So, in the *most general case* it is possible to conceive of the set of relations in Equation 4

$$\left.\begin{array}{l} \forall n = 1 \ldots i : x_n^N = f_n(x_1^R \ldots x_i^R, \mathscr{A}[\mathrm{A}]) \\ \forall n = 1 \ldots i : x_n^O = f'_n(x_1^N \ldots x_i^N, \mathscr{B}[\mathrm{B}]) \\ \forall n = 1 \ldots i : x_n^M = f''_n(x_1^Q \ldots x_i^Q, \mathscr{D}[\mathrm{D}]) \end{array}\right\}. \qquad (4)$$

The relations in Equation 4 mean that the values of the characteristics and/or the properties of an intermediate object are functions of the values of the characteristics and/or the properties of the intermediate object which preceeds it and of the operation it has been submitted to. It is also possible to write the relations in Equation 4 in another form.

$$\left.\begin{array}{l} \forall n = 1 \ldots i : x_n^M = F_n\,(x_1^R \ldots x_i^R; \\ \qquad\qquad\qquad \mathscr{A}[\mathrm{A}] \ldots \mathscr{D}[\mathrm{D}]) \\ (x_1^M \ldots x_i^M) = F.\,(x_1^R \ldots x_i^R; \\ \qquad\qquad\qquad \mathscr{A}[\mathrm{A}] \ldots \mathscr{D}[\mathrm{D}]) \end{array}\right\}. \qquad (5)$$

The general relations in Equation 5 mean that the value of the characteristics and/or the properties of a final object are functions of the values of the characteristics and/or the properties of the initial object and of the sequence of the operations it has been submitted to. The next question is how to set up the relations in Equation 5? Knowing the values of the characteristics and/or the properties of an initial object $(x_1^R, x_2^R \ldots x_i^R)$, then, which set of operations $(\mathscr{A}, \mathscr{B}, \mathscr{C} \ldots \mathscr{D})$ must be performed in order to obtain a final object with the values of its characteristics and/or properties $(x_1^M, x_2^M \ldots x_i^M)$? Also, when the relations in Equation 5 are known the following proposals may be given some answers. Having at our disposal a series of operations $\mathscr{A}, \mathscr{B}, \mathscr{C} \ldots \mathscr{D}$, which initial object must we start from to get a final object with the values of its characteristics and/or properties $(x_1^M, x_2^M \ldots x_i^M)$; or if the values of the characteristics and/or properties of a given initial object varies as a function of time, how must each operation $\mathscr{A}, \mathscr{B}, \mathscr{C} \ldots \mathscr{D}$ vary in order to maintain constant the values of the characteristics and/or the properties of a final object$(x_1^M, x_2^M \ldots x_i^M)$ as a function of time, when possible. Two important questions appear here:

(a) What are the importance, the validity and the reality of the relations in Equation 4 or 5 in Materials Science?

(b) How to set up these relations and what conclusions may be drawn from their existence? Let us try to start answering both questions.

The relations in Equation 4 are general and in fact emphasize the importance of "history" in the preparation of materials. A synthetic material very often "remembers" the materials it was prepared from and the history of its preparation. This is described in the relations of Equation 4. Ceramics and splat-cooled materials, for instance, are two subfields of Materials Science in which these concepts are important. In other subfields of Materials Science, such as thin solid film preparation, the use of such relations is less obvious, indeed the vapour which is projected and condensed on to a substrate may or may not "remember" the solid it was produced from. In our opinion these relations in Equation 4 are useful in order to approach better every subfield of Materials Science. The relations in Equation 4 can only be set up *one term after the other* if the different x_1^R, $x_2^R \ldots x_i^N \ldots x_i^M$ are known with *"enough precision"* and if the influence of each operation is "understood well enough" to give the appropriate physical relations. The case of ceramics is described here for illustration purposes. Ceramics can be defined as the subfield of Materials Science which studies the preparation and properties of inorganic non-metallic solids. This is the general definition of ceramics. However in Europe ceramics is sometimes understood in a more restricted way. That is, the scientific, technical and industrial field which deals with the preparation and the properties of inorganic solids containing less than 40% vitreous phase and which have been treated thermally during their preparation. The analysis of this definition makes us realize that ceramics is a wide field (oxides, nitrides, borides, silicides, silicates, etc.) and that which is called traditional ceramics is in fact a much more limited field which only deals with particular natural solids: clays, sands etc. The processing of ceramics can be described as follows:

Inorganic powders → Pretreatment of powders
(natural or synthetic) (milling, spray drying,etc)
——————→ Forming ——————→ Debonding
(pressing, extrusion, casting, etc) (drying, prefiring)
——————→ Firing ——————→ Final product.
(classical sintering, fast firing, etc)

Some operations may also be simultaneous, for instance: hot pressing, in which the forming and the firing operations are performed at the same time. So if one compares with Equation 1, R are inorganic powders and the processing (the application of the set of processes on R) consists of the sequence; pretreatment, forming, debonding, firing. The processing described here is most common* in ceramics: a roof tile or an alumina substrate are prepared according to the same general sequence. Ceramics has long been considered an art but is now acquiring a scientific status and being considered as a well-defined part of Materials Science. Recent papers [2, 3] claim that a better understanding of ceramic processing is necessary in order to make a decisive step towards complete scientific control of the fabrication of ceramics and therefore to give more confidence in ceramic products to potential users. The everyday experience of ceramists is such that enough information is available to say that any change introduced in one of the operations of the processing modifies the whole following of the sequence. So in ceramics a final product "remembers" its preparation and the raw materials used. Then in our opinion the relations in Equation 4 are worth considering. By using the relations in Equation 4 one realizes that a better knowledge of the processing is only possible if those relations can be set up. It is known that the relations in Equation 4 must be written one after the other. So $\forall n = 1 \ldots i: x_n^N = f_n(x_1^R \ldots x_i^R, \mathscr{A}[\mathrm{A}])$ must of course be set up before considering the second stage, $\forall n = 1 \ldots i: x_n^O = f'_n(x_1^N \ldots x_i^N, \mathscr{B}[\mathrm{B}])$. In the case of ceramics R are inorganic powders, either synthetic in the case of special ceramics (Al_2O_3, MgO, ZrO_2, SiC, Si_3N_4) or natural in the case of traditional ceramics (clays, sands, feldspars, minerals. . .). So the first question to be asked is whether the characteristics of the raw materials x_i^R are known with enough precision, that is: what to characterize, and do you dispose of enough tools to characterize a powder properly? The answer is unfortunately negative. Indeed, for instance, no method has received universal agreement for determining such an important parameter as the shape factor of a powder, even the definition of what is the morphology of a set of particles is in dispute; at the present time ceramists do not even know exactly which factors should be considered for a complete characterization of synthetic or natural powders. So the analysis of the relations in Equation 4 may lead to an important consequence, that is, that one priority in the field of ceramics would be to devise tools (equipements, methods etc.) for characterizing powders with enough precision. This is an example of what information may be obtained from the examination and the analysis of Equation 4. Conclusions on the use of Equation 4 in Materials Science will be drawn in the final part of this paper. Now we will consider to related concepts: "non-equilibrium" and "evolution" in Materials Science. This is the object of Section 3 of this paper.

3. "Non-equilibrium" and "evolution" of materials

It has already been said that the processing of raw materials into a new material consists of a series of operations performed out of equilibrium and very often the material which is obtained is a non-equilibrium one. In Section 3 of this paper two concepts will be considered, the concept of "non-equilibrium" and the concept of "evolution" of materials. Quite arbitarily we have made a distinction between these two concepts keeping in mind the following difference: an "out of equilibrium" material may develop spontaneously towards equilibrium through different non-equilibrium states of intermediate stability (Section 3.1), but very often an "out of equilibrium" material may also develop, giving other material structures

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*Exceptions may be found, for example, fusion cast materials.

through reaction or interaction with its environment, this latter point being called "evolution" in the following (see Section 3.2).

3.1. Non-equilibrium in Materials Science

In the introduction of the present paper several questions concerning the place of non-equilibrium in Materials Science were asked. The first question was: When a material is being processed, do the different transformations take place "close to" or "far from" equilibrium? In other words what part of thermodynamics is useful in Materials Science? As seen before the processing can be described as a series of successive operations performed on an initial object to produce a final object. Of course, in most cases the initial object, the intermediate ones and the final one are "out of equilibrium" materials capable of evolution. Moreover the operations are particular functions of the quantitites of energy that must have been introduced in order to pass from one intermediate object to another. The questíon asked here refers to the place and the role of thermodynamics in Materials Science. It can be posed differently in the form: Can the description of the prepared non-equilibrium objects and the operations be approached by classical thermodynamics? Can the classical thermodynamics [4] serve as a guide in Materials Science? My feeling is that indeed the world of Materials Science is "close" to equilibrium (close when compared for instance with "the physical world" described by the thermodynamics theories of the group of Professor Prigogine [5, 6], which consider conditions "far" from equilibrium). The classical thermodynamics approach describing closed systems going to equilibrium, chemical potentials, energy balance calculations, phase diagrams, heats of reaction, etc. should be considered as a guiding tool, keeping also in mind the ideality of such an approach. As classical thermodynamics generally deals with closed systems that are in equilibrium with respect to some processes but not with respect to others, in the author's opinion, the field of the application of thermodynamics to Materials Science is more that of irreversible processes close to equilibrium and that of metastable transition data. In the introduction of this paper another series of questions concerning other aspects of non-equilibrium in Materials Science were asked. These questions may be grouped and posed as follows. When disposing of a number of atoms, N, and of one particular method or of different methods of preparation, how many solids may be formed? The answer is of course many. If this is the case the formed solids of the same composition will be (with the exception of one) out of equilibrium. How will they develop when aging, when undergoing a thermal treatment, but without any direct chemical interaction with the environment? Which trajectory(ies) may they follow in their course to equilibrium? These points will be considered and illustrated on the basis of results obtained by studying non-equilibrium phases in amorphous and crystalline alloys prepared by vapour-quenching (VQ) and liquid quenching (LQ) which are two well-known adequate methods for preparing such phases. VQ refers to the different methods which consist of condensing a vapour onto a substrate held at a sufficiently low temperature and the materials obtained are thin solid films. LQ (splat-cooling) is the method developed by Duwez which consists of rapidly cooling melted alloys, the so obtained materials are foils. Let us suppose, for instance, that an alloy of A_xB_{100-x} composition can be prepared by these two methods. Of course for each method different equipment is available and a wide range of experimental parameters can be adjusted. Each method may lead to different non-equilibrium materials and so to different phases in thin films and to different phases in foils depending on the techniques and parameters used. Let us suppose that VQ leads under given conditions (temperature and nature of the substrate, evaporation rate, nature and shape of the evaporation source, distance between evaporation source and the substrate, etc.) to the following sequence:

$$\text{Film 1 (as-deposited)} \xrightarrow{T} \text{Film 2} \xrightarrow{T} \ldots \xrightarrow{T} \text{Film } i \xrightarrow{T} \ldots \xrightarrow{T} \text{Film } E$$

meaning that a given structure (amorphous or crystalline) is formed in the as-deposited Film 1, which will spontaneously go towards equilibrium through states of intermediate stabilities [7] (Ostwald's rule) when undergoing a thermal treatment T (it can also happen when aging, for instance). Some states of different stabilities may be more stable than the others and then have a chance to be detected [8]. Let us suppose that this is the case for Films 2, 3 . . . i . . . E, which may be amorphous or crystalline. All the structures of the films are out of equlibrium with the exception of Film E which is the equilibrium one. As far as LQ is concerned similar conclusions may be drawn about foils with:

$$\text{Foil 1 (as-rapidly cooled)} \xrightarrow{T} \text{Foil 2} \xrightarrow{T} \text{Foil 3}$$
$$\xrightarrow{T} \ldots \xrightarrow{T} \text{Foil } i \xrightarrow{T} \ldots \xrightarrow{T} \text{Foil } E,$$

with Foil $E =$ Film E and Foil E being the equilibrium structure. The important following question may be asked. Does Foil i belong to the same set as the one formed by Films? Do foils and films follow similar trajectories when going to equilibrium? Or is there one and just one finite set of possible structures which would be independent of the processing (history of the preparation) and of the raw materials but which would only be dependent on the chemical composition of the materials? Here again it seems that the answer to these questions is generally negative and has been partly analysed in two papers [9, 10], published a few years ago, in which parameters of VQ and LQ techniques as well as mechanisms of formation of solids by VQ and LQ were critically analysed. So for instance it appeared from using results available at the time that the VQ technique was not capable of preparing large unit cells containing a high number of atoms but, on the contrary, it showed a tendency to form close-packed structures. Besides for LQ, where the arrangements of atoms existing for a given liquid alloy may act as sources of nucleation no discrimination on the size of the unit cells formed was observed. This point has been quoted as an example. So, one might say that the application of a given process to some raw materials according to Equation 1 leads to the production of materials which are usually out of equilibrium and which, in their course to equilibrium, will pass through a set of states of intermediate stability. Each different process induces *another set* of states of intermediate stability, these sets being finite and containing a *small* number of easily detected states (showing well-differentiated structures and properties when compared one with the other). As previously stated this conclusion is tentative because of course one may find some contrary examples depending on the composition and chemistry of the materials studied, as for instance in tellurium-based alloy materials prepared by VQ or by LQ. Ten years ago the study of the preparation and the properties of tellurium-based alloys was a matter of great interest in numerous laboratories. Tellurium based alloys prepared by VQ or LQ were either amorphous or crystalline but presenting interesting properties (for instance, switching effects, semiconducting properties, superconduction in metastable simple cubic phases, hopping effects, unusual structures, etc.). Numerous binary, ternary and quaternary materials were prepared using mainly LQ (some by VQ too); tellurium being alloyed with Cu, Ag, Au, Al, Ga, In, Tl, Si, Ge, Sn, Pb. P. As, Sb, Bi, etc. By using the techniques available at that time most alloys prepared by LQ were X-ray amorphous, some ($Au_{30}Pd_{3.3}Te_{66.6}$, $Au_{16.7}Pd_{16.6}Te_{66.7}$, $Au_xTe_{100-x}(x = 15$ to $45)$, $Ag_{25}Te_{75}$, $In_{50}Te_{50}$, $Te_{70}(Cu, Ag, Au)_{30}$, etc.) presented the unusual simple cubic structure (1 atom per unit cell), others (P, for instance) led to great difficulties in their preparation, etc. The tellurium–thallium alloys were studied by VQ and LQ methods in a whole range of compositions. Details about this work may be found elsewhere [11]. Briefly it can be said that Te/Tl alloys prepared by VQ [12] (deposited at liquid nitrogen temperature) and LQ [13] (gun technique) were X-ray amorphous. Detailed studies on, for instance, $Te_{71}Tl_{29}$ amorphous alloy have shown that the crystallization path in films was very similar to that in foils leading to very similar metastable phases. The consequence of these results was that the structure of amorphous films and foils were probably very similar. This might be due to the particular covalent type of bonding between tellurium atoms leading to a chain-like structure close to the simple cubic one; this particular type of bonding remains predominant whatever method of preparation is used. The example of tellurium based alloys presented here is, in the author's opinion, an exception; the general rule being that *one* process leads to *one* given set of structures.

3.2. Evolution of materials interacting with their environment

Another concept which should be clarified is that of the "evolution" of materials placed in complex environments which usually occurs in practical applications. As previously stated, most of the materials which are used are "out of equilibrium" materials; moreover their utilization in dynamic conditions as well as their contact with complex environments make them evolve. This evolution is hard to describe correctly. Two examples of increasing complexities are given below; they concern the refractories and the biomaterials. One given refractory product may be used for different industrial applications; for instance, the same refractory material may be used either for glass or steel production. Refractory materials are usually non-equilibrium materials; most of the time they are systems in which chemical reactions are not complete, they may contain glassy phases, etc. Therefore they are materials capable of developing by themselves when placed at high temperatures which is their primary function. But moreover, when in practice they are in contact with either molten glass, alkaline vapours, slags, cast-iron, etc. Under such conditions they react with the environment. Their evolution, therefore, as a function of time, is due to *a set of mechanisms*: aging, completion of the chemical reactions inside the materials, devitrification of the glassy phases, chemical reactions with the phases with which they are in contact, influence of mechanical effects (thermal shock for instance). The interaction between mechanisms makes the global concept of "evolution" very hard to describe with enough precision. This lack of knowledge of the "evolution" concept is the reason why it is so difficult for users to risk replacing a well-known refractory product by a newly developed one. How is the evaluation of this new refractory material performed? Mainly on empirical procedures. When a new refractory material is produced, it is submitted to a series of well standardized tests and the results are compared with those obtained on other well-known commercial refractory materials. These tests are mainly concerned with the chemical and mechanical behaviour of refractory materials placed in situations only slightly similar to the real ones. When the results of these tests are considered satisfactory the risk of replacing some pieces (bricks for instance) of the new refractory material when an equipment is under repair may be taken and the behaviour of the new refractory material will then be judged during its use (by optical periscopic examination, for instance). Unfortunately it will only be possible to test it when the equipment is stopped, that is, after years of use. It has been seen previously that it is not possible to simulate the behaviour of a refractory material in its normal usage conditions and to describe its evolution with much confidence. All these reasons make it seem that progress in the field of refractories is very slow. The evolution concept of refractory materials appears to be complex although in fact most of the scientific parameters (kinetics of the reactions, thermodynamics data) necessary to describe each mechanism, taken separately, are known. In reality the problem of refractory materials may appear to be a simple one when compared, for instance, with biomaterials which will be treated now. Biomaterials are defined as man-prepared materials designed to achieve a specific biological or physiological behaviour. The use of bioceramics (alumina, hydroxyapatite, pyrolytic carbon, carbon fibres, sialon etc.), bioglasses (of different surface reactivities), numerous classes of biopolymers, biometals and biocomposites (ceramic–polymer for instance) provides additional versatility in the growing number of the materials available to solve health care problems. An increasing number of medical specialities are also concerned with the problem of using reliable biomaterials, e.g. orthopaedics and joint replacements, dental, cardiovascular, reconstructive surgery, etc. Of course in each of these large medical fields the problems are highly specific. The working out of the complete design of a knee prosthesis has very little in common with the one of a prosthesis suitable for the replacement of a damaged shoulder-blade, even for instance with a hip-bone although the latter is also a load bearing joint for which much experience has been gained in the last decade. Because of the large variety of functional requirements it is not surprising that an implant is preferably composed of different materials and must respond to a large number of requirements of different natures (biocompatibility, sufficient and appropriate mechanical properties, low friction and wear, nonthrombogenicity, long-term functionality, possibility of sterilizing, etc.) The problem of biomaterials is so complex that it is becoming an important subfield of Materials Science and the reader interested in it should refer to specialized texts, journals and courses. It is not the purpose of the present text to comment about biomaterials but to show examples of the complexity of the definition of the concept of "evolution" of such materials after implantation. A good example may be bioglasses [14]. Bioglasses are glasses with compositions which are designed in such a way that the surface of the material undergoes a selected chemical reactivity with the physiological system setting a chemical bond between tissues and the implant surface. The chemical reactions which occur are such that the bonded interface protects the implant materials from further deterioration with time. Thus the potential of this approach is to combine the high strength of quite inert bioceramics (alumina for instance) with surface chemical reactivity favourable to tissue bonding. Let us examine the possible conditions for the "evolution" concept of such materials after implantation taking an example where a bioglass material could be used as part of an implant replacing a load-bearing joint (knee, hip, ankle for instance). So, the bioglass material is in contact and in interaction with living bony tissues leading to a very complex evolutionary system. The behaviour of the living bony tissue may be affected by a series of poorly controlled mechanisms including among others the metabolism of cells, the kinetics of renewing of which is highly dependent on personal characteristics (health, condition and fitness of the patient or of the animal which has been operated on, absorbed medication, age, development of arterial supply to the bonded interface, etc.) So the bioglass is in contact with a living dynamic system the operation of which, at the present state of knowledge greatly depends on factors which are largely unreproducible. Let us add that of course experiments are carried out on animals presenting differences of all nature compared with human behaviours. The bioglass interacts (true chemical reactions) at the interface with the living tissue and becomes itself a dynamic system. Moreover, as it is a glass it may be corroded, leached out or devitrify with time. Moreover, and this appears to be an important factor, the answer is not clearly known to the question: Would a similar bonding occur under functionally loaded-conditions? It has only recently been found in the field of biomaterials that cellular activity yielding bone fixation is influenced to a large degree by the loading patterns and the motion occurring at the bone–biomaterial interface, making the situation even more complicated. Therefore, the implant and the surrounding tissues may be described as a dynamic system (evolving as a function of time) in which the different parts (living tissues, reactive material, quite inert material) may evolve by reaction with each other and by development on their own; all this through interacting mechanisms. In such a case an understanding of the concept of "evolution" is, at the present time highly hypothetical. How will this whole system evolve as a function of time? This is the full responsability of the multidisciplinary biomaterial teams where materials scientists are trying to find answers to these questions. The case of bioglasses has been chosen as an example but the problem of clarifying the whole concept of evolution which is very important in general and is particularly important in a field such as biomaterials. Other examples of the same complexity could have been considered such as the use of polymers (or other soft implants) in cardiovascular surgery for replacing arteria suffering from arteriosclerosis, the problems of carbon in an artificial heart, the materials used in non-load-bearing joints or the dynamics of systems containing totally resorbable bioceramics, etc.

4. Conclusions

It has already been noted in the introduction that one object of the present paper was to give a personal view of the field of Materials Science. When one works in a given field of activity it seems reasonable to obtain a global idea of the field in order to orientate oneself in the approach to problems. Materials Science has become a wide field which aims at preparing and studying solids of all natures. The global view which is proposed here is dictated by some key concepts: their content and their (mutual) action. Among others, three important key concepts appear: "relations between microstructures and properties", "processing" and "non-equilibrium and evolution". In summary it can be said that, on the one hand, in order to produce a material with well-defined properties it is necessary to handle properly Equations 1, 4 or 5 and to ensure that the processing takes place not too "far" from equilibrium. On the other hand when an adequate material is prepared one should be aware of the complexity of its possible developments and evolution. This is the first conclusion. The second is that it is not possible to dissociate the consequences of the existence of these key concepts (all having mutual effects) from each other. For example, it has been shown that *one* process (performed out of equilibrium) may lead to *one* given set of structures capable of development towards equilibrium state or evolution towards other material structures. The third conclusion concerns the relations in Equation 4. It has already been said that it seems that they might be worth considering in every subfield of Materials Science, indeed one should wonder how physical relations between the values of the characteristics and/or the properties of the used raw materials, those of the intermediate objects and of the final product may be set up. It is the hope of the author that scientists dealing with every particular subfield of Materials Science would try to set up such relations on the basis of the relations in Equation 4. In subfields where such relations may not be written because of a lack of knowledge, priorities of research should be proposed in the same way as it has been done for the subfield of ceramics in this text. As far as the evolution of materials due to the interaction with the environment is concerned it seems that another priority should be to conceive approaches leading to a better knowledge of the general concept of evolution in order to gain confidence for potential further uses. It was the purpose of the author to present here a reflective paper in order to initiate discussions, comments and reflections. It is hoped that this purpose has been obtained.

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