The Art of Ceramics
The Blend of Art and Science in Technology
N. Claussen (Editor)

CERAMIC RESEARCH IN BETWEEN SCIENCE AND ART

Roman PAMPUCH
Department of Advanced Ceramics, AGH Krakow, Poland

The paper addresses pros and cons of contemporary research in materials science & engineering. A significant part of this analysis is focused on "in-between science and art" research, which neither creates theories nor results in practical applications. In order to increase a significance of the "in-between" research new impulses are necessary. The constitution of living systems has been such a stimulus for research conducted by the author and his collaborators. This topic is described in the second part of the paper.

INTRODUCTION

It is a good tradition of the Forum of Academy of Ceramics to include papers addressing ideas, which underlie research activity in ceramic materials[1,2]. One of the objectives of this paper is to follow up this tradition by considering the pros and cons of the transition from "high" science to mass profession which took place in the second half of the XXth century. There are two antithetical opinions regarding the value of scientific activity in contemporary society. Some people claim that we are living in a world that relies on the creation of more knowledge for its survival. Others say that it is the capital, which counts for more than human work, including scientific activity. However, there are events external to science which make the latter claim not groundless, namely, the influence of globalisation of the economy and restructuring of the industry. Table 1 summarises these impacts. Some remarks have been taken from papers presented at the 2nd Forum of the Academy held in Cracow and the subsequent discussion[1,2].

To the opinion that something has gone wrong with science have contributed also internal developments in science. Before discussing them let us explain first the meaning of some words. At present, the term "science" is often applied to denote a broad range of activities. Sometimes it means a special method of discovering things, sometimes the whole knowledge gained through discoveries, sometimes the ability to get things done due to discoveries and sometimes the process itself of making things (Figure 1). The terms "science" and "art", as used in this paper, stand for two opposite poles of this range of activities. It is only here that the significance of activity can be assessed in a

TABLE 1 - The impact of globalisation of economy and world-wide information net on materials science & engineering.

Effects of globalisation of the economy and restructuring of the industry

Concentration of the industry on short term economical successes.

Growing belief in efficiency of the applications-driven, discovery-following model of research.

Economists are of the opinion that results of scientific research are always available and, therefore, can be bought at any time.

Effects of world-wide computer web

Cost reduction and higher frequency of information exchange.

Increase of the information accessibility for research and education.

Information is one of the most valued assets in some fields (e.g. economy).

The web furnishes information; however, this is not equivalent to understanding (the effect of a creative human process involving transformation of information) which permits an effective use of information.

Advantageous directions inside science

The industry needs flexible professionals of different options from the universities.

There is always a need for nation-wide culture- and health-linked research.

A need may arise for results of long-term basic research conducted at the universities.

In developed countries a close co-operation with the industry aiming at a medium term commercialisation of innovative materials is possible.

In developing countries education-linked research continues to be important because education enables to catch–up with developed countries in the future.

unambiguous way. Namely, in natural *sciences* research can be regarded as significant if there is an agreement between theory and experimental data. An adequate performance of installations, constructions, technologies etc. is the criterion for significance in the *art* of technical realisation.

Currently, there is a very large and growing volume of research activities which neither create theories nor result in practical applications. They shall be further referred to as "research-in- between science and art". Together with a massive participation in research this is a feature of contemporary science which has a little relation to the science of Archimedes, Copernicus, Galileo and others and shall be the subject of the following discussion. Let us recall the opinions of critics and advocates of this state of affairs (Tables 2 and 3).

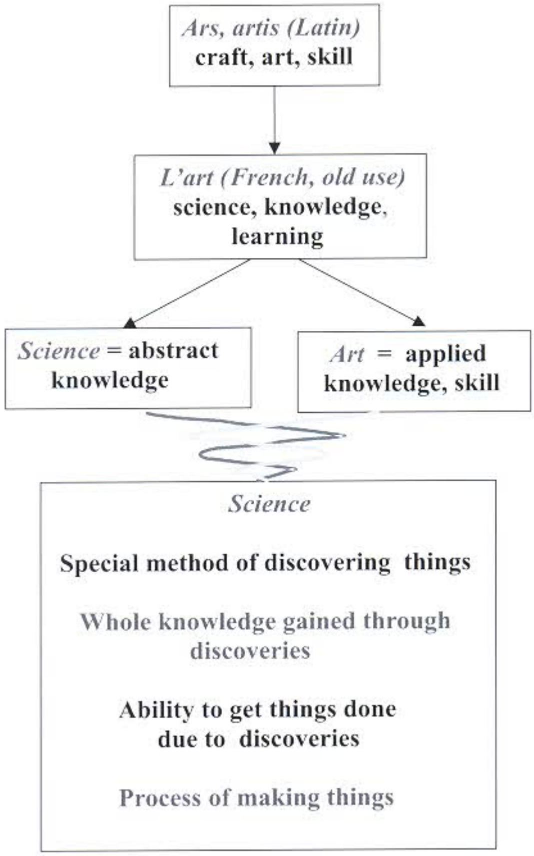

FIGURE 1 - The meaning of 'art' and 'science' in Latin and old French and at present (see ref. 4).

The arguments of the critics fail to demonstrate that there is an "end of science" as seen by some eminent scientist (see ref. 12). However, they cannot be neglected by anybody working in science. It has to be admitted that a disinterested pursuit of truth still exists in few fields such as cosmology and fundamental particles. Most experimental science has, however, ceased to be a sort of religion. It has become a down-to-earth mass – profession where, at best, attitudes between a "monomaniac mole" and "enjoying –science- as- a –hobby" one are encountered. A substantial increase of the volume of mass-scientific production in a given field is accompanied by a decrease of its scientific value (Figure 2).

This is due to an exhaustion of resources of inspiration for original and significant research with time[13]. Such a situation is observed in the field of ceramic materials science & engineering, which was created some forty-fifty

TABLE 2 - Consequences of science as a mass-profession, according to its critics.

Source	**Consequence**
Increasing number of researchers	Increased share of professionals utilising intellectual and physical tools developed by others. The share of mediocre researchers increases because of the Gaussian distribution of talents.
Growth of the volume of knowledge	Specialisation is unavoidable but the specialist often becomes someone between a *"monomaniac mole"*[5] or one enjoying science as a hobby; seeks refuge in modern "ivory towers" (specialised meetings, journals). Cross-fertilising is hampered while *'exchange of information is the decisive factor for good functioning of work of scientists'*[6]. Dominant position of research dealing with details and *'resolving problems that strengthen and broaden the topical paradigm and do not question it'*[7]..
Increasing number of ideas and information	Provided the information in internet and books is trustworthy *'all science is so overloaded that one does not know how to use this multitude'*[8]. Pursuit of originality often results in a "from – flower-to-flower-jumping" – attitude which may lead astray and culminate in pathological reactions like hunt for phantoms (cold fusion, C_3N_4 synthesis a.s.o.).
Growth of knowledge outside the realms of understanding by the specialist	Quantification of criteria of significance of research (Impact Factor, Science Citation Index), which often are used for comparative purposes. Quantitative criteria may be misleading and promote quantity over quality. The climate of frequent comparison and differentiation is a fertile soil for vanity. Team work is instrumental for a realisation of broad problems but often confined to exchange of technical services only; ideas and non-conformity may be victims.

TABLE 3 - Consequences of science as a mass-profession, according to its advocates.

Source	**Consequence**
Massive involvement in research	*'We are living in a world that relies on the creation of more knowledge for its survival'.* Growth of the number of people doing research is a natural reaction to this situation. The present development of science could not be attained without a massive involvement in research.
Use of known material and intellectual tools and research focusing on details	While critics say that *'a theory cannot be constructed from results of observations, it has to be invented'* [9]; research pursued with perseverance permits to discover details, which may force to reconsider premises of earlier theories. *'Experimental science owes its development to a great extent to the work of common people'* [10]. Such a research prepares the way for development of knowledge and acts as "dung" for "high" science. *'Gods do not unveil all the truth to the mortals but if we pursue the search we shall find it with time' (Xenophantes)*
Insignificant results	Nobody is able to judge the value of seemingly insignificant data because science happens at the borderland of the known. *'All theories and ideas should be retained because their day may come'* [11].

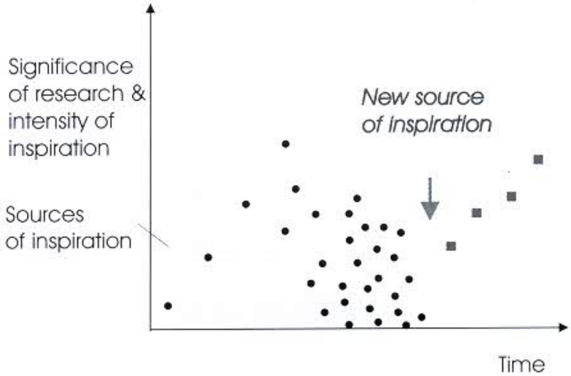

FIGURE 2 - Changes of significance of research in a given field with time. Legend: points correspond to successive publications; the intensity of inspiration is indicated in grey.

years ago. In order to increase the significance of the dominating 'in-between' research again a new impulse is needed. The impulse may be a discovery, a profound change of the system of ideas, a necessity and, finally, a cross-fertilisation by contact with other fields of science.

MATERIALS INSPIRED BY THE CONSTITUTION OF LIVING SYSTEMS

Research of an interdisciplinary kind, due to a collaboration with physicians and surgeons, is addressed below. Namely, research into materials inspired by the constitution of living systems. As mentioned in reference 1, solutions perfected by the natural evolution were always a source of suggestions and ideas for man. Among the recent examples are the imitation of insects limbs movements by the robot arms, imitation of the way earthworms move underground in developing machines for making tunnels, imitation of the bird's flight in designing improved aircraft, and many others. However, less examples can be found for materials mimicking living systems[14] although the constitution of these systems is such that they can perform their functions in an optimum way. As far as the mechanical functions are concerned this is due to a combination of low weight, high wear resistance, strength, flexibility, and fracture

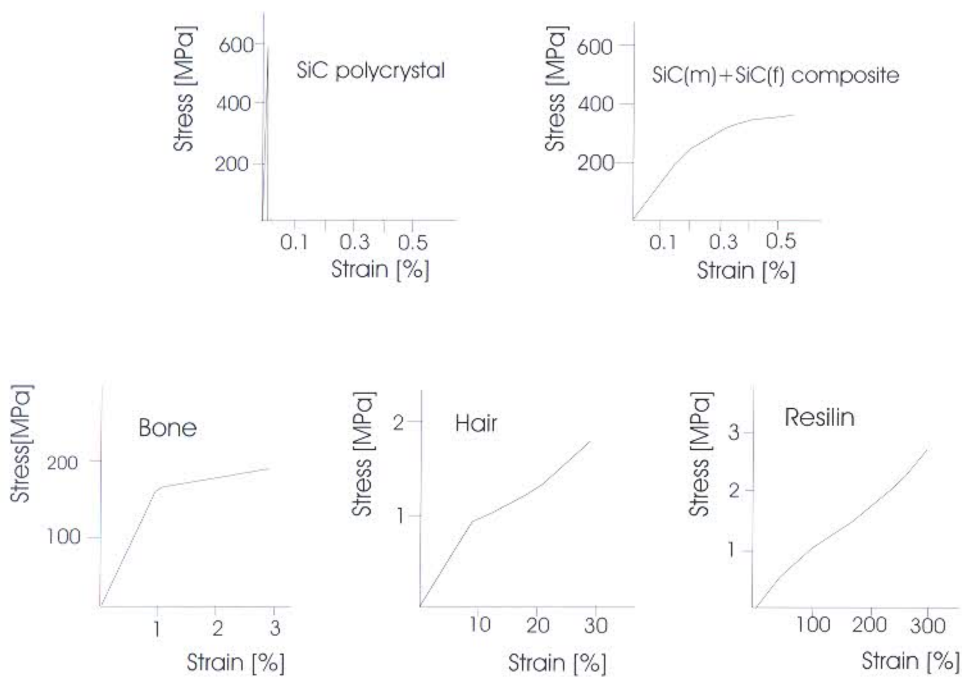

FIGURE 3 - Stress-strain curves for some man-made materials and organic systems.

toughness. The combination is ensured by the constitution of the living systems in form of: i. laminates of hard (inorganic) and soft (organic) tissue; ii. systems of interpenetrating fibres. Figure 3 shows the striking differences in the stress-strain curves of organic systems and man-made ceramic materials.

Ceramic materials are characterised by a low fracture toughness, K_{IC}, and a low reliability as indicated by a low Weibull modulus, *m* (Figure 4). Therefore, it is advantageous, especially here, to approach in some measure the properties of organic systems. High fracture toughness has been, indeed, observed in laminates[15,16] and fibre-reinforced materials[17,18,19,20], although a direct reference to living systems was only rarely made in this context, perhaps except for papers written by Aksay and his collaborators (see e.g. ref. 14).

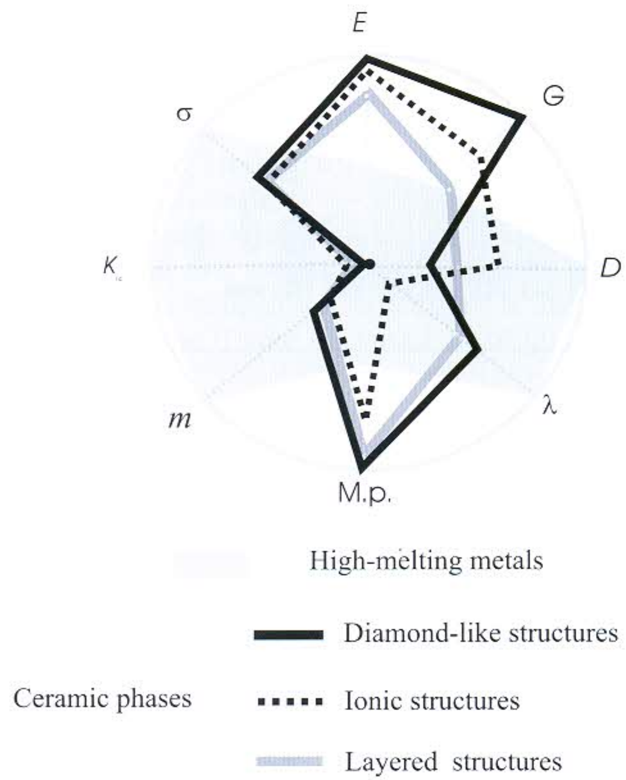

FIGURE 4 - Properties of ceramic phases and of high-melting metals (grey field). Legend: E – Young's modulus; G – shear modulus; D – density; λ – thermal conductivity; M.p. – melting point; m – Weibull modulus; K_{Ic} – fracture toughness; σ – tensile strength. The perimeter of the circular graph corresponds to the maximum value of a given property found among all materials compared; the lower values found with other materials are expressed in percentage of the maximum value.

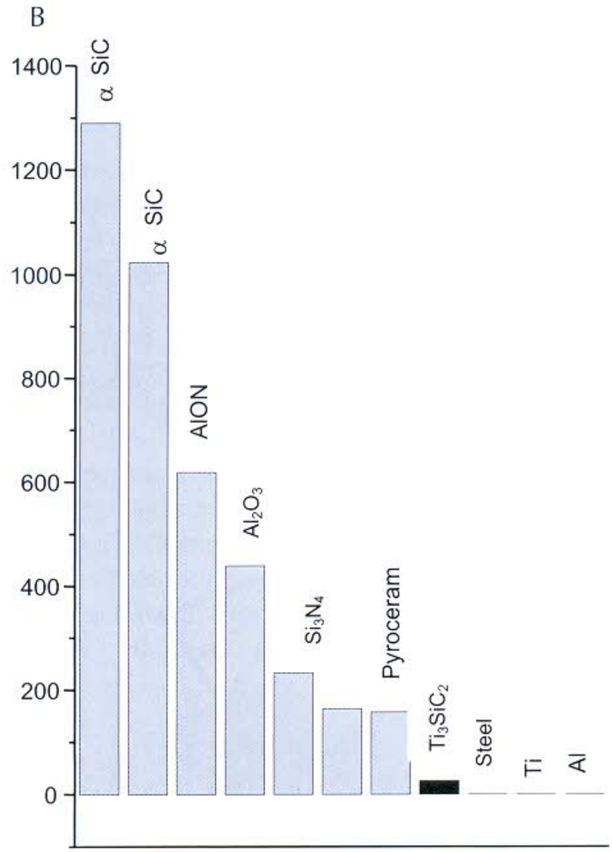

FIGURE 5 - The brittleness parameter, $B = H_{vc} E/K^2_{Ic}$ of some ceramic and metallic materials and of Ti_3SiC_2; after ref. 27. Legend: H_{vc} – Vickers hardness measured at the transition point from load dependent to lead independent values; E – Young's modulus. For definition of B see ref. 28.

Our research has been focused upon nanolaminates such as Ti_3SiC_2[21,22,23] and on graphite-like structures. Both have a hexagonal structure in which stiff layers of Ti-C octahedra and stiff packets of carbon atoms, respectively, are separated by silicon layers in the first case or linked by weak van der Waals forces in the second one. This facilitates shearing of the layers past each other. It has been possible to show that Ti_3SiC_2 deforms under load in pseudo- plastic way[24,25,26]. Properties of this refractory compound exhibit on the one hand a high workability and, on the other, a low brittleness. As shown in Figure 5 the brittleness index of Ti_3SiC_2 is lower than those of typical structural ceramics and it approaches a value characteristic for structural metals (Figure 5).

Nanolaminate-like structures of graphite-derived carbon fibres have inspired another research developments in which properties of laminated structures in the nanometer scale and properties of systems of interpenetrating fibres in the micrometer scale have been combined to succeed in higher strain at failure[29,30,31]. Positive effects of such a combination of a proper constitution in different dimensions are typical in living systems[14].

At the beginning of the research, more than twenty five years ago, some structures formed by carbon atoms, including the fullerenes, were not known yet. However, substantial modifications of properties had been achieved by changes in the molecular structure and the form of graphite - based materials. It was known at this time that the form of fibres decreases the number of defects and increases their mechanical strength. It remained, however, unknown how to alter the mechanical properties of the fibres for applications requiring a higher strain at fracture. The solution lay in tailoring their structure at the nanometer scale. The layers of carbon atoms which occur in the graphite structure are very stiff and strong due to high strength of the carbon - carbon bonds. Therefore, if packets of the graphite-like layers of carbon atoms are oriented approximately parallel to the fibre axis only low elastic strains are possible and high Young's moduli result. The elastic strain of the packets can, however, be high at an angle of 45-52 degrees to the plane of the layers because of an appreciable shear between the layers. Therefore, a production of fibres in such a way that the planes of the C-layers in the packets are not parallel to the fibre axis resulted in a higher strain at failure than with those of the better oriented type (Figure 6). Variations of fibres' properties brought

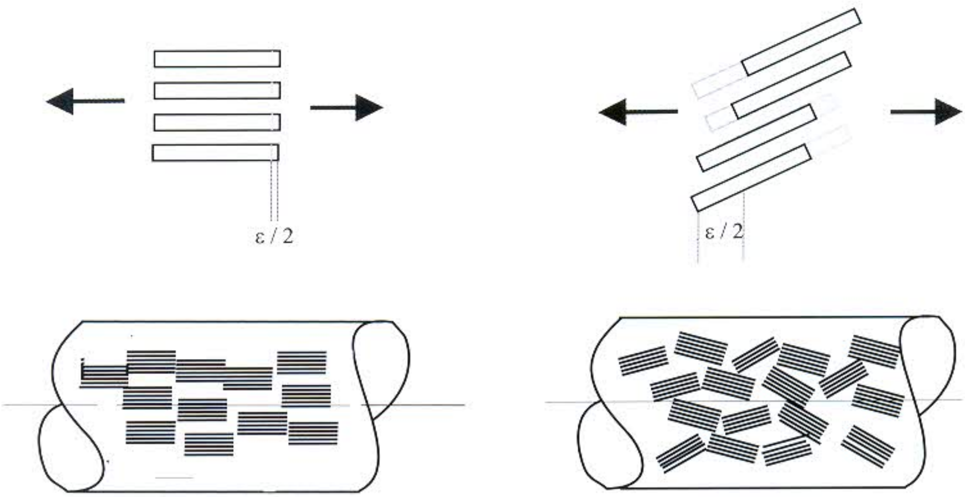

FIGURE 6 - The orientation of packets of carbon atom layers in two different types of carbon fibres and the behaviour of these fibre types under load (schematically).

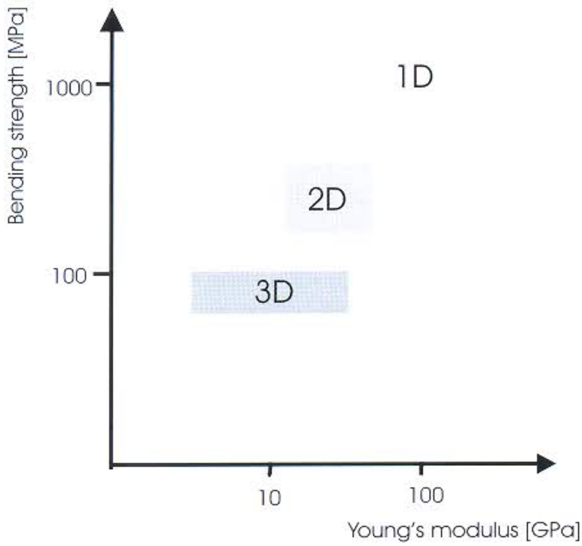

FIGURE 7 - Young's modulus vs. tensile strength of carbon-carbon composites. Legend: 1D – one-dimensional, 2D – two-dimensional; 3D – three-dimensional arrangement of carbon fibres in the carbon matrix; after [32].

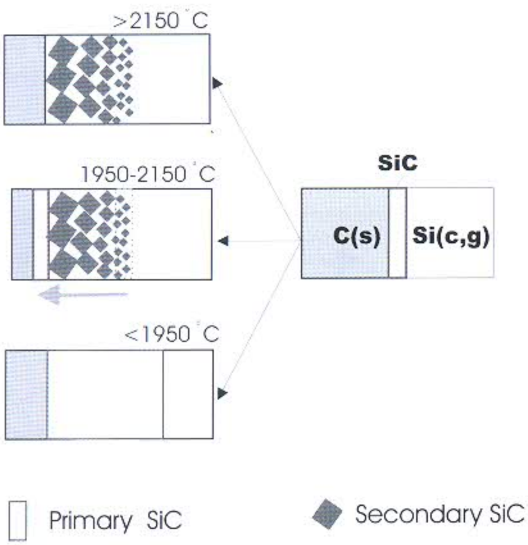

FIGURE 8 - The 'migrating thin reaction layer' mechanism which occurs in the reactive Si – C system at 1950 –2150 °C as compared with dissolution of carbon in liquid Si and growth of a thick SiC reaction layer after [33].

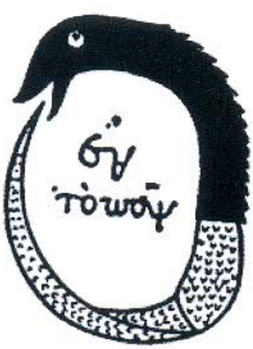

FIGURE 9 - The "ouroboros" serpent of ancient Egypt and Greece; quoted after [37].

about in this way have permitted tailoring of the properties of carbon fibres to given applications, especially to the ones in medicine where a high strain at failure is required.

Another important variation of the properties has been achieved by linking the effect of the laminate structure at the nanometer scale with the one of interpenetrating fibres at the micrometer scale. Namely, by introducing different types of carbon fibres arrangements in a carbon matrix. It is shown in Figure 7 that a change in the arrangement of the fibres brings about a one-order-of-magnitude difference in the strength and the Young's modulus of the resulting composite. This observation has enabled us to produce effective carbon stems of total hip prosthesis. Due to a different stiffness achieved in its different parts by different fibre arrangements it works in a way comparable to anatomical hip.

A by-product of the above research was the discovery of the mechanism of reaction of carbon fibres with silicon. The final product, secondary SiC, is formed here by precipitation from the supersaturated carbon solution in liquid silicon in the wake of a moving thin reaction layer constituted by primary SiC (Figure 8). This brings about a formation of pseudomorphoses of the carbon reactant by silicon carbide[33,34]. The mechanism has been utilised to transform the starting carbon fibres into SiC fibres[35] and, recently, by other authors to produce silicon carbide products which have the constitution of wood[36]. In this method wood is first transformed, by pyrolysis, to a carbonaceous residue which retains its original constitution. By reacting this residue with silicon a SiC material of the same constitution as wood is formed. The advantageous constitution of wood can be thus utilised by imparting to it the higher refractoriness of silicon carbide.

THE BOTTOM LINE

Research illustrated in the paper is but one example of developments due to a 'back-to-Nature' approach. This idea is well represented by the 'ouroboros' serpent of ancient Egypt and Greece (Figure 9) where the enclosed words "the all is one" refer to the Platonic idea of the unity of matter. Let this be the bottom line of the paper.

REFERENCES

1. G. Lanzavecchia, Materials and Society, in 'Role of Ceramics in a Self-sustaining Environment', R. Pampuch, K. Haberko (eds.), Techna, Monographs in Materials and Society vol. 4 , Faenza 1997, pp. 87-98.
2. F. Aldinger, Links between science and industry, *ibidem*, pp.103-118.
3. R. Roy, Keys to sucsessful materials synthesis, in S. Somiya, R.P.H. Chang,

M. Doyama, R. Roy (eds.), Materials Science and Engineering serving society, Elsevier Science, 1998, 2-5.
4. R.P. Feynman, The meaning of it all, Addison-Wesley-Longman Publ.Co., 1998.
5. A. Einstein, after M. Grabowski, The significant and insignificant in science (in Polish), Wyd. Rolewski, Torun, 1998.
6. P. Kapitsa, Experiment, Theory, Practice (in Russian), 2nd ed., Nauka, Moskva, 1977.
7. T. Kuhn, The Structure of Scientific Revolutions, (Polish edition), PWN, Warszawa, 1986.
8. G.W. Leibnitz (year 1668), quoted after K. Laisiepen, E. Lutterbeck, K-H. Meyer-Uhlenried, 'Grundlagen der praktischen Information und Dokumentation', Verl. Dokumentation, Munich-Berlin 1972.
9. K. Popper, The logic of scientific discovery (transl. from German), Hutchinson (1959).
10. J. Ortega y Gasset, Revolucion de las masas, Madrid , 1930.
11. P. Feyerabend, Killing the time (Polish edition), Znak Publ. Cracow, 1996.
12. J. Horgan, The end of science, Addison –Wesley-Longman Publ. Co. 1996.
13. I. Lakatos, Papers on philosophy of empirical sciences (Polish transl.), PWN, Warsaw, 1995.
14. I. Aksay, E. Baer, M. Sarikaya, D.A. Tirell (eds.), Hierarchically structured materials, Mat. Res. Symp. Proc., San Francisco Press. Inc., San Francisco, CA, 1993.
15. T. Ohji, Y. Shigegaki, N. Kondo, Y. Suzuki, Fracture toughness of multilayer silicon nitride with crack deflection, Mater. Letters, 40 (1999) 280.
16. C.J. Russo, M.P. Hermer, H.M. Chan, G.A. Miller, Design of laminated ceramic composite for improved strength and toughness, J. Am. Ceram. Soc. 75 (1992) 3386.
17. D.B. Marshall, A.G. Evans, Failure mechanisms in ceramic-fiber / ceramic-matrix composites, J. Am. Ceram. Soc. 68 (1985) 225.
18. B.N. Cox, D.B. Marshall, Concept for bridged cracks in fracture and fatigue, Acta Metallica Materials, 42 (1994) 341.
19. K.T. Faber, A.G. Evans, Crack deflection processes, Acta Metallica 31 (1983) 565, 577.
20. P.F. Becher, Microstuctural design of toughened ceramics, J. Am. Ceram. Soc. 74 (1991) 255.
21. R. Pampuch, J. Lis, L. Stobierski, M. Tymkiewicz, Solid combustion synthesis of Ti_3SiC_2, J. Europ. Ceram. Soc., 5 (1989) 283-287.
22. R. Pampuch, J. Lis, J. Piekarczyk, L. Stobierski, Ti_3SiC_2,- based materials produced by SHS and ceramic processing, J. Mater. Synthesis and Processing, 1 (1993) 93-99.
23. J. Morgiel, J. Lis, R. Pampuch, Microstructure of Ti_3SiC_2–based ceramic

materials, Mater. Lett. 27 (1996) 85-89.

24. R. Pampuch, J. Lis, Ti_3SiC_2 a pseudoplastic ceramic material in Ceramics, Charting the Future, P. Vincenzini ed., Techna, Faenza, 1995.
25. M.W. Barsoum, T. El-Raghy, Synthesis and characterisation of a remarkable ceramic: Ti_3SiC_2, J. Am. Ceram. Soc. 79 (1996) 1953-1956.
26. T. Okano, T. Tano, T. Iseki, Synthesis and mechanical properties of Ti_3SiC_2, ceramics, Trans. Met. Soc. Jpn., 14A (1993) 597-599.
27. R. Pampuch, Stuijts Memorial Lecture 1997: Ceramic science and technology facing changing paradigms, J. Europ. Ceram. Soc. 18 (1998) 993.
28. J.B. Quinn, G.D. Quinn, On the hardness and brittleness of ceramics, in: Key Engineering Materials, vols. 132-136, Trans Tech Publications, Uetikon-Zurich 1997, 1220.
29. R. Pampuch, S. Blazewicz, J. Chlopek, E. Balcerzyk, Technology of carbon fibres (in Russian), Obzor Polskoy Tekhniki, 4 (1988) 9.
30. R. Pampuch, S. Blazewicz, J. Chlopek, Carbon Fibres (in Polish), Acta Ceramica (Szklo i Ceramika) 7 (1981) 111.
31. R. Pampuch, S. Blazewicz, J. Chlopek, A. Górecki, W.M. Kus, New Carbon Materials in Technology and Medicine (in Polish), PWN, Warszawa, 1988.
32. J. Chlopek, Carbon-Carbon Composites, Elaboration and Application in Medicine (in Polish) Polish Academy of Sciences, Cracow, Papers of the Ceramic Commission, 52 (1997) 5.
33. R. Pampuch, J. Lis, L. Stobierski, Mechanism of heterogeneous reactions in the Si-C system under conditions of self-propagating combustion, w: Combustion and plasma synthesis of high-temperature materials, in Z.A. Munir, J.A. Holt (eds.), VCh Weinheim, New York, 1990, 226.
34. R. Pampuch, L. Stobierski, J. Lis, M. Raczka, Solid combustion synthesis of SiC, Mater. Res. Bull., 22, 1987, 1225.
35. R. Pampuch, E. Walasek, J. Bialoskórski, Reaction Between Carbon and Liquid Silicon at Elevated Temperatures, Ceramics Intern. 12 (1986) 99.
36. P. Greil, T. Lifka, A. Kandl, Cellular silicon carbide ceramics from wood, J. Europ. Ceram. Soc. 18 (1998) 1960.
37. J. Read, Chemistry in: James R. Newman (ed.) What is Science?, Washington Square Press, Inc. New York (1961).