Novel process for cellular materials with oriented structure

L. Tuchinskiy and R. Loutfy

Material and Electrochemical Research Corporation, Tucson, Arizona, USA

Abstract

A novel method for fabrication of metal and ceramic cellular materials with oriented structure (CMOS) is described. The method requires co-extrusion of a plasticized matrix powder and a removable filler, which creates microchannels after heat treatment. The microchannels create CMOS with anisotropy unless the channel orientation is randomized. The method may be used for production of metal, ceramic, and intermetallic isotropic and anisotropic CMOS that have porosity in the range 0 to 95%. The materials produced by this method have two kinds of porosity: (1) - channel porosity (ratio of the microchannel volume to the volume of all material); (2) – interchannel porosity (ratio of the volume of the pores in the interchannel walls to the volume of these walls).

The effect of porosity on the elastic moduli and tensile strength of CMOS with unidirectional porous structure was investigated. The potential applications of materials with anisotropic open porous structure are discussed.

1. Technology

The quest for weight reduction of automobiles, aircraft, building components, etc. has attracted considerable interest to low density metallic foams. Many methods for fabrication of these foams have been developed [1]. However, there are technological problems related to the control of structure and properties of the foams, which remain to be solved. The vast majority of existing techniques do not allow rigid control of shape, size and distribution of the pores. That brings about a wide scatter in mechanical and other characteristics of materials and components. The existing techniques are mostly designed for production of foams from a limited number of materials.

This work introduces a new fabrication method for *Cellular Materials with Oriented Structure* (CMOS), which complies with many of these requirements. The method [2] was successfully tested at Materials and Electrochemical Research Corporation (MER). The technology combines unique materials and processing technique and allows production of a variety of profiles, sheets, rods, tubes, and near-net-shape products. Properties of these products may be easily tailored for specific applications.

The technological process for the fabrication of the CMOS, as illustrated in Figure 1, consists of the following three steps. In step 1 bimaterial rods consisting of a shell and a core are produced. The shell comprises a mixture of a metal or ceramic powder with a polymer binder, such as is used for powder injection molding. The core comprises a mixture of the binder

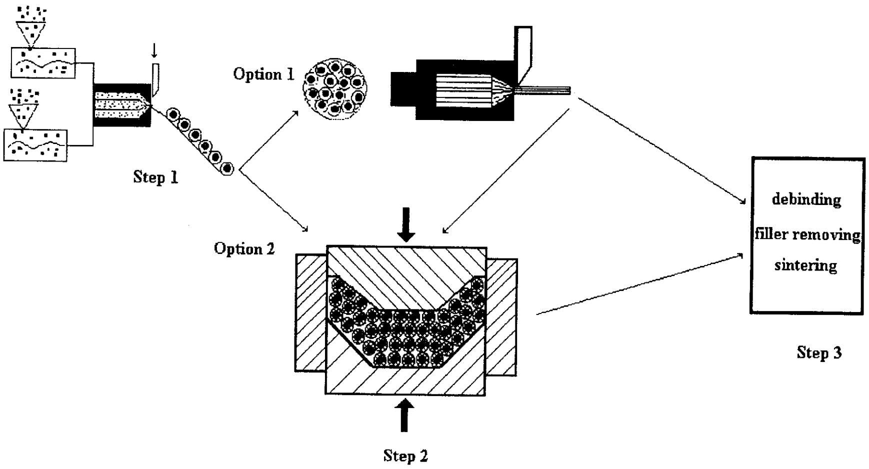


Figure 1. Fabrication steps for CMOS

with a channel forming filler, which can be removed afterwards by evaporation, melting, dissolution, etc. Two options for the step 2 may be used depending on the shape and dimensions desired for the final product. The first option includes a re-extrusion of the bundle of rods produced in step 1 through an extrusion die. As a result, a green composite rod of predetermined cross-section is produced.

The second option for step 2 calls for die compaction of the bimaterial rods produced in step 1. That makes possible fabrication of complex shape products. Plasticity of the green bodies may be controlled by temperature and by mixture composition; they can be subjected to any plastic deformation. In both options green bodies that comprise a powder + binder matrix and filler + binder fibers are obtained. The produced green bodies are debound and sintered (step 3). The filler fibers burn out during or after debinding with the resulting formation of the channels in the CMOS.

A variety of CMOS with a density and anisotropy tailored to the desired end use can be produced by this technique. The extrusion ratio and number of extrusion steps control the channel diameter, which may be accurately pre-assigned in the range from micron to millimeter sizes.

This process may be applied to virtually any materials – metals, alloys, intermetallics, ceramics and composites. It allows close control of size, shape, distribution, and number of channel pores. Materials and near-net-shape components with any pre-assigned relative density may be obtained. Structure, mechanical, and physical characteristics of the material may be adjusted for specific components. The process may be easily automated and adapted to industrial production. It does not require complicated or powerfull equipment.

Materials produced by the proposed technique can be used as elements of light structural panels, energy absorbers, high efficiency filters, heat-exchangers, catalyst carriers, high temperature insulation, transpiration cooling systems, gas and liquid heaters, vents, etc.

2. Elastic constants of unidirectional CMOS

As already noted, the proposed method is suitable for production of CMOS with any anisotropy. Here we consider oriented CMOS, which have the microchannels oriented in one direction and are classified as transversely isotropic materials. The plane of isotropy is the *YZ*-plane; the *X*-axis coincides in direction with the axes of the channels. The micrographs of unidirectional CMOS are shown in Fig.2.

The CMOS may be considered as composites reinforced with "void fibers". That means that the equations used for calculation of the elastic constants of fiber-reinforced composites may be modified for the CMOS assuming that the elastic constants of the "void fibers" are equal to zero. In this way we transform the known relations between the elastic constants of the unidirectional fiber reinforced composites and volume loading of the fibers [3, 4] in the following equations for the unidirectional CMOS:

$$E_x = E_m\,(1-\Pi) \tag{1}$$

$$\nu_{xy} = \nu_m \tag{2}$$

$$E_y = E_z = E_m\,(1-\Pi)\,/\,[\nu_m+(1-\nu_m^2)\,(1+2\Pi)] \tag{3}$$

$$\nu_{zx} = \nu_{yz} = 1-\frac{E_y}{E_x}\,[1-2\nu_m^2-(1-\Pi)\,(1-2\nu_m)\,(1+\nu_m)] \tag{4}$$

Here E_x, E_y and E_z are the normal elasticity moduli in the *X*, *Y* and *Z* directions, $\nu_{xy}, \nu_{yz}, \nu_{zx}$ are the Poisson's ratios determining the linear relative strain in the direction indicated by the second index upon action of a normal stress in the direction indicated by the first index. For the unidirectional CMOS:

$E_y = E_z$, $E_x\,\nu_{yx} = E_y\,\nu_{xy}$; $E_y\nu_{zy} = E_z\nu_{yz}$; $E_z\nu_{xz} = E_x\,\nu_{zx}$;

$\nu_{zx} = \nu_{yx}$; $\nu_{xy} = \nu_{xz}$; $\nu_{yz} = \nu_{zy}$

The equations (1) –(4) allow calculation of the elastic constants for the CMOS in a wide range for the channel porosity (Fig. 3). They give the correct values for the extreme cases:

$E_x=E_y=E_z=E_m$ for $\Pi=0$; $\nu_{xy}=\nu_{xz}=\nu_{yz}=\nu_m$ for $\Pi=0$; $E_x=E_y=E_z=0$ for $\Pi=1$

The equation (1) reflects the rule of mixtures, which is well recommended in practice. Eq. (3) gives a dependence of the transverse modulus upon the channel porosity that is close to the equation obtained from mechanical analysis of honeycombs made of square cells. It is assumed that for certain directions of loading elastic deformation of these honeycombs occurs by the axial extension or compression of the cell walls. If the length of the square cell is *l* and the wall thickness is *t*, the elastic moduli E_y and E_z may be calculated [5] as:

$$E_y = E_z = E_m\,(t/l) = E_m\,(1-\Pi^{1/2}) \tag{5}$$

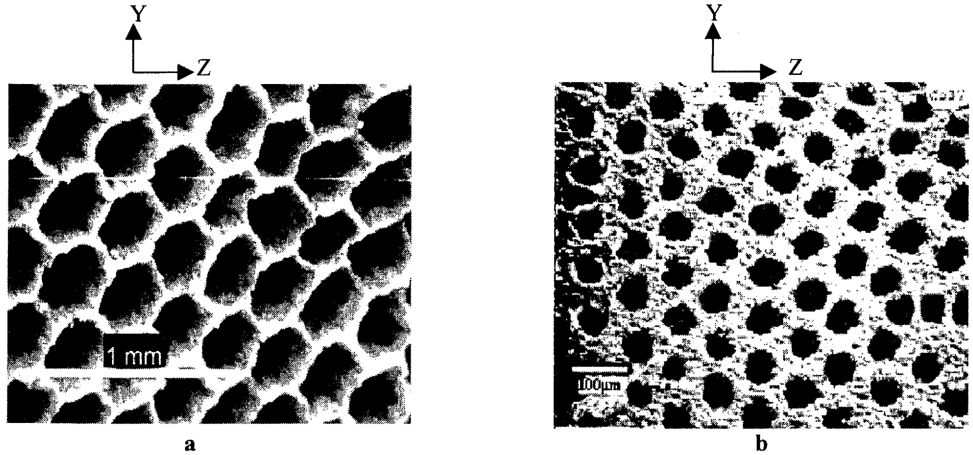
As may be seen from Fig.3, these relations correspond to the experimental data in a wide range of porosity.

Equations (1) –(4) determine the dependence of the elastic constants of the unidirectional CMOS on their channel porosity Π defined as the ratio of the volume occupied by the channels to the entire volume of the CMOS. The CMOS may additionally have an interchannel porosity Θ

(the porosity of the matrix or the porosity of the interchannel walls), which is equal to the ratio of the volume of the pores within the interchannel walls to the volume of the walls themselves. The effect of the interchannel porosity Θ on the elastic constants of the CMOS can be taken into account, if E_m and ν_m in (2)-(5) are expressed as dependant on Θ. For example, Skorokhod's equations may be used [6]:

$$E_m = E_s(1-\Theta)^2; \qquad \nu_m = (2-3\Theta)(4-3\Theta), \qquad (6)$$

where E_s is the Young's modulus of the solid matrix.



a

b

Fig. 2 Micrographs of CMOS: (a) - 86% porosity iron; (b) - 37% porosity alumina

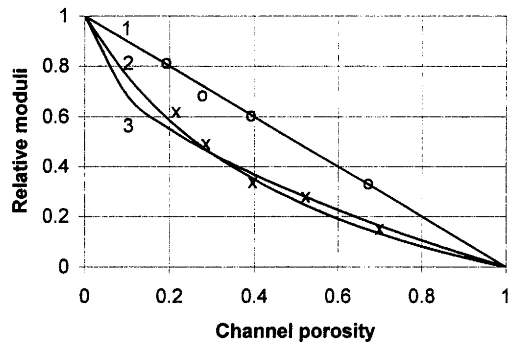


Fig. 3 Relative longitudinal $E_x^* = E_x/E_m$ (1) and transverse $E_y^* = E_y/E_m$ (2 and 3) **Young's moduli for CMOS vs. channel porosity Π**

1- calculation by eq. (1); 2 - by (3); 3 - by (5);

the points indicate the experimental results for iron CMOS: o - E_x^*, x - E_y^*

3. Tensile strength of the unidirectional CMOS

The results of tensile strength tests for unidirectional CMOS in the longitudinal and transverse directions are shown in Table 1. The samples were made of carbonyl iron. After extrusion, consolidation, debinding and filler removal, the samples were sintered in H_2 at 1250^0C forlhr. After sintering, the average diameter of the channels was ~150 μm. Unidirectional CMOS with channel porosity of 0, 20, 28, 40, 51 and 69% were produced and tested. The porosity of the interchannel walls was 10 –12%. Specimens 55x5x3mm were cut in such a way that channels were oriented along the length of the specimens for determination of longitudinal tensile strength σ_x, and perpendicular to the length for transverse strength σ_y.

As Fig. 4 suggests, the Π- dependence of the longitudinal tensile strength adheres to the rule of mixtures:

$$\sigma_x=\sigma_m\,(1-\Pi) \tag{7}$$

The experimental data for the transverse UTS σ_y may be described by the equation

$$\sigma_y=\sigma_m\,(1-\Pi^{1/2}) \tag{8}$$

As indicated by Table 1, the longitudinal UTS are 1.4 –2 times higher than transverse ones. The ratio (σ_x/σ_y) rises as the channel porosity increases.

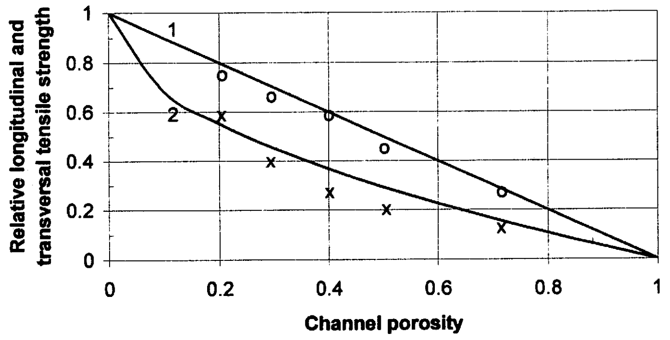


Fig.4. Relative longitudinal $\sigma_x^*=\sigma_x/\sigma_m$ (1) and transverse $\sigma_y^*=\sigma_y/\sigma_m$ (2) relative tensile strength for unidirectional iron CMOS vs. channel porosity Π

1 - calculation by eq. (7); 2 - by (8); the points indicate the experimental results

Table 1. Young's moduli and UTS of the unidirectional iron CMOS

Channel porosity *П*, %	Orientation of the channels	Young's modulus, GPa	Relative Young's modulus	Ultimate tensile strength, MPa	Relative UTS
0		143	1	153	1
20	Longitudinal	112	0.8	120	0.78
20	Transverse	92	0.64	86	0.56
28	Longitudinal	104	0.72	100	0.65
28	Transverse	77	0.53	58	0.38
40	Longitudinal	86	0.6	92	0.60
40	Transverse	53	0.37	50	0.33
51	Longitudinal	70	0.49	74	0.48
51	Transverse	38	0.26	36	0.24
69	Longitudinal	47	0.33	44	0.30
69	Transverse	26	0.18	22	0.15

4. Potential Applications

The CMOS produced by the proposed technique can be used as structural materials. Structural application of the traditional porous materials is limited by their poor mechanical performance. Traditional powder metallurgy methods produce materials with irregular shape and distribution of pores in the matrix. The pores serve as stress concentrators, thus causing a sharp degradation in strength and ductility, especially at high porosity. Therefore, the common porous materials practically are not used for structural purposes. However, the situation is changed in the case of the CMOS.

Since the walls between the channels may be porous, the perspective for creation of biporous filter appears. Such a type of filters may be used widely for cleaning Diesel engine exhaust gases, containing soot, and for other purposes.

The large surface of the CMOS opens wide prospects for their application in heat exchangers and channeled turbine blades. The method allows production of the blades with cooling channels oriented in the required directions. The CMOS may also be used as catalyst carriers, in particular in cars and chemical reactors. The method enables the production of highly porous structures with enhanced surface, smaller channels and thinner interchannel walls compared to known techniques.

The CMOS are prospective for biomedical applications, particularly as implants. The advantage of the polycapillary structures in comparison with conventional porous ones is a possibility to set the range of pore (channel) diameter and their distribution that provides the optimum resistance to the external force imparted to the implant. It is known, for example, that the 100 -1000 μm channels are preferable for penetration with a bone tissue; the 40-50 μm channels - with a fibrous tissue. Use of the implants with the different channels allows the combination of the hard and soft anchoring effects and accommodation of the implants to various cases of disease.

The CMOS may be used as elements of batteries, fuel cells, thermal insulation, burners, flame arresters, energy absorbers, systems for focusing X-ray and neutron radiation, etc.

New composite materials can be also developed on their base. For example, filling of the CMOS with lubricants makes it possible to create unique self-lubricating composites. The tribological test of the silicon nitride CMOS showed clearly that dramatic friction reduction with minimal loss of mechanical strength could be achieved through the filling of the channels in the silicon nitride with lubricants. Pure silicon nitride run against 52100 steel under ambient conditions has a friction coefficient of approximately 0.6 – 0.7, while silicon nitride with the channels fully filled with Krytox 226 grease has a friction coefficient less than 0.2, and in the best circumstance as low as 0.08.

It is pertinent to note that the volume fraction of the lubricant (i.e. of the channels) in the tested samples was 7%. Even with such small lubricant loading, low values of the friction coefficient have been reached. Traditional powder metallurgy methods do not allow fabrication of self-lubricating materials with such low porosity. If the porosity of a common powder material is 7%, practically all its pores are closed and they cannot be infiltrated. That is why traditional self-lubricating powder materials have porosity (and correspondingly lubricant volume fraction) in the range 20% or more. However, such high values of the porosity cause a dramatic reduction of mechanical characteristics and wear resistance.

Not only tribological, but also many other composites can be developed using the CMOS. For example, infiltration of the CMOS with low melt metal alloys or resins makes possible creation of a variety of composites with properties that are tailored to desired end use.

References

1. J. Banhart and J. Baumeister, "Production Methods for Metallic Foams", Porous and Cellular Materials For Structural Applications: symposium held April 13-15, 1998, San Francisco, California, U.S.A. / editors D. Shwartz, D. Shih, A. Evans and H. Wadley, pp.121-132
2. L. Tuchinskiy, "Multi-Channel Structures and Process for Making Such Structures", U.S. Patent 5,774,779.
3. L. Tuchinskiy and N. Kalimova, "Elastic Constants of Transversely Isotropically Porous Materials", *Powder Metallurgy and Metal Ceramics*, Vol. 33, No 5-6, 1994, p. 314 -318.
4. Composite Materials: Handbook [in Russian], edited by D. Karpinos, Naukova Dumka, Kiev, 1985
5. L. Gibson, M. Ashby, "Cellular solids: structure & properties", 2nd ed., Cambridge University Press, p.159, 1997
6. V. Skorochod, "Rheological Principles of Sintering Theory" [in Russian], Naukova Dumka, Kiev, 1972