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Research Article

Analysis of the Formation of Material Structures with Axial Symmetry by Strong Electric Field

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Abstract: To solve various technical problems, technologies are needed that allow creating new types of functionally graded anisotropic composite materials with directional properties. The formation of such structures based on additive technologies continues to retain its relevance every day. In this context, this paper proposes a new approach to creating a structure with axial symmetry and electrical or mechanical properties. In this case, the possibility of controlling the movement and direction of particles using strong electric fields is used. Taking into account the presence of a strong electric field in a condensed medium located in the interelectrode space, a mathematical model for the formation of a structure with axial symmetry is proposed, based on the analysis of the forces acting on the particles in the medium. For this model, as a result of some simplifications, analytical solutions were found. According to the results obtained, it is believed that a strong electric field also allows forming certain structures of materials and products with certain properties from microparticles, similar to polymer chemistry.

Keywords: *Gravity force, Archimedes force, Environment resistance, Nanosized particle, Bouguer–Lambert–Beer law, Strong electric field*

Güçlü Elektrik Alanı ile Eksenel Simetriye Sahip Malzeme Yapılarının Oluşumunun Analizi

Öz. Çeşitli teknik sorunları çözmek için, yönlü özelliklere sahip yeni türde işlevsel olarak derecelendirilmiş anizotropik kompozit malzemeler oluşturmayı mümkün kılan teknolojilere ihtiyaç duyulmaktadıt. Additive (eklemeli) teknolojilere dayalı bu tür yapıların oluşumu her geçen gün güncelliğini korumaya devam ediyor. Bu bağlamda, bu çalışmada, eksenel simetriye ve elektriksel veya mekanik özelliklere sahip bir yapı oluşturmaya yönelik yeni bir yaklaşım önerilmektedir. Bu durumda, parçacıkların hareketini ve yönünü kövvetli elektrik alanları ile kontrol etme özelliği kullanılmaktadır. Elektrotlar arası boşlukta bulunan yoğunlaştırılmış bir ortamda kuvvetli bir elektrik alanın varlığı da dikkate alınarak, ortamdaki parçacıklar üzerine etki eden kuvvetlerin analizine dayanarak, eksenel simetriye sahip bir yapının oluşumunun matematiksel bir modeli önerilmiştir. Bu model için bir takım basitleştirmeler sonucunda analitik çözümler bulunmuştur. Elde edilen sonuçlara göre, kuvvetlı elektrik alanının da, polimer kimyasına benzer bir şekilde mikropartiküllerden belirli özelliklere sahip bazı malzeme ve ürün yapılarının oluşumuna olanak sağladığı düşünülmektedir.

Anahtar kelimeler: *Yerçekimi kuvveti, Arşimet kuvveti, Çevre direnci, Nano boyutlu parçacık, Bouguer–Lambert–Beer yasası, Kuvvetli elektrik alanı*

1. Introduction

To solve various technical problems, technologies are needed that make it possible to create anisotropic materials with properties specified as to directions.

At present, these properties are possessed by composite materials, the creation of which uses mechanically aligned

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structures. An example of such structures are composites made by gluing (sintering) fibers or woven materials.

The initial threads, for mechanically built structures, have a natural thickness limit, which is tens of micrometers. Reducing the thickness of the threads leads to a sharp increase in the cost of the process and deterioration in the degree of orderliness of structures.

At the same time, it is clear that the smaller the size of the aligned particles and the higher the degree of order, the better the properties of the materials.

In this regard, it seems relevant to develop methods free from these shortcomings for creating materials with electrical, magnetic, or mechanical properties specified as to directions.

One of the possible ways to solve this problem is to use the control of the motion and orientation of particles by strong electric fields.

The processes of directional motion, orientation, stretching and sedimentation of particles under the action of Coulomb forces are quite effective for micro and nanoparticles [1-11].

The behavior of particles under the action of an electric field in gases has been studied in sufficient detail, which led to the creation of a number of industrial technologies [3-5].

At the same time, a significant part of modern materials is created using various kinds of chemical reactions initially in liquid or powder medium.

2. Statement of the problem

The use of controlling the movement and orientation of particles by strong electric fields, similar to polymer chemistry, creates materials with predetermined properties.

3. Mathematical Model of Formation of Structure with Axial Symmetry

In condensed media, the particles in the interelectrode gap are affected by the following main forces [3, 4, 11,12].

- gravity $\left(\vec{F}_g = m\vec{g}\right)$,

- the action of the electric field on the charge of the particle $\left(\vec{F}_q = (Q_+ - Q_-)\vec{E}\right)$,

-action on the electric dipole moment $\left(\vec{F}_{dipol} = \frac{Ql}{|E|}\nabla E^2\right)$,

- environment resistance $\left(\vec{F}_D = -6\pi\mu R\vec{v}\right)$,

- Archimedes $\left(\vec{F}_A = Sl\left(\rho_m - \rho_p\right)\vec{v}\right)$,

here $g = 9.81\ \frac{m}{s^2}$ is the free fall acceleration, Q_+, Q_-, are positive and negative charges on the particle, respectively, $\vec{E}$- is the electric field strength, $Q = \frac{\varepsilon_r - 1}{\varepsilon_r + 2}\varepsilon_0 SE$ -is the induced charge, l -is the particle length, S - is the surface area of particle, ε_0 and ε_r are the permittivity of free space and relative permittivities, η- is the viscosity of the medium, R- is the transverse particle size, ρ_m and ρ_p are the density of the medium and matter of the particle. With steady motion, the particles move uniformly, i.e. the sum of the forces is zero:

$$\vec{F}_g + \vec{F}_q + \vec{F}_{dipol} + \vec{F}_D + \vec{F}_A = 0 \tag{1}$$

Whence, taking into account the expressions for the forces, we obtain:

$$m\vec{g} + (Q_+ - Q_-)\vec{E} + \frac{Ql}{|E|}\nabla E^2 - 6\pi\eta R\vec{v} +$$

$$Sl\left(\rho_m - \rho_p\right)\vec{v} = 0 \tag{2}$$

When the electric field is oriented along the force of gravity, the speed of its directed movement will be:

$$v \approx \frac{1}{6\pi\eta R}\left[mg + (Q_+ - Q_-)E + \left(\rho_m - \rho_p\right)gSl\right] +$$

$$\frac{lR}{3\eta}\varepsilon_0 E\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\right) grad|E| \tag{3}$$

In a uniform electric field, the force acting on the electric dipole moment after the particle rotates along the field turns to zero, therefore:

$$v \approx \frac{1}{6\pi\eta R}\left[mg + (Q_+ - Q_-)E + \left(\rho_m - \rho_p\right)gSl\right] \tag{4}$$

Taking into account the fact that the particle mass $m = \rho_p\ Sl$ and its cross-sectional area $S\ \approx \pi R^2$, from (4) we obtain:

$$v \approx \frac{1}{6\pi\eta R}\left[g\rho_p\ Sl\quad + (Q_+ - Q_-)E + \left(\rho_m - \rho_p\right)gSl\right] =$$

$$\frac{1}{6\pi\eta R}\left[gm_m + (Q_+ - Q_-)E\right] \tag{5}$$

where $m_m = \rho_m\ Sl$ is the mass of the medium displaced by the body. It can be seen from expression (5) that the drift velocity is inversely proportional to η and R.

In order for the force acting on the particle to become much greater than the Archimedes force, the particle must acquire a charge $\gg Q_p = \frac{mg}{E}$, which for $\rho_m - \rho_p = 5\cdot 10^3\ \frac{kg}{m^3}$, $S = 10^{-12}\ m^2$, $l = 10^{-5}\ m$ $(M = 5\cdot 10^{-14}\ kg)$ at $E = 10^6\ \frac{V}{m}$ is $Q_p = \frac{mg}{E} = \frac{5\cdot 10^{-14}\ \times 9.81}{10^6} \approx 5\cdot 10^{-19}\ C$.

By choosing $Q = 5\cdot 10^{-8}\ C$ and the filling factor of the medium $k = 0.1$, we obtain that the specific volume charge in the medium is: $Q_m = \frac{Q}{Sl}\cdot k = 5\cdot 10^{-2}\ \frac{C}{m^3}$

For a sample with a size of $1\times 1\times 1\ cm^3$, the required charge will be $Q =\ 5\times 10^{-8}\ C$.

Such a charge is provided by a current with a density of $10^{-7}\ A\ /\ cm^2$ in a time of 0.5 seconds. Taking into account the filling factor of the medium $k\ =\ 0.1$, the time of current flow until the particles are charged will be 5 ... 10 seconds.

4. Results and Discussion

Until recently, the use of shortwave radiation in industrial technologies has been limited by the low capabilities of emitters. Modern LEDs and semiconductor lasers make it possible to obtain intense ultraviolet radiation in the wavelength range up to $200\ nm$.

Source of ionizing radiation intensity I with photon energy ε_f provides the charge density in the conduction band equal to:

$$n = \frac{\gamma I}{\varepsilon_f}\tau \tag{6}$$

where γ - is the probability of an electron being ejected by a photon into the conduction band, τ − is the lifetime of charges in the conduction band. In this case, the current density j will be:

$$j = n\mu Ee = \frac{\gamma I}{\varepsilon_f}\tau\mu Ee \quad (7)$$

where μ- is the mobility of charge carriers, $e = 1.6 \times 10^{-19}\ C$ is the electron charge.

From (7) we find the required intensity:

$$I = \frac{j\varepsilon_f}{\gamma e\mu\tau E} \quad (8)$$

For estimates, we will assume [3, 10, 14]: $j = 10^{-7}\ A/cm^2$, $\varepsilon_f = 5\ eV$, $\gamma = 0.01$,

$\tau = 10^{-8}\ s$, $\mu = 0.1\ cm^2/Vs$, $E = 10^4\ V/cm$, which gives:

$$I = \frac{10^{-7}\cdot 5\cdot 1.6\cdot 10^{-19}}{0.01\cdot 10^4\cdot 0.1\cdot 10^{-8}\cdot 1.6\cdot 10^{-9}} = 5\ \frac{W}{cm^2} \quad (9)$$

The resulting value is quite realizable using modern LEDs. Let's outline the main steps necessary for the implementation of the proposed technology on the example of the formation of a structure with axial symmetry. Suppose you need a cylindrical sample material with stiffness increasing in the axial direction along the radius.

In other words, the rigidity of the material in the axial direction near the axis is significantly less than near its boundary. To do this, we choose a filler in the form of rigid elongated micro or nanosized particles and place them in a compound with low conductivity.

The technology of mixing and degassing the mixture will not be considered here.

Let us present the main steps of developing the technology of the process. After preparing the mixture, we measure its transmission spectrum.

In order for the radiation penetration depth to be optimal, theoretical calculations of the radiation penetration depth into the sample were made using the Bouguer–Lambert–Beer law, which is responsible for the qualitative part of the spectrophotometric analysis, which states that the intensity of radiation passing through the medium decreases exponentially with distance [13]:

$$I(z) = I_0 exp(-\alpha \cdot d) \quad (10)$$

where I_0 is the initial intensity of incident radiation; $I(z)$ is the radiation intensity at depth z; α is the absorption coefficient; z is the radiation penetration depth, [cm]; d is the width of the absorbing layer.

Let us choose the radiation wavelength such that the radiation path length in the mixture is less than the sample radius. Let's choose the type of emitter according to the wavelength.

Let's make a mold from a segment of a quartz tube, fill it with a mixture. We will place it in a flat inter electrode gap. Let us place the emitters so that the surface of the sample is illuminated fairly uniformly (see fig.1).

Apply voltage to the gap and turn on the emitters. At the same time, the filler particles will acquire a charge, line up like iron filings in a magnetic field, and begin to move along the electric field. A schematic illustration of the formation of a structure with axial symmetry is shown in Fig. 2.

In the inner part of the sample, the radiation intensity is low and the effect of the field on the particles is much weaker. To prevent the deposition of particles, after they line up, the voltage from the gap must be removed.

During the curing of the compound, the alignment procedure must be repeated using voltage pulses of alternating polarity.

After curing the compound, the particles in the outer layers of the sample will be oriented strictly parallel to the axis, and as the axis is approached, the proportion of oriented particles will decrease, as will the rigidity in the axial direction.

When sufficiently transparent and liquid components are used, the displacement of particles to the outer part of the sample is possible due to the radial repulsion of like charges.

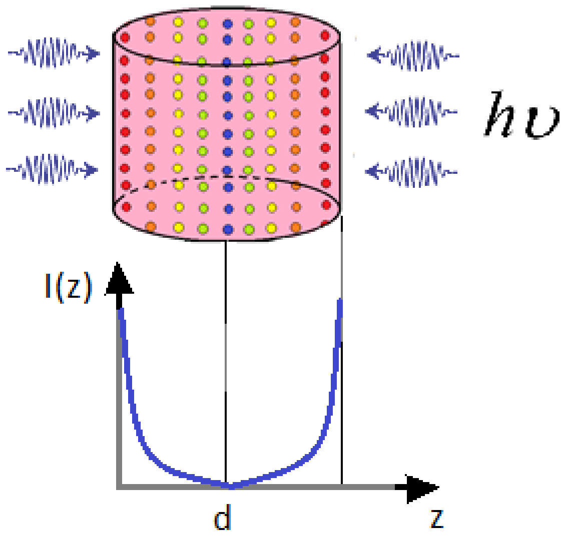

Figure 1. *Schematic illustration for determining the path length of radiation in a mixture.*

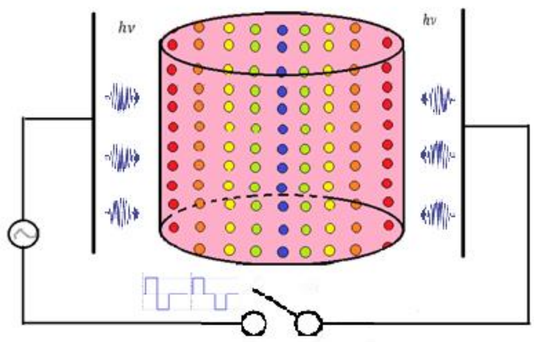

Figure 2. *Schematic illustration of the formation of a structure with axial symmetry*

5. Conclusion

In the case under consideration, the formation of materials with axial symmetry in a strong electric field can be interpreted as percolation theory, i.e. regular movement in a random environment. Note that from a mathematician's point of view, percolation theory should be classified as probability theory on graphs. From a physicist's point of view, percolation is a geometric phase transition. From a practitioner's point of view, it is a simple but powerful tool that allows one to easily solve a wide variety of life problems.

Based on the analysis of the task set, this study shows that, similar to polymer chemistry, which constructs molecular structures with specified properties, an electric field is also capable of constructing certain structures of materials and products from micro particles. It is believed that the current level of development of the element base and high-voltage technology allows us to move on to the practical implementation of such technologies.

Author Contribution

Data curation – Gülizar Alisoy (GA), Hasan Demir (HD), Hafiz Alisoy (HA); Formal analysis – (HA); investigation – (GA, HD); Experimental Performance –(HD, HA); Data Collection – (GA,HD);, Processing – (HA); Literature review – (GA, HD); Writing – (GA, HD); review and editing – (HA)

Declaration of Competing Interest

The authors declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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