PHILOSOPHICAL TRANSACTIONS A

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Introduction

Cite this article: Alexandrov DV, Zubarev AY. 2020 Patterns in soft and biological matters. *Phil. Trans. R. Soc. A* **378**: 20200002.
http://dx.doi.org/10.1098/rsta.2020.0002

Accepted: 15 January 2020

One contribution of 18 to a theme issue 'Patterns in soft and biological matters'.

Subject Areas:
materials science, mathematical modelling, biophysics, chemical physics, microsystems, statistical physics

Keywords:
patterns, heterogeneous materials, metastable and non-equilibrium states, soft matter, phase transformations, biophysical systems

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Patterns in soft and biological matters

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The issue is devoted to theoretical, computer and experimental studies of internal heterogeneous patterns, their morphology and evolution in various soft physical systems—organic and inorganic materials (e.g. alloys, polymers, cell cultures, biological tissues as well as metastable and composite materials). The importance of these studies is determined by the significant role of internal structures on the macroscopic properties and behaviour of natural and manufactured tissues and materials. Modern methods of computer modelling, statistical physics, heat and mass transfer, statistical hydrodynamics, nonlinear dynamics and experimental methods are presented and discussed. Non-equilibrium patterns which appear during macroscopic transport and hydrodynamic flow, chemical reactions, external physical fields (magnetic, electrical, thermal and hydrodynamic) and the impact of external noise on pattern evolution are the foci of this issue. Special attention is paid to pattern formation in biological systems (such as drug transport, hydrodynamic patterns in blood and pattern dynamics in protein and insulin crystals) and to the development of a scientific background for progressive methods of cancer and insult therapy (magnetic hyperthermia for cancer therapy; magnetically induced drug delivery in thrombosed blood vessels). The present issue includes works on pattern growth and their evolution in systems with complex internal structures, including stochastic dynamics, and the influence of internal structures on the external static, dynamic magnetic and mechanical properties of these systems.

This article is part of the theme issue 'Patterns in soft and biological matters'.

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1. Introduction

Soft complex systems and materials (patterned media, composites, biological tissues and cell cultures) attract a considerable amount of interest from researchers, medics and engineers because they are widespread in nature and actively used in progressive high industrial and biomedical technologies. The evolution and morphology of internal patterns, their effect on the physical properties and behaviour of these systems, and their nonlinear feedbacks on static and dynamic external fields in organic and inorganic soft matters of various physical natures represent the new developments of the present issue. The opportunity to control structure evolution and morphology with the help of external physical fields, temperature and composition gradients opens up new opportunities to create materials with new properties and behaviours. Note that internal structures in soft systems have different physical natures—they can be formed as a result of the solidification of liquids and melts, the self-organization of biological cell cultures, by particles embedded in polymer and other soft materials, hydrodynamic patterns in fluids induced by external physical fields, mechanical patterns and patterns formed by magnetic and electrical fields in heterogeneous materials (examples of crystalline and polymer patterns are shown in figures 1 and 2). Despite the differences in their physical natures, many of these structures can be studied by using analogical theoretical and experimental approaches, although the specifics of each type of pattern requires the development of original approaches. The entire physical spectrum of the formation and evolution of internal structures in non-organic and biological heterogeneous materials is presented: the kinetics of the crystallization of metastable liquids and the dissolution of the crystallites, the formation of thin films and dendrites, hydrodynamic patterns in liquids induced by alternating physical fields, drug transport and clustering, magnetic hyperthermia in systems of structured ferromagnetic particles and noise-induced patterning. The effect of internal structures on the physical properties and behaviour of complex systems represents the focus of the works in this theme issue. The similarities in the approaches used when studying physically different structures are demonstrated and discussed. The presented works are at the cutting edge in the field of complex soft matter and patterned systems and materials. The works, including experimental, theoretical and computational studies on systems and phenomena, are built upon the laws of soft matter physics and extend this field, highlighting the challenging problem of pattern formation in soft and biological matters. The importance of this thematic issue is defined by the application of the presented theories to biological systems. Modern biophysics, as well as new biomedical technologies for local drug implementation, require the development of theoretical foundations for understanding and describing the evolution of patterns in organic media (e.g. transport of medicinal compounds in blood vessels, the phase transformations in proteins in human retina responsible for the formation of cataracts, and the treatment of cancer using ferromagnetic nanoparticles heated by an alternating magnetic field). The issue is focused on the development of such theories and their computational and experimental verification in order to create a new foundation for future biomedical applications. This explains why the issue is timely.

The present issue will have a great impact on future research on pattern formation and evolution in soft and biological matter. First, research on patterning in soft matter materials will create a fundamental basis for rapidly developing research fields such as fast phase transitions in metastable liquids in the presence of convection and coalescence, hydrodynamic patterns in ferrofluids and microstructure evolution under the influence of an external magnetic field, pattern formation induced by external stochastic forcing, and the microstructural patterning of magnetic elastic and thermoplastic composites. This theoretical foundation will be further developed to study some important patterning phenomena that occur in biomedical applications. Applications such as the dissolution and transport of drugs in blood vessels, tumour growth due to heterogeneity, magnetic hyperthermia produced by clustered particles, and as a progressive method of cancer therapy, are analysed in the present issue. The new biophysical mechanisms detailed in these studies will provide a basis for future biomedical technologies (to develop new methods for transporting medicinal compounds in blood vessels and for enhancing the

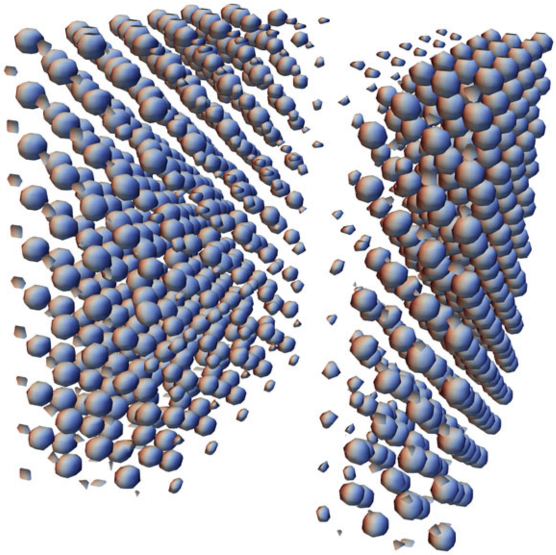

Figure 1. An example of crystalline patterns in liquid obtained by the phase-field crystal (PFC) model (body-centred cubic structures and liquid). The calculations were carried out by Ilya Starodumov especially for the present theme issue (for more details, see the monograph [1]). (Online version in colour.)

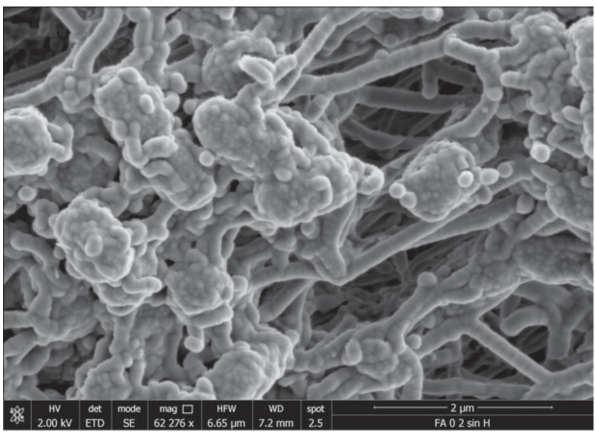

Figure 2. Electronic image of a magnetic fibrin-agarose hydrogel with magnetite nanoparticles. The gel is cross-linked under magnetic field with the strength 17 kA m^{-1}. The dense nodes are composed of the particles and polymer chains. This photograph is presented by Modesto T. Lopez–Lopez especially for the present theme issue.

effect of magnetic nanoparticles on cancer therapy, for example), and thus will be of wide public interest.

2. The general content of the issue

The present contributions have been selected to provide comprehensive coverage of the subject area. All authors are high-level experts in the theme of this issue. They have many papers published in high-impact journals. The authors work at different universities from around the world.

The structures considered in this issue arise during various phase and structural transformation processes, ranging from materials physics to biophysics and life sciences [1–15]. By using different external and combined processes (magnetic and electrical fields, hydrodynamic flows), one can tune these transformations and the final morphology of internal structures. In its turn, this opens up the possibility of controlling the macroscopic properties and behaviour of these materials with the help of external fields and other impacts. Recent studies have shown that in many important situations the structural and phase transitions in complex systems cannot be described in the framework of the classical theories on these phenomena. Very often, transport phenomena cannot be described by the standard parabolic equations: the adequate description of these phenomena requires generalization in the form of hyperbolic equations, memory integral equations or equations of anomalous transport [16–20]. Biological, chemically active, and various non-equilibrium systems can be very sensitive to external stochastic impacts; noise-induced patterning very often takes place in these systems [21]. The magnetic field induces clusterization of ferromagnetic nanoparticles, specific heating of biological systems with embedded ferroparticles, and excites hydrodynamic patterns in the biological liquids (blood) containing these particles. These phenomena find applications in cancer and insult therapy and regenerative medicine [22,23]: they require the development of an accurate method of quantitative description. Studies of these patterning phenomena and the effects of patterns on macroscopical properties of systems has opened up new and challenging fields in the physics of condensed matter and smart materials. In the present issue, the problems of the evolution of internal structures in metastable, chemically and biologically active systems, noise-induced structures, hydrodynamic and field structures in magnetically sensitive materials, and the effects of structural morphologies on the physical properties of soft composite materials are considered.

(a) Pattern evolution and the kinetics of growth

The papers start with those devoted to pattern formation due to new mechanisms of diffusion and fluid transport in the biophysical applications of soft matter phase transformations. The tumour heterogeneity phenomenon explaining how heterogeneity changes the tumour growth is considered in the pioneering paper presented by Gomez [24]. This study discusses that even a mild heterogeneity in the proliferation rates of different cell subpopulations leads to a much faster overall tumour growth when compared to a homogeneous tumour. The thin interface limit of the phase field model is extended to include transport via melt convection by Subhedar *et al*. [25] on the basis of the double sided model and coupling between the phase-field and Navier–Stokes equations.

Continuing these articles, new theories of particle evolution, clustering and patterning of their aggregates are developed in a series of papers. First, the nucleation and growth dynamics of particulate assemblages in metastable liquids is developed and tested against experimental data on phase transformations in aqueous solutions, undercooled melts and biomedical compounds in the manuscript by Alexandrova & Alexandrov [26]. Then this theoretical approach is developed and adopted by Ivanov *et al*. [27] to describe the nonlinear polydisperse ensembles of particles in channels in the presence of flowing liquid. Such a problem models the very important practical problem of the transport of drug crystals in blood vessels. Further, this theory is extended to describe the aggregate evolution from the intermediate stage to the concluding stage, where the process of coalescence (Ostwald ripening) takes place. This theory was elaborated by Alexandrov & Alexandrova [28] with allowance for the simultaneous operation of various mass transfer mechanisms in a metastable liquid. This problem has great potential applicability in describing the transitional regimes of metastable materials and their relaxation dynamics at the stage of Ostwald ripening, which occurs due to various mechanisms in organic and inorganic materials (reaction on the interface surface, volume diffusion, grain-boundary diffusion and diffusion along the dislocations). The theory developed by Nizovtseva & Alexandrov [29] is concerned with the phase transformation process in a mushy layer, which leads to various shapes of growing patterns. In this paper, a complete analytical solution for a very complex moving boundary problem with two boundaries of phase transition is obtained, with allowance for the density changes of a metastable material. This theory describes the nonlinear dynamics of the solid fraction, its shapes and the structural properties of a mushy layer: these are met in numerous problems of materials science, geophysics and biophysics (including biocrystallization and the crystallization of proteins and DNA complexes). A comprehensive review of various shapes of dendritic patterns is given in the next paper presented by Alexandrov & Galenko [30]. Here the authors show that dendritic patterns can evolve with the following tip shapes: circular/globular, parabolic/paraboloidal, fractional power and angled.

The following papers are concerned with the influence of external forcing on pattern formation. So, numerical analysis, presented by Kao *et al.* [31], demonstrates the key influence of applied magnetic field on buoyancy, the Marangoni effect, and the evolution of the solid–liquid frontal interface. The obtained results open new opportunities for controlling these phenomena with the help of an applied field. The work of Musickhin *et al.* [32] offers a theoretical study of hydrodynamic patterns induced in liquids (blood, for instance) by suspended ferromagnetic nanoparticles under an alternating magnetic field. The patterned flow can be used for intensification of drug delivery in thrombosed blood vessels for the treatment of insults, stenoses and thromboembolism. Another important contribution to patterning in a system of clustered particles is given by Abu-Bakr & Zubarev [33], where they consider the magnetic hyperthermia phenomenon and highlight its biomedical applications. Here, a theoretical model of heat production by dense clusters under an alternating magnetic field is elaborated. In addition, the thermal effect caused by the entire cluster and single particles is analysed. The effects frequently met in nature and numerous applications of stochastic and noised-induced phenomena on pattern formation in nonlinear systems are also detailed in papers presented by Kolinichenko *et al.* [34] and Bashkirtseva *et al.* [35]. Such effects are associated with pattern formation, when even a small inevitable noise which models fluctuations of various physical parameters (temperature, electromagnetic fields, and fluid or wind velocity, for example) can cause unexpected responses and generate dynamical regimes which have no analogues in deterministic models.

(b) Physical properties of patterned complex systems

Magnetic gels are a new generation of composite materials which have active biomedical, electronic and mechanical applications [36–38]. They consist of fine (nano- or micrometre-sized) magnetic particles embedded in a host polymer. The physical properties and behaviour of these systems strongly depend on the morphology of the particle's spatial disposition and the properties of the current polymer medium. Biocompatible alginate magnetic hydrogels are of special interest because of their application in regenerative medicine and bio-engineering. The presented work of Suarez-Fernandez *et al.* [39] is devoted to the experimental study of the effect of particle clustering on the rheological and magnetorheological properties of alginate magnetic fluids and hydrogels. The results demonstrate that the appearance of the clusters significantly (more than several times) enhances the viscous and elastic modulus of these systems. The effect of platelet particles clustered with fibre host polymers is studied experimentally in the work of Abrougui *et al.* [40]. The results demonstrate that this internal clustering significantly extends the range of variation of the rheological properties of the composites by applying a magnetic field. In turn, this extends the range of these systems' application in various high technologies.

New experimental methods of targeting internal patterns in soft magnetic composites are demonstrated in the work of Borin [41]. This method, based on small angle light scattering, allows one to clarify the links between the macroscopic physical properties of these systems and the intimate details of internal micro- and mesoscopic patterns in these systems. Methods for three-dimensional printing structured magnetic elastomers with willing internal structures are suggested by Dohmen *et al.* [42]. These methods enable the manufacture of elastomers with tailored magneto-mechanical properties. The dynamic reaction of systems of anisotropic (oblate) ferromagnetic particles, which form in-plane patterns in an elastic media, on an alternating magnetic field is studied theoretically by Tyulkina *et al.* [43]. New theoretical approaches that take into account the dipole–dipole interaction between structured particles are suggested in these works. The results provide an opportunity to develop a formal theory of collective magnetic phenomena in real physical systems and to study the interplay of two generic ordering mechanisms in an untypical case where the effective noise turns out to be diffusionless.

3. Conclusion

The present issue covers the rapidly developing research area of soft materials with complex internal structures (non-equilibrium systems such as metastable and biological ones, systems involved in a macroscopic patterned flow, magnetic materials under an alternating field and noise-sensitive systems), as well as composite field-sensitive soft materials. It covers multiple disciplines, ranging from condensed matter physics and material science to biomedical applications. To present a complex picture of micro- (nano) and meso-temporal and spatial scales in structural and phase transitions, a study of various heterogeneous materials (from metastable liquids to biological cell cultures) are included in this issue. Special attention is paid to the development of the scientific background of biomedical applications (phase transformations in the proteins in the human retina responsible for cataracts, magnetically stimulated drug delivery for the treatment of insults, stenosis and thromboembolism, and magnetic hyperthermia as a method of cancer therapy). Experimental and theoretical studies of dissipative, hydrodynamically and field-provoked structuration in soft materials are included. We also included articles devoted to noise-induced patterning in complex systems as well as works on anomalous transport in biologically and chemically active systems.

This issue presents overviews and regular articles on experimental, computational and theoretical studies on pattern formation in soft and biological matters. We hope that this issue is important for a wide audience, including scientists, engineers, lecturers, postgraduates and undergraduates, due to the educational and practical value of the included articles. An important point of our theme issue is the wider public interest in some of the vital biomedical applications of pattern formation in structural and phase transformations occurring in soft and biological matters.

Data accessibility. This article has no additional data.

Authors' contributions. All authors contributed equally to the present paper.

Competing interests. The authors declare that they have no competing interests.

Funding. This work was supported by the Russian Science Foundation (project no. 18-19-00008).

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