Mechanics and Materials Unit

Professor Eliot Fried

Abstract

FY2023 has been a year of productive year for the Mechanics and Materials Unit. The unit has substantially contributed to the field through the publication of seven peer-reviewed journal articles and numerous presentations at high-profile international conferences. Significant advancements were made in nanofluidic device fabrication via direct femtosecond laser writing, yielding innovative methods that bypass traditional complexities. Collaborative research led to pivotal insights into the wrinkling of nanocrystalline diamond films and the rheological properties of saltwater taffy, highlighting our interdisciplinary approach. Additionally, our studies on the isometric deformation of orthotropic materials have pushed the boundaries of material science, offering new perspectives on material behavior under deformation. The unit also filed for a Japanese patent and participated actively in community outreach and educational activities. These efforts underscore our commitment to advancing materials science and mechanical engineering through innovative research and collaboration.

1. Staff

As of March 31, 2023

- Dr. Eliot Fried, Professor
- Dr. Stoffel Janssens, Group Leader
- Dr. Vikash Chaurasia, Postdoctoral Scholar
- Dr. Vishesh Bhat, Postdoctoral Scholar
- Dr. Tiwari Sankalp, Postdoctoral Scholar
- Dr. David Vazquez Cortes, Research Unit Technician
- Mr. Michael Grunwald, Research Unit Technician
- Dr. Santo Chan, Research Unit technician
- Mr. Geoffry Acoba Garcia, Graduate Student
- Ms. Akyl Shakir, Graduate Student

- Mr. Francisco De Souza Forte Neto, Research Intern
- Ms. Mai Barnes, Research Unit Administrator

Alumni

- Bastien Konstans, Research Intern
- Victor Carlos Teixeira, Research Intern

Long-Term Visiting Researcher

- Prof. Yi-chao Chen (University of Houston)
- Prof. Fernando Duda (Federal University Rio de Janeiro)

2. Collaborations

2.1 Wrinkling of nanocrystalline diamond films through compressive strain

- Type of collaboration: Joint research
- Researchers:
  - Prof. Yi-Chao Chen, University of Houston, USA
  - Prof. Ken Haenen, Hasselt University, Hasselt, Belgium
  - Dr. Paulius Pobedinskas, Hasselt University, Hasselt, Belgium

2.2 Growth simulations of structures on substrates: inter-surface diffusion, cavities, and topological transitions

- Type of collaboration: Joint research
- Researchers:
  - Prof. Fernando Duda, Universidade Federaldo Rio de Janeiro, Rio de Janeiro, Brazil
  - Francisco De Souza Forte Neto, Universidade Federaldo Rio de Janeiro, Rio de Janeiro, Brazil

2.3 The rheology of saltwater taffy

- Type of collaboration: Joint research
- Researchers:
  - Professor Gareth H. McKinley, Massachusetts Institute of Technology, USA
  - F Dr. Simon J. Haward, Micro/bio/nanofluidics Unit, OIST

Selected media coverage

Physics World:

https://physicsworld.com/a/physics-of-salt-water-taffy-young-einstein-on-the-bbc-auction-opens-for-newtons-trees/

American Institute of Physics:
https://publishing.aip.org/publications/latest-content/the-sweet-physics-of-saltwater-taffy/

2.4 Marangoni spreading on liquid substrates in new media art

- Type of collaboration: Joint research
- Artist:
  - Ms. Akiko Nakayama, Japan https://www.akikopainting.com/

Selected media coverage

OIST: https://www.oist.jp/news-center/news/2024/2/29/beyond-ink-painting-physics

Forbes:
https://www.forbes.com/sites/evaamsen/2024/04/29/the-physics-of-dendritic-painting/?sh=69b3d99355e2

Physics World: https://physicsworld.com/a/the-physics-behind-fractal-painting-revealed/

2.5 Diamond MEMS for sensing applications

- Type of collaboration: Joint research
- Researchers:
  - Dr. Meiyong Liao, National Institute for Materials Science, Tsukuba, Japan
  - Dr. Satoshi Koizumi, National Institute for Materials Science, Tsukuba, Japan
  - Dr. Satoshi Fujii, Okinawa National College of Technology

2.6 Coupling between bulk diffusion and surface reaction diffusion

- Type of collaboration: Joint research
- Researchers:
  - Professor Fernando Duda, Federal University of Rio de Janeiro, Brazil
  - Mr. Francesco S. Forte Neto, Federal University of Rio de Janeiro, Brazil

2.7 Effects of incompatibility in fluid flows

- Type of collaboration: Joint research
- Researchers:
  - Professor Roger Fosdick, University of Minnesota, USA

2.8 Unstretchable two-dimensional materials

- Type of collaboration: Joint research
- Researchers:

- Professor Yi-chao Chen, University of Houston, Houston, TX, USA
- Professor Roger Fosdick, University of Minnesota, Minneapolis, MN, USA
- Professor Brian Seguin, Loyola University Chicago, IL, USA

2.9 Flow and microphase separation of diblock copolymer melts

- Type of collaboration: Joint research
- Researchers:
  - Professor Fernando Duda, Federal University of Rio de Janeiro, Brazil
  - Mr. Victor Carlos Teixeira, Federal University of Rio de Janeiro, Brazil

3. Activities and Findings

3.1 Nanofluidic device fabrication by direct femtosecond laser writing

We established the direct femtosecond laser writing of optically accessible nanochannels with arbitrary lengths. They exist between nanocrystalline diamond films and glass substrates, and their cross-sections resemble slits with width-to-height ratios on the order 100. The heights of such channels can be tuned precisely below 100 nm. We focused on understanding the mechanisms involved and showcased film patterning using the same technique. To demonstrate that our findings apply to the fabrication of devices, we designed and made a nanofluidic device while circumventing traditional fabrication techniques, which are often complex, expensive, and time-consuming. The figure shows reflected light microscopy (RLM) images of a nanofluidic device with air-filled and water-filled nanochannels. The figure also shows plots of experimental data and simulations that support the presence of water in the channels.

Publication in the journal Carbon:
https://doi.org/10.1016/j.carbon.2023.118455

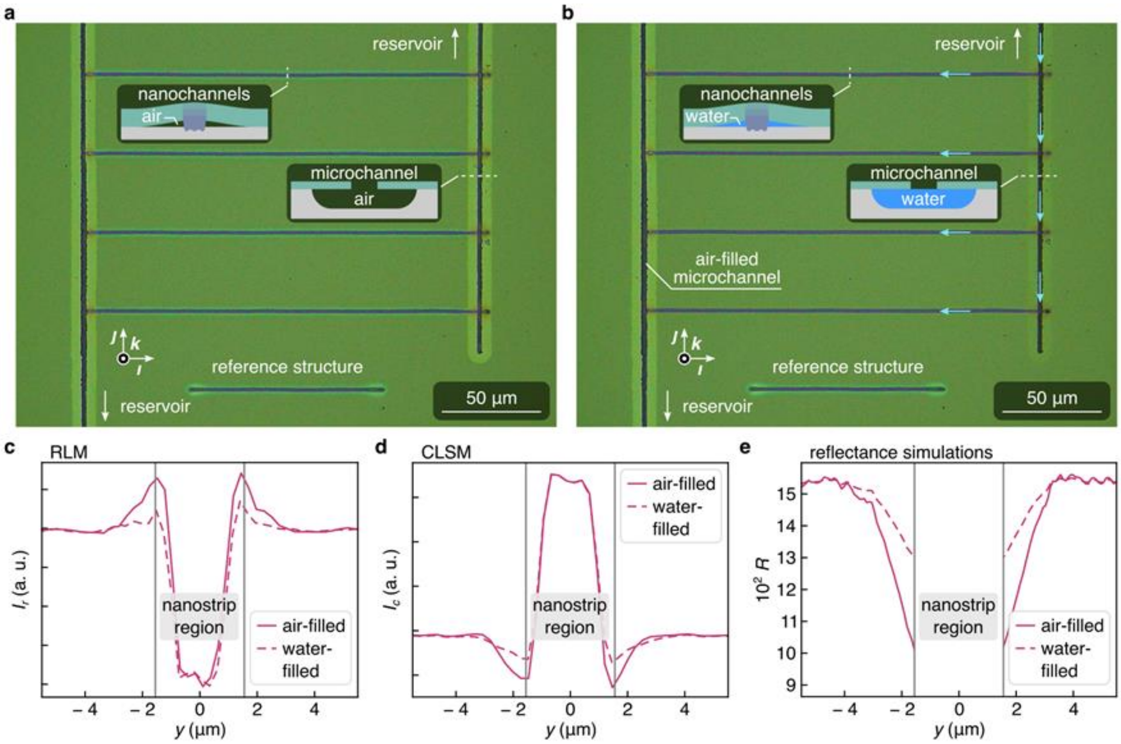


Figure 1. (a) Reflected light microscopy (RLM) image of an air-filled nanofluidic device. (b) RLM image of the device with water-filled nanochannels. (c) RLM intensity I_r plotted versus axis y, which points in the same direction as $\boldsymbol{J}$. (d) Confocal laser microscopy (CLSM) intensity I_c plotted versus y. (e) Specular reflectance R obtained through simulations plotted versus y. The simulations support the presence of water in the nanochannels.

3.2 Controlling the morphology of polycrystalline diamond films via seed density: influence on grain size and film texture

Controlling the morphology of polycrystalline diamond (PCD) films is crucial for various applications, including thermal management and quantum sensors. PCD films are typically produced by plasma-enhanced chemical vapor deposition on substrates seeded with nanodiamonds. Different film morphologies can be achieved by controlling growth rates of crystal-forming facets, which is commonly achieved through deposition temperature and hydrocarbon concentration in the plasma. However, the impact of seed density on film morphology remains largely unexplored. In this study, we observed that reducing seed density on silicon substrates has a similar effect on PCD film morphology as increasing hydrocarbon concentration in the plasma. Specifically, as seed density decreases, deposition rate increases, and film texture transitions from (1~1~1) to (1~0~0), followed by the formation of large grains with (1~0~0) facets surrounded by clusters of small grains. These changes were observed using electron microscopy, Raman spectroscopy, and X-ray diffraction.

To explain our results, we hypothesize that the silicon--plasma interface surrounding the growing diamond seeds acts as a diamond precursor source. Our proposed explanation requires relatively long precursor migration lengths compared to those assumed in standard diamond deposition theory. Finally, we also propose two new mechanisms for diamond precursor adsorption based on well-established physical phenomena and recent publications. Our findings may open new avenues in diamond research, applicable not only to polycrystalline but also to single-crystal diamond deposition.

3.3 The isometric deformation of orthotropic materials as a model for the bending of Origami structures

We are investigating deformations which preserve the length of vectors and angles between vectors on orthotropic material surfaces. This work takes the previous work of Professor Fried and extends it by considering materials which are orthotropic, whereas previously materials were only isotropic. An isotropic material is one with an infinite number of planes of symmetry, so that the material properties are the same regardless of the direction that forces are applied. Orthotropic materials on the other hand have only three planes of symmetry, so conventional stress-strain relations will be different depending on how forces are applied. We therefore present a comprehensive framework that allows one to determine the equilibrium shape of an inextensible material surface with an arbitrary reference configuration. Our model can accommodate applied edge tractions, edge moments, and conservative body forces. Our model is based on the minimization of the bending energy of the deformed configuration, from which we obtain the Euler-Lagrange equations. The solution to these Euler-Lagrange equations are the energy minimizing shapes of the deformed configuration. The salient feature of this work, which makes it stand out from other works is that we perform a dimensional reduction, by integrating along straight line generators of the deformed configuration, thereby reducing the problem from a partial differential equation, to an ordinary differential equation, as a function of the length around the perimeter of the deformed configuration.

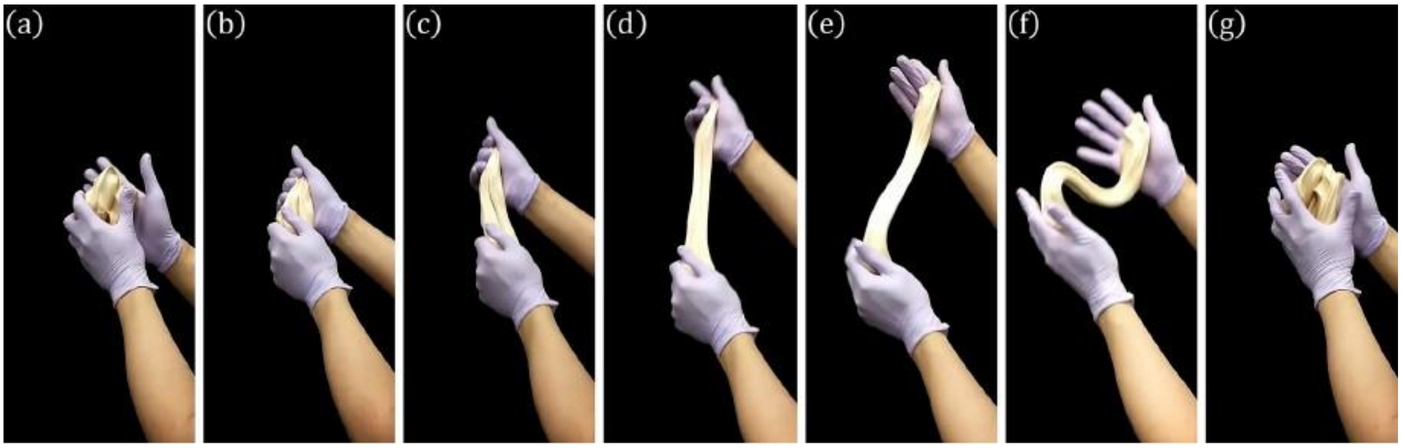
3.4 Rheological properties of saltwater taffy

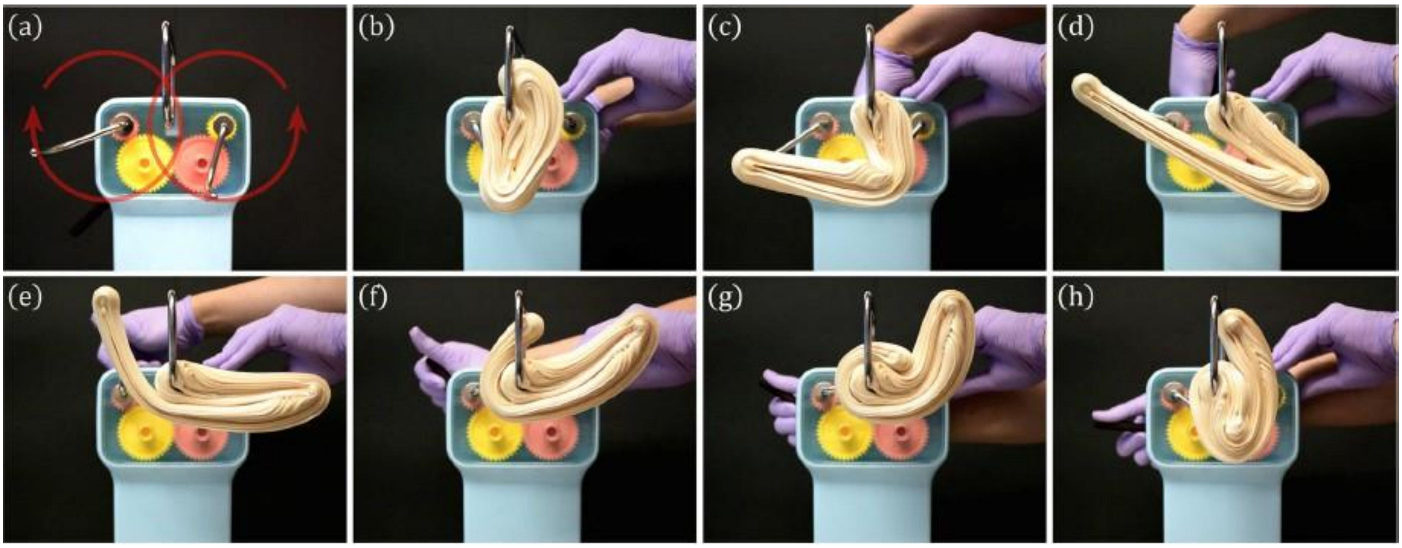
Saltwater taffy, a chewy American confection, is known for a distinctive texture derived from sugar, corn syrup, water, and oil. This study explores the viscoelastic properties of commercial saltwater taffy using a small amplitude oscillatory shear test. At low frequencies, the taffy exhibits behavior typical of a critical gel with self-similar relaxation characteristics, which are reflected in the power-law relationship, with frequency, of the storage and loss moduli.

The process of taffy-pulling, an iterative folding method, is crucial for incorporating air and emulsifying oil into the taffy. This technique contributes significantly to the observed rheological properties. Our work shows that the time–temperature superposition principle holds true for taffy, allowing the construction of master curves that predict behavior across various temperatures

Further, the behavior of taffy transitions from a critical gel-like state to an elastic solid-like state upon exceeding specific frequency thresholds. The fractional Maxwell gel model, using three parameters—a plateau modulus, a characteristic relaxation time, and a power-law exponent—effectively captures the viscoelastic response of taffy. This model also confirms that minor ingredients like flavorings do not significantly alter the fundamental viscoelastic properties of taffy.

The findings of this study extend beyond academic interest, suggesting potential for industrial applications where precise control over texture and rheology is desired. They also reinforce the critical role of traditional taffy-pulling in achieving the desired viscoelastic properties of commercial products.





3.5 Conformal deformations of dilational material surfaces

This study is concerned with two-dimensional dilational materials, which are characterized by their ability to preserve angles between pairs of material fibers during deformations. Such materials are a significant subset of metamaterials, offering novel mechanical properties derived from their unique geometric configurations. The research primarily examines the theoretical framework governing the conformal deformations of two-dimensional dilational elastic material surfaces, which are homogeneous and isotropic by nature.

In a two-dimensional setting, dilational materials demonstrate an inability to sustain in-plane shear, resulting in a Poisson's ratio of -1. This attribute sets the stage for examining the broader implications of conformal deformations that preserve the angles between material fibers under deformations. We employ a variational approach to articulate the conditions for equilibrium in these materials, properly taking into account the conformality constraints.

The analysis extends to the formulation of equilibrium equations and constitutive relations tailored to these materials, introducing a penalty method under which not only angles but also lengths are preserved. This method aids in approximating the deformations of theoretically unstretchable elastic surfaces, akin to how ordinary papers behaves.

This research offers insights into the design and application of materials that require precise control over their deformation characteristics, particularly in fields like material science and mechanical engineering where the behavior of two-dimensional surfaces is critical.

This focused examination not only advances theoretical understanding but also suggests practical applications in designing devices and structures that leverage the unique properties of two-dimensional dilational materials.

Dynamic coassembly of nanodiamonds and block copolymers in organic solvents

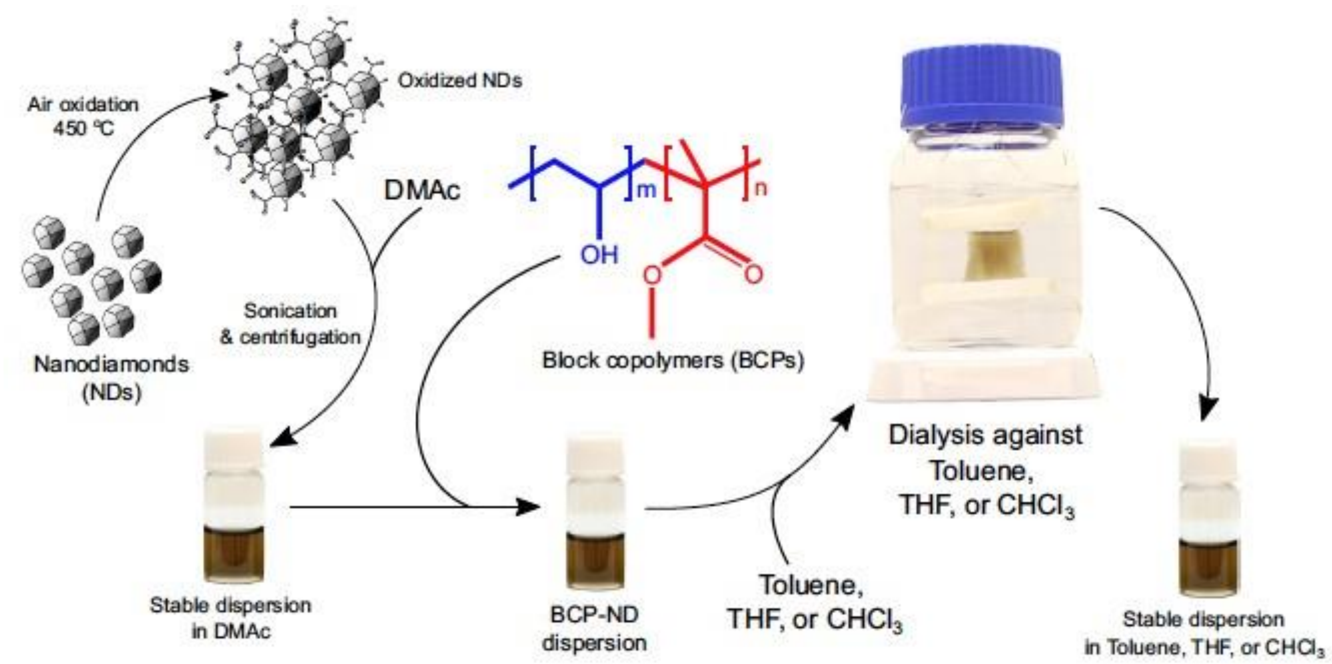
In this effort, we introduced a novel approach for stabilizing nonaqueous suspensions of nanodiamonds using block copolymers, primarily PVA-b-PMMA, in both nonpolar and polar aprotic solvents. The study focuses on overcoming the challenges of nanoparticle agglomeration in organic solvents, which is a common issue due to the inherent interparticle forces and the complex surface chemistry of nanodiamonds.

Specifically, we develop and test a three-step method to achieve stable ND suspensions: 1) Ultrasonication of air-oxidized nanodiamonds in dimethylacetamide (DMAc), 2) introduction of amphiphilic dispersants composed of block copolymers, and 3) solvent exchange to encourage the formation of composite micelles. In these micelles, the BCP forms the corona that encapsulates the oxidized nanodiamond forming the core. This method effectively prevents the agglomeration of nanodiamonds during the critical phase of solvent exchange.

The study demonstrates that the stabilization mechanism in nonpolar solvents like toluene predominantly relies on steric hindrance provided by the copolymers, whereas in polar solvents like tetrahydrofuran and chloroform, both electrostatic repulsion and steric hindrance are instrumental. Detailed characterization of these suspensions through dynamic light scattering, electron microscopy, and atomic force microscopy confirms the uniform size distribution and stability of the nanodiamonds in various solvents.

We also determined a critical weight ratio of block copolymers to nanodiamond that ensures effective stabilization, akin to the critical micelle concentration in surfactant systems. This is pivotal for predicting and controlling the behavior of nanodiamond suspensions across different solvent environments.

The implications of this study may be significant for applications requiring stable nanoparticle suspensions, such as in coatings, lubricants, and environmental remediation. Apart from advancing the fundamental understanding of nanomaterials dispersion, our findings open new avenues for the practical application of nanodiamonds in diverse fields.



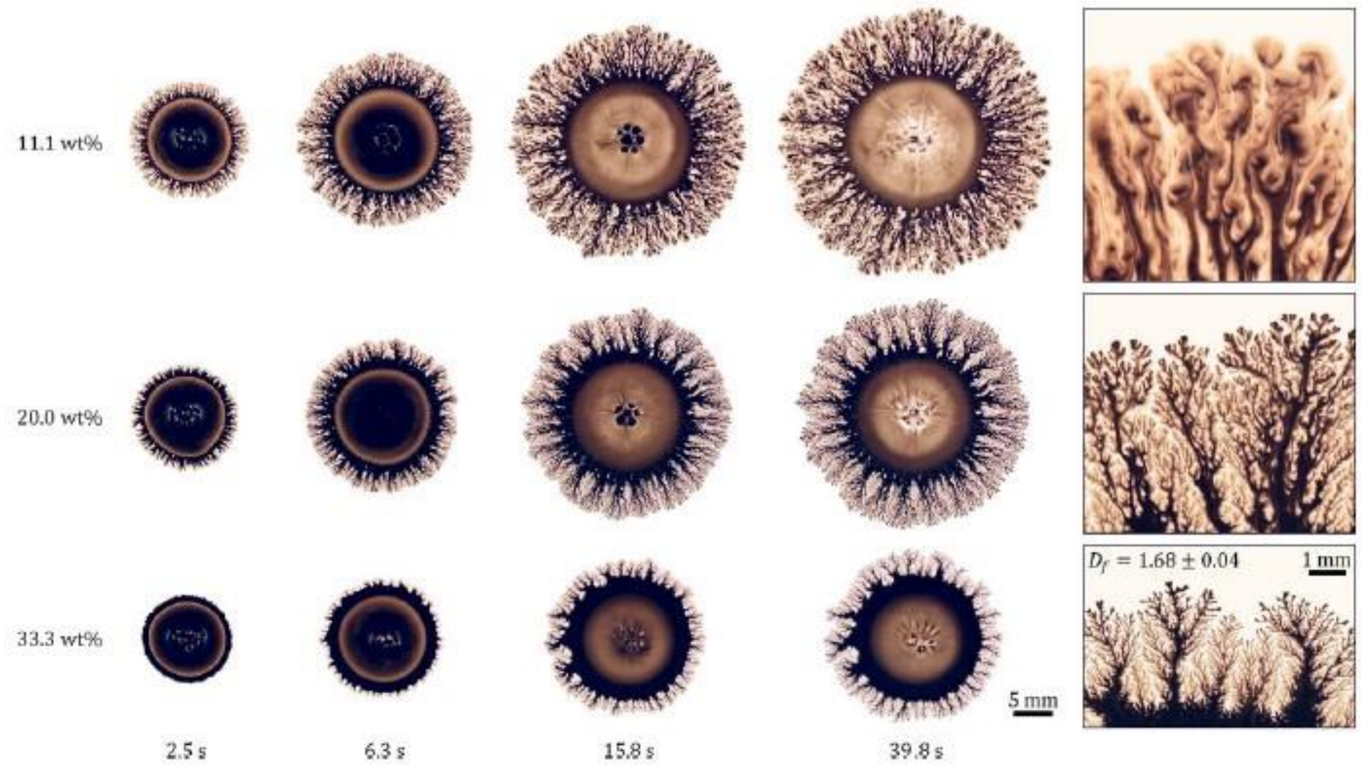
3.6 Marangoni spreading on liquid substrates in new media art

This study investigates the Marangoni spreading of ink and isopropanol (IPA) droplets over various liquid substrates to understand the intricate dendritic patterns observed in new media art. By employing different substrates with unique rheological properties, the research provides insights into the fluid dynamics that underpin this artistic technique, known as dendritic painting.

Our experimental results show that on Newtonian substrates like sugar syrup, the droplets exhibit distinct spreading dynamics characterized by two power laws related to viscous and Marangoni forces. The precursor film and main body of the droplet spread with exponents of 3/8 and 1/4, respectively. However, when a weakly shear-thinning acrylic resin substrate is used, similar power laws are observed, but with the emergence of dendritic structures and a roughened texture in the precursor film. This complexity increases with the inclusion of acrylic paint, which makes the resin more viscous and shear-thinning, leading to refined dendrite edges and further roughened precursor films.

Wealso explores the scaling laws governing these phenomena, connecting them to established principles in statistical mechanics and highlighting the significant role of the Marangoni effect—fluid motion driven by surface tension gradients—in these artistic creations. Moreover, the research delves into the nonlinear rheological properties of the liquid substrates, showing how these influence the local kinetic roughening of the droplet interface, potentially leading to new applications in industrial processes involving liquid spreading and coating.

Apart from advancing the understanding of a visually captivating art form, this work bridges the realms of art and science, providing a deeper appreciation of the physical processes that enable such creative expressions.



4. Publications

4.1 Journals

- V. Chaurasia, E. Fried. Stable Möbius bands from isometrically deformed circular helicoids, *Journal of Elasticity*, in press. (doi:10.1007/s10659-023-10008-x)
- S. Chan, E. Fried. Dendritic painting: Marangoni spreading on liquid substrates in new media art, *PNAS Nexus* **3** (2024), 1–12. (doi:10.1093/pnasnexus/pgae059)
- B. Sutisna, D. Vázquez-Cortés, N. Ishizu, S.D. Janssens, E. Fried. Dynamic coassembly of nanodiamonds and block copolymers in organic solvents, *Diamond & Related Materials* **141** (2024), 110609-1–9. (doi:10.1016/j.diamond.2023.110604)
- F.P. Duda, F.S. Forte Neto, E. Fried. Modeling of surface reactions and diffusion mediated by bulk diffusion, *Philosophical Transactions of the Royal Society of London Series A, Mathematical, Physical and Engineering Sciences* **381** (2023), 20220367-1–26. (doi:10.1098/rsta.2020.0367)
- Y.-C. Chen, E. Fried. Conformal deformations of a dilational material surface, *Journal of Elasticity*, **154** (2023), 517–530. (doi:10.1007/s10659-023-10003-2)
- S.T. Chan, S. Haward, E. Fried, G. McKinley. The rheology of saltwater taffy, *Physics of Fluids* **35** (2023), 093106-1–14. (doi:10.1063/5.0163715)
- S.D. Janssens, D. Vázquez-Cortés, B. Sutisna, E. Fried. Direct femtosecond laser writing of nanochannels by carbon allotrope transformation, *Carbon* **215** (2023), 118455-1–11. (doi:10.1016/j.carbon.2023.118455)

4.2 Books and other one-time publications

1. Book chapter : Coauthor in a book chapter "Early stages of Polycrystalline Diamond Film Desposition on Seeded Substrates." in book Novel Aspects of Diamond II. Authors: Stoffel D. Janssens, David Vazquez-Cortes, Alessandro Giussani, and Eliot Fried.

4.3 Oral and Poster Presentations

4.3.1 Oral Presentation

1. Eliot Fried. From seeds to structures: Advancements in the fabrication of nanocrystalline diamond films, OIST-UC Santa Barbara Mini-Symposium, Materials of Tomorrow: Harnessing Responsiveness, Intelligence, and Sustainability, March 2024.

2. Stoffel D. Janssens, David Vázquez-Cortés, and Eliot Fried. Direct laser writing of nanochannels between ultra-thin nanocrystalline diamond films and glass substrates, 2023 Materials Research Society (MRS) Fall Meeting & Exhibit, Hynes Convention Center & Sheraton Boston Hotel, Boston, MA, USA, November 26 to December 1, 2024.

3. Eliot Fried. Truesdell Lecture: Some exceptional linkages, their continuum limit, and isometric deformations from helicoids, 57th Meeting of the Society for Natural Philosophy, École Nathionale Supériure d'Architecture, October 16-18, 2023.

4. Eliot Fried. Möbius bands obtained by isometrically deforming circular helicoids 10th International Congress on Industrial and Applied Mathematics (ICIAM 2023), Waseda University, Tokyo, Japan, August 20-25, 2024.

5. Eliot Fried. A novel dimensional reduction for the equilibrium study of inextensional material surfaces, 10th International Congress on Industrial and Applied Mathematics (ICIAM 2023), Waseda University, Tokyo, Japan, August 20-25, 2023.

6. Eliiot Fried. Stable Möbius bands obtained by isometrically deforming circular helicoids, International Conference on Multi-scale Science and Engineering (ICMSE 2023), Okinawa, July 2023.

4.3.2 Poster Presentation

1. David Vázquez-Cortés, Stoffel D. Janssens, Burhannudin Sutisna, and Eliot Fried. Incubation period in polycrystalline diamond estimated by laser reflectance. Poster presentation at 33rd International Conference Diamond Carbon Materials, Mallorca, Spain. 10-14 September 2023.

2. David Vazquez-Cortes, Stoffel D. Janssens, and Eliot Fried. Effect of seed density on the deposition of polycrystalline diamond films by plasma-enhanced chemical vapor deposition. Poster presentation at the Hasselt Diamond Workshop 2024 - SBDD XXVIII in Kanazawa, Japan. February 28-March 1st, 2024.

3. David Vazquez-Cortes, Stoffel D. Janssens, and Eliot Fried. Effect of seed density on the morphology of polycrystalline diamond films. Oral presentation at The 71st JSAP Spring Meeting 2024 at the Setagaya Campus, Tokyo City University & Online. 22-25 March 2024.

5. Intellectual Property Rights and Other Specific Achievements

1. Japanese patent filed: 2023/073856.

2. KAKENHI: Grant-in-Aid for Scientific Research, Research Number: 00817629_Dr. Stoffel Janssens

3. Dr. Stoffel Janssens is a member of the programme committee of the 33rd International Conference on Diamond and Carbon Materials, Palau de Congressos de Palma, Mallorca, Spain, September 10 to 14.

4. Dr. Stoffel Janssens is an editorial board member of the journal Diamond and Related Materials.

6. Meetings and Events

6.1 Surface accretion of a pre-stretched halfspace: Biot's problem revisited

- Date: May 31, 2023
- Venue: OIST Campus Lab3, C700
- Speaker: Professor Giuseppe Tomassetti (Università degli Studi Roma Tre)

6.2 Bridging mechanics and chemistry in deformable solids

- Date: August 10, 2023
- Venue: OIST Campus Lab4, F01
- Speaker: Professor Fernando Duda (Federal University of Rio de Janeiro, Brazil)

6.3 Semi-discrete modeling of systems of disclinations and dislocations

- Date: August 28, 2023
- Venue: OIST Campus Lab3, C700
- Speaker: Professor Marco Morandotti (Department of Mathematical Sciences of Politecnico di Torino)

6.4 On the minimization of the Canham–Helfrich energy

- Date: August 30, 2023
- Venue: OIST Campus Lab3, C700
- Speaker: Professor Lucca Lussardi (Department of Mathematical Sciences of Politecnico di Torino)

6.4 Phase-field modeling of geologic fractures

- Date: November 28, 2023

- Venue: OIST Campus Ctr Bld, C210
- Speaker: Professor Jinhyun Choo (KAIST)

7. Other

Nothing to report.