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# The contact mechanics challenge: tribology meets soft matter

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In the fall of 2015, Martin Müser suggested a Contact Mechanics Challenge for the Tribology community. The challenge was an ambitious effort to compare a wide variety of theoretical and computational contact-mechanics approaches, and involved researchers voluntarily tackling the same hypothetical contact problem. The result is an impressive collection of innovative approaches – including a surprise experimental effort – that highlight the continuing importance of surface contact mechanics and the challenges of solving these large-scale problems. Here, we describe how the Contact Mechanics Challenge also reveals exciting opportunities for the Soft Matter community to engage intensely with classical and emerging problems in tribology, surface science, and contact mechanics.



The contact of real surfaces has widespread importance to nearly all fields of science, and numerous models that aim to predict contact area as a function of material and surface properties, surface topography, and applied loads continue to be developed by mathematicians, engineers, chemists, and physicists. The problem of determining the intimate contact geometry at an interface has tormented theorists and experimentalists for centuries.[1] This is largely because the intimate, real area of contact is vastly smaller than the apparent contact area. Even supposedly-pristine surfaces have some measure of atomic-scale roughness and defects, as frequently demonstrated experimentally using techniques like atomic force microscopy.[2,3] The actual contact between surfaces typically only occurs at an irregular distribution of microscopic patches at the peaks of surface asperities.[4–6] Furthermore, this contact is extremely hard to characterise, as all the essential details are usually buried at an inaccessible interface between two solids. Consequently, gaining access to inaccessible contact interfaces has been the subject of numerous *in situ* efforts pioneered by physicists, engineers, tribologists, and surface scientists (*e.g.* ref. 7, 8 and 9).

Details of the contact distributions are vital as they determine the deformations, forces, adhesion, and transport characteristics (*e.g.* fluid, electrical, and thermal) across contacting surfaces. These can then be used to help understand and control phenomena involving contact between two surfaces (a classic example being in the field of medical devices and implants, where a long history of research has clearly established the importance of surface roughness for device success[10–12]). Ideally, we would have a perfect theoretical understanding of the process of contact. However, due to its complexity, no single unified theory has been universally accepted. There are a breadth of models developed to address different theoretical and experimental concerns, but the problem then arises: how should one determine the quality of these models, particularly with scarce high-fidelity data for experimental comparisons?

These uncertainties led Martin Müser to propose an innovative solution to resolve this question in the fall of 2015.[13] His visionary approach was to openly distribute the complete mathematical description of a hypothetical, periodic, rough surface with challenging topography, steep slopes, sharp peaks, low modulus, and low adhesion. Using this hypothetical surface, researchers across the Tribology community could then candidly share results and predictions from analytical, numerical, and experimental efforts to model the total contact area, the distribution of contact spots (both in size and spatial location), the interfacial stresses, and the deformations as a function of the applied load. In the meantime, Müser would use a supercomputer to brute-force calculate a series of exact numerical solutions to the challenge, but would keep the solutions secret until all of the various entries to the challenge were submitted. The editors of Tribology Letters (Wilfred Tysoe and Nicholas Spencer) presented the hypothetical surface to the Tribology community,[14] and the 'Contact Mechanics Challenge' was born.

The response from the Tribology community to this scholarly challenge was remarkable; researchers from Austria, England, France, Germany, Italy, Iran, the Netherlands, Taiwan, and the United States all voluntarily submitted predictions and agreed

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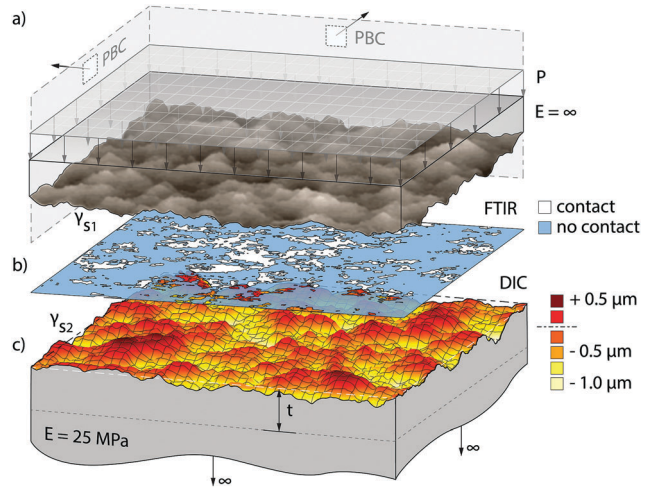


Fig. 1 Results from the soft matter experimental entry to the Contact Mechanics Challenge.[1,15–17] (a) A rigid, 3D-printed version of the challenge surface is brought into contact with a soft, flat, silicone-elastomer substrate, and indented with a pressure, *P*. Both the size of the indenting surface and Young's modulus of the substrate, *E*, were scaled appropriately to allow measurement of the contact area (b) and deformed substrate surface profile (c) using Frustrated Total Internal Reflection (FTIR) and Digital Image Correlation (DIC) respectively. (Note that the scale is exaggerated in the *z*-direction for ease of visualisation.) The experimental measurements were then re-scaled to allow direct comparison with the theoretical solutions to the challenge.

to openly share their results.[1] A diverse assortment of approaches and predictions were submitted to the challenge, and for the first time a single ensemble of predictions could be compared, contrasted, and assessed on their relative merits. A huge range of techniques were applied, ranging from numerical solutions to fractal-based theories, from classic models published by Greenwood and Williamson[5] to a wildcard soft-matter experiment using silicone elastomers with scaled-up 3D-printed surfaces that enabled direct visualisation of contact area and deformation (Fig. 1),[15–17] and a scaled-down molecular dynamics simulation of a hard-on-hard contact with calcium. Together, Müser and Greenwood evaluated the predictions, made comparisons to the exact solution, and recorded the results in the paper 'Meeting the Contact-Mechanics Challenge'.[1] Overall the multi-scale approaches based on Persson's theory most closely matched the brute-force solution to the problem, while also revealing that the bearing-area models, which are based on geometric considerations of contact area as a function of depth, are problematic and do not capture the correct scaling. Additionally, the scaled-up soft-matter experiment and the scaled-down hard-on-hard molecular dynamics simulations were both in close agreement with the solution. Thus, interestingly, the hard problem could provide insights into the soft problem, and *vice versa*.

That such a large cross-section of the Tribology community would undertake this collective challenge highlights the continuing importance and difficulty of understanding contact. Meeting this challenge was less of a competition than a celebration of a generation of tribologists who rose to the challenge and shared their best, current insights into the contact of real surfaces. But despite its complexity, the contact surface presented by Müser was still very specific, and consequently the Contact Mechanics Challenge still only touched the surface of the unknown in this area.

Moving forward, we hope that the results of this collective effort will serve as a springboard to attract new researchers, especially from the Soft Matter community, to engage with the long list of important outstanding challenges in contact mechanics. There are multiple reasons why our community has much to offer. Firstly, the challenge revealed a number of areas in which soft materials could be used in numerical and analytical models, as well as in experiments to improve predictions of contact for a wide range of applications. Soft matter experiments have the great advantage that they are often relatively simple and offer a magnification of relevant length scales, making it possible to readily explore new physics. Already, the use of soft transparent materials like silicone elastomers has recently emerged as a new tool to explore and measure elastic contact deformation optically under varying levels of applied force, adhesion, surface topography, contact stress, environment, and time.[15–33] Further, the soft matter experimental entry to the challenge performed extremely well in the competition, directly revealing many of the details of contact area and displacements at the interface, as shown in Fig. 1.[1,15–17]

Secondly, we are still discovering new aspects of adhesion and contact, especially in soft materials. This is both due to a burgeoning interest in biological adhesion[34–37] and the production of innovative biomimetic technology (*e.g.* ref. 38 and 39), as well as to the novel physics that arises in soft materials that alter the character of adhesion from that found in harder materials. For example, recent work has shown the existence of a wide array of new interfacial phenomena, with different effects emerging at different length and stiffness scales. Fig. 2 illustrates some of these effects, including how solid surface stresses can significantly alter adhesion behaviour below a critical elastocapillary length scale,[32,40,41] osmocapillary phase separation,[33,42] contact hysteresis,[43] and material inhomogeneity due to the finite spacing between crosslinks in a polymer network.[44] Beyond this phase diagram, there are many other important effects that can strongly affect adhesion, including capillary condensation (which can cause additional adhesion in humid environments),[45] cavitation,[46] nonlinear or viscoelastic rheology,[47,48] and plasticity.[49]

Finally, beyond the discovery of new physical phenomena, soft adhesion has ubiquitous practical applications across a wide variety of industrial and scientific fields, including large-scale manufacturing, soft robotics,[50] surgery and medical devices,[51] and the mechanical characterisation of any soft material, including living cells.[52,53]

The Contact Mechanics Challenge has both allowed us to take a great step forward towards an accurate, standardised model for understanding contact between real surfaces, and highlighted the active community and continuing importance of contact across many fields. Moving forward, we believe there are tremendous opportunities for the tools and techniques of soft-matter science to engage with unsolved problems in this area, and to pose new challenges across a wide variety of disciplines. With such broadly impactful applications, rich scientific challenges,

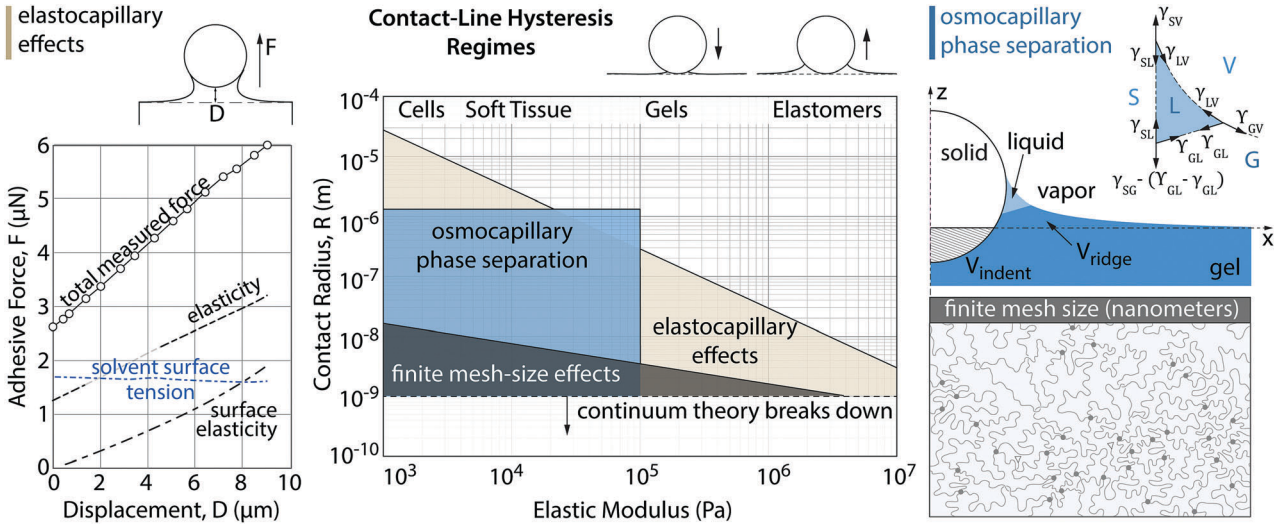


Fig. 2 Many new effects arise in adhesion at small length scales and in soft materials. The phase diagram shows when some of these can arise as a function of elastic modulus, $E$, and contact radius. Contact-line hysteresis is important throughout the phase diagram.[43] Solid surface stress and elastocapillary effects (beige) arise at the elastocapillary length, $\Upsilon/E$, where $\Upsilon$ is the solid surface stress.[54] This is illustrated by the force recorded during pull off of a small, spherical indenter from a soft silicone substrate (left-hand plot), which has a significant capillary contribution.[41] Osmocapillary effects (blue) arise in gels below the lengthscale, $\Omega/kT$, where $\Omega$ is the volume of a solvent molecule, $k$ is Boltzmann's constant, and $T$ is temperature.[42] The schematic on the top right illustrates typical phase separation during contact of a particle on a polymer gel, adapted from ref. 33. Finite mesh-size effects (grey; bottom right) arise when the indenter size is comparable to the average distance between crosslinks in an elastomer,[44] $L \sim n^{-1/3}$, where $n$ is the crosslinking density; from ideal rubber elasticity, $E \sim nkT$,[48] so $L \sim (kT/E)^{-1/3}$. Continuum mechanics also breaks down for indenter sizes close to the molecular scale.[55,56]

and exciting recent developments, we believe this is an ideal time and topic for the Soft Matter community to dive in more intensely. We anticipate a rich array of soft, contact phenomena will emerge on different length and time scales, all of which offer exciting opportunities for important new physical insights with direct practical applications.

## Conflicts of interest

There are no conflicts to declare.

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