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MECHANICAL INTERLOCKING ENABLES ADHESION CONTROL UNDER UNFAVOURABLE ENVIRONMENTAL CONDITIONS

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Abstract: *Engineering robust adhesion in challenging conditions, where van der Waals interaction effects are reduced (e.g., wet or dusty environments), is critical for medical, robotic, and space applications. Inspired by natural systems that utilize mechanical interlocking, this study presents a bio-mimetic approach to achieve tunable adhesion. We provide a new class of interlocking structures and a theoretical framework that enables the design of adhesive patches with the needed performances. The experimental findings confirm the robustness of adhesion performances of these new interlockers in dusty and wet environments. This technology could open new possibilities in traditionally problematic environments for standard adhesives and in applications requiring controlled grasping and manipulation.*

Keywords: *Mechanical interlocking, Adhesion control, Bio-inspired micropatterns, Underwater adhesion*

1. INTRODUCTION: AIM AND BIO-INSPIRATION

In environments where traditional adhesives fail due to surface contamination, mechanical adhesion is a robust alternative. This reversible interlocking strategy can be found in biological systems because it enables secure attachment and detachment regardless of the operating conditions [1,2]. These systems demonstrate the effectiveness of surface protrusions in achieving strong and reversible bonds through the strategic utilization of the elastic energy stored in the deformation of the interlocking structure. This principle allows for selective and adaptable adhesion, a capability observed across the natural world but not fully exploited in the current fastening technologies. Possible fields of application include medical devices, underwater adhesive systems, robotics, and space technology [3-6].

Bioinspired designs leverage this concept by creating surface features like micro-needles, pillars, and specialized shapes that facilitate interlocking with a substrate [7-9]. These engineered microstructures enhance contact and generate mechanical bonds. Dynamic approaches, such as inflatable or morphing structures, further expand the possibilities for switchable adhesion. While conventional dry and suction-based adhesives have drawbacks concerning environmental sensitivity and operational requirements [10-13], mechanical interlocking offers resilience to contaminants and allows for precise control over bond strength through the design of the interlocking elements.

The core of mechanical adhesion lies in the physical engagement of surface features, enabling selective attachment. The resulting bond strength can be substantial, particularly under shear forces. While theoretical models have explored specific interlocking geometries, a unified framework that captures the complexities of diverse microstructures and their collective behaviour remains an active area of research.

Existing theoretical investigations often provide limited scope by focusing on specific interlocking shapes and neglecting the statistical nature of multi-contact interactions. The gap between the mechanics of individual interlocking elements and the macroscopic behaviour of the entire interface is often addressed through simplifying assumptions [14-17]. Further research into the influence of the distribution of interlocking structures is also necessary. Overcoming these limitations through innovative design methodologies and comprehensive theoretical models will pave the way for developing adaptable, robust mechanical adhesion technologies capable of functioning reliably across a wide spectrum of challenging conditions and applications.

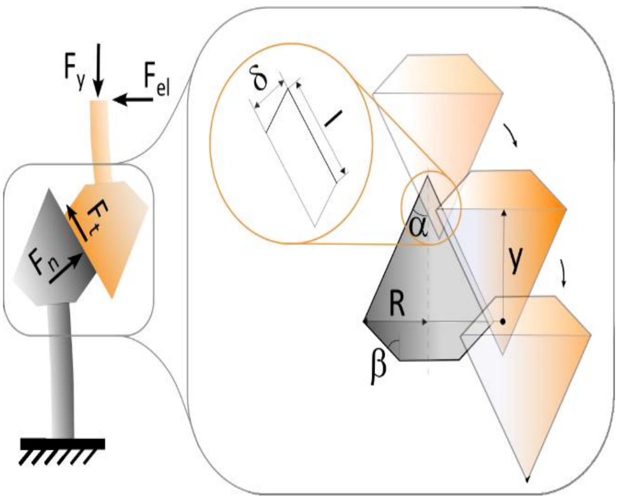

Figure 1. Kinematics of a double conical interlocker, depicting contact penetration (δ), contact length (l), and out-of-plane distance (y) between conical interlockers of radius R, tip opening angle a, and base opening angle b. Also shown is the free body diagram illustrating out-of-plane (Fy), in-plane (Fel), normal (Fn), and tangential (Ft) contact forces during interaction.

2. GEOMETRICAL AND PHYSICAL PARAMETERS AFFECTING MECHANICAL ADHESION

This work focuses on the fundamental mechanics of the single-pair interaction between double conical microgeometries. This shape's selection comes from its high tunability since it has three geometrical descriptors that are strictly related to the interlocking performance, the radius R has an impact on the overall strength of the interaction both in attachment and detachment phases, while the opening angles α and β can modify the adhesion performances in the attaching and detaching phase respectively. The quasi-static local contact model utilizes a Winkler foundation assumption, incorporating frictional dissipation via Coulomb's law and accounting for local adhesion (van der Waals forces). Figure 1 illustrates these shapes and their supporting rod deformation. In the same Figure, normal (F_n) and tangential (F_t) contact forces, penetration (δ) and contact radii (a), out-of-plane (F_y) and in-plane (F_{el}) forces, microstructure radius (R), out-of-plane distance (y), tip (α) and bottom (β) opening angles are defined.

For simplicity, individual interactions are treated as independent. In densely packed systems, we approximate the effect of neighboring structures by considering a constant in-plane lattice distance (l_0), an assumption analogous to an effectively infinite bending stiffness of the rod.

In the subsequent sections of this work, we will systematically investigate the role of: 1) the geometry of the interlockers; 2) the role of surface energy in the adhesive performance; 3) the influence of friction on the adhesive performance, and 4) an experimental section which demonstrate the robustness of the proposed family of interlockers.

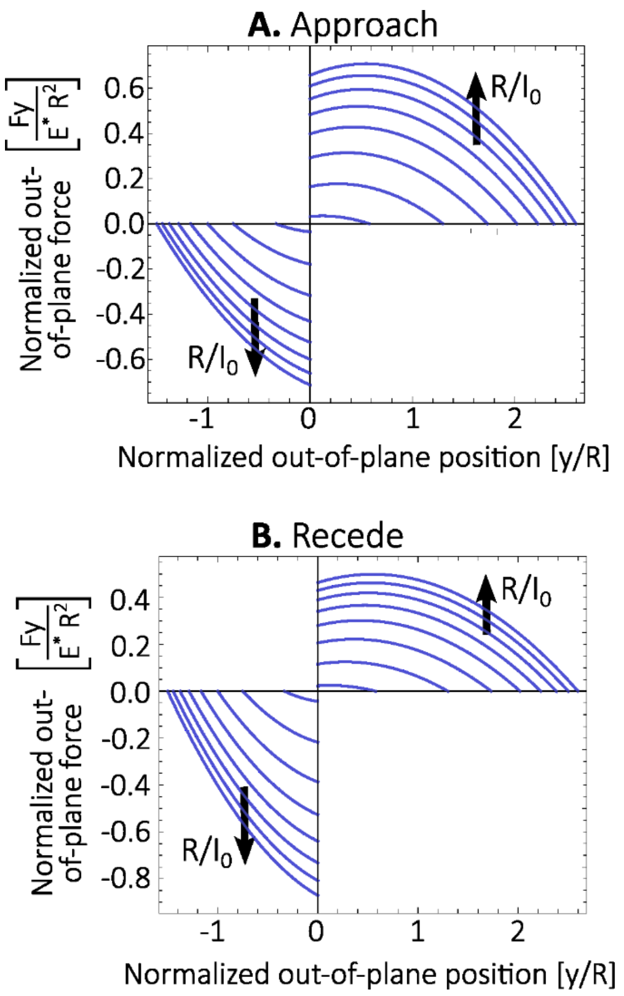

Figure 2. Normalized out-of-plane force (Fy) during conical interlocker interaction for varying R/l_0 ratios (0.4 to 2, step 0.2) during approaching (A) and receding (B) motion.

2.1 Geometry

For a Winkler foundation without adhesion, the normal force in a cylindrical contact is the following [18]:

$$F_{\mathrm{n}} = \frac{\pi}{4} E^{*} \delta(y, I) l(y, I). \qquad (1)$$

Following Figure 1 schematics it is possible to write the momentum equation in the vertical (out-of-plane) direction, thus relating the out-of-plane force to the deformation of the contacting cones

$$F_y = \begin{cases} \frac{\pi}{4} E * \delta(y, I) l(y, I)(\sin\alpha \pm \mu\cos\alpha) & y \geq 0 \\ \frac{\pi}{4} E * \delta(y, I) l(y, I)(-\sin\beta \pm \mu\cos\beta) & y < 0 \end{cases} \qquad (2)$$

While more intricate microgeometries would necessitate numerical contact mechanics approaches (e.g., finite element methods), the multiscale methodology developed herein remains applicable. For quantitative simplicity and due to its negligible impact on the overall effective work of adhesion, local adhesion is not included in the present model.

A key point to have a solvable system of equations is establishing the relationship between contact parameters (length l, penetration δ) and the relative positioning of two cones (in-plane distance I, out-of-plane distance y). This relationship is discontinuous, exhibiting distinct behaviours depending on the contacting region, as experimentally observed in the force measurements during attachment (Figure 3), these relations are obtained by geometrical considerations and are reported below:

$$\boldsymbol{\delta(y, I)} = \begin{cases} (2R - I)\cos\alpha - y\sin\alpha & y \geq 0 \\ (2R - I)\cos\beta + y\sin\beta & y < 0 \end{cases} \qquad (3)$$

$$\boldsymbol{l(y, I)} = \begin{cases} \dfrac{(2R - I)\cos\alpha - y\sin\alpha}{\sin 2\alpha} & y \geq 0, I < R \\ \dfrac{(2R - I)\cos\beta + y\sin\beta}{\sin(\alpha + \beta)} & y \geq 0, I \geq R \\ \dfrac{(2R - I)\cos\alpha - y\sin\alpha}{\sin(\alpha + \beta)} & y < 0 \end{cases} \qquad (4)$$

The non-interlocked state (y>0) further presents two sub-branches depending on the contact between the cone tips and surfaces (Figure 1).

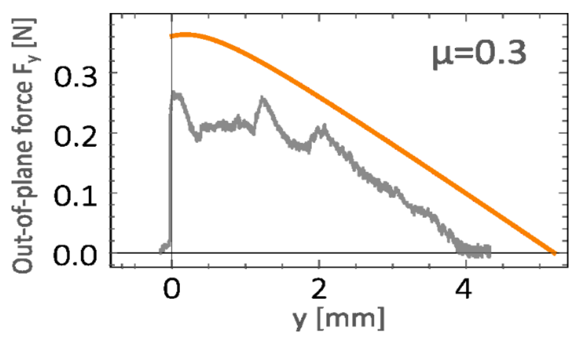

Figure 3. Comparison between numerical and experimental out-of-plane force during approaching motion of a single pair of conical interlockers (l_0=3mm; R=3mm; α=30°; β=60°)

Plotting the out-of-plane force for any value of out-of-plane distance is finally possible. Normalizing the system we performed a parametric investigation on the role of the dimension of the interlocker (Figure 2), and it is interesting to note that the normalized force increases with the R/l_0 value, suggesting that densely packed structures will result in a higher adhesive strength.

2.2 Surface Energy

Surface energy, denoted by Δγ, has negligible influence on the interlocking performance, specifically the out-of-plane force (F_y). Using the relations in [19] and [20] It is possible to build a Hertzian contact model that also includes surface energy. Still, a further numerical integration step along the contact line is needed to obtain the relation between F_y and y. Using this more accurate model and switching off the local adhesion component, no significant change in the overall mechanical response is observed, as reported in Figure 4.

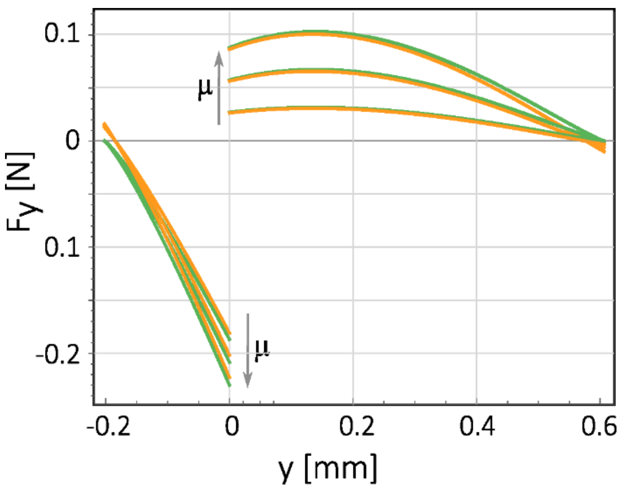

Figure 4. Predicted detachment force (Fy) of a soft double cone interlocker (E=4 MPa, R=0.7mm, l_0=1mm) at different friction coefficients (μ = 0, 0.2, 0.4), with a comparison between nearly-adhesionless (surface energy = 10^{-3} N/m) and adhesive (surface energy = 10 N/m) interactions.

This finding suggests that for the investigated interlocking mechanisms and scales, the contribution of surface energy is subordinate to the geometrical and frictional factors governing the interaction. Consequently, our primary model focuses on these dominant parameters to accurately predict interlocking behaviour.

2.3 Friction

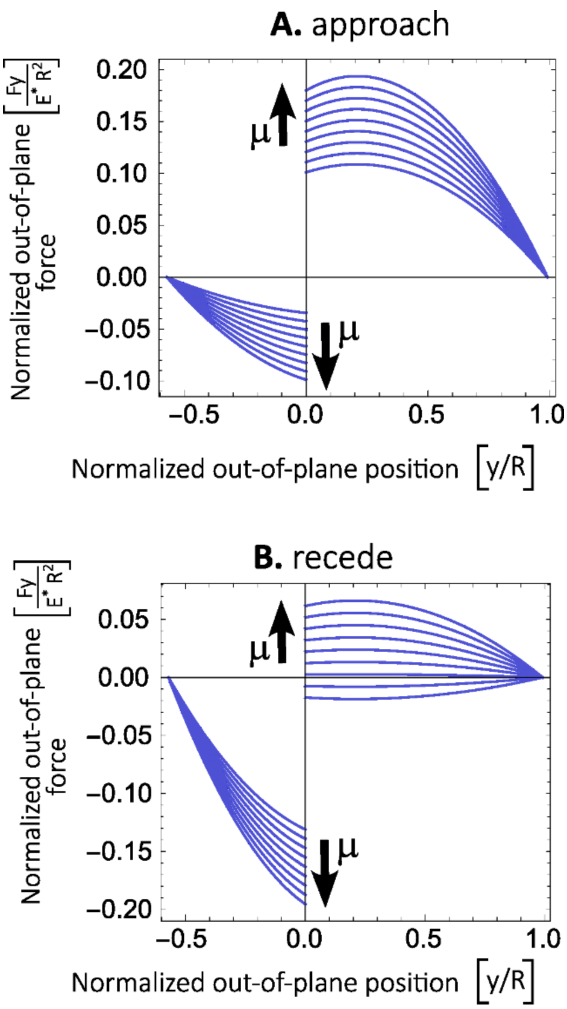

Figure 5. Normalized out-of-plane force (Fy) during conical interlocker interaction for varying friction coefficient values (0.14 to 0.7, step 0.07) during approaching (A) and receding (B) motion.

Friction plays a pivotal role in mechanical interlocking. It synergistically acts with the interfacially-stored elastic energy to resist detachment and enhance adhesive strength. Conversely, it increases the force required to engage the structures (see Figure 5). As already discussed, unlike traditional adhesives, which rely on van der Waals forces and often fail in contaminated or hydrated environments, interlocking systems can achieve high pull-off strength due to frictional contributions. These contributions are surely affected by surface cleanliness or humidity but not completely suppressed, as in the case of surface energy.

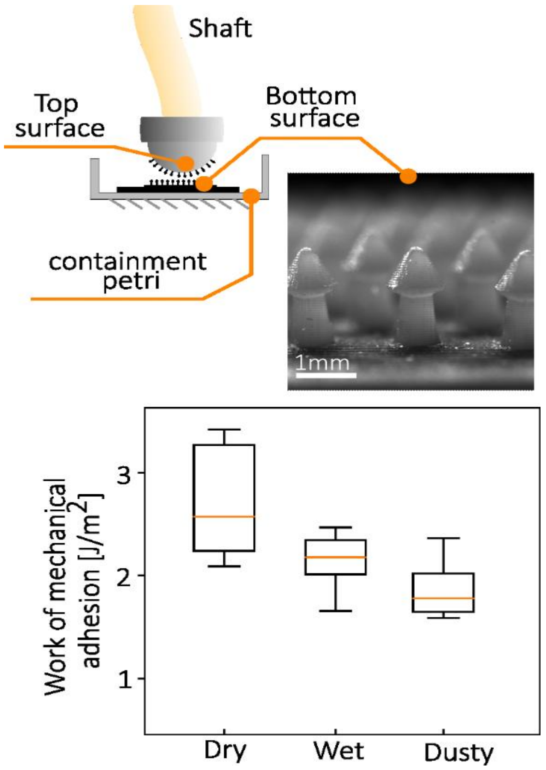

Figure 6. (TOP) Schematics of the experimental setup used to perform the interlocking tests and microscope image of the 3D printed samples (R=0.7mm; α=30°; β=60°). The out-of-plane force was measured using a load cell attached to the supporting shaft. (BOTTOM) Results of the interlocking tests, showing the box-plots (n=10) of the measured work of mechanical adhesion in dry, wet (distilled water), and dusty (talc powder) conditions.

The frictional coefficient also determines the critical tip angle (?) at which jamming (i.e., a non-reversible locking state) can occur in double conical interlockers, influencing whether the system engages in stick-slip behaviour or buckling. It is important, then, to characterize the contact pair friction in the operating environment to design the structure properly. In Figure 6 it is experimentally demonstrated that the friction coefficient directly affects the pull-off pressure and the effective work of mechanical adhesion—higher friction coefficients lead to stronger engagement and more energy required to disengage the interlocked surfaces.

3. CONCLUSIONS

This work analyzes a new family of reversible fastener geometry and sets the basis for understanding the roles of shape, friction, and surface energy in mechanical interlocking adhesives. It has been shown that by carefully designing the microscale contact geometry of these single pairs, it becomes possible to tune adhesion in a controlled manner for various applications. Our experimental validation in diverse environments (dry, underwater, and dusty) demonstrates the potential of this approach and the robustness to contamination of double conical interlockers. The design methods developed here offer a pathway for the reliable application of mechanical adhesion in fields where traditional adhesives struggle, such as industrial automation, biomedicine, and harsh environments. This research highlights the fundamental influence of geometry and friction in achieving controlled mechanical adhesion through the double-cone design.

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