

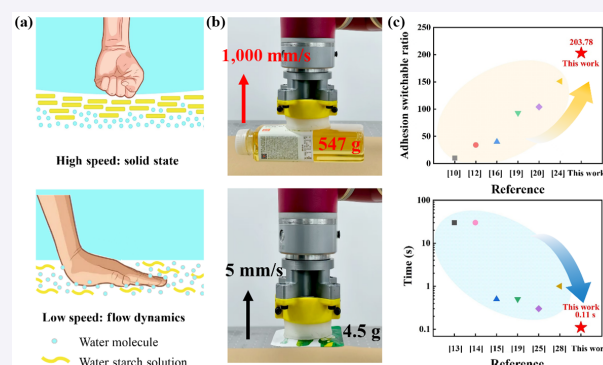
Speed-controlled adhesive gripper

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ABSTRACT: Adhesion systems with dynamically adjustable adhesion states have broad application prospects. In this work, for the first time, strong adhesion and easy detachment are achieved solely through the movement speed of the gripper without the use of any external stimulation. The flexible gripper based on the core-shell structure with a corn-starch suspension encapsulated by polydimethylsiloxane (PDMS) achieved a grasping ability of 33.71 g/cm², a ratio of adhesion to detachment of 203.78, and a response time of only 0.11 s. The rheological properties of non-Newtonian fluid (NNF) provide the regulatory ability of adhesion states. The designed speed-control method is superior to the strategies of changing the temperature through photothermal and Joule heating, applying an external magnetic field, and adjusting the stiffness of the backplate. This scheme not only breaks through the traditional external field-driving mode, successfully resolving the inherent contradiction between strong adhesion and easy detachment of the flexible adhesive gripper, but also enables universal grasping and rapid release of various materials and various target shapes. The gripper shows significant application potential in scenarios such as rapid transfer of electronic components, nondestructive picking of flexible materials, climbing and adhesion of small robots, and transportation of biomedical samples.

KEYWORDS: adhesive gripper; speed-controlled; non-Newtonian fluid (NNF); core-shell structure; adhesion/detachment regulation



1 Introduction

Adhesion systems with dynamically adjustable adhesion states have a wide range of applications in biomedical [1], transfer printing [2–4], climbing robots [5–7], and bionic adhesion [8–10]. To address the issue of insufficient adhesion strength control ability of the adhesion system [11, 12], various innovative solutions have been proposed, including adhesion control based on photothermal response [13–17], magnetic control technology [18–20], subsurface stiffness regulation [21–25], air pressure regulation [26–28], and mechanical stripping [29–31]. For instance, the adhesion properties of polydimethylsiloxane (PDMS) were altered through infrared laser [13] and heating [15]. However, there are some issues, such as response delay (adhesion and detachment time > 5 s) and low adhesion/detachment ratio (5–23) [13–16]. By applying an external magnetic field to drive the bending deformation of the mushroom-shaped tip of PDMS that incorporates hard magnetic particles, the adhesion state can be changed. The response time was reduced to 0.5 s, but this adhesion system can only capture nonmagnetic sensitive targets [18]. The particle-blocking gripper under vacuum negative

pressure control [21, 22] was capable of grasping objects weighing over 2 kg. The maximum ratio of adhesion to detachment was 92.8, and the fastest response time was 0.5 s. However, due to the use of a vacuum pump, miniaturization of the system was difficult to achieve. Through the aerodynamic control (positive/negative pressure) of interface stress distribution, although the ratio of adhesion to detachment was as high as 247, the maximum grasping weight was only 7.7 g, the response time was ~2 s, and there was a risk of instability under critical pressure [26–28]. The strategy of regulating the adhesion state by applying mechanical forces such as torque or vertical preload was only applicable to smooth or low-roughness surfaces, and the applied force may create a risk of deformation or damage to the material [29, 30].

Shear thickening fluids (STFs) are a type of non-Newtonian fluid (NNF) whose viscosity increases sharply with increasing shear rate, reaching several orders of magnitude of change. For instance, reversible “fluid–solid-like” phase transition behaviors, extremely fast response speeds, and outstanding cycle stability exist under different shear rates [32–36]. This inherent property, namely, the ability to solidify immediately upon being subjected to an impact and to automatically return to a flowing state after the

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impact, endows this material with outstanding shock absorption, energy dissipation buffering, and deformation adaptability. It has been widely applied in fields such as impact shock reduction, armor protection, and mechanical systems [37–39]. Aiming at problems such as a low ratio of adhesion to detachment, long response time, and poor grasping stability in the dynamic regulation of the existing adhesion system, this study innovatively proposes applying the rheological properties of NNF to the adhesion system. A flexible gripper with a core-shell structure using a corn-starch suspension encapsulated by PDMS was designed for the first time. The grasping capacity reached 33.71 g/cm², the ratio of adhesion to detachment was as high as 203.78, and the response time was as low as 0.11 s. This scheme not only breaks through the traditional external field-driving mode, successfully resolving the inherent contradiction between strong adhesion and easy detachment of the flexible adhesion gripper, but also enables universal grasping and rapid release of various materials and various target shapes. It provides a new idea for the development of low-cost, highly adaptable, and externally control-free adsorption systems.

2 Materials, core-shell structure, and characterization methods

2.1 Preparation of NNF and design of core-shell structure

The sodium carboxymethyl cellulose (CMC) used in this work was purchased from Shanghai Changguang Enterprise Development Co., Ltd., China. The role of CMC is to effectively inhibit the sedimentation of starch granules and improve the stability of the system [40, 41]. Starch was purchased from Beijing Gidley Food Co., Ltd., China. PDMS was purchased from Dow Corning Corporation, USA. Ecoflex 00-30 silica gel was purchased from Smooth-On, Inc., USA. Pure water (H₂O) was obtained from Hangzhou Wahaha Co., Ltd., China. By comparing different NNFs, we found that the water starch system has optimal shear thickening (ST) NNF characteristics and is the optimal core fluid to meet the core requirements of cross-scale regulation of adhesion in this study. NNF samples (NNF1–NNF4) were prepared by mixing sodium CMC solution (H₂O : CMC = 200 : 1) with starch at mass ratios of 12:14, 12:15, 12:16, and 12:17. The glass substrate used in the experiment is borosilicate glass (5 mm in thickness, 100 mm in diameter). The surface treatment optimization process is as follows: ultrasonic cleaning with anhydrous ethanol and deionized water for 15 min and then drying with dry N₂ to completely remove the residual water vapor on the substrate surface. The surface roughness of the cleaned and dried glass and PDMS specimens was characterized using a 3D white light interferometer (SuperView W1, Shenzhen Zhongtu Instrument Co., Ltd., China). Experiments were repeated at least three times to ensure data reliability. The surface roughness of all glass samples was approximately 1 nm, while that of the planar and spherical PDMS samples was approximately 9 and 292 nm, respectively (Fig. S1 in the Electronic Supplementary Material (ESM)). The experimental results confirm that this roughness range has no significant influence on the adhesive performance of PDMS.

Based on the rheological properties of NNF, a closed core-shell structure gripper was designed for the first time in this work, named NNF CS1 (Fig. 1). The gripper was mainly composed of the following components: composite flexible shell, NNF core, fluid perfusion and sealing system, and hard structural parts (Fig. 1(a)). The contact surface of the composite flexible shell was

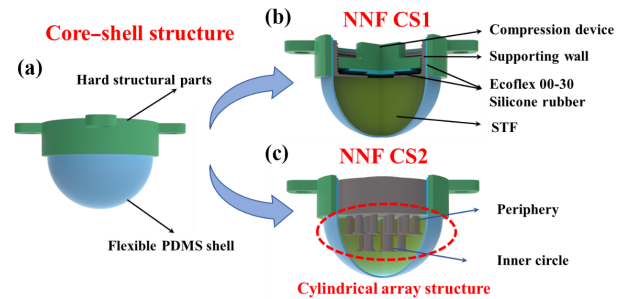


Fig. 1 Design of the core-shell structure gripper. (a) STF flexible shell core structure gripper structure diagram, (b) NNF CS1 internal structure diagram, and (c) NNF CS2 internal array structure diagram.

made of PDMS with a thickness of 1 mm and a radius of 30 mm, while the sidewalls and transition areas adopted Ecoflex 00-30 silicone. The closed core-shell structure was formed by integrating the PDMS contact surface and the silicone sidewall through an integrated molding process, and the core was filled with NNF. Double seals were formed between the sidewall and the inner wall of the silicone rubber through the thread locking structure. The structure is free of built-in obstacle columns, designed to verify the correlation between the NNF ST effect and speed as well as provide a reliable reference for subsequent structural optimization.

In this study, a derivative configuration named NNF CS2 (Fig. 1(c)) was further designed inside NNF CS1, and the main difference between NNF CS2 and NNF CS1 lies in the internal cavity structure: The internal cavity of NNF CS1 was only filled with NNF material, while NNF CS2 integrates a columnar structure array at the bottom of the cavity to enhance fluid shear disturbance. Specifically, this columnar structure was designed based on the bottom of the inner wall of a rigid hollow cylindrical bracket with a diameter of 58 mm and consists of two concentric circles. All cylinders had a diameter of 3.5 mm, where the inner circle contained 8 cylinders with a height of 16 mm, evenly distributed at a distance of 12 mm from the center, and the outer circle contained 16 cylinders with a height of 8 mm, evenly distributed at a radius of 20 mm. The top of each cylinder was also equipped with a cylindrical flexible cap-shaped structure with a diameter of 6.5 mm and a height of 1 mm to enhance local disturbance and structural stability, which was an optimized core-shell structure with a built-in columnar array. The design goal is to extend the path length of the NNF fluid in the shear process and increase the contact frequency of the shear surface through the flow channel regulation of the columnar array, thereby strengthening the ST effect, further improving the regulation range and stability of the adhesion force, and solving the problem of weak shear effect and insufficient regulation accuracy in the basic configuration of NNF CS1.

2.2 Characterization method of adhesion force

As the core index to evaluate the performance of flexible grippers, the accurate quantification of adhesion force is very important for the optimization of the core-shell structure. In this study, an adhesion force model was established based on Johnson–Kendall–Roberts (JKR) sphere-plane peeling theory, which accurately correlates adhesion force with material properties through axisymmetric contact analysis [42–44]. The standard adhesion test system (Fig. S2 in the ESM) was used to carry out the adhesion and detachment test, and a spherical PDMS shell structure was adopted to contact the fixed glass plate. The test process strictly follows the three-stage steps: (1) contact stage: The spherical core-shell structure contacts the glass plate at a constant

loading speed of 5 mm/s until the preset 5 N contact load is reached; (2) relaxation stage: The contact state is maintained for 5 s to ensure interface stress relaxation; (3) stripping stage: The spherical core-shell structure is vertically retracted at a gradient stripping speed in the range of 1–100 mm/s. Each group of parameters was tested 10 times ($n = 10$). In this work, the “adhesion force” was defined as the peak value of the normal force ($F_{\max}$) monitored during the peeling process, which comprehensively reflects the interfacial bonding strength and energy dissipation capacity. All experiments were carried out in a constant temperature and humidity environment (20–25 °C; 40%–60% RH) to ensure the consistency and repeatability of the experimental results.

3 Adhesion performance of the flexible gripper

The ST effect of NNF originates from the microscopic process of the transition from dispersed particles to agglomerates: When the shear rate exceeds the critical value, a hydrodynamic cluster is formed between the particles, causing a significant increase in apparent viscosity (Fig. S3 in the ESM) [32, 36].

This phenomenon has a significant rate dependence and reversibility; it exhibits fluid behavior at low shear rates, instantaneously solidifies under high-speed shear, and restores the flow state after the external force is removed (Fig. 2(a)). Based on the corn-starch suspension as the ST model system, the speed-controlled flexible gripper with a core-shell structure was designed for the first time. The dynamic regulation of rheological properties under the speed effect in the grasping process was realized, and this regulation ability was transformed into the response mechanism of peeling speed to adhesion force (Fig. 2(b)). Compared with the reported adhesion systems regarding the ratio of adhesion to detachment and response time, the designed adhesion system in this study has the best performance (Fig. 2(c)).

3.1 Dynamic adhesion enhancement and regulatory mechanism of ST of the core-shell structure

The dynamic control of the adhesion performance of the velocity-controlled viscous gripper based on the NNF core/PDMS shell-core structure is derived from the synergistic effect of the spherical contact geometry, the viscoelasticity of PDMS, and the ST effect of NNF. In this study, based on JKR contact theory [42–44], the Peel zone model [45, 46], and the ST mechanism [32, 34, 36], the traditional plane peeling model is extended to the spherical scene, and the static–dynamic adhesion theory system is established. The quantitative theory of interface failure in the dynamic peeling process is derived, and the internal mechanism of adhesion enhancement and interface stability is revealed.

The core-shell structure is composed of an elastic PDMS shell and an NNF core. To simplify the contact mechanics analysis, it is equivalent to a homogeneous elastomer based on the principle of flexibility superposition [47]. Considering the geometric characteristics that the shell thickness of the core-shell structure is much smaller than the core size, ignoring the geometric proportion correction, the equivalent flexibility (J^*), the shell flexibility (J_{shell}), and the core flexibility (J_{core}) satisfy $J^* = J_{\text{shell}} + J_{\text{core}}$. The equivalent elastic modulus (E^*) of the core-shell structure is in Eq. (1):

$$E^* = \frac{1}{J^*} = \frac{1}{\frac{1 - \nu_{\text{shell}}^2}{E_{\text{shell}}} + \frac{1}{E_{\text{core}}}} \quad (1)$$

where the elastic modulus of the PDMS shell measured by E_{shell} is 1.2×10^6 Pa, ν_{shell} is the measured Poisson's ratio of the PDMS shell, which is 0.48, and E_{core} is the equivalent elastic modulus of the NNF core [36].

Based on the classical contact theory of JKR [42–44], this study extends to the spherical contact scenario of a “hemispherical core-shell structure in contact with rigid glass (elastic modulus

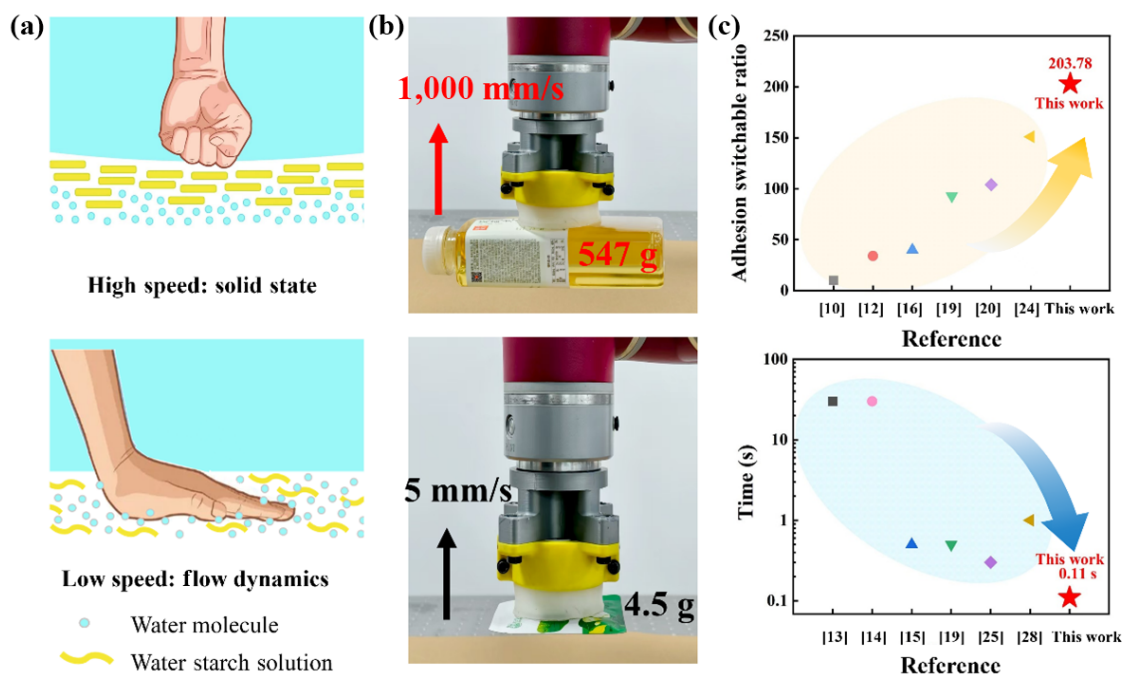


Fig. 2 Design principle of the gripper with a reversible liquid–solid transition. (a) Fluid characteristics of NNF at different velocities, (b) designed speed-controlled adhesion system, and (c) comparison of the adhesion–detachment ratio and adhesion response time with those of photothermal, magnetic control, subsurface stiffness regulation, and other adhesion/detachment regulation methods.

infinity)". Considering the squeezing effect of the initial normal prepressure and the effect of the interface adhesion energy, the initial contact radius (a_0) is derived:

$$a_0^3 = \frac{3F_N R}{4E^*} + \frac{6\pi\gamma R^2}{4E^*} \quad (2)$$

where F_N is the initial normal prepressure, the radius of curvature of the nucleus in the R hemisphere is 29 mm in this experiment, γ is the PDMS-glass interface energy (J/m²), and the value is 24 J/m² [45].

Combined with the force-energy balance principle of the Kendall peeling theory [42], considering the nonuniformity of the stress distribution in spherical contact, the curvature correction term is introduced to derive the spherical adhesion force (F_{st}) in a static scene:

$$F_{st} = 2\pi a G_c + \frac{\pi \sigma_{res} a^2}{2R} \quad (3)$$

where a is the instantaneous contact radius, which is approximately equal to a_0 in the static scene. G_c is the critical energy release rate of the PDMS-glass interface, which represents the energy required to peel off the interface per unit area. The experimental calculation is 25×10^{-3} J/m². σ_{res} is the residual stress of the core-shell structure, which is caused by the curing shrinkage of PDMS and the difference in the thermal expansion coefficient of the shell core. The value measured by the stress-strain test is 1.2×10^4 Pa. $\sigma_{res} a^2 / (2R)$ represents the spherical curvature correction force term, which is used to correct the limitations of the plane stripping model [45].

Velocity is the core variable of dynamic adhesion regulation, and the adhesion enhancement effect is derived from the synergistic effect of viscoelastic dissipation of the PDMS shell and velocity-sensitive ST dissipation of the NNF core. The ST characteristics of the NNF core show that the stiffness increases nonlinearly and monotonically with the peeling speed following a power-law relationship. Based on the correlation between the macroscopic mechanical performance and the rheological properties [32, 34], the power-law positive-correlated growth relationship between the equivalent elastic modulus of the core and the peeling speed is established:

$$E_{core} = E_{0,core} + kv^n \quad (4)$$

where $E_{0,core}$ is the initial equivalent elastic modulus of the NNF core [36], n is the shear-rate-peeling-velocity nonlinear exponent, reflecting the nonlinear variation of the internal shear rate of the NNF with the macroscopic peeling velocity, with an experimental fitting value of 1.986, k is the stiffness-velocity nonlinear sensitivity coefficient, and the experimentally fitted value is approximately 7.6×10^3 Pa·(mm/s)^{-1.986}, which characterizes the nonlinear growth rate of the core stiffness with the peeling velocity [32].

Based on the static model, a dynamic adhesion model is constructed by integrating the speed-dependent energy dissipation term. Referring to the extended peeling zone model of viscoelastic materials [45] and the velocity-force correlation law [46], the viscoelastic dissipation of PDMS and the ST dissipation of the non-Newtonian core are simplified into a unified power law form, and the dynamic adhesion force ($F(v)$) is obtained:

$$F(v) = 2\pi a G_c + \frac{\pi \sigma_{res} a^2}{2R} + Cv^n = F_0 + Cv^n \quad (5)$$

where v is the stripping velocity, and F_0 is a constant term integrated from the total static adhesion component, composed of

the critical interfacial energy release rate contribution term $2\pi a G_c$ and the spherical curvature correction force term $\pi \sigma_{res} a^2 / 2R$, which characterizes the fundamental adhesion force under static conditions. C is the comprehensive velocity dissipation coefficient, with an experimentally fitted value of $0.0152 \text{ N} \cdot \text{m}^{-2} \cdot (\text{m/s})^{-1.986}$, which characterizes the total dissipation intensity of PDMS and non-Newtonian cores, and Cv^n is a velocity-dependent energy dissipation contribution: Under high-speed conditions, the deformation hysteresis of PDMS molecular chains produces viscoelastic dissipation, the non-Newtonian core undergoes ST due to high-speed shearing, and the stiffness and energy dissipation are significantly improved, which together lead to the phenomenon of "low-speed low adhesion, high-speed high adhesion" [36, 46].

To quantify the interface failure characteristics during the dynamic peeling process, the contact area decay rate (CADR) is defined to characterize the stability of the contact area, and its expression is

$$\text{CADR} = \left(1 - \frac{A_t}{A_0}\right) \times 100\% \quad (6)$$

where A_0 is the initial contact area, and A_t is the residual contact area of the critical failure point. The smaller the CADR value is, the stronger the interface contact stability is. It is assumed that during the high-speed peeling process, the annular crack at the contact edge expands uniformly from the outside to the inside, and the remaining contact radius ($r(t)$) satisfies the following relationship:

$$r(t) = r_0 - v_c t \quad (7)$$

where v_c is the crack propagation rate, r_0 is the initial contact radius, and t is the peeling time. Substituting Eq. (7) into Eq. (6), the expression of the crack growth rate is obtained:

$$v_c = \frac{A_0 - A_t}{A_0 t} \frac{r_0}{\sqrt{A_0/\pi}} \quad (8)$$

The equation can directly calculate the crack growth rate through the experimentally measured A_0 , A_t , and t and quantify the speed of interface failure. Based on the Peel Zone model [45, 46], the crack growth rate and the peeling angle satisfy the power law relationship, which further reveals the influence of the peeling attitude on the interface stability:

$$v_c = k_\theta \theta^m \quad (9)$$

where $m = 1.8$ is the experimental fitting index, which characterizes the nonlinear effect of the peeling angle on crack propagation. k_θ is the characteristic coefficient related to the material properties; θ is the peeling angle, which is defined as the instantaneous macroscopic angle between the peeling movement direction of any point on the annular contact front of the spherical gripper and the tangent direction of the glass surface (Fig. S4 in the ESM).

Substituting Eqs. (8) and (9) into Eq. (6), the correlation between the peeling angle and the CADR can be obtained:

$$\text{CADR} = \left(1 - \frac{\sqrt{A_0/\pi} - k_\theta \theta^m t}{\sqrt{A_0/\pi}}\right) \times 100\% \quad (10)$$

The equation shows that a smaller peeling angle can significantly reduce interface instability, with the ST effect of NNF facilitating the synergistic inhibition of interface failure.

3.2 Adhesion behavior of the velocity response

The NNF-PDMS spherical core-shell structure shown in Fig. S1 in the ESM, named NNF CS1, was used to explore the relationship between the adhesion force and the peeling speed. From Fig. 3(a), it can be seen that as the stripping speed increases from 1 to 80 mm/s, the $F_{\max}$ of NNF CS1 increases significantly from 0.37 to 62.50 N, showing a significant nonlinear enhancement trend. This result intuitively proves that the adhesion performance of the NNF-PDMS core-shell structure has a strong stripping speed dependence. This trend is completely consistent with the prediction of Eq. (5): At low speed, the velocity-dependent energy dissipation term Cv^n accounts for a very low proportion, and the adhesion force is mainly contributed by the static terms G_c and $\sigma_{res}a/(2R)$, so the value is small. At high speed, Cv^n increases in a power-law manner, which becomes the dominant factor in the improvement of adhesion and eventually leads to the regulation of adhesion across three orders of magnitude. It is directly related to the high-speed strengthening mechanism of the energy dissipation term in Eq. (5). In addition, the core-shell structure exhibits ultrafast dynamic response characteristics: at a peeling speed of 80 mm/s, the adhesion response time T_{I-II} from the initial peeling point I to the maximum adhesion force point II was only 0.11 s, which was shorter than 0.5 s using magnetic field control and particle blocking control [18, 22]. By comparing and analyzing the adhesion between the water-based and NNF-based core-shell structures at different speeds, as shown in Fig. 3(b), it was found that the adhesion forces of both systems were very low at a slow speed of 5 mm/s, and the difference was slight. As the speed increases, the adhesion force of the NNF system increases rapidly. When the stripping speed reached 80 mm/s, the adhesion force reached 62.50 N and tended to be saturated, which was due to the limitation of the structure on the ST effect of the NNF system. The

adhesion force at 80 mm/s was 7.2 times higher than that of the water-based system. The ratio of adhesion-to-detachment reached 168.9 for NNF CS1 when comparing the adhesion force at a high speed of 80 mm/s and a low stripping speed of 1 mm/s. The above performance differences are mainly due to the difference in the separation mechanism of the core-shell core. (1) The water-based system always exhibits a viscous separation behavior, and the stripping area shrinks rapidly from the edge to the center (Fig. S5 in the ESM). (2) The NNF system exhibits fluid-like separation characteristics at a slow speed, while the ST effect is triggered during high-speed shearing, and the viscosity increases sharply, resulting in the “solidification” of the peeling zone morphology, showing the adhesion enhancement characteristics driven by the ST effect (Fig. 3(c)). Further analysis of the dynamic behavior diagram of the stripping process reveals the physical mechanism of adhesion enhancement: as the stripping speed increases, the core-shell structure changes from a smooth stripping mode at a slow speed to a fast vertical separation mode at a high speed, indicating that the adhesion behavior has a strong speed dependence [47, 48].

Substituting the adhesion test data at different speeds into Eq. (5) and conducting the analysis, it is found that the contribution ratio of F_0 to the dynamic adhesion force is less than 5%. Thus, for the dynamic peeling stage with a peeling velocity of 1–80 mm/s, the relationship between the adhesion force and peeling speed can be simplified as Eq. (11):

$$F(v) = k_v v^{1.986} \quad (11)$$

where k_v is the comprehensive coefficient for the power-law relationship between the adhesion force and peeling velocity. It is derived from the integration of F_0 and the comprehensive velocity dissipation coefficient C in the dynamic adhesion force model,

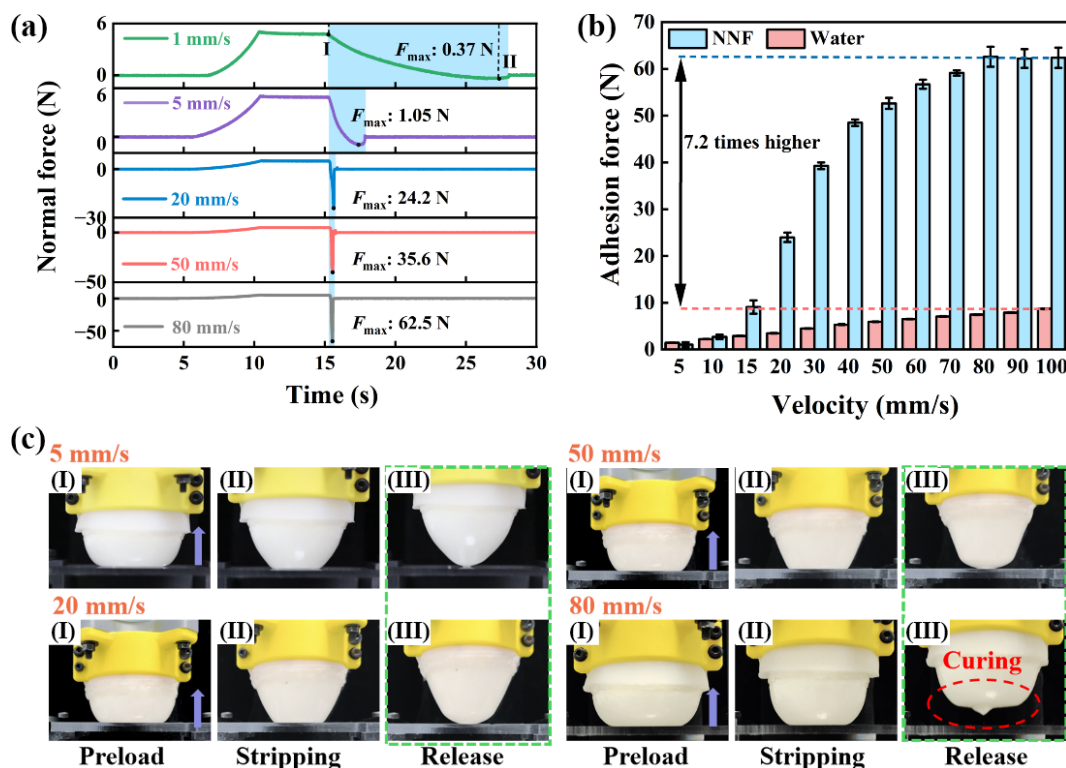


Fig. 3 Stick-off behavior of the NNF CS1 velocity response of the NNF core-shell structure. (a) Normal force-time curve of the gripper with NNF4 as the core at different speeds, point I: the initial point of contact, point II: $F_{\max}$. (b) Speed dependence comparison of water and NNF4 core peeling (NNF4 core adhesion force is 7.2 times higher than water at 100 mm/s). (c) Change law of the shape of the core-shell structure during the peeling process at different speeds.

characterizing the power-law growth characteristic of adhesion force with peeling velocity in this velocity range, with a value of approximately $279.8 \text{ N} \cdot (\text{m/s})^{-1.986}$. This simplified relationship reflects the unique advantages of the NNF core. Through the speed-dependent ST effect, the cross-scale regulation of the adhesion force from low speed to high speed is realized, which breaks through the bottleneck of the limited adjustment range of the adhesion force of the traditional viscous gripper and provides theoretical support for target grasping under different weights and different working conditions.

3.3 Effect of core-shell structure on adhesion behavior

The starch concentration, relaxation time, preload, thickness of the PDMS shell, core structure, and other parameters will affect the adhesion behavior. For this reason, a systematic verification experiment was further carried out, and the results are shown in Fig. 4. The verification test was carried out using an NNF CS1 structure with a PDMS shell thickness of 1 mm under a preload of 5 N and a peeling speed of 80 mm/s. The adhesion force increased significantly with increasing starch concentration, from 8.57 N (NNF1) to 59.0 N (NNF4). By strengthening the ST effect, the energy dissipation mechanism is optimized, thereby significantly improving the adhesion performance (Fig. 4(a)). This result is directly related to Eq. (4) in Section 3.1: The increase in starch concentration strengthens the ST effect, increases the speed sensitivity coefficient of core stiffness, and increases the growth rate of the equivalent elastic modulus with speed, thus optimizing the energy dissipation mechanism and finally significantly

improving the adhesion performance. The research on the influence of relaxation time indicates that under a preloading force of 5 N and a peeling speed of 80 mm/s, prolonging the interface contact time (0–30 s) will slightly increase the adhesion force, and this increase is mainly concentrated within the first 5 s (Fig. 4(b)). After more than 5 s, the adhesion tended to reach saturation, and the relaxation saturation effect of NNF4 (water : starch = 12 : 17) was the most significant. After contact for 5 s, the adhesion reached over 95% of the maximum value, so 5 s was set as the standard contact time for the subsequent experiments. The preload experiment confirmed that the adhesion force was positively correlated with the preloading force, which was consistent with the “conformal contact” theory [49–51]. The preload promoted the adaptive deformation of the PDMS membrane, thereby effectively enlarging the actual interfacial adhesion area and ultimately achieving a significant enhancement of the adhesion force (Fig. 4(c)). Substituting $F_N = 5 \text{ N}$ into Eq. (2), the initial contact radius is calculated to be approximately 20.75 mm, which is consistent with the experimental value. The effect of PDMS thickness on adhesion performance was evaluated in Fig. 4(d). The results showed that the adhesion force decreased significantly with increasing film thickness. In the high-speed region (80 mm/s), the adhesion force of PDMS with a 1 mm thickness (62.5 N) was 2.9 times higher than that of PDMS with a 2.5 mm thickness (21.5 N). In the slow-speed region (5 mm/s), the thickness effect was not significant. This is related to the equivalent elastic modulus, Eq. (1), in Section 3.1: The thinner PDMS shell has greater flexibility and more easily cooperates with the ST effect of the non-Newtonian core, so that the overall

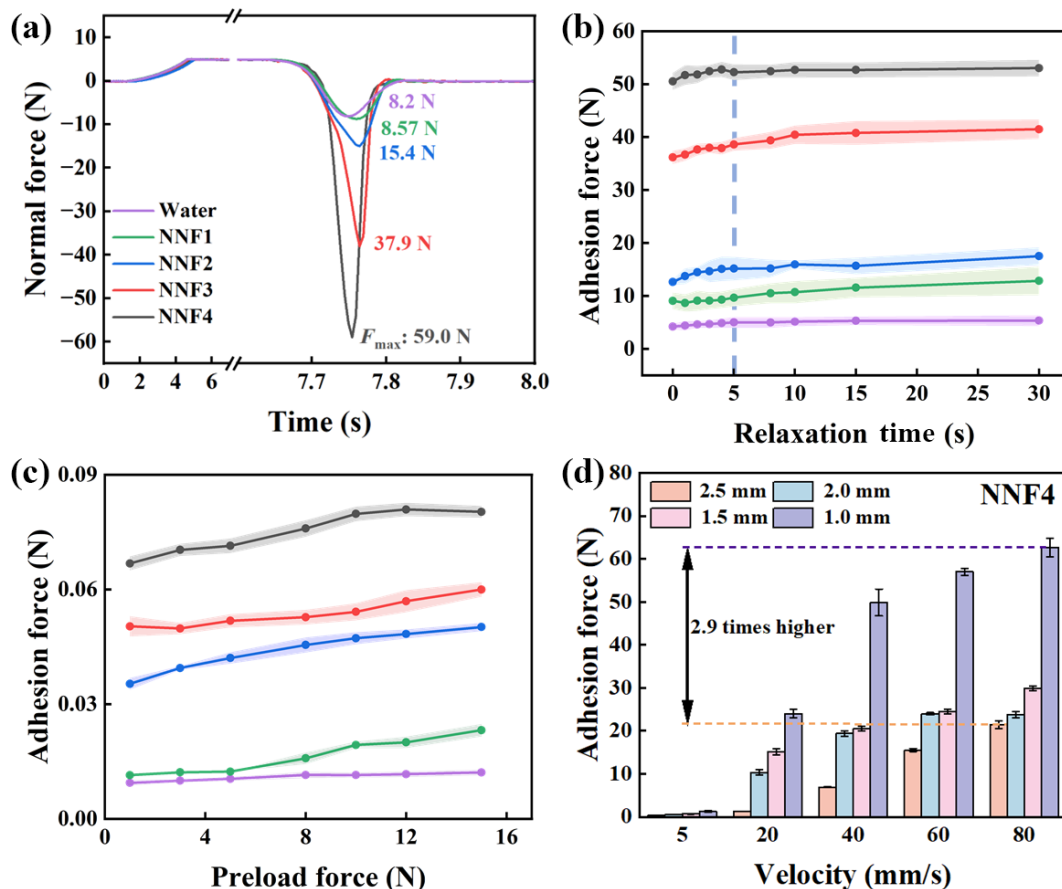


Fig. 4 Quantitative analysis of factors affecting adhesion. (a) NNF1–NNF4 (12:14, 12:15, 12:16, and 12:17) as the core, the change in adhesion force during the peeling process; (b) effect of interface contact relaxation time on the maximum adhesion force; (c) nonlinear relationship between adhesion and preload; (d) optimization of PDMS thickness.

equivalent elastic modulus of the core-shell structure changes more significantly with the speed, thereby optimizing the high-speed adhesion performance. This phenomenon shows that the design of a flexible gripper should give priority to the use of a thin PDMS shell (1 mm) to optimize the high-speed adhesion performance, but the tear strength should be balanced. The durability and structural stability of flexible grippers can be improved by material strengthening or composite strengthening strategies. The above multiparameter coordinated control research provides a theoretical basis and data support for the engineering optimization of ST-driven adhesion systems.

To further compare the adhesion/detachment behavior after structural optimization, the adhesion force curve was measured under different speed responses. From Figs. 5(a) and 5(b), it can be seen that the $F_{\max}$ of NNF CS2 increases significantly from 0.37 N at 1 mm/s to 75.4 N at 80 mm/s under slow speed conditions. By comparison with NNF CS1 (Fig. 3), it is found that the adhesion force of the two structures is consistent at a slow speed (1 mm/s). At a speed of 5 mm/s, the adhesion force of the NNF CS2 structure begins to respond and increases rapidly with increasing speed, and NNF CS1 still exhibits a low-speed peeling state at the same speed. The adhesion force reaches a peak of 75.4 N at 80 mm/s and remains stable, which is consistent with the velocity saturation law of NNF CS1, and the maximum adhesion-to-detachment ratio is 203. Compared with the NNF CS1 structure, the maximum adhesion force and adhesion ratio increase by 12.9 N and 20.7%, respectively. Therefore, by optimizing the internal structure of the core-shell core, the speed response performance and adhesion ability of the gripper are further improved.

To explain the influence of the core structure on the ST effect,

we established two simplified pipe structure models, a smooth pipe without a barrier cylinder and a pipe with a built-in barrier cylinder (Fig. S6 in the ESM), to explore the control effect of different core-shell structures on the fluid velocity. The calculation results show that the flow velocity decreases significantly when the fluid flows through the vicinity of the cylinder after the addition of the barrier cylinder. This phenomenon can be explained by the basic principle of fluid mechanics; that is, when the fluid approaches the cylinder, the cross section of the channel suddenly shrinks. According to the law of conservation of mass, the fluid must accelerate in the contraction region (as shown in the local high-speed region that may appear on both sides of the cylinder in Fig. S6(c) in the ESM). In addition, the sudden contraction of the flow channel will lead to an increase in the local pressure difference, and the viscous effect will form an eddy current zone of energy dissipation, which is the main reason for the increase in the internal columnar structure and the more significant ST effect in the core-shell structure.

3.4 Dynamic adhesion behavior of the NNF core-shell structure

To further reveal the inhibition mechanism of the dynamic adhesion behavior of the NNF core-shell structure on interface instability, dynamic peeling performance measurements were carried out. Taking the NNF CS1 structure as the research object, the results are shown in Fig. 6. At a peeling speed of 80 mm/s, the peeling angle of the water-based system continues to increase to 55.2°, resulting in a rapid shrinkage of the contact area, which is consistent with the results predicted by the Peel Zone model [52].

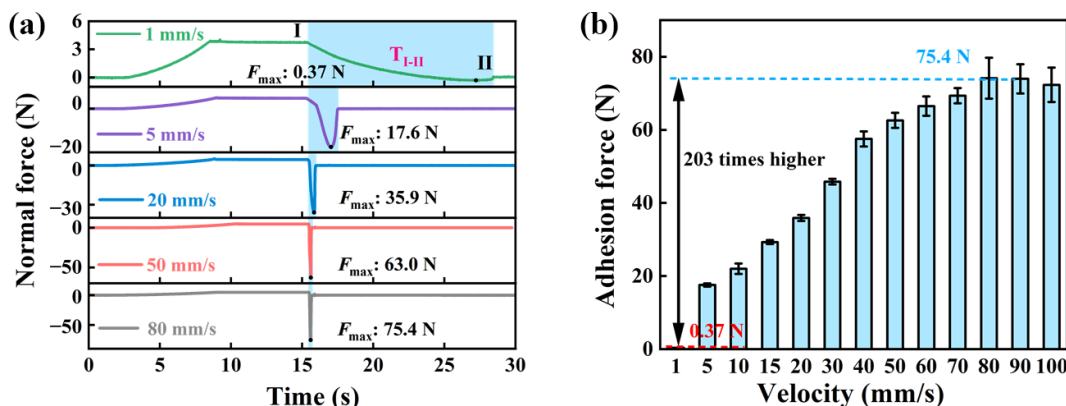


Fig. 5 Adhesion and detachment behavior of the velocity response of NNF CS2. (a) Normal force-time curves of NNF CS2 with NNF4 as the core at different speeds and (b) comparison of stripping speed dependence of NNF CS2.

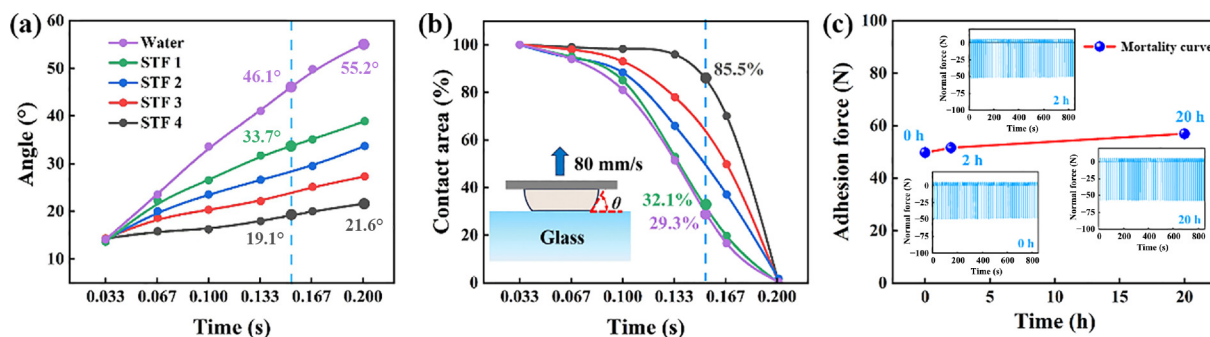


Fig. 6 High-speed stripping dynamic characteristics and long-term adhesion stability of the NNF gripper. (a) Change in the θ degree of the gripper with water and NNF1-NNF4 as the core during the 80 mm/s high-speed stripping process, (b) changes in the corresponding CADR during the stripping process, and (c) long-term cyclic stability of the adhesion force during grasping.

The NNF core shows a concentration-dependent inhibitory effect when the ratio of starch to water increases from 12:14 to 12:17. The peeling angle of the NNF core decreases to 21.6° when the ratio of starch to water increases from 12:14 to 12:17 (Fig. 6(a)).

By mapping the moment of $F_{\max}$ in Fig. 4(a) to the stripping angle and contact area curve (Figs. 6(a) and 6(b)), the stripping angle of the water-based system is 46.1°, the contact area is only 29.3°, and the CADR is reduced by 70.7°. With increasing starch-water concentration, the stripping angle of the NNF core decreased from 33.7° to 19.1°, and the contact area retention rate significantly increased from 32.1% in NNF1 to 85.5% in NNF4.

This result is consistent with the prediction of Eq. (11): A smaller peeling angle reduces the CADR and improves the interface stability. Substituting the measured r_0 (20.75 mm), the contact radii of the water-based system and the NNF4 core system at the maximum peeling force $r(t)$ (11.23 and 19.13 mm, respectively), and the response time (0.11 s) into Eq. (7), the calculation shows that the v_c of the water-based system is 86.55 mm/s, while that of the NNF4 core system is 14.73 mm/s. The crack propagation rate of the water-based system is 5.88 times that of the NNF4 core system, which is consistent with the prediction of Eq. (10). The mechanism behind this is that the high-concentration NNF triggers the ST effect during high-speed peeling: Its viscosity rises sharply, causing the interface to exhibit solid-like properties. By reducing the peeling angle, it significantly inhibits crack propagation and maintains the contact area (Fig. 6(b)) [53, 54].

Substituting the stripping angle parameter into Eq. (10), the stripping angle $\theta = 0.33$ rad of the NNF4 core system is calculated, and the calculated $k_\theta = 0.0105$ m/(s·rad^{1/3}); the peeling angle of the water-based system is $\theta = 0.963$ rad, and the calculated $k_\theta = 0.00865$ m/(s·rad^{1/3}). The k_θ value of the NNF4 core system is slightly higher than that of the water-based system, but the significant difference in the peeling angle (the peeling angle of the

water-based system is approximately 2.9 times that of the NNF4 system) dominates the influence on the v_c , which eventually leads to a significant difference in the v_c values of the two systems, which is consistent with the actual physical law.

To verify the long-term stability of the gripper, 40 groups of cyclic adhesion tests (5 N preload, 80 mm/s detachment speed, 15 min/group) were carried out at three time points of 0, 2, and 20 h. As shown in Fig. 6(c), the adhesion force shows a continuously increasing trend. The initial state (0 h) was 49.72 ± 1.30 N, which increased to 51.59 ± 1.10 N after 2 h and further increased to 56.92 ± 0.90 N after 20 h. This strengthening phenomenon can be attributed to the agglomeration effect caused by the swelling of starch granules [35, 36], which enhances the ST effect. It is worth noting that a high adhesion force of > 56 N is maintained after long-term testing, indicating that the flexible gripper meets the long-term operational reliability, and the NNF-based gripper can stably complete the fast adhesion/detachment grasping task in 20 h of continuous operation. In this work, the synergistic optimization of θ (a decrease of 60.9%) and CADR (a decrease of 56.2%) was achieved by starch concentration regulation (12:14 $\rightarrow$ 12:17), which provided the core criterion for the design of NNF-based flexible grippers under high dynamic conditions. Low θ inhibits interface instability, high CADR guarantees load reliability, and the particle swelling effect enables long-term adhesion enhancement.

3.5 Picking ability of the flexible gripper

To achieve the optimal adhesion performance of the gripper in the picking process, this study combines the Peel Zone Model [51] with previous research results, using the planar PDMS adhesion layer structure instead of the traditional spherical configuration. By reducing the initial peeling angle, the adaptability to both planar and curved targets is improved simultaneously. The

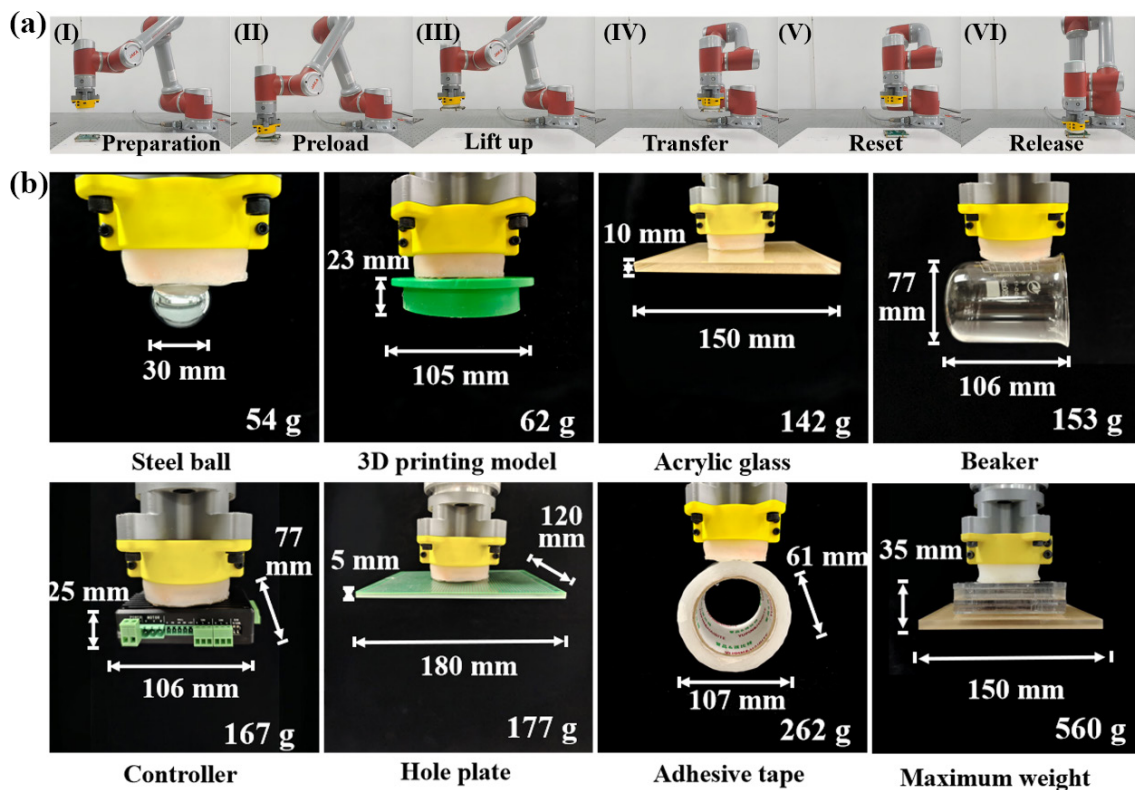


Fig. 7 Multiscale adaptive display of the grab release process and NNF gripper. (a) NNF gripper grasp release flow chart (I: preparation, II: preload, III: lift up, IV: transfer, V: reset, VI: release). (b) Multiscale grasping display of the NNF gripper for different weights, different materials, and different surface structures.

gripper can still maintain a low peeling angle on the nonideal surface, thereby suppressing interface instability and improving operational reliability. Combined with the JAKA manipulator system, the grasping process (Fig. 7(a)) mainly includes three stages. (1) At the low-speed approach stage (5 mm/s), contact is maintained for 5 s to establish adhesion. (2) In the high-speed picking and transfer stage, the ST effect is used to solidify the core in high-speed motion to maintain the structural shape, and the grasping and transfer speed is set to 250 mm/s. (3) In the slow-speed release stage (1 mm/s), nondestructive detachment is achieved by gravity. The standard test is set to 200 mm vertical displacement and 500 mm horizontal movement. The experimental results show that the gripper can successfully grasp eight objects with different physical properties, including a circuit board with components having a 7.8 mm height difference on the surface, a 3D-printed model with a rough surface, and a porous plastic-copper plate with a 1 mm aperture. In addition, there are samples of plastic (PP/ABS), metal (aluminum/copper), glass, and other materials (Fig. 7(b); Videos S1–S3 in the ESM). The maximum grasping weights based on the NNF CS1 and NNF CS2 structures are 262 and 560 g, respectively. The test shows that the gripper has excellent surface adaptability and load capacity when facing rough/irregular surfaces. For the grasping process of different materials, the NNF phase transition response provides strong adhesion grasping in the high-speed transfer stage and achieves ultralow detachment resistance at slow-speed release (1 mm/s). This experiment verifies that the NNF-based gripper shows strong advantages in adaptability, adhesion stability, and wide object grasping ability.

As shown in Fig. S7 in the ESM, to quantitatively evaluate the adhesion stability of the gripper in dynamic grasping and transfer operations, we selected smooth glass specimens with graded masses ranging from 60 to 500 g as the test objects. At different stages of the vertical grasping and lateral transfer processes, the grasped object was peeled off at a relative speed of 100 mm/s. The test results show that the adhesion force of the gripper exhibits gradual attenuation due to internal shear action, and the attenuation rate is positively correlated with the mass of the grasped object. However, the overall attenuation amplitude is controllable. Throughout the entire grasping-transfer cycle, the adhesive force consistently meets the requirements for stable holding, which can fully guarantee the stability and reliability of the gripper in practical applications.

To explore the influence of the normal surface velocity of the fluid approaching zero on the adhesion stability under static and lateral motion, we selected a square glass plate of 60 mm × 60 mm (weight 60 g) as the grasping object and designed two groups of experiments: One group remained static after grasping, and the other group transferred laterally at a speed of 100 mm/s (Fig. S8 in the ESM). The results showed that the grasping objects in the two groups did not fall off immediately. The static group fell off after approximately 4 s, and the adhesion time in the transverse transfer process was more than 10 s. The reason is that the residual stress and microstructure are retained after the STF flow stops, which provides continuous support for adhesion [52]. During lateral transfer, continuous shearing further strengthens the interparticle network and prolongs the adhesion time [35]. This result verifies that the gripper has good adhesion retention ability in dynamic transfer tasks.

4 Conclusions

In this study, a flexible gripper based on the NNF core-shell structure was proposed. This gripper utilized the speed response

characteristics of NNF to realize the dynamic regulation of adhesion and detachment states. By adjusting the stripping speed, the gripper triggers the ST effect of the NNF, and the fluid rapidly transforms into a solid-like core during high-speed grasping, resulting in a response time of only 0.11 s. This is 0.39 s faster than current external field control methods, such as magnetic field control and negative pressure control. The adhesion-detachment ratio is as high as 203.78, which is 2.2 times higher than the 92.8 achieved through vacuum negative pressure particle blocking regulation, demonstrating a higher adhesion-detachment ratio. The maximum grasping capacity is 33.71 g/cm². Experiments show that the gripper can stably grasp and transfer materials such as plastic, metal, and glass and adapt to various target shapes. For the grasping process of different materials, the phase transition response of NNF provides a strong attachment grasping ability during the high-speed transfer stage, thereby improving the grasping stability. Using the NNF velocity-adjustable adhesion-desorption characteristics independent of the external field, the gripper provides a feasible method for high-speed material transfer, flexible picking, and robotic adhesive climbing in industrial automation. Its dual advantages of low cost and high adaptability show unique value in applications with limited control complexity and equipment footprint, opening up a new dimension for the innovation promotion and industrial implementation of soft adhesion technology.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors Yu Tian and Jianning Ding are the Editorial Board members of this journal.

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