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(54) **Title:** METAMATERIAL ADHESIVES FOR PACKAGING, HANGING, HANDLING, AND SHEAR LOADING

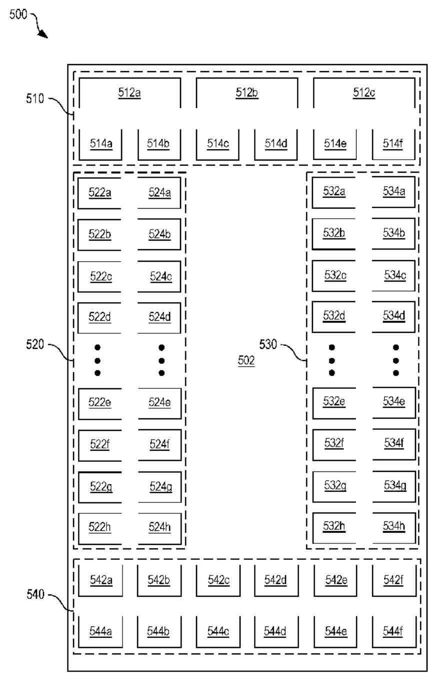

FIG. 5A

(57) **Abstract:** Metamaterial adhesives and metamaterial adhesive systems are described. The metamaterial adhesive systems simultaneously achieve strong and releasable adhesion with spatially selectable adhesion strength through programmed cut architectures. The programmed cut architectures define flap and interconnect regions on a metamaterial adhesive film or a substrate having the metamaterial adhesive film deposited on at least one side of the substrate, among other examples. An example metamaterial adhesive system includes a flexible strip having multiple flaps formed on the flexible strip and a metamaterial adhesive or film deposited on at least one side of one or more of the multiple flaps.

WO 2024/254321 A1

[Continued on next page]

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METAMATERIAL ADHESIVES FOR PACKAGING, HANGING, HANDLING, AND SHEAR LOADING

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0001] This invention was made with government support under grant number 2119105, awarded by the National Science Foundation (NSF). The government has certain rights in the invention.

CROSS REFERENCE TO RELATED APPLICATIONS

[0002] This application claims the benefit of and priority to U.S. Provisional Application Serial No. 63/471,448, filed June 6, 2023, titled "METAMATERIAL ADHESIVES FOR PACKAGING, HANGING, AND HANDLING," the entire contents of which are hereby incorporated herein by reference. This application further claims the benefit of and priority to U.S. Provisional Application Serial No. 63/621,398, filed January 16, 2024, titled "METAMATERIAL ADHESIVES FOR SHEAR LOADING," the entire contents of which are hereby incorporated herein by reference.

BACKGROUND

[0003] Adhesive strength is dictated by how cracks move across a bonded interface. By suppressing crack propagation, strong adhesives are created but are difficult to remove, while reusable adhesives promote separation which limits strength. This makes adhesives commonly either permanent and strong or reversible with limited strength. However, many applications are increasingly in need of adhesives that overcome this trade-off in properties and require strong adhesion with easy removal and extended reuse. This seemingly paradoxical combination of properties is important in applications such as in robotics for locomotion and grasping, in wearable electronics for strong attachment yet easy removal of devices to monitor health and deliver drugs, and in manufacturing for assembly and disassembly to reduce waste, repurpose materials and aid in recycling, among other applications.

SUMMARY

[0004] Metamaterial adhesives and metamaterial adhesive systems are described herein. The systems simultaneously achieve strong and releasable adhesion with spatially selectable adhesion strength through programmed cut architectures. The cut architectures define flaps and interconnect regions on a flexible and/or adhesive film or substrate. Non-linear cuts that define such flaps and interconnect regions uniquely suppress crack propagation by forcing cracks to propagate backwards, while allowing crack growth in the opposite direction for easy release and reusability. This mechanism functions in numerous adhesives and adhesive systems described herein on diverse substrates in wet and dry conditions and enables highly tunable adhesion with independently programmable adhesion strength in two directions simultaneously at any location. These multifunctional adhesive materials and systems can be created in a maskless, digital fabrication framework to rapidly customize adhesive characteristics with deterministic control for next-generation adhesives.

[0005] Aspects and advantages of embodiments of the present disclosure will be set forth in part in the following description or can be learned from the description or through practice of the embodiments. Other aspects and advantages of embodiments of the present disclosure will become better understood with reference to the appended claims and the accompanying drawings, all of which are incorporated in and constitute a part of this specification. The drawings illustrate example embodiments of the present disclosure and, together with the description, serve to explain the related concepts of the present disclosure.

[0006] According to one example embodiment, an adhesive system includes a flexible strip, a first flap on the flexible strip, and a second flap on the flexible strip. The first flap is pivotable about a hinge axis of the first flap. The hinge axis of the first flap extends between side edges of the first flap in a first extension direction. The second flap is pivotable about a hinge axis of the second flap. The hinge axis of the second flap extends between side edges of the second flap in a second extension direction. The second extension direction of the hinge axis of the second flap is different from the first extension direction of the hinge axis of the first flap.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Many aspects of the present disclosure can be better understood with reference to the following figures. The components in the figures are not necessarily to scale, with emphasis instead being placed upon clearly illustrating the concepts of the disclosure. Moreover, repeated use of reference characters or numerals in the figures is intended to represent the same or analogous features, elements, or operations across different figures. Repeated description of such repeated reference characters or numerals is omitted for brevity.

[0007] FIG. 1A illustrates an example metamaterial adhesive including cut patterns in an example adhesive film according to various aspects and embodiments of the present disclosure.

[0008] FIGS. 1B and 1C illustrate examples of adhesion achieved by the example metamaterial adhesive system of FIG. 1A according to various aspects and embodiments of the present disclosure.

[0009] FIGS. 1D and 1E respectively illustrate examples of the easy release achieved by the example metamaterial adhesive system of FIG. 1A according to various aspects and embodiments of the present disclosure.

[0010] FIG. 1F illustrates maximum force per total width, or maximum strength, of commercially-available adhesives and example metamaterial adhesives according to various aspects and embodiments of the present disclosure.

[0011] FIG. 1G illustrates an example metamaterial adhesive system showing high adhesion (e.g., maximum force) and easy release (e.g., minimum force) in opposite peel directions according to various aspects and embodiments of the present disclosure.

[0012] FIG. 1H illustrates example adhesion enhancement ratios over an unpatterned adhesive for various cut shapes according to various aspects and embodiments of the present disclosure.

[0013] FIG. 1I illustrates example adhesion directionality for various cut (or “flap”) shapes according to various aspects and embodiments of the present disclosure.

[0014] FIG. 2A illustrates a plot of example crack velocity versus time for an example metamaterial adhesive system and unpatterned adhesive system according to various aspects and embodiments of the present disclosure.

[0015] FIG. 2B illustrates a plot of example local peel angle near a crack tip associated with an example metamaterial adhesive system and unpatterned adhesive system from finite-element analysis (FEA) according to various aspects and embodiments of the present disclosure.

[0016] FIG. 2C illustrates a plot of example measured force versus time of an example metamaterial adhesive system according to various aspects and embodiments of the present disclosure.

[0017] FIGS. 2D, 2E, 2F, and 2G illustrate side profile images of an example peeling adhesive system, and FIGS. 2H, 2I, 2J, and 2K illustrate corresponding FEA results according to various aspects and embodiments of the present disclosure.

[0018] FIG. 2L illustrates a plot of example maximum force per cut (flap) pattern F_{max}/N_p versus half cut (flap) width $0.5\ w_p$ according to various aspects and embodiments of the present disclosure.

[0019] FIGS. 2M, 2N, 2O, and 2P illustrate images of example FEA results for an example metamaterial adhesive system showing crack arrest at interconnect tips (left) and crack morphology at $F = F_{max}$ (right) for $0.5w_p \geq l_{ch}$ (FIG. 2M and 2N) and $0.5w_p < l_{ch}$ (FIG. 2O and 2P) according to various aspects and embodiments of the present disclosure.

[0020] FIG. 3A illustrates a plot of example normalized maximum adhesion versus $0.5\ w_p/l_{ch}$ for different metamaterial adhesive materials according to various aspects and embodiments of the present disclosure.

[0021] FIG. 3B illustrates a plot of example maximum force per width of metamaterial adhesives versus unpatterned adhesives on diverse surfaces in dry and underwater environments according to various aspects and embodiments of the present disclosure.

[0022] FIGS. 3C and 3D illustrate comparison plots of example enhancement ratio versus adhesion directionality (FIG. 3C) and example adhesion directionality versus adhesion strength (FIG. 3D) according to various aspects and embodiments of the present disclosure.

[0023] FIG. 4A illustrates an example digital fabrication scheme for an example programmable metamaterial adhesive system according to various aspects and embodiments of the present disclosure.

[0024] FIG. 4B illustrates an example automated design to generate a layout of an example programmed adhesion strength represented by an output design according to various aspects and embodiments of the present disclosure.

[0025] FIGS. 4C, 4D, 4E, and 4F illustrate plots of example force versus position data for the example metamaterial adhesive system fabricated with the example automated design in FIG. 4B according to various aspects and embodiments of the present disclosure.

[0026] FIG. 4G illustrates a plot of example measured and programmed maximum forces for the example metamaterial adhesive system fabricated with the example automated design in FIG. 4B according to various aspects and embodiments of the present disclosure.

[0027] FIG. 4H illustrates a plot of example decoupling of directionality associated with the example metamaterial adhesive system fabricated with the example automated design in FIG. 4B according to various aspects and embodiments of the present disclosure.

[0028] FIG. 5A illustrates a top view of another example adhesive system according to various aspects and embodiments of the present disclosure.

[0029] FIG. 5B illustrates a dimensional diagram corresponding to the example adhesive system shown in FIG. 5A according to various aspects and embodiments of the present disclosure.

[0030] FIG. 5C illustrates an example resist-release shear force diagram corresponding to the example adhesive system shown in FIG. 5A according to various aspects and embodiments of the present disclosure.

[0031] FIG. 5D illustrates a top view of the example adhesive system shown in FIG. 5A coupled to flaps of a box according to various aspects and embodiments of the present disclosure.

[0032] FIG. 6A illustrates a front view of another example adhesive system according to various aspects and embodiments of the present disclosure.

[0033] FIG. 6B illustrates a dimensional diagram corresponding to the example adhesive system shown in FIG. 6A according to various aspects and embodiments of the present disclosure.

[0034] FIG. 6C illustrates a resist-release shear force diagram corresponding to the example adhesive system shown in FIG. 6A according to various aspects and embodiments of the present disclosure.

[0035] FIG. 6D illustrates a front view of the example adhesive system shown in FIG. 6A coupled to a hanging apparatus on one side and a vertical surface on another side according to various aspects and embodiments of the present disclosure.

[0036] FIG. 6E illustrates a side view of the example adhesive system shown in FIG. 6D coupled to the hanging apparatus on one side and the vertical surface on another side according to various aspects and embodiments of the present disclosure.

[0037] FIGS. 6F, 6G, 6H, and 6I illustrate views of a frame hung on a wall using an example adhesive system 600 according to various aspects and embodiments of the present disclosure.

[0038] FIGS. 6J, 6K, 6L, and 6M illustrate views of the frame of FIGS. 6F to 6I hung on a wall using an unpatterned adhesive.

[0039] FIG. 7A illustrates a front view of another example adhesive system according to various aspects and embodiments of the present disclosure.

[0040] FIG. 7B illustrates a dimensional diagram corresponding to the example adhesive system shown in FIG. 7A according to various aspects and embodiments of the present disclosure.

[0041] FIG. 7C illustrates a resist-release shear force diagram corresponding to the example adhesive system shown in FIG. 7A according to various aspects and embodiments of the present disclosure.

[0042] FIG. 7D illustrates a front view of the example adhesive system shown in FIG. 7A coupled to a glove according to various aspects and embodiments of the present disclosure.

[0043] FIG. 8A illustrates a top view of another example metamaterial adhesive system according to various aspects and embodiments of the present disclosure.

[0044] FIG. 8B illustrates plots of example force versus position data corresponding to the example metamaterial adhesive system shown in FIG. 8A and an unpatterned adhesive system according to various aspects and embodiments of the present disclosure.

[0045] FIGS. 8C, 8D, and 8E illustrate various top views of the example metamaterial adhesive system shown in FIG. 8A coupled to a wireless wearable human-in-the-loop motion control device according to various aspects and embodiments of the present disclosure.

[0046] FIGS. 8F, 8G, and 8H illustrate various views of the example metamaterial adhesive system shown in FIG. 8A coupled to on one side to a wireless wearable human-in-the-loop motion control device for controlling a robotic device and coupled on another side to a first human arm then a second human arm for controlling the robotic device using the wireless wearable human-in-the-loop motion control device according to various aspects and embodiments of the present disclosure.

[0047] FIG. 9A illustrates a front view of the example adhesive system according to various aspects and embodiments of the present disclosure.

[0048] FIG. 9B illustrates a dimensional diagram corresponding to the example adhesive system shown in FIG. 9A according to various aspects and embodiments of the present disclosure.

[0049] FIG. 9C illustrates a side view of the example adhesive system shown in FIG. 9A coupled to a surface and in a maximum shear force mode according to various aspects and embodiments of the present disclosure.

[0050] FIG. 9D illustrates another side view of the example adhesive system shown in FIG. 9A coupled to a surface and in a minimum shear force mode according to various aspects and embodiments of the present disclosure.

[0051] FIG. 9E illustrates another side view of the example adhesive system shown in FIG. 9A coupled to a surface and in a minimum shear force peeling mode according to various aspects and embodiments of the present disclosure.

[0052] FIG. 9F illustrates a perspective view of the example adhesive system shown in FIG. 9A during a zero-degree (0°) peel in a F_{max} direction according to various aspects and embodiments of the present disclosure.

[0053] FIG. 9G illustrates another perspective view of the example adhesive system shown in FIG. 9A during loading in a F_{max} direction according to various aspects and embodiments of the present disclosure.

[0054] FIG. 9H illustrates another perspective view of the example adhesive system shown in FIG. 9A during failure in a F_{max} direction according to various aspects and embodiments of the present disclosure.

[0055] FIG. 9I illustrates another perspective view of the example adhesive system shown in FIG. 9A during a 0° peel in a F_{min} direction according to various aspects and embodiments of the present disclosure.

[0056] FIG. 9J illustrates another perspective view of the example adhesive system shown in FIG. 9A during loading in a F_{min} direction according to various aspects and embodiments of the present disclosure.

[0057] FIG. 9K illustrates another perspective view of the example adhesive system shown in FIG. 9A during failure in a F_{min} direction according to various aspects and embodiments of the present disclosure.

[0058] FIG. 9L illustrates a plot of example adhesion force versus number of rows of flaps (number of patterns) data for the example metamaterial adhesive system shown in FIG. 9A in a F_{min} direction and a F_{max} direction according to various aspects and embodiments of the present disclosure.

DETAILED DESCRIPTION

[0059] As noted above, adhesives are typically either strong and permanent or reversible with limited strength. However, many applications are increasingly in need of adhesives that overcome this trade-off in properties and require strong adhesion with easy removal and extended reuse. This seemingly paradoxical combination of properties is important in applications such as in robotics for locomotion and grasping, in wearable electronics for strong attachment yet easy removal of devices to monitor health and deliver drugs, and in manufacturing for assembly and then disassembly to reduce waste, repurpose materials and aid in recycling, among other applications.

[0060] Many existing approaches to control adhesion typically focus on tuning interfacial chemistry or dissipating mechanical energy. These material-based mechanisms can result in very strong adhesives but often have no mechanisms for release, reusability or directionality (e.g., high strength in one direction relative to another) because dissipation near the crack tip is similar in all directions. Geometry and stiffness also control adhesion. This is achieved in some existing approaches through nano-to-micron-scale bioinspired surface features, passively varying stiffness through material patterning or actively varying stiffness with switchable adhesives, or adding incisions, cuts or discontinuities into adhesives. These features blunt or trap cracks, which then reinitiate and propagate again in the original, forward direction. This increases adhesion force but does not necessarily facilitate directionality or release. Directional strength can be achieved, but it is difficult to raise adhesion strength and directionality because geometric mechanisms typically result in adhesion strengths below material-based mechanisms. Strategies that leverage both material and geometric mechanisms through accessible fabrication approaches can open synergistic opportunities to systematically suppress crack propagation for strong adhesion yet facilitate crack propagation for release and reusability.

[0061] Embodiments of the present disclosure are directed to metamaterial adhesives and metamaterial adhesive systems that enable strong and reversible adhesion with directional, spatially selective adhesive strength through predefined or programmed non-linear cut architectures. The cut architectures define various shapes, sizes, and orientations of flaps and interconnect regions in adhesive films. Examples shapes, sizes, and orientations of such flaps and interconnect regions are illustrated in FIGS. 1A, 5A, 6A, 7A, 8A, and 9A. The non-linear cuts form open polygonal shapes, also called flaps, that control how adhesive cracks propagate by trapping cracks and then forcing them to reverse direction for high adhesion. Examples of flaps trapping cracks are illustrated in FIGS. 1B, 1C, 1D, 5C, 5D, 6C, 6D, 6E, 7C, 7D, 9D, 9E, and 9F. The flaps also allow cracks to propagate forward normally for low adhesion, and examples are illustrated in FIGS. 1D, 1E, 5C, 5D, 6C, 6D, 6E, 7C, 7D, 9D, 9E, and 9F.

[0062] Through reverse crack propagation, the adhesive systems described herein can decouple high global peel angles into low local peel angles at the adhesive interface. This mechanism enhances adhesion strength significantly (e.g., up to 60 times in some testing) for strong adhesion relative to the same material without cuts, while also enabling easy release on the order of an adhesive that does not have such non-linear cut architectures by peeling in the opposite direction. These characteristics of the adhesive systems described herein allow for independent control of adhesion strength and release with reusability. Reverse crack propagation facilitated by the adhesive systems also tunes adhesion strength at any film location and uniquely enables the programming of adhesive strength in two directions simultaneously in a single region of a film. The metamaterial adhesives and systems do not rely on specific chemistry or environmental conditions, micro-structured surfaces, or active or patterned stiffness to tune adhesion, but utilize non-linear cuts for highly systematic control of adhesive crack propagation and direction across a film.

[0063] The metamaterial adhesives and systems described herein decouple global applied loads into a deterministic local adhesive response, leveraging insight from mechanical metamaterials, which decouple local and global mechanical properties. This functionality is intrinsic to the geometry and allows for enhancement of properties and to enable unique adhesion behavior in a wide range of adhesives, on diverse surfaces, and in dry and wet environments. The applicability of the embodiments to diverse materials allows the metamaterial adhesives and systems to leverage both material and geometric mechanisms to span a spectrum of unique adhesive properties, from strong and extremely reversible to extremely strong with reversibility. Some example metamaterial adhesives and systems described herein can provide strengths of over 3,000 Newtons/meter (N m^{-1}) or Joules/m^{-2} (J m^{-2}).

[0064] The multifunctional metamaterial adhesives and systems provide highly systematic control of adhesive crack movement, and this property allows for an unconventional combination of strong adhesion and easy release, and programmable adhesive strength in two directions simultaneously. The adhesive systems of the present disclosure have various adhesive applications, a few of which are described herein with reference to and illustrated in FIGS. 5D, 6D, 6E, and 7D. A digital fabrication framework is also described to automate the design and rapid manufacture of the metamaterial adhesive systems with deterministic control of adhesive characteristics at any location across a film.

[0065] Turning now to the figures, FIGS. 1A to 1I provide an overview of example metamaterial adhesive systems according to various aspects and embodiments of the present disclosure. The metamaterial adhesive systems are formed using high-strength and easy-release metamaterial adhesives. FIG. 1A illustrates an example metamaterial adhesive including cut patterns in an example adhesive film. FIGS. 1B and 1C illustrate example high adhesion achieved by the example metamaterial adhesive system of FIG. 1A. The high adhesion is achieved in the maximum force direction, as shown in FIG. 1B, when cracks propagate at low angles and reverse direction to propagate backwards to separate, as depicted in FIG. 1C. FIGS. 1D and 1E illustrate examples of the easy release that can be achieved by the example metamaterial adhesive system shown in FIG. 1A. The easy release is achieved in the minimum force direction, as shown in FIG. 1D, as cracks continuously propagate forward to separate, as depicted in FIG. 1E.

[0066] FIG. 1F illustrates example maximum force per total width, or maximum strength, for certain commercially-available adhesives and example metamaterial adhesives according to various aspects and embodiments of the present disclosure. FIG. 1G illustrates an example metamaterial adhesive system showing high adhesion (e.g., maximum force) and easy release (e.g., minimum force) in opposite peel directions according to various aspects and embodiments of the present disclosure. FIG. 1H illustrates example adhesion enhancement ratios over an unpatterned adhesive for various cut or flap shapes according to various aspects and embodiments of the present disclosure. FIG. 1I illustrates example adhesion directionality for various cut flap shapes. Data are presented in the example shown as the mean ± standard deviation (s.d.) (n = 3 measurements from distinct samples for reversible and strong adhesive categories in FIG. 1F and from the same sample measured repeatedly for each example metamaterial adhesive system in FIGS. 1F, 1H, and 1I).

[0067] Characteristics of Metamaterial Adhesive Systems.

[0068] Metamaterial adhesive systems described herein can be embodied to include at least one of polydimethylsiloxane (e.g., a polydimethylsiloxane (PDMS) adhesive), polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel in various examples. In one example, a metamaterial adhesive system includes a PDMS adhesive. The PDMS adhesive may be supported on an inextensible polyethylene terephthalate (PET) backing in some embodiments. Cut architectures can be created in a digital design environment and can then be rapidly patterned in the PDMS adhesive by means of a laser cutter, for instance. The maximum adhesion force (F_{max}) is defined as the condition at which high adhesion is generated, and the minimum adhesion force (F_{min}) is defined as the condition at which low adhesion or easy release is attained. As adhesive force capacity for an adhesive material described herein is higher at small peel angles in various embodiments. The selective decoupling of the global and local peel angles provides a mechanism to have a high adhesion in one direction for F_{max} and easy release in the opposite direction for F_{min}.

[0069] The metamaterial adhesive systems are unique compared to a range of common reversible and strong adhesives, achieving easy release and reusability at F_{min}, with adhesive strength comparable to duct tape at F_{max}, as shown in FIG. 1F. This dramatic difference in F_{max} and F_{min} can be observed by hanging a weight on an example metamaterial adhesive system, as shown in FIG. 1G. In FIG. 1G, the high strength holds the weight in the maximum force peel direction, yet the metamaterial adhesive system releases rapidly in the minimum force peel direction.

[0070] Adhesion enhancement with easy release is also achieved for a variety of non-linear cut or flap patterns, including triangular, rectangular and hybrid cut or flap patterns. As shown in FIG. 1H, the rectangular and hybrid cuts and flaps display an approximate 60× increase in adhesion enhancement, and the triangular cuts and flaps display an approximate 40× increase in adhesion enhancement over the unpatterned adhesive in one example, quantified as the enhancement ratio ($F_{max}/F_{unpatterned}$). This adhesion enhancement has been shown to continue to function over 100 cycles.

[0071] Adhesion directionality is quantified as F_{max}/F_{min}, as shown in FIG. 1I. The hybrid design shows the highest enhancement ratio of approximately (~) 60× while showing exceptionally easy release with an adhesion directionality of ~25. F_{min} can be tuned in various metamaterial adhesive system embodiments by modification of the cut or flap structure into hybrid patterns, detuning of the adhesive layer through laser rastering and adhesive material selection, which enables F_{min} to be equal to or lower than the unpatterned region of the film while maintaining high F_{max}.

[0072] FIGS. 2A to 2P provide an example overview of adhesion enhancing through reverse crack propagation according to various aspects and embodiments of the present disclosure. FIG. 2A illustrates a plot of example crack velocity versus time for an example metamaterial adhesive system and unpatterned adhesive system. FIG. 2B illustrates a plot of example local peel angle near a crack tip associated with an example metamaterial adhesive system and unpatterned adhesive system from finite-element analysis (FEA). FIG. 2C illustrates a plot of example measured force versus time of an example metamaterial adhesive system. FIGS. 2D to 2G illustrate side profile images of an example peeling adhesive system and FIGS. 2H to 2K illustrate corresponding FEA results. FIG. 2L illustrates a plot of example maximum force per cut (flap) pattern F_{max}/N_p versus half cut (flap) width 0.5 w_p. The solid line in the example shown denotes the theoretical fit. FIGS. 2M to 2P illustrate images of example FEA results showing crack arrest at interconnect tips (left) and crack morphology at $F = F_{max}$ (right) for $0.5w_p \geq l_{ch}$ (FIGS. 2M and 2N) and $0.5w_p < l_{ch}$ (FIG. 2O and 2P). The contours in FIGS. 2H to 2K and 2M to 2P illustrate interface damage, which ranges from 0 (fully adhered) to 1 (completely delaminated). Data in FIG. 2L are presented as mean ± s.d. ($n = 3$ measurements from the same sample measured repeatedly).

[0073] Mechanistic Description of Reverse Crack Propagation.

[0074] To further explain the adhesion enhancement and directional release mechanisms of various metamaterial adhesive systems described herein, the crack propagation behavior can be quantified by plotting the crack front velocity versus time during a 90-degree (°) example peel experiment, which is shown in FIG. 2A. While an unpatterned adhesive separates at a constant, positive velocity (e.g., forward), the metamaterial adhesive systems of the present disclosure show distinct crack dynamics. Initially, in some implementations the crack propagates forward through the unpatterned region (FIG. 2A, zone 1), accelerates as it passes through the interconnects (FIG. 2A, zone 2) and then is arrested at the base of the rectangular cut or flap where the crack velocity drops to nearly zero and the applied force rises (FIG. 2A, zone 3). Further loading reverses the crack propagation direction in various embodiments of the metamaterial adhesive systems, as indicated by the negative crack velocity, into the adhered rectangular regions at low peel angles (FIG. 2A, zone 4). In this stage, the local peel angle near the crack tip (α_2) and resultant adhesion force (F) start to increase, resulting in complete adhesive delamination and energy release (FIGS. 2B and 2C). This reverse crack propagation at low angles is only present in the maximum force peeling direction and results in a dramatic rise in adhesive force, as observed in example experiments (FIG. 2D) and captured in simulations using FEA, as shown in FIG. 2E. In the minimum force peel direction and in unpatterned adhesive systems, the crack only propagates forward at low forces, as commonly observed in adhesive debonding. Linear cut patterns and closed-polygonal-shaped cuts or incisions only show primarily forward or lateral crack propagation, not systematic reverse crack propagation, which gives the various metamaterial adhesive systems of the present disclosure superior enhancement, directionality, and spatial control of adhesion.

[0075] Selection of the cut or flap size in different embodiments also facilitates optimized adhesion enhancement. When the width w_p of rectangular cuts in some embodiments (e.g., the width w of any of the flaps 512, 514, 522, 524, 532, 534, 542, 544) is varied with other dimensions fixed, the adhesion force per cut or flap, F_{max}/N_p, first increases with w_p and then saturates when $0.5w_p$ exceeds a critical value, as shown in FIG. 2L. The underlying mechanism is the transition between two distinct regimes of reverse crack propagation. When $0.5w_p$ exceeds a characteristic length l_{ch} in some embodiments, cracks originating at the tips of interconnects do not interfere with each other, leading to circular delaminated regions centered at each interconnect, as shown in FIGS. 2M and 2N. When $0.5w_p$ is smaller than l_{ch} in other embodiments, cracks from neighboring interconnect tips merge before F_{max} is reached, resulting in an approximately uniform crack front during reverse crack propagation (FIG. 2O and 2P). Theoretical analysis of example metamaterial adhesive systems described herein yields:

$$l_{ch} = \sqrt{\frac{2D}{G_c}\frac{w_{int}}{w}(N_p^* + 1)} \tag{1}$$

where D is the flexural rigidity of the adhesive film, w_{int} is the width of an interconnect, N_p^* is the optimal number of cut (flap) patterns that results in the highest F_{max}, w is the total width and G_c is the critical energy release rate. Whereas D, w_{int}, w and G_c are prescribed parameters, N_p^* can be either determined experimentally or solved algebraically. Theoretical analysis of example metamaterial adhesive systems described herein also shows that F_{max} is maximized when $0.5w_p = l_{ch}$, making l_{ch} a key length for cut (flap) design.

[0076] Applicability in Diverse Materials, Surfaces and Environments.

[0077] To evaluate the versatility of the characteristic length l_{ch}, rectangular cuts or flaps were applied with different width w_p to various sets of adhesives, including PET/PDMS and commercially-available adhesives. For each adhesive, the l_{ch} calculated using the theoretically solved N_p^* agrees well with the experimentally determined N_p^*. In FIG. 3A, example normalized maximum adhesive forces for all of these different adhesives collapse onto a single master curve normalized by l_{ch}. This example demonstrates that the metamaterial adhesive design approach described in embodiments herein is widely applicable to diverse materials and can be systematically designed around l_{ch}. Furthermore, other in-plane dimensions (e.g., spacing s, cut (flap) length l_p) should also be equal to or greater than l_{ch}. This avoids the premature interaction of adhesive cracks and allows for full adhesion enhancement, providing general guidance for the design of various example metamaterial adhesive systems herein.

[0078] FIGS. 3A to 3D illustrate performance comparison plots of metamaterial adhesives according to various aspects and embodiments of the present disclosure. The metamaterial adhesive strategy of the present disclosure is applicable to diverse substrates and conditions. When example metamaterial adhesive systems described herein were applied and measured underwater,

water was displaced and adhesion was enhanced (e.g., at least 30× and up to 56×) relative to unpatterned adhesives on glass, plastic/PMMA, aluminum, steel and Teflon, as also shown in FIG. 3B. These results validate that the metamaterial adhesive systems are applicable over a wide range of material types, substrates, and environments to enhance adhesion without specific chemistry or surface topology.

[0079] FIG. 3A illustrates a plot of example normalized maximum adhesion versus 0.5 w_p/l_{ch} for different metamaterial adhesive materials. The dashed line in the example shown indicates a single master curve where experimental data points collapse. FIG. 3B illustrates a plot of example maximum force per width of metamaterial adhesives versus unpatterned adhesives on diverse surfaces in dry and underwater environments. FIGS. 3C and 3D illustrate comparison plots of example enhancement ratio versus adhesion directionality and example adhesion directionality versus adhesion strength. The plots of example adhesion directionality versus adhesion strength (FIG. 3D) show that metamaterial adhesives occupy unique regions of the adhesive property space. This comparison is for passive adhesives (e.g., no trigger release), no kinetic control (e.g., not comparing low to high testing rates), and on nominally smooth surfaces. Data in FIG. 3A and 3B are presented as mean ± s.d. (n = 3 measurements from the same sample measured repeatedly).

[0080] Performance of Metamaterial Adhesive Systems.

[0081] The adhesion performance of the metamaterial adhesive systems is highlighted by comparing combinations of adhesion enhancement, directionality, and strength to previous literature results (FIGS. 3C and 3D). Here, metamaterial adhesive systems of the present disclosure are compared to hydrogels, chemical patterns, stiffness patterns, and bioinspired patterns. FIG. 3C illustrates that adhesives commonly show enhancement with little directionality (blue shaded region), or directionality with little enhancement (green shaded region), whereas metamaterial adhesive systems described herein can be made with both high enhancement and directionality (red shaded region). FIG. 3D illustrates that directional adhesives typically show low strength (green shaded region) whereas high-strength metamaterial adhesive systems described herein (blue shaded region) show little directionality.

[0082] The metamaterial adhesive systems of the present disclosure overcome these challenges and show unique adhesive properties, from strong and extremely directional (top-left quadrant) to extremely strong with directionality (bottom-right quadrant) while being reusable in all cases (red shaded region). In one example, this may include metamaterial adhesives with intrinsically strong acrylic adhesive layers such as 3M VHB (Very High Bond). This enhanced adhesion in this example beyond the already strong unpatterned adhesive and increased strength (e.g., which is equivalent to adhesion toughness for 90° peeling) to over 3,000 N m−1 (J m−2). Notably, these very strong metamaterial adhesives of at least one embodiment herein were still directional and were reusable over multiple testing cycles in various example implementations, which is uncommon because strong adhesives typically rely on bonding mechanisms which are not directional and do not function beyond a single cycle. These types of properties demonstrate the versatility of the metamaterial adhesive systems of the present disclosure and open exciting performance characteristics for adhesive materials.

[0083] FIGS. 4A to 4H illustrate an example digitalized adhesive fabrication process of an example metamaterial adhesive system and example force versus position data associated with the example metamaterial adhesive system. FIG. 4A illustrates an example digital fabrication scheme for an example programmable metamaterial adhesive system. FIG. 4B illustrates an example automated design generated layout of an example programmed adhesion strength represented by an output design. FIGS. 4C, 4D, 4E, and 4F illustrate plots of example force versus position data for the example metamaterial adhesive system fabricated with the automated design in FIG. 4B. FIGS. 4C, 4D, 4E, and 4F illustrate plots of example force versus position data for the example metamaterial adhesive system fabricated with the automated design in FIG. 4B in the forward direction (FIG. 4D) and in the backward direction (FIG. 4E), and example compiled data as a function of position (FIGS. 4C and 4F). FIG. 4G illustrates a plot of example measured and programmed maximum forces for the example metamaterial adhesive system fabricated with the automated design in FIG. 4B. In the plot illustrated in FIG. 4G forces in the example measured approximately correspond with programmed maximum forces. FIG. 4H illustrates a plot of example decoupling of directionality associated with the example metamaterial adhesive system fabricated with the automated design in FIG. 4B. The decoupling of directionality creates maximum/maximum forces at each region in both forward/backward directions, showing good agreement with programmed and measured results for both arbitrary and selected designs described in example embodiments herein. Data in FIGS. 4F to 4H are presented as mean ± s.d. (n = 3 measurements from the same sample measured repeatedly).

[0084] Digital Manufacturing and Design of Metamaterial Adhesives.

[0085] The metamaterial adhesive systems of the present disclosure provide spatial tunability of adhesion. In some examples digital fabrication may be utilized with computer-aided design and laser-based subtractive manufacturing to enable rapid, maskless fabrication of programmed adhesion profiles (FIG. 4A). As a demonstration, an example metamaterial adhesive with rectangular cut or flap patterns was designed and fabricated in the shape of the letters, "HELLO." Lower adhesion can also be achieved with the metamaterial adhesive systems by locally reducing width, allowing for adhesive force contrast ratios of over 320×. With selectable adhesion at specific locations, some embodiments can be designed to provide spatially anisotropic adhesion, where a specific region of a metamaterial adhesive system can be programmed to have a prescribed adhesive strength in two directions simultaneously. The metamaterial adhesive systems can also be designed to provide spatially programmed adhesion in discrete regions and decoupled directionality by including a second set of rectangular cuts or flaps into each adhesive region to independently tune the maximum force in both peel directions. Examples of this approach are shown in FIGS. 4B to 4F.

[0086] The design of the metamaterial adhesive systems can also be automated, where a user selects a desired F_{max} in the forward direction ($F_{max,1}$) and backward direction ($F_{max,2}$) for a specific location. Then, an inverse design algorithm automates a cut or flap pattern to achieve the $F_{max,1}$ and the $F_{max,2}$ for the specific location, and a laser cutter file is generated. The programmed and example experimental adhesion data show strong agreement for three different arbitrary designs, highlighting the ability to reliably create customized, spatially controlled adhesion (FIG. 4G). A plot of example bidirectional enhancement ratios ($F^{i}_{max,1}/F^{i*}_{max,2}$, where i is the location index) of each region is illustrated in FIG. 4H. Good agreement was observed in this example between measured and programmed force ratios for the arbitrarily generated designs and two selected designs to maximize the range of the bidirectional enhancement ratios. This enables a range of 0.018–41 in this example, a difference of over three orders of magnitude (~2,300×), showing tremendous ability to program adhesion force in two directions simultaneously at a single region of a film of any metamaterial adhesive system described herein. Chemical and microscale patterns and linear cut features may be able to spatially control adhesion by pinning cracks but are unable to readily control directional adhesive strength at specific locations as is demonstrated by the metamaterial adhesive systems and digital fabrication approach of the present disclosure.

[0087] Demonstrations of Metamaterial Adhesive Systems.

[0088] FIGS. 5A to 5D provide an overview of another example adhesive system 500, as well as an example application of the adhesive system 500 according to various aspects and embodiments of the present disclosure. FIG. 5A illustrates a top view of the example adhesive system 500. FIG. 5B illustrates a dimensional diagram corresponding to the example adhesive system 500 shown in FIG. 5A. FIG. 5C illustrates a resist-release shear force diagram corresponding to the example adhesive system 500 shown in FIG. 5A. FIG. 5D illustrates a top view of the example adhesive system 500 shown in FIG. 5A coupled to flaps of a box.

[0089] The adhesive system 500 is an example alternative embodiment of the metamaterial adhesive system described herein and illustrated in FIGS. 1A to 1E. The adhesive system 500 includes the same or similar structure and material (e.g., metamaterial adhesive). A difference between the adhesive system 500 and the metamaterial adhesive system of FIGS. 1A to 1E is the shape, size, number, orientation, grouping, and arrangement of the non-linear cuts that define various flap and interconnect regions on a metamaterial adhesive film or a flexible substrate having metamaterial adhesive deposited on at least one side of the substrate. Another difference between these systems is the adhesive system 500 may be designed and embodied as a tape in one example. For instance, as described herein and illustrated in FIG. 5D, the adhesive system 500 may be designed and embodied as a packing or shipping tape that may be used to position and hold multiple flaps of a box (e.g., shipping box or container) in a closed configuration.

[0090] Referring among FIGS. 5A to 5D, the adhesive system 500 includes a flexible strip 502. The flexible strip 502 can include a layer of a thermoplastic material, a thermosetting material, polyethylene terephthalate, polypropylene, polyimide, polystyrene, polycarbonate, polyethylene naphthalate, an elastomer material, a rubber material, a fabric material, or any combination thereof in one example. The flexible strip 502 can be embodied as a laminate of an inelastic layer and an elastic layer in another example. In some embodiments, the elastic layer can include at least one of polydimethylsiloxane, polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel. In other examples, the flexible strip 502 can be embodied as at least one of a polyethylene terephthalate-polydimethylsiloxane laminate, paper, paper having a low-tack pressure-sensitive adhesive on a side of the paper, a pressure sensitive adhesive, a soft skin adhesive, a porous material having the pressure sensitive adhesive, fabric, mesh, a metalized film, or another type of flexible adhesive strip or flexible strip having adhesive.

[0091] The flexible strip 502 is formed to a rectangular shape, although other geometries may be relied upon in some cases. The flexible strip 502 includes multiple regions 510, 520, 530 of opposing flaps formed on the flexible strip 502. The flexible strip 502 further includes a region 540 of aligned flaps formed on the flexible strip 502. The region 510 of opposing flaps and the region 540 of aligned flaps are located at opposing sections or ends of the flexible strip 502 relative to one another. Additionally, the regions 520 and 530 of opposing flaps are located at opposing sections or sides of the flexible strip 502 relative to one another.

[0092] The region 510 includes a row of flaps 512a, 512b, 512c (or "the flaps 512") and a row of flaps 514a, 514b, 514c, 514d, 514e, 514f (or "the flaps 514") formed on the flexible strip 502. The flaps 512, 514 are individually defined and formed on the flexible strip 502 by a non-linear cut passing through an entire thickness t of the flexible strip 502, the thickness t being in a direction projecting from the page of each of FIGS. 5A to 5D. Each non-linear cut defines side edges "s_a, s_b," a front edge "f." and a hinge axis "*H.A.*" of a respective flap 512, 514 on the flexible strip 502. For example, the flaps 512, 514 are individually defined and formed on the flexible strip 502 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. In the example shown, the hinge axis *H.A.* of each of the flaps 512, 514 extends between the side edges s_a, s_b of the flap in an extension direction D_1. Each of the flaps 512, 514 is pivotable about its hinge axis *H.A.*

[0093] The flaps 512 are each formed to a width "w_1" and a length "l_1" on the flexible strip 502. The flaps 514 are each formed to a width "w_2" and a length "l_2" on the flexible strip 502. The width w_1 of each of the flaps 512 is greater than the width w_2 of each of the flaps 514 in the example shown. In some embodiments, the width w_1 of at least one of the flaps 512 may be less than or approximately equal to the width w_2 of at least one of the flaps 514. Additionally, the length l_1 of each of the flaps 512 is approximately equal to the length l_2 of each of the flaps 514 in this example. In some embodiments, the length l_1 of at least one of the flaps 512 may be different from the length l_2 of at least one of the flaps 514, or vice versa in some cases.

[0094] The flaps 512, 514 are formed on the flexible strip 502 such that they are oppositely oriented on the flexible strip 502 relative to one another in this example. For instance, the side edges s_a, s_b of each of the flaps 512 project from their corresponding hinge axis *H.A.* in a direction that is opposite to a direction in which the side edges s_a, s_b of each of the flaps 514 project from their corresponding hinge axis *H.A.* In other words, the front edge f of each of the flaps 512 and the front edge f of each of the flaps 514 face in opposite directions.

[0095] The region 520 includes a row of flaps 522a, 522b, 522c, 522d, 522e, 522f, 522g, 522h (or "the flaps 522") and a row of flaps 524a, 524b, 524c, 524d, 524e, 524f, 524g, 524h (or "the flaps 524") formed on the flexible strip 502. The flaps 522, 524 are individually defined and formed on the flexible strip 502 by a non-linear cut passing through the thickness t of the flexible strip 502. Each non-linear cut defines the side edges s_a, s_b, the front edge f, and the hinge axis *H.A.* of a respective flap 522, 524 on the flexible strip 502. The flaps 522, 524 are individually defined and formed on the flexible strip 502 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 522, 524 extends between the side edges s_a, s_b of the flap in an extension direction D_2. Each of the flaps 522, 524 is pivotable about its hinge axis *H.A.* The extension direction D_2 of the hinge axis *H.A.* of each of the flaps 522, 524 is perpendicular to the extension direction D_1 of the hinge axis *H.A.* of each of the flaps 512, 514.

[0096] The flaps 522 are each formed to a width "w_3" and a length "l_3" on the flexible strip 502. The flaps 524 are each formed to a width "w_4" and a length "l_4" on the flexible strip 502. The widths w_3, w_4 of the flaps 522, 524, respectively, are approximately equal to one another and less than each of the widths w_1, w_2 of the flaps 512, 514, respectively. In some embodiments, the width w_3 of at least one of the flaps 522 may be different from the width w_4 of at least one of the flaps 524, or vice versa in some cases. Additionally, the lengths l_3, l_4 of the flaps 522, 524, respectively, are approximately equal to one another and greater than each of the lengths l_1, l_2 of the flaps 512, 514, respectively. In some embodiments, the length l_3 of at least one of the flaps 522 may be different from the length l_4 of at least one of the flaps 524, or vice versa in some cases.

[0097] The flaps 522, 524 are formed on the flexible strip 502 such that they are oppositely oriented on the flexible strip 502 relative to one another in this example. The side edges s_a, s_b of each of the flaps 522 project from their corresponding hinge axis *H.A.* in a direction that is opposite to a direction in which the side edges s_a, s_b of each of the flaps 524 project from their corresponding hinge axis *H.A.* In other words, the front edge f of each of the flaps 522 and the front edge f of each of the flaps 524 face in opposite directions. Also, the flaps 522, 524 are formed on the flexible strip 502 such that they have an orientation that is 90° offset from or perpendicular to an orientation of the flaps 512, 514 on the flexible strip 502. The front edge f of each of the flaps 522, 524 face in a direction that is 90° offset from or perpendicular to a direction in which the front edge f of each of the flaps 512, 514 face.

[0098] The region 530 includes a row of flaps 532a, 532b, 532c, 532d, 532e, 532f, 532g, 532h (or "the flaps 532") and a row of flaps 534a, 534b, 534c, 534d, 534e, 534f, 534g, 534h (or "the flaps 534") formed on the flexible strip 502. The flaps 532, 534 are individually defined and formed on the flexible strip 502 by a non-linear cut passing through the thickness t of the flexible strip 502. Each non-linear cut defines the side edges s_a, s_b, the front edge f, and the hinge axis *H.A.*

of a respective flap 532, 534 on the flexible strip 502. The flaps 532, 534 are individually defined and formed on the flexible strip 502 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 532, 534 extends between the side edges s_a, s_b of the flap in an extension direction D_3. Each of the flaps 532, 534 is pivotable about its hinge axis *H.A.* The extension direction D_3 of the hinge axis *H.A.* of each of the flaps 532, 534 is parallel to the extension direction D_2 of the hinge axis *H.A.* of each of the flaps 522, 524 and perpendicular to the extension direction D_1 of the hinge axis *H.A.* of each of the flaps 512, 514.

[0099] The flaps 532 are each formed to a width "w_5" and a length "l_5" on the flexible strip 502. The flaps 534 are each formed to a width "w_6" and a length "l_6" on the flexible strip 502. The widths w_5, w_6 of the flaps 532, 534 are approximately equal to one another and less than each of the widths w_1, w_2 of the flaps 512, 514, respectively. Also, the widths w_5, w_6 of the flaps 532, 534 are approximately equal to the widths w_3, w_4 of the flaps 522, 524 in the example shown. In some embodiments, the width w_5 of at least one of the flaps 532 may be different from the width w_6 of at least one of the flaps 534, or vice versa in some cases. Additionally, the lengths l_5, l_6 of the flaps 532, 534 are approximately equal to one another and greater than each of the lengths l_1, l_2 of the flaps 512, 514, respectively. Also, the lengths l_5, l_6 of the flaps 532, 534 are approximately equal to the lengths l_3, l_4 of the flaps 522, 524. In some embodiments, the length l_5 of at least one of the flaps 532 may be different from the length l_6 of at least one of the flaps 534, or vice versa in some cases. In some embodiments, at least one of the width or the length of at least one of the flaps 522, 524, 532, 534 may be different from that of at least one other flap of the flaps 522, 524, 532, 534.

[00100] The flaps 532, 534 are formed on the flexible strip 502 such that they are oppositely oriented on the flexible strip 502 relative to one another in this example. The side edges s_a, s_b of each of the flaps 532 project from their corresponding hinge axis *H.A.* in a direction that is opposite to a direction in which the side edges s_a, s_b of each of the flaps 534 project from their corresponding hinge axis *H.A.* In other words, the front edge *f* of each of the flaps 532 and the front edge *f* of each of the flaps 534 face in opposite directions. Further, the flaps 522, 532 are formed on the flexible strip 502 such that they have a same orientation on the flexible strip 502 relative to one another and the flaps 524, 534 are formed on the flexible strip 502 such that they have a same orientation on the flexible strip 502 relative to one another. The side edges s_a, s_b of each of the flaps 522, 532 project from their corresponding hinge axis *H.A.* in a same direction and the side edges s_a, s_b of each of the flaps 524, 534 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edge f of each of the flaps 522, 532 face in a same direction and the front edge f of each of the flaps 524, 534 face in a same direction. Also, the flaps 532, 534 are formed on the flexible strip 502 such that they have an orientation that is 90° offset from or perpendicular to an orientation of the flaps 512, 514 on the flexible strip 502. The front edge f of each of the flaps 532, 534 face in a direction that is 90° offset from or perpendicular to a direction in which the front edge f of each of the flaps 512, 514 face.

[00101] The region 540 includes a row of flaps 542a, 542b, 542c, 542d, 542e, 542f (or "the flaps 542") and a row 544 of flaps 544a, 544b, 544c, 544d, 544e, 544f (or "the flaps 544") formed on the flexible strip 502. The flaps 542, 544 are individually defined and formed on the flexible strip 502 by a non-linear cut passing through the thickness t of the flexible strip 502. Each non-linear cut defines the side edges s_a, s_b, the front edge f, and the hinge axis $H.A.$ of a respective flap 542, 544 on the flexible strip 502. The flaps 542, 544 are individually defined and formed on the flexible strip 502 by a non-linear cut having a starting point at a first end of the hinge axis $H.A.$ of the flap and an ending point at a second end of the hinge axis $H.A.$ of the flap. The hinge axis $H.A.$ of each of the flaps 542 extends between the side edges s_a, s_b of the flap in an extension direction D_4 and the hinge axis $H.A.$ of each of the flaps 544 extends between the side edges s_a, s_b of the flap in an extension direction D_5. Each of the flaps 542, 544 is pivotable about its hinge axis $H.A.$ The extension directions D_4, D_5 of the hinge axis $H.A.$ of each of the flaps 542, 544 are parallel to one another and parallel to the extension direction D_1 of the hinge axis $H.A.$ of each of the flaps 512, 514. Also, the extension directions D_4, D_5 of the hinge axis $H.A.$ of each of the flaps 542, 544 are both perpendicular to each of the extension directions D_2, D_3 of the hinge axis $H.A.$ of each of the flaps 522, 524 and the flaps 532, 534, respectively.

[00102] The flaps 542 are each formed to a width "w_7" and a length "l_7" on the flexible strip 502. The flaps 544 are each formed to a width "w_8" and a length "l_8" on the flexible strip 502. The widths w_7, w_8 of the flaps 542, 544, respectively, are approximately equal to one another and approximately equal to the width w_2 of the flaps 514. In some embodiments, the width w_7 of at least one of the flaps 542 may be different from the width w_8 of at least one of the flaps 544, or vice versa in some cases. In at least one embodiment, the width w_7 of at least one of the flaps 542 may be different from the width w_2 of at least one of the flaps 514. Additionally, the lengths l_7, l_8 of the flaps 542, 544, respectively, are approximately equal to one another and approximately equal to the length l_2 of the flaps 514. In some embodiments, the length l_7 of at least one of the flaps 542 may be different from the length l_8 of at least one of the flaps 544, or vice versa in some cases. In at least one embodiment, the length l_7 of at least one of the flaps 542 may be different from the length l_2 of at least one of the flaps 514.

[00103] The flaps 542, 544 are formed on the flexible strip 502 such that they have a same orientation on the flexible strip 502 relative to one another and relative to the flaps 514. The side edges s_a, s_b of each of the flaps 514, 542, 544 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edge *f* of each of the flaps 514, 542, 544 face in a same direction. Also, the flaps 542, 544 are formed on the flexible strip 502 such that they have an orientation that is 90° offset from or perpendicular to an orientation of the flaps 522, 524, 532, 534 on the flexible strip 502 in this example. The front edge *f* of each of the flaps 542, 544 face in a direction that is 90° offset from or perpendicular to a direction in which the front edge *f* of each of the flaps 522, 524, 532, 534 face.

[00104] The adhesive system 500 includes a pair of opposing flaps oppositely oriented on the flexible strip 502 relative to one another with each flap of the pair of opposing flaps being pivotable about a flap hinge axis extending in a first extension direction. For instance, the region 520 of opposing flaps includes the flaps 522a, 524a that are oppositely oriented on the flexible strip 502 relative to one another and are each pivotable about their own hinge axis *H.A.* extending in the extension direction D_2. The adhesive system 500 further includes a pair of aligned flaps oriented on the flexible strip 502 in a same orientation relative to one another with each flap of the pair of aligned flaps being pivotable about a flap hinge axis extending in a second extension direction at a defined angle relative to the first extension direction. For instance, the region 540 of aligned flaps includes the flaps 544a, 544b that are oriented on the flexible strip 502 in a same orientation relative to one another and are each pivotable about their own hinge axis *H.A.* extending in the extension direction D_5 which is 90° offset from or perpendicular to the extension direction D_2 of the hinge axis *H.A.* of each of the flaps 522a, 524a.

[00105] The adhesive system 500 includes a first flap on the flexible strip 502 that is pivotable about a hinge axis of the first flap with the hinge axis of the first flap extending in a first extension direction. For instance, the region 520 of opposing flaps includes the flap 522a that is pivotable about its own hinge axis *H.A.* extending in the extension direction D_2. The adhesive system 500 further includes a subset of opposing flaps that are oriented on the flexible strip 502 at a defined angle relative to the first flap (e.g., relative to the flap 522a). For instance, the region 510 of opposing flaps includes the flaps 512a, 514a, 514b that are each oriented on the flexible strip 502 at a 90° angle relative to the flap 522a. The subset of opposing flaps includes a second flap and a pair of aligned flaps that are oriented on the flexible strip 502 in a same orientation relative to one another and an opposite orientation relative to the second flap. For instance, the flaps 514a, 514b are oriented on the flexible strip 502 in a same orientation relative to one another and in an opposite orientation relative to the flap 512a. Each flap of the pair of aligned flaps and the second flap are pivotable about a flap hinge axis extending in a second extension direction at a defined angle relative to the first extension direction of a flap hinge axis of the first flap. For instance, the flaps 512a, 514a, 514b are each pivotable about their own hinge axis *H.A.* extending in the extension direction D_1 which is 90° offset from or perpendicular to the extension direction D_2 of the hinge axis *H.A.* of the flap 522a.

[00106] The flexible strip 502 has edges e_1, e_2 located at opposing regions or ends (e.g., longitudinal or distal ends) of the flexible strip 502 relative to one another and side edges s_1, s_2 located at opposing regions or sides (e.g., lateral or distal sides) of the flexible strip 502 relative to one another. The side edges s_1, s_2 of the flexible strip 502 extend a distance d_1 between the edges e_1, e_2 of the flexible strip 502 and the edges e_1, e_2 of the flexible strip 502 extend a distance d_2 between the side edges s_1, s_2 of the flexible strip 502. The distances d_1, d_2 are different, for example, the distance d_1 is greater than the distance d_2. In some embodiments, the distance d_1 may be less than or approximately equal to the distance d_2.

[00107] Respective front edges f of the flaps 512 are located at a distance d_3 from the edge e_1 of the flexible strip 502. The hinge axis *H.A.* of respective flaps 512 are located a distance d_4 from the hinge axis *H.A.* of respective flaps 514. The front edge f of the flap 514a is located at a distance d_5 from the side edge s_b of the flap 522a and the front edge f of the flap 514b is also located at the distance d_5 from the side edge s_a of the flap 524a. Additionally, the front edge f of the flap 514e is located at a distance d_6 from the side edge s_b of the flap 532a and the front edge f of the flap 514f is also located at the distance d_6 from the side edge s_a of the flap 534a. Respective side edges s_a, s_b of the flaps 522 and respective side edges s_a, s_b of the flaps 524 are located at a distance d_7 from one another. Respective side edges s_a, s_b of the flaps 532 and respective side edges s_a, s_b of the flaps 534 are located at a distance d_8 from one another. The side edge s_a of the flap 522h is located at a distance d_9 from the hinge axis *H.A.* of the flap 542a and the side edge s_b of the flap 524h is located at the distance d_9 from the hinge axis *H.A.* of the flap 542b. The side edge s_a of the flap 532h is located at a distance d_{10} from the hinge axis *H.A.* of the flap 542e and the side edge s_b of the flap 534h is located at the distance d_{10} from the hinge axis *H.A.* of the flap 542f. Respective front edges f of the flaps 542 are located at a distance d_{11} from the hinge axis *H.A.* of respective flaps 544 and respective front edges f of the flaps 544 are located at a distance d_{12} from the edge e_1 of the flexible strip 502.

[00108] The side edge s_a of the flap 512a, the side edge s_b of the flap 514a, the front edge f of each of the flaps 522, the side edge s_b of the flap 542a, and the side edge s_b of the flap 544a are each located at a distance d_{13} from the side edge s_1 of the flexible strip 502. The side edge s_b of the flap 512c, the side edge s_a of the flap 514f, the front edge f of each of the flaps 534, the side edge s_a of the flap 542f, and the side edge s_a of the flap 544f are each located at a distance d_{14} from the side edge s_2 of the flexible strip 502. Respective side edges s_a, s_b of the flaps 512 are located at a distance d_{15} from one another, respective side edges s_a, s_b of the flaps 514 are located at the distance d_{15} from one another, respective side edges s_a, s_b of the flaps 542 are located at the distance d_{15} from one another, and respective side edges s_a, s_b of the flaps 544 are located at the distance d_{15} from one another. Additionally, the hinge axis *H.A.* of each of the flaps 522 is also located at the distance d_{15} from the hinge axis *H.A.* of each of the flaps 524 and the hinge axis *H.A.* of each of the flaps 532 is located at the distance d_{15} from the hinge axis *H.A.* of each of the flaps 534. In the example shown, the distances d_4, d_6, d_{10}, d_{11}, d_{15} are approximately equal and the distances d_3, d_{13}, d_{14} are approximately equal. In some embodiments, any or all of the distances d_4, d_6, d_{10}, d_{11}, d_{15} may be less than or greater than any or all other distances of the distances d_4, d_6, d_{10}, d_{11}, d_{15}.

[00109] In some embodiments, any or all of the distances d_3, d_{13}, d_{14} may be less than or greater than any or all other distances of the distances d_3, d_{13}, d_{14}. The distances d_3, d_{12} are different, for example, the distance d_{12} is greater than the distance d_3. In some embodiments, the distance d_{12} may be less than or approximately equal to the distance d_3.

[00110] The portions of the flexible strip 502 between the flaps 512, 514, 522, 524, 532, 534, 542, 544 are interconnect regions and they are respectively defined in whole or in part by distances d_1 to d_{15}. Any or all of the flaps 512, 514, 522, 524, 532, 534, 542, 544 and any or all of the aforementioned interconnect regions on the flexible strip 502 may be designed and embodied to various geometries and dimensions. The metamaterial and anisotropic adhesive properties of the flexible strip 502 or those of a metamaterial adhesive that may be integrated in or coupled to the flexible strip 502, along with certain geometrical or dimensional designs of the flaps 512, 514, 522, 524, 532, 534, 542, 544 and/or the interconnect regions between the flaps allow for a variety of resist-release shear force modes to be designed for the adhesive system 500. Such resist-release shear force modes have a multitude of applications in shear loading where the adhesive system 500 is pulled parallel to and coupled to a surface. The adhesive system 500 includes metamaterial adhesive described in examples herein that simultaneously provides strong resist and easy release adhesion with spatially selectable adhesion strength through predefined or programmed flap and interconnect region architectures that may be designed for the adhesive system 500. In some embodiments, a distance between side edges of any neighboring adjacent flaps described herein can be uniform from respective hinge axis ends of the flaps to respective front ends of the flaps. In other embodiments, a distance between side edges of any neighboring adjacent flaps described herein at respective hinge axis ends of the flaps can be different from a distance between the side edges at respective front ends of the flaps.

[00111] The example resist-release shear force diagram illustrated in FIG. 5C and corresponding to the adhesive system 500 shows example F_{max} and F_{min} shear forces that can be provided by the flaps 512, 514, 522, 524, 532, 534, 542, 544 individually, in subgroups as the regions 510, 520, 530, 540, and collectively as the adhesive system 500. The F_{max} and F_{min} shear forces are represented in the example show as arrows that respectively point in a direction of the F_{max} or F_{min} shear force. The length of each arrow denotes and corresponds to a magnitude of the F_{max} or F_{min} shear force. The resist-release shear force mode provided by the adhesive system 500 facilitates strong bonding to one or more surfaces and ensures sealing in all directions, yet the adhesive system 500 can be removed on demand by peeling in a particular direction (FIGS. 5C and 5D).

[00112] High-adhesion yet easy-release capabilities are critical for numerous applications. In some embodiments, the adhesive system 500 may be coupled to a function component. For example, a top or a bottom side of the flexible strip 502 can be coupled to a functional component that can include, but is not limited to, at least one of a biosensor, an electrical or electronic circuit, a chemical sensor, a bio-monitoring patch, a graphic, a bandage, tape for adhering or coupling objects together, a box or container, a wall hanging apparatus, or a glove or textile.

[00113] To demonstrate an example application of the adhesive system 500 with packaging, the adhesive system 500 can be designed and embodied as, for example, a commercial shipping tape. For instance, as illustrated in FIG. 5D, the adhesive system 500 can be designed and embodied as a tape that can provide strong bonding to one or more flaps 550a, 550b of a box (e.g., a packaging, shipping, or cardboard box). The adhesive system 500 can ensure sealing in all directions across the flaps 550a, 550b, as well as facilitate the positioning and securing of the flaps 550a, 550b in a closed configuration. The adhesive system 500 can also be removed on demand by peeling in a particular direction as illustrated in FIGS. 5C and 5D.

[00114] In one example implementation, a box sealed with the adhesive system 500 withstood the weight and impact of a brick (1,550 grams (g)) over five drop impacts (FIGS. 5E and 5F), while the box sealed with tape embodied as the flexible strip 502 without the flaps 512, 514, 522, 524, 532, 534, 542, 544 completely collapsed after only two drops (FIGS. 5G and 5H).

[00115] FIGS. 6A to 6E provide an overview of another example adhesive system 600, as well as an example application of the adhesive system 600 according to various aspects and embodiments of the present disclosure. FIG. 6A illustrates a front view of the example adhesive system 600 according to various aspects and embodiments of the present disclosure. FIG. 6B illustrates a dimensional diagram corresponding to the example adhesive system 600 shown in FIG. 6A according to various aspects and embodiments of the present disclosure. FIG. 6C illustrates a resist-release shear force diagram corresponding to the example adhesive system 600 shown in FIG. 6A according to various aspects and embodiments of the present disclosure. FIG. 6D illustrates a front view of the example adhesive system 600 shown in FIG. 6A coupled to a hanging apparatus on one side and a vertical surface on another side according to various aspects and embodiments of the present disclosure. FIG. 6E illustrates a side view of the example adhesive system 600 shown in FIG. 6D coupled to the hanging apparatus on one side and the vertical surface on another side according to various aspects and embodiments of the present disclosure.

[00116] The adhesive system 600 is an example alternative embodiment of the metamaterial adhesive system described herein and illustrated in FIGS. 1A to 1E. The adhesive system 600 includes the same or similar structure and material (e.g., metamaterial adhesive). A difference between the adhesive system 600 and the metamaterial adhesive system of FIGS. 1A to 1E is the shape, size, number, orientation, grouping, and arrangement of the non-linear cuts that define various flap and interconnect regions on a metamaterial adhesive film or a flexible substrate having metamaterial adhesive deposited on at least one side of the substrate. Another difference between these systems is the adhesive system 600 may be designed and embodied as a hanging tape or system in one example. For instance, the adhesive system 600 may be designed and embodied as a hanging tape or system that can include a hanging apparatus with a hook coupled to one side of the adhesive system 600. The adhesive system 600 may be further coupled to a vertical surface such as, for instance, a wall on another side of the adhesive system 600. The adhesive system 600 can support an object that may be positioned on or otherwise hanging from the hook of the hanging apparatus coupled to the adhesive system 600.

[00117] With reference to FIGS. 6A to 6D, collectively, the adhesive system 600 includes a flexible strip 602. The flexible strip 602 can include a layer of a thermoplastic material, a thermosetting material, polyethylene terephthalate, polypropylene, polyimide, polystyrene, polycarbonate, polyethylene naphthalate, an elastomer material, a rubber material, a fabric material, or any combination thereof in one example. The flexible strip 602 can be embodied as a laminate of an inelastic layer and an elastic layer in another example. In some embodiments, the elastic layer can include at least one of polydimethylsiloxane, polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel. In other examples, the flexible strip 602 can be embodied as at least one of a polyethylene terephthalate-polydimethylsiloxane laminate, paper, paper having a low-tack pressure-sensitive adhesive on at least one side of the paper, a pressure sensitive adhesive, a soft skin adhesive, a porous material having the pressure sensitive adhesive, fabric, mesh, a metalized film, or another type of flexible adhesive strip or flexible strip having adhesive.

[00118] The flexible strip 602 is formed to a rectangular shape, although other geometries may be relied upon in some cases. The flexible strip 602 includes multiple regions 610, 620, 630 of opposing flaps formed on the flexible strip 602. The flexible strip 602 further includes a region 640 of aligned flaps formed on the flexible strip 602. The region 610 of opposing flaps and the region 640 of aligned flaps are located at opposing sections or ends of the flexible strip 602 relative to one another. Additionally, the regions 620 and 630 of opposing flaps are located between the regions 610, 620, with the region 620 being positioned closer to the region 610 relative to the region 630 and the region 630 being positioned closer to the region 640 relative to the region 620.

[00119] The region 610 includes a row of flaps 612a, 612b, 612c, 612d, 612e (or "the flaps 612") and a row 614 of flaps 614a, 614b, 614c, 614d, 614e (or "the flaps 614") formed on the flexible strip 602. The flaps 612, 614 are individually defined and formed on the flexible strip 602 by a non-linear cut passing through an entire thickness t of the flexible strip 602, the thickness t being in a direction projecting from the page of each of FIGS. 6A to 6D and across the page of FIG. 6E. Each non-linear cut defines side edges "s_a, s_b," a front edge "f," and a hinge axis "*H.A.*" of a respective flap 612, 614 on the flexible strip 602. The flaps 612, 614 are individually defined and formed on the flexible strip 602 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 612, 614 extends between the side edges s_a, s_b of the flap in an extension direction D_1. Each of the flaps 612, 614 is pivotable about its hinge axis *H.A.*

[00120] The flaps 612 are each formed to a width "w_1" and a length "l_1" on the flexible strip 602. The flaps 614 are each formed to a width "w_2" and a length "l_2" on the flexible strip 602. The width w_1 of each of the flaps 612 is approximately equal to the width w_2 of each of the flaps 614. In some embodiments, the width w_1 of at least one of the flaps 612 may be different from the width w_2 of at least one of the flaps 614, or vice versa in some cases. Additionally, the length l_1 of each of the flaps 612 is approximately equal to the length l_2 of each of the flaps 614. In some embodiments, the length l_1 of at least one of the flaps 612 may be different from the length l_2 of at least one of the flaps 614, or vice versa in some cases.

[00121] The flaps 612, 614 are formed on the flexible strip 602 such that they are oppositely oriented on the flexible strip 602 relative to one another. The side edges s_a, s_b of each of the flaps 612 project from their corresponding hinge axis *H.A.* in a direction that is opposite to a direction in which the side edges s_a, s_b of each of the flaps 614 project from their corresponding hinge axis *H.A.* In other words, the front edge f of each of the flaps 612 and the front edge f of each of the flaps 614 face in opposite directions.

[00122] The region 620 includes a row of flaps 622a, 622b, 622c, 622d, 622e (or "the flaps 622") and a row of flaps 624a, 624b, 624c, 624d, 624e (or "the flaps 624") formed on the flexible strip 602. The flaps 622, 624 are individually defined and formed on the flexible strip 602 by a non-linear cut passing through the thickness t of the flexible strip 602. Each non-linear cut defines the side edges s_a, s_b, the front edge f, and the hinge axis *H.A.* of a respective flap 622, 624 on the flexible strip 602. The flaps 622, 624 are individually defined and formed on the flexible strip 602 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 622, 624 extends between the side edges s_a, s_b of the flap in an extension direction D_2. Each of the flaps 622, 624 is pivotable about its hinge axis *H.A.* The extension direction D_2 of the hinge axis *H.A.* of each of the flaps 622, 624 is offset from and parallel to the extension direction D_1 of the hinge axis *H.A.* of each of the flaps 612, 614.

[00123] The flaps 622 are each formed to a width "w_3" and a length "l_3" on the flexible strip 602. The flaps 624 are each formed to a width "w_4" and a length "l_4" on the flexible strip 602. The widths w_3, w_4 of the flaps 622, 624, respectively, are approximately equal to one another and each of the widths w_1, w_2 of the flaps 612, 614, respectively. In some embodiments, the width w_3 of at least one of the flaps 622 may be different from the width w_4 of at least one of the flaps 624, or vice versa in some cases. Additionally, the length l_3 of each of the flaps 622 is shorter than each of the lengths l_1, l_2, l_4 of the flaps 612, 614, 624, respectively. Also, the length l_4 of each of the flaps 624 is approximately equal to each of the lengths l_1, l_2 of the flaps 612, 614, respectively.

[00124] The flaps 622, 624 are formed on the flexible strip 602 such that they are oppositely oriented on the flexible strip 602 relative to one another. The side edges s_a, s_b of each of the flaps 622 project from their corresponding hinge axis *H.A.* in a direction that is opposite to a direction in which the side edges s_a, s_b of each of the flaps 624 project from their corresponding hinge axis *H.A.* In other words, the front edge *f* of each of the flaps 622 and the front edge *f* of each of the flaps 624 face in opposite directions. Also, the flaps 622, 624 are formed on the flexible strip 602 such that they have a same orientation as that of the flaps 612, 614 on the flexible strip 602. The front edge *f* of each of the flaps 622 face in a same direction as the front edge *f* of each of the flaps 612, and the front edge *f* of each of the flaps 624 face in a same direction as the front edge *f* of each of the flaps 614.

[00125] The region 630 includes a row of flaps 632a, 632b, 632c, 632d, 632e (or "the flaps 632") and a row of flaps 634a, 634b, 634c, 634d, 634e (or "the flaps 634") formed on the flexible strip 602. The flaps 632, 634 are individually defined and formed on the flexible strip 602 by a non-linear cut passing through the thickness *t* of the flexible strip 602. Each non-linear cut defines the side edges s_a, s_b, the front edge *f*, and the hinge axis *H.A.* of a respective flap 632, 634 on the flexible strip 602. The flaps 632, 634 are individually defined and formed on the flexible strip 602 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 632, 634 extends between the side edges s_a, s_b of the flap in an extension direction D_3. Each of the flaps 632, 634 is pivotable about its hinge axis *H.A.* The extension direction D_3 of the hinge axis *H.A.* of each of the flaps 632, 634 is offset from and parallel to each of the extension directions D_1, D_2 of the hinge axis *H.A.* of each of the flaps 612, 614 and the flaps 622, 624, respectively.

[00126] The flaps 632 are each formed to a width "w_5" and a length "l_5" on the flexible strip 602. The flaps 634 are each formed to a width "w_6" and a length "l_6" on the flexible strip 602. The widths w_5, w_6 of the flaps 632, 634, respectively, are approximately equal to one another and each of the widths w_1, w_2 , w_3, w_4 of the flaps 612, 614, 322, 624, respectively. In some embodiments, the width w_5 of at least one of the flaps 632 may be different from the width w_6 of at least one of the flaps 634, or vice versa in some cases. Additionally, the length l_5 of each of the flaps 632 is shorter than each of the lengths l_1, l_2, l_3, l_4 of the flaps 612, 614, 622, 624, respectively. Also, the length l_6 of each of the flaps 634 is approximately equal to each of the lengths l_1, l_2, l_4 of the flaps 612, 614, 624, respectively.

[00127] The flaps 632, 634 are formed on the flexible strip 602 such that they are oppositely oriented on the flexible strip 602 relative to one another. The side edges s_a, s_b of each of the flaps 632 project from their corresponding hinge axis *H.A.* in a direction that is opposite to a direction in which the side edges s_a, s_b of each of the flaps 634 project from their corresponding hinge axis *H.A.* In other words, the front edge f of each of the flaps 632 and the front edge f of each of the flaps 634 face in opposite directions. Also, the flaps 632, 634 are formed on the flexible strip 602 such that they have a same orientation as that of the flaps 612, 614 and the flaps 622, 624 on the flexible strip 602. The front edge f of each of the flaps 632 face in a same direction as the front edge f of each of the flaps 612, 622, and the front edge f of each of the flaps 634 face in a same direction as the front edge f of each of the flaps 614, 624.

[00128] The region 640 includes a row of flaps 644a, 644b, 644c, 644d, 644e (or "the flaps 644") formed on the flexible strip 602. The flaps 644 are individually defined and formed on the flexible strip 602 by a non-linear cut passing through the thickness t of the flexible strip 602. Each non-linear cut defines the side edges s_a, s_b, the front edge f, and the hinge axis *H.A.* of a respective flap 644 on the flexible strip 602. The flaps 644 are individually defined and formed on the flexible strip 602 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 644 extends between the side edges s_a, s_b of the flap in an extension direction D_4. Each of the flaps 644 is pivotable about its hinge axis *H.A.* The extension direction D_4 of the hinge axis *H.A.* of each of the flaps 644 is offset from and parallel to each of the extension directions D_1, D_2, D_3 of the hinge axis *H.A.* of each of the flaps 612, 614, the flaps 622, 624, and the flaps 632, 634, respectively.

[00129] The flaps 644 are each formed to a width "w_7" and a length "l_7" on the flexible strip 602. The widths w_7 of the flaps 644 are approximately equal to one another and approximately equal to the widths w_1, w_2, w_3, w_4, w_5, w_6 of the flaps 612, 614, 622, 624, 632, 634, respectively. In at least one embodiment, the width w_7 of at least one of the flaps 644 may be different from the width w_7 of at least one other flap 614. In some embodiments, the width w_7 of at least one of the flaps 644 may be different from at least one of the widths w_1, w_2, w_3, w_4, w_5, w_6 of at least one of the flaps 612, 614, 622, 624, 632, 634, respectively. Additionally, the length l_7 of each of the flaps 644 is shorter than each of the lengths l_1, l_2, l_3, l_4, l_5 of the flaps 612, 614, 622, 624, 634, respectively. Also, the length l_7 of each of the flaps 644 is approximately equal to the length l_5 of the flaps 632.

[00130] The flaps 644 are formed on the flexible strip 602 such that they are similarly oriented on the flexible strip 602 relative to one another. The side edges s_a, s_b of each of the flaps 644 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edge *f* of each of the flaps 644 face in the same direction. Also, the flaps 644 are formed on the flexible strip 602 such that they have a same orientation as that of the flaps 614, 624, 634 on the flexible strip 602. The front edge *f* of each of the flaps 644 face in a same direction as the front edge *f* of each of the flaps 614, 624, and 634.

[00131] The flexible strip 602 has edges e_1, e_2 located at opposing regions or ends (e.g., longitudinal or distal ends) of the flexible strip 602 relative to one another and side edges s_1, s_2 located at opposing regions or sides (e.g., lateral or distal sides) of the flexible strip 602 relative to one another. The side edges s_1, s_2 of the flexible strip 602 extend a distance d_1 between the edges e_1, e_2 of the flexible strip 602 and the edges e_1, e_2 of the flexible strip 602 extend a distance d_2 between the side edges s_1, s_2 of the flexible strip 602. The distances d_1, d_2 are different, for example, the distance d_1 is greater than the distance d_2. In some embodiments, the distance d_1 may be less than or approximately equal to the distance d_2.

[00132] Respective front edges *f* of the flaps 612 are located at a distance d_3 from the edge e_1 of the flexible strip 602. The hinge axis *H.A.* of respective flaps 612 is located a distance d_4 from the hinge axis *H.A.* of respective flaps 614. Respective front edges *f* of the flaps 614 are located at a distance d_5 from respective front edges *f* of the flaps 622. The hinge axis *H.A.* of respective flaps 622 is located a distance d_6 from the hinge axis *H.A.* of respective flaps 624. Respective front edges *f* of the flaps 624 are located at a distance $_7$ from respective front edges *f* of the flaps 632. The hinge axis *H.A.* of respective flaps 632 is located a distance d_8 from the hinge axis *H.A.* of respective flaps 634. Respective front edges *f* of the flaps 634 are located at a distance $_9$ from the hinge axis *H.A.* of respective flaps 644. Respective front edges *f* of the flaps 644 are located at a distance d_{10} from the edge e_2 of the flexible strip 602.

[00133] The side edge s_a of the flap 612a, the side edge s_b of the flap 614a, the side edge s_a of the flap 622a, the side edge s_b of the flap 624a, the side edge s_a of the flap 632a, the side edge s_b of the flap 634a, and the side edge s_b of the flap 644a are each located at a distance d_{11} from the side edge s_1 of the flexible strip 602. The side edge s_b of the flap 612e, the side edge s_a of the flap 614e, the side edge s_b of the flap 622e, the side edge s_a of the flap 624e, the side edge s_b of the flap

632e, the side edge s_a of the flap 634e, and the side edge s_a of the flap 644e are each located at a distance d_{12} from the side edge s_2 of the flexible strip 602.

[00134] Respective side edges of the flaps 612a, 612b, the flaps 614a, 614b, the flaps 622a, 622b, the flaps 624a, 624b, the flaps 632a, 632b, the flaps 634a, 634b, and the flaps 644a, 644b are located at a distance d_{13} from one another. Respective side edges of the flaps 612b, 612c, the flaps 614b, 614c, the flaps 622b, 622c, the flaps 624b, 624c, the flaps 632b, 632c, the flaps 634b, 634c, and the flaps 644b, 644c are located at a distance d_{14} from one another. Respective side edges of the flaps 612c, 612d, the flaps 614c, 614d, the flaps 622c, 622d, the flaps 624c, 624d, the flaps 632c, 632d, the flaps 634c, 634d, and the flaps 644c, 644d are located at a distance d_{15} from one another. Respective side edges of the flaps 612d, 612e, the flaps 614d, 614e, the flaps 622d, 622e, the flaps 624d, 624e, the flaps 632d, 632e, the flaps 634d, 634e, and the flaps 644d, 644e are located at a distance d_{16} from one another.

[00135] The distances d_4, d_6, d_8 are approximately equal to one another, the distances d_5, d_7 are approximately equal to one another, and the distances d_3, d_{10} are approximately equal to one another. In another example, at least one of the distances d_4, d_6, d_8 may be different from at least one other distance of the distances d_4, d_6, d_8, one of the distances d_5, d_7 may be different from the other distance of the distances d_5, d_7, and/or one of the distances d_3, d_{10} may be different from the other distance of the distances d_3, d_{10}. The distances d_{11}, d_{12}, d_{13}, d_{14}, d_{15}, d_{16} are approximately equal to one another. In another example, at least one of the distances d_{11}, d_{12}, d_{13}, d_{14}, d_{15}, d_{16} may be different from at least one other distance of the distances d_{11}, d_{12}, d_{13}, d_{14}, d_{15}, d_{16}.

[00136] The portions of the flexible strip 602 between the flaps 612, 614, 622, 624, 632, 634, 644 are interconnect regions and they are respectively defined in whole or in part by distances d_1 to d_{16}. Any or all of the flaps 612, 614, 622, 624, 632, 634, 644 and any or all of the aforementioned interconnect regions on the flexible strip 602 may be designed and embodied to various geometries and dimensions. The metamaterial and anisotropic adhesive properties of the flexible strip 602 or those of a metamaterial adhesive that may be integrated in or coupled to the flexible strip 602, along with certain geometrical or dimensional designs of the flaps 612, 614, 622, 624, 632, 634, 644 and/or the interconnect regions between the flaps allow for a variety of resist-release shear force modes to be designed for the adhesive system 600. Such resist-release shear force modes have a multitude of applications in shear loading where the adhesive system 600 is pulled parallel to and coupled to a surface. The adhesive system 600 includes metamaterial adhesive described in examples herein that simultaneously provides strong resist and easy release adhesion with spatially selectable adhesion strength through predefined or programmed flap and interconnect region architectures that may be designed for the adhesive system 600.

[00137] The example resist-release shear force diagram illustrated in FIG. 6C and corresponding to the adhesive system 600 shows example F_{max} and F_{min} shear forces that can be provided by the flaps 612, 614, 622, 624, 632, 634, 644 individually, in subgroups as the regions 610, 620, 630, 640, and collectively as the adhesive system 600. The F_{max} and F_{min} shear forces are represented in the example show as arrows that respectively point in a direction of the F_{max} or F_{min} shear force. The length of each arrow denotes and corresponds to a magnitude of the F_{max} or F_{min} shear force. The resist-release shear force mode provided by the adhesive system 600 facilitates strong bonding to one or more surfaces and ensures sealing in all directions, yet the adhesive system 600 can be removed on demand by peeling in a particular direction (FIGS. 6C, 6D, and 6E).

[00138] High-adhesion yet easy-release capabilities are critical for numerous applications. In some embodiments, the adhesive system 600 may be coupled to a function component. For example, a top or a bottom side of the flexible strip 602 can be coupled to a functional component that can include, but is not limited to, at least one of a biosensor, an electrical or electronic circuit, a chemical sensor, a bio-monitoring patch, a graphic, a bandage, tape for adhering or coupling objects together, a box or container, a wall hanging apparatus, or a glove or textile.

[00139] To demonstrate an example application of the adhesive system 600 with a wall hanging apparatus, the adhesive system 600 can be designed and embodied as, for example, a wall hanging tape that includes or is able to be coupled to a wall hanging apparatus and/or a hook. For instance, as illustrated in FIGS. 6D and 6E, the adhesive system 600 can be designed and embodied as a wall hanging tape that can be coupled on one side of the flexible strip 602 to a vertical surface 650 (e.g., a wall) and include or be able to be coupled on another, opposite side of the flexible strip 602 to a wall hanging apparatus 660. In this example the wall hanging apparatus 660 includes a hook 662 projecting from the wall hanging apparatus 660 and positioned on the same side of the flexible strip 602 as the wall hanging apparatus 660. In this example, the adhesive system 600 can support an object that may be positioned on or otherwise hanging from the hook 662 of the wall hanging apparatus 660 coupled to the flexible strip 602 of the adhesive system 600.

[00140] The adhesive system 600 can provide strong bonding to both the vertical surface 650 (e.g., a wall) and the wall hanging apparatus 660. Additionally, the adhesive system 600 can ensure sealing in all directions across portions of the vertical surface 650 and the wall hanging apparatus

660 to which it is bonded. The adhesive system 600 can also be removed on demand by peeling in a particular direction as illustrated in FIGS. 6C, 6D, and 6E.

[00141] The adhesive system 600 can be used to hang objects on a wall, while still being easily removed (FIGS. 6C, 6D, and 6E). Furthermore, the adhesive system 600 provides the ability to control adhesion strength in two directions at one location to make the hanging more robust, where adhesion strength can be increased at any or all of the edges e_1, e_2 or side edges s_1, s_2 of the flexible strip 602 to prevent inadvertent release. For instance, the adhesive system 600 can be designed and embodied such that the flaps 644 and/or the surrounding interconnect region on the flexible strip 602 provide a certain adhesion strength to prevent inadvertent release of a lower portion of the adhesive system 600 from the vertical surface 650.

[00142] FIGS. 6F to 6I illustrate a frame hung on a wall with the adhesive system 600 according to various aspects and embodiments of the present disclosure. FIGS. 6F and 6H illustrate front views of the frame hung on the wall with the adhesive system 600 on day 1 and remaining on the wall on day 7, respectively, according to various aspects and embodiments of the present disclosure. FIGS. 6G and 6I illustrate cross-sectional side views of the frame hung on the wall with the adhesive system 600 on day 1 and remaining on the wall on day 7, respectively, according to various aspects and embodiments of the present disclosure. The frame remained supported in place by the adhesive system 600 for over 7 days without any observed delamination in one example implementation (FIG. 6I) and was then easily released. FIGS. 6J to 6M illustrate the frame of FIGS. 6F to 6I hung on a wall with an unpatterned adhesive. FIGS. 6J and 6L illustrate front views of the frame hung on the wall with the unpatterned adhesive at minute 1 and delaminating from the wall at minute 20, respectively, according to various aspects and embodiments of the present disclosure. FIGS. 6K and 6M illustrate cross-sectional side views of the frame hung on the wall with the unpatterned adhesive at minute 1 and delaminating from the wall at minute 20, respectively, according to various aspects and embodiments of the present disclosure. The frame supported by the unpatterned adhesive fell off within 20 min (FIG. 6M).

[00143] FIGS. 7A to 7D provide an overview of another example adhesive system 700, as well as an example application of the adhesive system 700 according to various aspects and embodiments of the present disclosure. FIG. 7A illustrates a front view of the example adhesive system 700 according to various aspects and embodiments of the present disclosure. FIG. 7B illustrates a dimensional diagram corresponding to the example adhesive system 700 shown in FIG. 7A according to various aspects and embodiments of the present disclosure. FIG. 7C illustrates a resist-release shear force diagram corresponding to the example adhesive system 700 shown in FIG. 7A according to various aspects and embodiments of the present disclosure. FIG. 7D illustrates a front view of the example adhesive system 700 shown in FIG. 7A coupled to a glove according to various aspects and embodiments of the present disclosure.

[00144] The adhesive system 700 is an example alternative embodiment of the metamaterial adhesive system described herein and illustrated in FIGS. 1A to 1E. The adhesive system 700 includes the same or similar structure and material (e.g., metamaterial adhesive). For instance, the adhesive system 700 includes a flexible strip 702 having the same or similar structure and metamaterial adhesive film as that of the metamaterial adhesive system of FIGS. 1A to 1E. A difference between the adhesive system 700 and the metamaterial adhesive system of FIGS. 1A to 1E is the shape and size of the metamaterial adhesive film used to embody the flexible strip 702 of the adhesive system 700 compared to the metamaterial adhesive film of the metamaterial adhesive system of FIGS. 1A to 1E. For example, the flexible strip 702 of the adhesive system 700 includes a base region and multiple stem regions projecting from the base region. All of such base and stem regions in this example include multiple non-linear cuts formed through the flexible strip 702 that define a plurality of flaps on the flexible strip 702. Another difference between the adhesive system 700 and the metamaterial adhesive system of FIGS. 1A to 1E is the shape, size, number, orientation, grouping, and arrangement of such non-linear cuts that define various flap and interconnect regions in the base and stem regions on the flexible strip 702. Another difference between these systems is the adhesive system 700 may be designed and embodied as a textile tape or system in one example. For instance, as described herein and illustrated in FIG. 7D, the adhesive system 700 may be designed and embodied as a textile tape or system that can be coupled on one side to a glove. For example, one side of the adhesive system 700 can be coupled to a front, palm-side, or palmar side of a glove. In this example, the adhesive system 700 can support an object that may be grasped and/or lifted by a user wearing such a glove having the adhesive system 700 coupled thereto.

[00145] With reference to FIGS. 7A to 7D, collectively, the adhesive system 700 includes a flexible strip 702. The flexible strip 702 can include a layer of a thermoplastic material, a thermosetting material, polyethylene terephthalate, polypropylene, polyimide, polystyrene, polycarbonate, polyethylene naphthalate, an elastomer material, a rubber material, a fabric material, or any combination thereof in one example. The flexible strip 702 can be embodied as a laminate of an inelastic layer and an elastic layer in another example. In some embodiments, the elastic layer can include at least one of polydimethylsiloxane, polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel. In other examples, the flexible strip 702 can be embodied as at least one of a polyethylene terephthalate-polydimethylsiloxane laminate, paper, paper having a low-tack pressure-sensitive adhesive on at least one side of the paper, a pressure sensitive adhesive, a soft skin adhesive, a porous material having the pressure sensitive adhesive, fabric, mesh, a metalized film, or another type of flexible adhesive strip or flexible strip having adhesive.

[00146] The flexible strip 702 is formed approximately to a human hand shape, although other geometries may be relied upon in some cases. The flexible strip 702 includes a base region 704 of flaps formed on the flexible strip 702 and one or more stem regions 720, 730, 740, 750, 760 of flaps formed on the flexible strip 702. The base region 704 corresponds to a palm region of a human hand and each of the stem regions 720, 730, 740, 750, 760 corresponds to a respective finger of a human hand. Each of the stem regions 720, 730, 740, 750, 760 projects from the base region 704 in a different direction relative to one another.

[00147] The base region 704 includes a row of flaps 706a, 706b, 706c, 706d (or "the flaps 706"), a row of flaps 708a, 708b, 708c, 708d, 708e (or "the flaps 708"), a row of flaps 710a, 710b (or "the flaps 710"), a row of flaps 712a, 712b (or "the flaps 712"), a row of flaps 714a, 714b (or "the flaps 714"), and a row of flaps 716a, 716b, 716c (or "the flaps 716") formed on the flexible strip 702. The flaps 706, 708, 710, 712, 714, 716 are individually defined and formed in the base region 704 on the flexible strip 702 by a non-linear cut passing through an entire thickness t of the flexible strip 702, the thickness t being in a direction projecting from the page of each of FIGS. 7A to 7D. Each non-linear cut defines side edges "s_a, s_b," a front edge "f," and a hinge axis "*H.A.*" of a respective flap 706, 708, 710, 712, 714, 716 on the flexible strip 702. The flaps 706, 708, 710, 712, 714, 716 are individually defined and formed on the flexible strip 702 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 706, 708, 710, 712, 714, 716 extends between the side edges s_a, s_b of the flap in an extension direction D_1, D_2, D_3, D_4, D_5, D_6, respectively. Each of the flaps 706, 708, 710, 712, 714, 716 is pivotable about its hinge axis *H.A.* The extension directions D_1, D_2, D_3, D_4, D_5, D_6 are offset from and parallel to one another.

[00148] The flaps 706 are each formed to a width "w_1" and a length "l_1" on the flexible strip 702. The flaps 708 are each formed to a width "w_2" and a length "l_2" on the flexible strip 702. The flaps 710 are each formed to a width "w_3" and a length "l_3" on the flexible strip 702. The flaps 712 are each formed to a width "w_4" and a length "l_4" on the flexible strip 702. The flaps 714 are each formed to a width "w_5" and a length "l_5" on the flexible strip 702. The flaps 716 are each formed to a width "w_6" and a length "l_6" on the flexible strip 702. The flaps 706, 708, 710, 712, 714, 716 are formed on the flexible strip 702 such that they are oriented on the flexible strip 702 in a same orientation relative to one another. The side edges s_a, s_b of each of the flaps 706, 708, 710, 712, 714, 716 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edges *f* of the flaps 706, 708, 710, 712, 714, 716 face in the same direction.

[00149] The stem region 720 includes a set of flaps 722a, 722b (or "the flaps 722") and a set of flaps 724a, 724b (or "the flaps 724") formed on the flexible strip 702. The flaps 722, 724 are individually defined and formed in the stem region 720 on the flexible strip 702 by a non-linear cut passing through an entire thickness *t* of the flexible strip 702, the thickness *t* being in a direction projecting from the page of each of FIGS. 7A to 7D. Each non-linear cut defines side edges "s_a, s_b," a front edge "*f*," and a hinge axis "*H.A.*" of a respective flap 722, 724 on the flexible strip 702. The flaps 722, 724 are individually defined and formed on the flexible strip 702 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. In the example shown, the hinge axis *H.A.* of each of the flaps 722, 724 extends between the side edges s_a, s_b of the flap in an extension direction D_7, D_8, respectively. Each of the flaps 722, 724 is pivotable about its hinge axis *H.A.*

[00150] The flaps 722 are each formed to a width "w_7" and a length "l_7" on the flexible strip 702. The flaps 724 are each formed to a width "w_8" and a length "l_8" on the flexible strip 702. The flaps 722 are formed on the flexible strip 702 such that they are oriented on the flexible strip 702 in a same orientation relative to one another. The side edges s_a, s_b of each of the flaps 722 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edges *f* of the flaps 722 face in the same direction. Additionally, the flaps 724 are formed on the flexible strip 702 such that they are oriented on the flexible strip 702 in a same orientation relative to one another. The side edges s_a, s_b of each of the flaps 724 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edges *f* of the flaps 724 face in the same direction.

[00151] The stem region 730 includes a set of flaps 732a, 732b, 732c, 732d (or "the flaps 732") formed on the flexible strip 702. The flaps 732 are individually defined and formed in the stem region 730 on the flexible strip 702 by a non-linear cut passing through an entire thickness *t* of the flexible strip 702, the thickness t being in a direction projecting from the page of each of FIGS. 7A to 7D. Each non-linear cut defines side edges "s_a, s_b," a front edge "f," and a hinge axis "$H.A.$" of a respective flap 732 on the flexible strip 702. The flaps 732 are individually defined and formed on the flexible strip 702 by a non-linear cut having a starting point at a first end of the hinge axis $H.A.$ of the flap and an ending point at a second end of the hinge axis $H.A.$ of the flap. In the example shown, the hinge axis $H.A.$ of each of the flaps 732 extends between the side edges s_a, s_b of the flap in an extension direction D_9. Each of the flaps 732 is pivotable about its hinge axis $H.A.$

[00152] The flaps 732 are each formed to a width "w_9" and a length "l_9" on the flexible strip 702. The flaps 732 are formed on the flexible strip 702 such that they are oriented on the flexible strip 702 in a same orientation relative to one another. The side edges s_a, s_b of each of the flaps 732 project from their corresponding hinge axis $H.A.$ in a same direction. In other words, the front edges f of the flaps 732 face in the same direction.

[00153] The stem region 740 includes a set of flaps 742a, 742b, 742c, 742d, 742e (or "the flaps 742") formed on the flexible strip 702. The flaps 742 are individually defined and formed in the stem region 740 on the flexible strip 702 by a non-linear cut passing through an entire thickness t of the flexible strip 702, the thickness t being in a direction projecting from the page of each of FIGS. 7A to 7D. Each non-linear cut defines side edges "s_a, s_b," a front edge "f," and a hinge axis "$H.A.$" of a respective flap 742 on the flexible strip 702. The flaps 742 are individually defined and formed on the flexible strip 702 by a non-linear cut having a starting point at a first end of the hinge axis $H.A.$ of the flap and an ending point at a second end of the hinge axis $H.A.$ of the flap. The hinge axis $H.A.$ of each of the flaps 742 extends between the side edges s_a, s_b of the flap in an extension direction D_{10}. Each of the flaps 742 is pivotable about its hinge axis $H.A.$

[00154] The flaps 742 are each formed to a width "w_{10}" and a length "l_{10}" on the flexible strip 702. The flaps 742 are formed on the flexible strip 702 such that they are oriented on the flexible strip 702 in a same orientation relative to one another. The side edges s_a, s_b of each of the flaps 742 project from their corresponding hinge axis $H.A.$ in a same direction. In other words, the front edges f of the flaps 742 face in the same direction.

[00155] The stem region 750 includes a set of flaps 752a, 752b, 752c, 752d, 752e (or "the flaps 752") formed on the flexible strip 702. The flaps 752 are individually defined and formed in the stem region 750 on the flexible strip 702 by a non-linear cut passing through an entire thickness t of the flexible strip 702, the thickness t being in a direction projecting from the page of each of FIGS. 7A to 7D. Each non-linear cut defines side edges "s_a, s_b," a front edge "f," and a hinge axis

"*H.A.*" of a respective flap 752 on the flexible strip 702. The flaps 752 are individually defined and formed on the flexible strip 702 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 752 extends between the side edges s_a, s_b of the flap in an extension direction D_{11}. Each of the flaps 752 is pivotable about its hinge axis *H.A.*

[00156] The flaps 752 are each formed to a width "w_{11}" and a length "l_{11}" on the flexible strip 702. The flaps 752 are formed on the flexible strip 702 such that they are oriented on the flexible strip 702 in a same orientation relative to one another. The side edges s_a, s_b of each of the flaps 752 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edges *f* of the flaps 752 face in the same direction.

[00157] The stem region 760 includes a set of flaps 762a, 762b, 762c, 762d (or "the flaps 762") formed on the flexible strip 702. The flaps 762 are individually defined and formed in the stem region 760 on the flexible strip 702 by a non-linear cut passing through an entire thickness *t* of the flexible strip 702, the thickness *t* being in a direction projecting from the page of each of FIGS. 7A to 7D. Each non-linear cut defines side edges "s_a, s_b," a front edge "*f*," and a hinge axis "*H.A.*" of a respective flap 762 on the flexible strip 702. The flaps 762 are individually defined and formed on the flexible strip 702 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 762 extends between the side edges s_a, s_b of the flap in an extension direction D_{12}. Each of the flaps 762 is pivotable about its hinge axis *H.A.*

[00158] The flaps 762 are each formed to a width "w_{12}" and a length "l_{12}" on the flexible strip 702. The flaps 762 are formed on the flexible strip 702 such that they are oriented on the flexible strip 702 in a same orientation relative to one another. The side edges s_a, s_b of each of the flaps 762 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edges *f* of the flaps 762 face in the same direction.

[00159] The widths w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8, w_9, w_{10}, w_{11}, w_{12} of each of the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762, respectively, are approximately equal to one another. In some embodiments, at least one of the widths w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8, w_9, w_{10}, w_{11}, w_{12} of at least one of the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762, respectively, is different from at least one other width of the widths w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8, w_9, w_{10}, w_{11}, w_{12} of at least one other flap of the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762, respectively. Additionally, the lengths l_1, l_2, l_3, l_4, l_5, l_6, l_7, l_8, l_9, l_{10}, l_{11}, l_{12} of each of the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762, respectively, are approximately equal to one another. In some embodiments, at least one of the lengths l_1, l_2, l_3, l_4, l_5, l_6, l_7, l_8, l_9, l_{10}, l_{11}, l_{12} of at least one of the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762, respectively, is different from at least one other length of the lengths l_1, l_2, l_3, l_4, l_5, l_6, l_7, l_8, l_9, l_{10}, l_{11}, l_{12} of at least one other flap of the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762, respectively.

[00160] The portions of the flexible strip 702 between the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762 are interconnect regions and they are respectively defined as various portions of the flexible strip 702 extending at various distances between the flaps themselves and between the flaps and edges of the flexible strip 702. Any or all of the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762 and any or all of the aforementioned interconnect regions on the flexible strip 702 may be designed and embodied to various geometries and dimensions. The metamaterial and anisotropic adhesive properties of the flexible strip 702 or those of a metamaterial adhesive that may be integrated in or coupled to the flexible strip 702, along with certain geometrical or dimensional designs of the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762 and/or the interconnect regions between the flaps allow for a variety of resist-release shear force modes to be designed for the adhesive system 700. Such resist-release shear force modes have a multitude of applications in shear loading where the adhesive system 700 is pulled parallel to and coupled to a surface. The adhesive system 700 includes metamaterial adhesive described in examples herein that simultaneously provides strong resist and easy release adhesion with spatially selectable adhesion strength through predefined or programmed flap and interconnect region architectures that may be designed for the adhesive system 700.

[00161] The example resist-release shear force diagram illustrated in FIG. 7C and corresponding to the adhesive system 700 shows example F_{max} and F_{min} shear forces that can be provided by the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762 individually, in subgroups as the base region 704 and the stem regions 720, 730, 740, 750, 760, and collectively as the adhesive system 700. The F_{max} and F_{min} shear forces are represented in the example show as arrows that respectively point in a direction of the F_{max} or F_{min} shear force. The length of each arrow denotes and corresponds to a magnitude of the F_{max} or F_{min} shear force. The resist-release shear force mode provided by the adhesive system 700 facilitates strong bonding to one or more surfaces and ensures sealing in all directions, yet the adhesive system 700 can be removed on demand by peeling in a particular direction (FIGS. 7C and 7D).

[00162] High-adhesion yet easy-release capabilities are critical for numerous applications. In some embodiments, the adhesive system 700 may be coupled to a function component. For example, a top or a bottom side of the flexible strip 702 can be coupled to a functional component that can include, but is not limited to, at least one of a biosensor, an electrical or electronic circuit, a chemical sensor, a bio-monitoring patch, a graphic, a bandage, tape for adhering or coupling objects together, a box or container, a wall hanging apparatus, or a glove or textile.

[00163] To demonstrate an example application of the adhesive system 700 with an article of clothing such as a glove, the adhesive system 700 can be designed and embodied as, for example, a textile tape that can be coupled on one side to a glove. For instance, as illustrated in FIGS. 7D, the adhesive system 700 can be designed and embodied as a textile tape that can be coupled on one side of the flexible strip 702 to a glove 770. In the example shown, one side of the adhesive system 700 is coupled to a front, palm-side, or palmar side of the glove 770. In this example, the adhesive system 700 can support an object that may be grasped and/or lifted by a user wearing such a glove having the adhesive system 700 coupled thereto.

[00164] The adhesive system 700 can provide strong bonding to both the glove 770 and any of a variety of objects that may be grasped and/or lifted by a user wearing the glove 770. Additionally, the adhesive system 700 can ensure sealing in all directions across portions of the glove 770 and object to which it is bonded. The adhesive system 700 can also be removed on demand by peeling in a particular direction as illustrated in FIGS. 7C and 7D.

[00165] The adhesive system 700 can be used in combination with the glove 770 to grip and/or lift various objects, while still being easily removed (FIGS. 7C and 7D). Furthermore, the adhesive system 700 provides the ability to control adhesion strength in two directions at one location to make the gripping and/or lifting more robust, where adhesion strength can be increased at the edges of the flexible strip 702 to prevent inadvertent release. For instance, the adhesive system 700 can be designed and embodied such that the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762 and/or the surrounding interconnect region on the flexible strip 702 provide a certain adhesion strength to prevent inadvertent release of a portion of the adhesive system 700 from the glove 770 and/or an object that may be grasped and/or lifted by a user wearing the glove 770.

[00166] The adhesive system 700 can also be applied in various wearable form factors. In one example, the adhesive system 700 and the glove 770 can be designed and embodied as a metamaterial adhesive pick-and-release glove that can be created by laser-machining non-linear cuts to define the flaps 706, 708, 710, 712, 714, 716, 722, 724, 732, 742, 752, 762 into an

elastomer-coated glove. This embodiment allows a user to pick up a flat object, hold it reliably and then effortlessly release the object into a predetermined location through wrist rotation (FIGS. 7C to 7H). In another experiment, an unpatterned glove dropped the same object.

[00167] FIGS. 8A to 8H provide an overview of another example adhesive system, as well as an example application of the adhesive system according to various aspects and embodiments of the present disclosure. FIG. 8A illustrates a top view of the example metamaterial adhesive system according to various aspects and embodiments of the present disclosure. FIG. 8B illustrates plots of example force versus position data corresponding to the example metamaterial adhesive system shown in FIG. 8A and an unpatterned adhesive system according to various aspects and embodiments of the present disclosure. FIGS. 8C, 8D, and 8E illustrate various top views of the example metamaterial adhesive system shown in FIG. 8A coupled to a wireless wearable human-in-the-loop motion control device according to various aspects and embodiments of the present disclosure. FIGS. 8F, 8G, and 8H illustrate various views of the example metamaterial adhesive system shown in FIG. 8A coupled to on one side to a wireless wearable human-in-the-loop motion control device for controlling a robotic device and coupled on another side to a first human arm then a second human arm for controlling the robotic device using the wireless wearable human-in-the-loop motion control device according to various aspects and embodiments of the present disclosure.

[00168] The metamaterial adhesive system of FIG. 8A can be designed and embodied as a wearable patch or device for various human-in-the-loop wearable device applications such as those illustrated in FIGS. 8C to 8H, for instance. In FIG. 8F, the example metamaterial adhesive system of FIG. 8A is used in combination with the wireless wearable human-in-the-loop motion control device (or "the device") of FIG. 8C to grip, lift, and transport an object by a robotic arm controlled by the device adhered to a user's arm by the example metamaterial adhesive system. In FIG. 8G, the device is transferred to another user's arm. In FIG. 8H, the device is used to transport and release the object. In the example shown, the metamaterial adhesive system of FIG. 8A had high adhesion at the edges for strong attachment with easy removal after initial peeling, which was qualitatively observed through substantial skin deformation in the F_{max} direction, relative to the unpatterned and F_{min} direction (FIG. 8B).

[00169] The wearable device of FIG. 8C, which captures human motion and wirelessly transmits the signal to a mirrored robotic arm, was attached to the arm of a first user where an object was gripped, lifted vertically, displaced horizontally, and released from the robotic arm

(FIG. 8F). In this example, the metamaterial adhesive system of FIG. 8A having the wireless control device coupled thereto was then transferred to another user to move the object again (FIGS. 8G and 8H). In other embodiments of the example metamaterial adhesive system of FIG. 8A, cut patterns can also be extended to a variety of adhesive patch shapes, including a circular adhesive patch for a wearable physiological monitoring device, for instance.

[00170] FIGS. 9A to 9E provide an overview of another example adhesive system 900, as well as an example application of the adhesive system 900 according to various aspects and embodiments of the present disclosure. FIG. 9A illustrates a front view of the example adhesive system 900 according to various aspects and embodiments of the present disclosure. FIG. 9B illustrates a dimensional diagram corresponding to the example adhesive system 900 shown in FIG. 9A according to various aspects and embodiments of the present disclosure. FIG. 9C illustrates a side view of the example adhesive system 900 shown in FIG. 9A coupled to a surface and in a maximum shear force mode according to various aspects and embodiments of the present disclosure. FIG. 9D illustrates another side view of the example adhesive system 900 shown in FIG. 9A coupled to a surface and in a minimum shear force mode according to various aspects and embodiments of the present disclosure. FIG. 9E illustrates another side view of the example adhesive system 900 shown in FIG. 9A coupled to a surface and in a minimum shear force peeling mode according to various aspects and embodiments of the present disclosure.

[00171] The adhesive system 900 is an example alternative embodiment of the metamaterial adhesive system described herein and illustrated in FIGS. 1A to 1E. The adhesive system 900 includes the same or similar structure and material (e.g., metamaterial adhesive). A difference between the adhesive system 900 and the metamaterial adhesive system of FIGS. 1A to 1E is the shape, size, number, orientation, grouping, and arrangement of the non-linear cuts that define various flap and interconnect regions on a flexible substrate. Another difference between the adhesive system 900 and the metamaterial adhesive system of FIGS. 1A to 1E is that rather than being formed as a film of metamaterial adhesive or as a flexible substrate with such a film deposited on at least one side, the flexible substrate of the adhesive system 900 includes metamaterial adhesive deposited on at least one side of at least one flap defined by a non-linear cut through a thickness of the flexible substrate.

[00172] With reference to FIGS. 9A and 9B, the adhesive system 900 includes a flexible strip 902. The flexible strip 902 can include a layer of a thermoplastic material, a thermosetting material, polyethylene terephthalate, polypropylene, polyimide, polystyrene, polycarbonate, polyethylene naphthalate, an elastomer material, a rubber material, a fabric material, or any combination thereof in one example. The flexible strip 902 can be embodied as a laminate of an inelastic layer and an elastic layer in another example. In some embodiments, the elastic layer can include at least one of polydimethylsiloxane, polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel. In other examples, the flexible strip 902 can be embodied as a flexible substrate such as at least one of a polyethylene terephthalate backing, a polyethylene terephthalate-polydimethylsiloxane laminate, paper, porous material, fabric, mesh, a metalized film, or another flexible substrate.

[00173] The flexible strip 902 is formed to a rectangular shape, although other geometries may be relied upon in some cases. The flexible strip 902 includes multiple regions 910, 920, 930 of aligned flaps formed on the flexible strip 902. The region 910 of aligned flaps and the region 930 of aligned flaps are located at opposing sections or ends of the flexible strip 902 relative to one another, with the region 920 of aligned flaps being positioned between the regions 910, 930.

[00174] The region 910 includes a row of flaps 912a, 912b, 912c, 912d, 912e, 912f, 912g (or "the flaps 912") formed on the flexible strip 902. The flaps 912 are individually defined and formed on the flexible strip 902 by a non-linear cut passing through an entire thickness t of the flexible strip 902, the thickness t being in a direction projecting from the page of each of FIGS. 9A and 9B and vertically across the page of each of FIGS. 9C to 9E. Each non-linear cut defines side edges "s_a, s_b," a front edge "f," and a hinge axis "*H.A.*" of a respective flap 912 on the flexible strip 902. The flaps 912 are individually defined and formed on the flexible strip 902 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 912 extends between the side edges s_a, s_b of the flap in an extension direction D_1. Each of the flaps 912 is pivotable about its hinge axis *H.A.*

[00175] The flaps 912 are each formed to a width "w_1" and a length "l_1" on the flexible strip 902. The widths w_1 of the flaps 912 are approximately equal to one another. In some embodiments, the width w_1 of at least one of the flaps 912 may be different from the width w_1 of at least one other flap 912. Additionally, the lengths l_1 of the flaps 912 are approximately equal to one another. In some embodiments, the length l_1 of at least one of the flaps 912 may be different from the length l_1 of at least one other flap 912.

[00176] The flaps 912 are formed on the flexible strip 902 such that they are similarly oriented on the flexible strip 902 relative to one another. The side edges s_a, s_b of each of the flaps 912 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edge *f* of each of the flaps 912 face in the same direction.

[00177] Each of the flaps 912a, 912b, 912c, 912d, 912e, 912f, 912g has opposing sides, for instance, with one side facing into the page of FIG. 9A and another side facing out of the page of FIG. 9A. Each of the flaps 912a, 912b, 912c, 912d, 912e, 912f, 912g has a unit of adhesive 914a, 914b, 914c, 914d, 914e, 914f, 914g (or "the adhesive units 914") deposited on and coupled to at least one of such opposing sides of a respective flap 912. Any or all of the adhesive units 914 may include or be embodied as a metamaterial adhesive described in examples herein. Any or all of the adhesive units 914 may include or be embodied as a low-tack pressure-sensitive adhesive, a pressure sensitive adhesive, a soft skin adhesive, or another type of adhesive.

[00178] The adhesive units 914 are each formed to a width "w_2" and a length "l_2" on at least one side of a corresponding flap 912 on the flexible strip 902. The widths w_2 of the adhesive units 914 are approximately equal to one another. In some embodiments, the width w_2 of at least one of the adhesive units 914 may be different from the width w_2 of at least one other adhesive unit 914. Additionally, the lengths l_2 of the adhesive units 914 are approximately equal to one another. In some embodiments, the length l_2 of at least one of the adhesive units 914 may be different from the length l_2 of at least one other adhesive unit 914. The adhesive units 914 are positioned closer to respective front edges *f* of their corresponding flaps 912. In other examples, the adhesive units 914 may each be positioned closer to a center or a hinge axis *H.A.* of their corresponding flap 912.

[00179] The region 920 includes a row of flaps 922a, 922b, 922c, 922d, 922e, 922f, 922g (or "the flaps 922") formed on the flexible strip 902. The flaps 922 are individually defined and formed on the flexible strip 902 by a non-linear cut passing through an entire thickness *t* of the flexible strip 902, the thickness *t* being in a direction projecting from the page of each of FIGS. 9A and 9B and vertically across the page of each of FIGS. 9C to 9E. Each non-linear cut defines side edges "s_a, s_b," a front edge "*f*," and a hinge axis "*H.A.*" of a respective flap 922 on the flexible strip 902. The flaps 922 are individually defined and formed on the flexible strip 902 by a non-linear cut having a starting point at a first end of the hinge axis *H.A.* of the flap and an ending point at a second end of the hinge axis *H.A.* of the flap. The hinge axis *H.A.* of each of the flaps 922 extends between the side edges s_a, s_b of the flap in an extension direction D_2. Each of the flaps 922 is pivotable about its hinge axis *H.A.*

[00180] The flaps 922 are each formed to a width "w_3" and a length "l_3" on the flexible strip 902. The widths w_3 of the flaps 922 are approximately equal to one another. In some embodiments, the width w_3 of at least one of the flaps 922 may be different from the width w_3 of at least one other flap 922. Additionally, the lengths l_3 of the flaps 922 are approximately equal to one another. In some embodiments, the length l_3 of at least one of the flaps 922 may be different from the length l_3 of at least one other flap 922.

[00181] The flaps 922 are formed on the flexible strip 902 such that they are similarly oriented on the flexible strip 902 relative to one another. The side edges s_a, s_b of each of the flaps 922 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edge *f* of each of the flaps 922 face in the same direction. Additionally, the flaps 912, 922 are formed on the flexible strip 902 such that they are similarly oriented on the flexible strip 902 relative to one another. The side edges s_a, s_b of each of the flaps 912, 922 project from their corresponding hinge axis *H.A.* in a same direction. In other words, the front edge *f* of each of the flaps 912, 922 face in the same direction.

[00182] Each of the flaps 922a, 922b, 922c, 922d, 922e, 922f, 922g has opposing sides, for instance, with one side facing into the page of FIG. 9A and another side facing out of the page of FIG. 9A. Each of the flaps 922a, 922b, 922c, 922d, 922e, 922f, 922g has a unit of adhesive 924a, 924b, 924c, 924d, 924e, 924f, 924g (or "the adhesive units 924") deposited on and coupled to at least one of such opposing sides of a respective flap 922. Any or all of the adhesive units 924 may include or be embodied as a metamaterial adhesive described in examples herein. Any or all of the adhesive units 924 may include or be embodied as a low-tack pressure-sensitive adhesive, a pressure sensitive adhesive, a soft skin adhesive, or another type of adhesive.

[00183] The adhesive units 924 are each formed to a width "w_4" and a length "l_4" on at least one side of a corresponding flap 922 on the flexible strip 902. The widths w_4 of the adhesive units 924 are approximately equal to one another. In some embodiments, the width w_4 of at least one of the adhesive units 924 may be different from the width w_4 of at least one other adhesive unit 924. Additionally, the lengths l_4 of the adhesive units 924 are approximately equal to one another. In some embodiments, the length l_4 of at least one of the adhesive units 924 may be different from the length l_4 of at least one other adhesive unit 924. The adhesive units 924 are positioned closer to respective front edges *f* of their corresponding flaps 922. In other examples, the adhesive units 924 may each be positioned closer to a center or a hinge axis *H.A.* of their corresponding flap 922.

[00184] The region 930 includes a row of flaps 932a, 932b, 932c, 932d, 932e, 932f, 932g (or "the flaps 932") formed on the flexible strip 902. The flaps 932 are individually defined and formed on the flexible strip 902 by a non-linear cut passing through an entire thickness *t* of the flexible strip 902, the thickness t being in a direction projecting from the page of each of FIGS. 9A and 9B and vertically across the page of each of FIGS. 9C to 9E. Each non-linear cut defines side edges "s_a, s_b," a front edge "f," and a hinge axis "$H.A.$" of a respective flap 932 on the flexible strip 902. The flaps 932 are individually defined and formed on the flexible strip 902 by a non-linear cut having a starting point at a first end of the hinge axis $H.A.$ of the flap and an ending point at a second end of the hinge axis $H.A.$ of the flap. The hinge axis $H.A.$ of each of the flaps 932 extends between the side edges s_a, s_b of the flap in an extension direction D_3. Each of the flaps 932 is pivotable about its hinge axis $H.A.$

[00185] The flaps 932 are each formed to a width "w_5" and a length "l_5" on the flexible strip 902. The widths w_5 of the flaps 932 are approximately equal to one another. In some embodiments, the width w_5 of at least one of the flaps 932 may be different from the width w_5 of at least one other flap 932. Additionally, the lengths l_5 of the flaps 932 are approximately equal to one another. In some embodiments, the length l_5 of at least one of the flaps 932 may be different from the length l_5 of at least one other flap 932.

[00186] The flaps 932 are formed on the flexible strip 902 such that they are similarly oriented on the flexible strip 902 relative to one another. The side edges s_a, s_b of each of the flaps 932 project from their corresponding hinge axis $H.A.$ in a same direction. In other words, the front edge f of each of the flaps 932 face in the same direction. Additionally, the flaps 912, 922, 932 are formed on the flexible strip 902 such that they are similarly oriented on the flexible strip 902 relative to one another. The side edges s_a, s_b of each of the flaps 912, 922, 932 project from their corresponding hinge axis $H.A.$ in a same direction. In other words, the front edge f of each of the flaps 912, 922, 932 face in the same direction.

[00187] Each of the flaps 932a, 932b, 932c, 932d, 932e, 932f, 932g has opposing sides, for instance, with one side facing into the page of FIG. 9A and another side facing out of the page of FIG. 9A. Each of the flaps 932a, 932b, 932c, 932d, 932e, 932f, 932g has a unit of adhesive 934a, 934b, 934c, 934d, 934e, 934f, 934g (or "the adhesive units 934") deposited on and coupled to at least one of such opposing sides of a respective flap 932. Any or all of the adhesive units 934 may include or be embodied as a metamaterial adhesive described in examples herein. Any or all of the adhesive units 934 may include or be embodied as a low-tack pressure-sensitive adhesive, a pressure sensitive adhesive, a soft skin adhesive, or another type of adhesive.

[00188] The adhesive units 934 are each formed to a width "w_6" and a length "l_6" on at least one side of a corresponding flap 932 on the flexible strip 902. The widths w_6 of the adhesive units

934 are approximately equal to one another. In some embodiments, the width w_6 of at least one of the adhesive units 934 may be different from the width w_6 of at least one other adhesive unit 934. Additionally, the lengths l_6 of the adhesive units 934 are approximately equal to one another. In some embodiments, the length l_6 of at least one of the adhesive units 934 may be different from the length l_6 of at least one other adhesive unit 934. The adhesive units 934 are positioned closer to respective front edges f of their corresponding flaps 932. In other examples, the adhesive units 934 may each be positioned closer to a center or a hinge axis $H.A.$ of their corresponding flap 932.

[00189] The flexible strip 902 has edges e_1, e_2 located at opposing regions or ends (e.g., longitudinal or distal ends) of the flexible strip 902 relative to one another and side edges s_1, s_2 located at opposing regions or sides (e.g., lateral or distal sides) of the flexible strip 902 relative to one another. The side edges s_1, s_2 of the flexible strip 902 extend a distance d_1 between the edges e_1, e_2 of the flexible strip 902 and the edges e_1, e_2 of the flexible strip 902 extend a distance d_2 between the side edges s_1, s_2 of the flexible strip 902. The distances d_1, d_2 are different, for example, the distance d_1 is greater than the distance d_2. In some embodiments, the distance d_1 may be less than or approximately equal to the distance d_2.

[00190] Respective front edges f of the flaps 912 are located at a distance d_3 from the edge e_1 of the flexible strip 902. The hinge axis $H.A.$ of respective flaps 912 is located a distance d_4 from respective front edges f of the flaps 922. The hinge axis $H.A.$ of respective flaps 922 is located a distance d_5 from respective front edges f of the flaps 932. The hinge axis $H.A.$ of respective flaps 932 is located a distance d_6 from the edge e_2 of the flexible strip 902.

[00191] The side edge s_a of the flap 912a, the side edge s_a of the flap 922a, and the side edge s_a of the flap 632a are each located at a distance d_7 from the side edge s_1 of the flexible strip 902. The side edge s_b of the flap 912g, the side edge s_b of the flap 922g, and the side edge s_b of the flap 932g are each located at a distance d_8 from the side edge s_2 of the flexible strip 902.

[00192] Respective side edges of the flaps 912a, 912b, the flaps 922a, 922b, and the flaps 932a, 932b are located at a distance d_9 from one another. Respective side edges of the flaps 912b, 912c, the flaps 922b, 922c, and the flaps 932b, 932c are located at a distance d_{10} from one another. Respective side edges of the flaps 912c, 912d, the flaps 922c, 922d, and the flaps 932c, 932d are located at a distance d_{11} from one another. Respective side edges of the flaps 912d, 912e, the flaps 922d, 922e, and the flaps 932d, 932e are located at a distance d_{12} from one another. Respective side edges of the flaps 912e, 912f, the flaps 922e, 922f, and the flaps 932e, 932f are located at a distance d_{13} from one another. Respective side edges of the flaps 912f, 912g, the flaps 922f, 922g, and the flaps 932f, 932g are located at a distance d_{14} from one another.

[00193] The distances d_3, d_4, d_5, d_6 are approximately equal to one another, the distances d_7, d_8 are approximately equal to one another, and the distances d_9, d_{10}, d_{11}, d_{12}, d_{13}, d_{14} are approximately equal to one another. In another example, at least one of the distances d_3, d_4, d_5, d_6 may be different from at least one other distance of the distances d_3, d_4, d_5, d_6, one of the distances d_7, d_8 may be different from the other distance of the distances d_7, d_8, and/or one of the distances d_9, d_{10}, d_{11}, d_{12}, d_{13}, d_{14} may be different from at least one other distance of the distances d_9, d_{10}, d_{11}, d_{12}, d_{13}, d_{14}. The extension directions D_1, D_2, D_3 are offset from and parallel to one another.

[00194] The portions of the flexible strip 902 between the flaps 912, 922, 932 are interconnect regions and they are respectively defined in whole or in part by distances d_1 to d_{14}. Any or all of the flaps 912, 922, 932 and any or all of the aforementioned interconnect regions on the flexible strip 902 may be designed and embodied to various geometries and dimensions. The flexible properties of the flexible strip 902 combined with the metamaterial and anisotropic adhesive properties of a metamaterial adhesive coupled to at least one side of at least one of the flaps 912, 922, 932 on the flexible strip 902, along with certain geometrical or dimensional designs of the flaps 912, 922, 932 and/or the interconnect regions between the flaps allow for a variety of resist-release shear force modes to be designed for the adhesive system 900. Such resist-release shear force modes have a multitude of applications in shear loading where the adhesive system 900 is pulled parallel to and coupled to a surface. The flaps 912, 922, 932 of the adhesive system 900 have a metamaterial adhesive described in examples herein coupled to a side of the flaps. The adhesive system 900 simultaneously provides strong resist and easy release adhesion with spatially selectable adhesion strength through predefined or programmed flap and interconnect region architectures that may be designed for the adhesive system 900.

[00195] Example resist (F_{max}) and release (F_{min}) shear force directions are illustrated in FIG. 9A, 9C, 9D, and 9E and correspond to the adhesive system 900. The example F_{max} and F_{min} shear forces denoted in the figures represent those that can be provided by the flaps 912, 922, 932 individually, in subgroups as the regions 910, 920, 930, and collectively as the adhesive system 900. The F_{max} and F_{min} shear forces are represented in the example show as arrows that respectively point in a direction of the F_{max} or F_{min} shear force. The resist-release shear force mode provided by the adhesive system 900 facilitates strong bonding to one or more surfaces and ensures sealing in all directions, yet the adhesive system 900 can be removed on demand by peeling in a particular direction (FIGS. 9C, 9D, and 9E).

[00196] High-adhesion yet easy-release capabilities are critical for numerous applications. In some embodiments, the adhesive system 900 may be coupled to a function component. For example, a side of the flexible strip 902 having the adhesive units 914, 924, 934 respectively coupled to the flaps 912, 922, 932 can be coupled to a functional component that can include, but is not limited to, at least one of a biosensor, an electrical or electronic circuit, a chemical sensor, a bio-monitoring patch, a graphic, a bandage, tape for adhering or coupling objects together, a box or container, a wall hanging apparatus, or a glove or textile. Other example applications of the adhesive system 900 include, but are not limited to, climbing robots, grabbing space garbage, and satellite repair among others as the adhesive system 900 can be implemented to easily engage and release different types of objects in such applications.

[00197] To demonstrate an example application of the adhesive system 900, the adhesive system 900 was evaluated in one implementation in both the F_{max} and F_{min} shear force directions as illustrated in FIGS. 9F to 9K, and example performance data collected based on such experimentation is plotted in FIG. 9L. The adhesive system 900 can provide strong bonding to a surface 950 (e.g., a wall, a box, or any surface) and can also be removed on demand by peeling in a particular direction as illustrated in FIGS. 9C to 9K.

[00198] FIG. 9F illustrates a perspective view of the example adhesive system shown in FIG. 9A during a 0° peel in a F_{max} direction according to various aspects and embodiments of the present disclosure. FIG. 9G illustrates another perspective view of the example adhesive system shown in FIG. 9A during loading in a F_{max} direction according to various aspects and embodiments of the present disclosure. FIG. 9H illustrates another perspective view of the example adhesive system shown in FIG. 9A during failure in a F_{max} direction according to various aspects and embodiments of the present disclosure.

[00199] FIG. 9I illustrates another perspective view of the example adhesive system shown in FIG. 9A during a 0° peel in a F_{min} direction according to various aspects and embodiments of the present disclosure. FIG. 9J illustrates another perspective view of the example adhesive system shown in FIG. 9A during loading in a F_{min} direction according to various aspects and embodiments of the present disclosure. FIG. 9K illustrates another perspective view of the example adhesive system shown in FIG. 9A during failure in a F_{min} direction according to various aspects and embodiments of the present disclosure.

[00200] FIG. 9L illustrates a plot of example adhesion force versus number of rows of flaps (number of patterns) data for the example metamaterial adhesive system shown in FIG. 9A in a F_{min} direction and a F_{max} direction according to various aspects and embodiments of the present disclosure.

[00201] Described in example embodiments herein are metamaterial adhesive systems and strategy functions with a range of adhesives on diverse substrates and conditions to enhance adhesion. Each of the embodiments provides directionality and spatially programable adhesive strength across an adhesive sheet in multiple directions simultaneously. Through a maskless, digital fabrication environment, diverse adhesive characteristics can be quickly designed and implemented, which cannot be done with chemical or microfeature patterns. Additionally, millimeter–centimeter scale cuts (flaps) could be created with roll-to-roll techniques such as rotary die cutting in some examples, providing avenues for scaling-up.

[00202] When used in applications with backings that are meant to tear, the cuts (flaps) of various example metamaterial adhesive systems described herein may be designed to introduce locations for possible rupture and thereby improve tearability in such applications, which might be useful for counterfeit protection and easy dispensing of tapes. The reverse crack propagation mechanism for programmable adhesion described in embodiments herein may also enable new opportunities in other fracture processes, such as toughening bulk materials, adhesion control in micro/nano systems and adhesion for locomotion in robotics. Thus, the metamaterial adhesive systems of the present disclosure can serve as the foundation for the exceptional control of adhesion in diverse materials and applications.

[00203] Disjunctive language, such as the phrase "at least one of X, Y, or Z," unless specifically stated otherwise, is to be understood with the context as used in general to present that an item, term, or the like, can be either X, Y, or Z, or any combination thereof (e.g., X, Y, and/or Z). Thus, such disjunctive language is not generally intended to, and should not, imply that certain embodiments require at least one of X, at least one of Y, or at least one of Z to be each present. As referenced herein in the context of quantity, the terms "a" or "an" are intended to mean "at least one" and are not intended to imply "one and only one."

[00204] As referred to herein, the terms "include," "includes," and "including" are intended to be inclusive in a manner similar to the term "comprising." As referenced herein, the terms "or" and "and/or" are generally intended to be inclusive, that is (*i.e.*), "A or B" or "A and/or B" are each intended to mean "A or B or both." As referred to herein, the terms "first," "second," "third," and so on, can be used interchangeably to distinguish one component or entity from another and are not intended to signify location, functionality, or importance of the individual components or entities. As referenced herein, the terms “couple,” “couples,” “coupled,” and/or “coupling” refer to chemical coupling (*e.g.*, chemical bonding), communicative coupling, electrical and/or electromagnetic coupling (*e.g.*, capacitive coupling, inductive coupling, direct and/or connected coupling), mechanical coupling, operative coupling, optical coupling, and/or physical coupling.

[00205] It should be emphasized that the above-described embodiments of the present disclosure are merely possible examples of implementations set forth for a clear understanding of the principles of the disclosure. Many variations and modifications can be made to the above-described embodiment(s) without departing substantially from the spirit and principles of the disclosure. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.

CLAIMS

Therefore, at least the following is claimed:

1. An adhesive system, comprising:

a flexible strip;

a first flap on the flexible strip, the first flap being pivotable about a hinge axis of the first flap, the hinge axis of the first flap extending between side edges of the first flap in a first extension direction; and

a second flap on the flexible strip, the second flap being pivotable about a hinge axis of the second flap, the hinge axis of the second flap extending between side edges of the second flap in a second extension direction, the second extension direction of the hinge axis of the second flap being different from the first extension direction of the hinge axis of the first flap.

2. The adhesive system of claim 1, further comprising:

first rows of opposing flaps on the flexible strip, the first rows of opposing flaps being oppositely oriented on the flexible strip relative to one another, the first rows of opposing flaps comprising the first flap; and

second rows of opposing flaps on the flexible strip, the second rows of opposing flaps being oppositely oriented on the flexible strip relative to one another, the second rows of opposing flaps comprising the second flap.

3. The adhesive system of claim 2, wherein the first rows of opposing flaps are oriented differently on the flexible strip relative to the second rows of opposing flaps.

4. The adhesive system of claim 2, wherein:

the first rows of opposing flaps further comprise a third flap on the flexible strip, the third flap having defined dimensions; and

at least one of the first flap or the second flap has a dimension that is different from a corresponding dimension of the defined dimensions of the third flap.

5. The adhesive system of claim 2, wherein:

the first rows of opposing flaps further comprise a first row of flaps and a second row of flaps on the flexible strip; and

individual flaps of the first row of flaps having a dimension that is different from a corresponding dimension of individual flaps of the second row of flaps.

6. The adhesive system of claim 2, further comprising:

third rows of opposing flaps on the flexible strip, the third rows of opposing flaps being oppositely oriented on the flexible strip relative to one another,

wherein the second rows of opposing flaps and the third rows of opposing flaps are located on opposing regions of the flexible strip.

7. The adhesive system of claim 6, wherein individual flaps of the second rows of opposing flaps and individual flaps of the third rows of opposing flaps have same dimensions.

8. The adhesive system of claim 6, wherein a flap of the second rows of opposing flaps has a dimension that is different from a corresponding dimension of at least one flap of the third rows of opposing flaps.

9. The adhesive system of claim 2, further comprising:

a row of flaps on the flexible strip, the row of flaps and the first rows of opposing flaps being located on opposing regions of the flexible strip.

10. The adhesive system of claim 9, wherein the first flap and individual flaps of the row of flaps have same dimensions.

11. The adhesive system of claim 9, wherein:

the first rows of opposing flaps further comprise a third flap on the flexible strip; and

a flap of the row of flaps has a dimension that is different from a corresponding dimension of at least one of the first flap, the second flap, or the third flap.

12. The adhesive system of claim 1, further comprising:

rows of opposing flaps on the flexible strip, the rows of opposing flaps being oppositely oriented on the flexible strip relative to one another, the rows of opposing flaps comprising the first flap; and

rows of aligned flaps on the flexible strip, the rows of aligned flaps being oriented on the flexible strip in a same orientation relative to one another.

13. The adhesive system of claim 12, wherein a row of flaps of the rows of opposing flaps is oriented on the flexible strip in the same orientation relative to at least one row of flaps of the rows of aligned flaps.

14. The adhesive system of claim 12, wherein the rows of opposing flaps and the rows of aligned flaps are located on opposing regions of the flexible strip.

15. The adhesive system of claim 1, wherein the flexible strip comprises a layer of a thermoplastic material, a thermosetting material, polyethylene terephthalate, polypropylene, polyimide, polystyrene, polycarbonate, polyethylene naphthalate, an elastomer material, a rubber material, or a fabric material.

16. The adhesive system of claim 1, wherein the flexible strip comprises a laminate of an inelastic layer and an elastic layer.

17. The adhesive system of claim 16, wherein the elastic layer comprises polydimethylsiloxane, polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel.

18. The adhesive system of claim 1, wherein the flexible strip comprises at least one of a polyethylene terephthalate-polydimethylsiloxane laminate, paper having a low-tack pressure-sensitive adhesive on at least one side of the paper, a pressure sensitive adhesive, a soft skin adhesive, a porous material having the pressure sensitive adhesive, fabric, mesh, or a metalized film.

19. The adhesive system of claim 1, wherein the flexible strip is coupled to a functional component, the functional component comprising at least one of a biosensor, an electrical or electronic circuit, a chemical sensor, or a bio-monitoring patch.

20. The adhesive system of claim 2, further comprising:

third rows of opposing flaps on the flexible strip, the third rows of opposing flaps being oppositely oriented on the flexible strip relative to one another; and

rows of aligned flaps on the flexible strip, the rows of aligned flaps being oriented on the flexible strip in a same orientation relative to one another,

wherein:

a first region of the flexible strip comprises the first rows of opposing flaps and is coupled to at least one of a first moveable flap or a second moveable flap of a box;

a second region of the flexible strip comprises the second rows of opposing flaps and is coupled to the first moveable flap of the box;

a third region of the flexible strip comprises the third rows of opposing flaps and is coupled to the second moveable flap of the box; and

a fourth region of the flexible strip comprises the rows of aligned flaps and is coupled to at least one of the first moveable flap or the second moveable flap of the box.

21. An adhesive system, comprising:

a flexible strip;

a pair of opposing flaps oppositely oriented on the flexible strip relative to one another, each flap of the pair of opposing flaps being pivotable about a flap hinge axis extending in a first extension direction; and

a pair of aligned flaps oriented on the flexible strip in a same orientation relative to one another, each flap of the pair of aligned flaps being pivotable about a flap hinge axis extending in a second extension direction at a defined angle relative to the first extension direction.

22. The adhesive system of claim 21, further comprising:

rows of opposing flaps on the flexible strip, the rows of opposing flaps being oppositely oriented on the flexible strip relative to one another, the rows of opposing flaps comprising the pair of opposing flaps; and a row of aligned flaps on the flexible strip, the row of aligned flaps being oriented on the flexible strip in the same orientation relative to one another, the row of aligned flaps comprising the pair of aligned flaps.

23. The adhesive system of claim 22, wherein the rows of opposing flaps are oriented at the defined angle relative to the row of aligned flaps on the flexible strip.

24. The adhesive system of claim 21, wherein a flap of the pair of opposing flaps has a dimension that is different from a corresponding dimension of a flap of the pair of aligned flaps.

25. The adhesive system of claim 21, wherein a flap of the pair of opposing flaps has a side edge dimension that is different from a corresponding side edge dimension of a flap of the pair of aligned flaps.

26. The adhesive system of claim 21, wherein a flap of the pair of opposing flaps has a front edge dimension that is different from a corresponding front edge dimension of a flap of the pair of aligned flaps.

27. The adhesive system of claim 21, wherein individual flaps of the pair of opposing flaps have same dimensions.

28. The adhesive system of claim 21, wherein individual flaps of the pair of aligned flaps have same dimensions.

29. The adhesive system of claim 21, wherein a first flap of the pair of opposing flaps has a dimension that is different from a corresponding dimension of a second flap of the pair of opposing flaps.

30. The adhesive system of claim 21, wherein a first flap of the pair of aligned flaps has a dimension that is different from a corresponding dimension of a second flap of the pair of aligned flaps.

31. The adhesive system of claim 22, further comprising:

second rows of opposing flaps on the flexible strip, the second rows of opposing flaps being oppositely oriented on the flexible strip relative to one another,

wherein the rows of opposing flaps and the second rows of opposing flaps are located on opposing regions of the flexible strip.

32. The adhesive system of claim 31, wherein individual flaps of the rows of opposing flaps and individual flaps of the second rows of opposing flaps have same dimensions.

33. The adhesive system of claim 22, further comprising:

second rows of opposing flaps on the flexible strip, the second rows of opposing flaps being oppositely oriented on the flexible strip relative to one another,

wherein the row of aligned flaps and the second rows of opposing flaps are located on opposing regions of the flexible strip.

34. The adhesive system of claim 33, wherein at least one flap of the second rows of opposing flaps has a dimension that is different from a corresponding dimension of a flap of the row of aligned flaps.

35. The adhesive system of claim 33, wherein a row of flaps of the second rows of opposing flaps is oriented on the flexible strip in the same orientation relative to the row of aligned flaps.

36. The adhesive system of claim 21, wherein the defined angle comprises a 90 degree angle.

37. The adhesive system of claim 21, wherein the flexible strip comprises a layer of a thermoplastic material, a thermosetting material, polyethylene terephthalate, polypropylene, polyimide, polystyrene, polycarbonate, polyethylene naphthalate, an elastomer material, a rubber material, or a fabric material.

38. The adhesive system of claim 21, wherein the flexible strip comprises a laminate of an inelastic layer and an elastic layer.

39. The adhesive system of claim 38, wherein the elastic layer comprises polydimethylsiloxane, polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel.

40. The adhesive system of claim 21, wherein the flexible strip comprises at least one of a polyethylene terephthalate-polydimethylsiloxane laminate, paper having a low-tack pressure-sensitive adhesive on at least one side of the paper, a pressure sensitive adhesive, a soft skin adhesive, a porous material having the pressure sensitive adhesive, fabric, mesh, or a metalized film.

41. An adhesive system, comprising:

a flexible strip;

a first flap on the flexible strip, the first flap being pivotable about a hinge axis of the first flap, the hinge axis of the first flap extending in a first extension direction; and

a subset of opposing flaps on the flexible strip, the subset of opposing flaps comprising:

a second flap on the flexible strip; and

a pair of aligned flaps oriented on the flexible strip in a same orientation relative to one another and an opposite orientation relative to the second flap,

wherein each flap of the pair of aligned flaps and the second flap is pivotable about a flap hinge axis extending in a second extension direction at a defined angle relative to the first extension direction.

42. The adhesive system of claim 41, further comprising:

first rows of opposing flaps on the flexible strip, the first rows of opposing flaps being oppositely oriented on the flexible strip relative to one another, the first rows of opposing flaps comprising the first flap; and

second rows of opposing flaps on the flexible strip, the second rows of opposing flaps being oppositely oriented on the flexible strip relative to one another, the second rows of opposing flaps comprising the subset of opposing flaps.

43. The adhesive system of claim 42, wherein the first rows of opposing flaps are oriented at the defined angle relative to the second rows of opposing flaps on the flexible strip.

44. The adhesive system of claim 41, wherein the first flap has a dimension that is different from a corresponding dimension of at least one of the second flap or one or more flaps of the pair of aligned flaps.

45. The adhesive system of claim 41, wherein the first flap has a side edge dimension that is different from a corresponding side edge dimension of the second flap and each flap of the pair of aligned flaps.

46. The adhesive system of claim 41, wherein the first flap has a front edge dimension that is different from a corresponding front edge dimension of the second flap and each flap of the pair of aligned flaps.

47. The adhesive system of claim 41, wherein individual flaps of the pair of aligned flaps have same dimensions.

48. The adhesive system of claim 41, wherein the second flap has a dimension that is different from a corresponding dimension of at least one flap of the pair of aligned flaps.

49. The adhesive system of claim 41, wherein the second flap has a front edge dimension that is different from a corresponding front edge dimension of each flap of the pair of aligned flaps.

50. The adhesive system of claim 41, wherein the second flap has a side edge dimension that is equal to a corresponding side edge dimension of each flap of the pair of aligned flaps.

51. The adhesive system of claim 42, further comprising:

third rows of opposing flaps on the flexible strip, the third rows of opposing flaps being oppositely oriented on the flexible strip relative to one another,

wherein the first rows of opposing flaps and the third rows of opposing flaps are located on opposing regions of the flexible strip.

52. The adhesive system of claim 51, wherein individual flaps of the first rows of opposing flaps and individual flaps of the third rows of opposing flaps have same dimensions.

53. The adhesive system of claim 42, further comprising:

a row of aligned flaps on the flexible strip, the row of aligned flaps being oriented on the flexible strip in a same orientation relative to one another,

wherein the row of aligned flaps and the second rows of opposing flaps are located on opposing regions of the flexible strip.

54. The adhesive system of claim 53, wherein at least one flap of the third rows of opposing flaps has a dimension that is different from a corresponding dimension of a flap of the row of aligned flaps.

55. The adhesive system of claim 53, wherein:

a row of flaps of the second rows of opposing flaps is oriented on the flexible strip in the same orientation relative to the row of aligned flaps; and

the row of flaps of the second rows of opposing flaps comprises the pair of aligned flaps.

56. The adhesive system of claim 41, wherein the defined angle comprises a 90 degree angle.

57. The adhesive system of claim 41, wherein the flexible strip comprises a layer of a thermoplastic material, a thermosetting material, polyethylene terephthalate, polypropylene, polyimide, polystyrene, polycarbonate, polyethylene naphthalate, an elastomer material, a rubber material, or a fabric material.

58. The adhesive system of claim 41, wherein the flexible strip comprises a laminate of an inelastic layer and an elastic layer.

59. The adhesive system of claim 58, wherein the elastic layer comprises polydimethylsiloxane, polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel.

60. The adhesive system of claim 41, wherein the flexible strip comprises at least one of a polyethylene terephthalate-polydimethylsiloxane laminate, paper having a low-tack pressure-sensitive adhesive on at least one side of the paper, a pressure sensitive adhesive, a soft skin adhesive, a porous material having the pressure sensitive adhesive, fabric, mesh, or a metalized film.

61. An adhesive system, comprising:

a flexible strip;

first rows of opposing flaps on the flexible strip, the first rows of opposing flaps comprising a first flap and a second flap on the flexible strip, the first flap and the second flap each having same defined dimensions and being oppositely oriented on the flexible strip relative to one another; and

second rows of opposing flaps on the flexible strip, the second rows of opposing flaps comprising a third flap and a fourth flap on the flexible strip, the third flap and the fourth flap being oppositely oriented on the flexible strip relative to one another, the third flap having the same defined dimensions of the first flap and the second flap, and the fourth flap having a dimension that is different from a corresponding dimension of the first flap, the second flap, and the third flap.

62. The adhesive system of claim 61, wherein the first rows of opposing flaps are at a first location on the flexible strip and the second rows of opposing flaps are at a second location on the flexible strip that is different than and separate from the first location of the first rows of opposing flaps on the flexible strip.

63. The adhesive system of claim 61, wherein:

the first rows of opposing flaps comprise a first row of flaps and a second row of flaps on the flexible strip, the first row of flaps being oppositely oriented on the flexible strip relative to the second row of flaps, the first row of flaps comprising the first flap, and the second row of flaps comprising the second flap; and

the second rows of opposing flaps comprise a third row of flaps and a fourth row of flaps on the flexible strip, the third row of flaps being oppositely oriented on the flexible strip relative to the fourth row of flaps, the third row of flaps comprising the third flap, and the fourth row of flaps comprising the fourth flap.

64. The adhesive system of claim 61, further comprising:

third rows of opposing flaps on the flexible strip, the third rows of opposing flaps comprising a fifth flap and a sixth flap on the flexible strip, the fifth flap and the sixth flap being oppositely oriented on the flexible strip relative to one another,

wherein the fifth flap has the same defined dimensions of the first flap, the second flap, and the third flap, and

wherein the sixth flap has a dimension that is different from the corresponding dimension of the first flap, the second flap, the third flap, and the fifth flap and different from the dimension of the fourth flap.

65. The adhesive system of claim 64, wherein:

the third rows of opposing flaps comprise a fifth row of flaps and a sixth row of flaps on the flexible strip, the fifth row of flaps being oppositely oriented on the flexible strip relative to the sixth row of flaps, the fifth row of flaps comprising the fifth flap, and the sixth row of flaps comprising the sixth flap.

66. The adhesive system of claim 61, wherein a first distance between a hinge axis of the first flap and a hinge axis of the second flap is equal to a second distance between a hinge axis of the third flap and a hinge axis of the fourth flap.

67. The adhesive system of claim 64, wherein a first distance between a hinge axis of the first flap and a hinge axis of the second flap is equal to a second distance between a hinge axis of the fifth flap and a hinge axis of the sixth flap.

68. The adhesive system of claim 61, wherein the first rows of opposing flaps and the second rows of opposing flaps are oriented on the flexible strip in a same orientation relative to one another.

69. The adhesive system of claim 64, wherein the first rows of opposing flaps, the second rows of opposing flaps, and the third rows of opposing flaps are oriented on the flexible strip in a same orientation relative to one another.

70. The adhesive system of claim 61, wherein the first rows of opposing flaps are positioned closer to an end of the flexible strip relative to the second rows of opposing flaps.

71. The adhesive system of claim 64, wherein:

the first rows of opposing flaps are positioned closer to an end of the flexible strip relative to the second rows of opposing flaps; and

the second rows of opposing flaps are positioned closer to the end of the flexible strip relative to the third rows of opposing flaps.

72. The adhesive system of claim 61, further comprising:

a row of flaps on the flexible strip, the row of flaps and the first rows of opposing flaps being located on opposing regions of the flexible strip.

73. The adhesive system of claim 72, wherein the first flap and a flap of the row of flaps are each oriented in a same orientation on the flexible strip relative to one another.

74. The adhesive system of claim 72, wherein a flap of the row of flaps has a dimension that is different from a corresponding dimension of the first flap, the second flap, the third flap, and the fourth flap.

75. The adhesive system of claim 61, wherein the flexible strip comprises a layer of a thermoplastic material, a thermosetting material, polyethylene terephthalate, polypropylene,

polyimide, polystyrene, polycarbonate, polyethylene naphthalate, an elastomer material, a rubber material, or a fabric material.

76. The adhesive system of claim 61, wherein the flexible strip comprises a laminate of an inelastic layer and an elastic layer.

77. The adhesive system of claim 76, wherein the elastic layer comprises polydimethylsiloxane, polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel.

78. The adhesive system of claim 61, wherein the flexible strip comprises at least one of a polyethylene terephthalate-polydimethylsiloxane laminate, paper having a low-tack pressure-sensitive adhesive on at least one side of the paper, a pressure sensitive adhesive, a soft skin adhesive, a porous material having the pressure sensitive adhesive, fabric, mesh, or a metalized film.

79. The adhesive system of claim 61, wherein the flexible strip is coupled to a functional component, the functional component comprising at least one of a biosensor, an electrical or electronic circuit, a chemical sensor, or a bio-monitoring patch.

80. The adhesive system of claim 61, further comprising:

third rows of opposing flaps on the flexible strip, the third rows of opposing flaps being oppositely oriented on the flexible strip relative to one another;

a row of flaps on the flexible strip, the row of flaps and the first rows of opposing flaps being located on opposing regions of the flexible strip; and

a mounting or hanging apparatus coupled to the flexible strip between the third rows of opposing flaps and the row of flaps on the flexible strip.

81. An adhesive system, comprising:

a flexible strip comprising a base region and a stem region;

a first flap on the flexible strip, the first flap being in the base region of the flexible strip and being pivotable about a hinge axis of the first flap, the hinge axis of the first flap extending between side edges of the first flap in a first extension direction; and

a second flap on the flexible strip, the second flap being in the stem region of the flexible strip and being pivotable about a hinge axis of the second flap, the hinge axis of the second flap extending between side edges of the second flap in a second extension direction, the second extension direction of the hinge axis of the second flap being different from the first extension direction of the hinge axis of the first flap.

82. The adhesive system of claim 81, further comprising:

a third flap on the flexible strip, the third flap being in the stem region of the flexible strip and being pivotable about a hinge axis of the third flap, the hinge axis of the third flap extending between side edges of the third flap in a third extension direction, the third extension direction of the hinge axis of the third flap being different from at least one of the first extension direction of the hinge axis of the first flap or the second extension direction of the hinge axis of the second flap.

83. The adhesive system of claim 81, further comprising:

multiple second stem regions, at least one of the multiple second stem regions comprising a third flap on the flexible strip, the third flap being pivotable about a hinge axis of the third flap, the hinge axis of the third flap extending between side edges of the third flap in a third extension direction, the third extension direction of the hinge axis of the third flap being different from at least one of the first extension direction of the hinge axis of the first flap or the second extension direction of the hinge axis of the second flap.

84. The adhesive system of claim 81, further comprising:

multiple second stem regions, at least one of the multiple second stem regions comprising multiple flaps on the flexible strip, each of the multiple flaps being pivotable about a respective hinge axis extending between respective side edges of each of the multiple flaps, the respective hinge axis of each of the multiple flaps extending in a same extension direction.

85. The adhesive system of claim 81, further comprising:

a second stem region comprising multiple flaps on the flexible strip, the multiple flaps projecting from the base region in a same direction relative to one another and being oriented in a same orientation relative to one another along the second stem region.

86. The adhesive system of claim 81, further comprising:

a second stem region comprising a third flap, a fourth flap, a fifth flap, and a sixth flap on the flexible strip, the third flap being located closer to the base region relative to the fourth flap, the fourth flap being located closer to the base region relative to the fifth flap, the fifth flap being located closer to the base region relative to the sixth flap, and the third flap and the sixth flap being located at opposing regions of the second stem region.

87. The adhesive system of claim 81, further comprising:

a second stem region comprising multiple flaps on the flexible strip, the multiple flaps having same dimensions.

88. The adhesive system of claim 81, further comprising:

a second stem region, a third stem region, a fourth stem region, and a fifth stem region, each of the second stem region, the third stem region, the fourth stem region, and the fifth stem region comprising a flap on the flexible strip, the flap being pivotable about a hinge axis extending between side edges of the flap and having an end located at an opposite region of the flap relative to the hinge axis, the hinge axis of the flap being located closer to the base region relative to the end of the flap.

89. The adhesive system of claim 81, wherein the base region is defined by multiple sides and the stem region is defined in part by a side that is different from the multiple sides of the base region.

90. The adhesive system of claim 81, wherein the first flap and the second flap have same dimensions.

91. The adhesive system of claim 81, wherein a dimension of the first flap and a corresponding dimension of the second flap are different.

92. The adhesive system of claim 82, wherein a dimension of the third flap is different from a corresponding dimension of at least one of the first flap or the second flap.

93. The adhesive system of claim 81, wherein the base region further comprises:

a row of flaps on the flexible strip, the row of flaps comprising the first flap, and the first flap and a flap of the row of flaps each being oriented in a same orientation on the flexible strip relative to one another.

94. The adhesive system of claim 81, wherein the base region further comprises:

a first row of flaps and a second row of flaps on the flexible strip, the first row of flaps comprising the first flap and the second row of flaps comprising a third flap on the flexible strip, the third flap being pivotable about a hinge axis of the third flap, the hinge axis of the third flap being offset from and parallel to the hinge axis of the first flap.

95. The adhesive system of claim 81, wherein the flexible strip comprises a layer of a thermoplastic material, a thermosetting material, polyethylene terephthalate, polypropylene, polyimide, polystyrene, polycarbonate, polyethylene naphthalate, an elastomer material, a rubber material, or a fabric material.

96. The adhesive system of claim 81, wherein the flexible strip comprises a laminate of an inelastic layer and an elastic layer.

97. The adhesive system of claim 96, wherein the elastic layer comprises polydimethylsiloxane, polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel.

98. The adhesive system of claim 81, wherein the flexible strip comprises at least one of a polyethylene terephthalate-polydimethylsiloxane laminate, paper having a low-tack pressure-sensitive adhesive on at least one side of the paper, a pressure sensitive adhesive, a soft skin adhesive, a porous material having the pressure sensitive adhesive, fabric, mesh, or a metalized film.

99. The adhesive system of claim 81, wherein the flexible strip is coupled to a functional component, the functional component comprising at least one of a biosensor, an electrical or electronic circuit, a chemical sensor, or a bio-monitoring patch.

100. The adhesive system of claim 81, further comprising:

a second stem region, a third stem region, a fourth stem region, and a fifth stem region, each of the second stem region, the third stem region, the fourth stem region, and the fifth stem region comprising a flap on the flexible strip, the flap being pivotable about a hinge axis extending between side edges of the flap in an extension direction that is different from at least one of the first extension direction of the hinge axis of the first flap or the second extension direction of the hinge axis of the second flap,

wherein the flexible strip is coupled to a glove comprising a palm region, a first digit region, a second digit region, a third digit region, a fourth digit region, and a fifth digit region,

the base region of the flexible strip being coupled to the palm region of the glove, and

the stem region, the second stem region, the third stem region, the fourth stem region, and the fifth stem region of the flexible strip being respectively coupled to the first digit region, the second digit region, the third digit region, the fourth digit region, and the fifth digit region of the glove.

101. An adhesive system, comprising:

a flexible strip;

a row of flaps on the flexible strip, the row of flaps comprising multiple flaps oriented in a same orientation on the flexible strip relative to one another, the multiple flaps comprising a flap on the flexible strip, the flap having opposing sides; and

an adhesive coupled to a side of the opposing sides of the flap.

102. The adhesive system of claim 101, wherein:

the flap further comprises a hinge axis, side edges, and an end, the hinge axis extending between the side edges, the side edges extending from the hinge axis to the end, and the side edges having a first length; and the adhesive extends from the end of the flap toward the hinge axis, the adhesive having a second length that is equal to or shorter than the first length of the side edges of the flap.

103. The adhesive system of claim 101, wherein:

the flap further comprises a hinge axis, side edges, and an end, the hinge axis extending between the side edges, the side edges extending from the hinge axis to the end, and the hinge axis having a first width; and

the adhesive extends between the side edges of the flap, the adhesive having a second width that is equal to or narrower than the first width of the hinge axis of the flap.

104. The adhesive system of claim 101, wherein:

the flap further comprises a hinge axis extending between side edges of the flap;

the multiple flaps comprise a second flap on the flexible strip, the second flap comprising a hinge axis extending between side edges of the second flap; and

the hinge axis of the flap and the hinge axis of the second flap extend in a same extension direction.

105. The adhesive system of claim 104, wherein the flap and the second flap are respectively pivotable about the hinge axis of the flap and the hinge axis of the second flap in a same rotational direction.

106. The adhesive system of claim 101, further comprising:

a second row of flaps on the flexible strip, the second row of flaps comprising multiple second flaps oriented in a same second orientation on the flexible strip relative to one another, the multiple second flaps comprising a second flap on the flexible strip, the second flap having opposing sides; and

a second adhesive coupled to a side of the opposing sides of the second flap.

107. The adhesive system of claim 101, further comprising:

a second row of flaps on the flexible strip, the second row of flaps comprising a second flap oriented in the same orientation on the flexible strip relative to the multiple flaps of the row of flaps, the second flap having opposing sides; and a second adhesive coupled to a side of the opposing sides of the second flap.

108. The adhesive system of claim 107, wherein:

the second flap comprises a hinge axis extending between side edges of the second flap; and

the hinge axis of the flap is offset from and parallel to the hinge axis of the second flap.

109. The adhesive system of claim 107, wherein:

the second flap comprises a hinge axis extending between side edges of the second flap; and

the flap and the second flap are respectively pivotable about the hinge axis of the flap and the hinge axis of the second flap in a same rotational direction.

110. The adhesive system of claim 101, further comprising:

multiple second rows of flaps on the flexible strip, each of the multiple second rows of flaps comprising multiple second flaps oriented in a same second orientation on the flexible strip relative to one another, each of the multiple second flaps having opposing sides; and

a second adhesive coupled to a side of the opposing sides of each of the multiple second flaps.

111. The adhesive system of claim 101, further comprising:

a second row of flaps on the flexible strip, the second row of flaps comprising multiple second flaps oriented in a same second orientation on the flexible strip relative to one another, the multiple second flaps comprising a second flap on the flexible strip, the second flap having opposing sides;

a third row of flaps on the flexible strip, the third row of flaps comprising multiple third flaps oriented in a same third orientation on the flexible strip relative to one another, the multiple third flaps comprising a third flap on the flexible strip, the third flap having opposing sides;

a second adhesive coupled to a side of the opposing sides of the second flap; and

a third adhesive coupled to a side of the opposing sides of the third flap.

112. The adhesive system of claim 111, wherein:

the second flap comprises a hinge axis extending between side edges of the second flap;

the third flap comprises a hinge axis extending between side edges of the third flap; and

the hinge axis of the flap is offset from and parallel to each of the hinge axis of the second flap and the hinge axis of the third flap.

113. The adhesive system of claim 111, wherein:

the second flap comprises a hinge axis extending between side edges of the second flap;

the third flap comprises a hinge axis extending between side edges of the third flap; and

the flap, the second flap, and the third flap are respectively pivotable about the hinge axis of the flap, the hinge axis of the second flap, and the hinge axis of the third flap in a same rotational direction.

114. The adhesive system of claim 111, wherein the flap and at least one of the second flap or the third flap have same dimensions.

115. The adhesive system of claim 111, wherein the adhesive and at least one of the second adhesive or the third adhesive have same dimensions.

116. The adhesive system of claim 101, wherein the flexible strip comprises a layer of a thermoplastic material, a thermosetting material, polyethylene terephthalate, polypropylene, polyimide, polystyrene, polycarbonate, polyethylene naphthalate, an elastomer material, a rubber material, or a fabric material.

117. The adhesive system of claim 101, wherein the flexible strip comprises a laminate of an inelastic layer and an elastic layer.

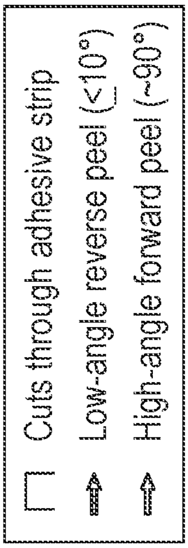
118. The adhesive system of claim 117, wherein the elastic layer comprises polydimethylsiloxane, polyurethane, block copolymer elastomer, thermoplastic elastomer, acrylate-based material, synthetic rubber, natural rubber, hydrogels, or ionogel.

119. The adhesive system of claim 101, wherein:

the flexible strip comprises at least one of a polyethylene terephthalate-polydimethylsiloxane laminate, paper, a porous material, fabric, mesh, or a metalized film; and

the adhesive comprises at least one of a low-tack pressure-sensitive adhesive, a pressure sensitive adhesive, or a soft skin adhesive.

120. The adhesive system of claim 101, wherein the flexible strip is coupled to a functional component, the functional component comprising at least one of a biosensor, an electrical or electronic circuit, a chemical sensor, or a bio-monitoring patch.



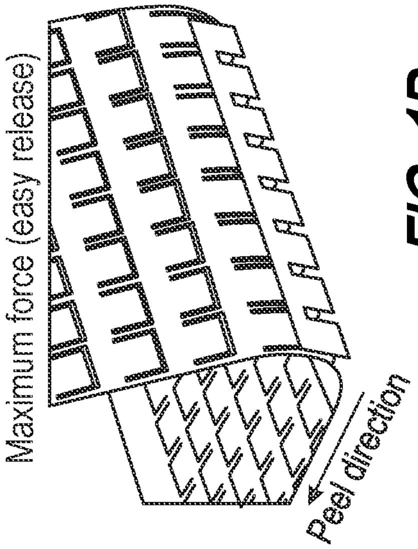


FIG. 1D

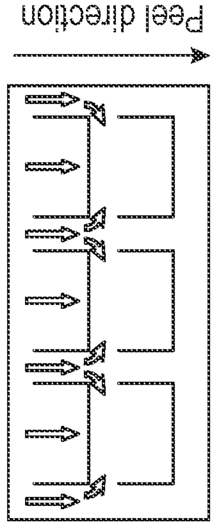


FIG. 1E

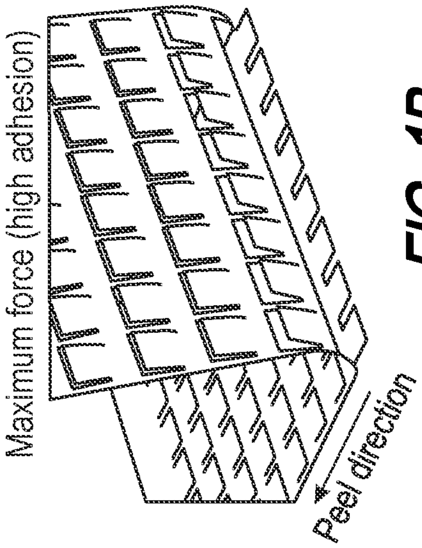


FIG. 1B

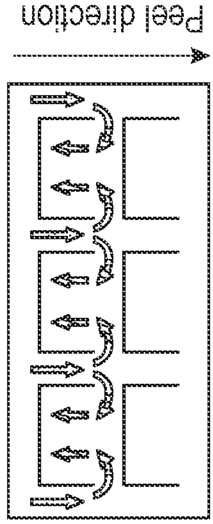


FIG. 1C

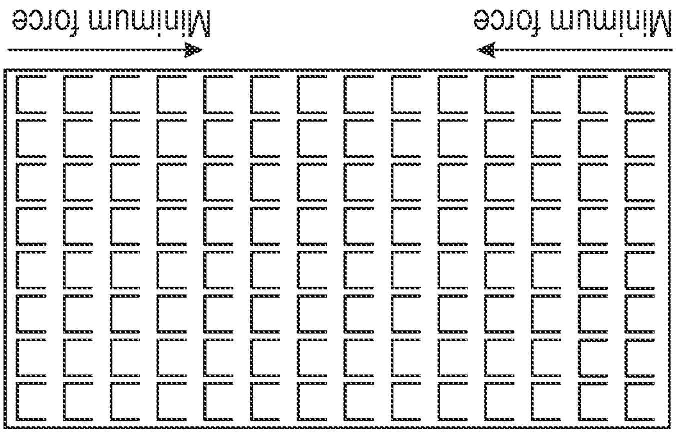
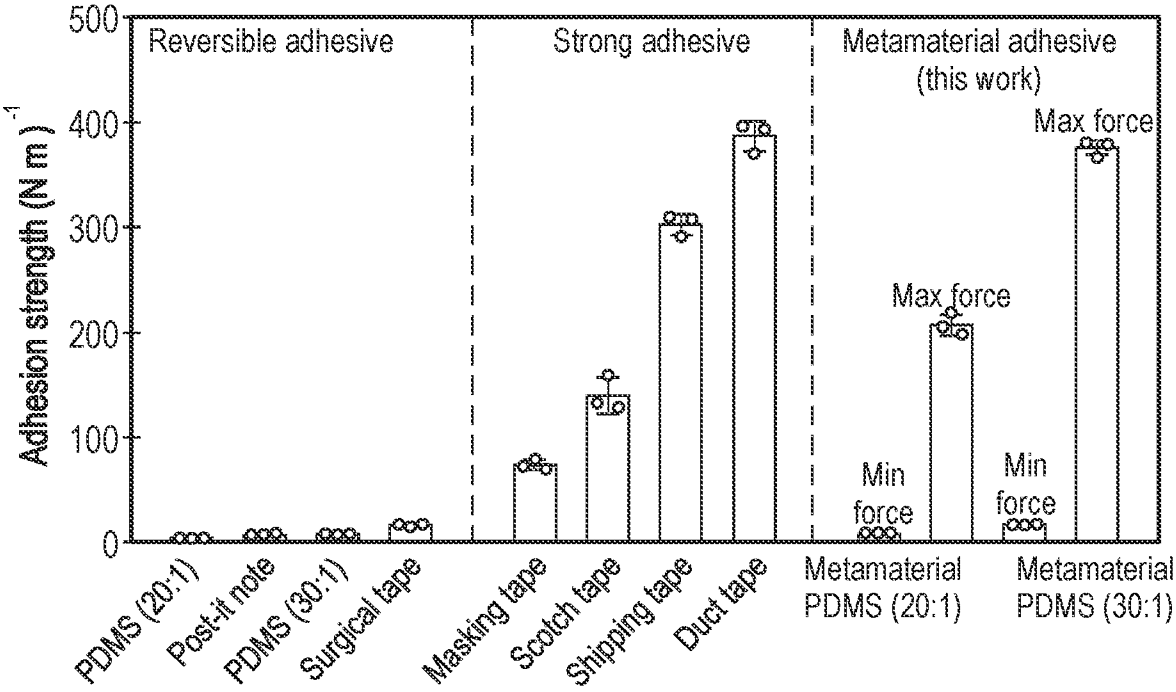
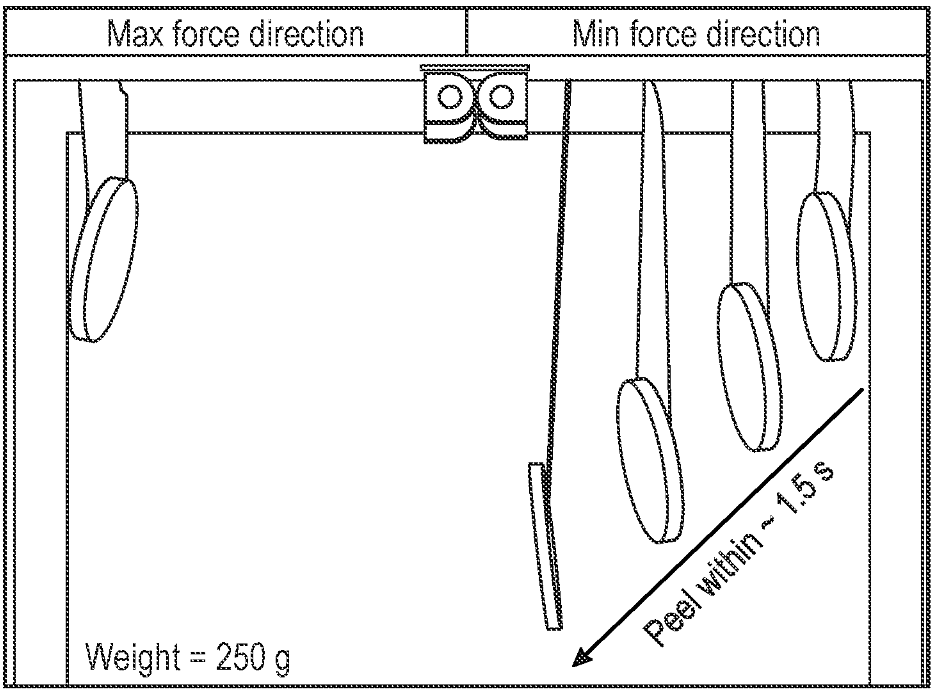


FIG. 1A



Adhesion strength (N m)$^{-1}$
0
100
200
300
400
500
Reversible adhesive
Strong adhesive
Metamaterial adhesive (this work)
Min force
Max force
Min force
Max force
PDMS (20:1)
Post-it note
PDMS (30:1)
Surgical tape
Masking tape
Scotch tape
Shipping tape
Duct tape
Metamaterial PDMS (20:1)
Metamaterial PDMS (30:1)

FIG. 1F



Max force direction
Min force direction
Peel within ~ 1.5 s
Weight = 250 g

FIG. 1G

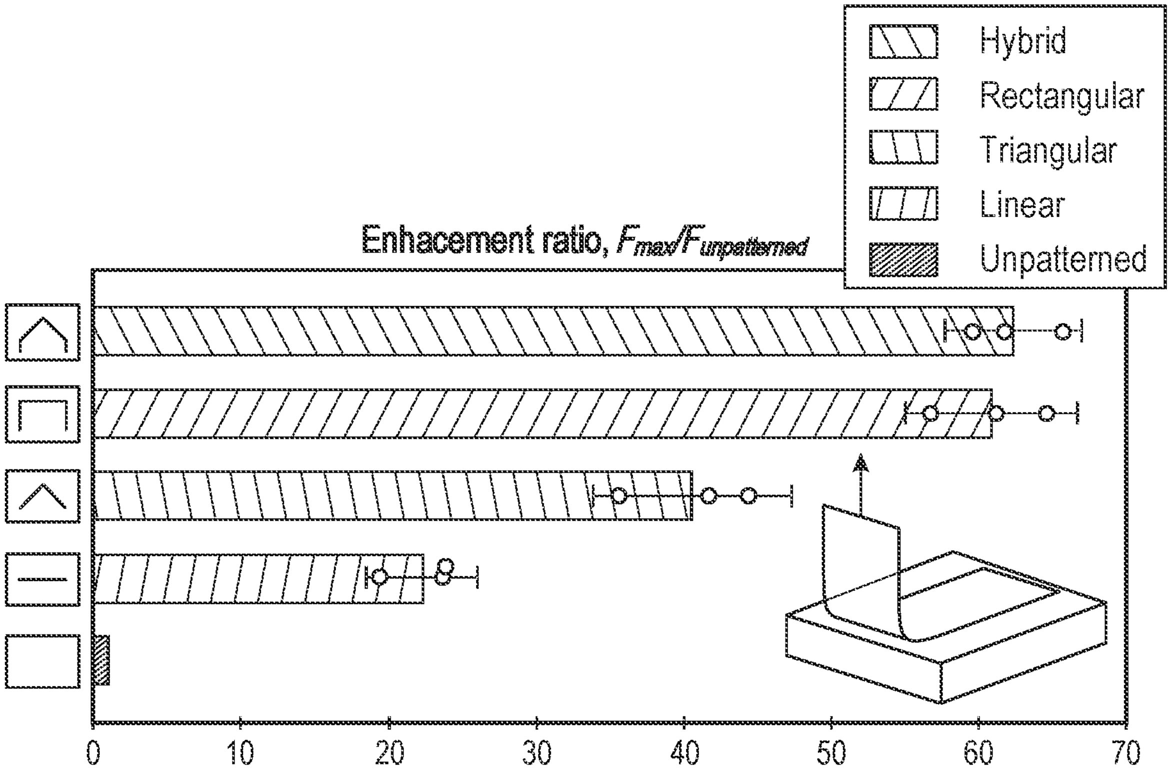

Hybrid
Rectangular
Triangular
Linear
Unpatterned
Enhacement ratio, $F_{max}/F_{unpatterned}$
0
10
20
30
40
50
60
70

FIG. 1H

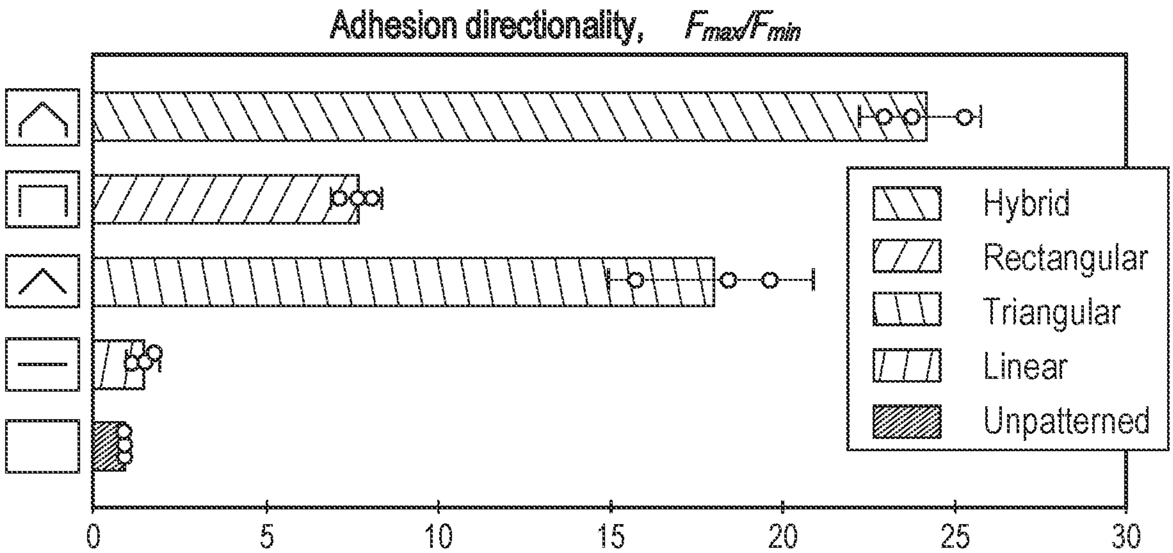

Adhesion directionality, F_{max}/F_{min}
Hybrid
Rectangular
Triangular
Linear
Unpatterned
0
5
10
15
20
25
30

FIG. 1I

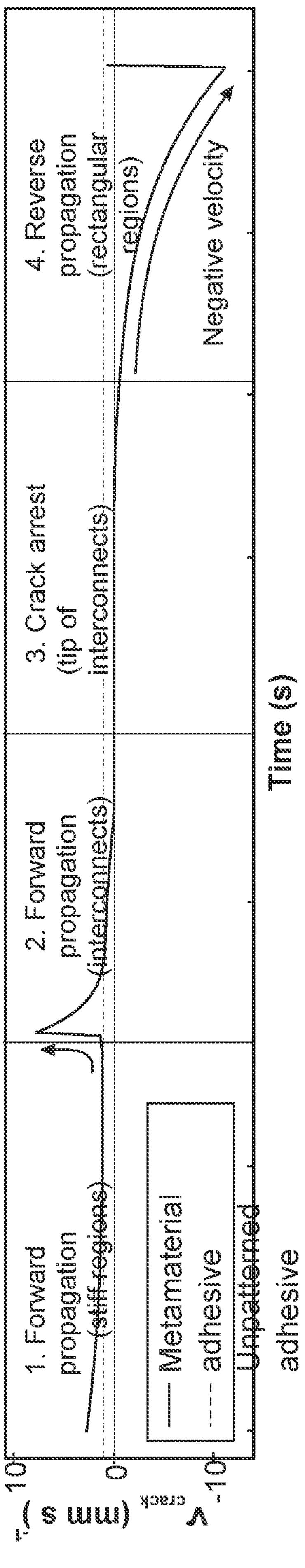


FIG. 2A

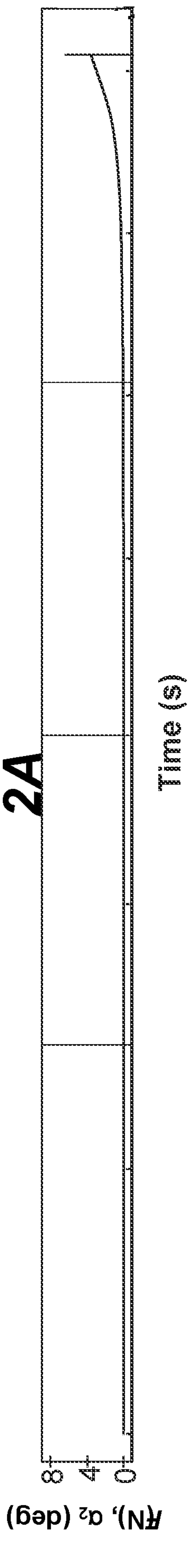


FIG. 2B

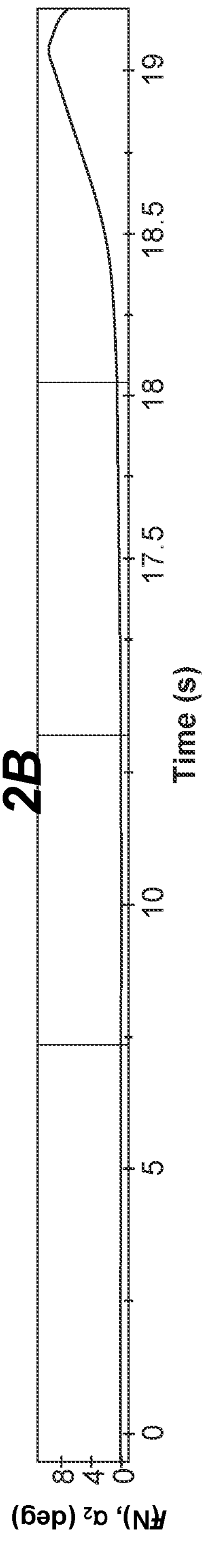


FIG. 2C

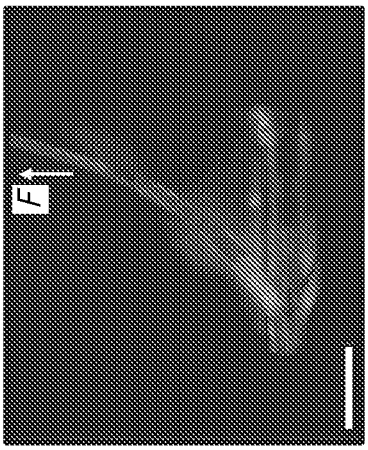


FIG. 2D

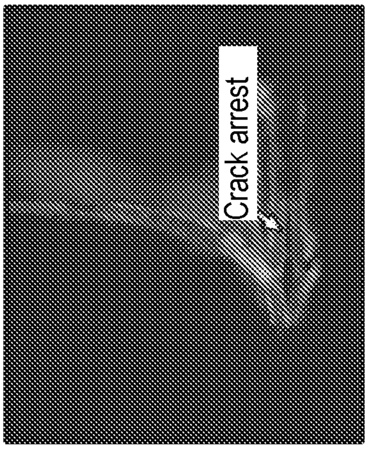


FIG. 2E

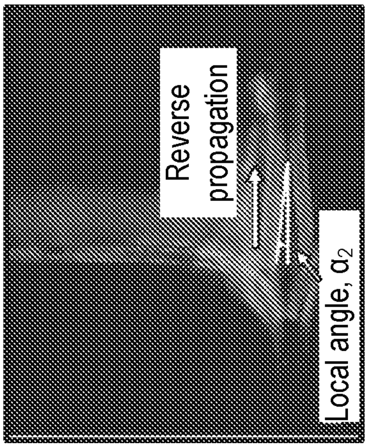


FIG. 2F

FIG. 2G

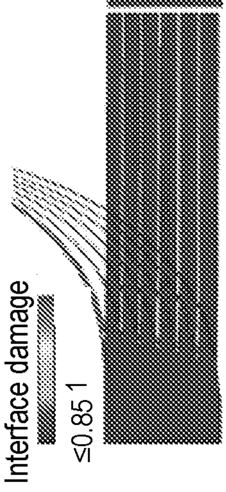


FIG. 2H

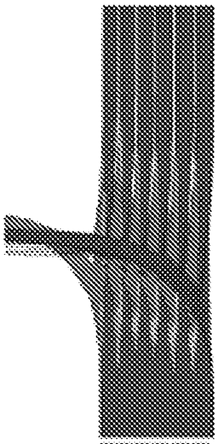


FIG. 2I

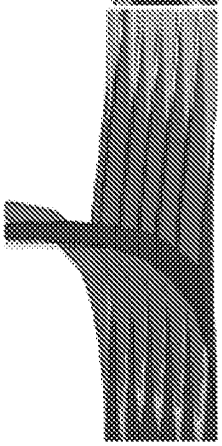


FIG. 2J

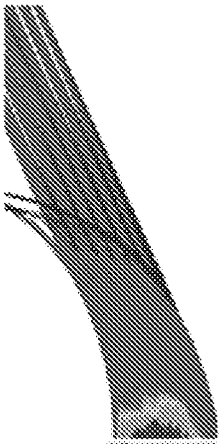


FIG. 2K

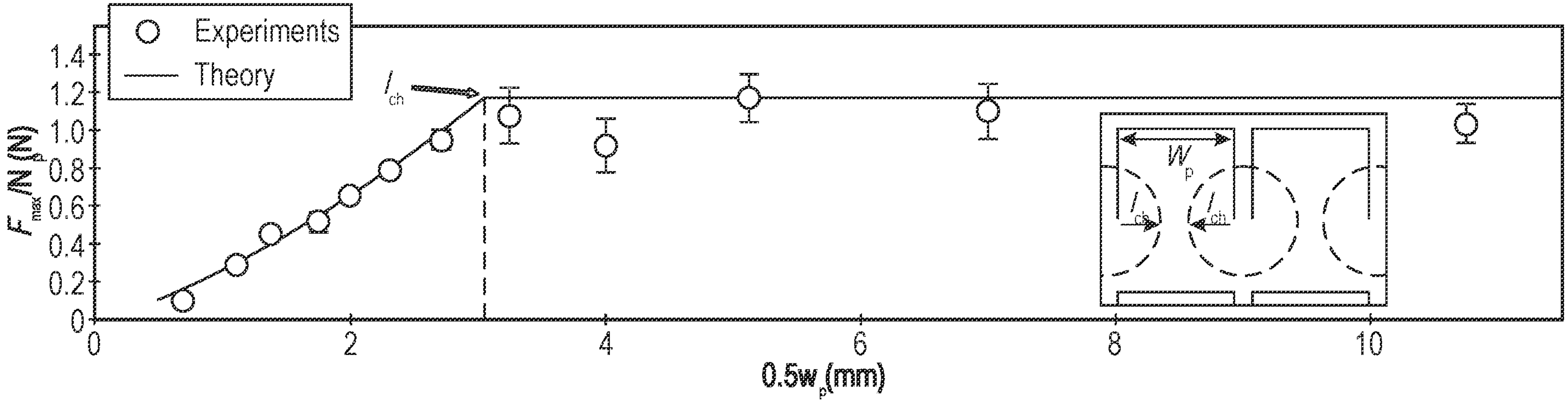


FIG. 2L

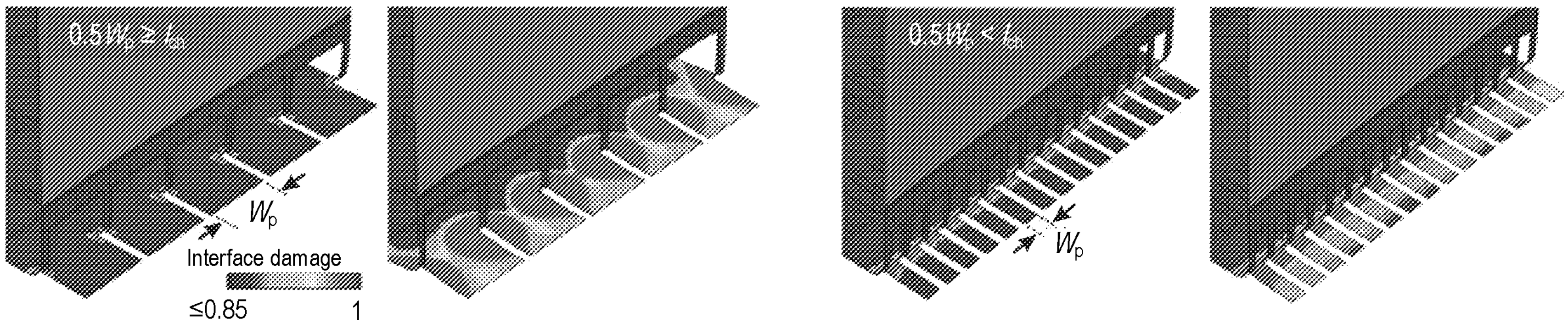


FIG. 2M FIG. 2N FIG. 2O FIG. 2P

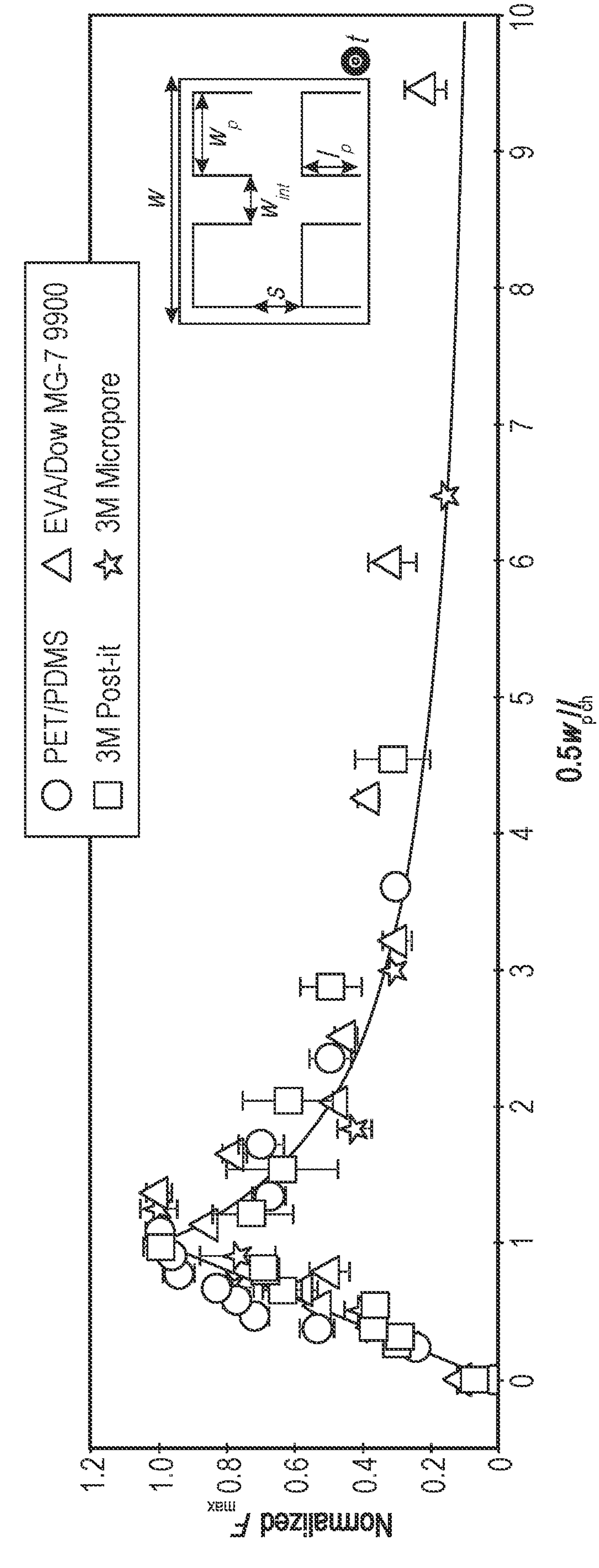

PET/PDMS
EVA/Dow MG-7 9900
3M Post-it
3M Micropore
w
w_p
w_{int}
l_p
s
t
Normalized F_{max}
$0.5w/l_{pch}$
0
0.2
0.4
0.6
0.8
1.0
1.2
1
2
3
4
5
6
7
8
9
10

FIG. 3A

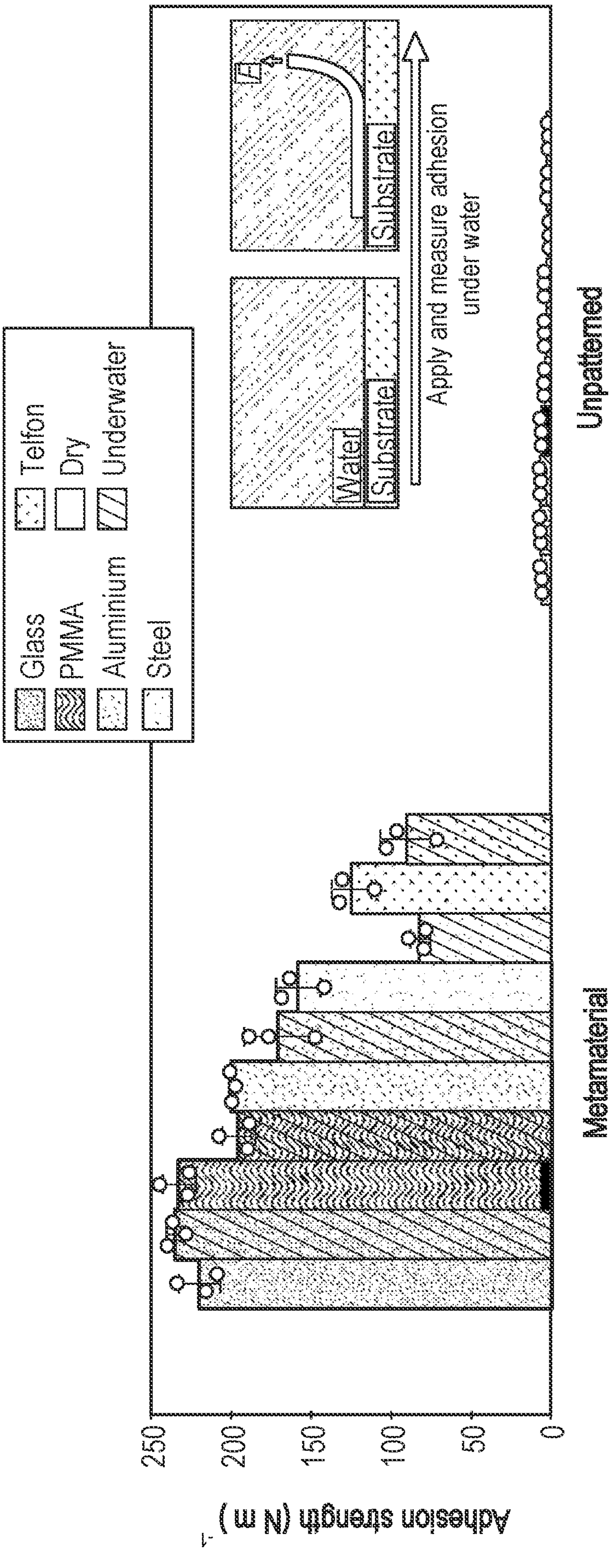

Adhesion strength (N m)$^{-1}$
250
200
150
100
50
0
Metamaterial
Unpatterned
Glass
PMMA
Aluminium
Steel
Telfon
Dry
Underwater
Water
Substrate
Substrate
F
Apply and measure adhesion under water

FIG. 3B

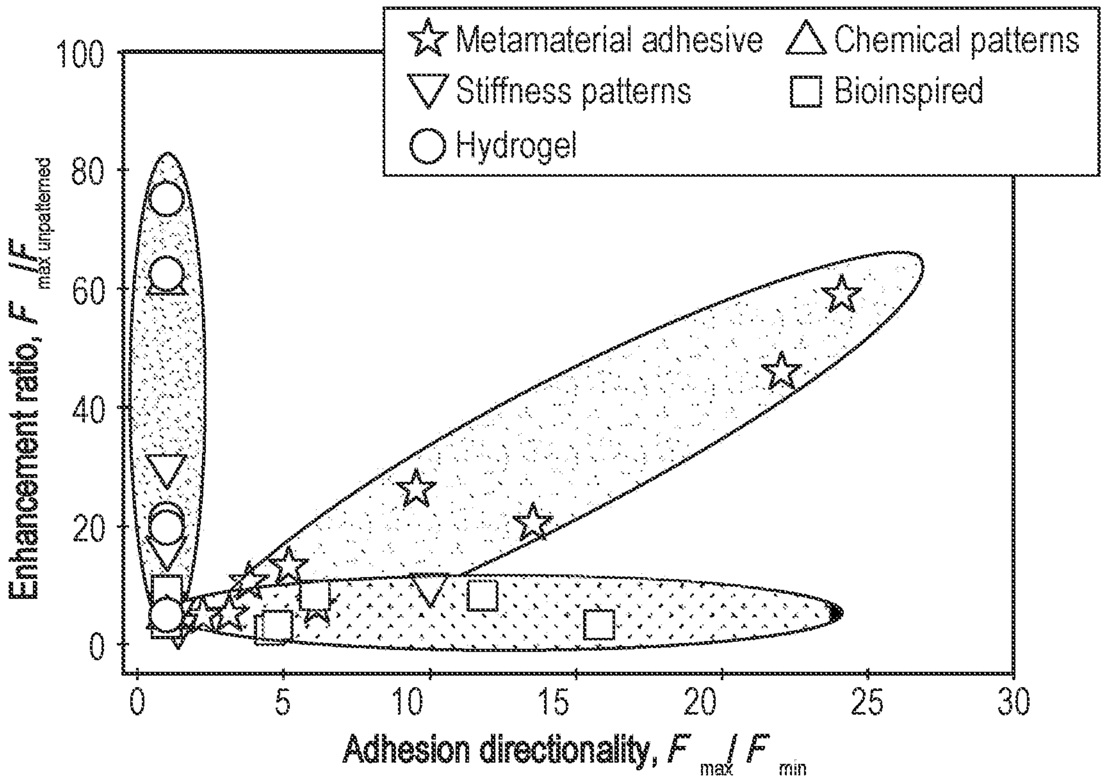

Metamaterial adhesive
Chemical patterns
Stiffness patterns
Bioinspired
Hydrogel
100
80
60
40
20
0
Enhancement ratio, $F_{max}/F_{max\ unpatterned}$
0
5
10
15
20
25
30
Adhesion directionality, F_{max}/F_{min}

FIG. 3C

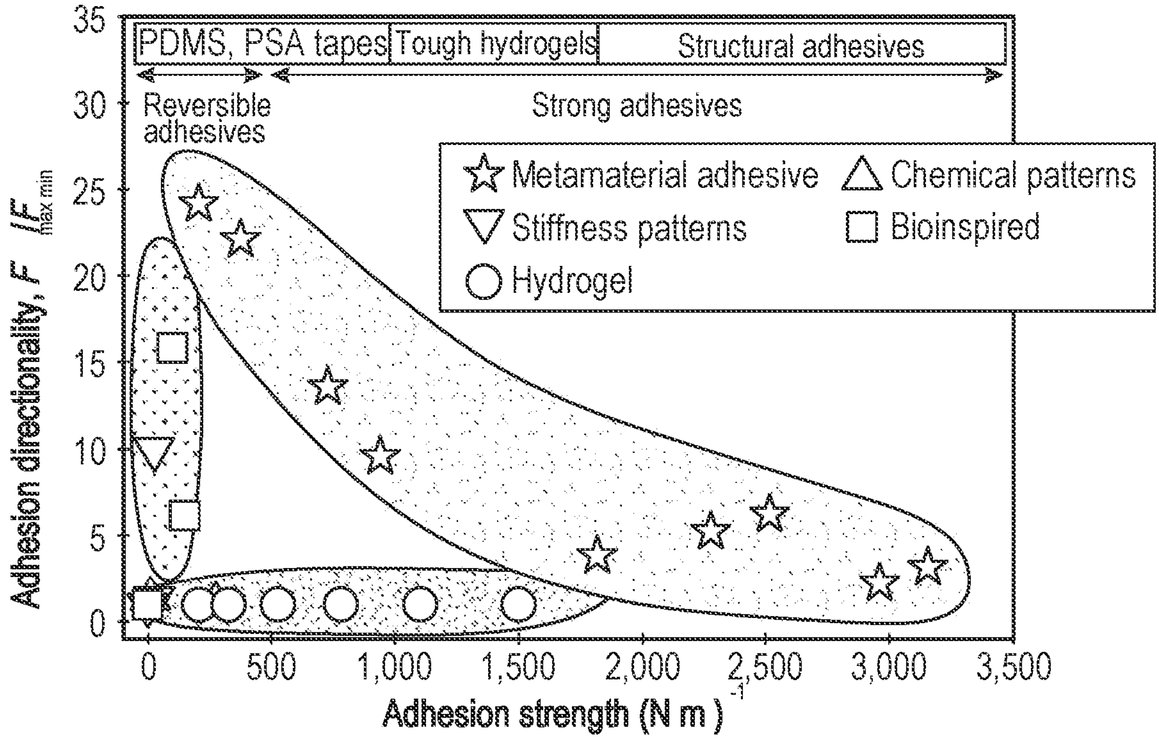

PDMS, PSA tapes
Tough hydrogels
Structural adhesives
Reversible adhesives
Strong adhesives
Metamaterial adhesive
Chemical patterns
Stiffness patterns
Bioinspired
Hydrogel
35
30
25
20
15
10
5
0
Adhesion directionality, F_{max}/F_{min}
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Adhesion strength (N m^{-1})

FIG. 3D

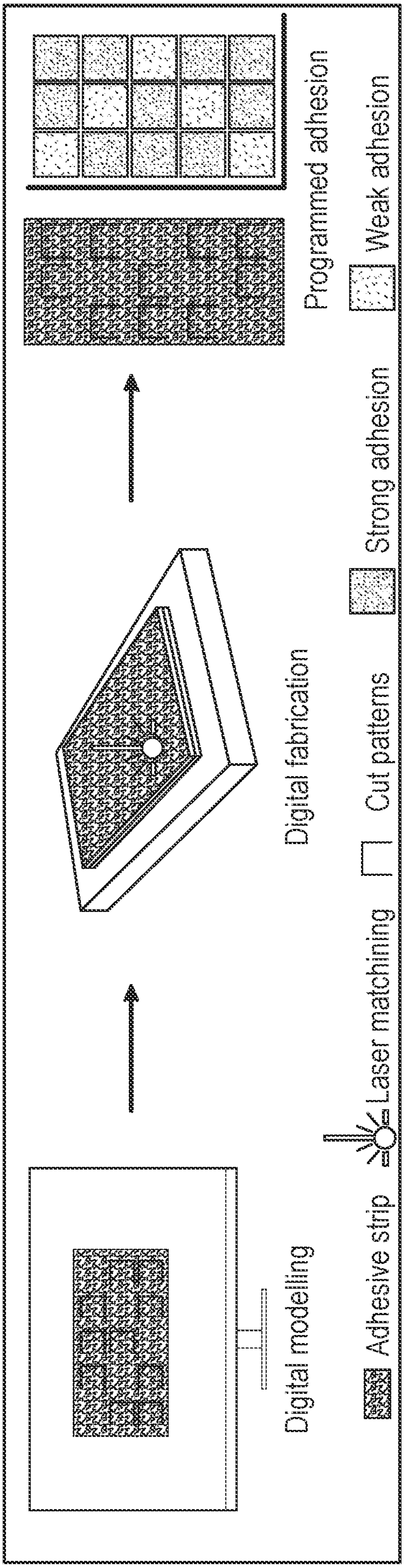

Digital modelling
Digital fabrication
Programmed adhesion
Adhesive strip
Laser matching
Cut patterns
Strong adhesion
Weak adhesion

FIG. 4A

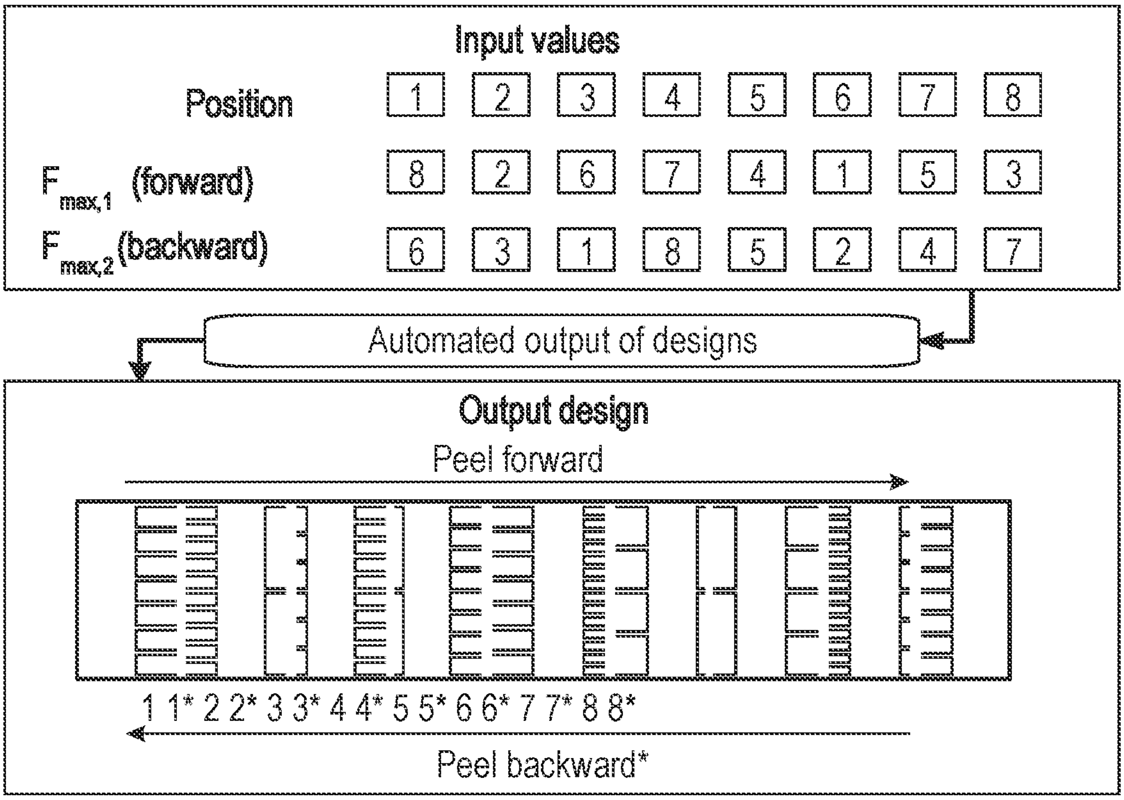

Input values
Position
1 2 3 4 5 6 7 8
$F_{max,1}$ (forward)
8 2 6 7 4 1 5 3
$F_{max,2}$ (backward)
6 3 1 8 5 2 4 7
Automated output of designs
Output design
Peel forward
1 1* 2 2* 3 3* 4 4* 5 5* 6 6* 7 7* 8 8*
Peel backward*

FIG. 4B

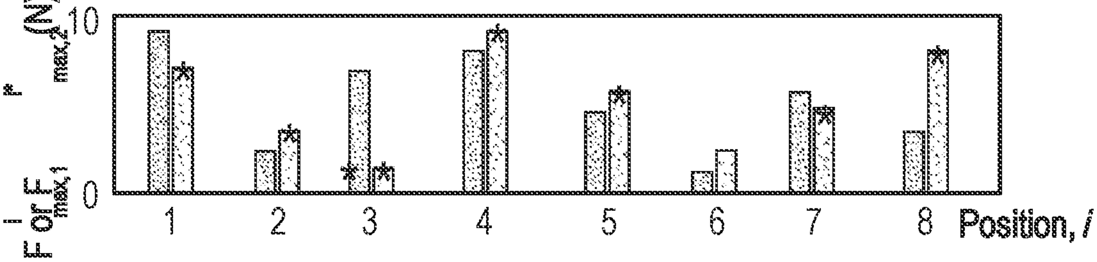

$F_{max,1}$ or $F^*_{max,2}$ (N)
10
0
1 2 3 4 5 6 7 8
Position, i

FIG. 4C

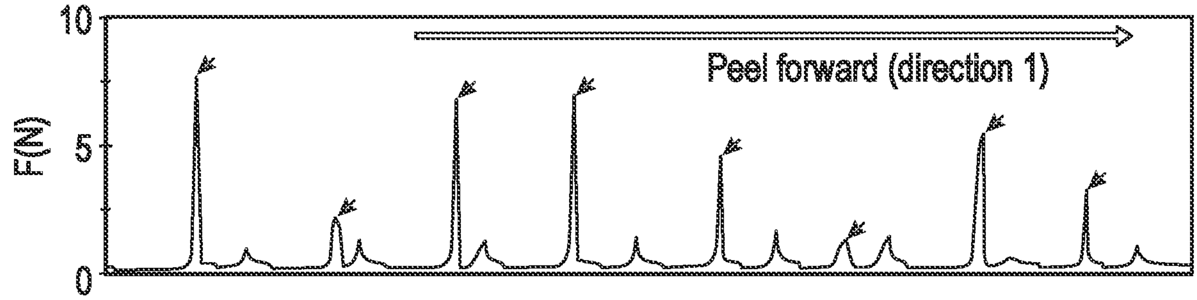


FIG. 4D

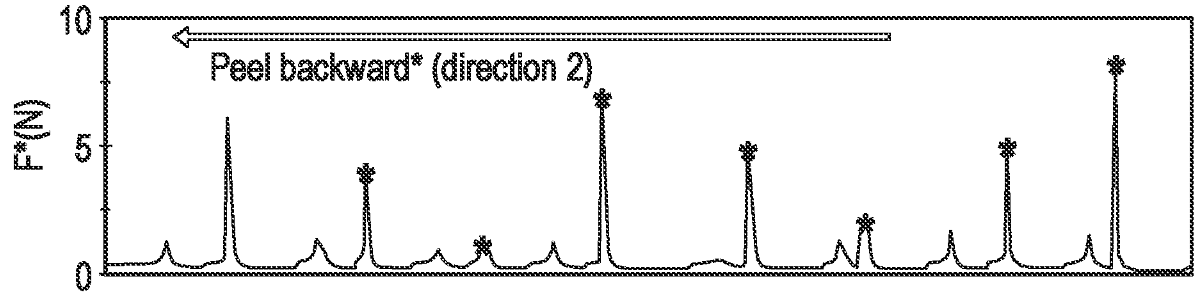


FIG. 4E

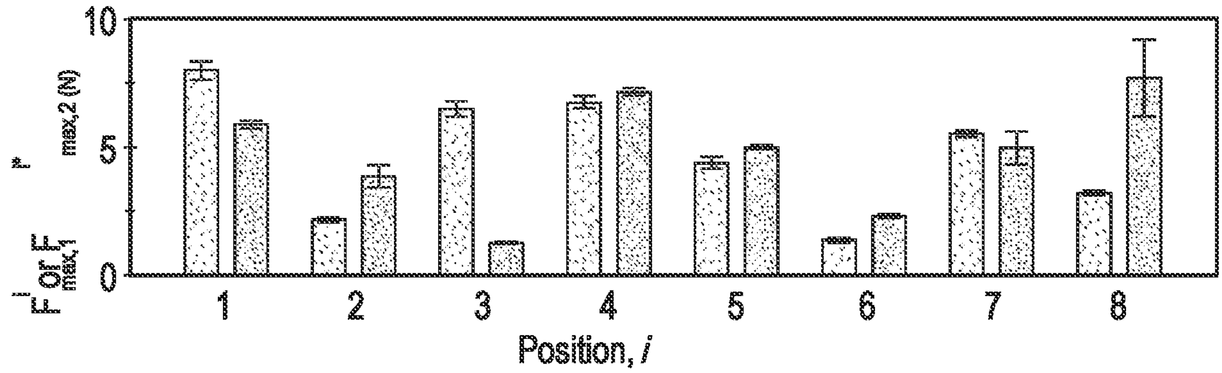
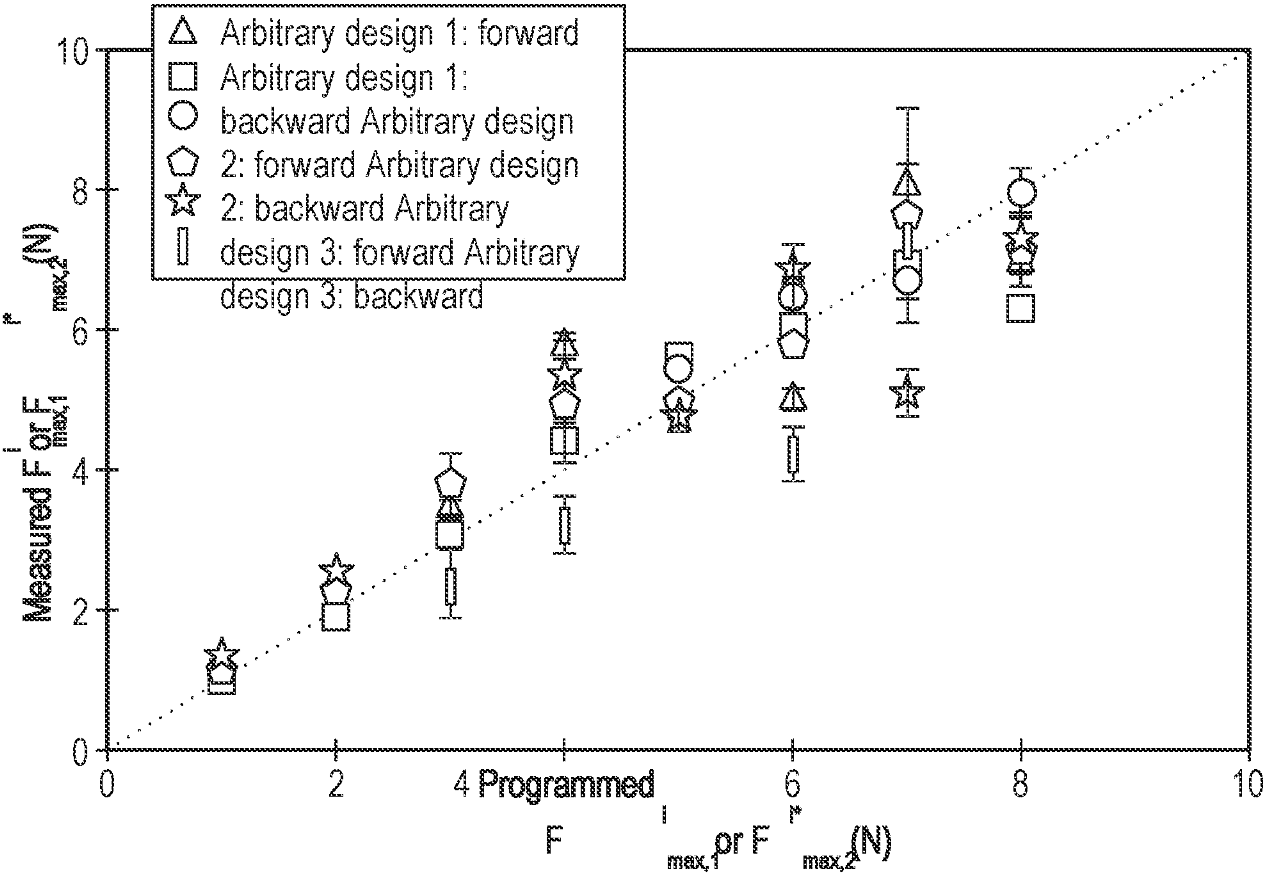
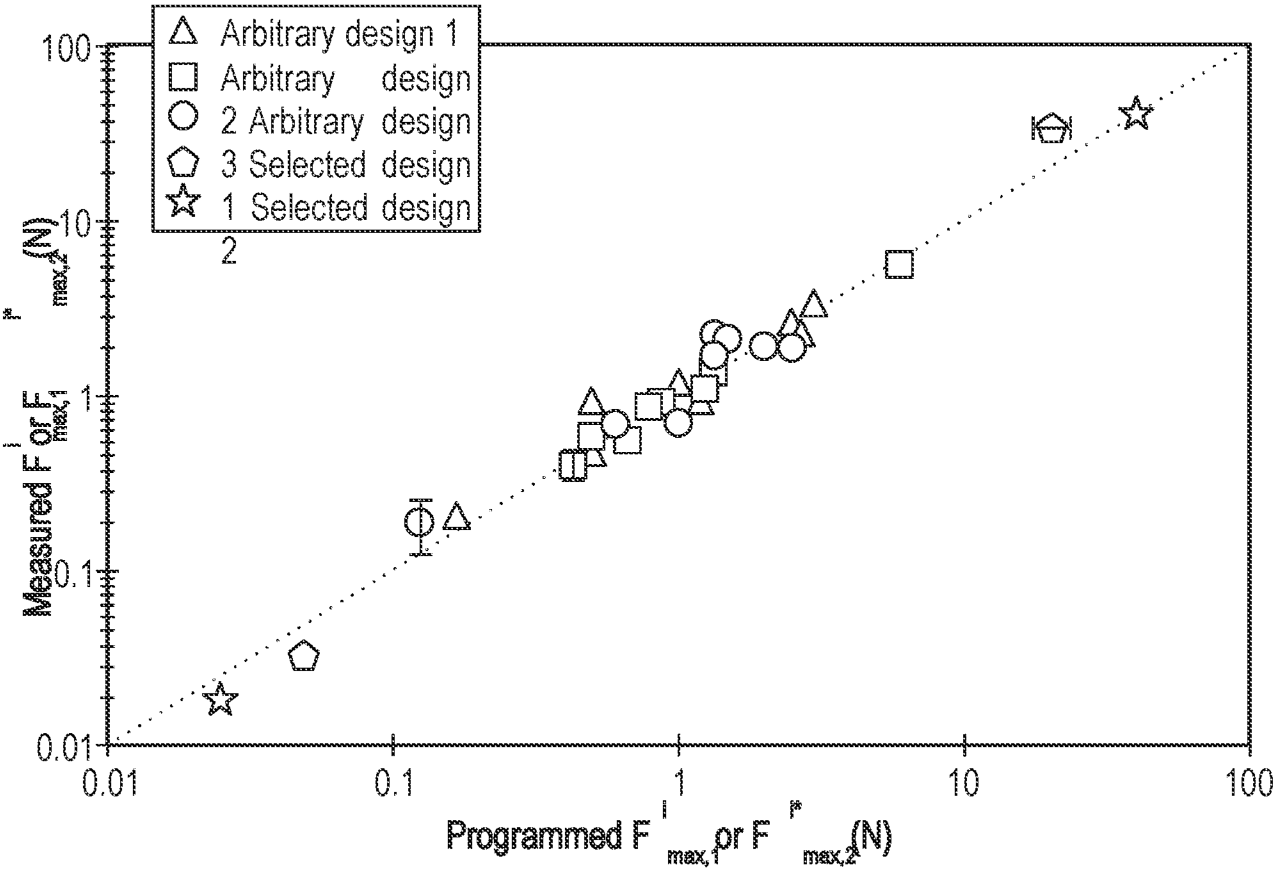


FIG. 4F



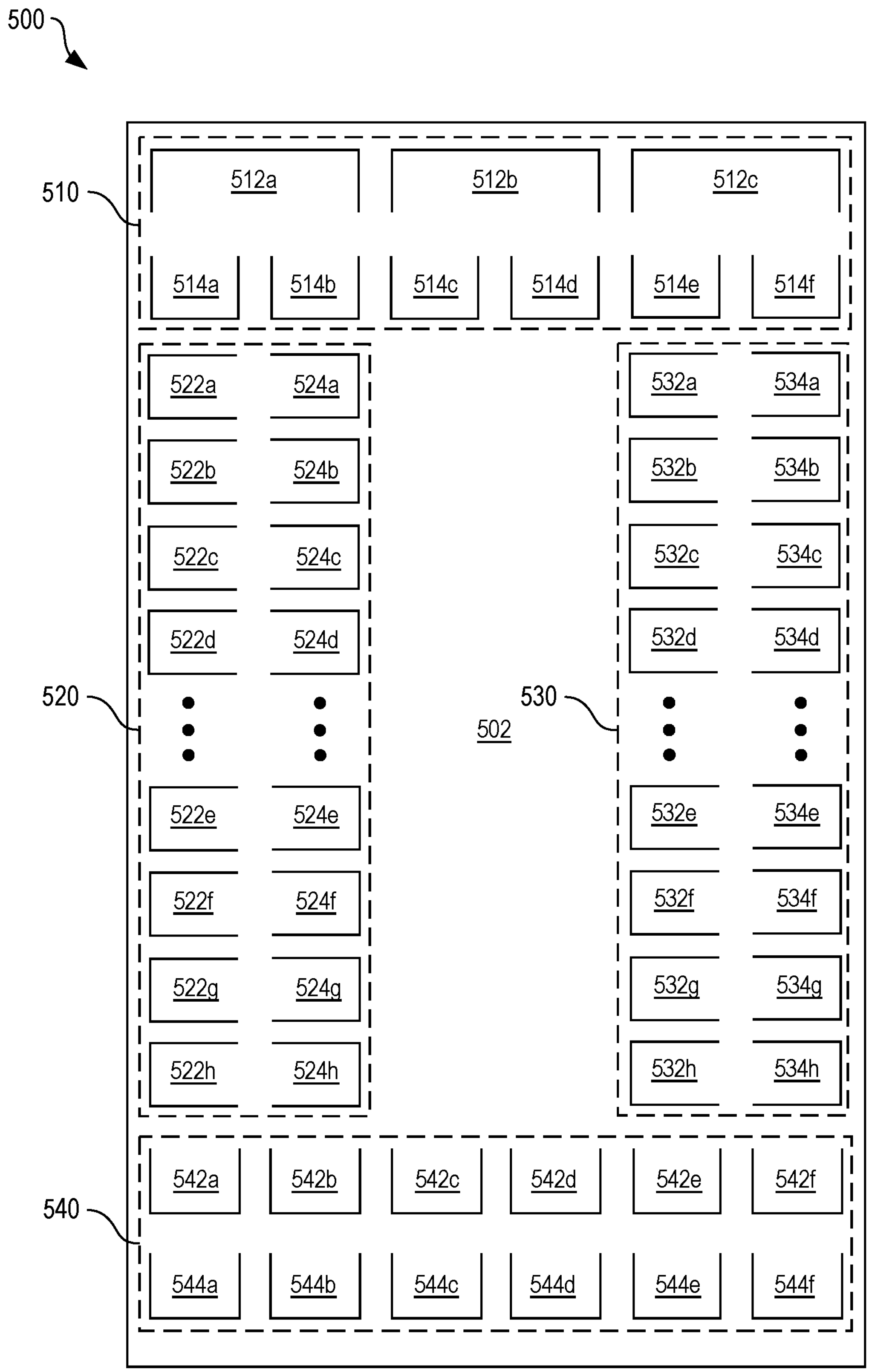
Arbitrary design 1: forward
Arbitrary design 1:
backward Arbitrary design
2: forward Arbitrary design
2: backward Arbitrary
design 3: forward Arbitrary
design 3: backward
Measured F or F (N)
0
2
4
6
8
10
Programmed F or F (N)

FIG. 4G



Arbitrary design 1
Arbitrary design
2 Arbitrary design
3 Selected design
1 Selected design
2
Measured F or F (N)
0.01
0.1
1
10
100
Programmed F or F (N)

FIG. 4H



500
510
512a
512b
512c
514a
514b
514c
514d
514e
514f
520
522a
524a
522b
524b
522c
524c
522d
524d
522e
524e
522f
524f
522g
524g
522h
524h
502
530
532a
534a
532b
534b
532c
534c
532d
534d
532e
534e
532f
534f
532g
534g
532h
534h
540
542a
542b
542c
542d
542e
542f
544a
544b
544c
544d
544e
544f

FIG. 5A

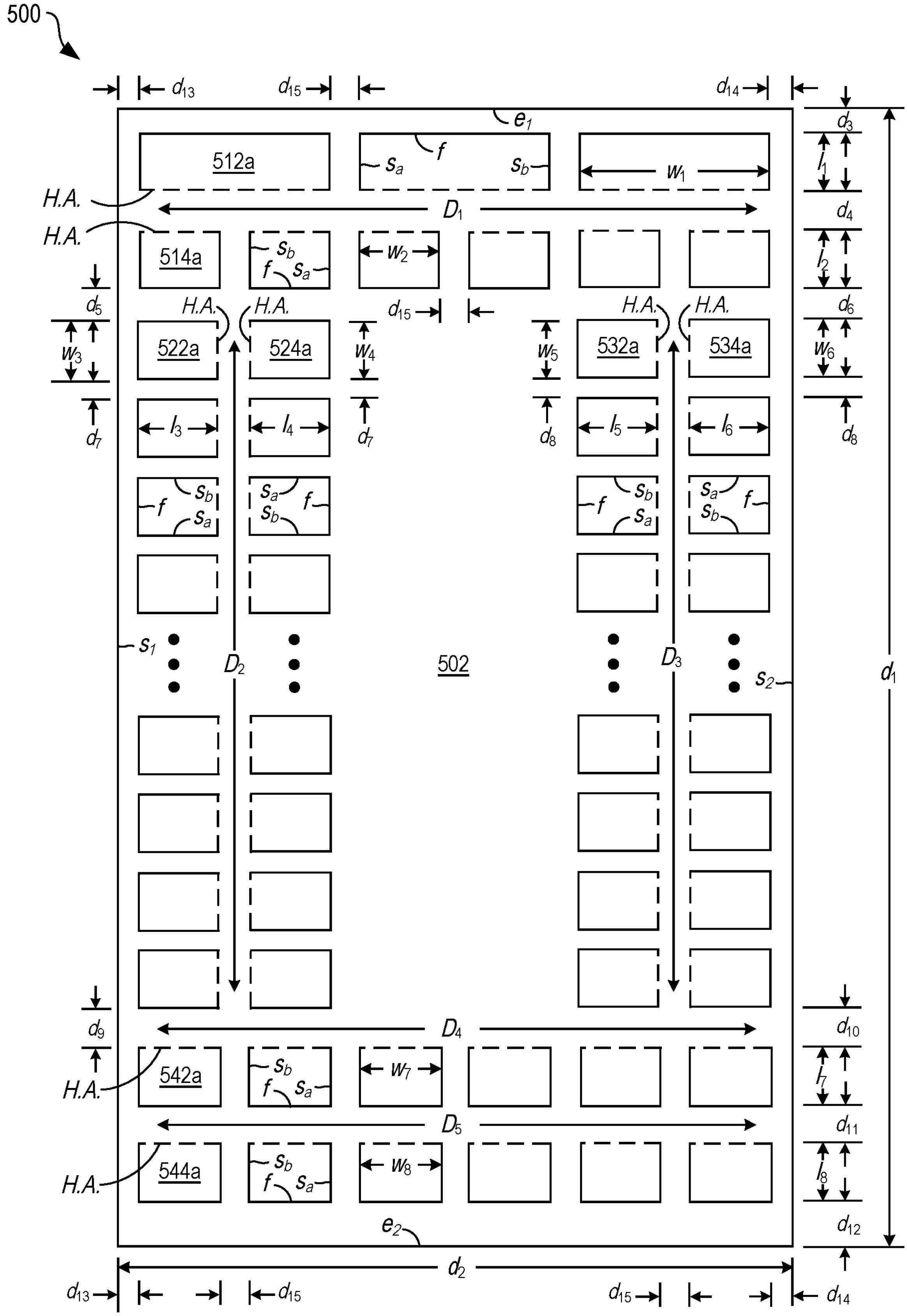

500
512a
514a
522a
524a
532a
534a
542a
544a
502
H.A.
D1
D2
D3
D4
D5
d1
d2
d3
d4
d5
d6
d7
d8
d9
d10
d11
d12
d13
d14
d15
w1
w2
w3
w4
w5
w6
w7
w8
l1
l2
l3
l4
l5
l6
l7
l8
e1
e2
s1
s2
sa
sb
f

FIG. 5B

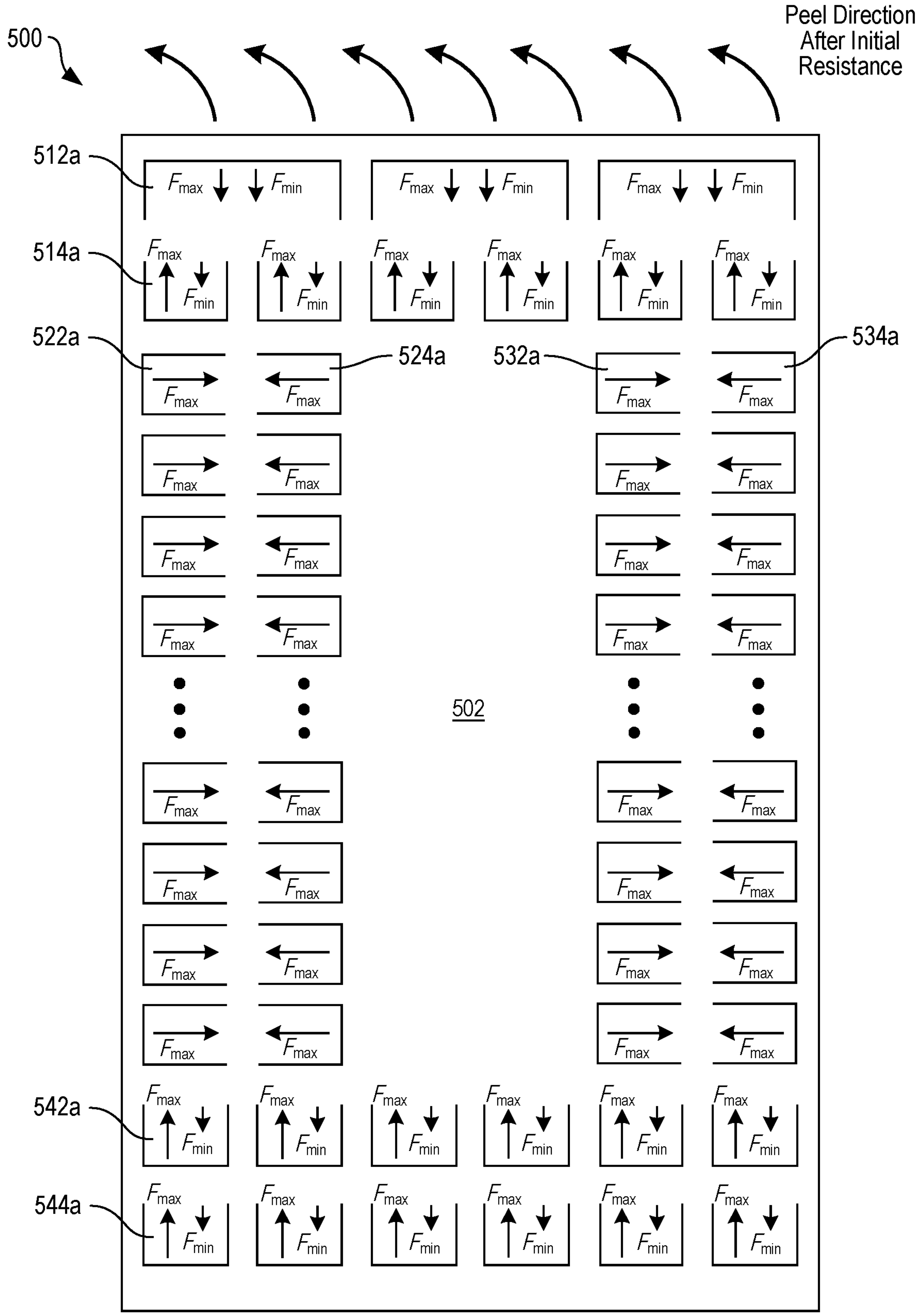

500
Peel Direction
After Initial
Resistance
512a
514a
522a
524a
532a
534a
502
542a
544a
F_{max}
F_{min}

FIG. 5C

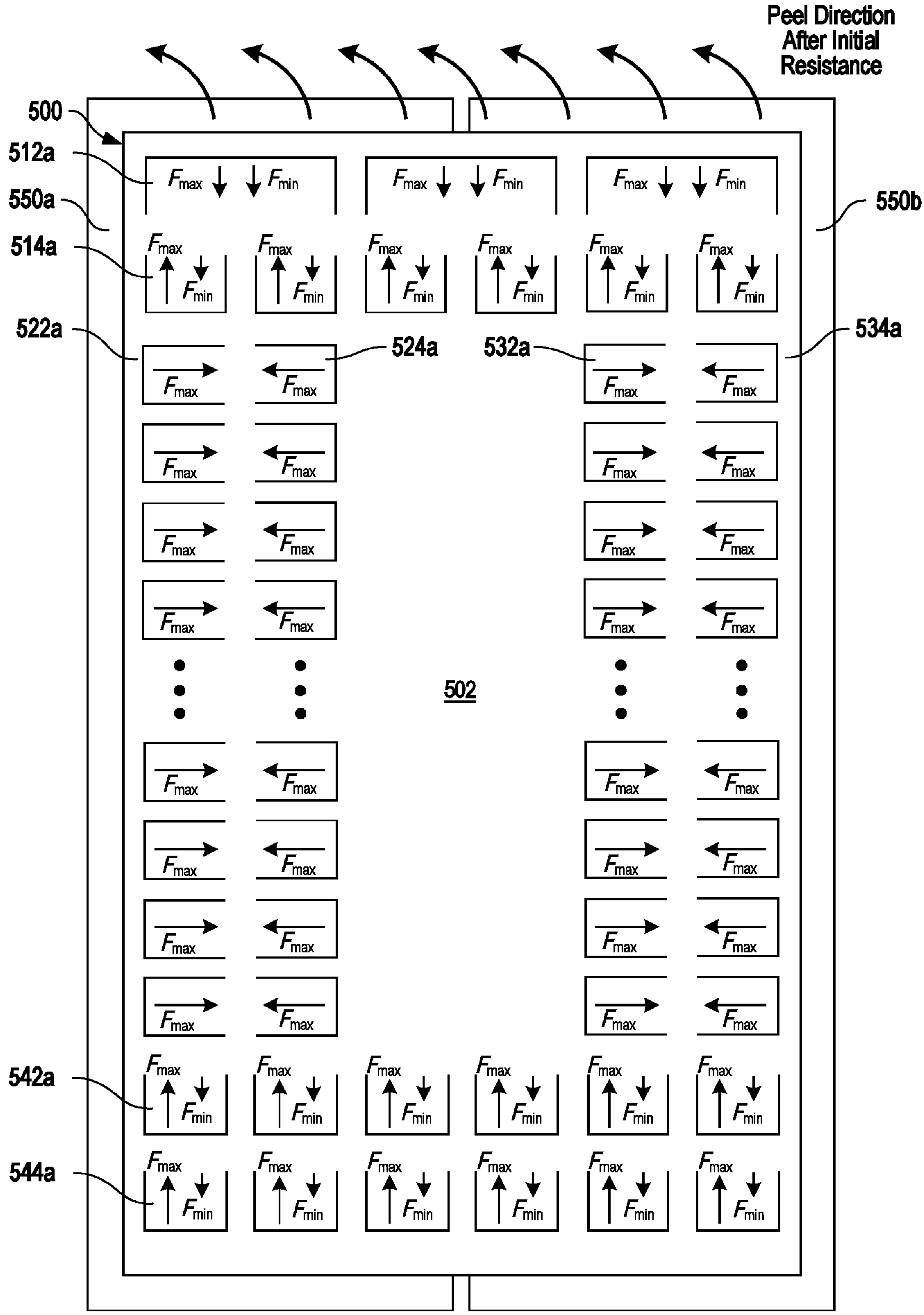

Peel Direction
After Initial
Resistance
500
512a
550a
550b
514a
522a
524a
532a
534a
502
542a
544a
F_{max}
F_{min}

FIG. 5D

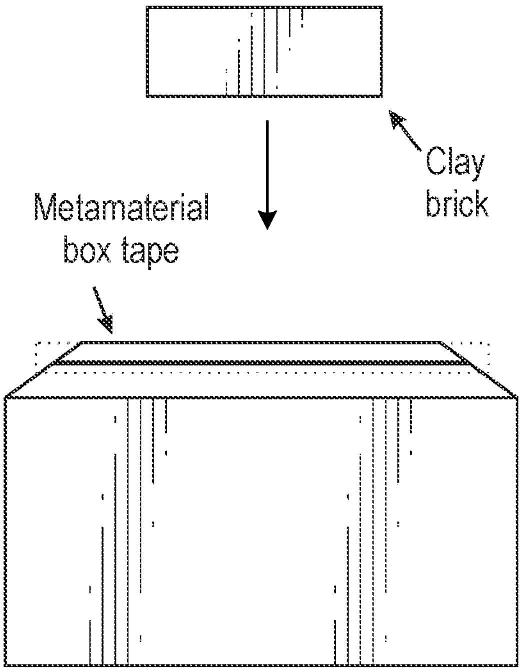


FIG. 5E

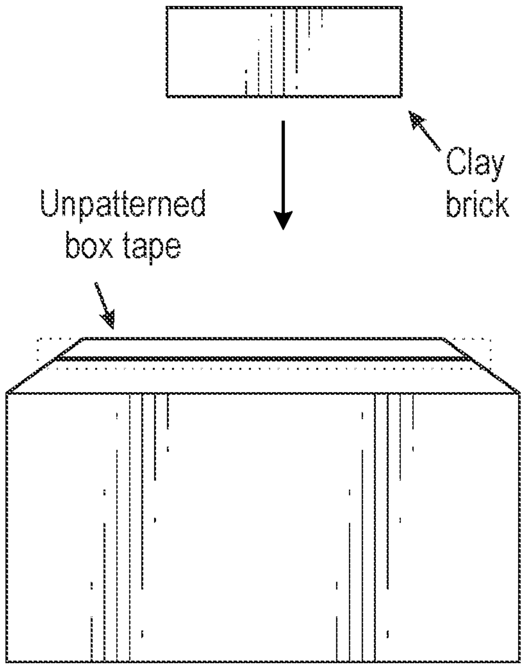


FIG. 5G

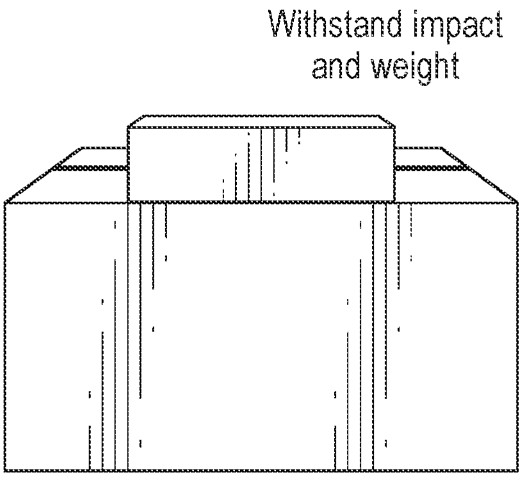


FIG. 5F

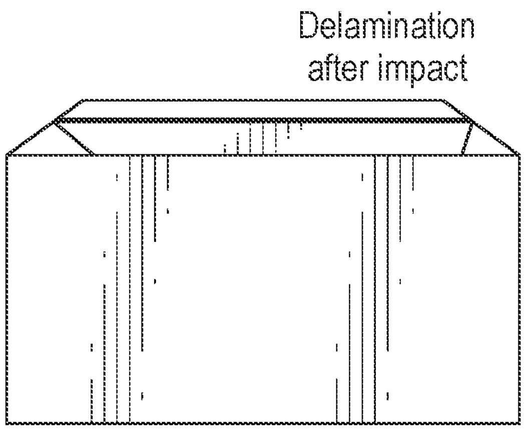


FIG. 5H

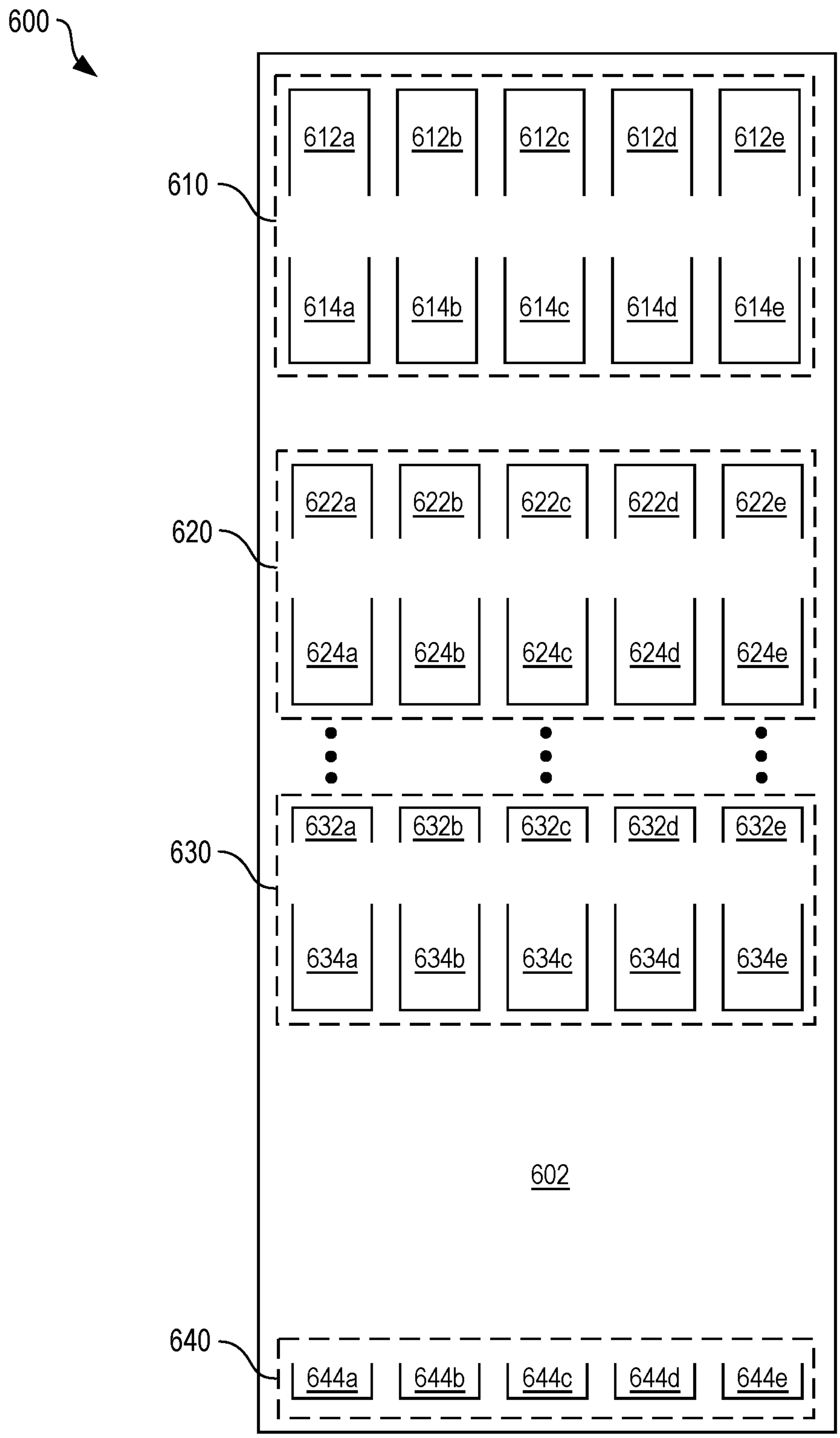

600
610
612a
612b
612c
612d
612e
614a
614b
614c
614d
614e
620
622a
622b
622c
622d
622e
624a
624b
624c
624d
624e
630
632a
632b
632c
632d
632e
634a
634b
634c
634d
634e
602
640
644a
644b
644c
644d
644e

FIG. 6A

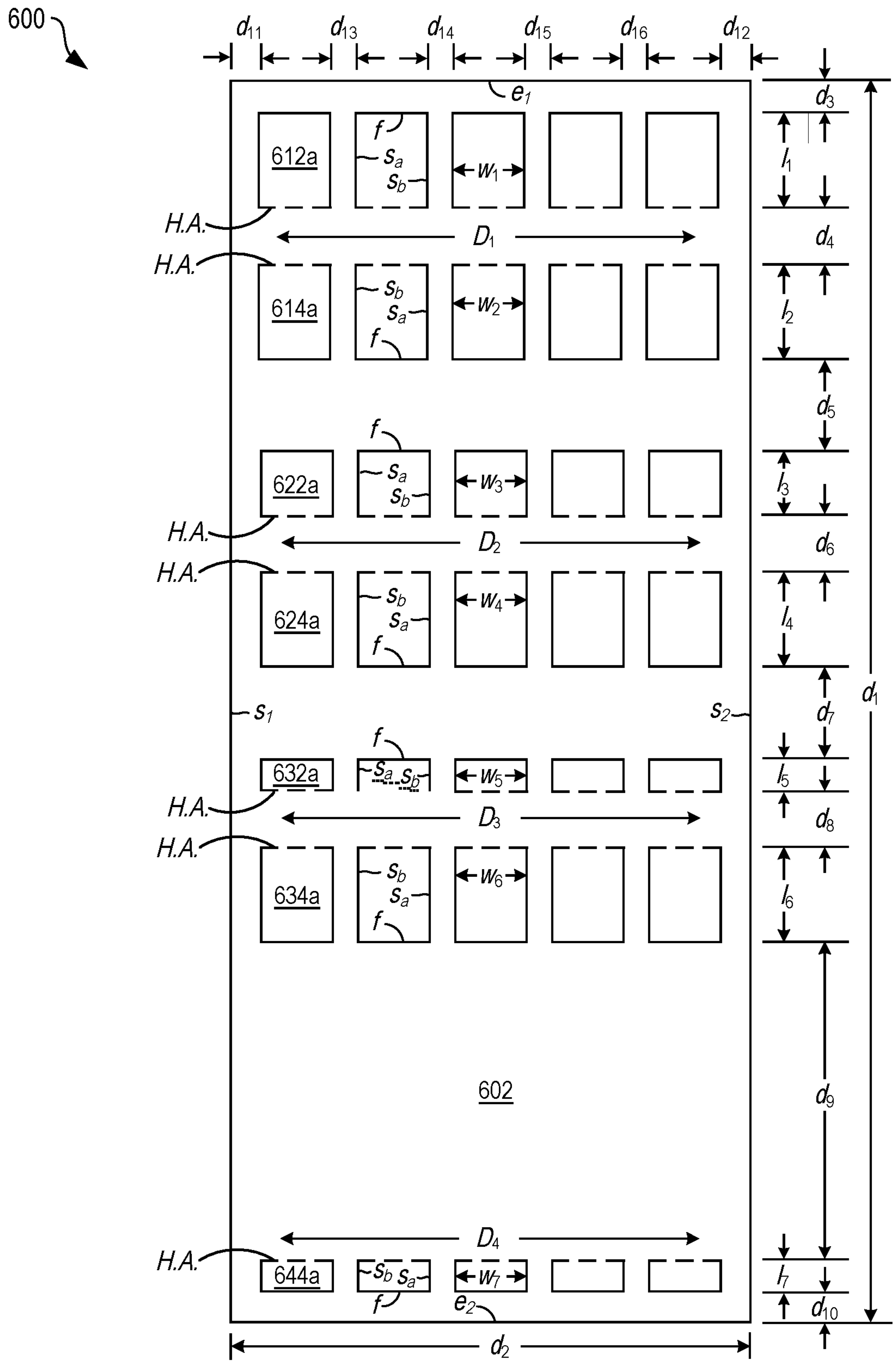

600
612a
614a
622a
624a
632a
634a
644a
602
H.A.
D1
D2
D3
D4
d1
d2
e1
e2
s1
s2

FIG. 6B

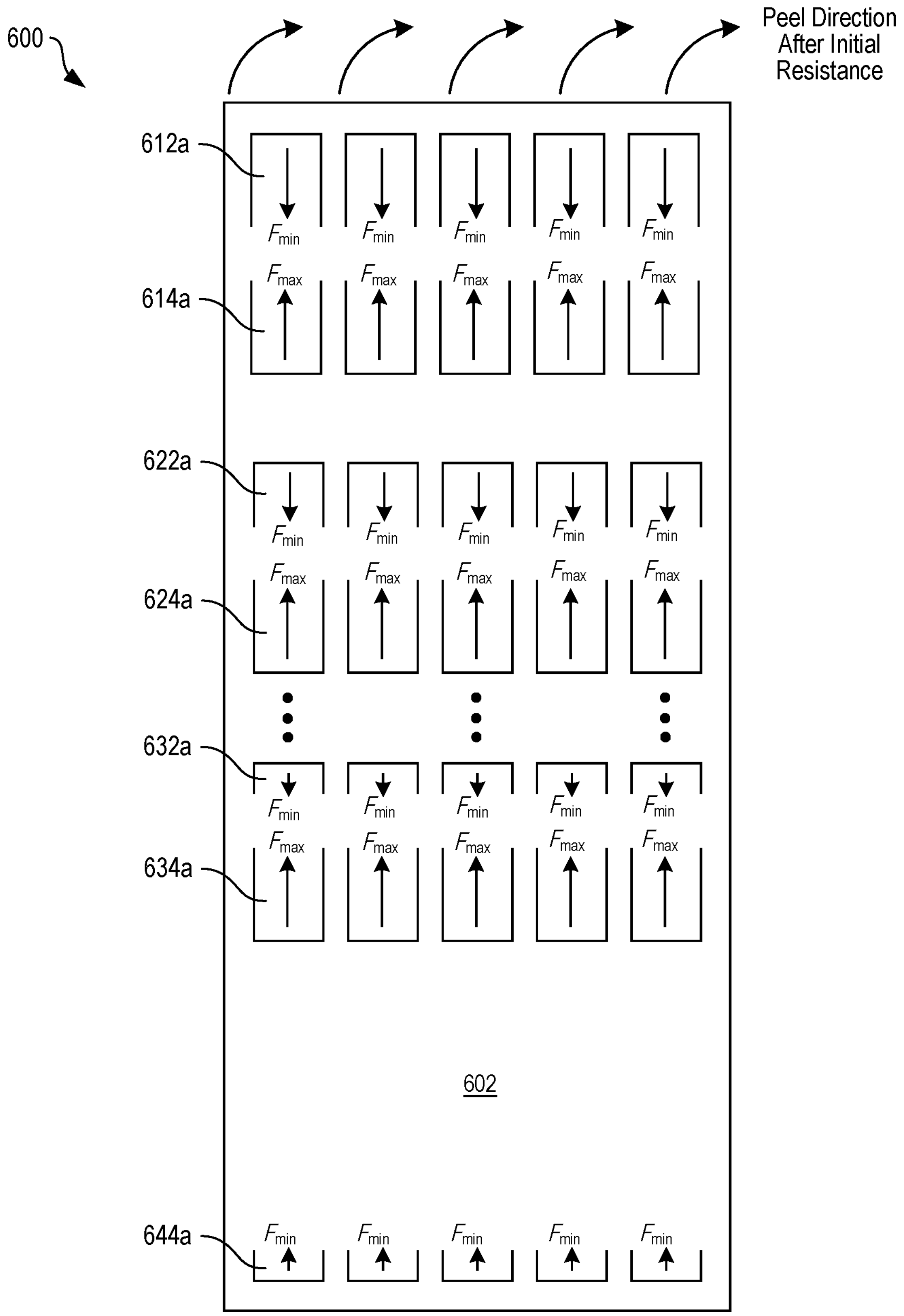
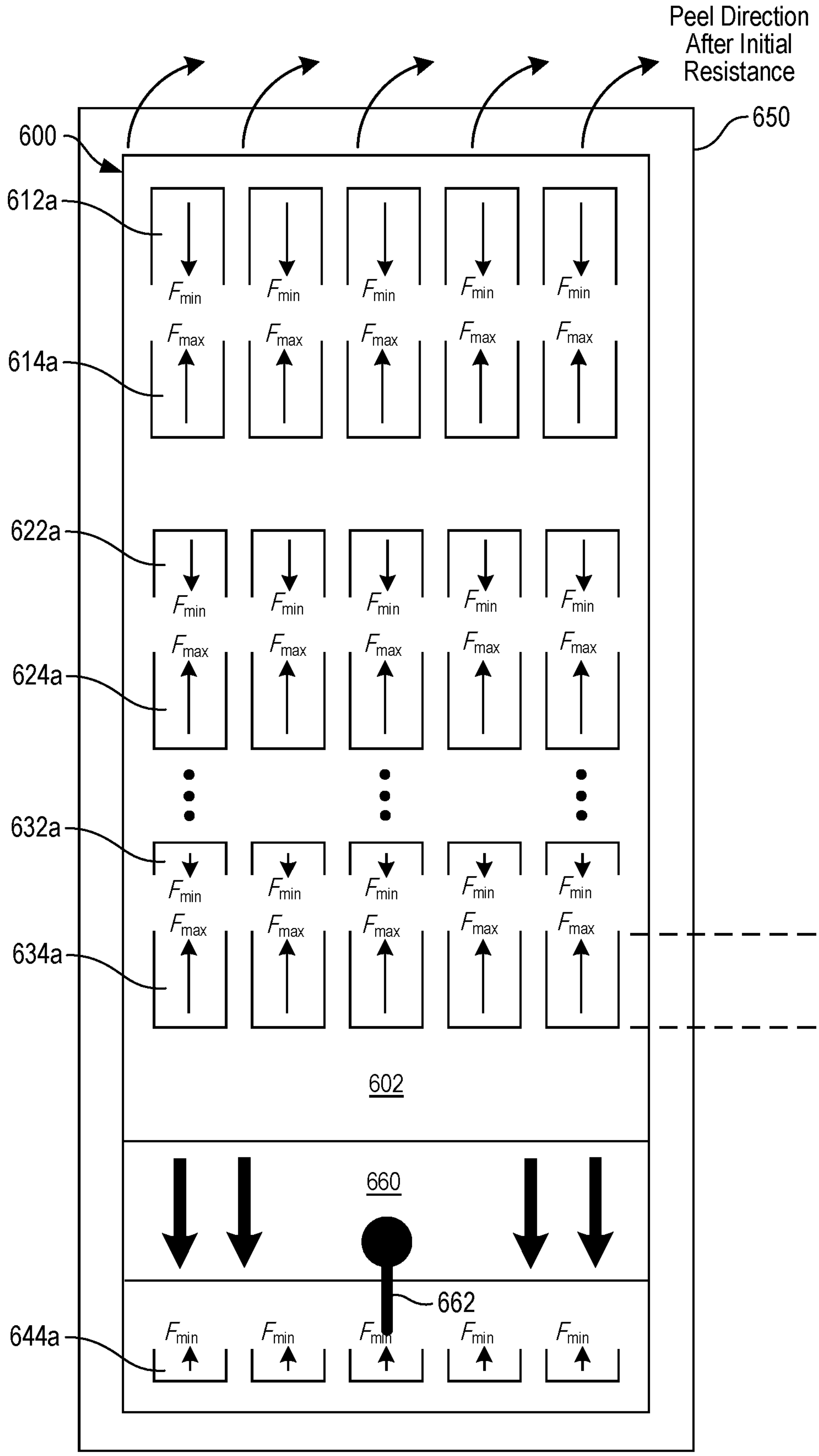
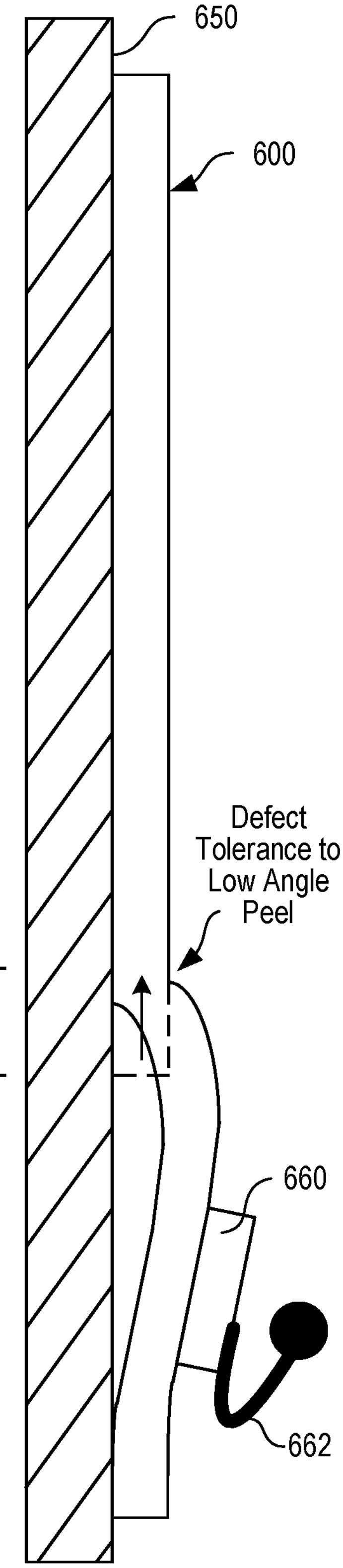

600
Peel Direction After Initial Resistance
612a
614a
622a
624a
632a
634a
644a
602
F_{min}
F_{max}

FIG. 6C



Peel Direction After Initial Resistance
600
650
612a
614a
622a
624a
632a
634a
644a
F_{min}
F_{max}
602
660
662

FIG. 6D



650
600
Defect Tolerance to Low Angle Peel
660
662

FIG. 6E

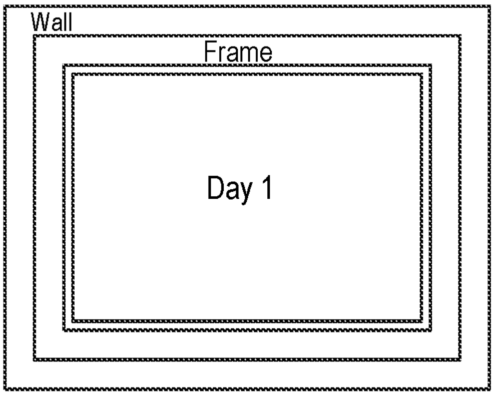


FIG. 6F

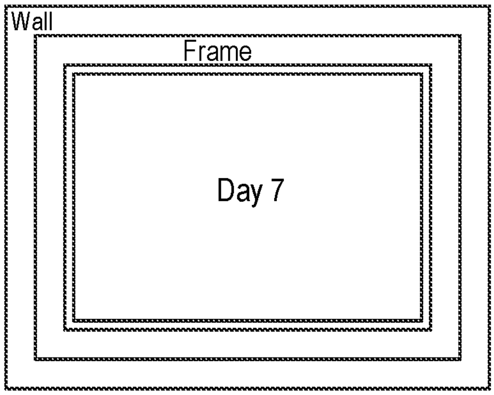


FIG. 6H

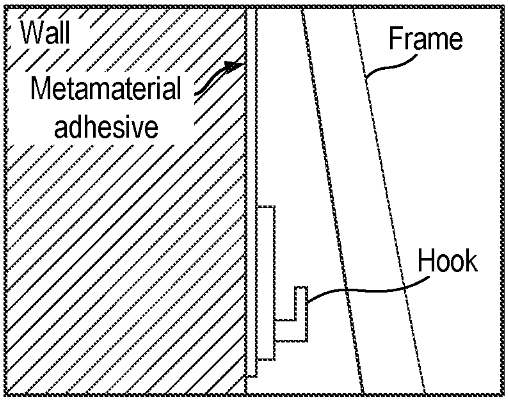


FIG. 6G

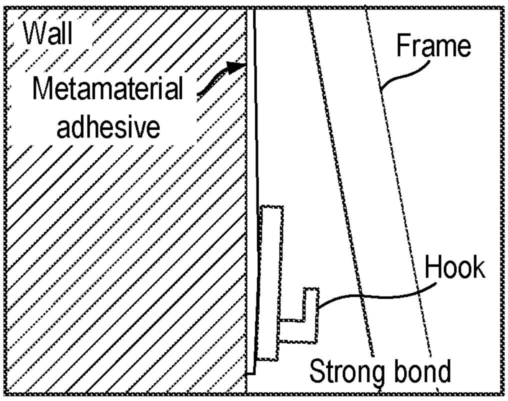


FIG. 6I

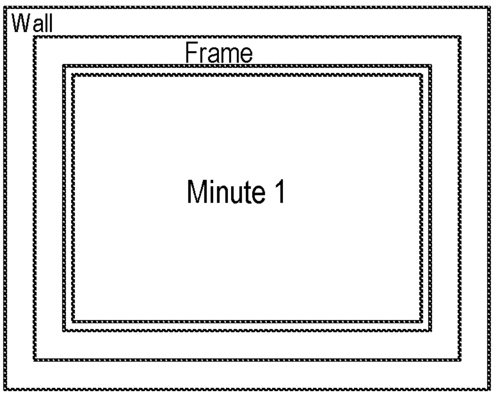


FIG. 6J

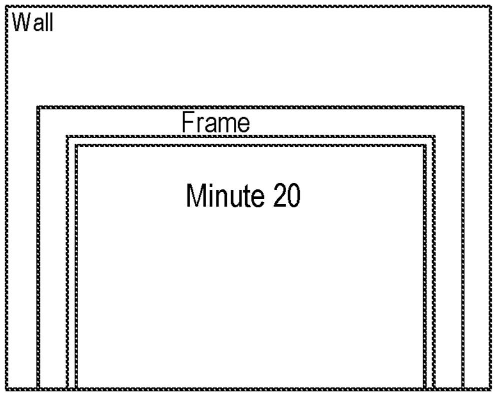


FIG. 6L

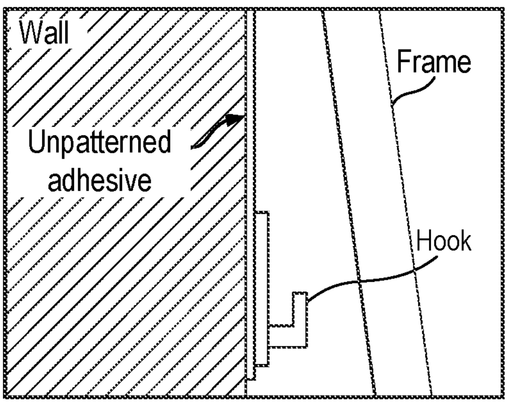


FIG. 6K

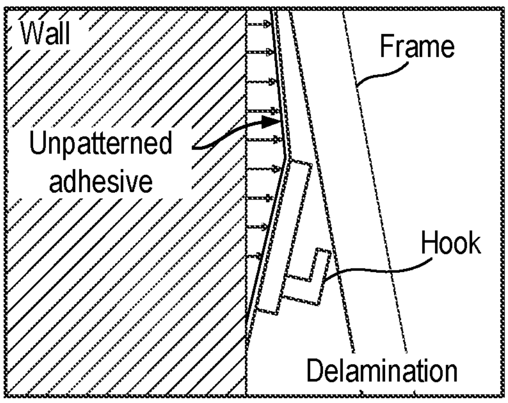


FIG. 6M

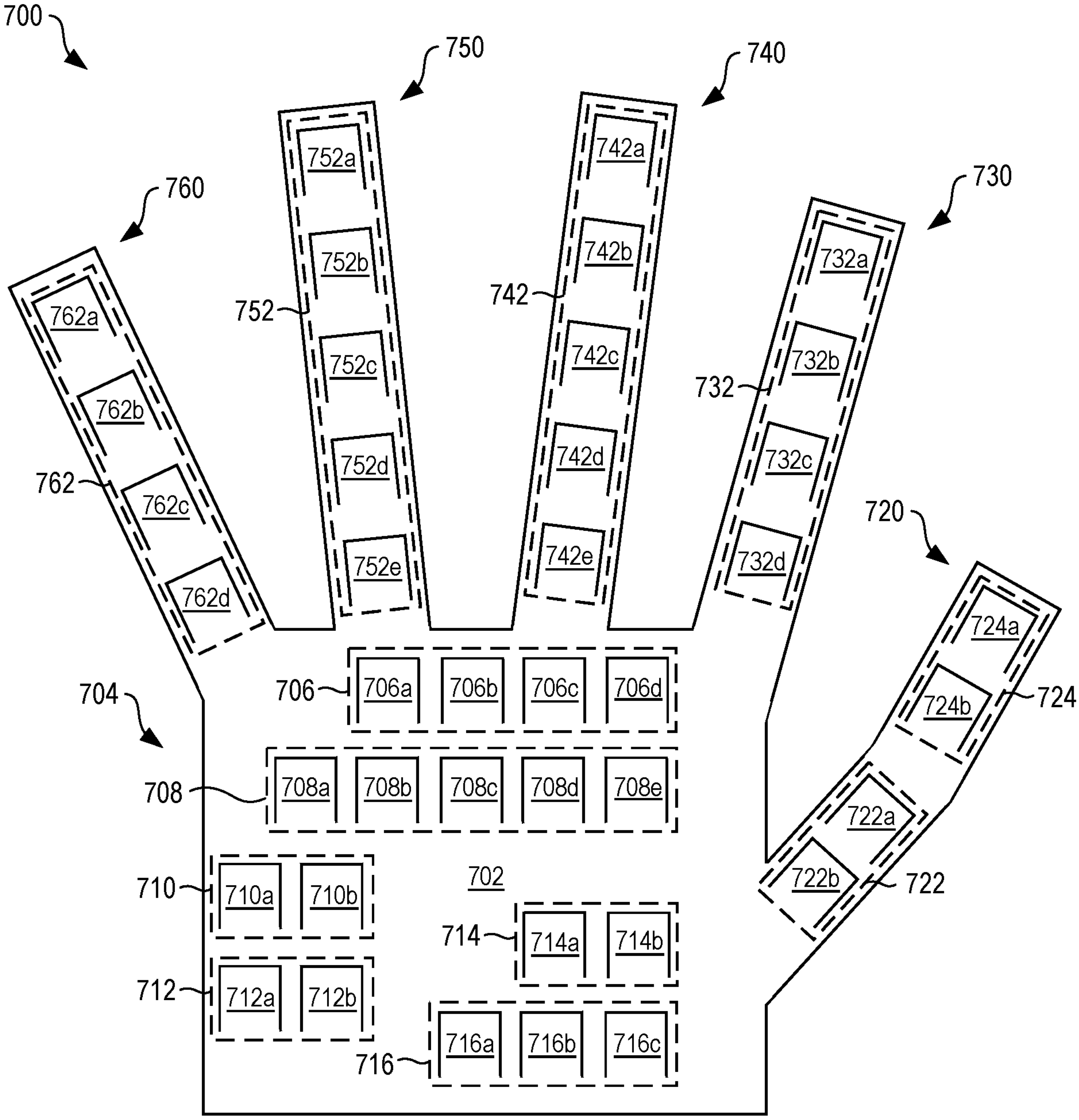

700
750
740
760
730
752a
742a
732a
762a
752b
742b
752
742
732b
762b
752c
742c
732
762
752d
742d
732c
762c
720
752e
742e
732d
762d
724a
706
706a
706b
706c
706d
724b
724
704
708
708a
708b
708c
708d
708e
722a
710
710a
710b
702
722b
722
714
714a
714b
712
712a
712b
716
716a
716b
716c

FIG. 7A

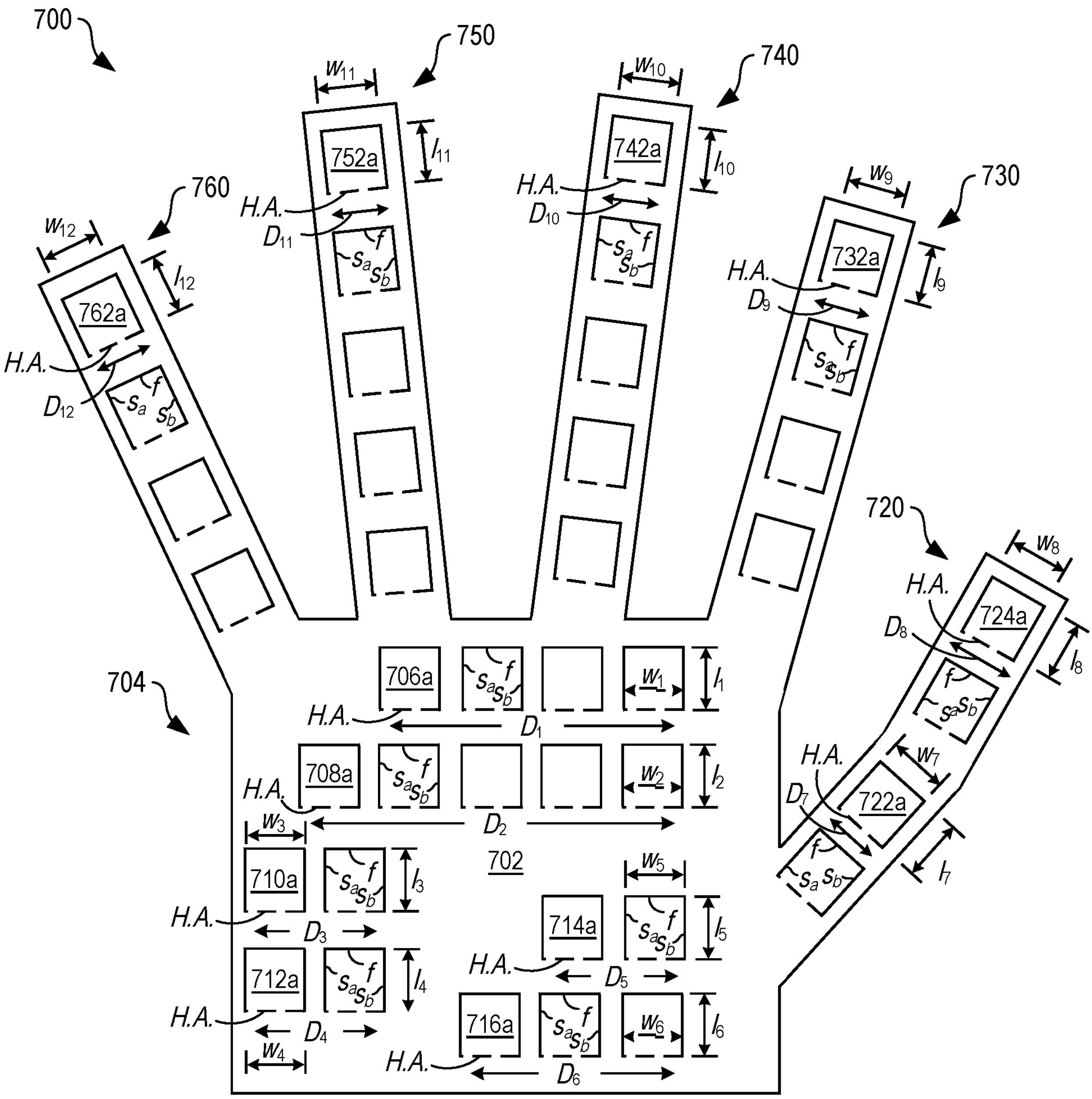

700
750
740
730
760
720
704
702
752a
742a
732a
762a
724a
722a
706a
708a
710a
712a
714a
716a
H.A.
f
s_a
s_b
w_1
w_2
w_3
w_4
w_5
w_6
w_7
w_8
w_9
w_{10}
w_{11}
w_{12}
l_1
l_2
l_3
l_4
l_5
l_6
l_7
l_8
l_9
l_{10}
l_{11}
l_{12}
D_1
D_2
D_3
D_4
D_5
D_6
D_7
D_8
D_9
D_{10}
D_{11}
D_{12}

FIG. 7B

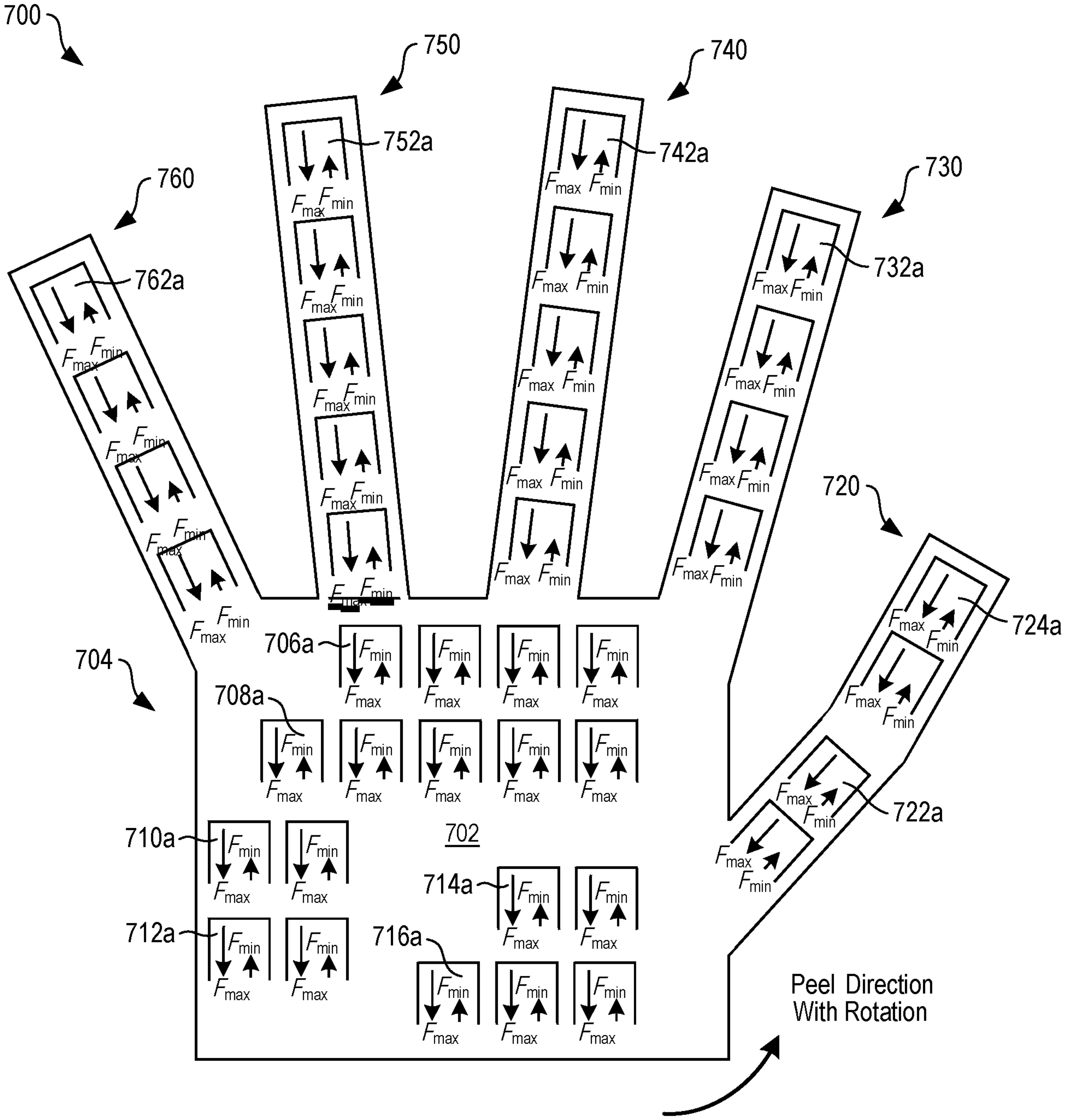

700
750
740
730
760
752a
742a
732a
762a
720
724a
722a
704
706a
708a
710a
712a
714a
716a
702
Fmax
Fmin
Peel Direction With Rotation

FIG. 7C

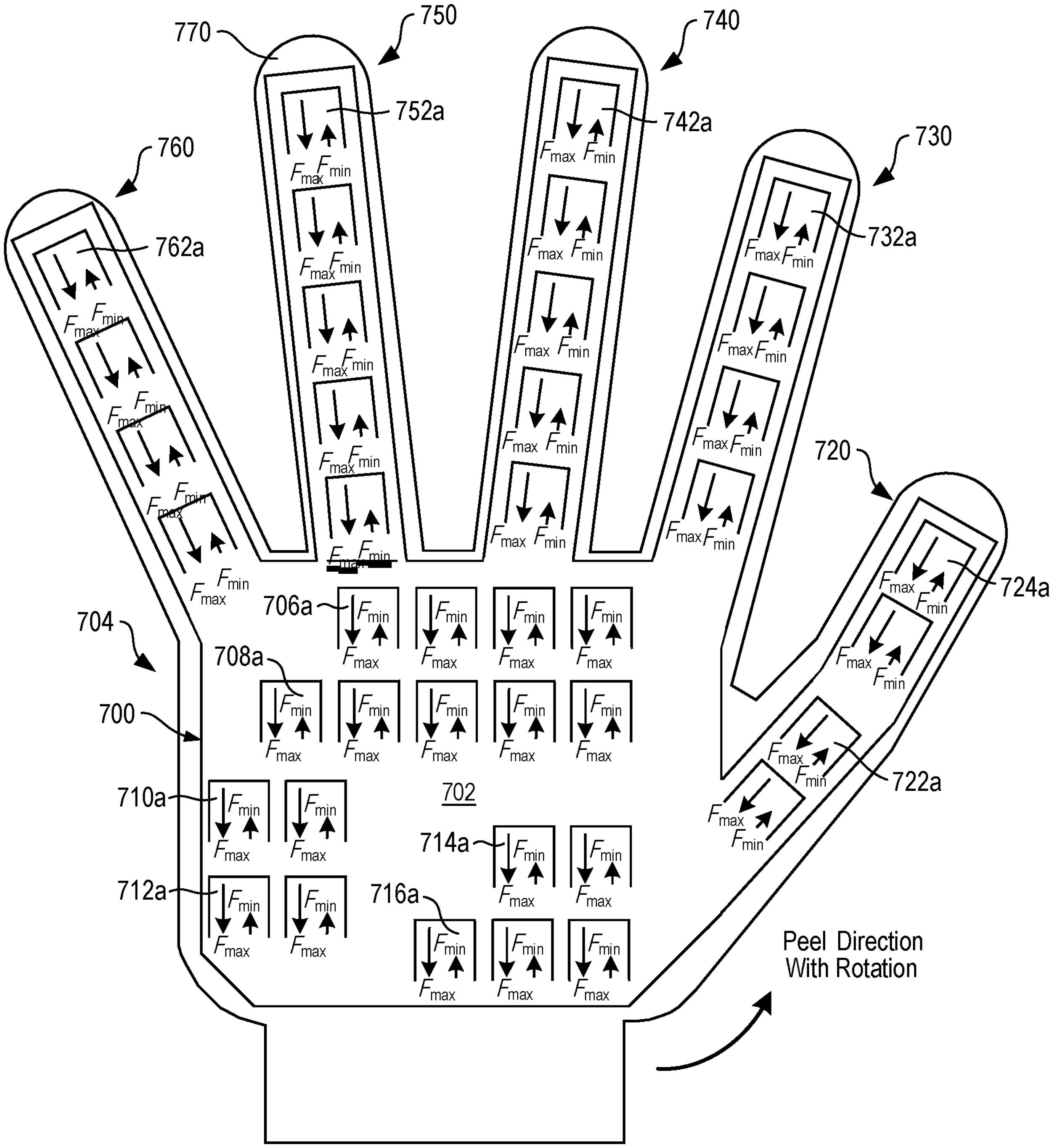

770
750
740
730
760
720
752a
742a
732a
762a
724a
722a
704
700
706a
708a
710a
712a
714a
716a
702
F_{max}
F_{min}
Peel Direction
With Rotation

FIG. 7D

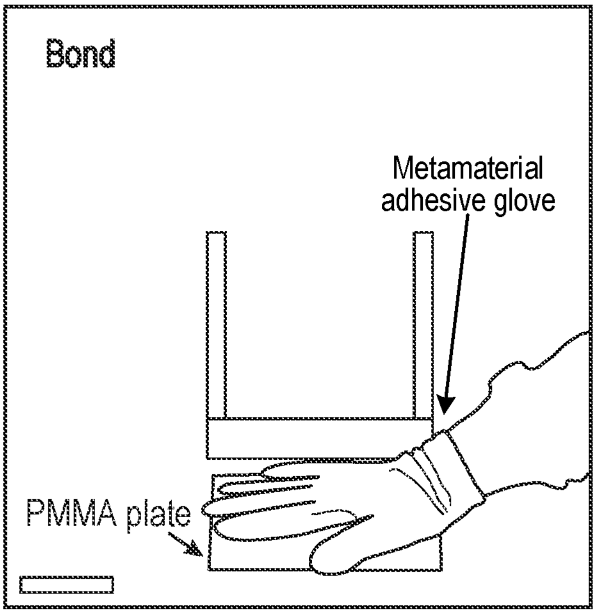


FIG. 7E

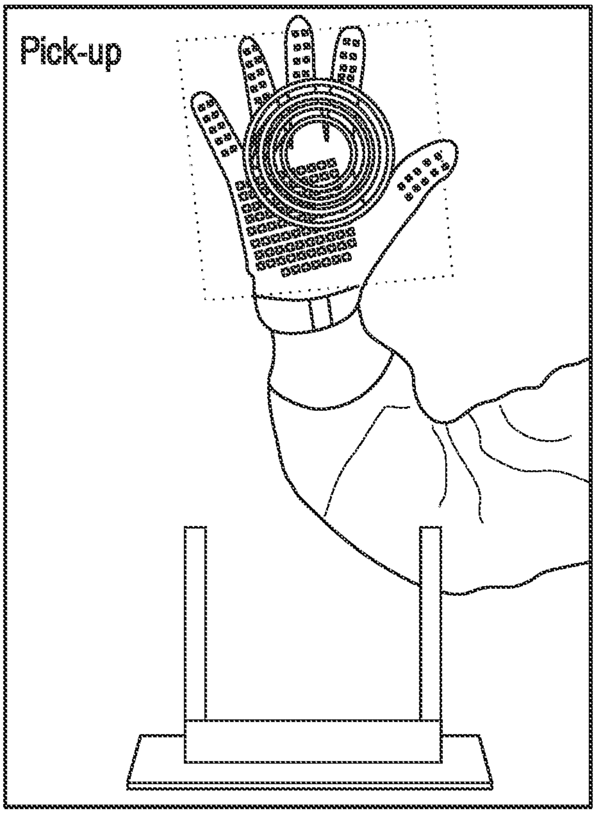


FIG. 7F

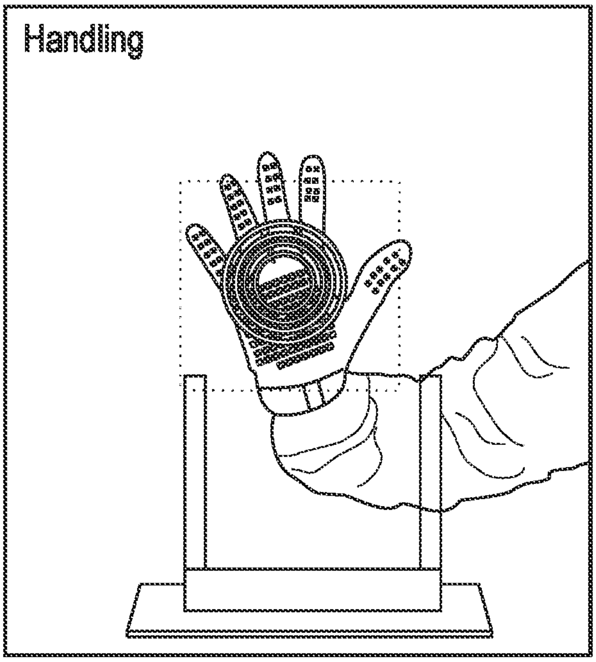


FIG. 7G

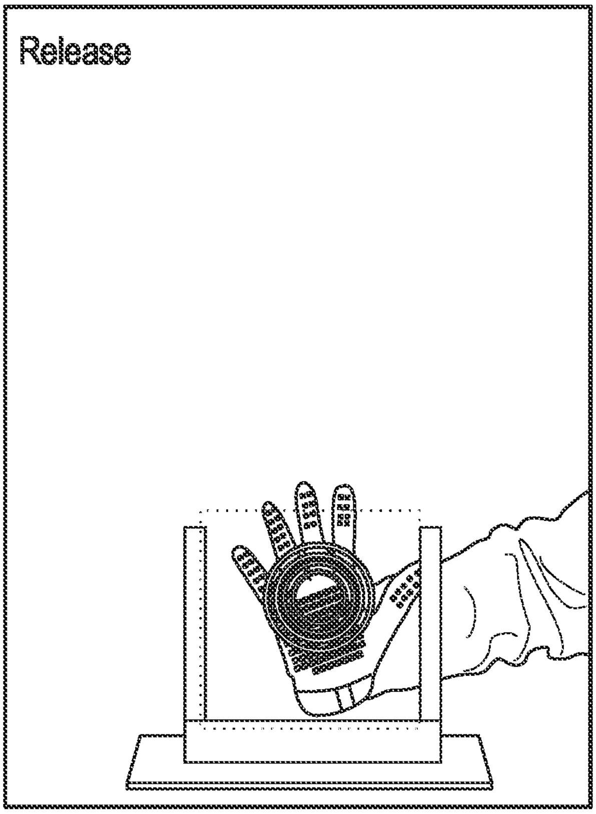


FIG. 7H

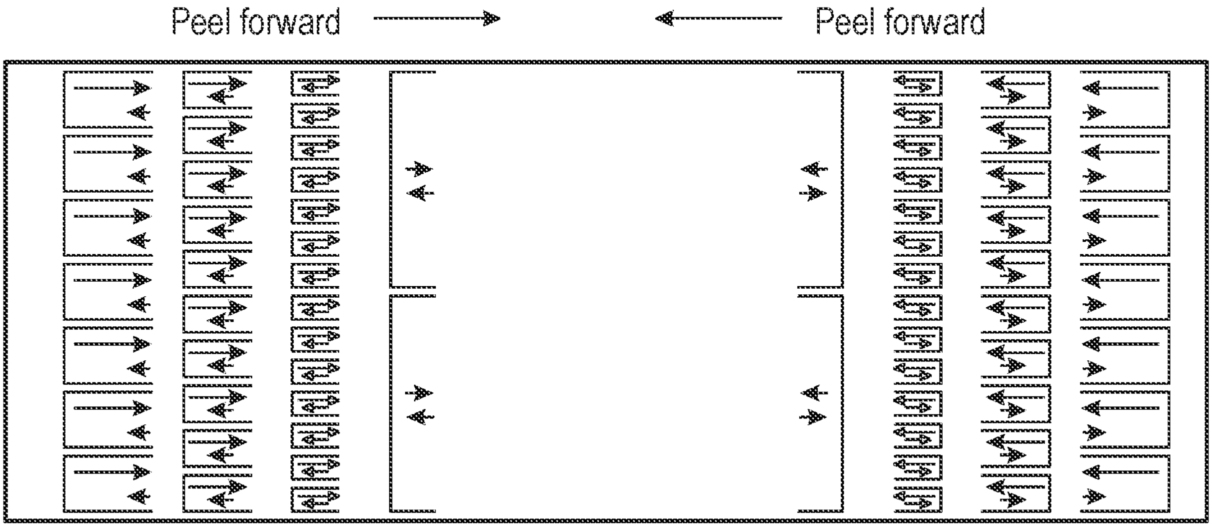

Peel forward
Peel forward

FIG. 8A

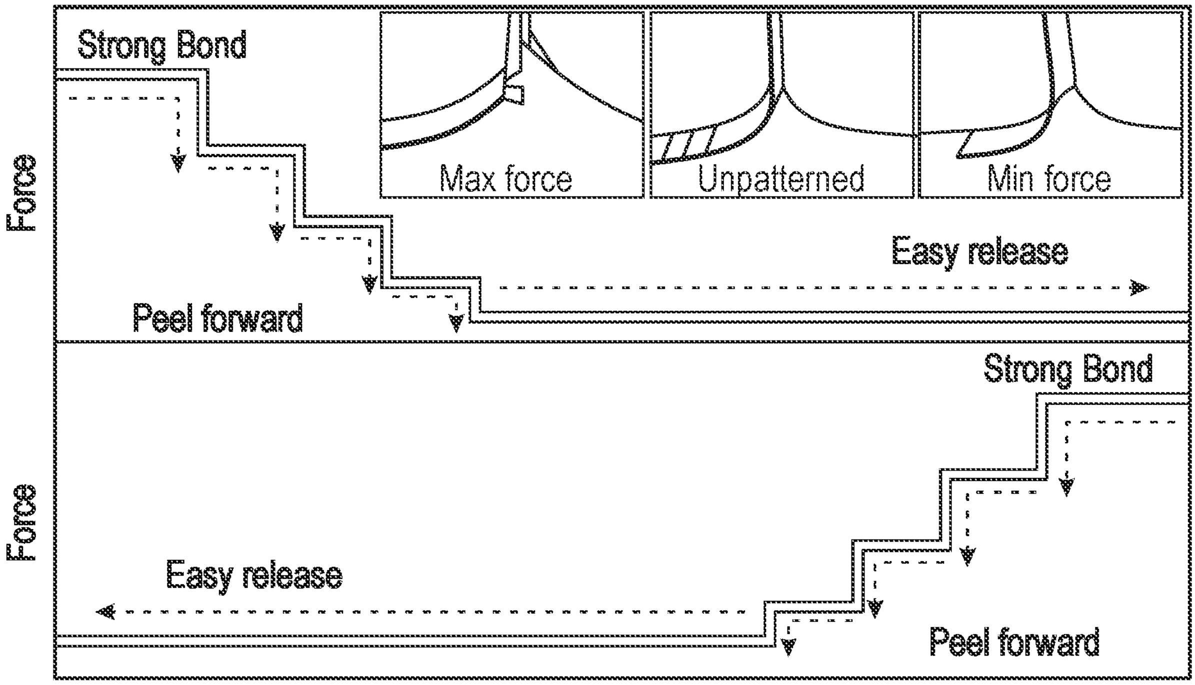

Strong Bond
Max force
Unpatterned
Min force
Force
Easy release
Peel forward
Strong Bond
Force
Easy release
Peel forward

FIG. 8B

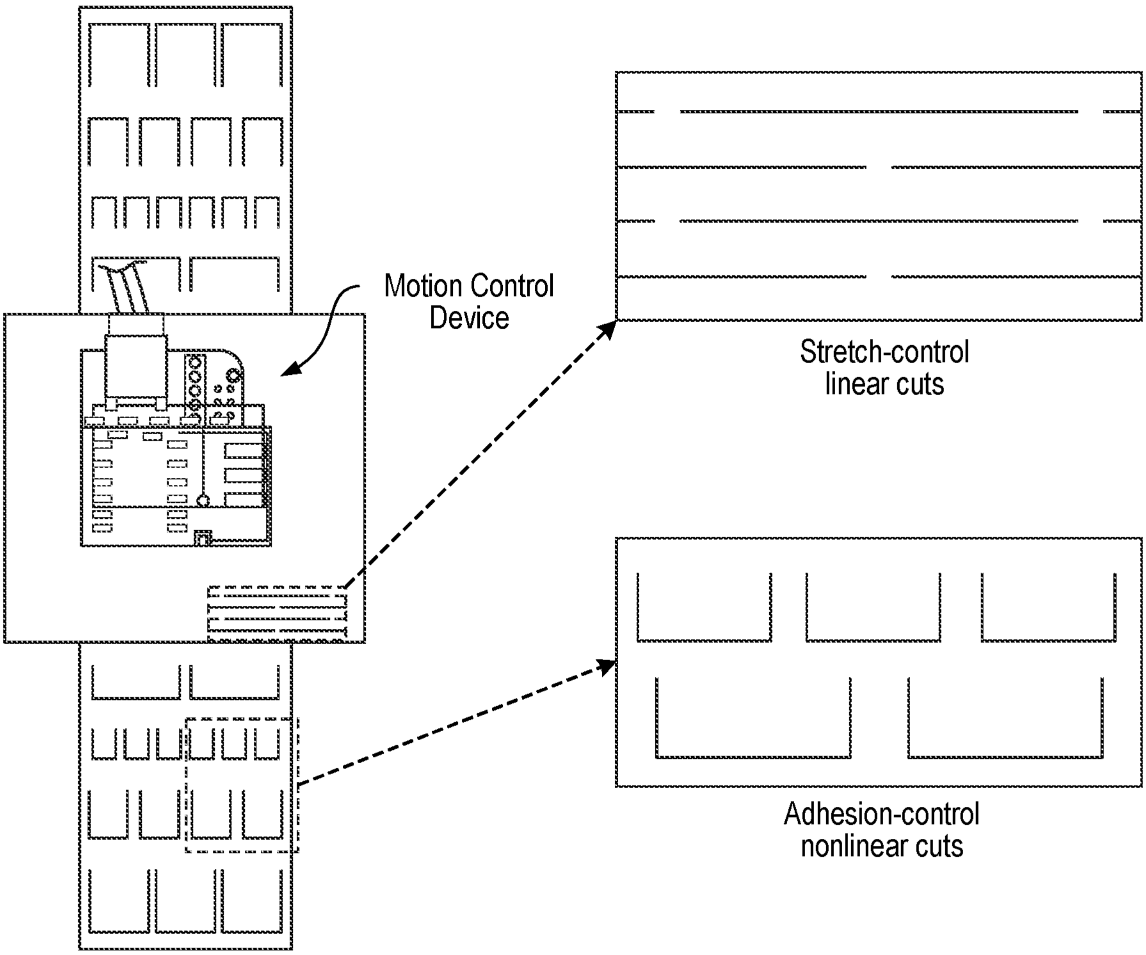


FIG. 8C

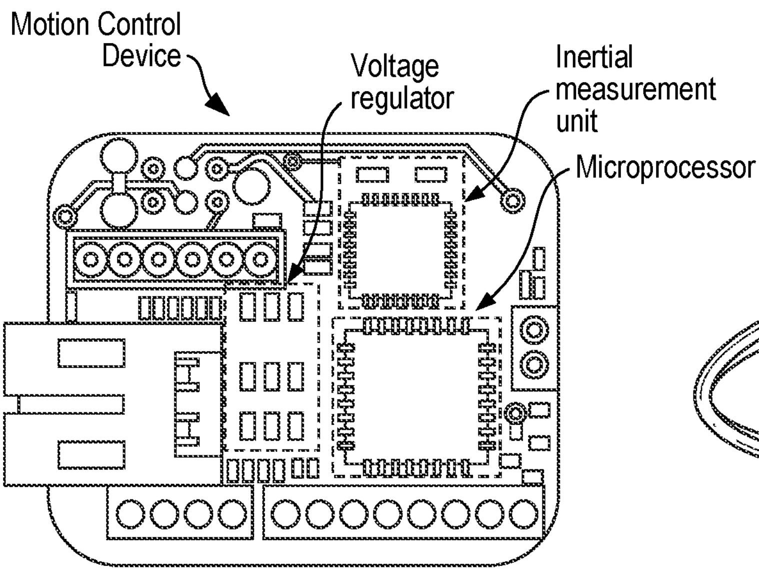


FIG. 8D

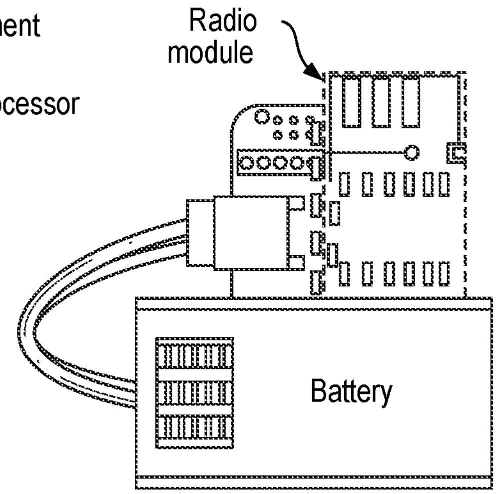


FIG. 8E

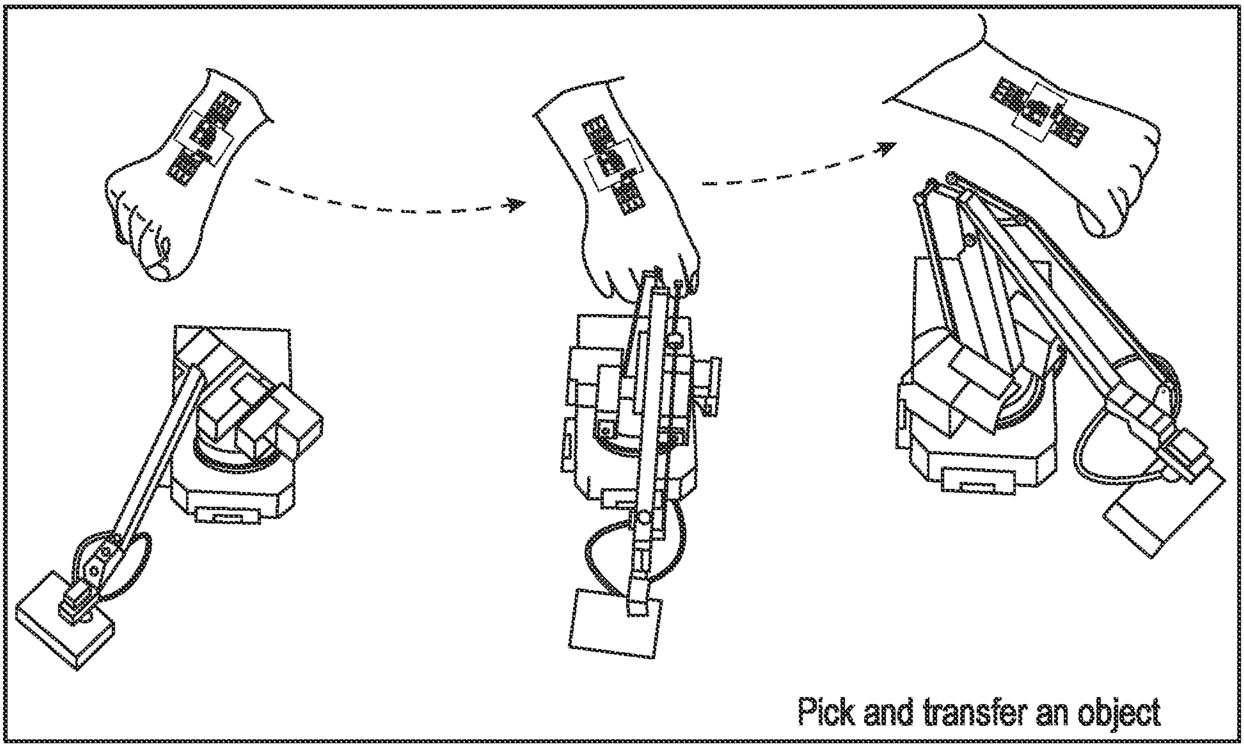

Pick and transfer an object

FIG . 8F

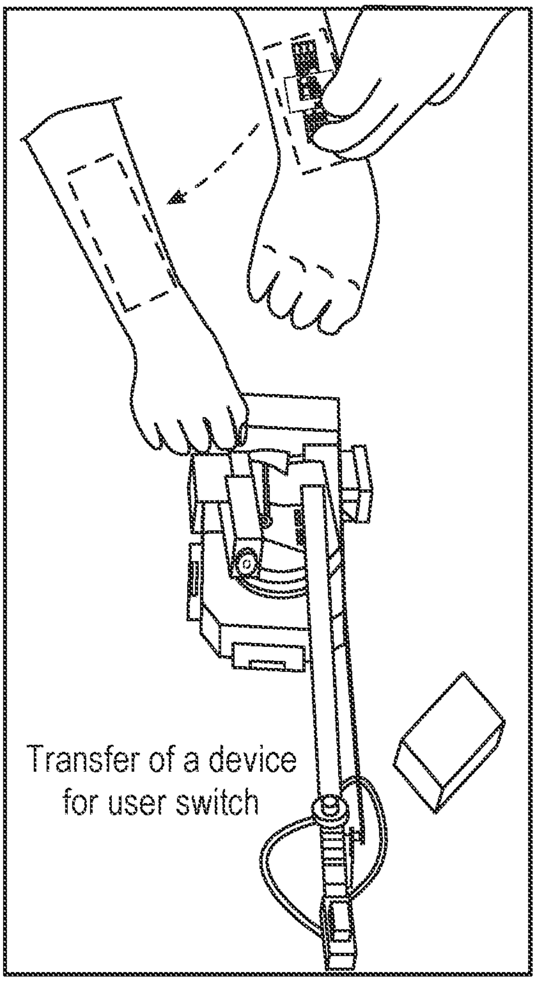

Transfer of a device
for user switch

FIG . 8G

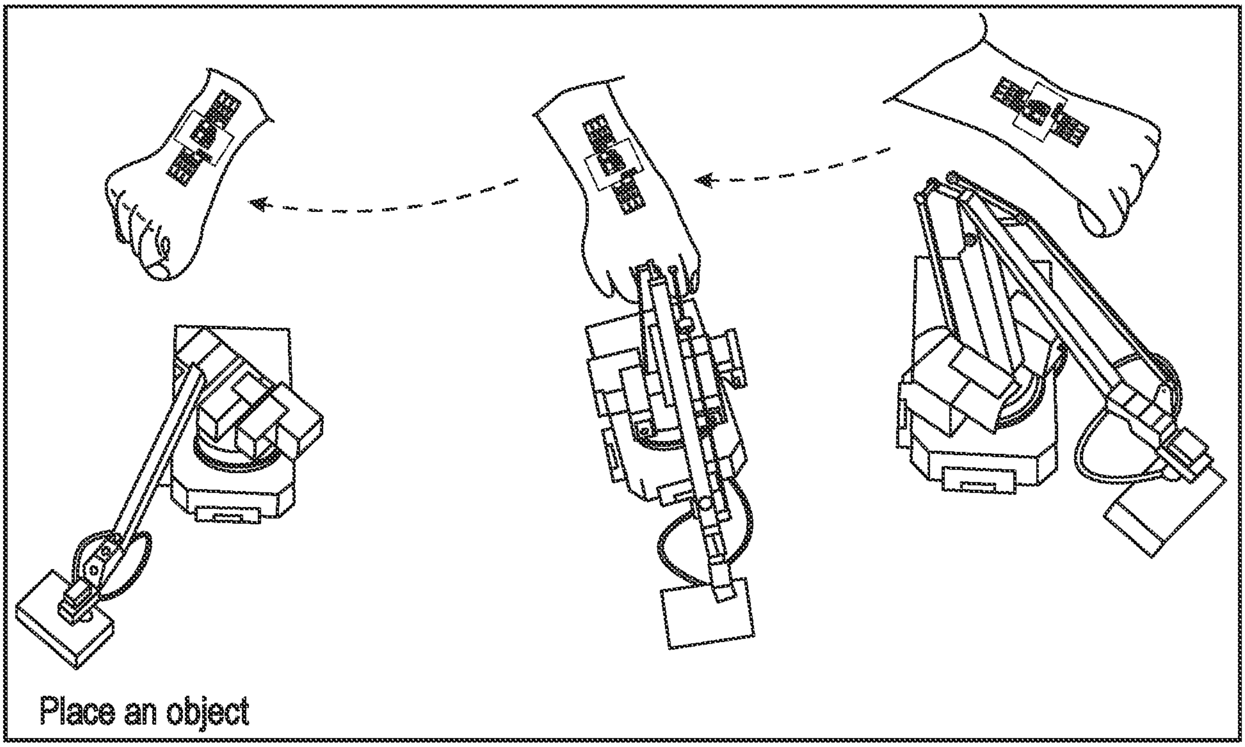


FIG . 8H

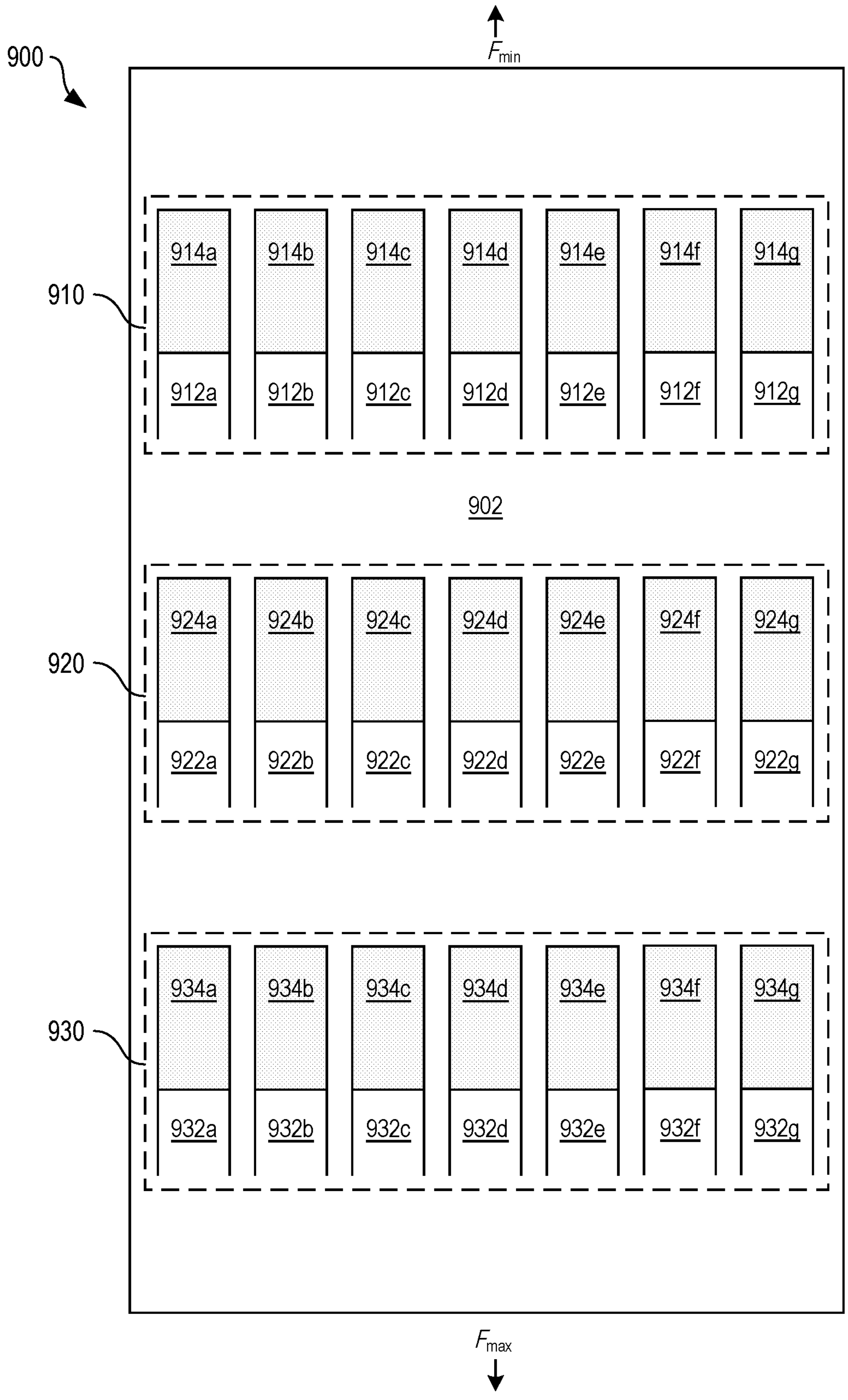

900
F_{min}
910
914a
914b
914c
914d
914e
914f
914g
912a
912b
912c
912d
912e
912f
912g
902
920
924a
924b
924c
924d
924e
924f
924g
922a
922b
922c
922d
922e
922f
922g
930
934a
934b
934c
934d
934e
934f
934g
932a
932b
932c
932d
932e
932f
932g
F_{max}

FIG. 9A

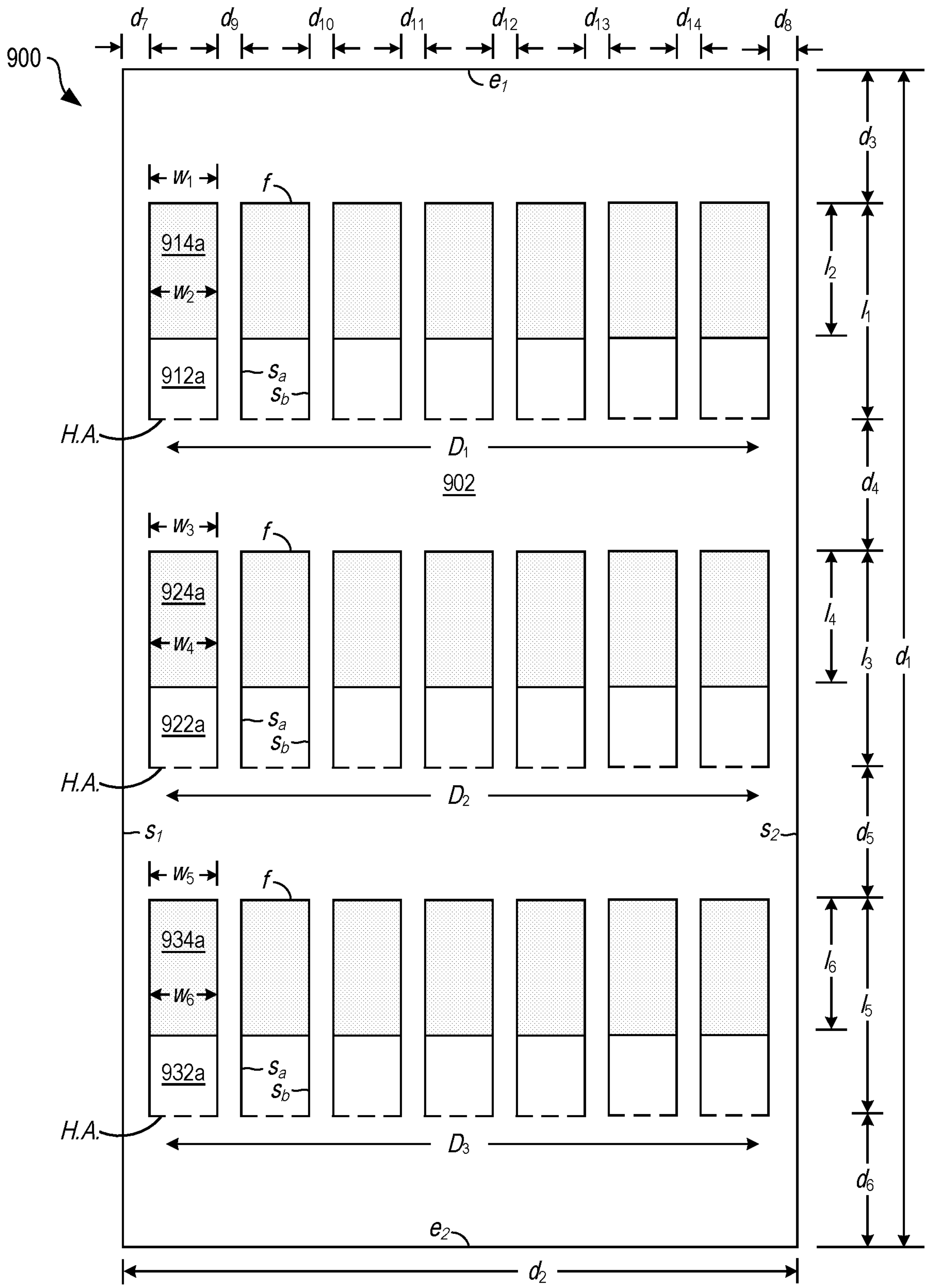

900
d7
d9
d10
d11
d12
d13
d14
d8
e1
d3
w1
f
914a
w2
l2
l1
912a
sa
sb
H.A.
D1
902
d4
w3
f
924a
w4
l4
l3
d1
922a
sa
sb
H.A.
D2
s1
s2
d5
w5
f
934a
w6
l6
l5
932a
sa
sb
H.A.
D3
d6
e2
d2

FIG. 9B

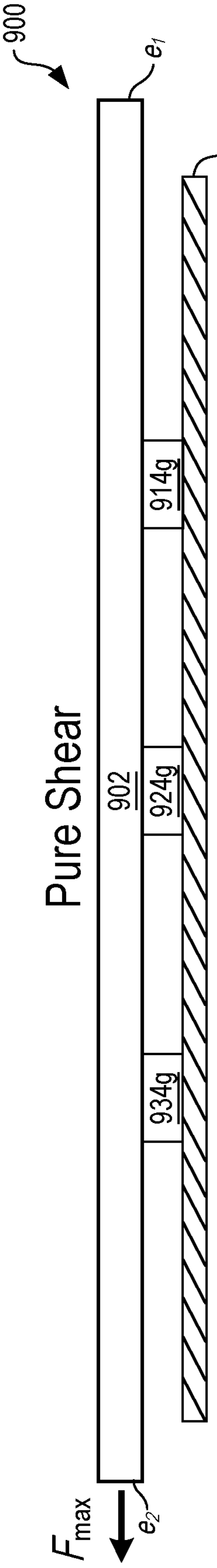


FIG. 9C

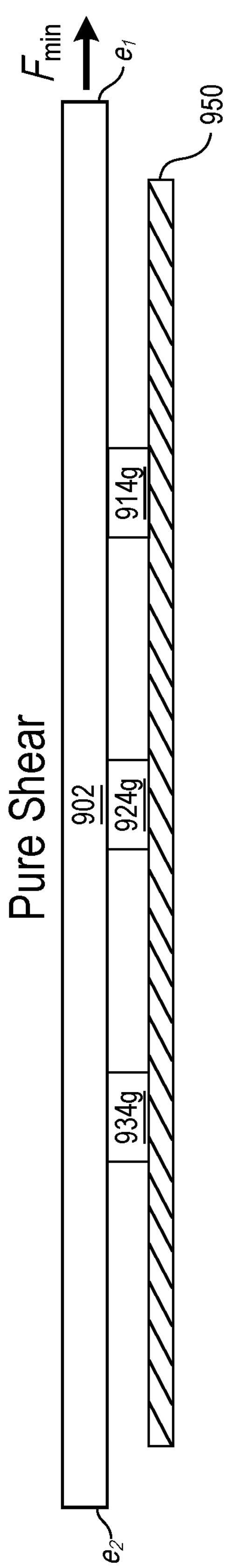


FIG. 9D

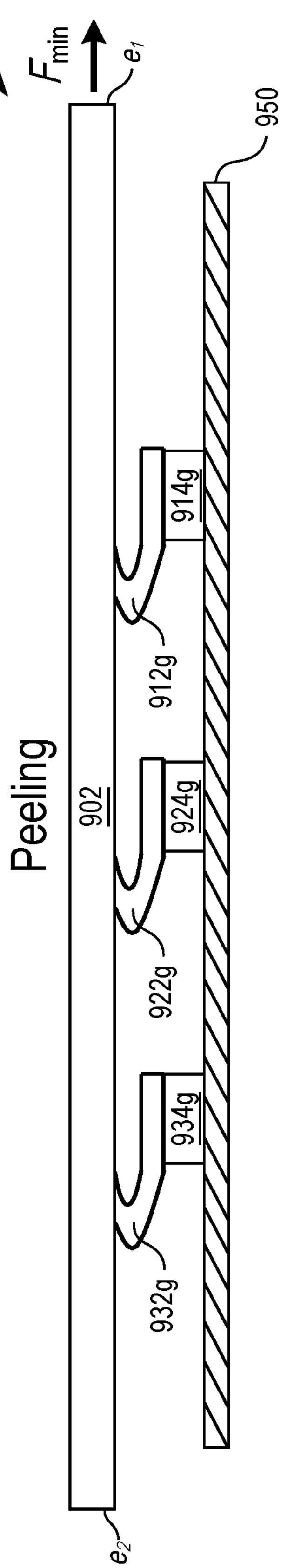


FIG. 9E

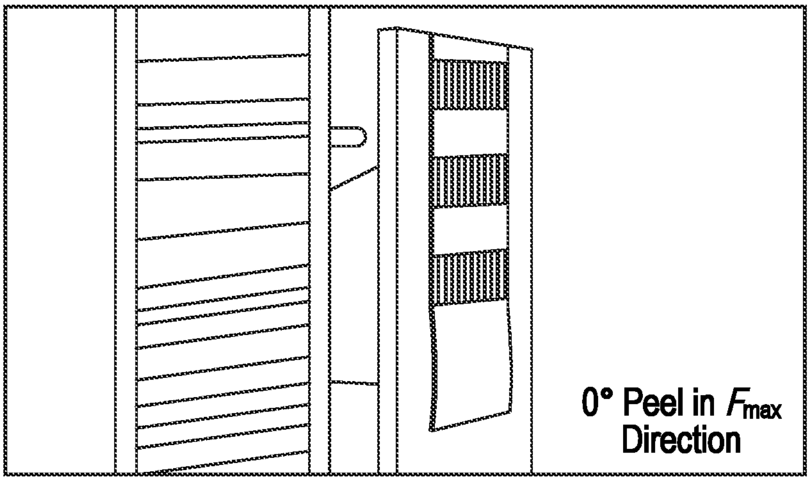


FIG . 9F

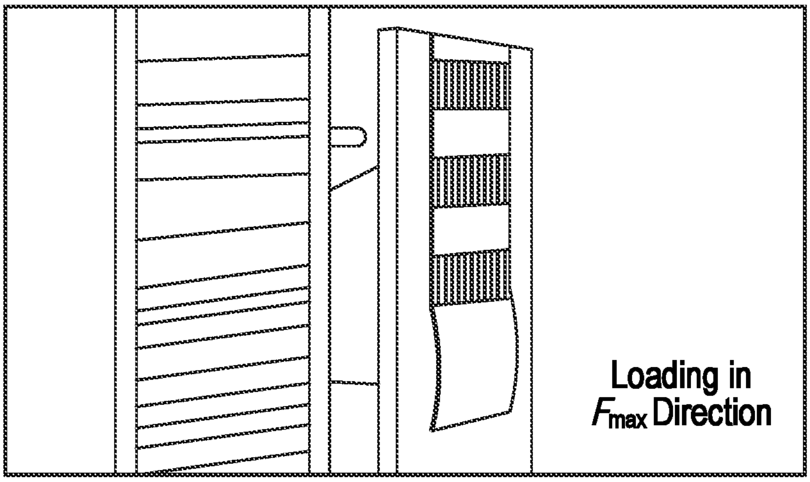


FIG . 9G

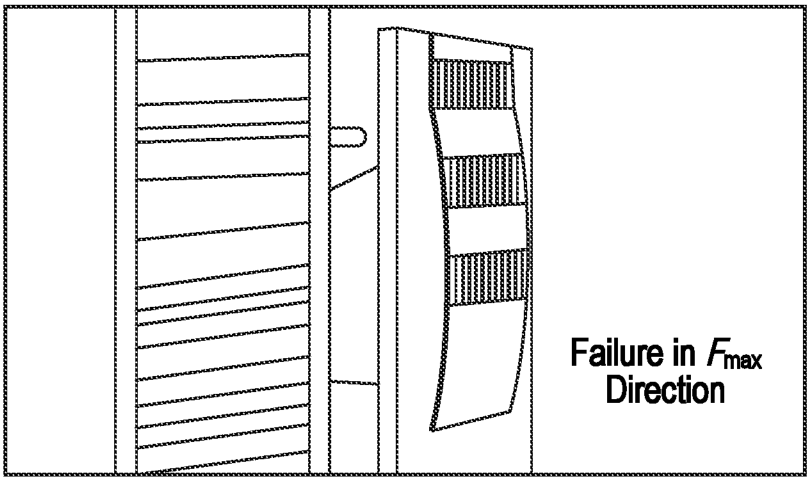


FIG . 9H

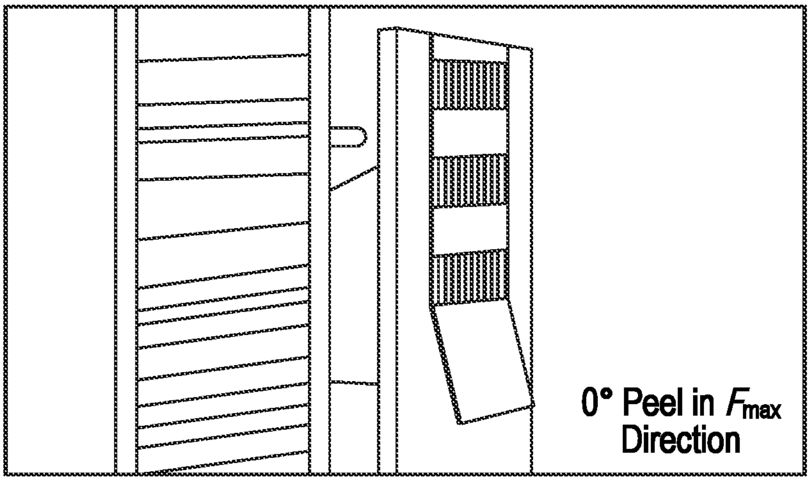


FIG. 9I

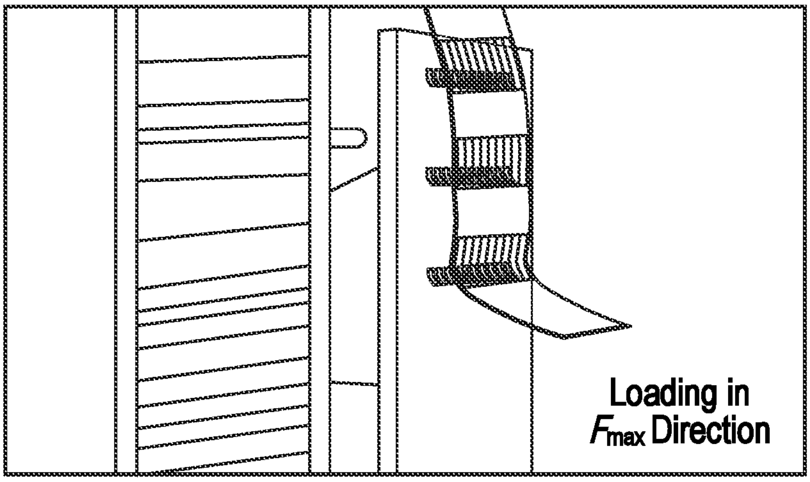


FIG. 9J

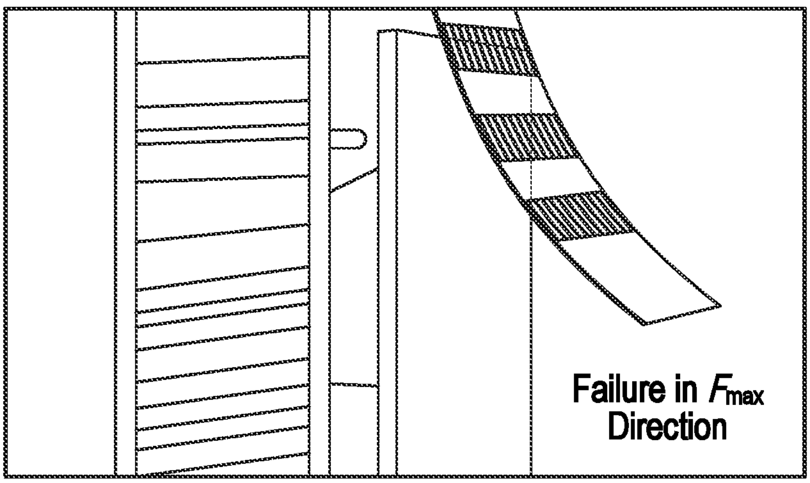
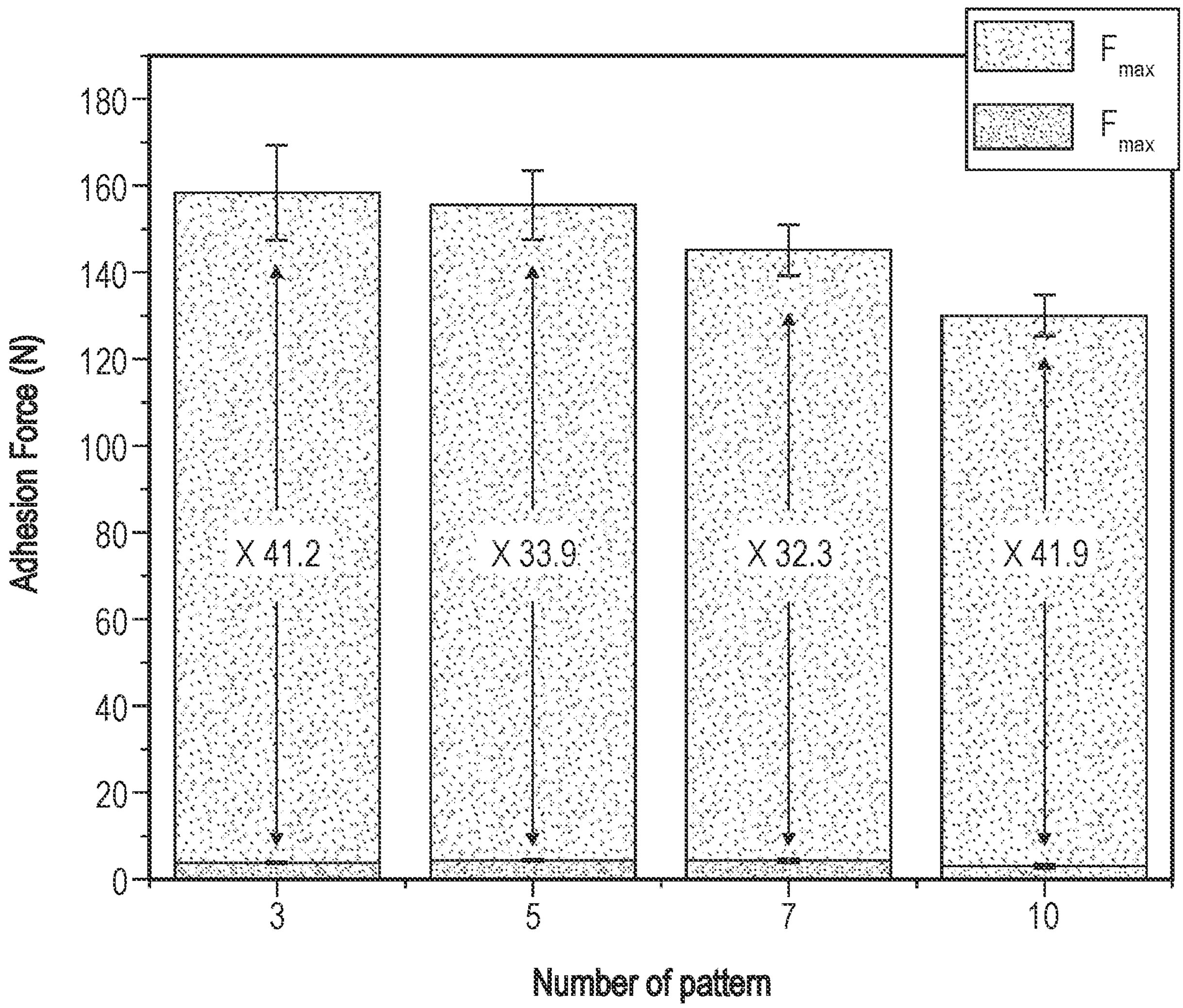


FIG. 9K



Adhesion Force (N)
0
20
40
60
80
100
120
140
160
180
Number of pattern
3
5
7
10
X 41.2
X 33.9
X 32.3
X 41.9
F_{max}
F_{max}

FIG . 9L

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2024/032826

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***B32B 3/26*** (2024.01); ***B32B 7/06*** (2024.01); ***B32B 25/08*** (2024.01); ***B32B 25/20*** (2024.01)

CPC: ***B32B 3/266; B32B 25/08; B32B 25/20; B32B 7/06;*** *B32B 2405/00*

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History Document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

See Search History Document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History Document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	DE 3007088 A1 (QUIRIN) 03 September 1981 (03.09.1981)	
X	see machine translation	1-14, 81-94
Y	see machine translation	15-19, 95-99
	JP 11-181375 A (ASAHIPEN CORP.) 06 July 1999 (06.07.1999)	
Y	see machine translation	15-18, 95-98
	US 2020/0187859 A1 (NITTO DENKO CORPORATION) 18 June 2020 (18.06.2020)	
Y	entire document	19, 99
	US 4,335,172 A (SATO) 15 June 1982 (15.06.1982)	
A	entire document	1-20, 81-100

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 September 2024 (10.09.2024)	**23 October 2024 (23.10.2024)**
Name and mailing address of the ISA/US **COMMISSIONER FOR PATENTS MAIL STOP PCT, ATTN: ISA/US P.O. Box 1450 Alexandria, VA 22313-1450 UNITED STATES OF AMERICA** Facsimile No. **571-273-8300**	Authorized officer **TAINA MATOS** Telephone No. **571-272-4300**

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-20 and 81-100, is drawn to a flexible strip comprising a base region.

Group II, claims 21-60, is drawn to a subset of opposing flaps on the flexible strip.

Group III, claims 61-80, is drawn to the first flap and the second flap each having same defined dimensions and being oppositely oriented on the flexible strip relative to one another.

Group IV, claims 101-120, is drawn to the row of flaps comprising multiple flaps oriented in a same orientation on the flexible strip relative to one another.

The inventions listed as Groups I-IV do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

The special technical features of the Group I invention: a flexible strip comprising a base region and a stem region; the first flap being in the base region of the flexible strip, the hinge axis of the first flap extending between side edges of the first flap; the second flap being in the stem region of the flexible strip, the second extension direction of the hinge axis of the second flap being different from the first extension direction of the hinge axis of the first flap as claimed therein are not present in the invention of Groups II-IV. The special technical features of the Group II invention: a subset of opposing flaps on the flexible strip, the subset of opposing flaps comprising: a second flap on the flexible strip; and a pair of aligned flaps oriented on the flexible strip in a same orientation relative to one another and an opposite orientation relative to the second flap, wherein each flap of the pair of aligned flaps and the second flap is pivotable about a flap hinge axis extending in a second extension direction at a defined angle relative to the first extension direction as claimed therein are not present in the invention of Groups I, III and IV. The special technical features of the Group III invention: first rows of opposing flaps on the flexible strip, the first rows of opposing flaps comprising a first flap and a second flap on the flexible strip, the first flap and the second flap each having same defined dimensions and being oppositely oriented on the flexible strip relative to one another; and second rows of opposing flaps on the flexible strip, the second rows of opposing flaps comprising a third flap and a fourth flap on the flexible strip, the third flap and the fourth flap being oppositely oriented on the flexible strip relative to one another, the third flap having the same defined dimensions of the first flap and the second flap, and the fourth flap having a dimension that is different from a corresponding dimension of the first flap, the second flap, and the third flap as claimed therein are not present in the invention of Groups I, II and IV. The special technical features of the Group IV invention: the row of flaps comprising multiple flaps oriented in a same orientation on the flexible strip relative to one another, the multiple flaps comprising a flap on the flexible strip, the flap having opposing sides; and an adhesive coupled to a side of the opposing sides of the flap as claimed therein are not present in the invention of Groups I-III.

Groups I-IV lack unity of invention because even though the inventions of these groups require the technical features of an adhesive system, comprising: a flexible strip; a first flap on the flexible strip, the first flap being pivotable about a hinge axis of the first flap, the hinge axis of the first flap extending in a first extension direction; and a second flap on the flexible strip, the second flap being pivotable about a hinge axis of the second flap, the hinge axis of the second flap extending between side edges of the second flap in a second extension direction; a row of flaps on the flexible strip, these technical features are not special technical features as it does not make a contribution over the prior art.

Specifically, US 4,335,172 to Sato teaches an adhesive system (label strip 1; figures 1-3), comprising: a flexible strip (strip layer of label material 2; figure 1); a first flap on the flexible strip (first flap formed by cut line 7; figure 1), the first flap being pivotable about a hinge axis of the first flap (as shown; figures 1, 5), the hinge axis of the first flap extending in a first extension direction (hinge axis of first cut line 7 as shown; figure 5); and a second flap (second flap formed by cut line 7; figure 1) on the flexible strip (as shown; figure 1), the second flap being pivotable about a hinge axis of the second flap (as shown; figures 1, 5), the hinge axis of the second flap

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2024/032826

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

extending between side edges of the second flap in a second extension direction (hinge axis of second cut line 7 as shown; figure 5); a row of flaps on the flexible strip (row of flaps formed by cut lines 7; figure 1).

Since none of the special technical features of the Groups I-IV inventions are found in more than one of the inventions, unity of invention is lacking.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☑ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.: **1-20, 81-100**

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.