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REVIEW ARTICALE

REINFORCEMENT AND SELF-HEALING STRATEGIES IN NEXT-GENERATION SILICONES FOR MAXILLOFACIAL PROSTHETICS: A NARRATIVE REVIEW

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ABSTRACT

Background: Maxillofacial silicone prosthesis plays a vital role in restoring facial structures and function but lack color stability, mechanical properties, and lifespan. These limitations affect both durability and patient satisfaction.

Objectives: This review highlight recent advancements in silicone elastomer modifications, focusing on nanoparticle incorporation, self-healing system, and multifunctional strategies to improve the longevity, aesthetics, and clinical performance of prosthesis.

Results: Nanoparticle such as silica aerogels, carbon nanotubes, and magnetic nanoparticles enhance optical stability, UV resistance, hydrophobicity, antimicrobial activity, and mechanical strength. Self-healing systems enables crack repair, whereas high-adhesive elastomers, multifunctional coatings, and flexible sensors increase clinical applications. Despite these advantages, standardized testing, long-term in vivo validation, and, biocompatible formulations remains challenging.

Conclusion: Innovations in next-generation silicone elastomers promise durable, adaptive, and patient-centered maxillofacial prostheses. Their successful translation could substantially improve clinical outcomes and patient quality of life.

Keywords*:* silicone elastomers; aerogel; maxillofacial prosthesis; self-healing silicones; nanosilicones

INTRODUCTION

The interdisciplinary field of maxillofacial prosthetics is an integration of maxillofacial surgery and dentistry to address rehabilitation of patients with congenital or acquired defects of head, neck, and face[1]. Defects resulting from trauma, oncologic resection, or developmental anomalies can compromise both functional capacity and psychosocial well-being [2]. Thus, the primary objective of maxillofacial prosthesis is to anatomically restore and reestablish naturally appearing lost structure thereby improving the patient's overall quality of life [3].

Prosthetic materials evolved from waxes, metals, and resins to synthetic polymers, and silicones. Currently, medical grade silicones are the most preferred choice for extraoral applications as they provide consistent coloration, biocompatibility, flexibility, ease of processing, thermal stability, low density, and the ability to replicate human morphology[1,3]. Despite these advantages, the clinical lifespan of silicone prostheses is limited (6 to 24 months), due to degradation from moisture, UV radiation, pollutants, and mechanical fatigue[4]. This limited longevity, combined with low tear resistance, marginal fragility, and pigment leaching, can compromise the durability and aesthetics of the prosthesis over time.

Recent advancements in silicone elastomers through incorporation of nanoparticles, such as titanium dioxide (TiO_2), zinc oxide (ZnO), and silicon dioxide (SiO_2), enhance mechanical and optical properties. These nanoparticles improve UV protection, tear resistance, and resilience to aging[4]. Furthermore, the development of self-healing silicones influences bond strength and reversible network architectures, extending the life of

prostheses while maintaining flexibility and biocompatibility[5]. However, the search of aesthetically appealing, durability, and highly functional single, ideal maxillofacial prosthetic material remains a challenge, emphasizing continuous need for prosthetic material science innovation. This review provides a comprehensive overview of recent developments in medical grade maxillofacial silicone elastomers, highlighting on nano reinforcement, self-healing, and multifunctional integration that enhances prosthetic durability and clinical performance.

Convention vs modified silicone elastomers

Conventional maxillofacial silicones are limited by color instability, mechanical fragility, moisture sensitivity, and lack of self-repair, restricting prosthesis longevity. These limitations are overcome by recent innovations including nano-oxide and hybrid nanocomposites, superhydrophobic silica aerogels, carbon nanotube reinforcements, dynamic self-healing systems, and multifunctional coatings offer significant improvements in durability, aesthetics, and biological performance. (Figure 1)

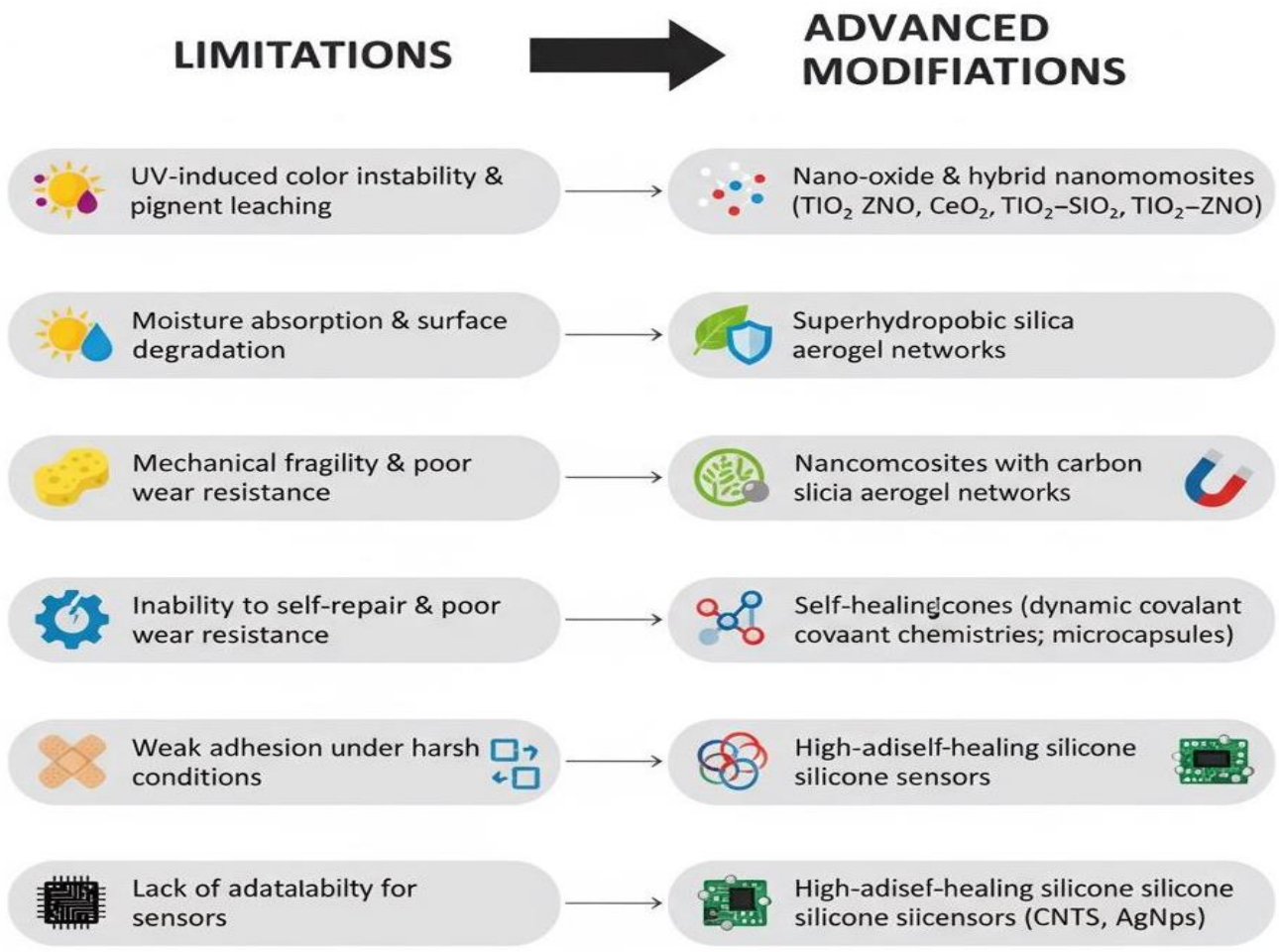

Figure 1. Limitations of conventional maxillofacial silicones and corresponding advanced material modifications

1. Nano-Oxides & Hybrid Nanocomposites

Conventional maxillofacial silicones are prone to color instability due to UV-induced degradation and pigment leaching. To address this, nano-oxide and hybrid nanocomposite systems such as TiO_2, ZnO, CeO_2, TiO_2–SiO_2, and TiO_2–ZnO have been developed, which absorb and scatter UV radiation, stabilize the polymer matrix, protect pigments, provide antimicrobial effects, and extend prosthesis service life beyond 6–12 months while maintaining clinically acceptable color stability.

1.1 Nano-Oxides in UV Protection and Color Stability

Nano-oxides such as TiO_2, ZnO, CeO_2, Al_2O_3, SiO_2, and nanoparticles like polyhedral oligomeric silsesquioxane (POSS) have been incorporated into conventional silicones to enhance color stability, increase durability, and extend service life by absorbing and scattering harmful UV radiation.

Different oxides offer unique benefits:

• TiO_2 provides strong UV blocking but can make the material opaque if too much is used.[6,7]

• ZnO offers transparent UV protection, making it perfect for products that need to match skin tones or stay clear. [8,9]

• CeO_2 is also a great UV absorber and is ideal for applications requiring both protection and clarity.[10]

For better results, a small amount typically 1% to 2.5% is added. Using too much can cause the particles to clump together, which actually reduces their effectiveness. Among these, TiO_2 is the most stable, showing almost no color change over time. ZnO is excellent at preserving pigment colors, while CeO_2 provides effective UV absorption without sacrificing the material's see-through quality. [7,10]

1.2 Hybrid Nanocomposites

Hybrid nanocomposites, including TiO_2–SiO_2 and TiO_2–Al_2O_3, exhibit synergistic improvements in UV shielding, resistance to photo-oxidation, and color retention compared with single-filler systems[11,13]. These multifunctional composites simultaneously provide UV protection, antimicrobial activity, and mechanical reinforcement. Formulations such as TiO_2–ZnO and TiO_2–SiO_2 enhance nanoparticle dispersion, limit photocatalytic degradation, and improve optical stability[10,13].

The incorporation of nano-oxides markedly reduces perceptible color changes, keeping ΔE values within clinically acceptable thresholds (<3.0) and extending prosthesis longevity beyond the typical 6–12 month service period[9,14]. Hybrid nanocomposite systems provide additional advantages by combining UV resistance with antimicrobial functionality, thereby promoting sustained aesthetic performance and enhanced biological safety[7,10].

2. Superhydrophobic Silica Aerogel Networks

Another persistent limitation of conventional silicones often absorb moisture and degrade in humid environments, compromising durability and hygiene. **Superhydrophobic silica aerogel networks** address this by providing self-cleaning ability, extreme water repellence, reduced microbial colonization, improved tear strength, and lightweight properties, making them ideal for delicate periorbital and auricular prostheses.

Silica aerogels are sol–gel-derived nanostructured materials characterized by ultralow density (<0.05 g/cm³), high porosity (90–99% air by volume), large surface area (>1000 m²/g), low thermal conductivity (<0.02 W/mK), and optical translucency. Conventional aerogels synthesized from tetramethoxysilane (TMOS) or tetraethoxysilane (TEOS) are inherently hydrophilic due to surface hydroxyl groups, which compromises their stability in humid environments. Surface modification strategies have been developed to produce hydrophobic aerogels with improved structural stability, moisture resistance, and expanded biomedical applications[15].

Mechanical Reinforcement

Although silica aerogels exhibit remarkable properties such as low density (0.003–0.3 g/cm³), high porosity (>90%), and large specific surface area (200–1200 m²/g), their intrinsic mechanical brittleness limits direct biomedical applications[16]. For maxillofacial prostheses, aerogels are often reinforced or surface-modified to enhance strength and compatibility within silicone elastomers. One effective approach involves molecular cross-linking with polyurethane precursors such as diisocyanates. These react with surface silanol groups (–SiOH), forming urethane linkages that conformally coat the silica network. This process widens interparticle necks, reduces pore collapse, and introduces flexible organic segments, resulting in higher density, reduced hygroscopicity, and significantly improved mechanical strength. Cross-linked aerogels resist cracking during freeze–thaw cycling, remain stable in aqueous environments, and exhibit rupture loads more than 100-fold higher than native silica[17]. When incorporated into maxillofacial silicone matrices, such reinforced aerogels enhance tear strength while maintaining lightweight properties, reducing the prosthesis burden on delicate periorbital and auricular regions.

Surface Properties

Hydrophobicity in silica aerogels can be introduced during synthesis by co-gelling organosilanes such as methyltrimethoxysilane (MTMS) or trimethylethoxysilane (TMES) with TMOS. MTMS introduces $–CH_3$ groups, forming $Si–O–Si–CH_3$ linkages that enhance water resistance. Optimal performance is reported at moderate MTMS/TMOS ratios (~0.7), which balance hydrophobicity and transparency. Higher organosilane content further improves water resistance but compromises optical clarity due to pore enlargement, while post-synthesis surface treatments are comparatively less effective[16]. Superhydrophobic aerogels with extremely high water contact angles (up to 173°) have been synthesized using MTMS precursors[18]. These aerogels exhibit self-cleaning effects by lowering surface energy, thereby reducing microbial colonization and maintenance requirements. Such properties are particularly advantageous for maxillofacial prosthetic devices, where long-term hygiene, durability, and patient comfort are critical[15].

3. Nanocomposites with Carbon Nanotubes (CNT) and Magnetic Nanoparticles

Mechanical fragility and poor wear resistance further limit traditional silicones, often leading to premature failure. This has been countered by nanocomposites with carbon nanotubes and magnetic nanoparticles, which act as structural reinforcers. These composites exhibit high wear resistance, exceptional toughness, and strong antifouling properties, with stable hydrophobicity even after 45,000 abrasion cycles. Additionally, they provide corrosion resistance of the underlying metal prosthesis and durability in extreme pH conditions, broadening their biomedical applicability.

Carbon exists in multiple forms, from carbon black to diamonds, enabling diverse applications. Among these, **CNTs** have attracted attention in dentistry for their exceptional mechanical and functional properties. CNTs reinforce dental materials, serve as scaffolds, and enable targeted drug delivery, showing optimal

performance at ~10 vol% due to efficient load transfer at the CNT–matrix interface.

Beyond mechanical reinforcement, incorporating bioactive materials into CNT-based composites stimulates tissue responses, controls microbial infection, promotes remineralization, reduces inflammation, and supports tissue regeneration, enhancing both clinical performance and biological compatibility[19].

Recent advances in nanocomposite design have demonstrated the potential of combining polyurethane (PU), CNTs, and magnetic nanoparticles (e.g., $NiFe_2O_4$) to produce multifunctional superhydrophobic and superoleophilic materials. Such composites exhibit exceptional liquid repellence, durability, and self-cleaning capacity. A PU–CNT–$NiFe_2O_4$ sponge, for example, achieved water contact angles above 150° and displayed rapid droplet repellence in video observations. These sponges demonstrated high sorption capacities (21–45 g/g) while maintaining mechanical robustness and reusability[20]. At 6 wt% functionalized CNTs (fCNTs), contact angles reached 164–167° with sliding angles below 1°, mimicking lotus-leaf-like repellence. Importantly, these coatings maintained stability under extreme pH conditions, resisted corrosive liquids, and sustained antifouling and self-cleaning performance. The durability was attributed to hierarchical surface roughness generated by papillae, nanofibers, and nanoparticles, combined with low surface energy chemistry[21].

Mechanical Reinforcement

CNTs have consistently demonstrated reinforcement effects in polymer matrices. In fCNT coatings, strong substrate adhesion (grade 1) was achieved through interlocking and crosslinking, while high wear resistance was observed withstanding up to 45,000 abrasion cycles without loss of hydrophobicity (contact angles >140°). The coatings also resisted crack formation during repeated bending and maintained thermal stability up to 400 °C, with degradation initiating beyond 500 °C. In multi-walled CNT (MWCNT) composites, optimal reinforcement occurred at 5 wt% loading, producing a 44% increase in elastic modulus and a 27% increase in hardness. However, higher concentrations (≈10 wt%) led to agglomeration and stress concentration, diminishing performance. These composites have been described as "cement-like" systems, where CNTs act as structural reinforcers[21].

Corrosion Resistance

Modified carbon nanotubes improve the anticorrosive performance of composite films by forming a denser structure that limits solvent and water penetration. Silane-modified CNTs act as molecular bridges, enhancing interfacial bonding and reducing chain mobility, thereby protecting metal or polymer prostheses and dental restorations from chemical attack.[22] fCNT coatings also provide remarkable anticorrosion performance. Corrosion current density was reduced to 6.1×10^{-11} A/cm², corresponding to a protection efficiency of 99.997%. Electrochemical impedance spectroscopy (EIS) confirmed long-term stability, attributed to barrier effects, air-trapped surface roughness, and passive oxide film formation facilitated by conductive fCNT networks [21].

Table 1 summarizes various studies on nanoparticle and nanocomposite modifications in prosthetic materials and highlights the key inferences obtained from each study.

Reference	Type of Modification	Interference from the study
23	Surface-treated SiO_2 nanoparticles (3%) in A-2186 silicone elastomer	Enhanced overall mechanical properties of silicone elastomer.
24	Nanosized TiO_2 and silica particles in A-2000 silicone	Reinforcement did not cause any color degradation during the first 2 months.
25	TiO_2, fumed silica, and silaned silica nanoparticles in commercial silicone elastomer	Found to be nontoxic, indicating safety for prosthesis fabrication.
26	Carbon nanotube-modified titanium plate scaffolds	Showed potential for drug delivery and radiotherapy-support; variable biological responses noted, requiring further in vivo testing.
27	Silicon-substituted hydroxyapatite (Si-HAP) with varying Si content	3 mol% Si found optimal; promoted osteoblast growth, ECM synthesis, and bone mineralization, suitable for orthopaedic and maxillofacial use.
28	Chitosan–TiO_2 nanocomposite incorporated in A-2168 silicone	Improved mechanical properties, tensile/tear strength, and aging resistance; dual nanoparticle system performed better than single fillers.
29	Hydroxyapatite (HA) incorporated in silicone acrylate (SA) network via sol-gel APD technique	Showed high biocompatibility, suitable as alternative biomaterial for soft tissue applications.

Table 1. Studies on nanoparticle and nanocomposite modifications

4. Self-Healing Silicones

Since conventional silicones cannot self-repair when cracks or tears occur, necessitating replacement, self-healing silicones have been developed using dynamic covalent and non-covalent bonding chemistries. Intrinsic systems based on disulfide, imine, hydrogen, or siloxane bonds achieve up to 90–97% recovery of tensile strength, while extrinsic approaches using PDMS-filled microcapsules can restore mechanical integrity on crack formation, although with limited repeatability. These advances dramatically extend the functional lifespan of prostheses.

4.1 Intrinsic self-healing via siloxane bond rearrangements:

Self-healing silicones exploit intrinsic dynamic chemistries that enable the autonomous repair of cracks and damage within the polymer network. Intrinsic self-healing relies on reversible interactions or dynamic bonds incorporated into the polymer backbone, allowing multiple cycles of healing without requiring external reservoirs of healing agents. This strategy is widely employed in elastomers such as polydimethylsiloxane (PDMS), polyurethanes (PU), epoxidized natural rubber (ENR), and polysiloxane-based nanocomposites[21,30]. The following mechanisms underpin intrinsic self-healing in silicones.

Dynamic Covalent Bonds

Dynamic covalent bonds including disulfide, imine, thiourethane, boronic ester, boroxine, and Diels–Alder (DA) adducts can reversibly break and reform under specific stimuli, such as heat, light, or chemical triggers. For instance, PDMS elastomers incorporating furan–maleimide DA adducts exhibited self-healing efficiencies up to 92.3% following thermal treatment (130 °C for 10 min and 80 °C for 48 h), although higher crosslink densities restricted chain mobility and reduced subsequent healing cycles[31]. Dual disulfide–imine networks in PDMS and PU demonstrated room-temperature healing with complete crack closure under heat or UV irradiation; however, tensile strength recovery can be limited due to restricted molecular mobility arising from high bond energies[30].

Non-Covalent Interactions

Non-covalent self-healing systems exploit reversible interactions of lower bond energy, including hydrogen bonding, ionic interactions, metal–ligand coordination, π–π stacking, van der Waals forces, and host–guest chemistry. Such interactions facilitate healing at ambient conditions due to facile bond reformation. For example, PDMS elastomers featuring Fe(III)–2,6-pyridinedicarboxamide coordination networks demonstrated healing at temperatures as low as −20 °C and could sustain strains up to 4500%[32]. Hydrogen-bonded networks, often combined with complementary interactions in PU or polyimide elastomers, achieved healing efficiencies exceeding 90% with moderate tensile strength. Dual ionic–hydrogen bond networks in natural rubber and carboxylated SBR reached up to 92% efficiency, offering enhanced mechanical robustness[30].

Dynamic Siloxane Bonds

Siloxane (Si–O–Si) bonds are inherently dynamic under catalysis, enabling intrinsic self-healing, recycling, and reprocessing without additional functionalization. Early studies on living PDMS networks prepared via anionic equilibration reported effective thermal self-healing at 90 °C, with fracture toughness comparable to pristine elastomers (~70 J/m²)[19]. Catalysts such as silanolate groups, fluoride ions, organic bases (e.g., TBD, P4tBu), and Brønsted or Lewis acids accelerate bond exchange, producing vitrimer-like behavior with stress relaxation, shape memory, and reprocessability[32]. Notably, PDMS elastomers incorporating F^--encapsulating germoxane cages achieved repeatable healing cycles under humid conditions, combining extrinsic-like controlled release with intrinsic bond dynamics[33].

Stimuli-Responsive Intrinsic Systems

Intrinsic self-healing can be triggered by external stimuli to facilitate bond rearrangements. For instance, CO_2 exposure temporarily weakens ionic crosslinks in PDMS, enabling rapid chain mobility and subsequent healing, with original mechanical strength restored upon air replacement[32]. Light-activated systems employing diselenide or ditelluride exchanges allow room-temperature or visible-light-triggered repair. Thermal activation remains common in DA or disulfide networks, typically between 60–130 °C, balancing healing efficiency and mechanical recovery[30,31].

Hybrid Covalent–Non-Covalent Systems

Hybrid networks that combine covalent and non-covalent interactions provide a favorable balance between mechanical robustness and healing efficiency. PU elastomers featuring disulfide–hydrogen bond networks achieved up to 97% healing efficiency at room temperature while maintaining moderate tensile strength. Similarly, DA adducts combined with hydrogen bonds in PDMS-based elastomers recovered up to 96% of tensile stress, whereas boroxine–hydrogen bond dual networks in ENR maintained 91% healing efficiency over multiple cycles at room temperature. The primary challenge in hybrid systems is achieving room-temperature healing without sacrificing mechanical strength, as many rely on elevated temperatures (>60 °C) to activate covalent bond reversibility.[30]

4.2 Extrinsic microcapsule approaches:

Extrinsic self-healing strategies rely on the incorporation of external healing agents within the polymer matrix, which are released upon mechanical damage to repair cracks or defects. Inspired by biological systems in which localized repair is triggered by injury, extrinsic approaches differ from intrinsic mechanisms in that the healing agents are finite and stored externally.

A widely studied example in silicone elastomers involves embedding urea–formaldehyde microcapsules containing PDMS precursors and catalysts. Upon crack

formation, these microcapsules rupture, releasing the encapsulated components, which undergo hydrosilylation reactions to restore the mechanical integrity of the polymer. In PDMS-based systems, this mechanism has been shown to recover over 70% of the original tear strength at room temperature within 48 h; however, repeated healing at the same location is not possible due to depletion of the encapsulated agents[32].

To enhance control over healing and enable multiple cycles, hybrid extrinsic–intrinsic systems have been developed. For instance, fluoride ions (F^-) encapsulated in molecular cages, such as polyhedral oligomeric silsesquioxane (POSS) or germoxanes, can catalyze siloxane bond rearrangements upon release. These systems demonstrated approximately 72% healing efficiency under humid conditions, effectively combining the controlled release of healing agents with intrinsic dynamic chemistry[33]. Nevertheless, challenges remain, including uncontrolled bond rearrangements, formation of volatile by-products, and limitations associated with mechanical integrity.

Despite these advancements, conventional extrinsic self-healing systems are constrained by several factors: reduced transparency due to microcapsule incorporation, limited repeatability of healing cycles, and potential compromise of network continuity, which can decrease overall mechanical performance.

5. High-adhesion self-healing silicones:

Another challenge is weak adhesion and reduced reliability under harsh conditions, which is addressed by high-adhesion self-healing silicones. These advanced elastomers exhibit strong and tunable adhesion across metals and polymers, maintain performance under acidic, alkaline, or saline conditions, and demonstrate repeatable healing. Their adhesion strength, far exceeding commercial sealants, ensures secure retention and improved clinical outcomes.

High-adhesive self-healing silicones combine dynamic bonding networks with intrinsic hydrophobicity, enabling strong adhesion and autonomous repair under diverse and harsh conditions.

PDMS-Based Dynamic Silicone Elastomers

Dynamic PDMS elastomers with hydrogen, imine, and disulfide bonds exhibit tunable adhesion from 42.8 kPa on polypropylene to 485 kPa on paper. Adhesion remains robust under acidic (85.2%), alkaline (83.7%), saline (80.5%), petroleum ether (78.3%), and aqueous (83.2%) conditions. Thermal stability is high at low temperatures (985 kPa at −20 °C) but decreases at elevated temperatures (4.1 kPa at 80 °C). Strong adhesion is observed on metals (Cu, Fe, Al) and non-metals (paper, PI, PLA, PP, glass), outperforming commercial silicone sealants while maintaining mechanical strength and elongation[34].

Autonomous Self-Healing ASHA-C1 Elastomers

ASHA-C1 elastomers exhibit high elasticity (elongation >1000–2000%) and robust cyclic recovery (≈83% after ten cycles). Self-healing efficiency depends on poly(BCOE) content, with 30–50 wt% enabling full toughness recovery at 20 °C within 2 days, faster at 40 °C and slower at 0 °C. Healing is repeatable under water immersion, and post-healing adhesion retains ~57% of the original strength, limited mainly by substrate interface detachment[35].

Thermo-Reversible UPy-Functionalized Silicones

UPy-functionalized silicones allow remotely controlled, thermo-reversible self-healing. Cuts fully recover tensile strength and elongation at 70 °C, partially at 55 °C ($\eta\varepsilon = 56\%$, $\eta\sigma = 66\%$), and do not heal at room temperature. Incorporation of 20 wt% magnetic particles enables AMF-induced localized heating, improving healing efficiencies to $\eta\varepsilon = 78\%$ and $\eta\sigma = 70\%$ within 12 h at 40 °C. SEM analysis confirms complete interface closure, and recyclability is preserved after repeated solvent casting [36].

6. Flexible Self-Healing Silicone Sensors

Beyond structural reinforcement, traditional silicones also lack adaptability for modern sensing applications. To bridge this gap, flexible self-healing silicone sensors have emerged. These materials combine stretchability exceeding 2000% with rapid self-repair and electrical conductivity when filled with CNTs or silver nanoparticles. They function as strain and pressure sensors for monitoring pulse, speech, or swallowing, all while being re-healable and recyclable, opening new avenues for bio-integrated prosthetics.

Flexible self-healing silicone materials (SHSMs) have emerged as promising candidates for next-generation sensors due to their inherent self-healability, stretchability, and durability, making them suitable for wearable electronics, electronic skins, and soft robotics [37,38].

6.1 Flexible Strain Sensors

Strain sensors detect mechanical stress or deformation and are extensively used in wearable electronics for monitoring human motion, such as finger and elbow bending. SHSMs provide the necessary combination of stretchability, durability, and high sensitivity for effective performance.

Hydrogen-Bonded Networks: Self-healing elastomers with quadruple hydrogen bonding exhibit stretchability up to 2000%, high durability, and precise motion sensing in multilayer strain sensor designs[39].

Dynamic Covalent and Boronic Ester Networks: Hierarchical siloxane elastomers with reversible disulfide and boronic ester bonds achieve ultrafast self-healing and self-adhesion, with tensile strengths of 0.43 MPa, elongation of 1500%, and full strength recovery within 30 s at room temperature[40,41].

Microphase-Separated Elastomers: Transparent, recyclable elastomers with disulfide and hydrogen bonds demonstrate tensile strengths of 1.89–3.33 MPa, elongation of 350–1720%, and fracture toughness up to 28.6 $MJ \cdot m^{-3}$. “Sandwich-structured” sensors fabricated from these materials can be cut, healed, and reused without loss of functionality[37].

Conductive Nanocomposites: Electrical conductivity is achieved by incorporating fillers such as MWCNTs, CFCNTs, and AgNPs. Bilayer sensors combining ionically cross-linked polysiloxane and conductive fillers exhibit high gauge factors (up to 5536), strong self-adhesion, and excellent durability, with healing efficiencies up to 98%[42,43].

6.2 Flexible Pressure Sensors

Piezoresistive self-healing pressure sensors are critical for soft robotics, wearable health monitoring, and electronic skins[37,38].

Conductive Silicone Elastomers (CSEs): Films with microstructured surfaces show high sensitivity (8.7 kPa^{-1}), low detection limits (50 Pa), fast response/relaxation (40/117 ms), and long-term repeatability (>10,000 cycles). These sensors can monitor human motion, including pulse, voice, and joint movement, with wireless capability[43].

Thermal Self-Healing Elastomers: Hyperbranched polysiloxane elastomers with Diels–Alder chemistry achieve tensile strengths of 0.87 MPa and ~85% self-healing efficiency upon thermal treatment. Conductive fillers enhance electrical performance but may reduce mechanical strength and healing efficiency[38].

Room-Temperature Self-Healing Systems: Polysiloxanes crosslinked via dynamic acid–amine interactions in bilayer conductive sensors achieve gauge factors of 33.99 at 55% strain, strong self-adhesion, and long-term durability, suitable for monitoring subtle physiological signals such as coughing and swallowing[38].

Multi-Dynamic Bonding Approaches: Elastomers crosslinked via disulfide, imine, and hydrogen bonds exhibit 91% healing efficiency, elongation at break of 672%, tensile strength of 1.41 MPa, gauge factor of 24.1, fast response (120 ms), and long-term stability over 4000 cycles, making them ideal for wearable electronics[38].

Table 2 summarizes various studies on flexible pressure and strain sensor modifications and highlights the key inferences obtained from each study.

Reference	Type of Modification	Interference from the study
44	Smart face mask with pressure and temperature sensor	Enabled real-time monitoring of 8 breathing patterns; distinguished oral vs. nasal breathing; high sensitivity and skin-conformal for comfortable wear.
45	Strain/pressure sensor: soft, conformal, stretchable electrodes integrated with HCI-based biofeedback system	High-fidelity EMG recording for swallowing; excellent stretchability (>100%) and bendability (up to 180°); reduced motion artifacts; suitable for dysphagia rehabilitation.
46	Flexible strain sensor: ionic conductive hydrogel (PVA + borax + silk fibroin + tannic acid)	Self-healing, adhesive, stretchable, and biocompatible; sensitive to both large (joints) and small (facial expressions, breathing) strains; stable electrical and mechanical performance; suitable for wearable strain sensors.

Table 2. Studies on flexible pressure and strain sensor modifications

6.3 Actuator

Recent actuator developments focus on self-healing (SH) dielectric elastomers with high strain, energy density, and tunable electromechanical properties. These include Fe(III)-coordinated SHSMs with ultrahigh stretchability (10,000%) for artificial muscles, thermo-reversible triblock copolymer with high dielectric permittivity, self-healing via Diels–Alder bonds, and shape memory (>90% recovery)[47]; PDMS/Fe_3O_4 SH nanocomposites for magnetic actuation[48]; dielectric elastomer generators with healable conductive rubber electrodes enabling artificial muscle applications[49]; and SH silicone elastomers with tunable permittivity, enabling recyclable actuators showing 3.8–5.4% strain, suitable for soft robotics[50].

7. Advanced Coatings and Micro/Nanocapsule-Integrated Silicones

Finally, conventional silicones are vulnerable to fouling, corrosion, and biofilm formation, reducing their longevity. This has been mitigated by advanced coatings and micro/nanocapsule-integrated silicones, which release antifouling or anticorrosion agents in response to environmental triggers such as pH, ions, or pressure. These intelligent systems not only extend prosthesis service life but also enhance biological safety and multifunctionality in biomedical settings.

Micro-/nanocapsule technologies:

Microcapsule-integrated coatings (MICs) exhibit diverse functionalities due to microcapsule incorporation, enabling intelligent responses in complex environments. Their emerging applications include anti-corrosion, anti-fouling, self-lubrication, and temperature regulation.

For anti-corrosion, MICs encapsulate inorganic or organic inhibitors such as cerium nitrate, BTA, and 8-HQ, which are released under pH, ion, or pressure triggers to form protective films, enable self-healing, and provide corrosion sensing of the underlying metallic structure, significantly extending material lifespan. In anti-fouling applications, MICs prevent bacterial, biofilm, and scale adhesion by releasing agents like capsaicin, or iodine-loaded microparticles, offering controlled, environment-responsive protection in medical settings. Overall, MICs provide intelligent, durable, and multifunctional coatings with potential for

industrial and biomedical applications, though scalability and biocompatibility remain key challenges[51].

Table 3 provides a comprehensive compilation of various modifications in silicone-based prostheses, detailing the materials used, their functional properties, and corresponding applications.

Category	Materials	Functional	Application
Nano-Oxides & Hybrid Nanocomposites	TiO_2, ZnO, CeO_2; TiO_2–SiO_2, TiO_2–ZnO	UV protection, pigment stabilization, antimicrobial, enhanced nanoparticle dispersion	Prolonged color stability and prosthesis longevity
Superhydrophobic Silica Aerogel Networks	Surface-modified silica aerogels	Water repellence, self-cleaning, reduced microbial colonization, enhanced tear strength	Lightweight, durable prosthesis
Nanocomposites with CNTs & Magnetic Nanoparticles	MWCNTs, $NiFe_2O_4$, magnetic nanoparticles	Structural reinforcement, high wear resistance, antifouling, corrosion resistance	Mechanically robust, durable prostheses
Self-Healing Silicones	Dynamic covalent/non-covalent bonds; PDMS microcapsules	Intrinsic healing, extrinsic repair; extended functional lifespan	Crack/self-repairing prostheses
High-Adhesion Self-Healing Silicones	Dynamic bonding networks	Strong/tunable adhesion, stable under harsh environments, repeatable healing	Secure retention and improved clinical outcomes
Flexible Self-Healing Silicone Sensors	H-bonded, dynamic covalent/boronic ester, CNT/AgNP composites	Stretchability, rapid self-repair, conductivity, strain/pressure sensing	Wearables, electronic skins, bio-integrated prostheses
Advanced Coatings & Micro/ Nanocapsules	MICs with antifouling/anticorrosion agents	Triggered release, multifunctionality, extended service life	Enhanced hygiene, corrosion protection, biomedical applications

TABLE 3. MODIFICATIONS IN SILICONE-BASED PROSTHESES, THEIR FUNCTIONAL PROPERTIES, AND APPLICATIONS

CONCLUSION

Maxillofacial prosthetics face ongoing challenges of color instability, mechanical fragility, and limited longevity. Advances in nanotechnology, surface engineering, and smart polymer chemistry such as nano-oxide and hybrid nanocomposite incorporation, silica aerogels, carbon nanotubes, and self-healing silicones have improved UV resistance, durability, hydrophobicity, and autonomous repair, enhancing both esthetics and clinical lifespan. High-adhesion systems and multifunctional coatings further expand applicability in prosthetic rehabilitation and bio-integrated sensors. However, clinical translation requires careful optimization of biocompatibility, scalability, and long-term stability. Future efforts should focus on standardized testing, in vivo validation, and integration of multifunctional properties to develop prostheses that are durable, adaptive, and patient-centered, leveraging the convergence of nanotechnology and self-healing chemistry.

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Competing interests

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REFERENCES

1. Gradinariu AI, Racles C, Stoica I, Stelea CG, Simionescu AA, Jehac AE, Costan VV. Silicones for Maxillofacial Prostheses and Their Modifications in Service. Materials (Basel). 2024 Jul 4;17(13):3297.
2. Karaman G, Altıntaş E. Investigation of the effects of different nanoparticle additionals on the mechanical properties of silicone elastomer used in maxillofacial prosthesis. J Health Sci Med 2022; 5(6): 1654-1660
3. Mitra A, Choudhary S, Garg H, H G J. Maxillofacial prosthetic materials- an inclination towards silicones. J Clin Diagn Res. 2014 Dec;8(12):ZE08-13
4. Radey NS, Al Shimy AM, Ahmed DM. Effect of extraoral aging conditions on mechanical properties of facial silicone elastomer reinforced with titanium-oxide nanoparticles (in vitro study). Alexandria Dental Journal. 2020 Dec 1;45(3):29-36.

5. Bishal AK, Wee AG, Barão VA, Yuan JC, Landers R, Sukotjo C, Takoudis CG. Color stability of maxillofacial prosthetic silicone functionalized with oxide nanocoating. The Journal of Prosthetic Dentistry. 2019 Mar 1;121(3):538-43.
6. Mohan AS, Manju V, Babu AS, Krishnapriya V. Effect of particle size of nano-oxides on color stability and mechanical properties of maxillofacial silicone elastomers: an in vitro study. Int J Prosthodont. 2021 Jan 1;34:54-60.
7. Gupta P, Deshpande S, Radke U, Ughade S, Sethuraman R. The color stability of maxillofacial silicones: A systematic review and meta analysis. The Journal of Indian Prosthodontic Society. 2021 Apr 1;21(2):138-49.
8. Charoenkijkajorn D, Sanohkan S. The effect of nano zinc oxide particles on color stability of MDX4-4210 silicone prostheses. European Journal of Dentistry. 2020 Oct;14(04):525-32.
9. Hatamleh MM. Color Stability of Digital and Conventional Maxillofacial Silicone Elastomers Mixed with Nano-Sized Antimicrobials: An In Vitro Study. Prosthesis. 2025 Aug 5;7(4):96.
10. Sonnahalli NK, Chowdhary R. Effect of nanoparticles on color stability and mechanical and biological properties of maxillofacial silicone elastomer: A systematic review. The Journal of Indian Prosthodontic Society. 2020;20(3):244-54.
11. Rashid F, Barman A, Farook TH, Jamayet NB, Yhaya MF, Alam MK. Factors affecting color stability of maxillofacial prosthetic silicone elastomer: A systematic review and meta-analysis. Journal of Elastomers & Plastics. 2021 Oct;53(6):698-754.
12. Al-Kadi FK, Abdulkareem JF, Azhdar BA. Hybrid chitosan–TiO2 nanocomposite impregnated in type A-2186 maxillofacial silicone subjected to different accelerated aging conditions: An evaluation of color stability. Nanomaterials. 2023 Aug 20;13(16):2379.
13. Bunyan SF, Suhaimi FM, Zardawi FM, Noor SN, Zabidi MA. The Effect of Hybrid Nano Addition on the Color Stability of Maxillofacial Rehabilitation Silicone Material after Weathering. Medical Journal of Babylon. 2024 Nov 1;21(Suppl 2):S288-96.
14. Cifter ED, Ozdemir-Karatas M, Cinarli A, Sancakli E, Balik A, Evlioglu G. In vitro study of effects of aging and processing conditions on colour change in maxillofacial silicone elastomers. BMC Oral Health. 2019 Jun 19;19(1):122.
15. Anderson AM, Carroll MK. Hydrophobic silica aerogels: review of synthesis, properties and applications. Aerogels handbook. 2011 Mar 28:47-77.
16. Pierre AC, Pajonk GM. Chemistry of aerogels and their applications. Chemical reviews. 2002 Nov 13;102(11):4243-66.
17. Leventis, N., Sotiriou-Leventis, C., Zhang, G., & Rawashdeh, A.M.M. (2011). Nanoengineering strong silica aerogels. *Nano Letters*, 2(9), 957–960.
18. Rao AV, Kulkarni MM, Amalnerkar DP, Seth T. Superhydrophobic silica aerogels based on methyltrimethoxysilane precursor. Journal of Non-Crystalline Solids. 2003 Nov 15;330(1-3):187-95.
19. Castro-Rojas MA, Vega-Cantu YI, Cordell GA, Rodriguez-Garcia A. Dental applications of carbon nanotubes. Molecules. 2021 Jul 22;26(15):4423.
20. Kudaibergenova RM, Roman FF, Silva AS, Sugurbekova GK. Carbon-Nanotube-Based superhydrophobic magnetic nanomaterial as absorbent for rapid and efficient Oil/Water separation. Nanomaterials. 2024 Dec 3;14(23):1942.
21. Elbakyan L, Zaporotskova I. Composite nanomaterials based on polymethylmethacrylate doped with carbon nanotubes and nanoparticles: a review. Polymers. 2024 Apr 29;16(9):1242.
22. Hao G, Li X, Wang S, Wang S, Ryu M, Yang J. Surface modification of carbon nanotubes in silicone–polyurethane for improved mechanical and anticorrosion properties. Coatings. 2023 Mar 17;13(3):634.
23. Zayed SM, Alshimy AM, Fahmy AE. Effect of surface treated silicon dioxide nanoparticles on some mechanical properties of maxillofacial silicone elastomer. International journal of biomaterials. 2014;2014(1):750398.
24. Cevik P. Effects of the addition of titanium dioxide and silaned silica nanoparticles on the color stability of a maxillofacial silicone elastomer submitted to artificial aging. Cumhuriyet Dental Journal. 2016 Jan 3;19(1):9-15.
25. Akay C, Cevik P, Karakis D, Sevim H. In vitro cytotoxicity of maxillofacial silicone elastomers: Effect of nano-particles. Journal of Prosthodontics. 2018 Jul;27(6):584-7.
26. Hudecki A, Łyko-Morawska D, Likus W, Skonieczna M, Markowski J, Wilk R, Kolano-Burian A, Maziarz W, Adamska J, Łos MJ. Composite nanofibers containing multiwall carbon nanotubes as biodegradable membranes in reconstructive medicine. Nanomaterials. 2019 Jan 4;9(1):63.
27. Balamurugan A, Rebelo AH, Lemos AF, Rocha JH, Ventura JM, Ferreira JM. Suitability evaluation of sol–gel derived Si-substituted hydroxyapatite for dental and maxillofacial applications through in vitro osteoblasts response. Dental Materials. 2008 Oct 1;24(10):1374-80.
28. Al-Kadi FK, Adbulkareem JF, Azhdar BA. Evaluation of the mechanical and physical properties of maxillofacial silicone type A-2186 impregnated with a hybrid chitosan–TiO2 nanocomposite subjected to different accelerated aging conditions. Biomimetics. 2023 Nov 11;8(7):539.
29. Sani NS, Malek NA, Jemon K, Kadir MR, Hamdan H. Preparation and characterization of hydroxyapatite

incorporated silica aerogel and its effect on normal human dermal fibroblast cells. Journal of Sol-Gel Science and Technology. 2019;90(2):422-33.
30. Utrera-Barrios S, Verdejo R, López-Manchado MA, Santana MH. Evolution of self-healing elastomers, from extrinsic to combined intrinsic mechanisms: A review. Materials Horizons. 2020;7(11):2882-902.
31. Yan Q, Zhao L, Cheng Q, Zhang T, Jiang B, Song Y, Huang Y. Self-healing polysiloxane elastomer based on integration of covalent and reversible networks. Industrial & Engineering Chemistry Research. 2019 Oct 31;58(47):21504-12.
32. Hayashi T, Shimojima A. Self-healing materials based on dynamic properties of siloxane networks. Journal of Sol-Gel Science and Technology. 2025 Apr 7:1-5.
33. Zheng P, McCarthy TJ. A surprise from 1954: siloxane equilibration is a simple, robust, and obvious polymer self-healing mechanism. J Am Chem Soc. 2012 Feb 1;134(4):2024-7.
34. Dai S, Li M, Yan H, Zhu H, Hu H, Zhang Y, Cheng G, Yuan N, Ding J. Self-healing silicone elastomer with stable and high adhesion in harsh environments. Langmuir. 2021 Nov 10;37(46):13696-702.
35. Zhang Z, Ghezawi N, Li B, Ge S, Zhao S, Saito T, Hun D, Cao PF. Autonomous self-healing elastomers with unprecedented adhesion force. Advanced Functional Materials. 2021 Jan;31(4):2006298.
36. Ogliani E, Yu L, Javakhishvili I, Skov AL. A thermo-reversible silicone elastomer with remotely controlled self-healing. RSC advances. 2018;8(15):8285-91.
37. Deriabin KV, Filippova SS, Islamova RM. Self-healing silicone materials: Looking back and moving forward. Biomimetics. 2023 Jul 3;8(3):286.
38. Kowalewska A, Majewska-Smolarek K. Synergistic self-healing enhancement in multifunctional silicone elastomers and their application in smart materials. Polymers. 2024 Feb 9;16(4):487.
39. Yu T, Shan Y, Li Z, Wang X, Cui H, Yang K, Cui Y. Application of a super-stretched self-healing elastomer based on methyl vinyl silicone rubber for wearable electronic sensors. Polymer Chemistry. 2021;12(42):6145-53.
40. Zhang K, Wang Z, Liu Y, Zhao H, Gao C, Wu Y. Cephalopods-inspired repairable MWCNTs/PDMS conductive elastomers for sensitive strain sensor. Chinese Journal of Polymer Science. 2022 Apr;40(4):384-93.
41. Tang M, Li Z, Wang K, Jiang Y, Tian M, Qin Y, Gong Y, Li Z, Wu L. Ultrafast self-healing and self-adhesive polysiloxane towards reconfigurable on-skin electronics. Journal of Materials Chemistry A. 2022;10(4):1750-9.
42. Mai D, Mo J, Shan S, Lin Y, Zhang A. Self-healing, self-adhesive strain sensors made with carbon nanotubes/polysiloxanes based on unsaturated carboxyl–amine ionic interactions. ACS Applied Materials & Interfaces. 2021 Oct 11;13(41):49266-78.
43. Yang Z, Li H, Li C, Lai X, Zeng X. Conductive and room-temperature self-healable polydimethylsiloxane-based elastomer film with ridge-like microstructure for piezoresistive pressure sensor. Chemical Engineering Journal. 2022 Feb 15;430:133103.
44. Pang Z, Zhao Y, Luo N, Chen D, Chen M. Flexible pressure and temperature dual-mode sensor based on buckling carbon nanofibers for respiration pattern recognition. Scientific reports. 2022 Oct 19;12(1):17434.
45. Lee Y, Nicholls B, Sup Lee D, Chen Y, Chun Y, Siang Ang C, Yeo WH. Soft electronics enabled ergonomic human-computer interaction for swallowing training. Scientific Reports. 2017 Apr 21;7(1):46697.
46. Zheng H, Lin N, He Y, Zuo B. Self-healing, self-adhesive silk fibroin conductive hydrogel as a flexible strain sensor. ACS Applied Materials & Interfaces. 2021 Aug 10;13(33):40013-31.
47. Feng Z, Guo J, Cao X, Feng G, Chen Z, Zhang XH. A thermo-reversible furfuryl poly (thioether)-b-polysiloxane-b-furfuryl poly (thioether) triblock copolymer as a promising material for high dielectric applications. Polymer Chemistry. 2022;13(10):1376-86.
48. Tao HQ, Yue DW, Li CH. A Fast Self-Healing Magnetic Nanocomposite for Magnetic Actuators. Macromolecular Materials and Engineering. 2022 Feb;307(2):2100649.
49. Zang W, Liu X, Li J, Jiang Y, Yu B, Zou H, Ning N, Tian M, Zhang L. Conductive, self-healing and recyclable electrodes for dielectric elastomer generator with high energy density. Chemical Engineering Journal. 2022 Feb 1;429:132258.
50. von Szczepanski J, Danner PM, Opris DM. Self-Healable, Self-Repairable, and Recyclable Electrically Responsive Artificial Muscles. Advanced Science. 2022 Aug;9(22):2202153.
51. Zhao Y, Cheng X, Zhao R, Li X, Meng J, Wang S. Recent Advances of Microcapsule-based Intelligent Coatings: From Bioinspired Designs, Material Selections, to Potential Applications. Advanced Science. 2025 Jul 28:e06557.