Compression Molding and Nickel Molds for Directional Gecko-Inspired Adhesives

Capella F. Kerst[1]
Department of Mechanical Engineering,
Stanford University,
Stanford, CA 94305
e-mail: ckerst@stanford.edu

Mark R. Cutkosky
Professor
Fellow ASME
Department of Mechanical Engineering,
Stanford University,
Stanford, CA 94305

In the fabrication of directional gecko-inspired adhesives, a new capability made possible by the availability of metal molds is hot compression molding. This molding process allows the use of elastomers with much higher toughness than those cast at ambient temperature and pressure, as has been the common case in fabricating adhesives. In addition, it permits fast cycle times (minutes instead of hours), which is useful for volume manufacturing. We present the results of hot compression molding of elastomers in metal molds created with overhanging and tapered microscopic surface features, which give rise to anisotropic adhesion. We show that the adhesive performance so obtained is equivalent to that obtained earlier with polydimethylsiloxane (PDMS). [DOI: 10.1115/1.4051139]

1 Introduction

Numerous synthetic dry adhesives and associated fabrication methods have been proposed; reviews include [1–7]. In the majority of cases, the adhesive materials are fabricated by casting polymers in a mold. A particularly common choice for such materials is to use an elastomer such as silicone rubber (e.g., polydimethylsiloxane (PDMS)) or urethane. The choice of elastomer represents a tradeoff: it should be soft enough to conform to surfaces for a large real area of contact but stiff enough to prevent self-sticking or "clumping" and to avoid rapidly becoming fouled with dirt [8,9]. In addition it should ideally be tough, i.e., resistant to tearing and abrasion. A relatively common choice among researchers is Dow Corning Sylgard 170 or 184 PDMS, cast at ambient temperature and pressure, with curing potentially accelerated using an oven.

When considering elastomeric products such as medical products and cooking utensils, the silicone elastomers used (e.g., NuSil MED series) are considerably tougher than PDMS. These silicones are typically far too viscous for casting microscopic features without added heat and pressure. This requirement in turn argues for the use of a durable metal mold. An additional benefit of using a metal mold and hot compression or injection molding is that the cycle time can be relatively fast: of the order of minutes instead of hours or days.

The need to achieve fast curing for producing adhesives in quantity has been recognized previously in the literature, with reported examples using UV-cured polymers and roll-to-roll manufacturing for nondirectional adhesives with a polymeric mold [10,11].

The use of injection molding and compression molding with microscopic features is well established for products other than gecko-inspired adhesives. Relevant reviews include [12,13]. Many of these products (e.g., Refs. [14–16]) have a smaller overall dimension that the desired mold size for fabricating adhesives, which makes microinjection molding attractive for them. For adhesives, the relatively flat overall geometry makes compression molding attractive. In addition, one does not need to apply a vacuum as in some microinjection molding processes [17–19]. One concern, however, is that the high pressures involved could damage a fragile mold or a component such as a fabric or plastic backing that is inserted along with the elastomeric material prior to compression.

The particular motivation for the present work is to produce strongly directional adhesives that produce little adhesion unless loaded in a particular direction. The design and performance of these adhesives has been described in detail in previous work [20–22]. The adhesive microstructures consist of thin, angled, and tapered wedges that produce a profile with overhanging sections, as seen in Fig. 1. These features present a manufacturing challenge for creating a durable mold. In the present case, we use a mold described recently in Ref. [23] that involves creating a metal replica from a micromachined wax master. The mold was demonstrated to withstand many casting cycles without degradation using PDMS as the cast material. In this technical brief we present a molding process for using elastomers designed for hot compression molding. We also demonstrate that the adhesion obtained with these much tougher elastomers is comparable to that obtained previously with PDMS.

2 Elastomers for Molded Adhesives

Silicone rubbers come in a wide range of durometers, tear strengths, and viscosities prior to curing. Concerning durometer, the elastomer needs to strike a balance between being soft enough to conform to local surface irregularities but stiff enough to prevent self-sticking or "clumping" [8]. For adhesives based on microwedges [20,24] and similar structures, good results have been obtained with materials such as PDMS (Sylgard 170; Dow Corning, Inc., Midland, MI), Dragon Skin 30 and Mold Star 30 (Smooth-On Polymers, Inc.) and with some space-qualified RTV silicones (e.g., SCV2-2590) [24]. All of these silicones have a durometer in the range of 30–50 Shore A. If we are looking for a more durable replacement material while keeping approximately the same size and profile of the microscopic features we should begin with something of similar durometer.

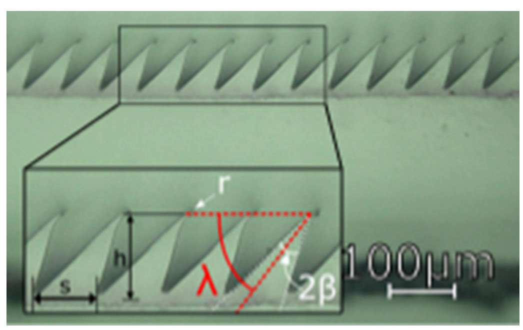

Fig. 1 The upper microscopic cross section shows microwedges of NuSil MED4950 created by hot compression molding. For comparison, the lower image shows wedges of Syglard 170 with a kapton film backing, cast from a wax mold. The images were taken on the Keyence VHX-6000 with magnification 200×, darkfield "ring" lighting. Parameters: $s = 50\,\mu m$ is the spacing between adjacent wedges; $h = 90\,\mu m$ is the wedge height; $r \approx 1\,\mu m$ is the tip radius; $\lambda = 60$ deg is the angle of inclination; $\beta = 7.5$ deg is the wedge half angle.

[1]Corresponding author.

Contributed by the Manufacturing Engineering Division of ASME for publication in the Journal of Micro- and Nano-Manufacturing. Manuscript received November 8, 2020; final manuscript received May 4, 2021; published online June 17, 2021. Assoc. Editor: Takashi Matsumura.

A second concern is the viscosity. The castable elastomer needs to have a low viscosity to entirely fill deep cavities (e.g., as seen in Fig. 1), which has lead several groups including [25–27] to use materials like Sylgard 170, which has a viscosity of 3,000 cP as compared to other elastomers of similar durometer such as Mold Star 30 (Smooth-on polymers), which has a viscosity of 12,500 cP and which, in the authors' experience, requires no added pressure to completely fill the mold.

In comparison to elastomers designed for mixing and casting under ambient conditions, there are a number of medical grade silicone elastomers with comparable stiffness, but substantially higher tear strength (e.g., NuSil MED4950 [28]). A few of these are listed in Table 1. These elastomers are not suitable of casting at ambient temperature and pressure because they have the consistency of dough or putty. A question addressed in this study was whether, with hot compression molding, they could completely fill the deep grooves that produce the $r \approx 1 \mu m$, tip radius seen on the wedges in Fig. 1. A successful molding process is described in Sec. 2.1.

2.1 Compression Mold Fabrication Process. The main steps of creating the adhesive patch through compression molding are illustrated in Fig. 2; labels A, B, etc. Correspond to the paragraphs below.

2.1.1 Setup and Preparation. The process starts with mixing the two-part material either in a mixing gun or by hand. The uncured materials have the consistency of putty, and one can use a folding and layering technique as used by bakers for making pastry dough. This operation alternates with rolling the mixture into thin sheets using a roller. For the manual process, after ≈20 cycles of folding and rolling, the material is ready to roll into its final dimensions (76 × 127 mm, 1 mm thick) for placing into the center of the mold. The mold area with microwedges is slightly larger at 101 × 152 mm.

A backing layer, typically of kapton film (20–50 μm thick), or a thin fiberglass fabric, or a silicone-coated nylon fabric (e.g., Silnylon), is placed atop the rolled material, depending on the final intended application. This material needs to be highly flexible, comparatively inextensible, and strong enough to withstand the radial shear stress pattern during molding. It will become part of the final adhesive product.

The resulting assembly is sandwiched between two aluminum plates, ≈2.5 mm thick, and placed into a heated hydraulic press.

2.1.2 Pressing. The hydraulic press is preheated and held at 100 °C. The pressing must be done fairly quickly to ensure that material does not cure before being pressed into the features. The platens apply a pressure of 3.4 MPa to ensure full penetration into the narrow mold cavities.

2.1.3 Curing. The pressure and temperature are maintained for 5 min before removal to ensure that the silicone is fully cured.

2.1.4 Removing From the Press. The pressure is released and the mold assembly is removed. The mold can either be air cooled or water quenched to save time.

2.1.5 Removal of Part. Once the mold and material have fully cooled, a corner of the backing is lifted to assist with the removal of the part from one end. No mold release is required.

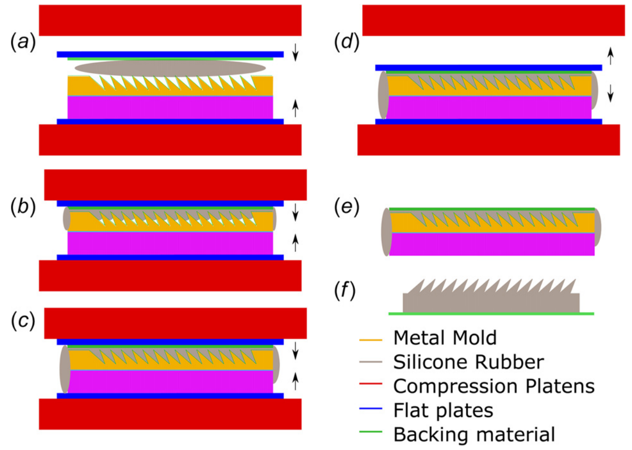

Fig. 2 Flow diagram showing the steps of hot compression molding with metal molds. The steps (A–F) are described in Sec. 2.1.

2.1.6 Compression Molded Part. The compression molded part is fully cured and ready for use. It has become bonded to the backing film placed in step A. The part is trimmed, cutting away any excess material and backing film at the periphery. It can also be cut into smaller pieces.

3 Results

The first test of the success of the hot compression molding process is whether the molded microwedges have the correct profile, especially at the tops of the wedges which terminate in a tin tip with $r \approx 1 \mu m$ radius. As seen in Fig. 1 the wedge profiles for hot compression molded wedges of NuSil MED4950 are essentially identical to those molded in Sylgard 170 from a soft wax mold following the approach in Ref. [20].

From a functional standpoint, the most important test is whether adhesive patches from the hot compression molded silicone have equivalent performance to those cast previously from Sylgard 170 using a soft wax mold. There are a few ways to test adhesion. One common approach, relevant for applications that load the adhesive mainly in shear, is to conduct a pull test and record the force at which the patch starts to slip. For other applications such as a climbing robot, combinations of shear and normal adhesion are of interest. A useful measure of the overall adhesive performance is an empirical limit curve, as plotted in Fig. 3. To generate this curve one repeatedly loads the adhesive patch with a controlled apparatus, pulling it away from a surface at a range of angles and recording the maximum normal and tangential force as it detaches for each pull. The testing method is described in detail in Refs. [22] and [27].

Figure 3 shows that patches of the hot compression molded NuSil MED 4950 and Sylgard 170 cast in a wax mold are comparable, especially at the limiting cases of light loading (low shear and correspondingly low normal force) and when loaded nearly in pure shear. For intermediate values, the normal adhesion from NuSil MED 4950 is somewhat lower, although still useful at ≈ 20 kPa. The trial-to-trial variation, which produces some

Table 1 Material properties for different silicone rubbers [28,29]

Material	Durometer (Shore A)	Tear strength (kN/m)	Tensile strength (MPa)	Elongation (%)
Sylgard 170	47	3.5	2.9	165
NuSil MED4735	35	34.39	10.6	1055
NuSil MED6015	50	N/A	8.28	100
NuSil MED4950	50	42.86	6.9	700

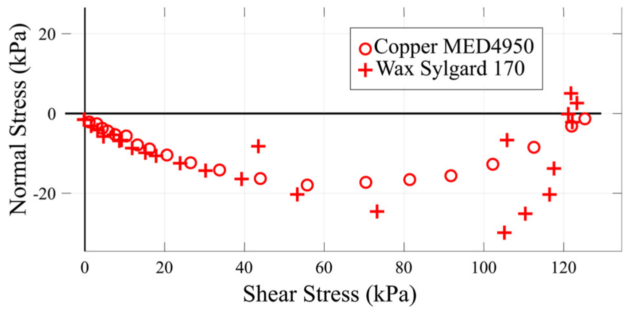

Fig. 3 Empirical limit curves show maximum combinations of normal and shear stress before failure (by detachment or slipping). Circles show results for compression-molded NuSil MED 4950 in a copper plated mold [23]; plus symbols show corresponding results for Sylgard 170 from a wax mold, created as described in Ref. [20].

scatter in the points, is greatest for those combinations of loading that also produce the highest normal stresses.

A final test concerns durability. We know from the manufacturer's data in Table 1 that NuSil MED 4950 has a much higher tear strength than Slygard 170; qualitatively it also feels much stronger in handling. The remaining test is to check that the adhesion also remains nearly constant over many loading/unloading cycles. Figure 4 shows the results of a repeated loading test using an automated stage and load cell. For each test, a 7.5×7.5 mm sample of material is brought into contact with a smooth acrylic surface and loaded to approximately 85% of its initial maximum shear stress (i.e., to $\approx$100 kPa). The reasons for loading to slightly below the maximum shear stress are that (i) in most applications one does not repeatedly load an adhesive to failure and (ii) if the adhesive is loaded to failure the subsequent slippage can eventually abrade the surface and reduce adhesion. Each dot in the plot represents the average of 5000 automated test cycles; a black line shows the standard deviation. The variability between dots represents some setup-to-setup variation between automated runs. There is slightly more variation as we approach 100,000 trials, which is likely due to wear in the setup that includes a tendon attached to the sample. The overall shear adhesion is not substantially reduced.

4 Conclusions and Future Work

This manuscript presents what to the authors knowledge is the first practical process for using hot compression molded silicone elastomers for a highly directional gecko-inspired adhesive. Using a metal mold and elevated pressure and temperature, it is possible for the viscous elastomer to fill the deep cavities that produce thin wedge tips that are responsible for directional adhesion. The microscopic geometry and surface finish of the wedges are identical to those previously obtained using Sylgard 170 PDMS in a micromachine wax mold. The adhesion performance is also substantially the same, with slightly less normal adhesion at intermediate shear loads. This is likely due to the slightly stiffer material employed, which increases the bending stiffness of the angled wedges. The main advantage of the hot compression molding is that it permits the use of silicone rubbers that are much stronger and more tear resistant than those cast at ambient temperature and pressure. Hot compression also allows a relatively fast cycle time, which paves the way for future volume production.

Looking ahead, the next area of improvement will be in the durability of the metal mold. The mold used for the experiments reported in this technical brief is a plated copper replica mold from a PDMS master, described in Ref. [23]. A mold with a harder and more durable surface is possible using nickel plating. Preliminary experiments suggest that the mold quality obtained from nickel will be equivalent to that obtained from copper.

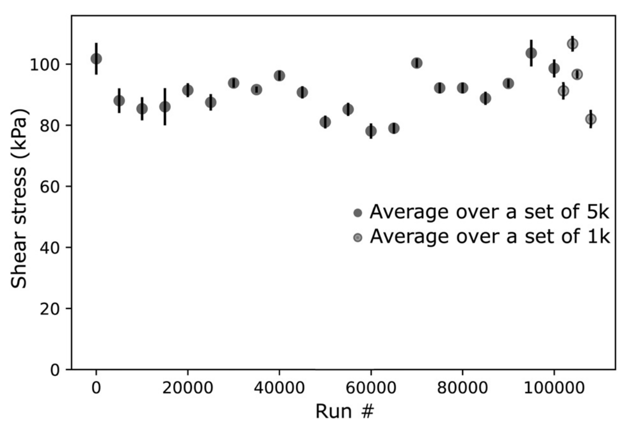

Fig. 4 Durability over 100,000 cycles with a compression molded adhesive patch. The adhesive is loaded to 85% of its initial maximum shear stress, relaxed, and repeated for batches of 5000 cycles. After each batch of 5000 cycles the adhesive is manually repositioned and aligned.

Acknowledgment

The authors thank the staff and facilities of the Stanford Nanofabrication Facility (SNF) for guidance in various steps including imaging on the Keyence VHX-6000. The authors also thank Phoenix De-Ventures' facilities and staff for their expertise in compression molding in particular Jeff Christian. Work was performed in part in the nano@Stanford labs.

Funding Data

- Ford-Stanford Research Alliance and Honda R&D (Funder ID: 10.13039/100002427).
- NSF as part of the National Nanotechnology Coordinated Infrastructure (ECCS-1542152; Funder ID: 10.13039/100014073).

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