COMPARATIVE ANALYSIS OF POLYDIMETHYLSILOXANE (PDMS) AND LIQUID SILICONE RUBBER (LSR) IN BIOMEDICAL APPLICATIONS

Mingde Qin
Jiyang Mei
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Introduction by
Nick Price

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Introduction

Polydimethylsiloxane (PDMS) and liquid silicone rubbers (LSRs) are two widely used elastomers in the biomedical industry, offering unique properties and applications. This whitepaper aims to provide an in-depth comparative analysis of PDMS and LSRs, shedding light on their key characteristics, performance attributes, and suitability for various biomedical applications. By exploring their material properties, fabrication techniques, biocompatibility, mechanical properties, and processability, this study aims to assist researchers, engineers, and professionals in making informed decisions regarding the selection of the most appropriate elastomer for their specific biomedical needs. By understanding the strengths and limitations of PDMS and LSRs, we can identify the optimal material for diverse applications, ultimately driving advancements and innovations in the field of biomedical engineering.

PDMS and its Application

Polydimethylsiloxane (PDMS) is a silicone elastomer widely employed in advanced microfluidic or lab-on-a-chip applications for creating devices with precise microstructures. PDMS offers exceptional attributes including high transparency, low surface energy, biocompatibility, and excellent chemical resistance. It is typically formed as a viscous liquid (before curing) or as a solid elastomer (after curing), depending on the degree of cross-linking. The material can be easily molded into diverse shapes and can be cured either at room temperature or through the application of heat. Notably, SylgardTM 184, a renowned silicone elastomer manufactured by Dow Corning, is commonly used in the fabrication of microfluidic chips, and serves as a widely adopted commercial PDMS variant in biological research endeavors.

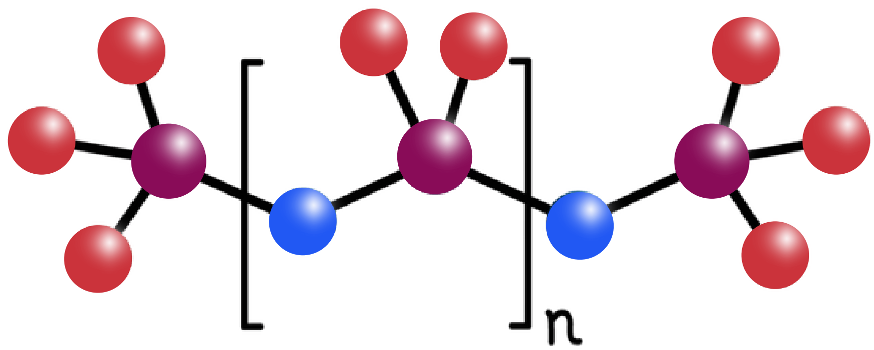

Fig. 1. Illustration of PDMS molecular structure. Purple, blue, and red spheres represent silicon atom, oxygen atom, and methyl group, respectively

A typical example of the process of making PDMS circuits in the application of microfluidics involves several steps (see Fig. 2):

1. Designing the circuit: The initial step involves utilizing computer-aided design (CAD) software to create the desired circuit structure, which can range from a simple straight circuit to a complex network of channels and chambers.
2. Generating a master mold: Once the circuit design is finalized, a master mold is fabricated using photolithography. This process entails coating a silicon wafer with a photoresist, exposing it to UV light through a photomask, and subsequently removing the exposed areas using a developer solution. This results in the desired circuit pattern being etched onto the wafer.
3. Preparing the PDMS mixture: A PDMS prepolymer and curing agent are combined at a specified ratio (e.g., 10:1 for base to curing agent), and the mixture is degassed to eliminate air bubbles. It is then poured onto the master mold and cured in an oven at a specific temperature and duration.
4. Demolding the PDMS replica: Following the curing process, the PDMS replica is cautiously detached from the master mold using a scalpel or tweezers. Any residual PDMS can be eliminated using a solvent like ethanol.
5. Creating inlets and outlets: To establish entry and exit points for the circuit, small holes are punched through the PDMS using a biopsy punch or a syringe needle. These holes are aligned with the circuit pattern on the PDMS.

6. Bonding PDMS to a substrate: The PDMS replica is subsequently bonded to a substrate such as glass or plastic. Prior to bonding, the surfaces of both materials undergo specific treatments to activate them, ensuring a tight and secure bond. The inlets and outlets can be connected to tubing for fluid delivery and collection.
7. Device ready for application: With the PDMS chip successfully fabricated, it is now primed for diverse research applications, such as cell culture and other relevant endeavors.

This process can be repeated to create multiple copies of the same circuit design. Other techniques to make the master include 3D printing, micromilling, and cutting acrylics sheet, etc. There are also a few different methods to bond the PDMS piece to glass or plastic, such as oxygen plasma, corona discharge, UV/ozone bonding, silane coupling agent, etc.

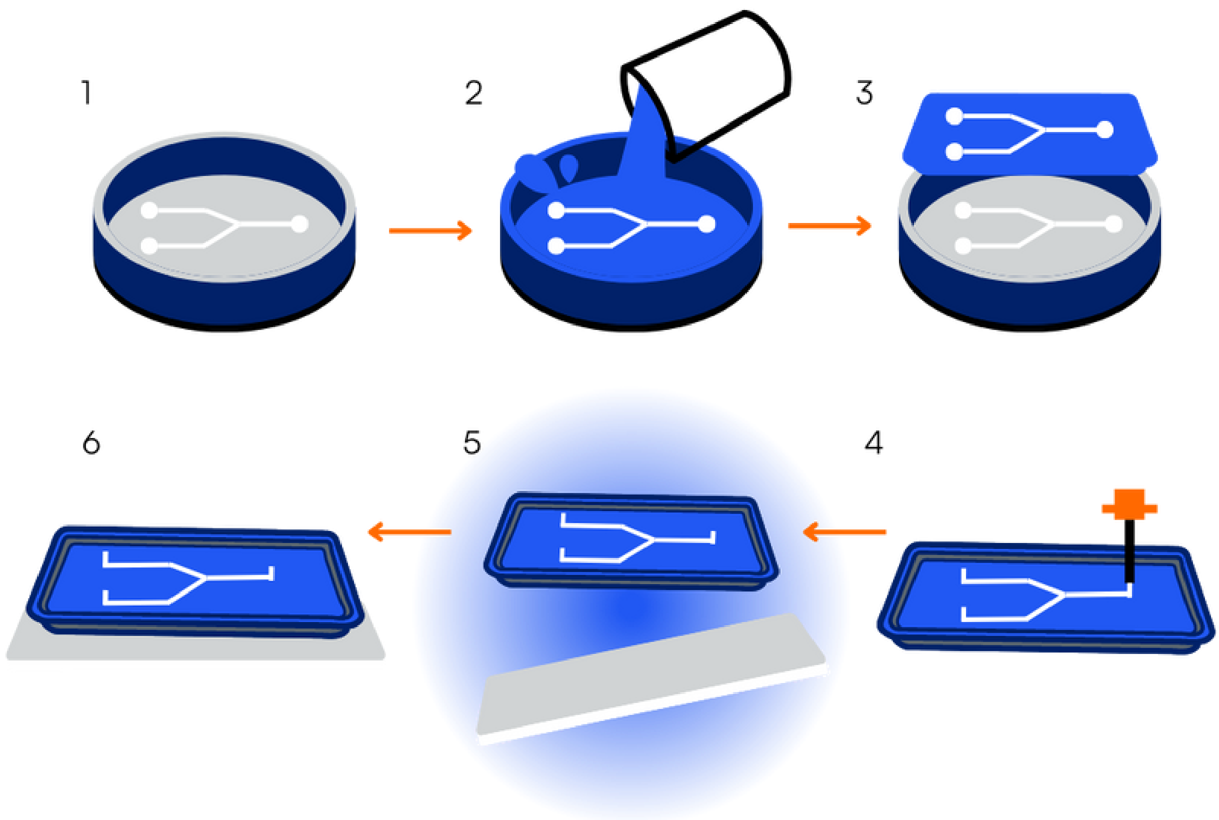

Fig. 2. Illustration of the step-by-step fabrication process of a PDMS chip by replica molding: (1) Fabricate silicon master mold using photolithography; (2) Pour the PDMS prepolymer and curing agent mixture onto the master mold and have the mixture cure at elevated temperature; (3) Demold the cured PDMS replica from the master mold; (4) Punch the inlet and outlet holes; (5) Activate the PDMS and glass surface by plasma treatment to facilitate the bonding; (6) Bond the PDMS replica onto the glass, the chip assembly is then ready to use.

PDMS possesses many advantages, especially for biological studies. Some of them are summarized below:

- Biocompatibility: PDMS exhibits excellent biocompatibility, posing minimal harm to cells and tissues, rendering it well-suited for biological applications. Its gas-permeable nature facilitates gas supply for cell culture, ensuring optimal conditions.
- Optical transparency: PDMS boasts remarkable optical transparency, enabling convenient visualization and monitoring of microfluidic processes and biological samples with clarity and precision.
- Ease of fabrication: PDMS offers ease of fabrication through soft lithography techniques, empowering the creation of intricate microfluidic devices with exceptional precision, even at dimensions as small as ~10 μm.
- Elasticity: With its high elasticity, PDMS demonstrates remarkable flexibility, effortlessly adapting and conforming to the contours of underlying structures such as microfluidic channels and wells, ensuring effective sealing and enhanced functionality.
- Cost-effectiveness: PDMS is an economically viable choice compared to other materials commonly employed in microfluidics. Its relative affordability makes it accessible to researchers with limited resources, facilitating broader participation and innovation in the field.

However, there are certain limitations to consider:

- Challenges in mass production: The manual nature of molding PDMS circuits and the dependency of its properties on curing conditions make it challenging to achieve efficient mass production, hindering scalability for large volume manufacturing.
- Permeability concerns: PDMS exhibits permeability to gases and certain chemicals, which can lead to issues such as water evaporation and device drying. This permeability factor necessitates careful consideration in applications where containment and control of substances are critical.
- Limited long-term stability: PDMS is subject to aging and degradation over time, particularly when exposed to oxygen and UV light. This degradation can impact the mechanical and optical properties of the material, prompting the need for careful monitoring and potential replacement over extended durations.
- Adhesion limitations with specific materials: PDMS may exhibit poor adhesion to certain plastics and metals, posing challenges in device assembly and integration. While various bonding methods can overcome this limitation, the additional complexity involved adds to the overall fabrication process.

In summary, PDMS proves to be a versatile material with extensive applications, particularly in the fields of microfabrication and biomedical engineering, rendering it highly suitable for laboratory research scenarios.

Liquid Silicone Rubber and its Application

Liquid silicone rubbers (LSRs) represent a diverse group of silicone elastomers that differ from PDMS in their chemical composition. LSRs are polymers comprising siloxanes with various side groups, such as hydride, vinyl, hydroxyl, phenyl, and trifluoropropyl. The composition of these side groups, along with factors like molecular weight distribution and the presence of additives or functional groups, determines the chemical properties and mechanical characteristics (e.g., hardness, flexibility, refractive index, moisture permeability, and solvent resistance) of a specific LSR formulation. Similar to PDMS, commercial LSRs are typically supplied as a two-part kit, with part A containing the catalyst (often Pt-based) and part B containing the crosslinker and catalyst inhibitor. Upon thorough mixing, the crosslinker initiates covalent bonding among the base polymer chains with the assistance of the catalyst, transforming the liquid-like raw material into a rubber-like consistency. This irreversible curing process, commonly referred to as LSR curing, can be expedited by heat, allowing LSR to be molded into desired shapes.

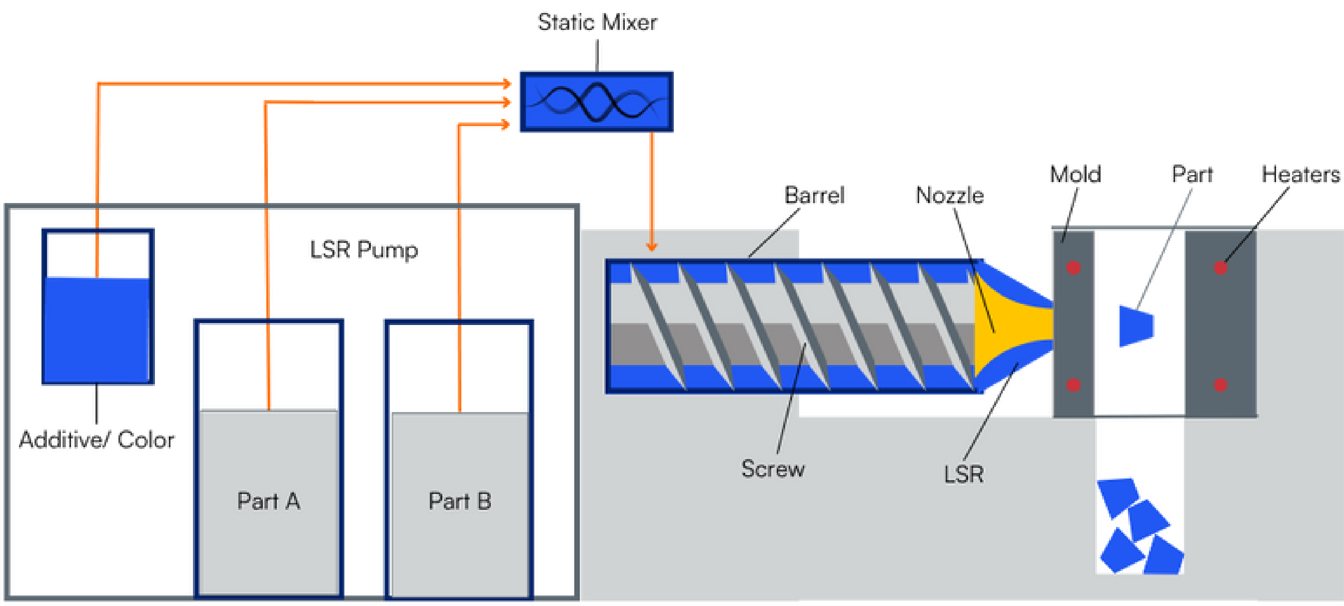

Fig. 3 Schematic drawing of LSR LIM machine with two bucket pump system, barrel, screw, and mold with heaters inside.

Within the manufacturing industry, products made from LSRs are commonly manufactured using liquid injection molding (LIM) techniques. A typical LSR-LIM machine consists of an LSR pump system, which includes the necessary components such as part A, part B, and additives if required. This pump system is followed by a static mixer, barrel, and screw assembly, culminating in a heated master mold with its base attached to the end of the nozzle, as illustrated in Figure 3. The LSR-LIM process typically involves the following sequential steps:

1. Mold Design: Similar to PDMS molding, the first step in LSR manufacturing involves designing the mold to define the desired shape and features of the product using CAD software.
2. Master Mold Creation: For microfluidic applications, the master mold requires the production of micro-nanoscale features using specialized techniques such as LIGA-based technologies (lithography, electroplating, molding), deep reaction ion etching (DRIE), laser ablation, 3D micro-drilling, and micromachining.
3. Raw Material Preparation: LSR consists of part A and part B, which are typically mixed in a 1:1 ratio. Viscous raw materials are degassed to eliminate air bubbles and ensure a homogeneous mixture.
4. Injection Molding and Curing: The freshly mixed LSR liquid is injected into the heated mold cavity under pressure, typically up to 2.5 MPa, using a pneumatic or hydraulic system. Commercial LSRs usually cure within 2-3 minutes at temperatures ranging from 120-160 °C. Certain grades of LSRs can also be overmolded onto plastic and metal substrates if desired.
5. Demolding of Cured LSR: Once the LSR has cured, the replica is removed from the master mold. Fully automatic manufacturing machines often utilize ejector pins for efficient demolding.
6. Post-Curing Treatment and Device Assembly: Similar to PDMS, molded LSR replicas can undergo surface treatment or modification before being bonded to glass and plastics. The molded LSR replicas are then integrated into larger functional devices, allowing for various applications.

LSR is a silicone elastomer that encompasses all the advantages of PDMS, such as biocompatibility, easy fabrication, and high elasticity. Additionally, LSR offers unique benefits that surpass PDMS in certain aspects:

- Versatile Material Properties: Commercially available LSRs provide a wide range of material properties, allowing for tailored characteristics such as stiffness, permeability, temperature, and UV stability, among others, to meet specific application requirements.
- Suitable for High-Volume Production: LSR is highly suitable for high-volume production, making it favorable for industrial manufacturing. Unlike the manual casting and demolding process of PDMS, LSR-LIM is a fully automatic process capable of continuous operation, enabling easy scalability for large-scale production. With a simple press of a button, the LSR-LIM machine can produce numerous LSR replicas.

However, it is important to consider the drawbacks of LSR. The initial investment in LIM machines and the cost of LSR molds, designed to withstand high pressure, can be higher compared to PDMS.

Table 1

Direct comparison of PDMS and LSR in raw materials, fabrication routes, and suitable applications.

FEATURE	PDMS	LSR
Material Chemistry	• Silicone-oxygen backbone and methyl side groups. • Sold as two-part kits at ratios of 10:1.	• Silicone-oxygen backbone with various side groups (e.g., methyl, hydride, vinyl, hydroxyl, and phenyl, etc.) at different contents. • Sold as two-part kits at a ratio of 1:1.
Facility Investment	• Low, only require an oven to cure PDMS.	• High, requires the initial investment of LSR LIM machine to conduct injection molding.
Mold Fabrication	• Method and cost highly depend on the mold features and any specific requirement.	• Like PDMS mold, mold cost is highly dependent on its feature. • Might require extra coating and surface treatment to withstand injection molding pressure and improve wear resistance for continuous use.
Process and Handling	• Straightforward, can cure without pressure in an oven. • Cured parts can be demolded manually.	• Complicated, might require optimization of pressure, temperature, and time to cure. • Demolding can be achieved by automatic ejector.
Post-Fabrication Assembly	• Can bond to glass and thermoplastics after some surface treatments.	• LSR replicas can also bond to glass and thermoplastics after surface treatments.
General Product Property	• Biocompatible, optically transparent, highly elastic, etc.	• LSR retains all benefits from PDMS, better properties can be possessed on special grade LSR.
Special Grade Selection	• Not too many special grades or variations. • Usually suffer from high permeability and low aging resistance.	• Lots of special grades and variations are commercially available, more possibility to fit a special requirement.

Manufacturing Automation	• Not applicable, PDMS molding is a largely manual process that requires researcher to fabricate piece by piece.	• Yes, the process can be fully automatic, and the LSR replicas can be produced 24 x 7 once the settings are given.
High Volume Production	• Not applicable, the volume of production is limited by its largely manual process.	• Yes, its fully automatic manufacturing process can easily achieve high-volume production.
Unit Price	• High, raw material is not expensive but takes time and labor to fabricate.	• Low, similar raw material price, but fully automatic high-volume production can greatly reduce the unit price.
Suitable Scenario	• Research work doesn't require a lot of replicas. • Unit price is not a major concern.	• For commercial products, a large number of replicas are required. • Unit price becomes important.

Conclusion

The comparison between PDMS and LSR reveals their unique advantages and considerations in various applications. PDMS excels in lab and research settings, offering benefits such as biocompatibility, easy fabrication, and high elasticity. On the other hand, LSR stands out in commercial product manufacturing, providing a wide range of material properties, suitability for high-volume production, and cost-effectiveness. Both materials have their respective strengths and drawbacks, and the choice between PDMS and LSR should be based on the specific requirements of the intended application. By understanding the characteristics and capabilities of PDMS and LSR, researchers and manufacturers can make informed decisions to achieve optimal results in their projects and products.

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