# Applications of polydimethylsiloxane (PDMS) in Engineering

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Polydimethylsiloxane (PDMS) is an elastomer with excellent optical, electrical and mechanical properties, which makes it well-suited for several engineering applications. Due to its biocompatibility, PDMS is widely used for biomedical purposes. Some properties can be improved by adding additives.

polydimethylsiloxane | PDMS properties | PDMS applications | PDMS | PDMS composites | mechanical properties | optical properties | biocompatibility

## 1. Introduction

Polydimethylsiloxane (PDMS) is an elastomeric polymer with interesting properties for biomedical applications, including physiological indifference, excellent resistance to biodegradation, biocompatibility, chemical stability, gas permeability, good mechanical properties, excellent optical transparency and simple fabrication by replica moulding [1][2][3][4][5]. Due to these characteristics, PDMS has been widely used in micropumps [6], catheter surfaces [7], dressings and bandages [8], microvalves [9], optical systems [10][11], in the in vitro study of diseases [12][13], in implants [14][15], in microfluidics and photonics [16][17][18][19]. Moreover, soft-lithography technology has driven the use of PDMS in microelectromechanical systems (MEMS) applications and in microfluidic components [17][18][20]. Soft-lithography techniques such as micro-contact printing, replica moulding, micro-transfer moulding, micro-moulding in capillaries and solvent-assisted micro-moulding usually require the use of PDMS to create an elastomeric stamp or mould that incorporates nano- and microstructures for the transfer of patterns onto a subsequent substrate [18][21].

MEMS are approaches that use electronic and mechanical technologies to deal with biomedical problems on the micro-scale [22]. MEMS-based devices have been widely used in the biomedical area for applications such as diagnostics and therapeutics. These systems can be microsensors or microtransducers, and are helpful in areas such as physics, mechanics, electronics and biomedicals, as they can provide very precise and fast results [23]. The investigation and improvement of already existing MEMS are more and more common. As they are increasingly commercialized, the necessity to find processes and materials that enable mass production while reducing cost has emerged [21]. MEMS are traditionally silicon-based and the pursuit for a more biologically friendly material is needed. Polymers allow rapid prototyping and mass production techniques as well as having a lower cost in relation to silicon, making them particularly attractive for the development of MEMS [21]. Photolithography is the most commonly used technique in microfabrication, however, this method is expensive [24]. With the

introduction of polymers in microsystems, new manufacturing techniques have been studied, such as soft-lithography, which can be a cheaper method comparatively to photolithography, even when a costly mould is needed for patterning; once a mould is created, it can be reused several times [20]. Additionally, there are alternatives which are attempting to reduce the cost of the moulds, relying on cleanroom less approaches [25]. Candidate polymers for the production of MEMS are polycarbonate (PC), polymethylmethacrylate (PMMA), polyvinylchloride (PVC), polyethylene (PE) and PDMS [21].

Additionally, PDMS is the most commonly used material in the manufacturing of microfluidic devices, which are an important technology for the development of systems such as drug delivery, DNA sequencing, clinical diagnostics, point of care testing and chemical synthesis [26]. The used materials in these systems should be biocompatible, optically transparent and provide fast prototyping and low fabrication cost [27], features found in PDMS.

In addition to applications in microfluidics, PDMS has been widely used in the fabrication of biomodels (flow phantom) for the in vitro hemodynamic study of diseases such as aneurysms and stenosis [28][29][30][31]. The biomodels developed in PDMS allow good replicability of the lumen of the arteries and good transparency, being ideal for the application of optical techniques of micro particle image velocimetry (micro-PIV), particle image velocimetry (PIV), particle tracking velocimetry (PTV) and non-evasive techniques [32][33][34]. These experimental tests have provided a greater understanding of these pathologies, validated numerical techniques and tested medical devices such as stents [35][36][37].

PDMS has also been investigated in the field of medical implants [38][39][40][41][42]. These types of implants are usually made with titanium or its alloys; however, such materials do not allow good osseointegration [39]. In order to overcome this limitation, PDMS has been studied to produce coatings with microscale features that help the bonding between the implant and the bone. The main characteristics for its use in implants are its high biocompatibility, excellent resistance to biodegradation and flexibility, which makes PDMS one of the most successful polymers in implanted devices, presenting only mild foreign body reactions [43][44][45]. Common applications include cardiac pacemakers, cuff and book electrodes in the PNS, cochlear implants, bladder and pain controllers and planar electrode arrays in the CNS [45][46].

## 2. PDMS Properties

Silicon, glass and polymers are the typical materials used for micro devices fabrication: silicon, because of its thermal conductivity and the availability of advanced fabrication technologies; glass, mainly due to its transparency; polymers, because of its low cost, optical transparency and flexibility. Compared to glass and silicon, PDMS turns out to be the most promising elastomer, because the other two materials have a high manufacturing cost, require greater labour intensity and are rigid in nature. The variable elasticity of PDMS in medical applications is also favourable; its modulus of elasticity is 1–3 MPa (compared to ~50 GPa of glass) [2][47]. PDMS is also chemically inert, thermally stable, permeable to gases, simple to handle and manipulate, exhibits isotropic and homogeneous properties and can replicate submicron features to develop microstructures [19][21][48]. Additionally, this elastomer is optically transparent, can work as a thermal and electrical insulator and degrades quickly in the natural

environment [49]. PDMS presents a hyperelastic behaviour, which is the ability of a material to undergo large deformations before rupture [50]. This characteristic is also found in biological tissues and, for that reason, PDMS is a well-suited material to mimic, for example, blood vessels [49]. Another characteristic of this elastomer is its biocompatibility, which means that PDMS is compatible with biologic tissues [49]. PDMS presents a transmittance up to 90% for the wavelength from 390 nm to 780 nm [51][52][53] and, due to this characteristic, PDMS-based microsystems allow the direct observation of the mimicked blood flow inside the mimicked vessels and the integration of optical detection systems, hence playing an important role in this field.

With the purpose of extending the lifespan of a chip, PDMS is used to embed or encapsulate electronic components by casting. Due to its thermal and electrical insulation capability, PDMS protects the components from environmental factors and mechanical shock within a large temperature range (−50–200 °C) [23][48]. In **Table 1**, some physical properties of PDMS are listed.

**Table 1.** Typical properties of cured PDMS.

| Property (Unity) | Result | References |
|---|---|---|
| Transmittance at range 390 nm to 780 nm (%) | 75–92 | [54][55] |
| Index of refraction | 1.4 | [56] |
| Thermal conductivity (W/m·K) | 0.2–0.27 | [57][58] |
| Specific heat (kJ/kg·K) | 1.46 | [56] |
| Dielectric strength (kV/mm) | 19 | [57] |
| Dielectric constant | 2.3–2.8 | [56] |
| Electrical conductivity (ohm·m) | $4 \times 10^{13}$ | [56] |
| Volume resistivity (ohm·cm) | $2.9 \times 10^{14}$ | [57] |
| Young's modulus (kPa) | 360–870 | [59] |
| Poisson ratio | 0.5 | [60] |
| Tensile strength (MPa) | 2.24–6.7 | [56][57] |
| Hardness (Shore A) | 41–43 | [55][61] |
| Viscosity (Pa·s) | 3.5 | [57] |
| Hydrophobicity—contact angle (°) | ~108° ± 7° | [62] |
| Melting Point (°C) | −49.9 to −40 | [63] |

Despite these advantages, PDMS has some properties that can present a limitation in some applications. Due to its $CH_3$ groups, PDMS presents a hydrophobic surface (contact angle with water ~108° ± 7°) [62][64][65], often limiting its application in solutions composed of biological samples [66]. Additionally, PDMS tends to swell when combined with certain reagents [17][48]. In some applications, the absorption of small molecules flowing through the channels makes it difficult to quantitatively analyse experiments in proteomic drug discovery and cell culture [67][68]. In microchannels, the hydrophobicity of PDMS generates complications that include impedance to the flow of polar liquids, which makes it difficult to wet its surface with aqueous solvents [49]. On the other hand, much effort has been made to make the PDMS surface hydrophilic and resistant to protein adsorption [19][69][70][71][72][73].

Strategies employed in attempting to solve PDMS hydrophobicity include surface activation methods such as: oxygen plasma; UV/ozone treatments; corona discharges, which are widely used for PDMS surface oxidation to promote microchannel wettability. The main benefits of these methods are the short treatment time and easy operation; however, the PDMS surface recovers its hydrophobicity when in contact with air within a few minutes [74][75][76].

Another method is physisorption, which is a simple and efficient approach that relies on surface hydrophobic or electrostatic interactions. This method includes the following techniques: layer-by-layer deposition; non-ionic surfactants; charged polymers. The disadvantages are the lack of covalent bonds between PDMS and surface modifiers, which lead to the loss of modifiers quickly through desorption [77][78][79].

In order to improve the difficulties encountered in physisorption, chemical modification methods allow for maintaining a long-term stability of the modified surface. These methods include: chemical vapor deposition, surface segregation and self-assembled monolayers, silanization, and polymer brushes via grafting methods [1][62][80][81][82].

Adding waxes such as paraffin or beeswax to PDMS has been demonstrated to potentially increase the corrosion resistance, hydrophobicity and thermal and optical properties of PDMS, which is useful in applications such as sensors, wearable devices and superhydrophobic coating [83].

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