Silicone Mold Accuracy in Polyurethane Vacuum Casting

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Vacuum casting of polyurethane (PUR) in silicone molds is used industrially for the production of prototypes and small series as well as in various noncommercial research areas. This includes the reproduction of archeological findings, biological samples or electronic devices. In this study, the authors investigate the molding accuracy of different commercial silicones and PUR casting resins both on microscopic and macroscopic scales. For this, they used a variety of master models to generate silicone rubber casting molds. The resulting PUR castings are investigated by helium ion microscopy, confocal laser scanning microscopy, and optical 3D-scanning.

1. Introduction

Vacuum casting with silicone rubber molds is one of the oldest and most widespread methods of rapid tooling. It is used industrially for the replication of prototypes and small batches. Common products are not only technical components for prototypes such as housing or functional components but also visible elements with high demands on optics and haptics – the latter depending, among other things, on the impression of the surface texture. One of the most common casting materials used in vacuum casting is polyurethane (PUR).[1] Besides that, wax parts for metal investment casting, epoxy resins, polyester resins, polyamides, silicones, concrete, ceramics, or low melting point metals can also be used for casting. For mold production, the master model, which can for example be 3D printed, is embedded in a two-component, room temperature vulcanizing, polydimethylsiloxane (PDMS)-based silicone rubber (RTV-2). Fumed silica fillers are used to give the silicone better dimensional stability, especially for large master models, where the cavity can be distorted under the molds weight. The PUR resin is degassed in a vacuum, mixed and poured into the mold. After the resin has cured, a precise thermoset replica is produced, which is manually demolded.[2] Due to the diffusion of resin components into the silicone, the casting molds can only be used about 15–30 times (the number of achievable casting cycles can greatly diverge).[3,4] One of the most important reasons for using vacuum casting is the extremely short duration from development to series maturity. In contrast to most 3D printing processes, excellent material properties are possible that approach those offered by injection molding. In addition, the diversity of castable geometries and their dimensional accuracy plays an important role. Dimensional accuracy has been examined in the context of micro-fabrication techniques such as soft lithography with unfilled PDMS and different casting materials. In general, replications down to the submicrometer range can be produced.[5–7] However, the industrial application of polyurethane vacuum casting with commercial materials has not yet been examined in detail with regard to dimensional accuracy. In this study, it has thus been examined considering different master models at both the macroscopic and microscopic level. The paper gives a brief introduction to the topic and highlights several influencing factors that may be addressed in future research.

2. Results and Discussion

In principle, the transfer of the mold first from the model to silicone and then from silicone to PUR is equally important for the replication’s dimensional accuracy. There are several size scales that can be used to evaluate the molding accuracy. Firstly, there is the microscopic dimension of the component, which determines surface characteristics such as gloss, haptics or roughness, as well as the quality of inscriptions – here, dimensional deviations range from nano- to micrometers. This type of dimensional deviation is largely dependent on the viscosity of the respective silicone or PUR. What counts here is the ability to penetrate the surface texture of the model, which presumably also depends on the compatibility of the surface tension of the non-cross-linked polymers and the surface energy of the model. Figure 1 shows roughness measurements using CLSM and a qualitative comparison of the topology using HIM taking a laser-edged ripple profile in a brass plate as an example. The precise impression of the surface texture down to the sub-micrometer range can best be seen by comparing HIM images of the trough and crest.
topology. A quantitative comparison of the roughness values is seen in Table 1. Most noticeable here is the relatively smoother topology of the H$_{12}$MDI casting, which indicates an increased surface tension during cross-linking.

The best measure of shape accuracy here is the change in profile depth. Since the silicone does adhere neither to the model nor to the PUR, volume shrinkage – most pronounced towards the end of addition polymerization – leads to separation of the interfaces. SF13, which (recognizable by its lower hardness) has a lower proportion of shrinkage-reducing fumed silica filler, shows the greatest depth profile (PD) deviation. On the other hand, the higher viscosity of the SE42 shows only marginal influence on the surface texture.

Then, there is the macroscopic dimension of the model, where dimensional deviations range from micro to millimeters and

| Table 1. Arithmetic mean roughness values and profile depths of structures shown in Figure 1, measured by CLSM. |
|---------------------------------------------------------------|
| **PD** | **Master model** | **SE42** | **SE13** | **MDI-resin** | **H$_{12}$MDI-resin** |
|---------------------------------------------------------------|
| **coarse profile (Figure 1 first row)** | | | | | |
| PD | 44.7 | 48.8 ($+4.1$) | 51.3 ($+6.6$) | 44.9 ($+0.2$) | 42.2 ($−2.5$) |
| $R_a_{\text{yellow}}$ | 1.6 | 1.5 ($−0.1$) | 1.6 (0.0) | 1.3 ($−0.3$) | 2.1 ($+0.5$) |
| $R_a_{\text{green}}$ | 0.5 | 0.6 ($+0.1$) | 0.9 ($+0.4$) | 0.6 ($+0.1$) | 0.5 (0.0) |
| **fine profile (Figure 1 last row)** | | | | | |
| PD | 52.3 | 56.0 ($+3.7$) | 58.0 ($+5.7$) | 54.5 ($+2.2$) | 54.3 ($+2.0$) |
| $R_a_{\text{yellow}}$ | 4.0 | 2.9 ($−1.1$) | 2.6 ($−1.4$) | 2.3 ($−1.7$) | 2.6 ($−1.4$) |
| $R_a_{\text{green}}$ | 1.4 | 1.4 (0.0) | 1.1 ($−0.3$) | 0.7 ($−0.7$) | 0.9 ($−0.5$) |

The value in brackets is the deviation from the master model.
can significantly affect the functionality of the product. This type of dimensional deviation is largely dependent on the percentage volume shrinkage of the silicone during mold manufacturing and then on the volume shrinkage of the PUR during casting. Volume shrinkage depends on the chemical reaction of the initial components. The 3D scans in Figure 2 reveal precise macroscopic shape accuracy with a maximum dimensional deviation of $-0.45$ mm, similar to what Vaezi et al. found with epoxy resin.\(^8\) Generally, for highest precision, the comparatively expensive addition-curing silicone is used. Condensation-curing silicone is less expensive, but due to the alcohol condensate, it shows greater volume shrinkage during cross-linking (0.3% for SE20 according to the manufacturer). The average deviation is thus greater than in SE13. It is of course to be expected that the larger the mold, the greater the absolute deviation. More pronounced deviations as seen in Figure 2c result from sink marks produced by entrapped air.

Figure 3a-e show the $\text{H}_2\text{MDI}$ resin replication of an FDM printed bending guide. By filling the mold with short carbon fibers, the mechanical strength can be significantly increased without compromising the surface quality.

An important factor when casting complex structures with undercuts is the hardness of the silicone. If, for the sake of simplicity, multiple parting planes are not desired, softer silicones...
facilitate demolding of undercuts. Especially more brittle PUR, such as that produced from H₁₂MDI-resin, can break with severe undercuts. Figure 3e-h show cast replicas of a CNC milled impeller. The images illustrate that even very delicate structures with severe undercuts can be cast, provided the demolding forces are not too large (see Figure 3h). Although release agents facilitate demolding considerably, they leave a clearly visible film on transparent products.

3. Conclusion and Outlook

It has been shown that commercial PUR vacuum casting has very high dimensional accuracy both macroscopically and microscopically. Numerous influencing factors were addressed, which – to be examined in detail – are well beyond the scope of a short summary. Regarding the absolute dimensional deviations, the tested materials show only marginal differences. Percentage deviations are more relevant for large, industrial-scale models. Nevertheless, the versatile applicability of the process could be demonstrated using a variety of different models. Various measuring methods were examined, which can be utilized for experimental studies of the different aspects of dimensional accuracy in industrial application of vacuum casting.

4. Experimental Section

For the production of casting molds, three commercial PDMS-based RTV-2 silicones were used as provided: Köraform A 42 (addition-curing, Shore A hardness = 42, viscosity = 62,000 mPas; CHT Germany GmbH, Tübingen, Germany), SF13 (addition-curing, Shore A hardness = 13, viscosity = 4,500 mPas; Silikonfabrik, Ahrensburg, Germany) and HS620 (condensation-curing, Shore A hardness = 20, viscosity = 19,000 mPas; Silikonfabrik), referred to as silicone elastomers SE42, SE13, and SE20, respectively. The non-cross-linked silicones were degassed for 5 min before casting into a wooden frame to remove air entrapments. For the castings, two commercial PUR resins, consisting of the components polyol and isocyanate, were used. PX226 (viscosity = 2000 mPas; SikaAxson, Bad Urach, Germany), which is based on 4,4’-methylene diphenyl diisocyanate (MDI) and which contains tri-, tetra- and penta-functional phenyl isocyanates, commonly known as polymeric MDI (PMDI); and PRC 1710 (viscosity = 400 mPas, Synthene, Ferme de l’Évêché, France), which is based on hydrogenated MDI (4,4’-methylene dicyclohexyl diisocyanate, H₁₂MDI). Those are referred to as MDI-resin and H₁₂MDI-resin. In vacuum casting, both resins were degassed for 5 min at about 1 mbar before mixing and cured at 70°C. Investigations were performed with a confocal laser-scanning microscope (CLSM) VK-8710 (Keyence Deutschland, Neu-Isenburg, Germany) and by the helium-ion microscope (HIM) Orion Plus (Carl Zeiss, Oberkochen, Germany). HIM was performed at an acceleration voltage of 36 kV and the spot control was set between 5.6 and 6.0 to obtain a beam current of 0.2 to 1.2 pA. To avoid charging effects during secondary electron detection, an electron flood gun was used after each line scan with a flood energy of 540 eV, flood time of 10 μs, and a focus of 107 V. Optical 3D-Scanning was performed using an ATOS III Triple Scan device (GOM GmbH, Braunschweig, Germany) with 15 measurements per scan. Figures show best fit overlays of castings and master models. The models were coated with an opaque TiO₂-spray prior to scanning.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

polyurethane, silicone mold, vacuum casting

[1] M. Wortmann, N. Frese, W. Keil, J. Brikmann, J. Biedinger, B. Brockhagen, B. Hüs gen, ACS Applied Polymer Materials 2020, XX, XXX.

[2] W. C. Ng, H. L. Seet, K. S. Lee, N. Ning, W. X. Tai, M. Sutedja, X. P. Li, J. Mater. Process. Technol. 2009, 209, 4434.

[3] M. Wortmann, N. Frese, A. Heide, J. Brikmann, O. Strube, R. Dalpke, B. Hüs gen, Polym.-Plast. Technol. Eng. 2018, 57, 1524.

[4] M. Wortmann, A. Hoffmann, N. Frese, A. Heide, J. Brikmann, N. Brandt, B. Hüs gen, Polymer-Plastics Technology and Materials 2019, 58, 1937.

[5] Z. Xiao, R. Zheng, Y. Liu, H. He, X. Yuan, Y. Ji, T. He, Water Res. 2019, 155, 152.

[6] S. C. H. Thian, J. Y. H. Fuh, Y. S. Wong, H. T. Loh, P. W. Gian, Y. Tang, Microsystems technologies 2008, 14, 1125.

[7] A. Trautmann, F. Heuck, C. Mueller, P. Ruther, O. Paul, Replication of microneedle arrays using vacuum casting and hotembossing. In The 13th International Conference on Solid-State Sensors, Actuators and Microsystems, 2005. Digest of Technical Papers. TRANSDUCERS’05, 2005, Vol. 2, 1420–1423. IEEE.

[8] M. Vaezi, D. Safaeian, C. K. Chua, Rapid Prototyping J. 2011, 17, 107.