Improving Mechanical Durability of SLA-Printed Components for Load-Bearing

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Abstract This study explored the impact of post-printing parameters in stereolithography (SLA) technology, particularly focusing on how photopolymerization affected the mechanical properties of samples. Building on previous research, the investigation revealed that different curing temperatures significantly influenced the rigidity and stiffness of the printed samples. The mechanical properties of the samples were evaluated through three-point bending tests. Curing at 60 °C left some polymer chains uncured, resulting in less rigid samples but increased load capacity (up to 30 ± 2.4 N) and deflection (2.9 ± 0.6 mm). On the other hand, curing at 70 °C enhanced the rigidity and stiffness, especially for larger samples. The results demonstrated that photopolymerization and the resulting polymer chain cross-linking are crucial for achieving the desired mechanical properties. Notably, as the diameter of the samples decreased, the difference in stiffness between the 60 and 70 °C cured samples also reduced. The findings highlight the importance of optimizing curing temperatures to tailor the mechanical performance of SLA-printed components for specific applications.

Keywords Post-curing temperature · Mechanical durability · Stereolithography printing

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Introduction

Additive manufacturing, particularly stereolithography (SLA), is a key technology for creating precise, complex parts with smooth surfaces [1]. SLA works by curing layers of liquid resin into solid forms using a UV laser. This method is popular in industries such as aerospace, automotive, and medical devices due to its ability to produce detailed and durable components [2, 3]. The final mechanical properties of SLA-printed parts depend heavily on post-processing steps, especially post-curing, which strengthens the material [4, 5].

Photopolymerization is a fundamental process in SLA printing, driven by the interaction between UV light and specific chemical components within the resin, known as photoinitiators. When exposed to UV radiation, these photoinitiators undergo a transformation that generates reactive intermediates, such as free radicals. These reactive species play a crucial role in initiating the polymerization of monomers within the resin, leading to the formation of extensive polymer chains that progressively solidify the material [6]. During the SLA printing process, a UV laser precisely targets the resin layer by layer, selectively curing each section to gradually construct the desired part. Despite the solidification of each layer, the material remains in a semi-cured state, holding unreacted monomers and partially formed polymer networks. This semi-cured state is deliberately maintained to facilitate the successive addition of layers, ensuring the stability and accuracy of the part as it is being built [7]. However, at this stage, the printed component does not yet exhibit the full range of its intended mechanical properties [8, 9].

Without post-curing, the material remains susceptible to mechanical weaknesses due to the presence of unreacted monomers and insufficiently cross-linked polymer chains, which can compromise the part's structural integrity and performance in real-world applications. During post-curing, the printed part is exposed to additional UV light and controlled heat, which serve to further drive the polymerization process to completion. This step is critical for promoting the full cross-linking of the polymer chains, resulting in a denser and more robust material structure [10, 11].

The design and functionality of the post-curing chamber also play a significant role in determining the final properties of SLA-printed parts. Modern post-curing chambers are equipped with multi-directional UV lights and heating elements that ensure uniform exposure to UV light and consistent temperature throughout the part. This uniformity is essential for achieving consistent mechanical properties across the entire part, as uneven curing can lead to areas of varying strength and stiffness [12]. Sahrir et al. [13] investigated the impact of UV light wavelength and intensity on the post-curing process. They found that higher light intensities during post-curing improve color stability in 3D-printed resin crowns because they promote more complete polymerization of the resin material. Bayarsaikhan et al. [14] higher post curing temperatures improve the mechanical properties of 3D-printed dental resins because they enhanced the degree of polymerization, leading to more extensive cross-linking within the resin structure.

This study investigates the effect of post-curing at different temperatures (60 and 70 °C) on the mechanical properties of 3D-printed parts produced by stereolithography (SLA) technique. By evaluating properties such as peak load, deflection, and stiffness, this research aims to provide a deeper understanding of how post-curing conditions can be tailored to meet specific performance requirements in engineering applications. The insights from this study are expected to contribute to the optimization of post-processing procedures for 3D-printed samples using the SLA method, ensuring that the printed parts meet the requirements of modern manufacturing applications.

Materials and Method

Two groups of cylindrical samples, each with diameters of 10, 8.3, 7.3, and 6.3 mm and a height of 170 mm, were fabricated using stereolithography (SLA) technology. The designs were crafted in SolidWorks software. These CAD models were subsequently transferred to PreForm software (Formlabs) to change their format to Standard Triangle Language (STL). To ensure high resolution and superior print quality, the slice thickness set to 50 μm. Given the model height of 170 mm, this slicing resolution resulted in approximately 3400 layers per sample.

For the material, rigid resin from Formlabs was selected. The printing process was carried out using the Form 3 printer, a state-of-the-art SLA machine renowned for its accuracy and reliability in fabricating high-resolution parts.

Following the printing process, the samples underwent a comprehensive post-processing routine. Initially, the samples were washed using the automated Form Wash system (Formlabs), which utilized isopropanol alcohol (IPA, 99% purity) to remove any residual uncured resin from the surface of the printed parts. This step is crucial for ensuring that the final parts are clean and free of contaminants that could affect the subsequent curing process. After washing, the samples were divided into two groups for post-curing. The post-curing process was conducted at two distinct temperatures: 60 and 70 °C, with each group being exposed to these conditions for one hour. The curing process employed 13 multi-directional LED lights, which emit ultraviolet (UV) light at optimal wavelengths, ensuring thorough and uniform curing throughout the samples.

To assess the mechanical properties of the cured samples, a 3-point bending test was conducted using a universal testing machine (MTS Insight, Electromechanical 30 kN Standard Length). The test parameters were carefully controlled, with a crosshead speed of 10 mm/min and a span of 160 mm, to ensure consistent and accurate measurements. This test is designed to evaluate the flexural strength, stiffness, and toughness of the samples, providing critical data on how the curing temperature influences the mechanical performance of the SLA-printed parts.

Results and Discussion

The deflection test results across all diameters revealed a clear trend, shown in Fig. 1. Samples cured at 60 °C consistently exhibited higher deflections compared to those cured at 70 °C. The 10 mm sample cured at 60 °C deflected by 8.41 ± 1.2 mm under load, whereas the same sample cured at 70 °C deflected by only 6.23 ± 0.9 mm. This trend continued across smaller diameters as well, with the 6.3 mm sample cured at 60 °C showing a deflection of 15.87 ± 1.7 mm, compared to 13.38 ± 1.4 mm for the 70 °C cured sample. This consistent observation across all samples suggests that the material cured at the lower temperature retains greater flexibility or ductility.

The increased deflection observed in the 60 °C cured samples indicates that the material did not achieve the same level of cross-linking as the samples cured at 70 °C. Cross-linking in photopolymer resins, like the Rigid Resin 10 K, is directly related to the mobility of polymer chains within the material. At 60 °C, the resin may not have reached its full polymerization potential, resulting in a higher percentage of uncured monomers or partially polymerized chains. These uncured regions contribute to the material's flexibility, as the polymer chains can move more freely under applied stress, leading to greater deflection. On the other hand, the reduced deflection observed in the samples cured at 70 °C suggests a higher degree of polymerization, resulting in a denser and more rigid cross-linked network. At this higher temperature, the resin achieved more complete polymerization, which reduced the mobility of the polymer chains and thus their ability to deform under load. This lead to lower deflection values, indicating that the material is stiffer and more suitable for applications where rigidity is essential.

Stiffness, defined as the ratio of peak load to deflection, is shown in Fig. 2. Samples cured at 70 °C exhibited higher stiffness across all diameters. 10 mm sample cured at 70 °C had a stiffness of 51.36 ± 3.2 N/mm, compared to 42.40 ± 2.4 N/mm for the sample cured at 60 °C. This pattern was consistent across the range of sample diameters, with the smallest difference in stiffness observed in the 6.3 mm samples (7.28 ± 1.3 N/mm at 70 °C versus 5.79 ± 0.8 N/mm at 60 °C). The increased stiffness in samples cured at 70 °C indicates a more rigid material. This is likely

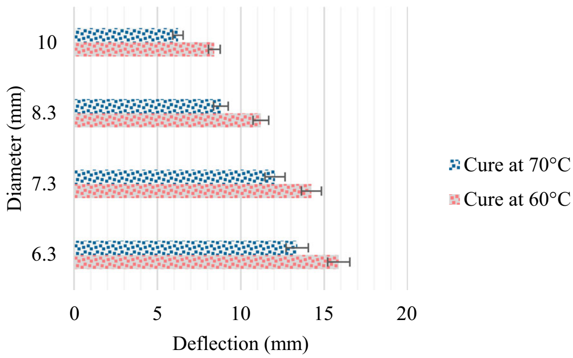

Fig. 1 Deflection of cylinders with various diameters and cured at 60 and 70 °C

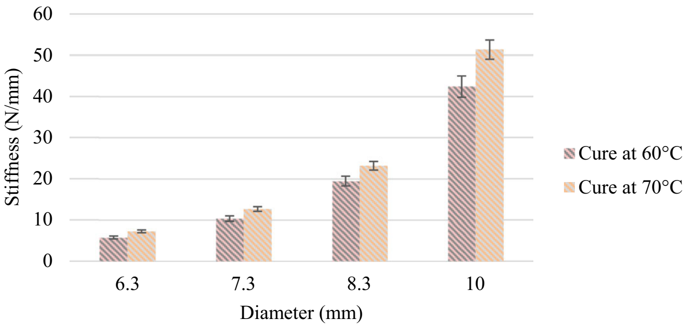

Fig. 2 Stiffness of cylinders with various diameters and cured in 60 and 70 °C

because the higher temperature led to more complete polymerization and a tighter, denser cross-linked network in the material. The results of this study clearly showed that curing at 70 °C produces a material that is better suited for such applications, as it consistently demonstrates higher stiffness and lower deflection compared to samples cured at 60 °C. Chen et al. [15] concluded regardless of ambient temperature and post-polymerization time duration, the provisional resin with post-polymerization were significantly stronger than the groups without post-polymerization.

While the primary focus has been on deflection and stiffness, peak load data provides additional insight into the material's behavior, shown in Fig. 3. Interestingly, the peak load was higher in samples cured at 60 °C for the larger diameters (10 and 8.3 mm), suggesting that the material's ability to withstand maximum load before failure is somewhat enhanced at the lower curing temperature. The peak load for the 10 mm sample was 355.5 ± 20.4 N at 60 °C compared to 320.5 ± 19.7 N at 70 °C. A similar trend was observed for the 8.3 mm sample. This result may seem surprising at first, as stiffer materials are generally expected to support higher loads. However, the key to understanding this lies in the difference between stiffness and toughness. Toughness refers to the amount of energy a material can absorb before it breaks. More flexible materials, such as those cured at 60 °C, can absorb more energy by deforming under load. This ability to bend and stretch allows them to carry heavier loads without failing immediately. Although the samples cured at 60 °C are less stiff, their flexibility allows them to distribute stress more evenly throughout the material. This even distribution of stress helps to prevent cracks from forming quickly, enabling the material to bear a higher peak load before it fails [16, 17].

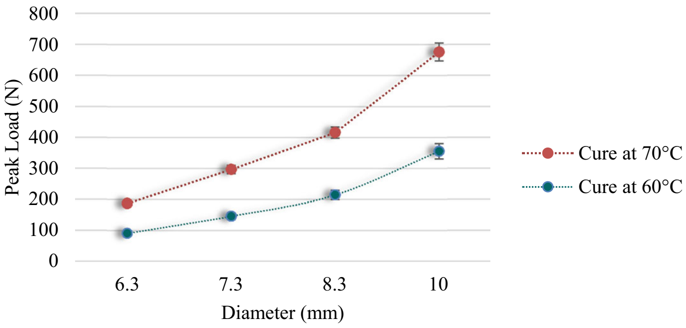

Fig. 3 Peak load of different samples cured at 60 and 70 °C

Conclusion

In conclusion, this study demonstrated that post-curing temperatures significantly impact the mechanical durability of SLA-printed components intended for load-bearing applications. Cylinders cured at 70 °C exhibited higher stiffness and rigidity, making them more suitable for applications that require minimal deflection and greater structural integrity. Conversely, samples cured at 60 °C, while less rigid, showed increased flexibility and peak load capacity, which can be beneficial for applications where toughness and the ability to absorb energy are more critical. These findings underscore the importance of optimizing post-curing conditions to tailor the mechanical properties of SLA-printed parts to specific performance requirements.

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