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Abstract

This study aims to assess the performance of an Additive Manufacturing (AM) machine, specifically a Selective Laser Sintering (SLS) machine, through the design and evaluation of a benchmarking artifact. Drawing from insights gained in previous research, the artifact is meticulously crafted with two distinct materials to explore potential variations in geometric accuracy. The artifact comprises two types: one featuring straight geometries and another incorporating curved elements. The research methodology involves printing both artifact types at default machine settings, followed by precise measurements using a 3D scanner. The inclusion of straight and curved features facilitates a comprehensive examination of the machine's ability to reproduce diverse geometries. The amalgamation of these features into a combined artifact provides a holistic assessment of the machine's overall performance. To validate the benchmarking artifact, the final design is reproduced, and its output is compared not only with the original design but also with real-life parts. The results show that flexible polymers offer higher accuracy but lower resolution, while rigid polymers provide better resolution but with a greater number of defects. This comparative analysis serves to highlight the accuracy and reliability of the benchmarking artifact in reflecting the machine's performance in practical scenarios. In conclusion, this study endeavours to advance the understanding of an SLS machine's capabilities by leveraging a carefully designed benchmarking artifact.

1. Introduction

Additive manufacturing, often referred to as 3D printing, has revolutionized the landscape of modern manufacturing by fundamentally altering traditional production paradigms [1, 2]. The ability to rapidly prototype and iterate designs has positioned additive manufacturing as a catalyst for innovation, enabling engineers and designers to test concepts quickly and refine products with unprecedented speed [3–7]. The critical evaluation of additive manufacturing (AM) processes is paramount to advancing the precision and quality of fabricated components [8, 9]. Specifically, benchmarking serves as a crucial tool for assessing the performance of AM systems, with a primary focus on geometry accuracy [10, 11]. Geometrical benchmarking plays a crucial role in additive manufacturing processes in assessing and understanding the capabilities and limitations of AM systems in producing precise and accurate geometric features [12]. The layer-by-layer fabrication inherent to AM introduces challenges, such as uneven part shrinkage and the distinctive 'staircase effect,' impacting dimensional accuracy [13, 14]. Moreover, post-processing requirements further underscore the necessity for comprehensive benchmarking methodologies. While benchmarking is a widely accepted practice, it takes on a unique significance in the context of Selective Laser Sintering (SLS) machines. The inherent risks associated with direct measurements of SLS components, particularly the use of high-power lasers, necessitate reliance on indirect measurements via test artifacts for performance evaluation [15].

Historically, the design of benchmark artifacts lacked standardization, leading to variations in features that often exceeded the capabilities of measuring instruments or were tailored solely for specific company interests rather than academic research [15]. Subsequent developments, such as the incorporation of overhang features by Mahesh and the emphasis on repeatability by Delgado *et al*, underscored the evolving nature of benchmark artifact design [16, 17]. Considering the impact of part orientation on geometric accuracy, recent experiments by Matuš *et al* shed light on the significant influence of orientation angles in the build chamber [18]. Townsend *et al* recommend several methods for measuring the surface of the additive manufacturing test artifacts but it's only limited to small builds [19]. Leirmo & Semeniuta, allocated test artifacts in fixed grid patterns within the build chamber and found that the xy-plane has a major influence on the geometric accuracy [20]. While their findings provide valuable insights, it is essential to acknowledge potential variations for larger specimens.

Recognizing the time-consuming nature of the tweaking process to optimize AM parameters, the proposal of a benchmark artifact emerges as an expedited method for gauging AM system performance [16]. This project attempts to design a benchmarking artifact tailored for assessing the geometric accuracy of an SLS machine named Sinterit Lisa Pro. The test artifact is constructed using two different types of polymeric materials to discern potential variations in part quality. The aim is to contribute to the ongoing discourse on refining AM processes and ensuring the reliability of fabricated components.

2. Methods

2.1. Artifact design

The study initiates with the meticulous design of benchmark artifacts, which are systematically categorized into three types: slanted, straight, and curved features. The artifact design phase results in the creation of two distinct designs, each emphasizing specific geometric characteristics. One design predominantly incorporates straight features, while the other accentuates curved elements. The envisioned benchmark artifacts comprise a comprehensive set of features for evaluating the performance of the additive manufacturing (AM) system.

The first type of benchmark artifact prioritizes curved features, encompassing circular holes, cylinders, curved thin walls with slots, a cylindrical freeform structure, and a gear-shaped real-life part (refer to figure 1(a)). The second type of benchmark artifact concentrates on straight, parallel features. It includes square shapes of various sizes, fins with differing widths at the sides, stair-like features, and rectangular holes (refer to figure 1(b)). The third benchmark artifact design represents a synergistic combination of both straight and curved features, emphasizing an efficient layout in terms of feature placement and complexity (refer to figure 1(c)). The testing method for each feature was adopted from Rabaioli *et al* [15].

2.2. Artifact materials

Two distinct powder materials supplied by Sinterit were employed to assess their influence on the additive manufacturing process. The first material, Polyamide 12 (PA 12) smooth, is recognized for its rigidity and is categorized in this study as the 'hard' material. The second material utilized in this study is Flexa Grey, classified as the 'soft' material. Flexa Grey is commonly employed as a rubber material for prototyping purposes and serves as the standard material for parts made from Thermoplastic Polyurethane (TPU). TPU is renowned for its flexibility and resilience, making it ideal for applications where softer material properties are required.

2.3. Artifact printing

The test artifacts drawn from CAD files are to be converted into .stl format and uploaded to a 3D printing software that is connected to the SLS machine. The printing parameters are set to default; the only edits that were made are the orientation and position, the rest are not touched upon. The default parameters include but not limited to, a layer height of 0.125 mm, laser power ratio of 1, print surface temperature offset of 0 °C, and a shrink ratio of 1 for all axes. The purpose of default parameters is test the original printing performance of the machine without any prior adjustments. The parameter setting is shown in figure 2.

The only parameter to be changed is the orientation of the artifact, the artifacts were printed in 3 different nesting orientations, namely flat placement, vertically and horizontally. The first batch is the testing batch, where they were built without considering too much warping, thus, they are built by placing it flat on the base of the build chamber. The second batch is built in flat-placed, vertical and horizontal orientation, this time without touching the base of the build chamber as shown in figure 3. The third batch has the same build process as the previous ones, the difference is that it is built with soft materials instead. Each artifact is printed in three different orientations, giving a total of six artifacts for hard materials, and six more for soft materials.

Once the parameters and orientation of the artifacts are set, the 3D printing software 'slices' the object, in other words, it converts the files into .scode format, which is a variant of G-code for 3 d printers. The software will display information about the build process after finished slicing the parts, which includes the total build

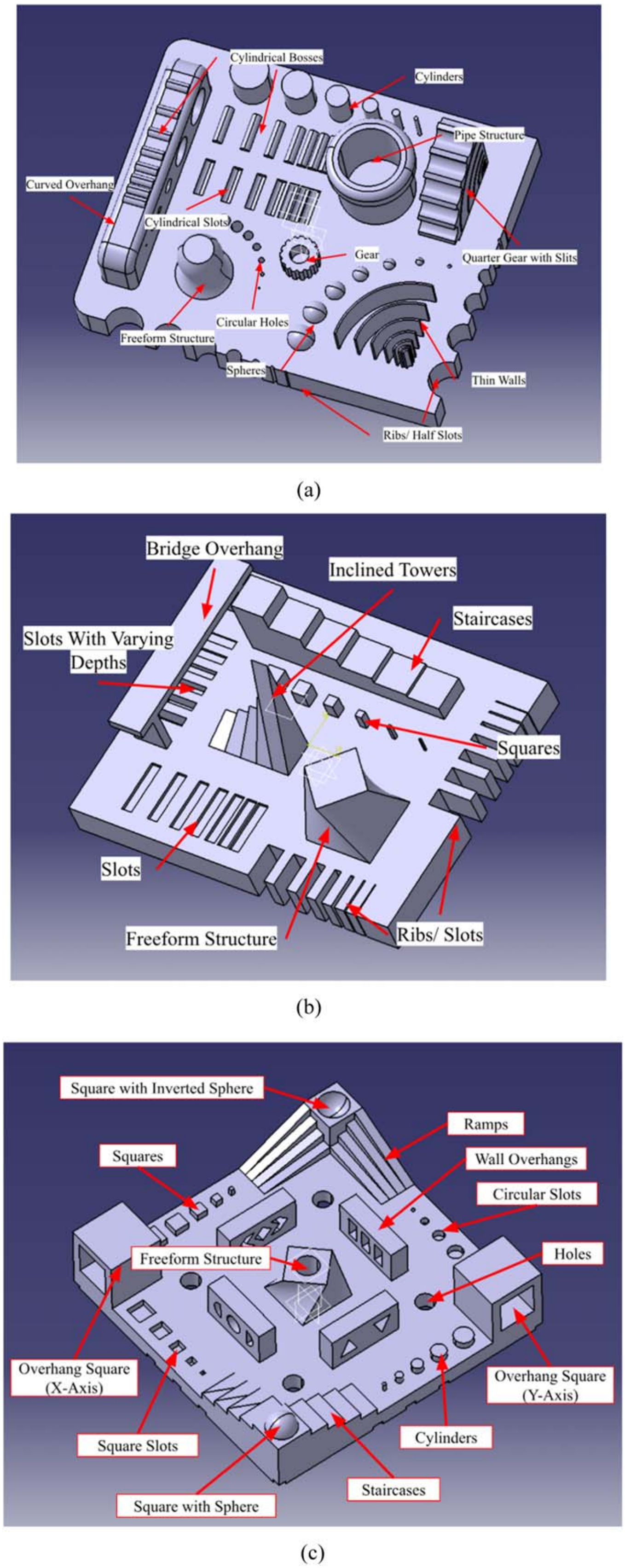

Figure 1. List of features for (a) curve test artifacts, (b) straight test artifacts, (c) combined test artifacts.

time for the artifacts, the theoretical amount of material required, and the build volume used. On average, 2 to 3 parts require up to 3 days of build time, which includes 1–2 h of prepping the material, and at least 3–4 h for the parts to cooldown after finish printing. The .scode file is automatically uploaded to the machine via Wi-Fi.

Figure 2. Printing parameters of 3D printing software.

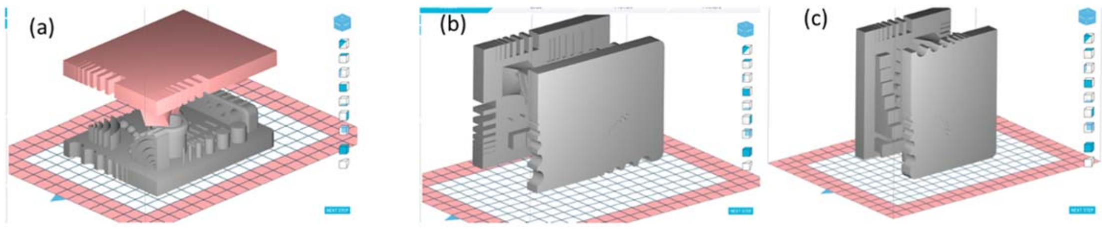

Figure 3. (a) Flat-placed orientation (b) horizontal orientation and (c) vertical orientation.

2.4. 3D scanning

Once finished printing, the artifacts are brought to a 3D scanner to scan them digitally, and this digital model is to be compared with the original CAD drawing to analyze any deviations in the printed parts. The 3D scanner is a stationary scanner by the brand name of 'Perceptron Smart3D'. This is a laser scanner that can capture dimensional data in one direction, thus, the specimen is placed on a rotating table, allowing the scanner to scan each surface of the artifact.

The sequence process of operating the scanner is shown in figure 4. Features that are either too difficult to print or are unable to be detected by the scanner for any reason are tweaked/rejected in the final artifact design, in which the features are to be combined. The final design is printed again to validate the features, and a design guideline is proposed for designing a benchmark artifact for an SLS machine.

2.5. Feature validation

The features are validated for the final design, as there is a possibility that some features may not be suitable for testing the machine's performance. Once the suitable features are identified and verified, a new artifact is designed. This artifact incorporates all the acceptable features. The combined feature artifact is then printed to verify the inclusion and functionality of these features.

Additionally, several real-life parts, including a clutch inner plate, two circular discs, a mounting plate, and a large syringe holder (see figure 5), are printed as part of this process. These parts are created to test the machine's performance in fabricating actual working components. All parts are printed in a single printing process using default parameters, and their orientation is flat during printing.

3. Results and discussion

The artifacts are printed with 2 types of material known as PA12 and TPU. The analysis starts with the artifacts built using hard material (PA12). The artifacts reveal noticeable signs of warping, characterized by curling that is observed at the bottom of the flat-placed part. Additionally, both vertically and horizontally oriented parts exhibit sagging along the sides. The flat-placed artifact, being in direct contact with the base of the build chamber during construction, experiences warping due to excess heat (Refer figure 6). Furthermore, small bulges at the edges suggest part growth, a result of suboptimal laser power and bed temperature settings. In contrast, the vertically and horizontally oriented parts, constructed at the centre and away from the base, minimize base

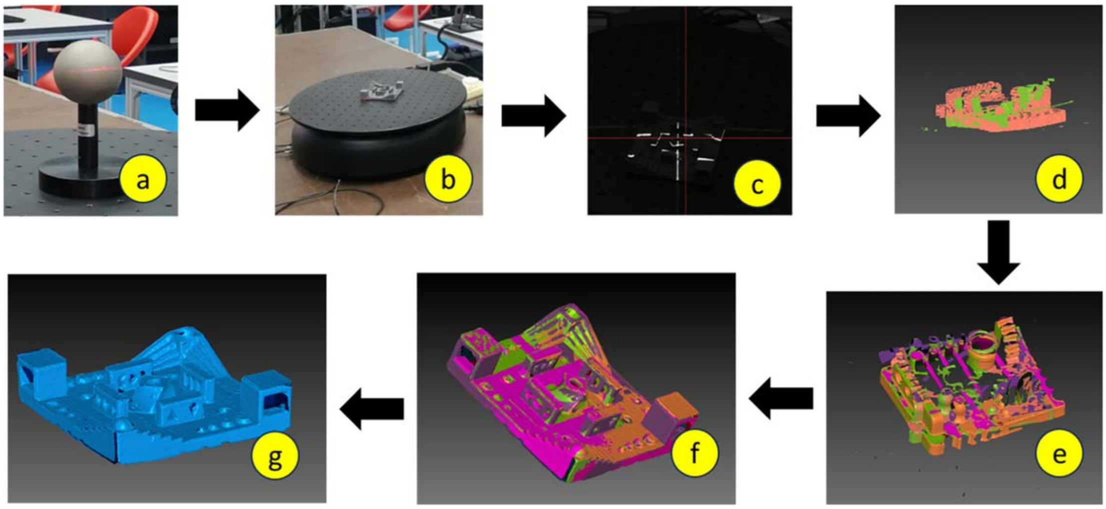

Figure 4. The sequence process of 3D scanning. (a) calibrating sphere for scanner. (b) scanning process of specimen. (c) aiming of scanner to specimen. (d) scanning process of specimen in viewport. (e) finished scan without alignment. (f) aligned surface scans. (g) merged surface scans to form a 3D model.

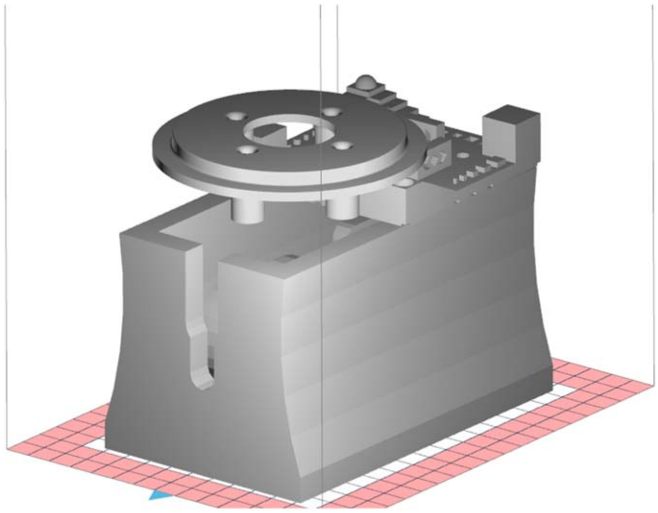

Figure 5. Printing setting of combined part with real-life parts.

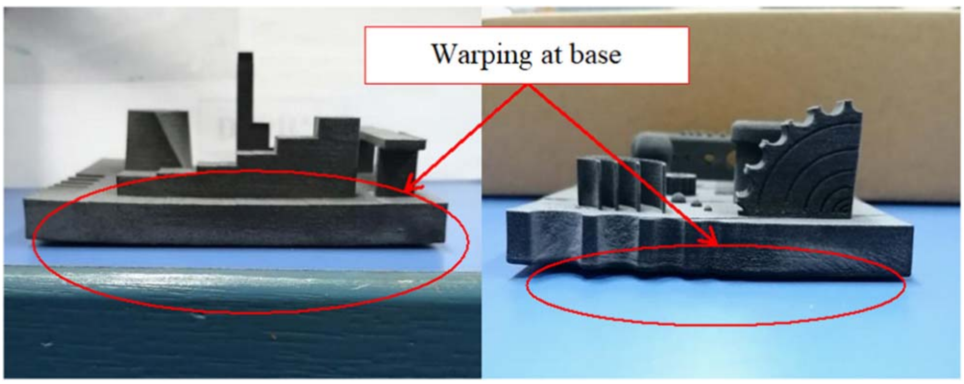

Figure 6. Warped base of artifact due to close proximity to base of build chamber.

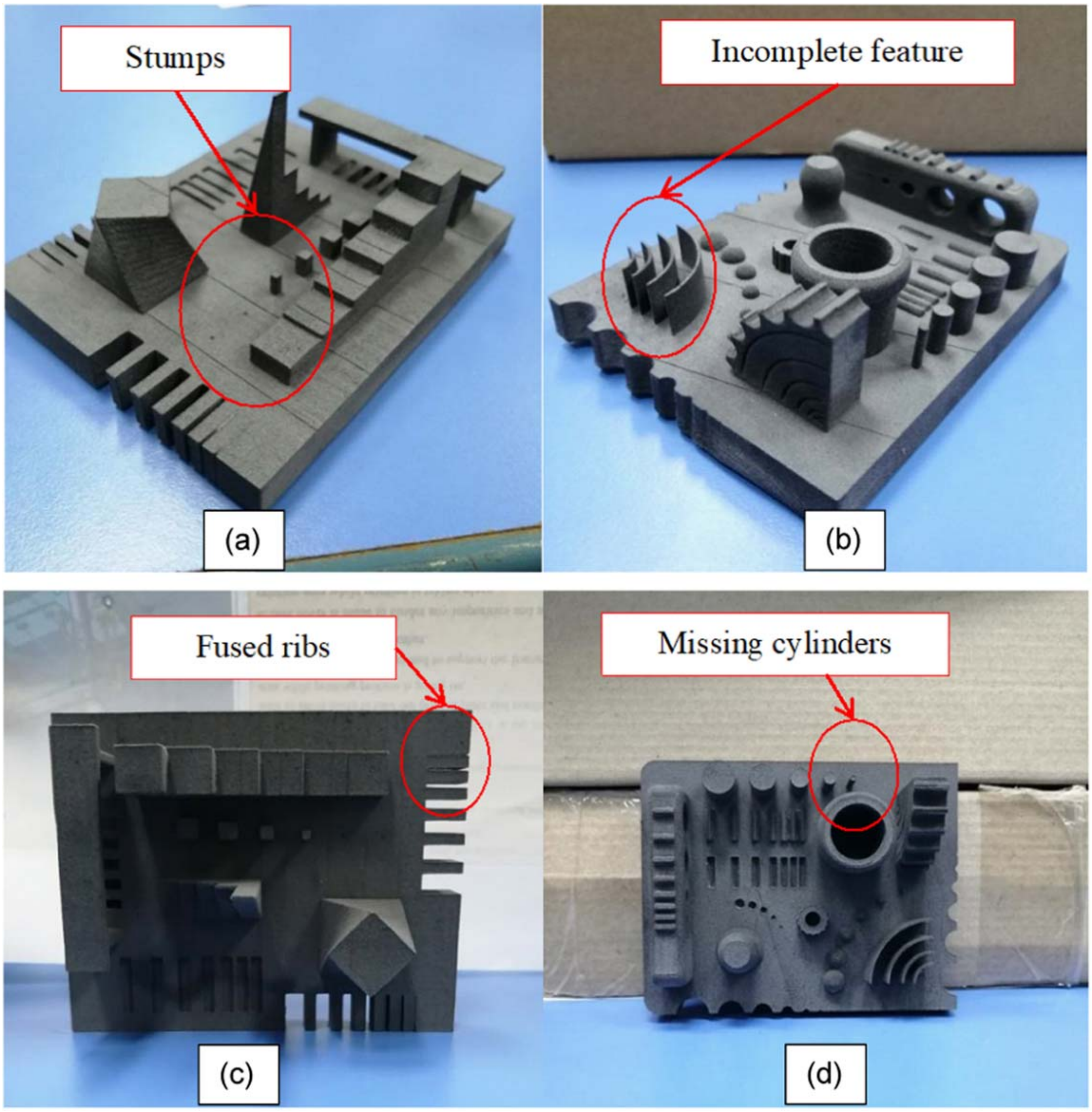

Figure 7. Feature resolutions & feature defects; (a) stumps (b) incomplete feature (c) fused ribs and (d) missing cylinders.

warping but introduce sagging due to higher laser power and bed temperature, aligning with the recoating direction.

For feature clarity, most components display sharp resolutions. However, limitations emerge in finer details such as ribs, squares, cylinders, bosses, and holes (refer figure 7). Some challenges include fused material clumping in ribs, an inability to build the smallest 0.5 mm $\times$ 0.5 mm square, and imperfectly constructed holes, rendering certain features unusable. Warping is also evident in the overhangs of both artifacts, where the bar overhang of the flat-placed artifact bulges upwards, and the horizontally and vertically oriented bar overhangs appear crooked in the recoating direction (Refer figure 8). Warping effects features across all orientations, influenced by both the recoating blade dragging layers and overall artifact warping. For flat-placed artifacts, features tilt towards the recoating direction, exacerbating the curling effect (Refer figure 9). Fine features exhibit more significant deviations than larger ones, with vertical deviations particularly pronounced for features with dimensions less than 1 mm. The staircase effect, a common aesthetic defect in 3D printing, is evident in the artifacts, with freeform features from straight feature artifacts displaying more visible lines compared to the smoother surface of freeform features in the curved artifact (Refer figure 10).

All six specimens for soft material exhibit a notable absence of significant warping, regardless of orientation. This remarkable resilience is attributed to the flexibility of the material, allowing controlled expansion and contraction during the cooling process, thus helping preserve the original dimensions of the artifacts. Unlike their hard material counterparts, these soft material artifacts showcase a remarkable resistance to warping, and post-process defects, such as broken overhangs in one straight feature specimen, are minimal. All features, including fine details, are successfully built without breakage, underscoring the robustness of the soft material in

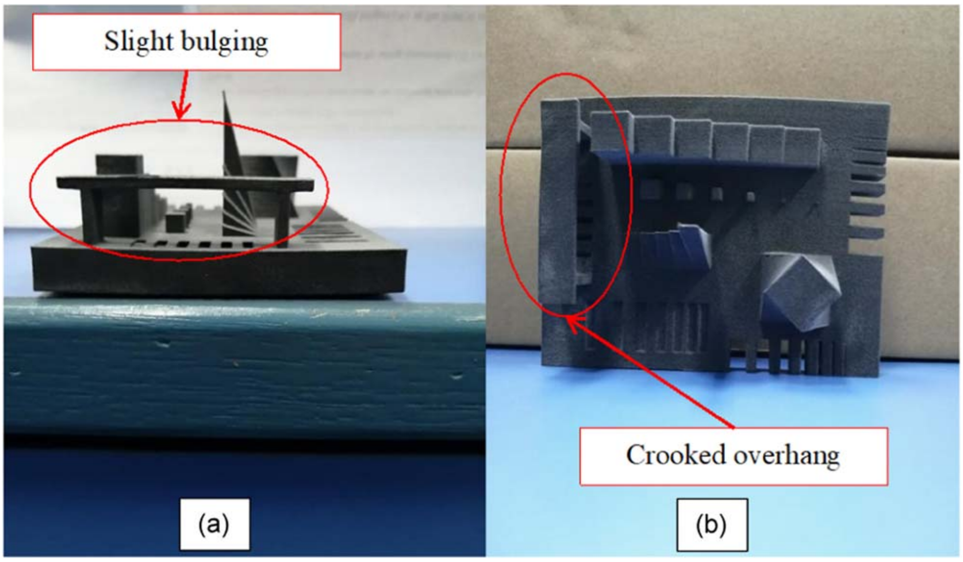

Figure 8. Warped overhangs in differing build orientations; (a) slight bulging and (b) crooked overhang.

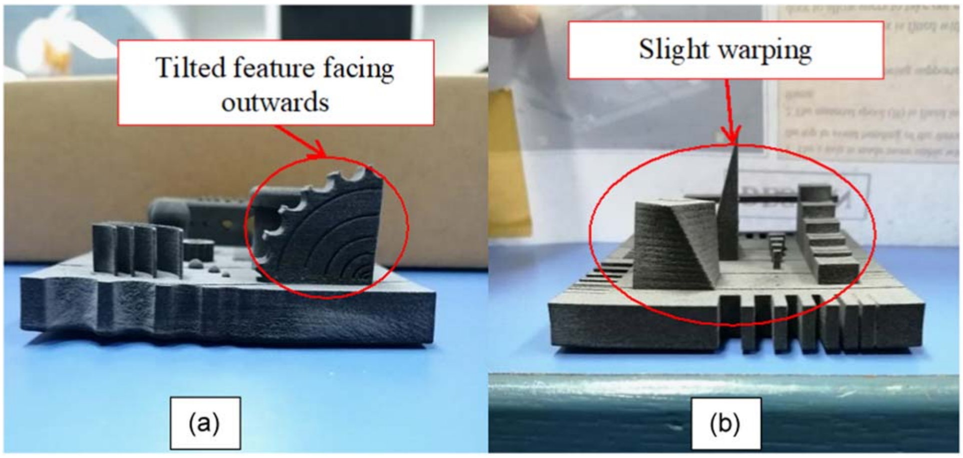

Figure 9. (a) Warped features tilting outwards and (b) slight warping.

maintaining structural integrity. However, there is a visible difference in feature resolution compared to those printed with hard materials. Although the obtained measurements generally align with design specifications, the soft material exhibits lower feature resolution. For instance, the smallest square displays an average deviation of 0.2 mm, with the flat-placed part showing a deviation of 0.067 mm, exceeding the 10% deviation threshold. Fine features, especially those at the 0.5 mm or lower range, tend to exhibit greater dimensional deviation, and it's worth noting that manual measurements were necessary due to scanner limitations, introducing potential user error.

Similar to artifacts printed with hard material, fine features at or below 0.5 mm are fused with surrounding material, particularly evident in the ribs on the sides and front. A notable contrast is observed in the holes of the curved artifact, which are properly built up to the fifth smallest circle (Refer figure 11). Additionally, the soft material artifact showcases narrower distances fused for all three types of features compared to its hard material counterpart. The quarter gear in the soft artifact also displays fused slits, a result of the lower melting temperature causing support material to melt and fuse with features during cooling (Refer figure 12). In summary, artifacts fabricated with soft material exhibit significantly less warping than those with hard material. Warping is found to be dependent on orientation and recoating pressure from the blade, emphasizing the need for precise calibration parameters. Despite the absence of warping issues, long build times impact finer features, leading to fusion with the surrounding material. This exploration of artifacts printed with soft materials provides valuable insights into the material-specific challenges and advantages in the additive manufacturing process.

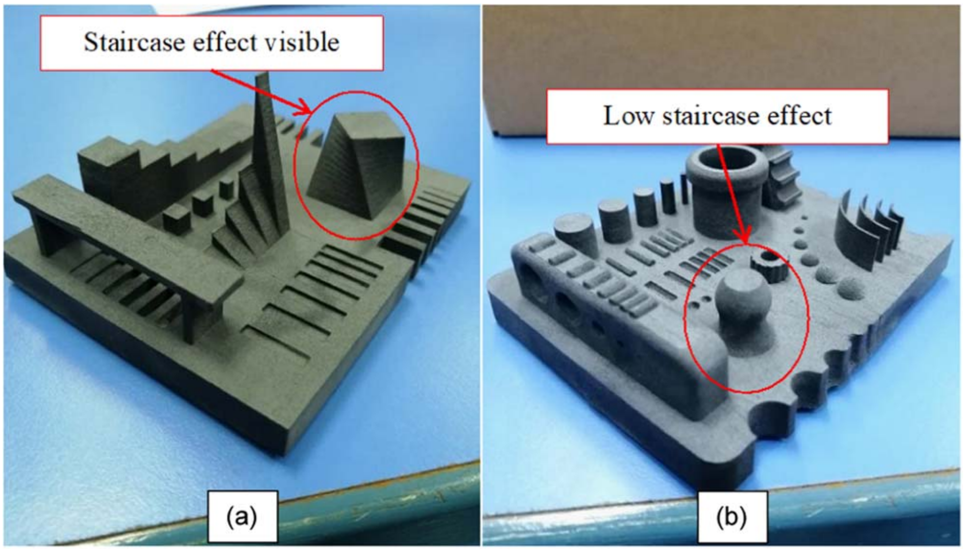

Figure 10. Free form structures with (a) staircase effect visible and (b) low staircase effect.

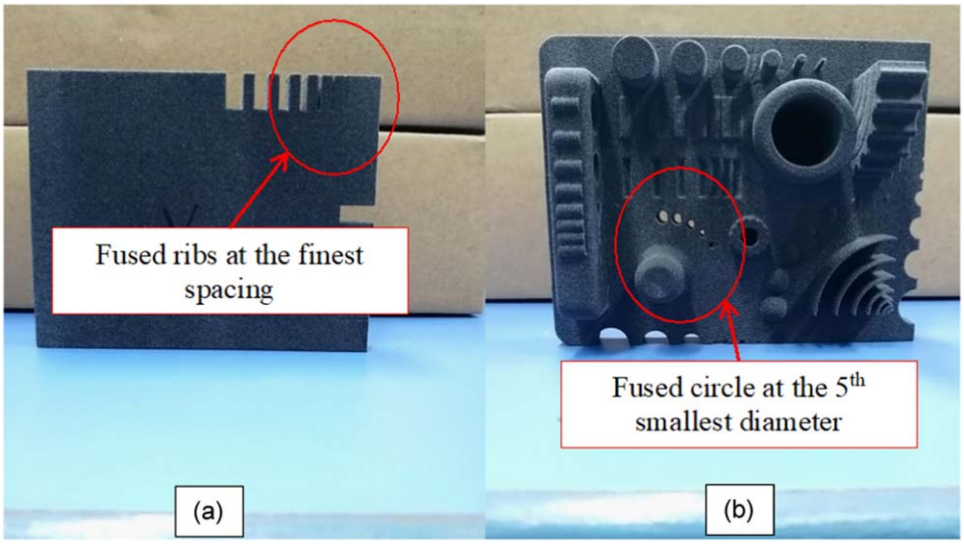

Figure 11. Fused fine features for soft artifacts; (a) fused ribs at the finest spacing and (b) fused circle at the 5th smallest diameter.

Based on the results for both materials, it suggested that feature sizes below 1 mm are unsuitable for testing on the artifacts. The cooling process causes some fine features to fuse with surrounding material, impacting readings. The project's goal to print these artifacts using default settings further discourages the use of smaller feature sizes, particularly those at or below 0.5 mm. To ensure the artifact can be built in any spot within the build chamber, grooves are added to minimize the warping of the base. Feature placement is designed to evenly distribute material concentrations, preventing warping due to different shrink rates. This redesign transforms the artifact into a symmetrical form, with the choice to make the base a square, allowing flexibility in selecting suitable build orientations without concerns about exceeding preheating boundaries (Refer figure 13).

The final design artifact, printed with hard material in a flat orientation and above the base to avoid warping, exhibits well-built features. However, challenges persist, with the smallest cylinder not being printed at all, and the smallest slots being too small for the machine to print. Despite these limitations, the resolution of the features remains sharp, even with a build layer thickness of 0.125 mm. Warping has reduced compared to previous artifacts, with no significant bulging at the centre (Refer figure 14). However, the corners of the artifact exhibit upward curling, indicating uneven shrinkage, likely due to the artifact's thinness. Despite these issues, features, except those at the corners, do not experience significant warping or deviations from their original positions.

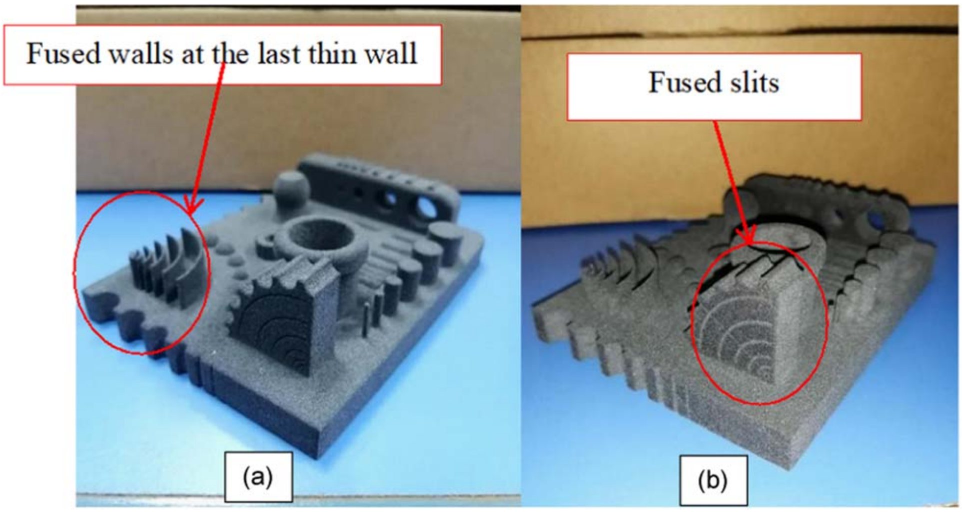

Figure 12. (a) Fused thin walls and (b) fused slits.

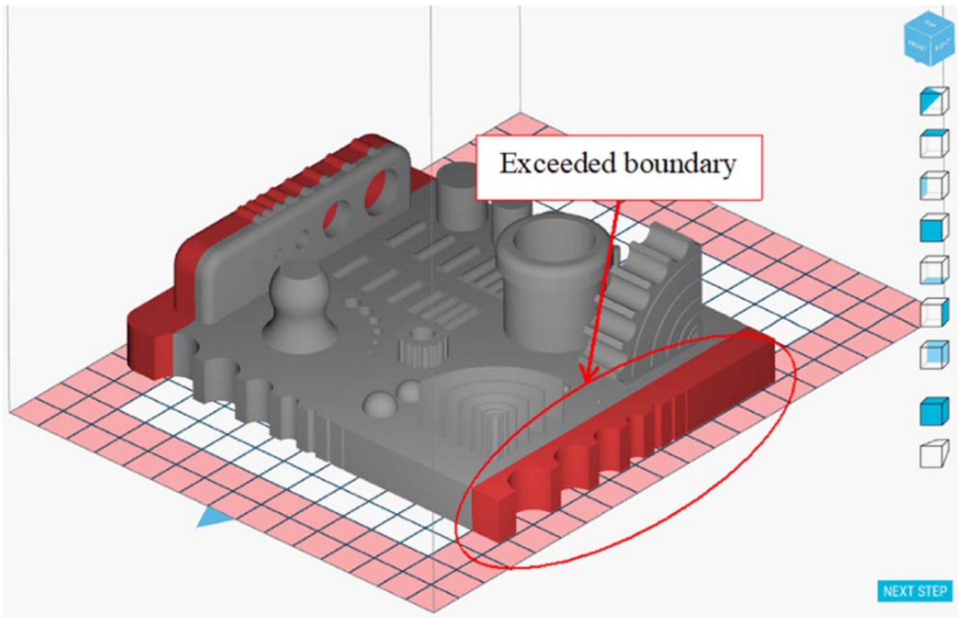

Figure 13. 3D Model exceeds preheat boundary of build chamber.

Figure 14. Warped base of combined artifact.

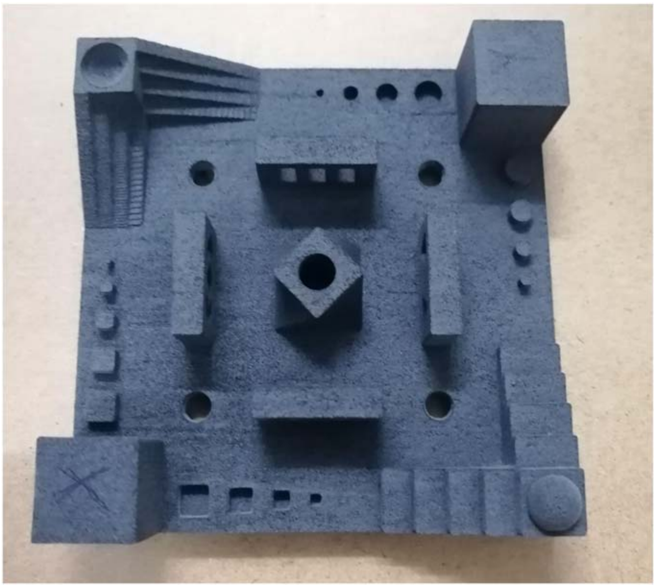

Figure 15. Combined artifact.

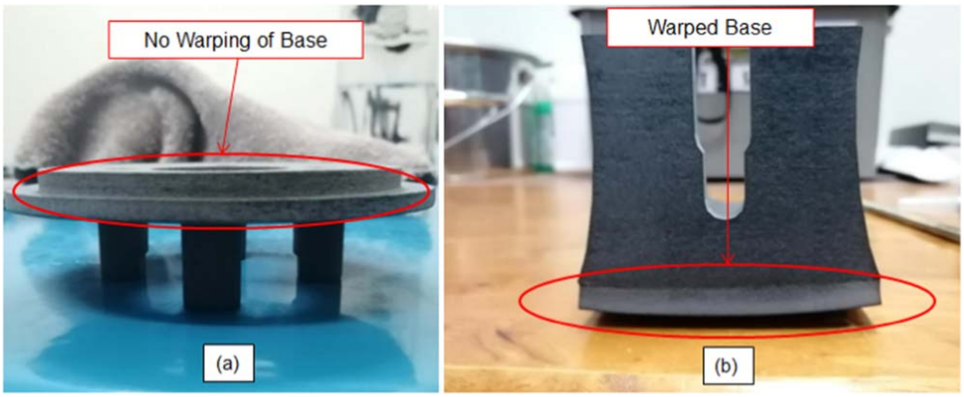

Figure 16. Warping in clutch plate and syringe holder.

Unfortunately, the corner features still display distortion, tilting outward from the centre. The x-axis overhang experiences a more significant tilt than the y-axis overhang, with the U-shaped layer facing recoating being more susceptible to drag. Despite this, features with a solid foundation at their base, such as the ramps, exhibit less distortion. The staircase feature shows minimal warping, with only the outer corner tilted. Staircase effects are visible but smoothed out on the spheres, with more pronounced effects on the ramps due to low-angle requirements and fewer build layers. The wall overhangs around the freeform structure exhibit no significant distortions, as their thicker walls and different patterns reduce the impact of recoating drag. The freeform structure itself shows no warping and passes a perpendicular test with no visible defects (Refer figure 15).

The overall profile of the part appears normal, with some warping on features. The base of the part is flat compared to the combined artifact, as the clutch plate, built later, has less exposure to heat. Despite the flat base, the poles of the clutch plate bend outward due to minimal initial layer support. The syringe holder experiences significant warping at the bottom due to its position at the bottom of the build chamber, leading to internal overheating and deformation (Refer figure 16). The container of the syringe holder shows no warp or recoating blade drag but has slight warping at the top (Refer figure 17). The mounting plate, printed vertically, displays drag marks but is straight and usable. Circular discs, also printed vertically, exhibit drag-induced defects, impacting their intended function (Refer figure 18).

In summary, while the artifact design achieves success in reducing warping compared to previous attempts, refinements are needed, particularly in determining a suitable range for smaller feature sizes. The artifact's overall design is considered acceptable, bearing in mind that the observed warping signifies the potential for

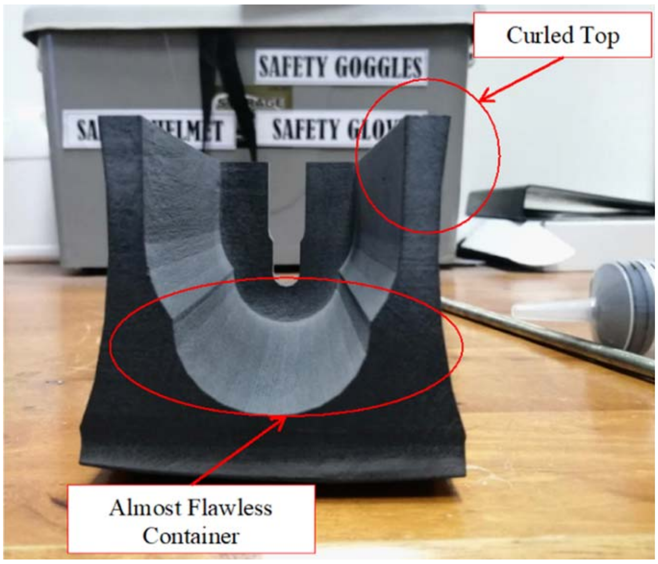

Figure 17. Container of syringe holder.

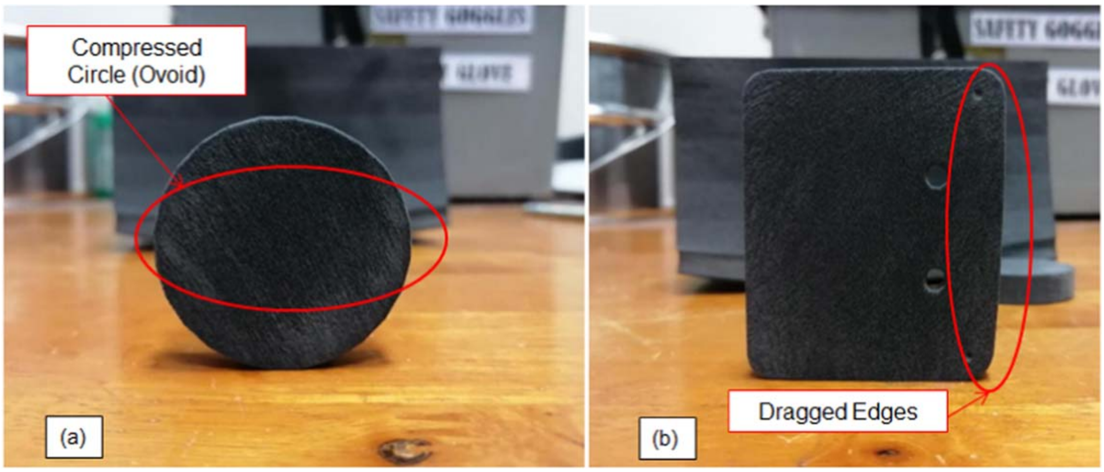

Figure 18. Drag defect on mounting plate and syringe holder.

calibration improvements to eliminate warping entirely. The investigation into machine parameters reveals their profound impact on printability and part quality. The default hatch spacing, when not carefully adjusted, leads to issues such as fusion of features and warping, emphasizing the need for meticulous parameter tuning. Laser power, layer thickness, and build orientation are identified as crucial factors influencing defect rates, feature resolution, and overall part quality. It is consistent with previous studies that have demonstrated how variations in laser power can significantly affect the sintering process, influencing thermal energy transfer and, consequently, the final part surface roughness and mechanical properties [21, 22]. Additionally, layer thickness plays a critical role in determining surface finish, dimensional accuracy, and mechanical strength [23, 24]. While our study does not provide direct experimental data on these parameters, our results align with prior research that emphasizes the importance of optimizing these factors to improve the precision and functionality of SLS-produced components. This study provides a set of design guidelines for optimal SLS printing, addressing factors such as feature size, base geometry, and feature distribution.

Our work contributes to the body of research in SLS by introducing a new benchmarking artifact specifically designed to assess the geometric accuracy of SLS machines across different materials. Unlike previous studies that focus on single material or limited geometries, our artifact includes both straight and curved geometries, offering a more comprehensive evaluation of machine performance. Additionally, the comparison of flexible and rigid polymers within the same benchmark provides valuable insights into material-specific behavior under SLS processing.

In our study, we avoided incorporating features smaller than 1 mm in the benchmarking artifact to mitigate potential inaccuracies in the printed geometry. While this decision is based on the limitations observed in our experimental setup, it is important to note that SLS machines, including the Sinterit Lisa Pro, may face challenges in accurately reproducing small features due to factors such as resolution, material behavior, and machine calibration. However, these limitations are not inherent to SLS technology itself but are influenced by the machine's settings and material properties. In real-world applications, features below 1 mm may require careful consideration, such as adjusting processing parameters (e.g., laser power, layer height) or using machines with higher resolution capabilities to achieve the desired geometric accuracy. Moreover, while slanted features were not included in the current design of the benchmarking artifact, we acknowledge that such features could provide valuable insights into the machine's ability to replicate angled surfaces. Future work will explore the inclusion of slanted geometries to broaden the scope of benchmarking for SLS machines

While the present study focuses on the performance of the Sinterit Lisa Pro, we recognize that other SLS machines from different manufacturers may have distinct specifications and capabilities, which could influence the results. The conclusions drawn from our work, especially those related to material behavior and geometric accuracy, are generally applicable across SLS machines. However, adjustments in processing parameters such as laser power, scan speed, and layer thickness may be required depending on the specific machine being used. We recommend that practitioners consider these factors when adapting the benchmarking approach to other SLS systems, as different machines may require fine-tuning of their parameters to achieve similar results.

4. Conclusion

In conclusion, this study presents a comprehensive exploration of the performance of a selective laser sintering (SLS) machine through the design and testing of a benchmarking artifact. The findings underscore the critical influence of material selection and machine parameters on the quality and characteristics of printed parts. Soft material emerges as a favourable option for prototyping purposes, exhibiting fewer defects than hard material, albeit at the expense of lower resolution. The observed defect rates in hard material-printed parts highlight the significance of machine default parameters, particularly in relation to sintering temperatures. The study found a trade-off between material types in terms of defect rates. Rigid polymers generally exhibit better resolution but with a higher incidence of defects, while flexible polymers offer better accuracy at the expense of resolution. This trade-off is an important consideration for SLS machine users. Finally, we recommend that future practitioners of SLS, particularly those using the Sinterit Lisa Pro, consider using the proposed benchmarking artifact to evaluate the performance of their machines. However, it is important to note that the design of the artifact should be adapted based on specific application needs and machine capabilities. For example, adjustments in geometry and material choice may be required for different SLS machines. In essence, this research not only contributes to the specific understanding of SLS printing but also lays the groundwork for a standardized testing approach applicable to diverse AM methods.

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Conflicts of interest

The authors declare no conflicts of interest.

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

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