# Immersion Polishing Post-treatment of PLA 3D Printed Formed Parts on Its Surface and Mechanical Performance

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Steps were taken to improve the surface and mechanical performance of PLA 3D printed formed parts, reduce the "step texture" produced by the fused deposition process, and improve the quality of 3D printing by means of post-treatment. The PLA 3D formed parts were immersion polished with chloroform solution to investigate the effects of immersion polishing on the surface roughness, surface gloss, mechanical properties, and other factors of PLA formed parts. The results of the pre-experiment showed that 90% of the effect was due to the optimal concentration value of chloroform solution and 10% was the optimization of time for immersion polishing. Under the pre-experimental conditions, the surface roughness of the formed parts was reduced by 87%, and the surface gloss was increased by 510%, the surface quality and gloss were significantly improved, and the "step texture" was significantly reduced; meanwhile, the tensile and compressive ultimate strength of the formed parts were increased by 9.41% and 13.09%, respectively, and the mechanical performance were improved, and the quality of 3D printing post-treatment was significantly improved.

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## INTRODUCTION

Polylactic acid (PLA) is a bio-based biodegradable material made from starch extracted from renewable plant resources (*e.g.*, corn, cassava, *etc*.). It has the characteristics of low shrinkage and large molding size; it is not easy to warp and crack; it has no irritating odor; it is safe and environmentally friendly; and it is a commonly used consumable in the fused deposition 3D printing process (Ding *et al*. 2022). As the fused deposition 3D printing process uses layer-by-layer stacking of materials to generate a solid model, the differences in the shape of the contour of the layers and the height difference between adjacent layers cause the “step texture” when the material is stacked, which affects the surface quality of the model and printing accuracy (Feng *et al*. 2022).

Polishing is the process of sanding the surface of 3D printed formed parts, the main purpose of which is to improve the surface and mechanical performance of the formed parts and reduce the “step texture.” Commonly used methods include mechanical sanding, surface primer treatment, and chemical treatment (Huang *et al*. 2022). Three types of chemical treatment can be described as cold steam treatment, hot steam treatment, and immersion treatment. Cold steam treatment is slower, and the surface treatment effect is not obvious. Hot steam treatment can easily produce a large amount of organic solvent vapour, which can cause harm to the human body after inhalation. Immersion treatment is faster, the surface treatment effect is obvious, and at the same time this approach reduces the organic solvent vapour production, such that safety and high efficiency characteristics can be achieved (Qi *et al.* 2023).

The molecular structure of PLA contains carbonyl group (C=O) and methyl group ($CH_3$). Among them, the oxygen atom in the carbonyl group (C=O) is more polar, attracting the electrons on the carbon atom to shift to the oxygen atom, resulting in uneven charge distribution, so the carbonyl group is a polar group. Methyl is the structure of the triangular nail, the main distribution of electrons in the "tail" of the three C-H bond, while the methyl bonding single electron "head" is only a small number of electrons, resulting in uneven distribution of charge, so the methyl is a polar group. In summary, PLA molecules containing carbonyl (C=O) and methyl ($CH_3$) polar groups are polar. The chloroform molecule is an asymmetric tetrahedral structure with more electrons on the three C-Cl bonds than on the C-H bonds. Therefore, the chloroform molecule is also polar (Wang *et al*. 2023). Because the polarity is similar, the two are soluble. The solubility parameter of chloroform is 19.0, and that of PLA is 19.0 to 20.5. Because of similar values, both are soluble (Han *et al*. 2022). Through the dissolving effect of chloroform solution on PLA, the microscopic raised parts on the surface of the PLA formed parts are dissolved. Under the influence of surface tension of the liquid and gravity, the solution in the raised parts flows to the concave parts, and after solidification, a uniform and smooth surface effect is produced (Qi *et al*. 2019).

Taking PLA 3D printed formed parts as an example, this paper explores the effects of immersion polishing on the surface roughness, surface gloss, spatial dimensions, color properties, and mechanical performance of PLA 3D printed formed parts. The data provides a reference for the application of immersion polishing in the post-treatment of PLA 3D printed formed parts.

## EXPERIMENTAL

### Materials

Polylactic acid (PLA) filament (light blue, 1.75 mm diameter, Anycubic, China) was used for additive manufacturing by the fused deposition method.

Chloroform reagent (analytical reagent, concentration 98%, Yanshan petrochemical, China) was used to prepare chloroform solution for immersion polishing.

### Specimen Preparation

SolidWorks software was used to design the "square", "dumbbell", and "cylinder" formed parts as shown in Fig. 1.

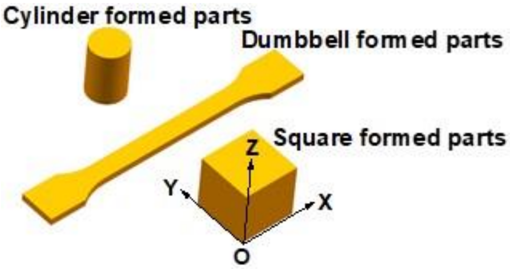


**Fig. 1.** Schematic structure of formed parts

The 3D model files created by SolidWorks software were exported to STL format and then imported to Cura software for slicing. The main task of slicing was to set the 3D printing parameters. Among them, the temperature of the extrusion head was set to 210 °C, the layer height was set to 0.2 mm, the printing speed was set to 40 mm/s, the thickness of the top and bottom layers was set to 1.2 mm, the infill type was set to mesh, the infill rate was set to 15%, and the extrusion multiplication rate was set to 100%.

A Kobra 3D printer (XYZ printing, 0.4 mm nozzle diameter, Anycubic, China) and PLA filament were used for additive manufacturing by the fused deposition method. The entire 3D printing process was driven by the G-code and did not require any manual manipulation. At the end of the 3D printing, the formed part was removed from the printing platform using a spatula to strip away excess material such as the base and supports.

The immersion polishing experiment is carried out at 25 °C ambient temperature. The specific process was as follows: firstly, add anhydrous ethanol to prepare a suitable concentration of chloroform solution, and pour the solution into a beaker of about 150 mL. Then, completely immerse the PLA formed parts made by 3D printing into the chloroform solution, and then take them out after a certain time of immersion. Finally, the immersed formed parts were dried naturally until completely dry, and the standard time for drying was 60 min.

## Performance Test

The surface roughness of the formed parts after immersion polishing was tested using a surface roughness tester (JB-4C, Shanghai Taiming, China), and $R_a$ (the arithmetic mean difference of contours) was selected as the main parameter for evaluating the degree of surface roughness of PLA formed parts.

The surface gloss of the formed parts after immersion polishing was tested using a surface gloss tester (HG-268, Shenzhen San En Shi, China), and the test data at 60° incidence angle was selected as the main parameter for evaluating the surface gloss of the PLA formed parts.

The surface color of the immersion-polished formed parts was tested using a portable spectrophotometer (CI-60, X-Rite; USA), and three color properties, namely, brightness, saturation, and hue, were selected for quantitative analysis.

The surface morphology of the formed parts was observed using an industrial flush-focus microscope (CL-MA-48M, Colomer; China).

A universal mechanical testing machine (AG-X, Shimadzu, Japan) was used to test the tensile and compressive properties of "dumbbell-shaped" and "cylindrical" formed parts, respectively. The tests were carried out in a quasi-static loading state, with reference to the standards ISO 527-1 (2012) and ISO 604 (2002). The tensile loading speed was 2 mm/min, and the compressive loading speed was 1 mm/min.

## RESULT AND DISCUSSION

### Pre-experimentation of Immersion Polishing Concentration

Chloroform solutions of 50, 60, 70, 80, and 90% were prepared in 150 mL each, and five groups of PLA formed parts (three samples per group) were immersed in the chloroform solution for 10 s. The surface roughness and surface gloss are shown in Figs. 2 and 3, respectively. With chloroform less than 70%, the difference between the surface roughness and surface gloss before and after polishing was small, and the polishing effect was not obvious. The chloroform solution with a concentration of ≥70% showed a greater reduction of surface roughness after polishing. The difference between the surface gloss increased, and the polishing effect was obvious. Among them, 90% chloroform yielded the most and exhibited an obvious polishing effect, and the surface roughness of the formed parts after polishing was reduced by 87%. The surface gloss was increased by 510%, which was judged to be the optimal concentration for this pre-experiment.

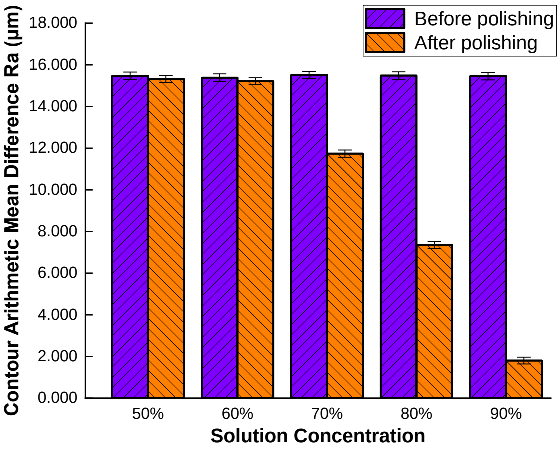


**Fig. 2.** Comparison of surface roughness

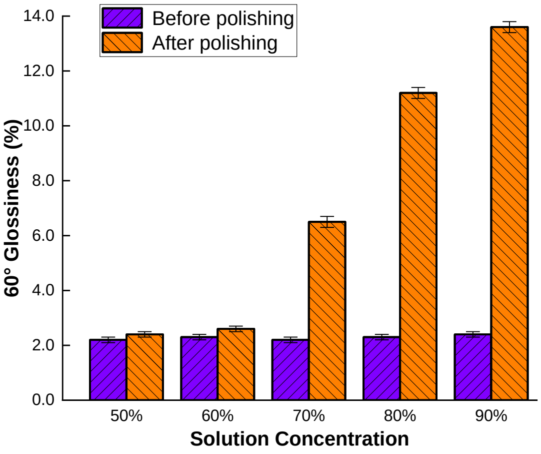


**Fig. 3.** Comparison of surface gloss

The solubility of a polymer in a liquid is determined by the magnitude of the intermolecular forces between the liquid molecules and the polymer molecules. Intermolecular force is essentially an electrical attraction; the greater the liquid concentration, the greater the number of molecules, the greater the electrical attraction between the molecules (Yang *et al*. 2022). At <70% chloroform, the solution contained an insufficient proportion of chloroform molecules, which was not enough to break the polymer molecules between the chain of secondary bonds in PLA. When the concentration of the chloroform solution was ≥70%, the number of chloroform molecules contained in the solution gradually increased. As a consequence, the electrical attraction between the chloroform molecules and the PLA molecules gradually increased sufficiently to break the secondary bonds between the polymer molecule chains. The PLA molecules gradually dissolved in the chloroform, becoming a thin layer of polymer adhered to the surface of the formed parts. Under the action of liquid surface tension and gravity, the thin layer of polymer solution flowed and spread, cutting the peaks and filling the valleys of the "step texture" on the surface of the formed parts, and achieving the effect of surface polishing (Li *et al*. 2022).

From the microscopic observation of the physical picture (Fig. 4), the surface of the PLA formed parts without chloroform solution polishing had a "step texture", and the surface contour is shown as a "water wave-like" curve (Fig. 5). After polishing with 90% chloroform solution, the surface of PLA formed parts became smooth. The "step texture" was obviously weakened (Fig. 4), and the "water wave-like" curve also became smooth (Fig. 5).

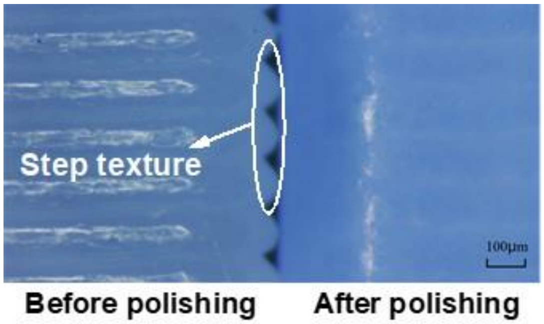


**Fig. 4.** Pre-experimental micrographs

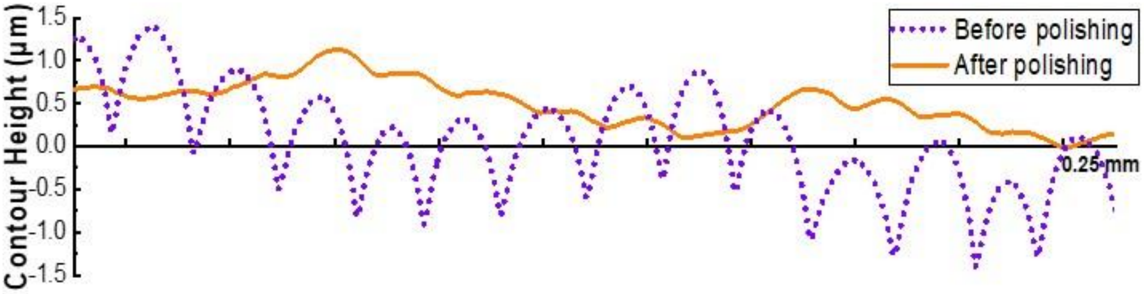


**Fig. 5.** Surface contour of PLA formed parts

## Pre-experimentation of Immersion Polishing Time

Four groups of PLA formed parts (three samples per group) were immersed in chloroform solution for 5, 10, 15, or 20 s. The surface roughness and surface gloss are shown in Figs. 6 and 7, respectively. The surface roughness values of the four groups of PLA formed parts before polishing were close to each other. When polishing was done for 5 s, the surface roughness value of the PLA formed parts decreased by 53%, and the surface gloss value increased by 270%. When polishing was done for 10 s, the surface roughness value of the PLA formed parts decreased by 87%, and the surface gloss value increased by 510%. When polishing was done for 15 s, the surface roughness value decreased by 82%, and the surface gloss value increased by 392%. After polishing for 20 s, the surface roughness value of the PLA formed parts decreased by 77%, and the surface gloss value increased by 348%. Therefore, 10 s was judged to be the optimum time for polishing of PLA formed parts in 90% chloroform solution.

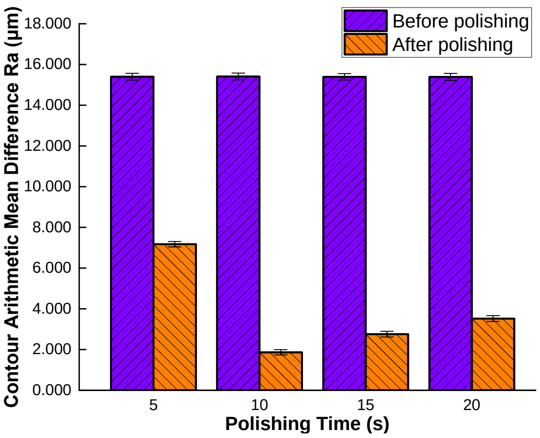


**Fig. 6.** Comparison of surface roughness

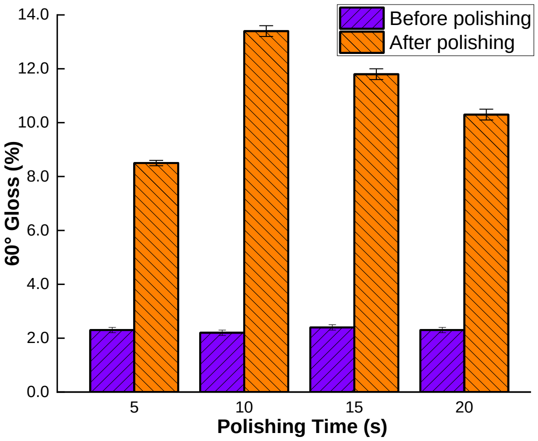
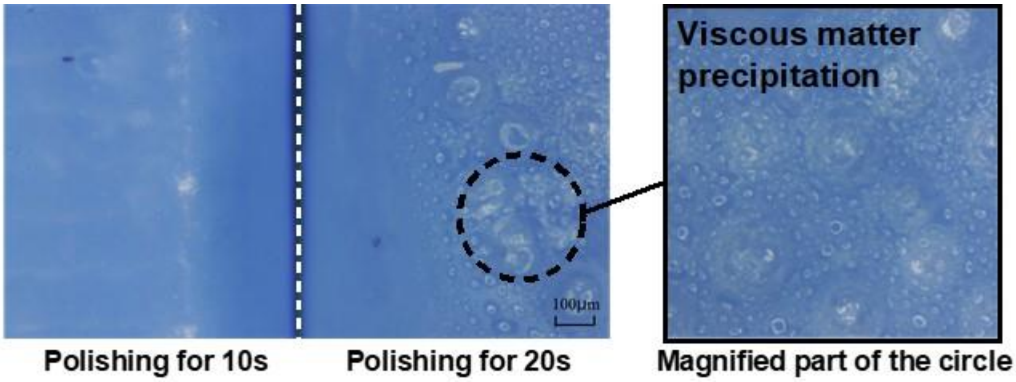


**Fig. 7.** Comparison of surface gloss



Polishing for 10s Polishing for 20s Magnified part of the circle

**Fig. 8.** Pre-experimental micrographs

When polishing the PLA formed parts with 90% chloroform solution, due to the direct contact between the formed parts and the chloroform solution, the Van der Waals force rapidly generated between the chloroform molecule and the PLA molecule, which broke the secondary bond between the polymer molecular chains, produced dissolution in a short time, eliminated the "step texture" on the surface of the formed parts, and improved the surface quality of the formed parts (Mo *et al*. 2022). When the immersion time was too long, the dissolving effect of chloroform solution penetrated from the outside to the inside, more and more chloroform molecules dissolved the PLA molecules inside the formed parts, forming more viscous matter (high concentration polymer solution) attached to the surface of the formed parts. After drying, the viscous matter precipitated and accumulated (Fig. 8), which caused the surface of the formed parts to become increasingly rough with reduced gloss, thus reducing the polishing effect (Feng *et al*. 2019).

According to the results of the pre-experiment above, 90% solution concentration and 10 s immersion time were judged to be the optimal parameter combination for this pre-experiment. Therefore, 90% chloroform solution was used for all subsequent immersion polishing experiments, and the immersion time was 10 s for all of them.

## Effect of Immersion Polishing on the Spatial Dimensions of PLA Formed Parts

The spatial dimensions (OX, OY, OZ dimensions) of the "square" PLA formed parts (design dimensions: 30*30*30 mm) were measured before immersion polishing. The PLA formed parts were immersed into 90% chloroform for 10 s.

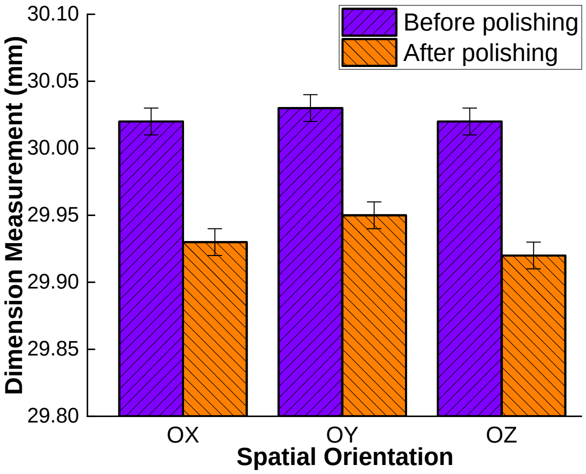


**Fig. 9.** Comparison of spatial dimensions

The spatial dimensions of the PLA formed parts were measured again after drying, as shown in Fig. 9. Before polishing, the spatial dimensions OX, OY, and OZ of the PLA formed parts were 30.02 mm, 30.03 mm, and 30.02 mm, respectively. After immersion polishing, the spatial dimensions OX, OY, and OZ of the PLA formed parts were 29.93 mm, 29.95 mm, and 29.92 mm, respectively, which corresponds to reductions by 0.30%, 0.27%, and 0.33%, respectively.

Because the polishing time and concentration were the preferred parameters in the pre-experiment, immersion polishing did not have a significant effect on the dimensional changes of the PLA formed parts. After polishing, the dimensions of PLA formed parts decreased slightly in all directions, which was attributed to the fact that the polishing process cut down the peaks and filled the valleys of the "step texture" on the surface of the formed parts. The process caused the surface of the formed parts to be flattened. With the disappearance of the peaks and raised parts of the "step texture", the surface of the formed parts became smoother, and the size of the formed part decreased slightly in all directions (Liu *et al*. 2019).

## Effect of Immersion Polishing on Color Properties of PLA Formed Parts

The three color properties of the "square" PLA formed parts were tested for brightness, saturation, and hue, and the results are shown in Fig. 10. The brightness, saturation and hue values of the PLA formed parts were 46.37, 65.53, and 286.26°, respectively, before polishing. After polishing, the brightness, saturation, and hue values of the PLA formed parts were 50.38, 69.98, and 286.26°, respectively, and the brightness and saturation values had increased by 8.65% and 6.79%. The hue values remained unchanged.

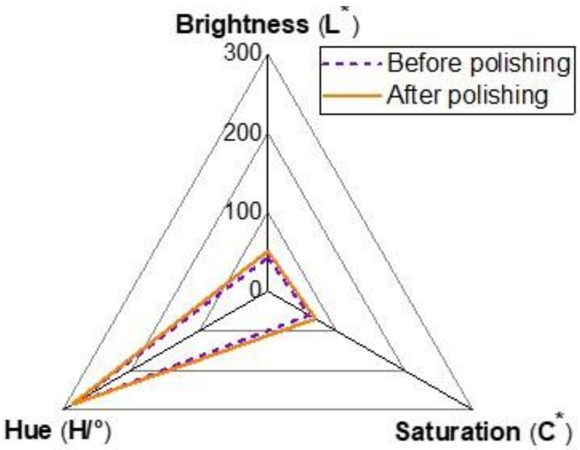


**Fig. 10.** Comparison of color properties

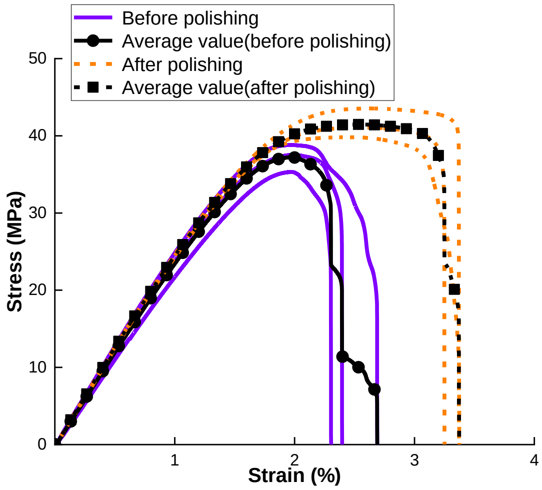
Brightness is a characteristic quantity that represents the reflectance of light from an object. The higher the light reflection coefficient of an object's surface, the higher the brightness of its color (Li *et al*. 2020). Due to the significant increase in the light reflection coefficient of the formed part surface after polishing, the brightness value of the formed part surface increases.

The saturation value characterizes the purity of the color. When the incident light irradiates on the surface of the formed parts, it is reflected on the surface of the formed parts (the first surface reflection), and the rest of the incident light is absorbed by the selective absorption of the material (Liu *et al*. 2020). The main color light of the material is reflected, and the color that the human eye observes is the mixing of the reflected light of the first layer surface and the main color light (Zhou and Xu 2022). The surface roughness value of PLA formed parts without polishing is larger, and the first surface reflection shows non-directionality, which is easy to be recognized by the human eye. As the first surface reflection light is neutral color white light, when the main color light is mixed with neutral color white light, the saturation of the main color light decreases, and the color of the PLA formed parts looks dull. After polishing, the surface gloss of PLA formed parts increases, the first layer of reflected light shows a high degree of directionality, not easy to enter the human eye, the main color light mixed in the first layer of the surface reflective light is less, the color saturation of the main color light increases, and the color of the PLA formed parts appears bright.

Hue is the main feature that distinguishes one color from another color, and its properties depend on the subjective feeling produced by the stimulation of the human eye by the radiation spectrum (Yang *et al*. 2021). Because polishing changes the gloss of the surface of the formed parts and does not change the essential properties of the color, the spectral composition of the reflected light on the surface of the formed parts is still the same as the spectral composition of the incident light, and the hue of the formed parts remains unchanged.

## Effect of Immersion Polishing on the Mechanical Performance of PLA Formed Parts

The tensile and compressive properties of two groups of "dumbbell-shaped" and "cylindrical" PLA formed parts (three samples per group) were tested, and the results are shown in Figs. 11 and 12.



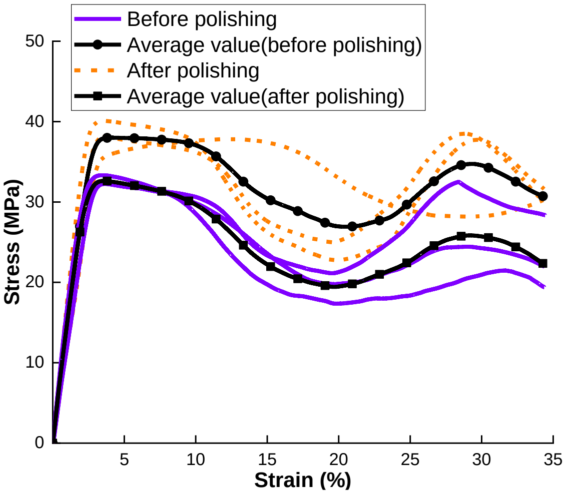


**Fig. 11.** Comparison of tensile properties **Fig. 12.** Comparison of compression properties

The average tensile ultimate strength of three "dumbbell- shaped" PLA formed parts before polishing was 37.7 MPa, and the average tensile ultimate strength after polishing was 41.3 MPa, which represents an increase of 9.4%. The average compressive ultimate strength of three "cylindrical" PLA formed parts before polishing was 34.0 MPa, and the average compressive ultimate strength after polishing was 38.4 MPa, which represented an increase of 13.1%.

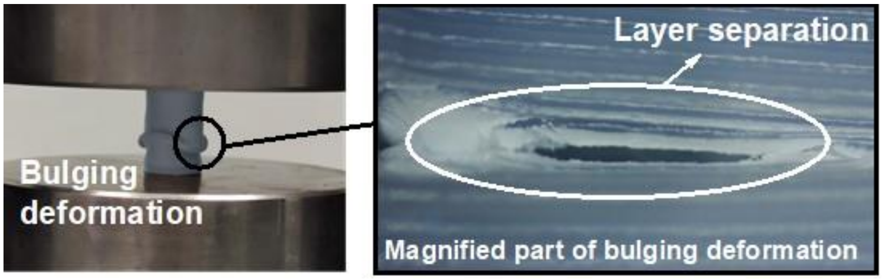


**Fig. 13.** Microscopic morphology of the layer separation region

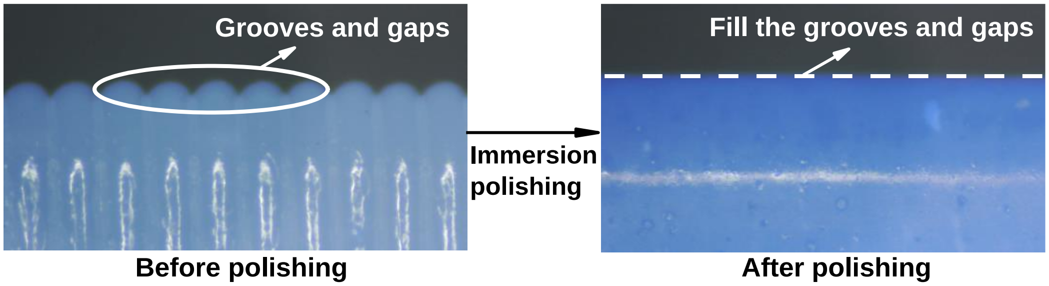


**Fig. 14.** Grooves and gaps micrographs

The interlayer adhesion of PLA formed parts was affected by the internal filling structure and external wall structure of the formed parts. Because immersion polishing has no effect on the internal filling structure of the formed parts, the effect of immersion polishing on the interlayer adhesion is mainly reflected in the external wall structure of the formed parts (Wang *et al*. 2022). The PLA formed parts without polishing, due to the outer wall structure showed the characteristics of “step texture.” Thus, there are grooves and gaps between adjacent layers. The grooves and gaps are prone to stress concentration, which affects the interlayer adhesion performance of the formed parts (Wang *et al*. 2019). Take the compression test as an example, when the “cylinder” formed part is axially compressed, with the increase of compression displacement, the transverse (X-Y direction) deformation of the formed part increases, showing obvious bulging deformation. The bulging deformation causes shear stresses to be generated at the interlayer adhesive interface where the bonding force is weak. Under the influence of shear stress, the grooves and gaps are prone to stress concentration and lead to the cracking of the interlayer adhesive interface (Wang *et al*. 2020). The microscopic morphology of the layer separation region is shown in Fig. 13. However, after polishing, the dissolved PLA solution flowed into the grooves and gaps between adjacent layers of the formed parts under the action of surface tension of the liquid, and after the diffusion, infiltration and solidification of the PLA molecules, the mechanical embedded force and intermolecular van der Waals force were formed to fill the grooves and gaps between adjacent layers of the formed parts (Fig. 14). These changes further enhanced the mechanical performance of the formed parts (Liu *et al*. 2021).

## CONCLUSIONS

1. The results of the pre-experiment showed that 90% was the optimal concentration value of chloroform solution and 10 s was the optimal time for immersion polishing. Under the pre-experimental conditions, the surface roughness of the formed parts was reduced by 87%, and the surface gloss was increased by 510%, the surface quality and gloss were significantly improved, and the "step texture" was significantly reduced.
2. Using 90% chloroform solution, the PLA formed parts were immersed and polished for 10 s, and the measured spatial dimensions were reduced by 0.30%, 0.27%, 0.33%, respectively, with small spatial dimensional changes; the brightness value and saturation value were increased by 8.65%, 6.79%, and the hue value was kept unchanged. The colors of the formed parts appeared to be brighter and more vibrant; the tensile and compressive strengths were increased by 9.4%, 13.1%, and the mechanical performance of the formed parts was improved.

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