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PREPARATION AND SELECTIVE LASER SINTERING OF WOOD-PLASTIC COMPOSITE POWERS AND POST PROCESSING

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A mixing process was successfully developed to prepare Wood-Plastic Composite(WPC) powders. Before mix, the wood flour is alkalized for reducing the hydrophilic nature of wood fiber and improving the wettability and the adhesion actions of the interface. Green parts were formed from WPC by selective laser sintering (SLS) process, when the applied laser energy density was 283W/mm^2, the SLS green parts had sufficient strengths for features as small as 0.1mm to be built and post-processed, and relatively high dimensional accuracy. In order to further improve the properties of the pattern, the post-processing – infiltration with wax – is introduced. Through post-processing, the void fraction is decreased from 51% to 7%, the mechanical properties are significantly improved, the average tensile strength, bending strength, and impact strength are 1.157 MPa, 2.72 MPa and 1.4125KJ/m^2. Compared with those without post processing, the tensile strength is 87 times higher than without post processing and the bending strength increased by 384% while the impact strength increased by 94%. After post-processing, surface quality is greatly improved, Ra is below 0.013mm on average, and after grinding and polishing the surface is smoother and Ra is below 0.007mm on average.

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1. Introduction

The rapid prototyping technologies are manufacturing techniques for building objects from three-dimensional computer aided design (CAD) models. The product to be fabricated is presented as an amultilayered CAD model, where successively each layer is converted into a physical layer then bonded to the preceding layers, until the product is completed. Since the mid-eighties, a variety of rapid prototyping technologies have been developed, including the stereolithography (SLA) (Charles, 1986)[1], the selective laser sintering (SLS) (Deckard, 1986)[2], the fused deposition modelling (FDM) (Crump, 1988)[3], the laminated object manufacturing (LOM) (Feygin, 1988)[4], and the three-dimensional printing (Pham and Gault, 1998; Rochus et al., 2007)[5,6]. Selective Laser Sintering(SLS) is a powder-based rapid prototyping (RP) process, a method of sintering and building up powder heated with a laser beam, and was conducted for the first time by C.R.Dechard from the University of Texas in 1989[7]. SLS directly forms solid components according to a three-dimensional CAD model by selective sintering of successive layers of powdered raw materials (Kumar, 2003)[8]. Currently, SLS is in a rapidly developing trend and is widely used in investment casting[9,10].

A wide range of materials can be used in SLS, such as nylon, polycarbonate, ABS, sand, wax and metal[11], but the high price of materials is the bottleneck to constraining widespread application of SLS, so reducing the cost of materials has always been a research focus. Wood-Plastic Composites (WPC) is a green biological material, it has many advantages such as good mechanical properties, high hardness, anti-aging, dimensional stability, easy to color, easy to texturize and is

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also recyclable, with an important advantage of its low-cost. In this paper, WPC is adopted as an SLS material to make parts with good mechanical properties as well as with good laser sintering properties, the cost parameters of the material is confined to 30 RMB per kilogram. In order to further improve the properties of the pattern, the post-processing – infiltrating with wax – is introduced.

2. Laser sintering characteristics and energy distribution

SLS is a solid freeform fabrication technique. It consists of a high-melting-point powder material and a low-melting-point powder material, and under the laser radiation, the low-melting-point powder melts, the liquid formed by the molten material binds the high-melting-point powder and solidifies when the temperature decreases, which leads to consolidation and the formation of parts. The outstanding advantage of SLS is that the un-sintered powder on the powder bed remains in its place to support the structure of sintered powder, thus no need to consider a support system, so very complex 3D parts can be achieved by SLS.

In the SLS RP process, CO_2 and the Nd:YAG laser are used as power. The CO_2 laser has high efficiency, launching an invisible laser of 10.6μm wavelength causing no damage to the working medium, therefor it is an ideal laser. The interaction between the laser beam and the WPC materials depends on the laser energy density distribution, as it nearly follows a Gaussian relationship. It is assumed that P is the laser power, ω_0 is the radius of the laser spot, therefore the laser energy density distribution q can be calculated as[12]:

$$q = \frac{2P}{\pi\omega_0^2}\exp\left(-2\frac{\rho^2}{\omega_0^2}\right) \quad (1)$$

where ρ is the radial distance from the center of the laser beam. When ρ=0, the energy density reaches max value; When $\rho=\omega_0$, the energy density decreases to $1/e^2$ of the central value; when ρ continues to increase, the energy density continues to decrease and gradually approaches zero. Circular of radius ω_0 is defined as the laser spot, it is assumed that I_0 is the max laser intensity in the middle of laser spot and I is the laser intensity value with distance ρ from the center of the laser spot, so I can be calculated as:

$$I = (1 - R_e)I_0 \exp\left(-2\frac{\rho^2}{\omega_0^2}\right) \quad (2)$$

Fig.1 shows the energy distribution of the Gaussian laser beam within the scope of the laser spot, which is divided into 40 × 40 spots, the value of the laser beam energy on every spot shows as different colors, the reddest color indicates the highest laser energy density(corresponding to value 1), the bluest color indicates the lowest laser energy density(corresponding to value 0).

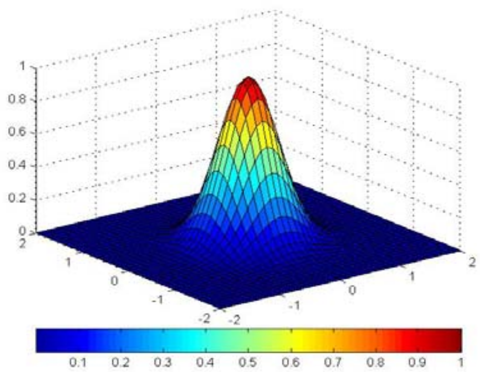
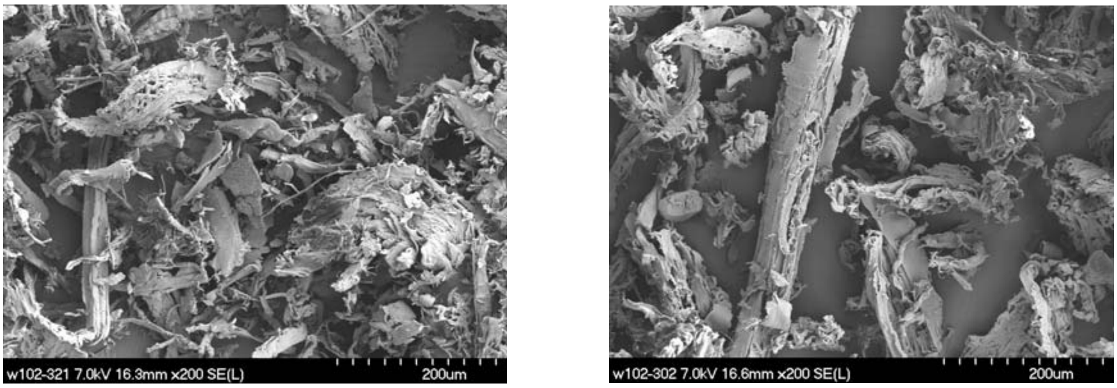


Fig.1 3D graphics of the energy distribution of Gaussian laser

3. WPC powder preparation

WPC is mainly composed of wood flour and a hot-melt adhesive powder, and the two components accounted for more than 90% of the total mass. There are also other additives in WPC such as a viscosity reducer and light stabilizer, etc.

Wood flour must be alkalized before use, and the alkalization process is as following: the wood flour is placed in the 10%~16% NaOH or KOH solution for twenty-four hours, then washed with water until the PH is 7, and then finally dried. Wood flour is made of cellulose, hemicellulose, lignin and extract. The cellulose cells contain so many hydrogen bonds that there is a strong hydrogen bonding interaction between the cells; the hydrophilicity is up to 8%~10%. There is strong hydrophilicity and chemical polarity, as Fig.2(a) shows. After alkalization, a part of pectin lignin hemicellulose and some other low-molecule impurities are dissolved and removed, as well as many hydrogen bonds. The surface of the fiber becomes rough, and this enhances the binding capacity of the interface between the fiber and the resin. After alkalization treatment, the remaining substance is mainly wood fiber, as Fig.2(b) shows. The alkaline solution opens the hydroxyl of the crystalline wood fiber, so the wood fiber becomes fluffy, and the surfaces are easy to adequately connect to the coupling agent, which will react with the hydroxyl of plant fiber, reduce the hydrophilic nature of wood fiber, and improve the wettability and the adhesion actions of the interface. The alkalization treatment makes the fiber split smaller reducing the diameter of the fiber, while the aspect ratio increases, while furthermore the interface with the matrix enlarges. It can be seen by comparing the wood flour SEM images before and after alkalization. During the washing process, the dust and other impurities in wood powder can also be removed.



(a) (b)

Fig.2 Wood flour before and after alkalization

The hot-melt adhesive powder used in the experiment is a co-polyester(CO-PES) hot-melt adhesive powder, as Fig.3 shows. It is a kind of plasticity adhesive, and in a certain temperature range its physical state changes with the temperature change while maintaining the same chemical properties. It is a non-toxic, tasteless and environmentally friendly chemical product, and its performance parameters are shown in Table.1.

Table 1. Performance parameters of Co-PES hot-melt adhesive powder.

Chemical Composition	Melt Range (℃)	Melting Index g/10min @160℃	Viscosity Pa.s@ 160℃	Heat bonding Conditions		
				Temperature (℃)	Pressure (kg/cm^2)	Time (s)
CO-PES	105-115	30	380	125-150	0.5-1.5	5-20

The alkalized wood flour is basically a wood fiber and has an irregular shape, making it easy to aggregate unlike granular chemical materials such as nylon, spreading the powder uniformly on a bed by a leveling roller is difficult. So it is necessary to add some amount of a viscosity reducer (graphite, white carbon black, calcium carbonate, talcum or glass powder) to improve the powder spreading effect.

Wood fiber carbonyls can act as chromophoric groups (aging initiator) which can accelerate the aging of the organic filler and make the surface of the composite fade, forming a thin aging layer and generating large areas of brittle fracture. Adding a light stabilizer can slow aging, increase aesthetics and the lifetime of the parts.

In WPC, alkalized wood flour and Co-PES hot-melt adhesive powder have a volume ratio of 10:8 ~ 9, they are the main ingredients of WPC. The viscosity reducer accounts for 5%～20% of the total mass of WPC, and the light stabilizer accounts for 0.2%～6% of the total mass of WPC, as Fig.4 shows.

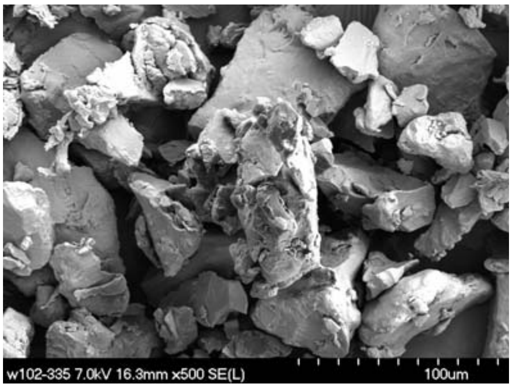


Fig.3 Co-PES hot-melt adhesive powder

Fig.4 WPC powder

4. Selective laser sintering process

Under laser radiation, the hot-melt adhesive powder melts, the liquid formed by the molten hot-melt adhesive powder binds the wood powder and solidifies when the temperature decreases, leading to consolidation ultimately forming parts.

The rapid prototypes were manufactured using a HRPS-IIIA type SLS machine built at Huazhong University of Science and Technology (HUST) in Wuhan, P.R. China. Experimental parameters are set as following: a CO_2 laser source with a wavelength of 10.6μm, maximum output power is 50W, power consumption is 39%, diameter of the laser spot is 0.3mm, scan space is 0.15mm, layer thickness is 0.2mm and the scanning speed is 2000 mm/s.

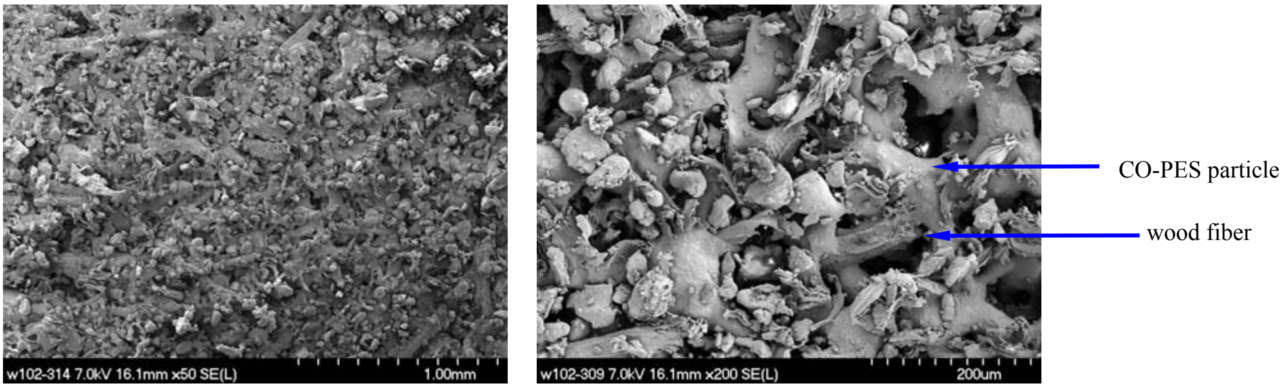
Before the laser is scanned, the entire machine bed is preheated to just below the melting point of the material by infra red heaters to minimize thermal distortion and to facilitate fusion to the previous layer. For WPC, the hot-melt adhesive powder has a lower melting point, and in this paper the fusion range of Co-PES hot-melt adhesive powder is between 105-115℃, as Table.1 shows, so preheating temperature must below 105℃.

Fig.5 shows the green parts, bevel gear with 120mm diameter is showed in Fig.5a), turbine disk with 136mm diameter is shown in Fig.5b). It can be seen the surface of the part is very rough and covered with a powder that can easily be removed.

a) b)

Fig.5 SLS green parts

Fig.6 shows the surface SEM photograph of one green part, from the microscopic point of view, the hot-melt adhesive powder melts and binds the wood powder together under the laser radiation, but there still exists a void fraction and its void fraction is 51%. Because of that, the surface of the part is very rough and the mechanical properties are very low, therefore post processing is necessary for WPC Green parts to improve surface quality and mechanical properties.

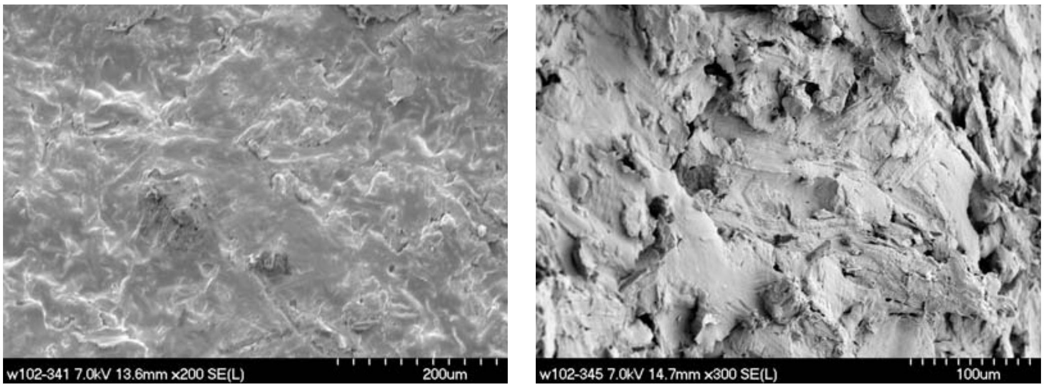


a) b)

Fig.6 Surface SEM photographes of part

5. Post Processing

Post processing – infiltrating with wax – is discussed in this study. When the green parts are immersed in the melting wax, the melting wax would infiltrate the green parts through capillarity action. After post-processing, most of the void is filled with wax, and the voids fraction is decreased from 51% to 7%. As shown in Fig.7, although there are some voids and naked WPC particles, most of the WPC particles are well wrapped by wax. It indicates that wax shows good bonding with WPC because both Co-PES hot-melt adhesive powder and the alkalized wood powder are non-polar materials



a) b)

Fig. 7 Surface SEM photographes of WPC specimen after post-processing

After Post processing – infiltrating with wax, the density of parts is greatly improved, it is 1.4~1.8 times as that before post processing. The mechanical properties are related to density and are significantly improved, The dimensions of Wax-infiltrated parts after post-processing in the X direction, Y direction and Z direction were slightly increased, but the increased value is below 0.1mm, so post-processing makes little impact on the dimensional precision of Wax-infiltrated parts. But after post-processing, surface quality has been greatly improved and surface roughness has been greatly decrease, as shown in Fig. 8.

a) b)

Fig.8 SEM images of WPC specimens after post-processing

6. Mechanical Properties Testing

Mechanical Properties of parts include tensile strength, bending strength, impact strength and elongation rate, etc. Tests are made to compare the mechanical properties between green parts and Wax-infiltrated parts.

Tensile strength：The dog-bone-shaped tensile specimens having a typical dimension of 165 × 13 × 4 mm, were measured using a Regear computer controlled Universal Testing Machine (Shenzhen Regear Instrument Cooperation, China) according to ASTM D638-2004. A crosshead speed of 5 mm/min and a gage length of 50 mm were used for the test.

Bending：Specimens measuring 80 × 13 × 4 mm were measured under three-point bending using the same Universal Testing Machine in accordance with ASTM D790-2004. A crosshead speed of 1.9 mm/min and a span length of 64 mm were used for the test.

Impact: Specimens measuring 80 × 10 × 4 mm were measured under three-point bending using the Combination Impact Testing Machine in accordance with GB /T 1043 – 1993(China).

Table 2 shows mechanical properties testing results of green part and Table 3 shows that of wax-infiltrated parts. From results it can been known, after post processing－infiltrating with wax, the green parts become compact and the density is improved, so the mechanical properties are significantly improved.

Table 2 Mechanical properties testing results of green part.

	Tensile strength (MPa)	Bending strength (MPa)	Impact strength (kJ/m^2)
Green parts	0.014	0.475	0.567

Table 3 Mechanical properties testing results of wax-infiltrated parts.

	Test No.1	Test No.2	Test No.3	Average value
Tensile strength (MPa)	1.23	1.38	1.032	1.214
Bending strength (MPa)	2.7	2.79	2.71	2.73
Impact strength (kJ/m^2)	1.6679	1.2274	1.3422	1.4125
Elongation rate	0.3%	0.12%	0.322%	0.247%
Breakdown strength (Mpa)	2.22	2.35	2.29	2.29
Elastic modular (GPa)	0.51	0.56	0.53	0.53

For wax-infiltrated parts, the average tensile strength is 1.214 Mpa, the average bending strength is 2.73 MPa and average impact strength is 1.4125kJ/m^2, as showed in Table 3, compared with those without post processing, the tensile strength is 87 times, the bending strength is 4.7 times and impact strength is 2.5 times, respectively, as Fig. 9 shows.

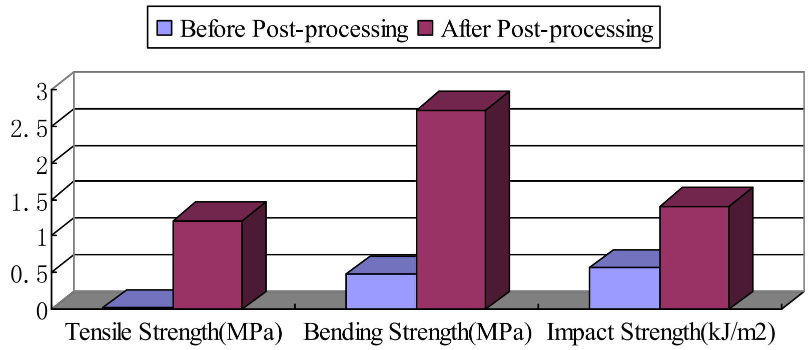


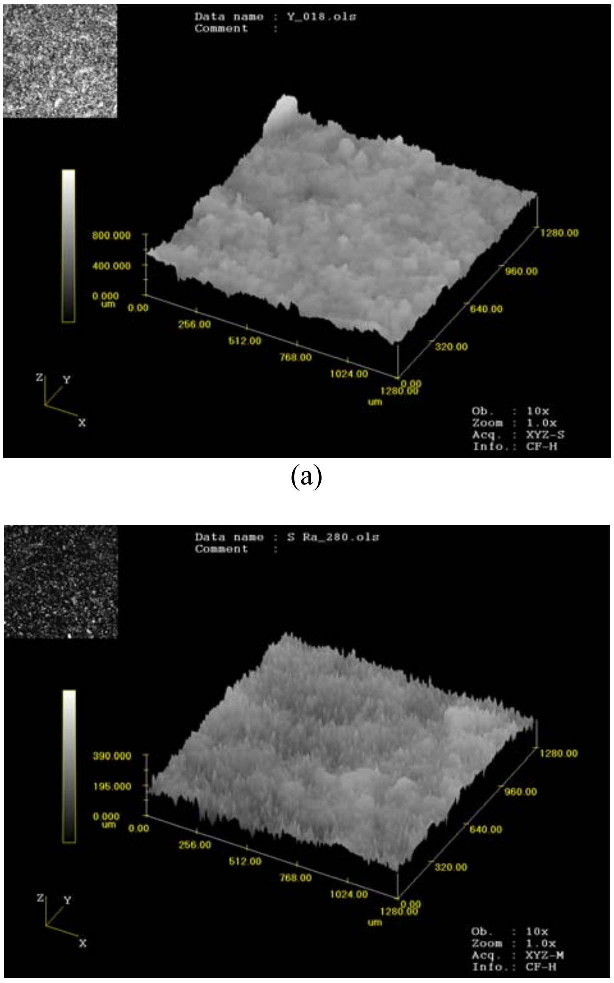
Fig. 9 Mechanical properties comparison

7. Surface quality testing

For the parts, surface quality is very important. Tests are made to compare surface quality between green parts and wax-infiltrated parts. A laser scanning confocal microscope is used to detect parts surface in the tests.

The laser scanning confocal microscope makes laser as the light source, adopts the principle and installations of conjugate focus based on the traditional optical microscope, and uses a computer to process the digital images of the observing object. It is an observation, analysis and output system. Its major systems include the laser light source, an automatic microscope, a scanning module (including confocal light path channel and pinhole, scanning mirror, detector), a digital signal processor, the computer, and the image output device (monitor, color printer), etc.. By the laser scanning confocal microscope, scanning imaging of different heights can be observed, therefore, non-destructive observation and analysis of the surface in a three-dimensional spatial structure can be made.

Three-dimensional spatial structure photos of green part surface and wax-infiltrated parts surface are shown in Fig.10, magnification is 10 times. It can be seen that after post-processing–infiltrating with wax, the surface is more flat, with a maximum height of protrusion on green part surface of 800μm, while that on the wax-infiltrated part is only 390μm, thus surface roughness decreases.



(a)

(b)

Fig. 10 Three-dimensional spatial structure photoes of surface

Surface roughness testing results are showed in Table.4. Ra values of ten different square areas are tested, then the average value is calculated, and the dimension of the square area is 150μm×150μm.

Table.4 Surface roughness testing results of parts

SRa (μm)	Area No.1	Area No.2	Area No.3	Area No.4	Area No.5	Area No.6	Area No.7	Area No.8	Area No.9	Area No.10	Average value
Green parts	13.51	16.06	17.89	15.17	16.74	18.59	14.10	17.96	18.29	15.93	16.42
Wax-infiltrated parts	11.05	11.05	10.72	11.19	10.97	16.06	12.86	17.50	18.25	8.67	12.83
Wax-infiltrated parts after polish	2.95	4.13	4.25	2.79	2.51	3.50	4.91	7.41	6.87	5.71	4.50

From Table. 4, it can be known that the average Ra value of green parts is below 17μm, after post-processing, surface quality has been greatly improved, and Ra is below 13μm on average, through polishing, the surface is more smooth and the average Ra is below 5μm , compared to those without post processing, surface roughness decrease 22% and 73% respectively, as Fig. 11 shows.

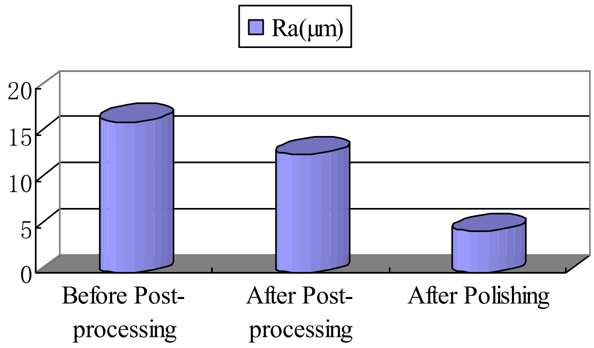


Fig. 11 Surface quality comparison of WPC SLS parts

8. Conclusion

In this paper, WPC is successfully developed to make parts by SLS process according to its advantages, such as green biological, good mechanical properties, high hardness, anti-aging, dimensional stability, easy to color, with a wood texture and also recyclable, with its most important advantage being its low-cost. A mixing process was successfully developed to prepare Wood-Plastic Composite(WPC) powders. Before mix, the wood flour is alkalized for reducing the hydrophilic nature of wood fiber and improving the wettability and the adhesion actions of the interface. Green parts were formed from WPC by selective laser sintering (SLS) process, when the applied laser energy density was 283W/mm^2, the SLS green parts had sufficient strengths for features as small as 0.1mm to be built and post-processed, and relatively high dimensional accuracy. In order to further improve the properties of the pattern, the post-processing – infiltration with wax – is introduced. Through post-processing, the void fraction is decreased from 51% to 7%, the mechanical properties are significantly improved, the average tensile strength, bending strength, and impact strength are 1.157 MPa, 2.72 MPa and 1.4125KJ/m^2, compared with those without post processing. The tensile strength is 87 times higher than without post processing and the bending strength increased by 384% while the impact strength increased by 94%. After post-processing, surface quality is greatly improved, Ra is below 0.013mm on average, and after grinding and polishing the surface is more smooth and Ra is below 0.007mm on average.

Acknowledgments

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