Improving the Surface Roughness of SL Parts Using a Coating and Grinding Process

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Rapid prototyping (RP) technology can fabricate any 3D physical model regardless of geometric complexity using the layered manufacturing (LM) process. Stereolithography (SL) is the best-known example of RP technology. In general, the surface quality of a raw SL-generated part is unsatisfactory for industrial purposes due to the step artefact created by the LM process. Despite of the increased number of applications for SL parts, this side effect limits their uses. In order to improve their surface quality, additional post-machining finishing, such as traditional grinding, is required, but post-machining is time consuming and can reduce the geometric accuracy of a part. Therefore, this study proposes a post-machining technology combining coating and grinding processes to improve the surface quality of SL parts. Paraffin wax and pulp are used as the coating and grinding materials. By grinding the coating wax only up to the boundary of the part, the surface smoothness can be improved without damaging the surface. Finally, moulding and casting experiments were performed to confirm the suitability of the SL parts finished using the proposed process with rapid tooling (RT) techniques.

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1. Introduction

The rapid prototyping and manufacturing (RP&M) process has traditionally focused on rapid tooling (RT) techniques. The RT techniques allow the quick and efficient manufacture of tools for injection moulding or die-casting operations, such that the resultant part will be representative of production material. RT has a great potential to meet the needs for a high degree of product variety and small manufacturing lot sizes, through improvement to conventional manufacturing processes. For example, RT has reduced the time required for the investment casting process from the usual ten to fourteen weeks to about four weeks, because the need to manufacture the injection mould has been eliminated.[1]

One of the most critical factors in using RT techniques is the surface smoothness of the patterns. However, the surface quality of most RP processed parts is unsatisfactory for patterns in secondary tooling process due to the step effect, which is the result of thin layers accumulating on the inclined surfaces of the RP parts.[2] Stereolithography (SL) is a typical RP technology. Step artefacts limit the use of SL parts despite the increase in the number of applications. Therefore, if SL parts are to be used as patterns in RT, improving surface roughness of the SL parts is indispensable.

Conventional manual finishing using an instrument such as a hand grinder because of its simplicity and speed has been the most widely used technique for improving the surface smoothness of SL parts. Cobb[3] et al. developed more efficient finishing techniques, such as abrasive blasting, barrel tumbling, and vibration finishing. However, these techniques inevitably alter the original part boundary, and are very time consuming. Another interesting approach to remove the steps uses electrical discharge machining (EDM) electrodes with copper-coated SL parts.[4] This finishing technique has the potential to produce a significantly improved surface, but it is even more time consuming and expensive than the others. Recently, Williams et al.[5] developed a finishing process for SL parts using abrasive flow machining (AFM). Statistical analysis has been used to determine the effect of AFM finishing according to media grit size, media pressure, build orientation, and other factors. The greatest improvements in surface smoothness were achieved with one AFM cycle. Most of these finishing techniques are not only time-consuming, but also detrimental to the SL work pieces because of their uneven size and random contact with the abrasive media. Hence, the development of faster, more efficient finishing techniques that do not damage the original SL parts is required.

This study proposes a post-machining technology that combines coating and grinding processes to improve the surface quality of SL parts. First, the part is coated with paraffin wax, which has suitable properties for the proposed post-machining technique. The surface of the SL part is not damaged because only the wax coating is ground. Silicon rubber moulding and casting experiments demonstrate that SL parts finished using the proposed post-machining process can be applied in RT as a pattern.

2. Coating and Grinding Processes

2.1 Surface roughness distribution of SL parts

The major factors that affect surface quality in a general RP process are layer thickness, fabrication direction, surface angle, layer profile angle, build style, material property, and other factors. The general surface profile of an RP processed part has a stepped geometry, as shown in Fig. 1. This is called the step effect, which occurs as a result of the layered manufacturing (LM) process. From this simplified surface profile geometry, the depth (X) of the step can be found using equation (1).

$$X = L(\sin\theta\tan\theta + \cos\phi) \qquad (1)$$

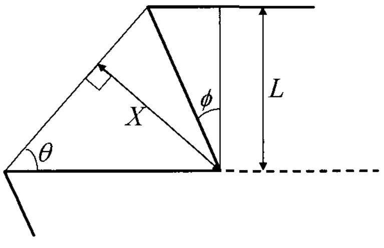


Fig. 1 Surface profile schematic of an SL part

In equation (1), L denotes the layer thickness, θ is the surface angle, and ϕ is the profile angle. A theoretical surface roughness distribution curve based on the change in surface angle can be obtained from Eq. 1, as shown in Fig. 2. The applied layer thickness and profile angle are 0.1 *mm* and 5°, respectively.

In an actual RP manufacturing environment, the roughness distribution is changed according to the RP machine, build style, material, and other conditions.[7] In addition, a print-through effect occurs on a downward-facing surface (where the normal vector of the surface is downward) due to gravity and surface tension in the concave corner of the step. This effect can be used to smooth roughness.[6] Therefore, the differences between the theoretical and real roughness distribution curves are remarkable because of theses factors.

Figure 3 shows a real roughness distribution curve, which was obtained by measuring an SL test part. The geometry of the test part is a twisted pillar with a range of angle planes. The range is convenient for measurement in three-degree increments from 0 to 360°. The test parts were assessed using surface roughness measuring equipment. The layer thickness, build style, and material of the test part fabricated in the SLA 350 equipment are 0.1 mm, Exact-X, and SL5510, respectively. Except for the surfaces near 0, 90, and 180°, the average surface roughness is greater than that of general NC machined parts by more than 10 μm.

2.2 Paraffin Coating and Grinding Process

The state of surface roughness in each step of the process for manufacturing tools, such as moulds and dies, using RP technology is shown in Fig. 4. First, the surface outline of the CAD model is shown in Fig. 4(a) by the triangle facets of the STL file format.

After the pre-processing stage determines the fabrication direction, slicing, generated tool path and other variables, the main build process is as shown Fig. 4(b). After completing the build process, the surface profile becomes stepped, as shown in Fig. 4(c), and has the roughness distribution characteristics discussed in paragraph 2.1.

In this study, the surface roughness of the SL-processed part is improved using the following coating and grinding process. In the coating process, the steps are covered with wax, as illustrated in Fig. 4(d). In the grinding process, only the fully wax-coated areas are ground and polished based on the surface boundary of the SL part, as shown in Fig. 4(e).

Therefore, using the SL pattern processed by the proposed post-process, a practical RT can scenario be accomplished, as shown in Fig. 4(f).

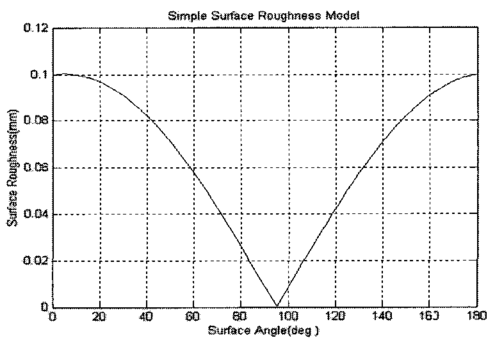


Fig. 2 Theoretical surface distribution curve of an SL part

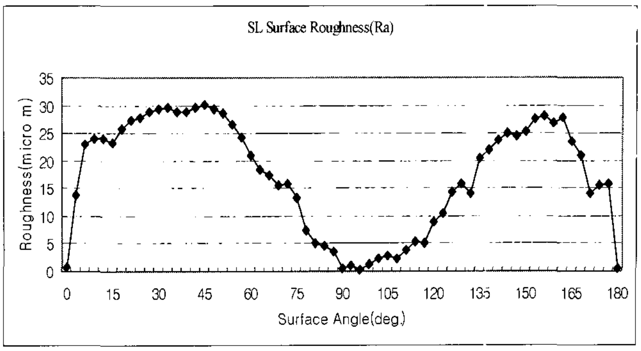
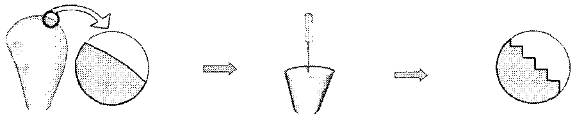
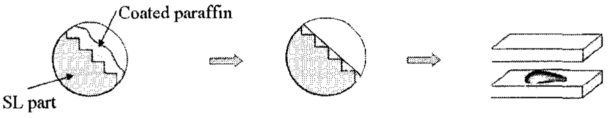


Fig. 3 Measured surface roughness data of an SL part



(a) CAD model (b) Building (c) SL part with star step



(d) Coating (e) Grinding (f) Tooling

Fig. 4 Surface profile of the SL part in each rapid tooling process

2.2.1 Coating process

In order to achieve an efficient coating process, the selection of a suitable coating material is important. In this study, paraffin wax was used to coat the surface of the SL parts. Paraffin is a wax that is separated and refined from the decompressed distillate of petroleum at room temperature; it is composed of straight hydrocarbon structures in which the carbon atoms are linked linearly. The average number of carbon atoms per molecule is 20 to 35, and its molecular mass ranges from 300 to 500. The general characteristics of paraffin are as follows: 1) it contains a small amount of emulsified oil, 2) it has relatively high hardness, 3) it becomes a white solid at room temperature, 4) it melts at temperature from 45 to 70°C, 5) it is not volatile, 6) it is easily burned without producing harmful gases, 7) it has very low viscosity under 10cSt at the melted state of 100℃, 8) it is water-proof and damp-proof, 9) hardens within ten minutes at normal temperatures, and 10) it has good glutinousness and machinability for plastic compared with other materials.[8] Its short hardening time, machinability for plastic, low viscosity, and water- and dampness-resistance make it useful for coating the surfaces of SL parts. Therefore, paraffin wax was selected as the coating material. When the coating process is performed using paraffin wax, the melted wax quickly solidifies after spray coating at room temperature. Therefore, a dipping method was used in this study. The coating process is completed in two stages and each stage consists of three sub-steps–melting, dipping, and cooling–to produce a strong, even covering. To produce a coat less than 1~2 *mm* thick, the appropriate conditions were determined after numerous coating tests, as shown in Table 1, where, the volume of paraffin wax is 100 mm^3 and that of the test SL part is 50 mm^3.

Table 1 Paraffin coating conditions

	1st Condition		2nd Condition	
	Temp. (℃)	Time (min)	Temp. (℃)	Time (min)
Melting	70 to 90	5 to 7	60 to 70	1 to 2
Dipping	70 to 90	2 to 3	60 to 70	1 to 2
Cooling	18 to 20	2 to 3	18 to 20	5 to 10

The details of the coating procedure and conditions are as follows. First, the paraffin is heated to melting in the first coating stage. The suitable heating temperature was determined to be 70 to 90°C from several coating experiments. At this temperature, the SL part is not harmed by the heat and paraffin wax does not evaporate. The volumes of the part and paraffin determine the amount of time required to reach the melting temperature. For a base volume of 100 mm^3, the required heating time was five to seven minutes at a room temperature of 18 to 20°C. Second, the part is dipped in the melted paraffin solution for two to three minutes. Third, after removing the part from the vat, it is cooled for about two minutes. A single coating is usually insufficient; hence, a second coating applied. The second melting step takes three to four minutes at 60 to 70°C. The part is dipped a second time for one to two minutes at the same temperature. The final cooling process takes one to two minutes at room temperature. After the second coating step is completed, the part has a uniform covering 2 to 3 *mm* thick.

2.2.2 Grinding process

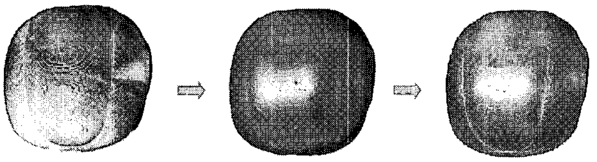
The hardness of the grinding tool must be lower than that of the SL part and higher than that of paraffin, so that the surface of the part is undamaged, as shown in Fig. 4(e). Good machinability for paraffin is required. In addition, the heat should not deform the machined surface, which is apt to occur in the moulding process. To meet these requirements, the abrasiveness of the pulp material was determined in a number of grinding experiments. The pulp abrasive grinding tool was specially manufactured for the proposed post-machining. Cotton and wool pads were used to polish the surface.

The part was machined by fitting the pulp abrasive tool to the axis of a hand grinder. The surface of the pulp abrasive tool is likely to become coated with paraffin chips (the pseudo-loading effect) during grinding. The paraffin chips are easily removed by heating the loaded tool to over 60°C. That is to say, dressing is simply performed by using the pulp abrasive. To machine a particular area, such as the edges and corners, a cotton material is used on the polishing tool. Finally, a wool pad is used to polish the part to achieve the desired aesthetics.

3. Experiment and estimation

The knob on the end of the gearshift lever in an automobile was used as a test part because it has a freeform surface and a remarkable step effect. The knob test part was built on an SLA-350machine using SL5510 resin, used an Exact-X build style, and had a 0.1-*mm*-thick layer, as shown in Fig. 5(a). The proposed coating process for the test was completed under the conditions presented in Table 1. The average coating thickness was about 2 *mm*. As a result, the step and narrow concave area are not outwardly evident, as illustrated in Fig. 5(b). The coated part was also processed for about 15 minutes using the proposed grinding and polishing methods. After completing the polishing process, the surface geometry was closer to that of the original SL part without the step deformity, as shown in Fig. 5(c). Figure 6 is a magnified surface photograph of the test part taken using an optical microscope (CK40M, Olympus) at 200x magnification and at an angle of 35°. The improvement in surface roughness is easily seen in this figure. Figure 6(a) shows the step effect on the inclined surfaces before processing. This rough surface was completely improved using the proposed post-machining process, as shown in Fig. 6(b).

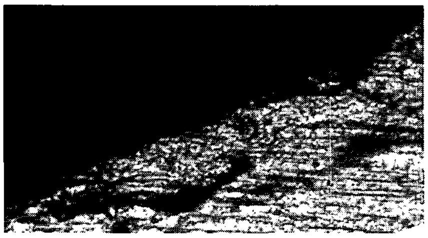
In order to compare the required processing time between the traditional and proposed post-machining techniques, the processing time was measured by manufacturing a spherical test part with a radius of 30 *mm*. The sphere was built using the same conditions as the knob SL test part. The traditional post-machining technique using sandpaper and a grinder took about 30 seconds for a 10-mm^2 unit plane area to be machined to an average roughness of 1 μm. Therefore, the traditional post-processing technique would take a minimum of 0.9 hours to machine the entire surface of the sphere. In actuality, it took more than two hours to machine the sphere. Moreover, the machining caused excessive damage the surface of the part, as expected. Conversely, the proposed post-machining technique took only 0.5 hours for the same test part. Moreover, the surface was not damaged during machining, as shown in Fig. 6(b). This occurred because the abrasive material is softer than the SL part and harder than the paraffin wax.



(a) SL part (b) Coated part (c) Ground part

Fig. 5 A processed SL test part created using the proposed post-machining process

(a) Before



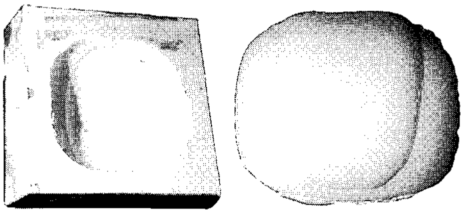
(b) After

Fig. 6 Photograph of the surface of the SL test part

4. Rapid Tooling

4.1 Rapid Tooling Test

Rapid tooling is a process that can manufacture a tool for injection moulding and die casting operations quickly and efficiently, so that the resulting part is representative of the production material.[2] Recently, RP&M technologies including high-speed cutting (HSC) have also been called RT.[2] The traditional method of investment casting with an injection mould requires 10 to 20 weeks. Conversely, rapid prototyping technologies can save time by eliminating the need to manufacture the injection mould. Hence, the required time can be reduced to only about four weeks.[9] In addition to reducing the processing time, the surface quality of the RP pattern is also important in RT technology applications.



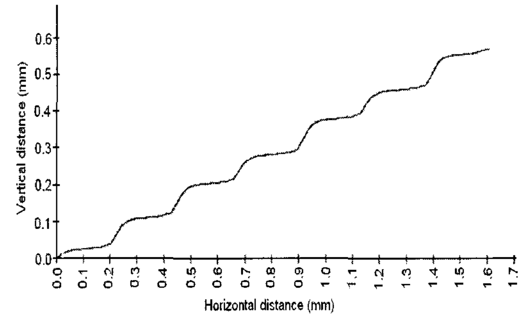
(a) Silicon rubber mould (b) Casting part

Fig. 7 Silicon mould and casting part using the SL pattern

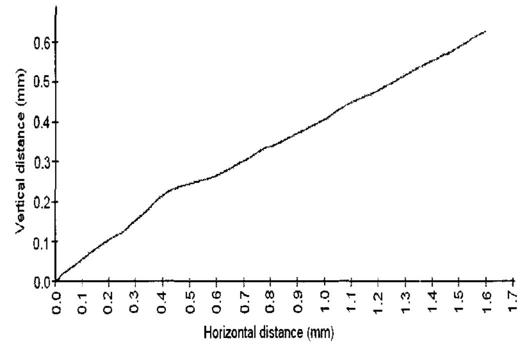
To demonstrate the applicability of the SL test part to RT technology, a test mould was manufactured using a pattern that was processed using the proposed post-machining technique, as shown in Fig. 7(a). Since the paraffin-wax coats the surface of the knob test part, its melting point should be considered when manufacturing the test mould. Therefore, after drying for 16 hours at 35°C, the mould was manufactured using a silicon rubber mould.[10] The final cast part was obtained by filling the silicon rubber mould with slurry, as shown in Fig. 7(b). The slurry is epoxy resin-annexed aluminium powder.

4.2 Evaluation for Rapid Tooling

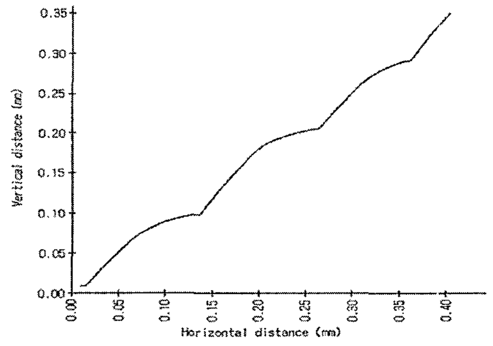
To evaluate the state of the improved surface roughness, the surface profiles of the test parts were measured using a surface profile meter. The measured profiles are shown in Fig. 8. The scope of the measuring device is 100 x 50 *mm* according to the x-y axis and the resolution is 0.1 and 0.2 μm along the respective axis.[11] Therefore, the improvement in the roughness of the parts can be measured sufficiently. Each item in Fig. 8 shows the measured surface profile before and after implementing the proposed post-machining technique at surface angles of 15° and 45°. As the figure shows, the surface roughness was improved remarkably for surface angles of both 15° and 45°. In addition, few sharp bends were seen in the surface profiles of the cast part. This shows that the improved surface was not influenced by the heat generated during the moulding process. In order to quantify the roughness, a surface roughness tester (Surftest SV-414) was used to measure the average surface roughness values, as shown in Fig. 9. Figures (a)-(c) and (d)-(f) show the data measured at surface angles of 15° and 45°, respectively. The average roughness values and profiles were measured on the SL test part, the pattern, and the casting part. Comparison of the SL part with the other parts verified that the average surface roughness was improved remarkably - changing the roughness from 20 μm to 1 μm at surface angles of both 15° and 45°. As can be seen by comparing the data in Fig. 9(b) and (c) and in Fig. 9(e) and (f), the amount of roughness is almost equal. This result indicates that the improved surface was not influenced by a rapid tooling process, such as moulding. Consequently, it also shows that the SL pattern processed using the proposed post-machining technique can be used in rapid tooling.



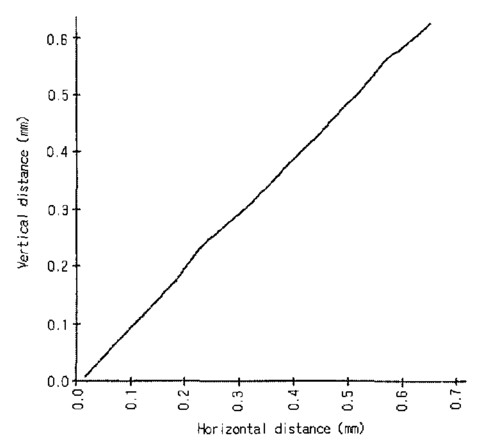
(a) Measured surface profile of the SL part at 15°



(b) Measured surface profile of the casting part at 15°

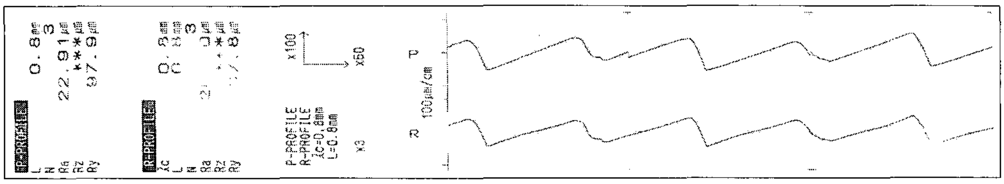


(c) Measured surface profile of the SL part at 45°

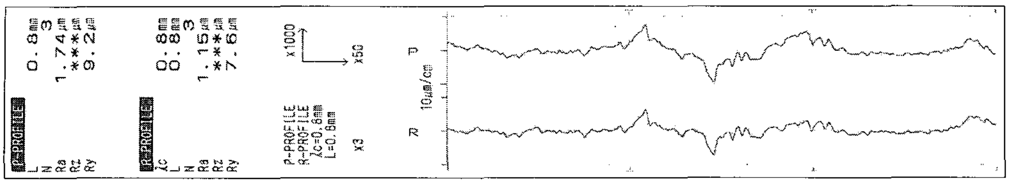


(d) Measured surface profile of the casting part at 45°

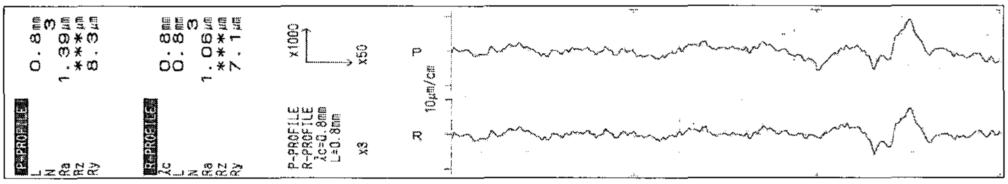
Fig. 8 Surface profile curves of the knob test model



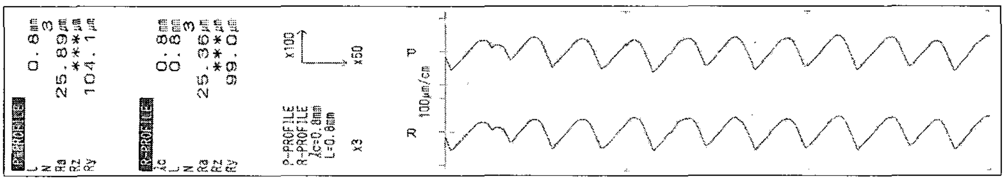
(a) Measured surface roughness of the SL part at a 15° surface angle



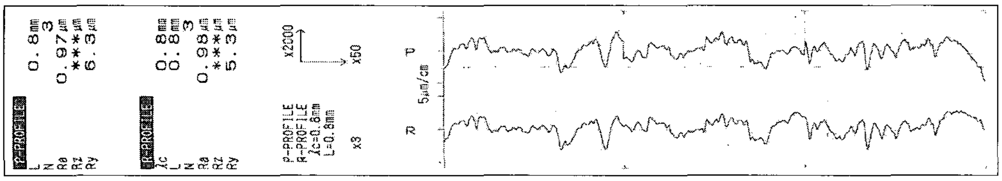
(b) Measured surface roughness of the pattern at a 15° surface angle



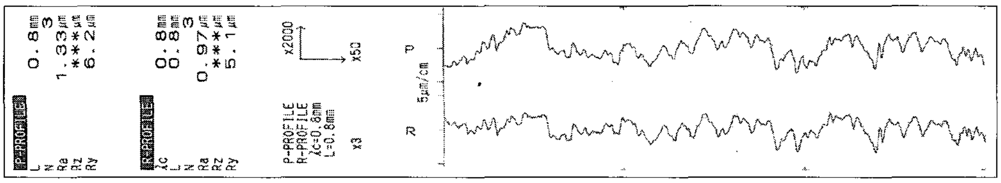
(c) Measured surface roughness of the casting part at 15° surface angle



(d) Measured surface roughness of the SL part at a 45° surface angle



(e) Measured surface roughness of the pattern at a 45° surface angle



(f) Measured surface roughness of the cast part at a 45° surface angle

Fig. 9 Measured surface roughness data of the SL part, pattern, cast part for the knob test model

5. Conclusions

In this study, a coating and grinding post-machining process has been proposed to improve the surface roughness of SL processed parts. Paraffin-wax and pulp were used as coating and grinding material. Suitable coating and grinding conditions for SL parts were obtained from several experiments. The surface roughness of the SL part was remarkably improved without causing any damage in the knob test part experiment. Also, the post-processing time can be reduced up to 50%. Finally, silicon rubber moulding and casting experiments demonstrated that SL parts finished using the proposed post-machining process could be applied in RT as a pattern.

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