Surface Finishing of Selective Laser Sintering Parts with Robot

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ABSTRACT

Compared with conventional subtractive manufacturing technologies, RP has great benefits in shortening the design-manufacture cycle time of a product. Even if mechanical properties are not considered, most RP products still cannot be directly used in applications until the requirements for overall surface quality are satisfied. To improve the overall surface quality of Selective Laser Sintering parts, a robotic finishing system has been developed as a part of an ongoing research project. A finishing tool is held by a robot and moved according to programmed paths generated from the original CAD model data. This paper describes the experimental system in detail and shows that the surface roughness, dimensional accuracy, and geometrical accuracy can be improved.

Keywords: Rapid Prototyping (RP), Selective Laser Sintering (SLS), Surface Finishing, Robot.

INTRODUCTION

Rapid prototyping is now widely regarded as a major technological breakthrough similar to the development of computer numerical control (CNC) technology. Compared with conventional subtractive manufacturing technologies, RP has demonstrated benefits in shortening the design-manufacturing cycle time. Over the last decade, RP has been developed quickly and is widely used in industries such as automotive, aerospace, medical and consumer electronics. As users become experienced, they seek more functional and practical RP parts in which the overall surface quality must compare with products manufactured by conventional technologies.

According to Wohlers in 1997 [1], almost one-third of all RP parts are being used for fit and functional applications, also more than one-quarter are being used as patterns for secondary tooling. These applications require RP parts to have a good overall quality, which includes surface quality and quality of mechanical properties. With the development of RP technologies and material science, the quality on mechanical properties of RP parts is improving and will continue to improve in future. But the surface quality is always influenced by some factors such as stair-steps and shrinkage since RP parts are produced layer by layer. Looking through all RP technologies at present, it is difficult to find a suitable RP technology by which the surface quality of parts produced can be comparable with CNC machining or precision machining. Without finishing or polishing in post-processing, RP parts can not be directly used in industries due to their poor surface quality.

With many materials capable of being processed, nearly any RP application can use a suitable SLS part as the required prototype. It is therefore important to improve the surface quality on SLS parts. Considering the combined characteristics of SLS and industrial robotics, an ongoing project in which a robotic finishing system has been developed for improving the surface quality on SLS parts. Experiment results have shown that the surface roughness, dimensional accuracy, and geometrical accuracy can be improved.

THE OVERALL SURFACE QUALITY ON SLS PARTS

In the field of manufacturing engineering, the exact degree of overall surface quality, which affects the functioning of a component and also its cost, is considerably important [2]. Usually, the overall surface quality includes surface roughness, dimensional accuracy, and geometrical accuracy. Surface roughness is the recurrent irregularities of a surface, which are inherent in the production process. The most common indicator of surface roughness is R_a, the arithmetic average roughness value over one sampling length. Accuracy is the correctness of dimension or geometry. Different manufacturing processes can obtain different overall surface quality [3]. For design engineers or production process planning engineers, the most important thing they should be concerned with is determining a set of suitable manufacturing processes in the shortest lead time for satisfying the application requirements on the overall surface quality.

In SLS, the overall surface quality of parts is influenced by many factors, some of which are shown in figure 1.

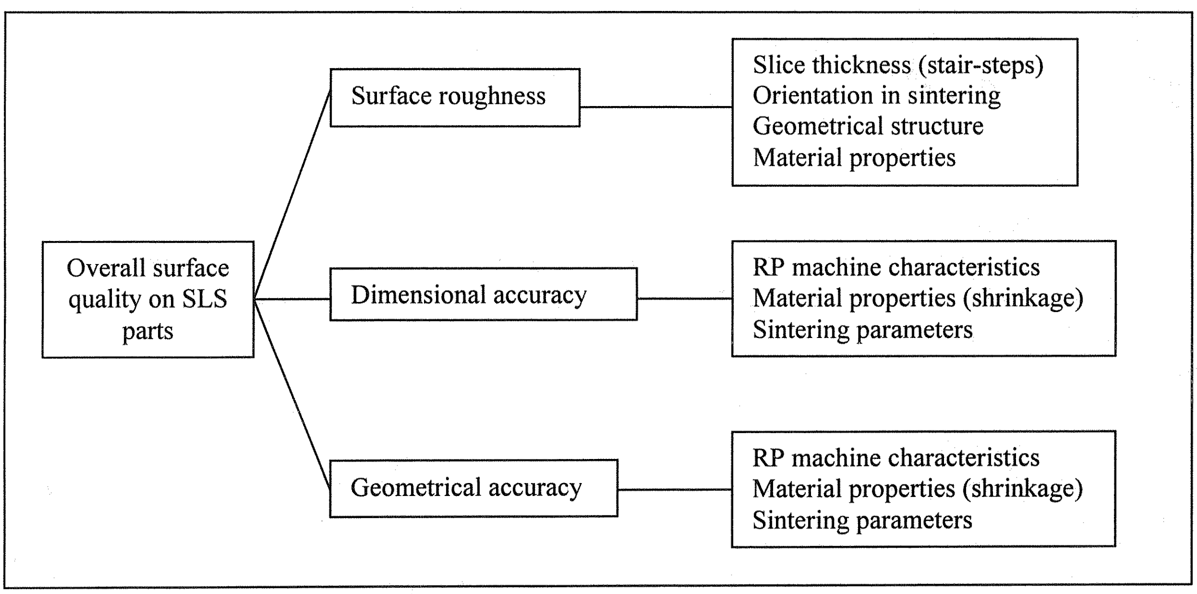

Figure 1 Influence factors of overall surface quality on SLS parts

To improve the overall surface quality on SLS parts, some efforts should be carried out on improving RP machine characteristics, optimizing sintering parameters, decreasing slice thickness, and improving material properties. At present, the minimum slice thickness in DTM SinterStation 2000 or 2500 systems is 0.003". The shrinkage of material is also unavoidable in the sintering process. Most SLS parts still have need of surface finishing or polishing to obtain a good surface quality. An industrial robot, with its programming flexibility and advanced kinematic structure, can assist in performing this finishing task.

ARCHITECHTURE OF ROBOTIC FINISHING SYSTEM

To improve the overall surface quality of SLS parts, a robotic finishing system has been developed. The architecture of the system is shown in Figure 2

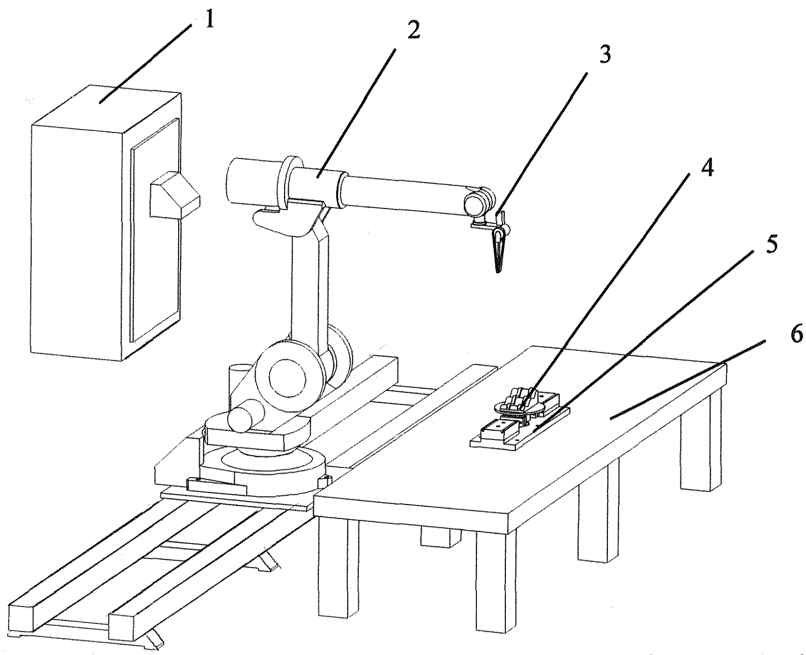

Figure 2 The architecture of the robotic finishing system: 1-controller; 2-articulated manipulator; 3-finishing tool; 4-SLS part; 5-fixture; 6-platform.

In the 3D modelling stage, a design part is produced using EDS Unigraphics (UG) software, which outputs a STL file to a SinterStation 2000 machine. If needed, a base fitting is added to the part. After the sintering process, the SLS part is placed in a fixture that is compatible with the base fitting. The position and orientation of the part relative to the robotic system is determined in the calibration process. The robot holds a high-speed finishing tool and moves over the surfaces according to a programmed path.

ABB IRB1400 Robot

This system uses an ABB IRB1400 robot, an industrial robot with 6-axis articulated movement and a linear external axis [4]. The robot is programmed using the machine-specific RAPID language [5]. In order to finish a part, the robot holds a finishing tool as its end-effector. Using a high-speed finishing tool, combined with the complex motion of the robot, results in a fine finish on the surfaces of the SLS part.

Finishing Tool

To achieve a smooth surface in the shortest time, the finishing tool should be changed according to the RP material, finished surfaces and surface requirements. The finishing tools used in this research include abrasive belts, ballnose endmills, spiral endmills, polishing bobs and special end brushes. Currently, finishing tool change is not automatic. Suitable finishing tools result in good surface quality.

Fixture and the Base Fitting

To be finished by the robot system, the SLS part should first be placed on a fixture. Since RP caters for different geometries, it is impossible to design a general fixture that is suitable for fixing all parts. It is therefore necessary to add a standard base fitting to the part at the design stage, which is fabricated during the sintering process. Some parts, such as injection rapid tooling molds, have their own base fitting and do not need this additional feature. Using this method, many designs can be placed on a single fixture. The base fitting can also be designed to aid the position and orientation of the part relative to the robotic system during the calibration process.

CALIBRATION AND ROBOTIC PATH PROGRAMMING

Co-ordinate systems exist within the robot system for the tool, user, object, base and world. It is necessary to define these correctly by calibration. The calibration procedure is divided into two steps: tool data calibration and base fitting calibration. Tool data calibration expresses co-ordinates in terms of the tool centre point (TCP). Base fitting calibration relates the position and orientation of the part relative to the base co-ordinates. Both calibration data are needed in programming robotic finishing paths.

The robotic paths are programmed using the ABB RAPID language. A software module was developed for generating robotic finishing paths. It was programmed using Visual C++ on a PC platform. The principle is based on the corresponding relationships between the RAPID language and the cutter location source file (CLSF) generated using UG software. The CLSF is a tool path file that describes machining processes in a UG manufacturing application [6].

EXPERIMENTAL STUDY

With a DTM SinterStation 2000 system, SLS parts were produced using polycarbonate, nylon composite, fine nylon, true form and rapidsteel powders. After sintered or infiltrated with copper, some parts were then finished with the robot. Experimental results are shown in table 1 to table 3, figure 3 to figure9. The surface roughness and surface profile were measured with a TAYLOR HOBSON surface texture-measuring machine (Form-Talysurf Series 2). The flatness was measured with a MITUTOYO coordinate-measuring machine (BLN122).

	Polycarbonate	Nylon Composite	Fine Nylon	True Form
Slope-planar surface (up 15^0)	30~35μm	28~35μm	28~35μm	22~24μm
Slope-Planar surface (down 15^0)	24~28μm	15~18μm	12~16μm	13~15μm
Planar surface (up)	18~22μm	14~17μm	12~16μm	7~10μm
Curved surface	32~36μm	32~36μm	32~36μm	30~34μm

Table 1 Surface roughness (R_a) in the unfinished SLS parts (slice thickness=0.1mm, other parameters are default)

In table 1, it is very clear to see that surface roughness in the unfinished SLS parts is very poor especially in slope-planar surfaces and curved surfaces. It is also shown that surface roughness is varied with material types, geometrical structures and orientations.

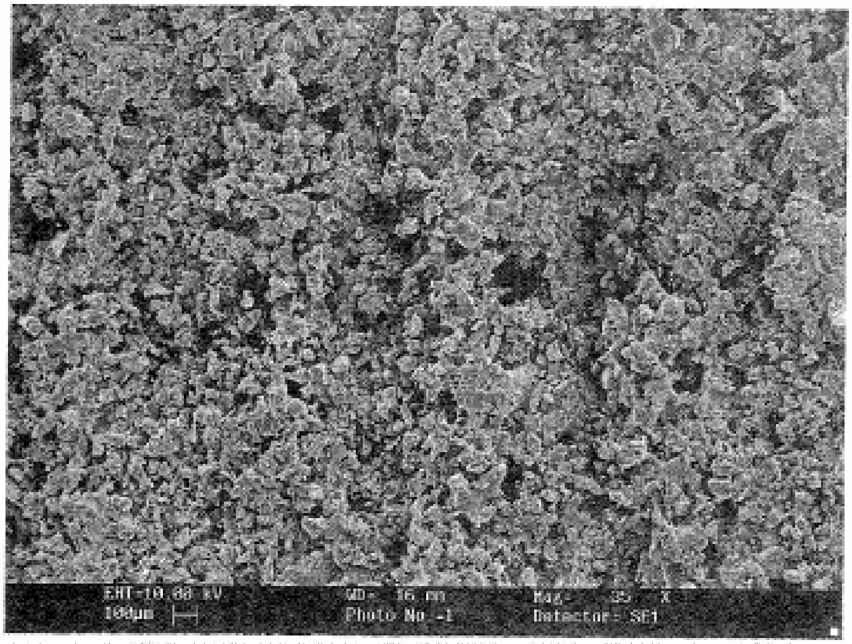

Figure 3 A microstructure of an unfinished slope-planar surface (material: fine nylon, slice thickness=0.1mm, slope angle=15^0 (upward), other parameters are default).

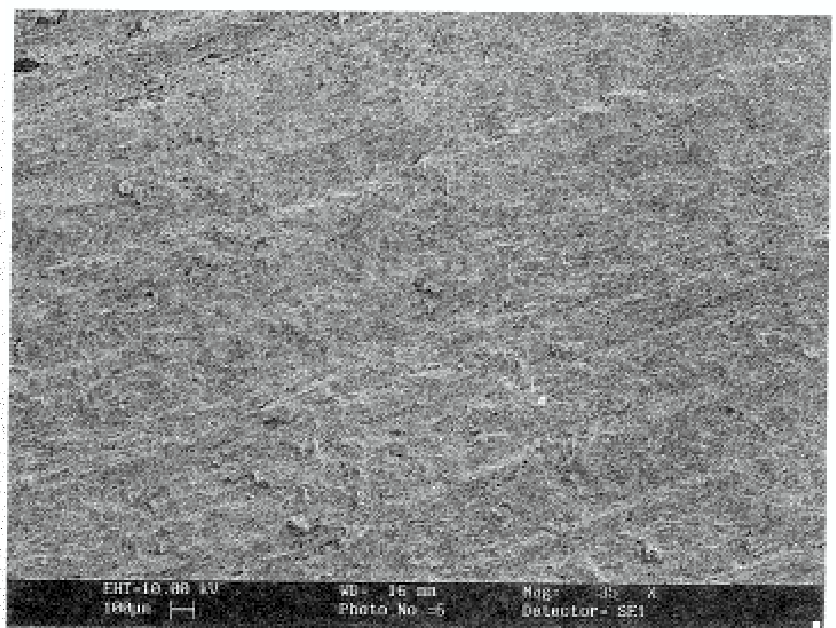

Figure 4 A microstructure of a finished slope-planar surface (material: fine nylon, slice thickness=0.1mm, slope angle=15^0 (upward), other parameters are default; finishing tool: abrasive belt, type: Zirconia, grit: Z#120).

In figure 3, we can see that particles adhered to adjacent surfaces. Stair-stepping can be seen clearly in this figure. When finished with abrasive belt, stair-steps were diminished and some grit marks were left on the surface in figure 4. Therefore, the surface roughness is decreased after finishing. Figure 5 and figure 6 are surface roughness profiles on an unfinished curved surface and a finished curved surface. R_t is the vertical height between the highest and lowest points of the profile within the sampling length. Comparing figure 5 with figure 6, it is shown that both R_a and R_t are greatly decreased after robotic finishing.

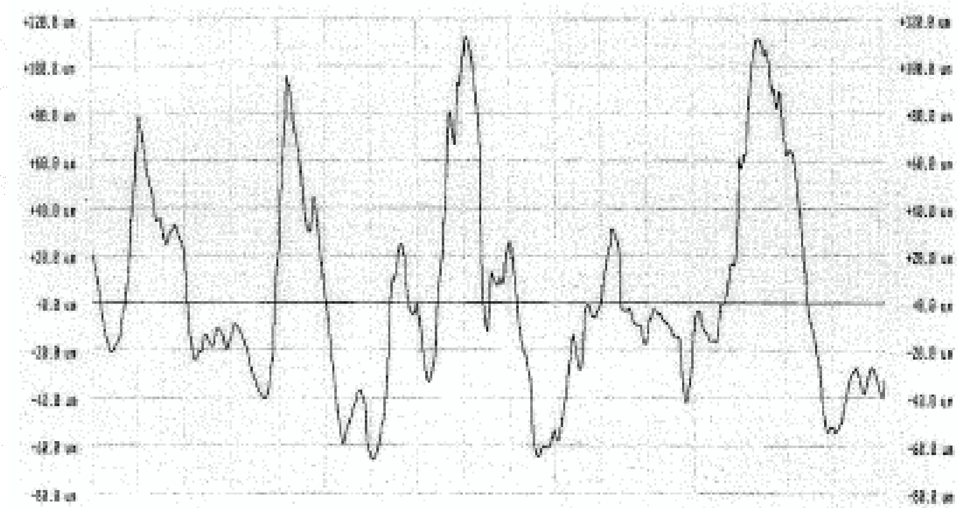

Figure 5 Surface roughness profile on an unfinished curved surface (material: fine nylon, slice thickness=0.1mm, other parameters are default, R_a =33.9250μm, R_t =179.0299μm; horizontal scale: 200μm/division).

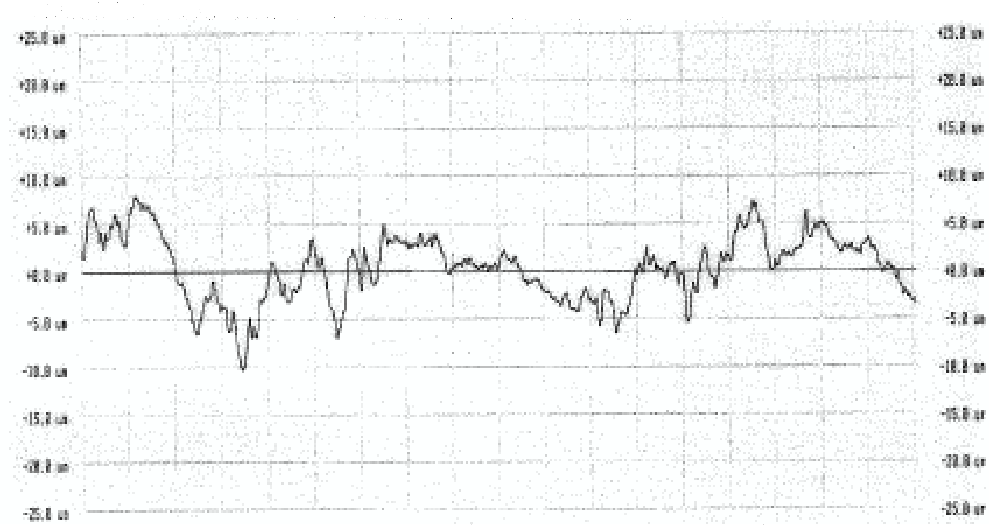

Figure 6 Surface roughness profile on a finished curved surface (material: fine nylon, slice thickness=0.1mm, other parameters are default; finishing tool: abrasive belt, type: Zirconia, grit: Z#120; R_a=2.7754μm, R_t=18.3384μm; horizontal scale: 200μm/division).

During finishing, some particles on the surface were melted due to machining temperature. Since the main defects on the surface are grit marks from tools, which influence the surface roughness, with the change of finishing tools it is possible to obtain different surface roughness as shown in table 2.

	Abrasive belt (type: Zirconia)			Ballnose endmill	Spiral endmill
	Z#80	Z#120	Z#180		
Fine nylon	6.0~10μm	2.8~4.5μm	2.5~3.8μm	3.2~4.8μm	3.5~4.2μm
RapidSteel	2.0~5.2μm	1.5~4.0μm	1.0~1.8μm	2.0~3.2μm	1.5~2.0μm

Table 2 Surface roughness R_a obtained by different finishing tools.

Another finishing example is on two RapidSteel molds. The two molds in figure 7 were made with RapidSteel at the same time. After furnace treatment, only one mold was finished by robot. Some experimental results are shown in table 3, figure 8 and figure 9.

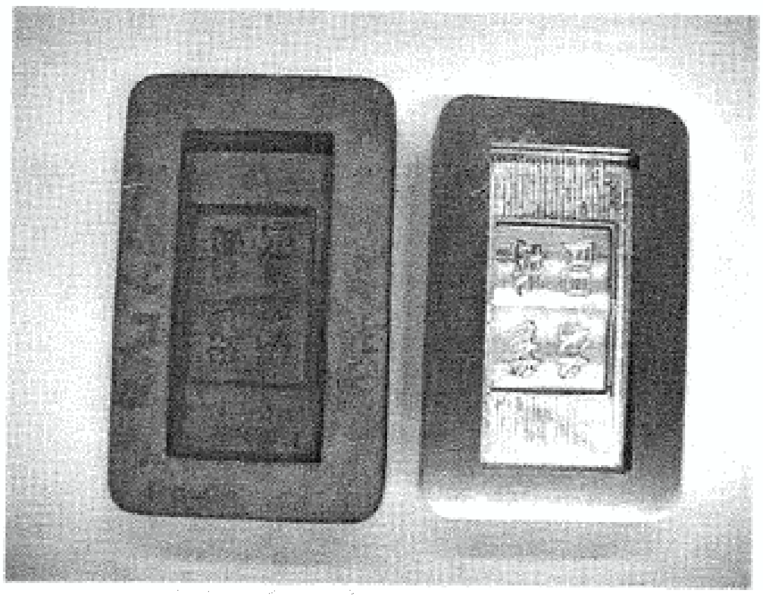

Figure 7 The two injection molds of HKU badge: left-unfinished (A); right-finished (B).

	Surface roughness		Dimensional accuracy		Flatness
	Curved surface	Planar surface	Length 50.25mm	Length 102.50mm	
Mold A (unfinished)	*Ra*:14.5~15.5μm *Rt*:165~220μm	*Ra*:8.5~9.5μm *Rt*:128~135μm	49.38± 0.10mm	101.65± 0.15mm	0.20mm/ 100mm
Mold B (finished)	*Ra*:5.0~7.0μm *Rt*:73.8~75.0μm	*Ra*:1.2~1.5μm *Rt*:17~20μm	50.35± 0.05mm	102.65± 0.10mm	0.05mm/ 100mm

Table 3 Surface quality comparison between the two injection molds.

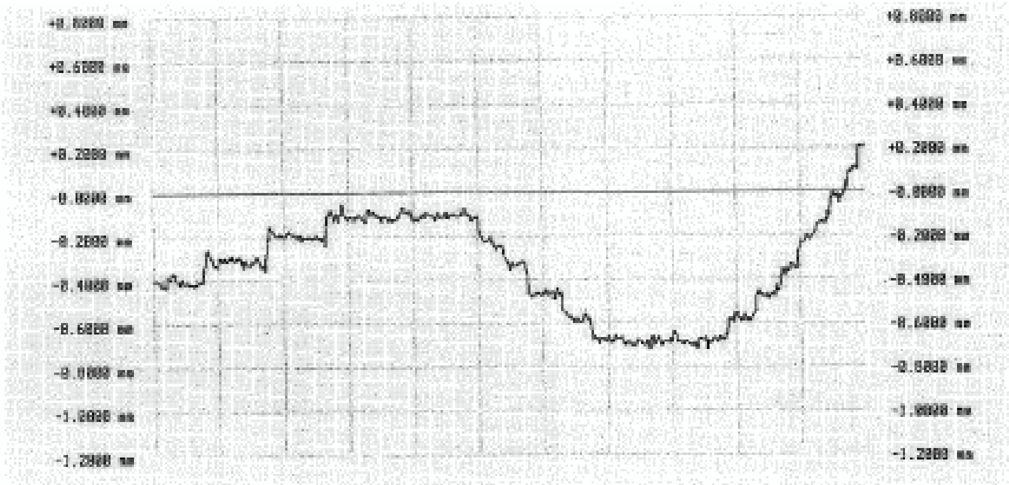

Figure 8 A section surface profile of mold A (horizontal scale: 2.0mm/division)

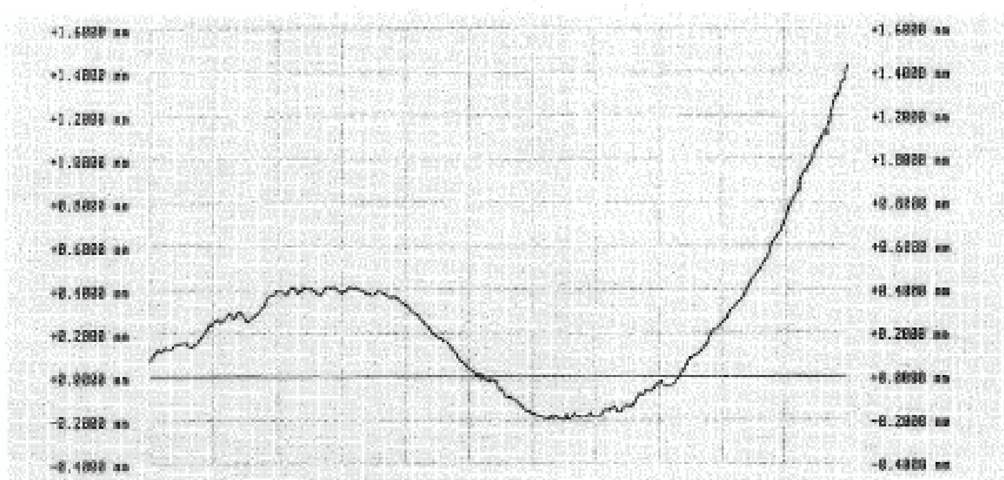

Figure 9 A section surface profile of mold B (horizontal scale: 2.0mm/division)

Table3 is the surface quality comparison between the two injection molds. It is shown that surface roughness, dimensional accuracy and flatness are improved after the mold was finished. In mold A, it is very clear to see the stair-steps on the curved surface in figure 8. The top and bottom area of the curved surface appears planar due to lamination. After finished with the robot, we can see in figure 9 that stair-steps were diminished but their fragments still left on the surface profile. Because the robotic finishing paths are generated from the original CAD data, the geometrical accuracy of the surface profile was improved after the mold was finished. The overall surface quality of the injection mold will directly determine the surface quality of the final injected products.

CONCLUSIONS

The overall surface quality of SLS parts is influenced by many factors. To improve the surface quality, some efforts should be carried out on improving RP machine characteristics, optimizing sintering parameters, decreasing slice thickness, and improving material properties. Due to stair-steps and shrinkage, surface finishing on SLS parts is needed.

The overall surface quality of SLS parts can be improved using a robotic finishing system. Because the robotic finishing paths are generated from the original CAD model data, the finishing process can eliminate the influences of stair-steps and shrinkage in the finished parts. Experimental results have demonstrated that surface roughness, dimensional accuracy and geometrical accuracy are improved in the finished SLS parts.

With the change of finishing tools, different surface roughness can be obtained. But dimensional accuracy and geometrical accuracy of the finished parts are mainly dependent on the robot accuracy. Further research will include continued experiments with different geometry parts, decision support for suitable finishing tools, development of an intelligent calibration technique and changing the open-loop control mode to a tool-based closed-loop mode.

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