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Virtual Models for 3D Printing

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ABSTRACT

Surface texture denotes a set of tiny repetitive geometric features on an object surface. 3D Printing can readily create a surface of controlled macro-textures of high geometric complexity. Designing surface textures for 3D Printing, however, is difficult due to complex macro-structure of the tiny texture geometry since it needs to be compatible with the non-traditional manufacturing method. In this paper we propose a visual simulation technique involving development of a virtual model-an intermediate geometric model-of the surface texture design prior to fabricating the physical model. Careful examination of the virtual model before the actual fabrication can help minimize unwanted design iterations. The proposed technique demonstrated visualization capability by comparing the virtual model with the physical model for several test cases.

Key words : 3D Printing, Surface texture, CAD, Virtual model, Visual simulation

1. Introduction

Rapid prototyping (RP) refers to a group of emerging technologies for fabricating physical objects directly from computer-based geometry descriptions of part designs[1]. Since actually constructing of a physical model from a product design using traditional techniques can be quite expensive, several RP apparatus have recently been used to construct physical models for design verification in the area of medical modeling[2], artistic design[3], and jewellery design[4] as well as in general manufacturing[5]. Although the method can dramatically reduce the time and cost for producing the physical models, more economical methods are desirable considering that a typical RP apparatus usually requires a minimum of a few hundreds U.S. dollars for fabricating a complex physical part with dimension of 250 by 250 by 250 cubic millimeter. Since the design cost might increase in direct proportion to the number of iterations for model fabrication, developing a virtual model-an intermediate geometric model-of the design and then carefully inspecting the virtual model before fabricating the physical model might help avoid unnecessary part fabrication for design verification purpose. Surface texture design is one such case that can be greatly aided by this technique.

Surface texture denotes a set of tiny repetitive geometric features on an object surface. The use of porous macro-texture on the surface of an orthopedic implant to promote bone ingrowth, for example, offers a valuable alternative to acrylic bone cements as a means of fixation[6] as shown in Fig. 1. Fabrication of surface textures using existing technologies, however, is confined to a simple surface texture with little room for varying surface parameters. Furthermore, they affect the fatigue strength of a stem material during the fabrication process. Recently, **3D printing (3DP)** has been reported to be capable of creating a surface of controlled macro-textures with high geometric complexity with no reduction in bulk mechanical strength of the material as shown in Fig. 2, which makes it a promising alternative to current manufacturing techniques for surface textures[7].

3DP is one of the highly flexible RP processes that was originally developed at Massachusetts Institute of Technology[8]. It allows for the fabrication of components and assemblies of any shape in any material

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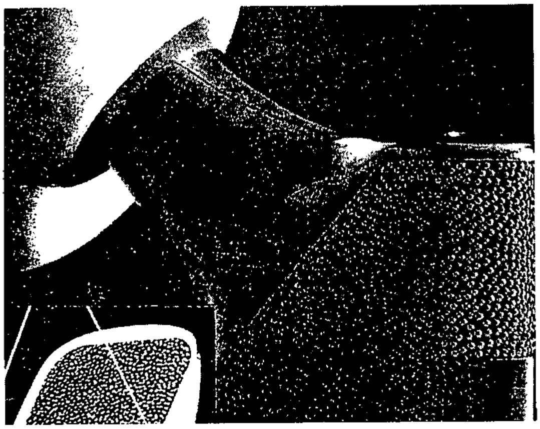

Fig. 1. An example of surface texture for orthopaedic implants.

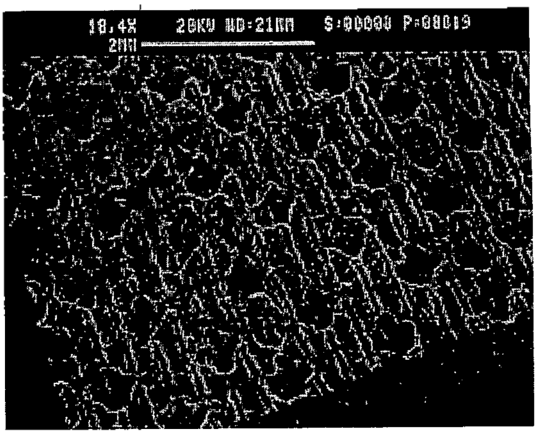

Fig. 2. A casted surface texture directly from 3D printed mold.

that can be obtained as a powder. 3DP functions by the deposition of a powdered material in layers and computer-specified selective binding of the powder by **ink-jet** printing of a binder material. It creates a part by vertically stacking thin layers of powder, each of which contains one particular cross-section of that part in the form of jointed particles. The sum of all these thin slices finally forms the desired shape. Control information for each layer is obtained by applying a slicing algorithm to the computer model of the part that identifies and extracts the outline of each individual cross-section. Following the sequential application of layers, the unbound powder is removed, resulting in a complex three dimensionally part. Fig. 3 shows the sequence of printing process involved in 3DP. The first step consists of spreading a layer of fine powder inside a container with a movable bottom. After the new layer is spread, the printhead starts to raster-scan the surface of the so called **powder bed** and prints a liquid binder into the loose powder. The liquid binder is delivered through a continuous-jet type ink-jet printhead. The printhead

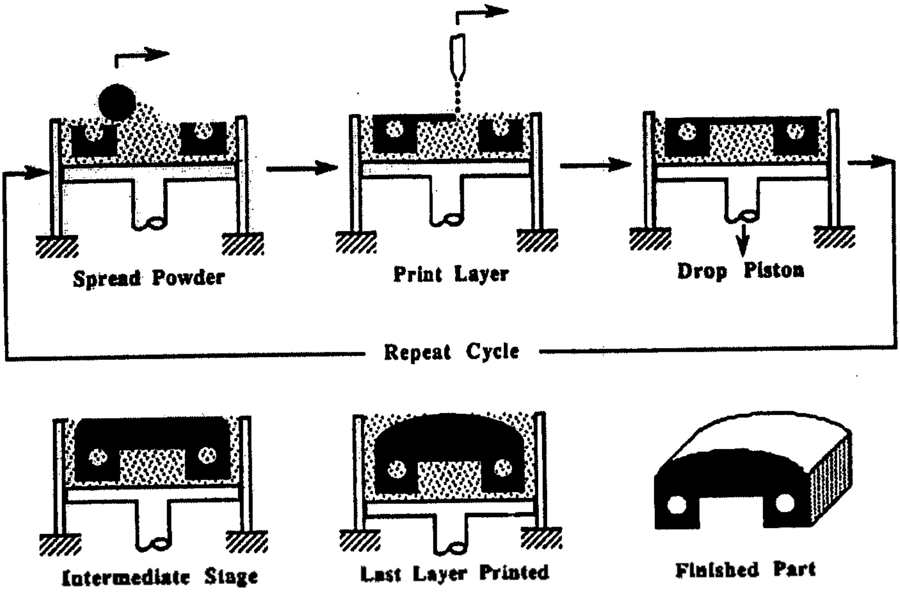

Fig. 3. The sequence of printing process involved in 3DP.

holds a nozzle which dispenses the pressurized binder, and the continuous stream of binder that passes through this nozzle with 45 micron orifice is made to break up into a small regular series of droplets by a piezoelectric disc attached to the nozzle vibrating at about 60 hertz. Thus the powder bed gets selectively glued together by the binder droplets. Whenever a binder droplet hits the powder, a little ball of bounded powder particles (**DPP**: drop placement primitive) is formed after the liquid component in the binder has evaporated. Consecutive droplets form a solid line, and adjoining lines merge into a surface, thereby forming a cross-section of the part. In the last step of the sequence, the bottom that supports the powder bed-the piston-is lowered a certain distance, typically 120 to 200 micron, to make room for a new layer. The spreading and printing sequences are repeated again until all the required layers are stacked on top of the previous layers and the whole part is completely formed.

Designing millimeter or sub-millimeter surface textures for 3DP, however, is difficult due to complex macro-structure of the tiny texture geometry since it needs to be compatible with the non-traditional manufacturing method of 3DP. In this paper we propose a visual simulation technique for facilitating surface texture designs to be made by 3DP. The implemented technique takes into account necessary geometric attributes of physical phenomena of the 3DP process and hence provides designers with ability for verifying unseen fabrication capability of the existing prototyping machine in the embodiment of the surface texture design. The visualization capability of the proposed method can be demonstrated by comparing the virtual model of a design with the physical model.

2. Creation of Virtual Models

2.1 Visualization and rapid prototyping

Visualization, in general, is a method of extracting meaningful information from complex data sets through the use of interactive graphics and imaging. It provides processes for seeing and steering the unseen, thereby enriching existing scientific methods. Volume visualization as a subfield of visualization, for example, is a method of interpreting complex volumetric data. The field of volume visualization can be traced back to the early 1970's when the use of volumetric data, particularly in 3D medical imaging, was first reported[9]. It has provided the mechanisms that make it possible to reveal and explore the inner or unseen structures of volumetric data and allow visual insight into opaque or complex data sets[10].

Several geometric modeling algorithms that creating virtual model, on the other hand, have also been used for interaction between virtual and real world. Called virtual manufacturing, these algorithms have become important part of intelligent machining systems by allowing for the precise modeling of existing technologies. For instances, they can automatically generate, simulate, and verify numerically controlled machining programs[11] and applications of these algorithms can also be found elsewhere[12,13]. Modeling a product and its related manufacturing process as well as human activities for management are also important function of these algorithms[14].

One approach for visualizing the physical model frequently used by RP community has been approximating the surface of the object by a collection of surface patches, which results in display of a smooth, shaded object of the physical model[15]. As being fabricated by an RP apparatus, however, an object is supposed to be built by laying down material layers in a gradual, controlled way, which results in staircase (or laddering) effect on what should actually be smooth surfaces. Traditional geometry-based modelers which display a smooth, shaded object of the physical model hence provides a designer with no information on the actual surface finish of the object. For example, a sphere fabricated by an RP apparatus is supposed to look like a stack of discrete, differently-sized circular disks rather than a simple smoothly skinned crystal-like ball. Depending on application area such as surface texture fabrication, the staircase can have a significant effect on part fabrications[16]. Chandru and his colleague[17] have once created a virtual model for layered manufacturing by suggesting a voxel-based modeling for evaluating the geometrical effect on the surface of a physical part made by RP techniques.

2.2 Visual simulation for virtual models

The purpose of the simulation is to explore the various outputs that might be obtained from the real system[18]: This does not need to be confined to a descriptive modeling that enables us to understand a real system itself. In this paper we propose a visual simulation technique for creating virtual models and facilitating surface texture designs to be made by 3DP. In order to develop a visual simulation tool according to the 3DP process rules, dimensional parameters such as incremental movements of binder drops along the three axes of the 3DP machine, printing accuracy, and printing layer thickness must be incorporated to properly describe the geometry of virtual surface texture model. In essence, a virtual model can be built purely based on the physical 3DP build file.

2.2.1 Drop placement primitive

As with many manufacturing processes, application area for 3DP are partly determined by resolution, accuracy, and minimum feature size that can be made. Since 3DP is an additive manufacturing process as opposed to a subtractive, forming, or phase change processes, the material is added as droplets ejected from a nozzle hit and bind a small region of the powder bed. The size of a resulting primitive, what is called drop placement primitive (DPP), corresponds to the powder-binder agglomerate formed by a single droplet as shown in Fig. 4. In this method, a DPP can be approximated to be a ball primitive as shown in Fig. 5, and its diameter has a default value of 200 micron based on an experimental result with 50 micron Aluminum powder mixed with 75 micron colloidal silica. This, however, can be continuously updated as using information from a 3DP build file.

2.2.2 Printing parameters

In the 3DP process, features can be defined as a positive feature when created by an aggregate of DPPs, or a negative feature when surrounded by several aggregates of DPPs. Several printing parameters such as layer thickness, printing row width, and incremental movements of binder drops along 2-D printing layer as shown in Fig. 6 needs to be specified to delineate a virtual model that can adequately approximate the physical model. The resolution of 3DP is bound by incremental movement of the DPP in the powder bed; the scale of incremental movement of binder drops along the two printing directions-fast axis and slow axis. It, therefore, is actually the limiting factors that needs to be considered to determine the printability of very fine surface macro-textures. All these parameters are determined by physical 3DP build file.

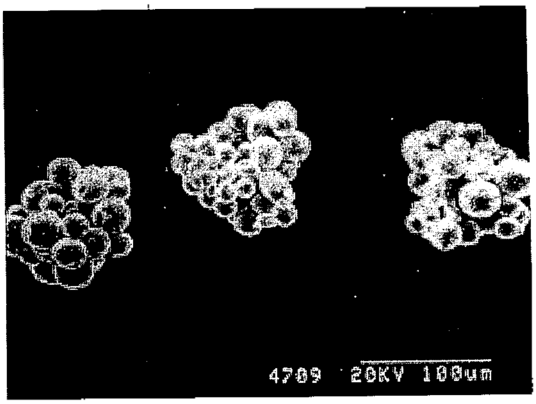

Fig. 4. Drop placement primitives.

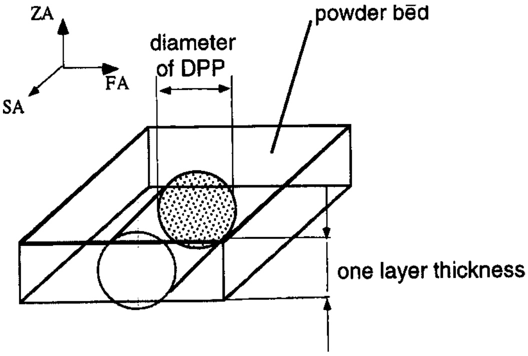

Fig. 5. A drop placement primitive model.

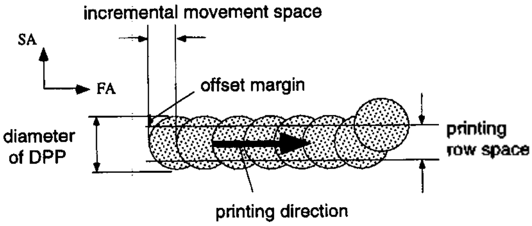

Fig. 6. Printing parameters for visual simulation.

2.2.3 Printing accuracy

Printing accuracy of the 3DP machine will also have to be considered as a contributor to the accuracy and conformity of a printed physical part from a designed CAD model. In fact, an ability to reproduce fine surface textures relies heavily on the machine accuracy: In this paper, it is defined as the maximum deviation of a binder drop position from the numerical fabrication code along the three orthogonal printing directions. This accuracy depends on the errors introduced in the system by each component of the machine. The final combination of the machine errors, including the controller errors, can be made within an error budget. Manufacturing rules must reflect this printing accuracy to explain any unpredictable discrepancy in geometry between a designed CAD model and the physical part to be made by 3DP.

2.2.4 Printing style

Two different visually simulated models in accord with different printing styles of 3DP are possible in the CAD tool implemented using the proposed method. **Binary deflection printing (BDP)**, for example, is a printing style in which the lines of drop placements are parallel to the printing direction (Fig. 7; left). **Proportional deflection printing (PDP)**, on the other hand, is a different printing style in which the lines of drop placements follow the edge contour of the 2-D layered CAD data, which provides smoother edges in the shape of a fabricated complex part (Fig. 7; right). Fig. 8 shows a sample set of three different models; an example texture CAD model (left), BDP virtual model (middle) and PDP virtual model (right) made using the implemented tool.

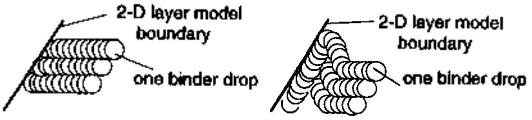

Fig. 7. Two printing styles of 3DP process-BDP (right) and PDP (left).

2.3 Implementation of virtual models

As mentioned before, a surface texture geometry consists of a set of numerous tiny repetitive geometric features, called unit cells. There is a critical minimum value in defining the size of the unit cell due to printing limits of the 3DP machine. In this paper a custom texture unit cell for orthopedic implants has been designed using an implemented CAD tool[16] and fabricated by the 3DP machine. As shown in Fig. 9, the unit cell is first designed using CSG block primitives (upper left) and then four identical unit cells are connected together in order to check their connectivity when mapped onto a implant model (upper right). These original CAD models are then converted into visually simulated models in 3-D virtual space; two visual simulations are performed, one for each printing style, BDP model (lower left) and PDP model (lower right). All simulated virtual objects are polygonal 3-D models. The texture is originally provided by **Johnson & Johnson's, Inc.** and remodeling was implemented on **Silicon Graphics Indigo2** machine with **GL** library to validate the proposed method.

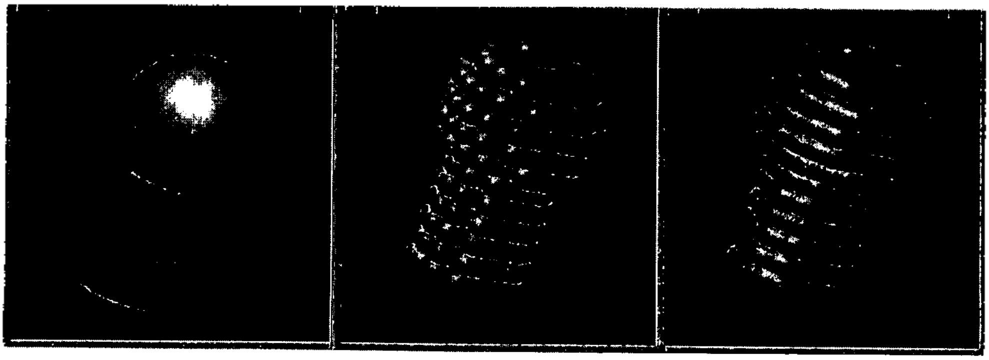

Fig. 8. An example surface texture CAD model with two virtual models.

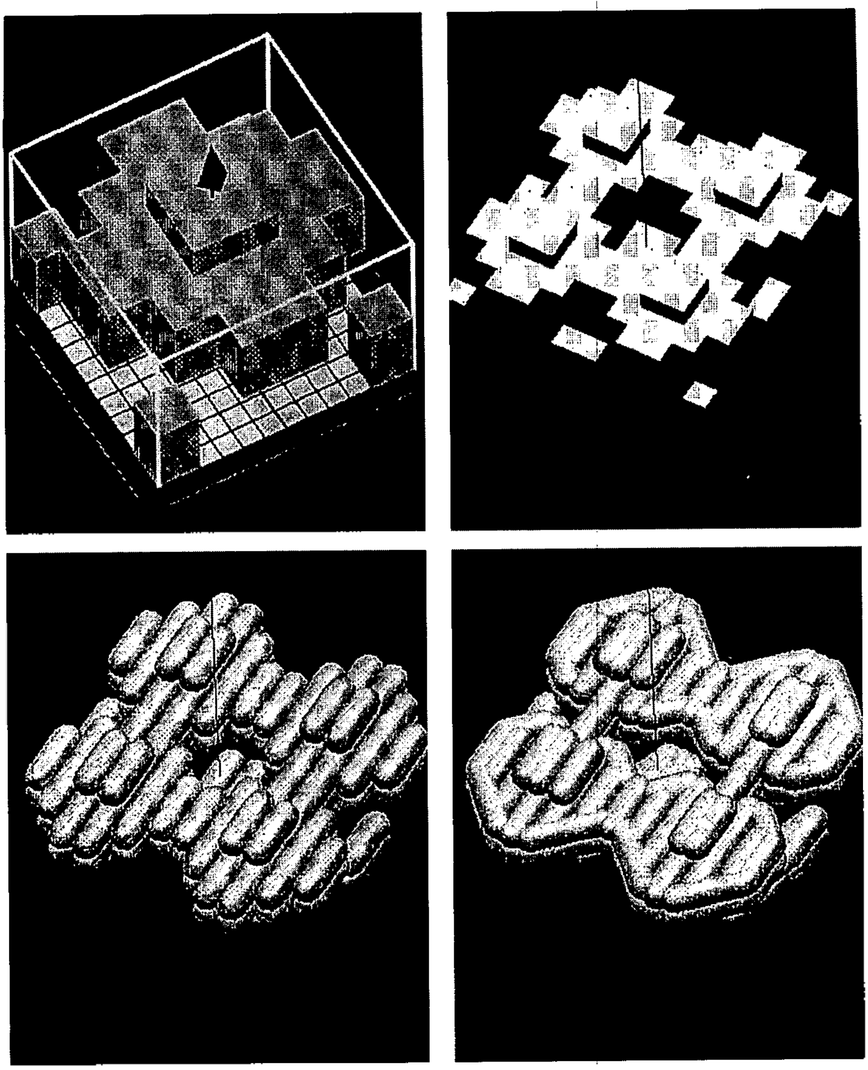

Fig. 9. Design processes for a commerical surface texture CAD model.

3. Virtual Model and Physical Model

3.1 Test models for visual comparisons

Even with the developed tool for visual simulation, however, the geometrical similarity of a visually simulated 3-D image to the physical model after the actual fabrication is still purely hypothetical since the method is based only on a modeling theory. Hence, it must be verified by checking the visual correspondence between the virtual model and the physical model. In other words, we want to know whether the developed tool can really work as a precise visualizer of the physical model as desired.

Fig. 10 shows several test CAD models of the unit cell modeled for experimental verification of the implemented visual simulation tool. Each model represents a texture unit cell in different scales and/or different orientations, for examples, 1.0x, 1.5x, and 2.5x, where 1.0x is perhaps the smallest manufacturable limit, i.e., printability just around the fabrication scale limit. A possible feature orientation can be generally determined by two types of angle; one is the azimuth angle β and the other the angle of inclination α where $0 \le \alpha \le 90$, $0 \le \beta \le 90$ in the 3DP machine space. In short, every possible printing direction is considered at this time. For example, $\alpha=0$

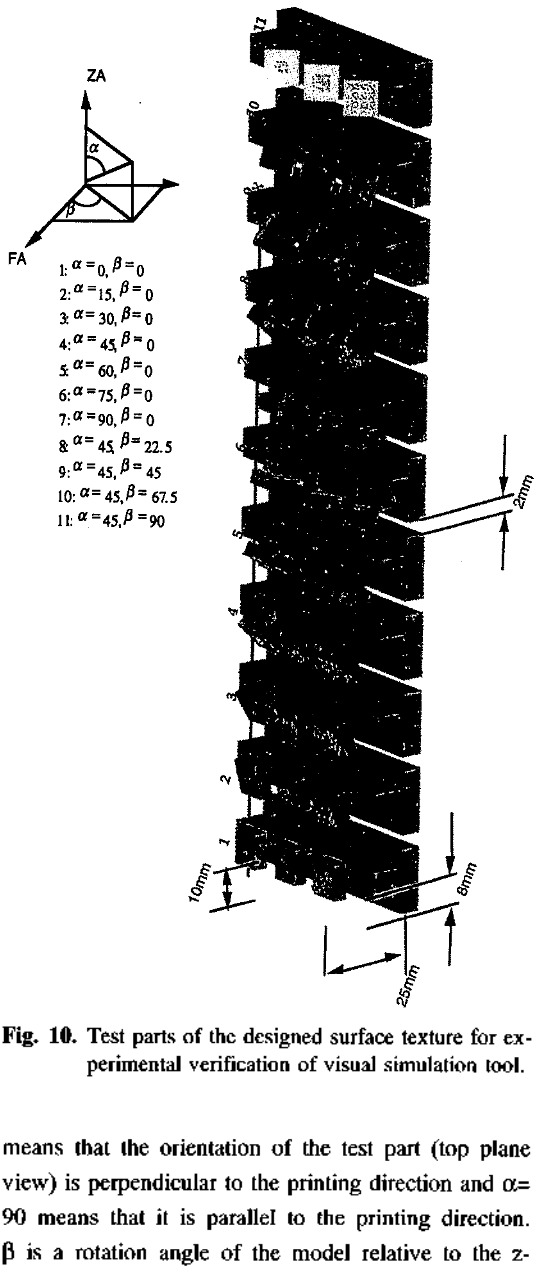

Fig. 10. Test parts of the designed surface texture for experimental verification of visual simulation tool.

means that the orientation of the test part (top plane view) is perpendicular to the printing direction and α=90 means that it is parallel to the printing direction. β is a rotation angle of the model relative to the z-axis. Since the CAD model of a texture unit cell is made of several CSG blocks assembled together, pairs of the model orientation (α=0 or 90) and (β=0 or 90) can be considered to be the optimum printing direction. There is no staircase mark in these orientation.

Fig. 11 to 16 show sample pairs of virtual (left) and physical (right) models that has close visual correspondence between them. Virtual model images made from the test CAD models using the implemented technique are first provided on the left side of the figures, while the physical models made from same CAD models using 3DP are provided on the right side. Each physical model, after the fabrication, is marked carefully and then a magnified photograph is taken using scanning electron microscope (SEM).

3.2 Optimal printing direction

As shown in Fig. 11 and 12, an optimum printing direction with an appropriate dimensional scale larger than 1.0x provides a close visual correspondence between the virtual and physical models. The reason is that for the present scale and orientation, the fabrication rules (staircase mark or layer accumulation) do not heavily dominate the geometrical shape of a fabricated part. Fig. 13, on the other hand, does not show a good result regardless of the optimum printing direction since the scale is on the order of the printing limit of the 3DP machine.

3.3 Non-optimal printing direction

Pairs of models in the vicinity of non-optimal printing direction are shown in Fig. 14 to 16, and some partial visual correspondences are observed in Fig. 14 and 15. For model pair in the vicinity of the fabrication limit in figure 16, visual correspondence can be somewhat unclear because it is either near the fabrication limit or oriented along a non-optimal direction.

3.4 Overall visual matching

First, physical models for the scale of 1.5x and 2.5x generally show good visual matching regardless of the orientation. The 1.0x scale, however, does not always show good visual matching even for the optimum printing direction, for it already loses the geometry information due to the limited printing capability. In short, as the scaling goes down, printing orientation will become less important.

Secondly, even though the optimum printing direction with reasonable scaling provides best printability, a small deviation from this optimum printing direction could be worse than a simple 45 degree printing direction since staircase effects are

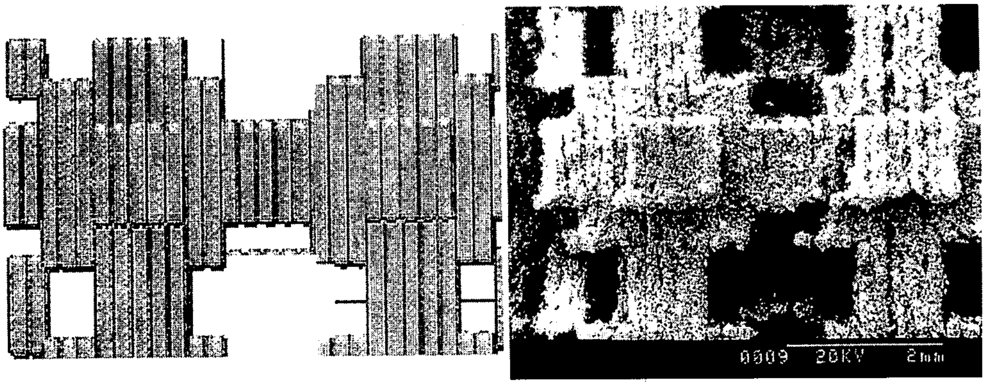

Fig. 11. Test part I (2.5x, α=0, β=0).

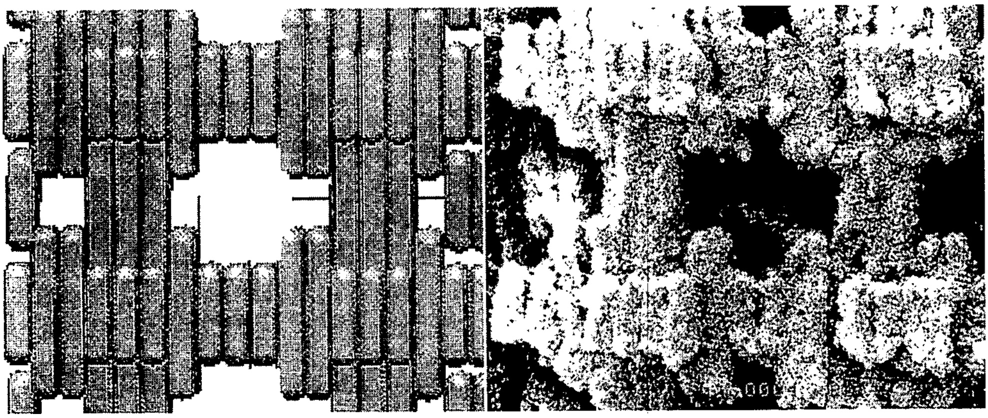

Fig. 12. Test part II (1.5x, α=0, β=0).

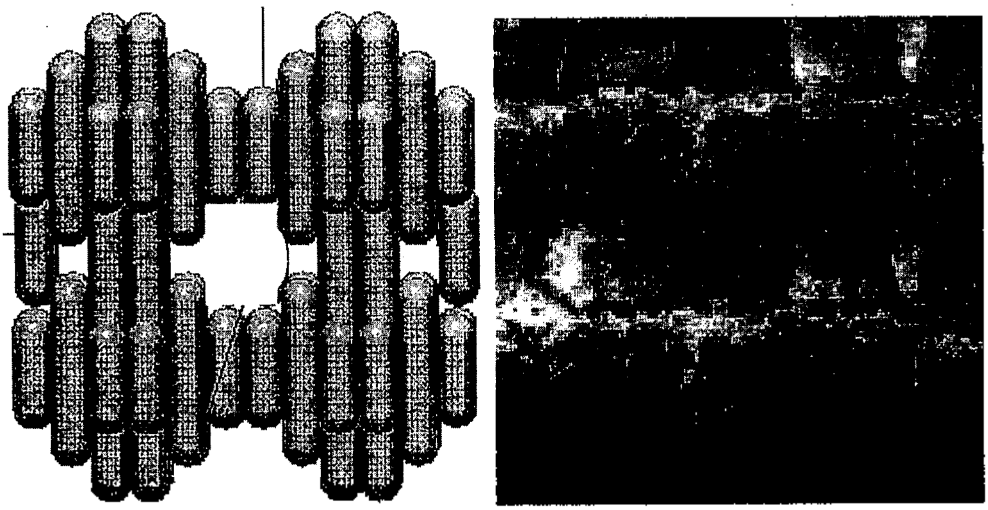

Fig. 13. Test part III (1.0x, α=0, β=0).

maximized at small non-zero angles.

Thirdly, observed poor matching results between virtual models and physical models suggest the presence of either the machine error or physical

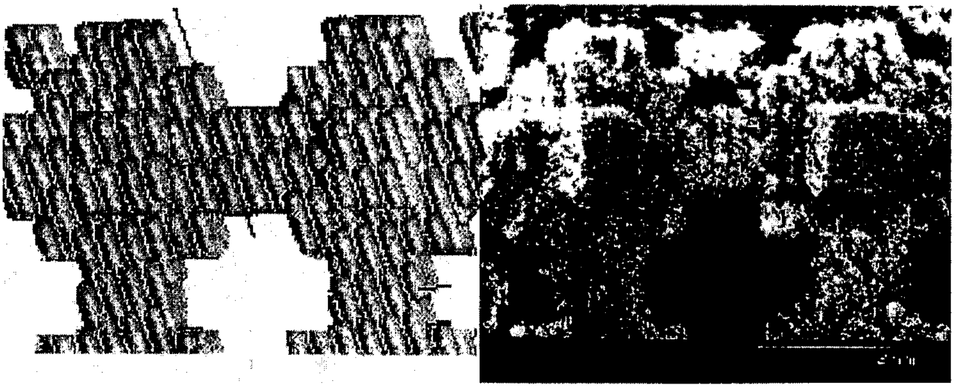

Fig. 14. Test part IV (2.5x, α=045, β=67.5).

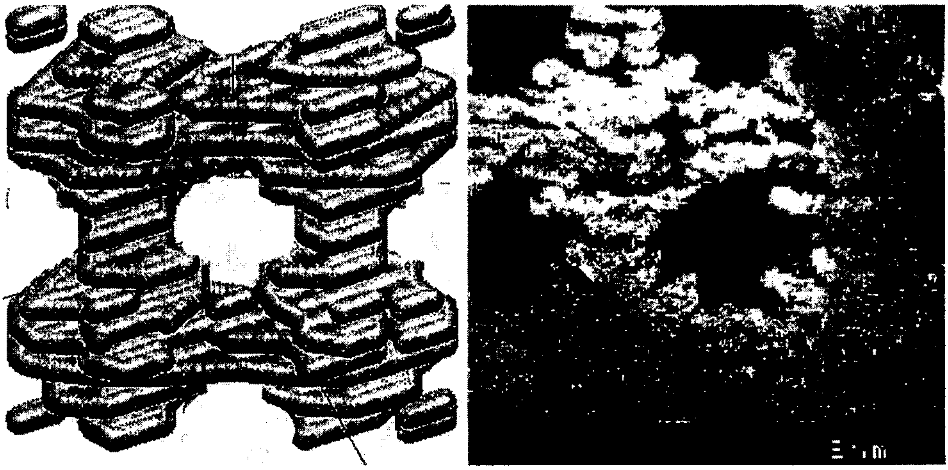

Fig. 15. Test part V (1.5x, α=45, β=67.5).

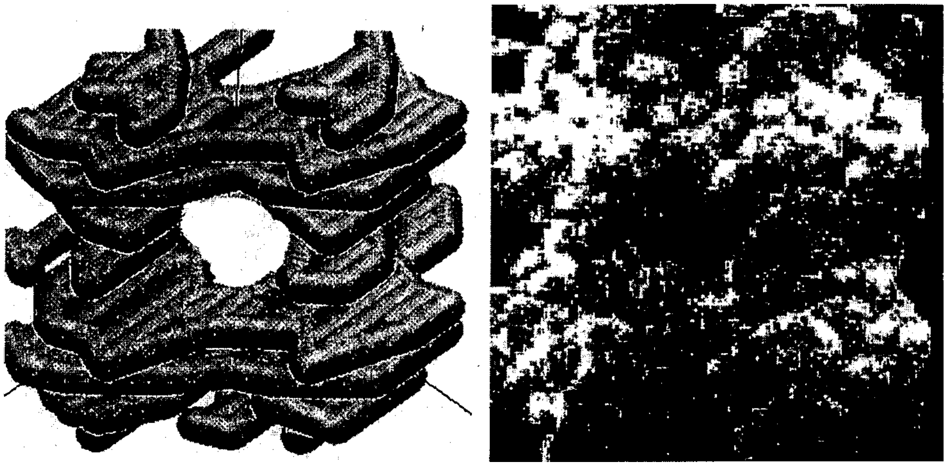

Fig. 16. Test part VI (1.0x, α=45, β=45).

causes such as binder-powder agglomeration, shaking unbounded powder and curing shrinkage after the printing, which can not easily be captured by the implemented tool.

4. Conclusion

The proposed technique provides surface texture designers with a valuable tool for interactions between virtual and real world and helps realize a manufacturable design with minimum iteration by taking the full fabrication process rules of 3D printing into account. Surface texture is an unusual solid geometry that can barely be realized by the new technology, 3D printing, and designing surface textures is difficult due to complex macro-structure of the tiny texture geometry since it must be compatible with the non-traditional manufacturing method of 3D printing. With the implemented visual simulation tool proposed in this paper, designers can figure out an approximated visual image to the physical model in the embodiment of the surface texture design without actually fabricating it. It incorporates necessary geometric attributes of physical phenomena of the 3D printing process and hence provides designers processes with a valuable tool for verifying unseen fabrication capability of the existing prototyping machine.

In fact, the simulation paradigm proposed in this paper can not yet cover all known issues in RP community such as material, surface property, and dimensional tolerance. Instead, it will only be limited to part geometry, the least common denominator involving process capability of all available RP techniques. A common manufacturing capability such as minimum feature size relative to the dimension of one material layer can hence be captured and submitted to a designer so that it lead to manufacturable designs. In process of finding unidentified geometric errors of a physical model after the fabrication can also be aided using the implemented tool, provided that the exact matching error tables can be obtained as future works.

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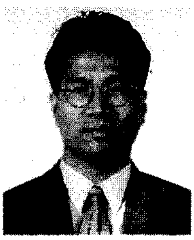

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