Surface Texture by 3D Printing

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ABSTRACT

Three Dimensional Printing is a solid freeform fabrication process which creates parts directly from a computer model by depositing in layers. Each layer is created by depositing powder and selectively joining the powder with binder applied by a modulated ink-jet printhead. This paper explores the application of 3D Printing to the manufacture of surface textures, where the geometric freedom of 3D Printing is used to create repetitive millimeter and sub-millimeter surface structures with overhangs and undercuts. A related aspect of the work concerns the development of computer representations of these complex structures.

In one investigation, a "mushroom field" surface texture was modeled and printed. Each mushroom consists of a cylinder with a ball on top. These features are printed in a hexagonal array with each feature parallel to the local surface normal of a complex curved surface. In another investigation, textures were printed into ceramic molds. The textures were transferred to metal (tin-lead, CoCr) castings as positive surface features with overhangs and undercuts and typical dimensions of 700 x 350 x 350μm. The application of such cast textures to bone fixation in orthopaedic implants is discussed.

MOTIVATION

Limitations of current methods

Custom surface textures can be produced on cast or forged metal parts by various standard manufacturing processes. Current surfacing methods, such as chemical etching and sintering, are highly specialized and permit little variation over the surface texture characteristics. These processes involve heat or chemical treatments which can alter the crystal structure or create micro-notches on the surface, thereby reducing the fatigue strength of the bulk material. In addition, these methods are all performed as secondary operations and thus represent significant increases in component cost and lead time.

3D Printing introduces fundamental improvements to standard methods. First, it provides an extended choice of geometric shape and surface texture configuration and second, parts can be modified and built directly from a CAD system (see figure 1a &b). Another key attribute is the uniformity of physical properties attained by the simultaneous fabrication of part and texture (see figure 4). In other words, 3D Printing eliminates disruptive intermediate manufacturing steps, such as the surfacing post-processes mentioned above.

Application example

3D Printing (3DP) technology can be used to produce parts by different strategies. For example, 3DP can be used to make molds for investment casting, porous preforms for metal matrix composite, or direct polymer, ceramic, metal and composite objects in whatever shape desired.

In one investigation, a texture printed on a ceramic mold was transferred to a metal casting to create millimeter scale hooks or overhangs (see figure 3), much like "Velcro". This type of 3D texture can be used to improve the fixation strength of two joined surfaces, where the hooks act as anchors for the adhesive material. To illustrate an application of such texture, we intend to use 3D printing to produce functional orthopaedic prostheses with bone ingrowth surface texture. In this case, we wish to firmly attach the orthopaedic implant to the adjacent bone.

Orthopaedic Implant Application

Orthopaedic implants for knees and hips are mainly manufactured from standard processes such as investment casting (lost wax) and forging of cobalt-chrome or titanium alloys. In addition, surface post-processing is required in order to create the necessary mirror finished surface and porous surface texture at selected locations on the prosthesis.

A major issue with orthopaedic joint prosthesis is establishing their permanent fixation to the adjacent bone. The use of porous surface texture for biologic attachment of implants by the ingrowth bone offers a valuable alternative to acrylic bone cement as a means of fixation[1]. Specific surface porosity and pore size are essential conditions for providing bone cells an environment conducive to osseointegration. Numerous surfacing techniques have been designed to attach or carve fine porous surface textures depending on the desired feature geometry, size and material used. For instance, textures can be shaped from fine wax fabrics glued on the prosthesis wax pattern, sintered directly onto the metal part, laser trimmed, electrochemically etched or by electrical-discharge machining (EDM). For example, since forged parts exhibit very hard surfaces, texture need to be carved by EDM or chemical etching which provide a 2 dimensional profile only. More complex texture can be laser trimmed, sintered or even cold formed on cast parts.

However, most of these techniques affect the fatigue strength of material, and are restrained to a specific surface texture with little room for varying surface parameters critical to the performance of the prosthesis. For this reason, a process like 3D Printing, which allows the designers to tailor at will surface characteristics of cast parts, (see figure 2) is considered as a promising alternative method.

PRINTING SURFACE TEXTURE; BASIC CONSIDERATIONS

Two basic factors need to be considered to print accurate surface texture conform to a CAD model. First, the CAD file protocol needs to efficiently handle the geometric complexity associated with the surface texture. Second, the limitation of the fabrication processes must be considered in determining the minimum possible feature sizes.

CAD development

Introduction

Mapped-surface patterns in computer graphics have been widely used for adding visual authenticity to an image since it was first suggested by Catmull in 1974[2]. For example, material recognition is greatly enhanced by wrapping a wood grain pattern image around a rectangular solid to create the impression of a block of wood. In contrast with two-dimensional patterned surfaces, surface textures are three-dimensional features physically made on object surfaces.

Geometric Information Handling

A CAD file representing even a simple repetitive surface texture will have to store the information for thousands of single surface features. However, complication arises since standard CAD systems have not been designed to handle that many small geometric features, resulting in an overflow of CAD information which ultimately overloads the systems. The generally accepted standard CAD model (STL) format reached its limitations with attempts to represent texture information as part of the main CAD model even with the use of efficient tolerance-driven tessellation algorithms[3].

A more effective method has been introduced to model this specific kind of repetitive geometry. This new format currently known as a procedure model[4] does not store the CAD model itself but the *procedure* generating the CAD model which requires much less storage space.

With this new protocol, the geometry of a unit feature forming the surface texture is characterized with the minimal amount of information necessary to keep its conformity and minimize data storage space. For example, the model of a mushroom feature (see figure 1a) composed of a cylinder with a sphere on top, would be built from just a few bytes of parametric information labeled by a given call number. All the mushroom features assembled on the whole surface texture are then represented only by their call number, position and orientation attributes. In other words, since all of the individual features are exactly the same, they could be simply copied from one template CAD model instead of being stored individually.

Control Of Texture Arrangement

Another important issue is the distribution of the texture features on the object surface with the desirable spacing and location. To indicate the specific region on the object surface where the texture features may be located, a texture field should be defined by the user. The various software control actions deciding the final position of all individual texture features are based on distribution rules applied to that particular texture field boundary. Using this method, the position of thousands of texture features can be precisely defined in order to satisfy predetermined design conditions assuring the desired surface properties.

Cad Implementation Preliminary Results

A first effort to implement a CAD model with surface texture using the procedural method has been made on quadratic object surfaces such as spheres, conic cylinders, and toroids using an IRIS-4D-70GT-Indigo workstation as platform. An example of a CAD model and its physical 3D printed part are shown in figure 1a & 1b. Currently, the texture field is defined as a complex surface bound by an arbitrary NURBS curve user-interactively defined in the (u, v) parametric domain. Once the texture field is defined, each position of single texture feature is carefully computed by considering the desired spacing and size of the texture feature set by the user. Those same position points defined in the parametric domain are then mapped onto the real object domain in order to set the real position of each feature on the object surface. Thereafter, the template CAD model of one feature (mushroom for example) is copied into every single position previously calculated in order to construct the entire surface texture arrangement. The orientation of each feature will exactly coincide with the normal vector pointing outside the object at each particular location. Finally, once the CAD information of a part and texture is well characterized, the model can now be directly translated into manufacturing machine commands necessary to control the 3D Printing machine.

As described before, the CAD model constructed in this example is only for demonstration and verification of the underlying concepts. The next step is to generalize the method for random part shapes described with the STL format, combined with a procedural format to represent the texture characteristics.

Dimensional Limits

As with any manufacturing process, 3D Printing fields of application are partly determined by the resolution, accuracy and minimum feature size it can achieve. In 3D Printing, features can be defined as positive feature (or protrusion) when created by an aggregate of primitives, or negative feature (cavity) when surrounded by a group of primitives. The minimum positive feature size is defined by the primitives size or in other words, the size of single drops and lines of drops forming the building blocks of the parts. The minimum negative feature size can be smaller as it is determined by the need to remove powder to define the feature.

The overall accuracy of the 3D printer is determined by the combination of the errors introduced by each machine component. Printing surface textures is a particularly demanding application and makes a thorough understanding of these errors a crucial step to success.

Minimum Feature Size

3D Printing is a material additive manufacturing process as opposed to a subtractive, forming or phase change process. The material is added, as droplets ejected from a nozzle hits and binds a small region of the powder bed. The primitive size corresponds to the powder-binder agglomerate formed by a single droplet. The printed ball diameter is determined by various factors including binder drop chemical composition and size, powder chemical composition and size, layer thickness, powder bed density and surface tension. A succession of drop primitives forms lines which will form planes into a solid 3D object on a layer by layer basis. The minimum size of the positive feature (protrusion) forming surface texture is bound by the drop primitive size mentioned above.

For example, a 75μm drop of colloidal silica printed on a 175μm layer thickness of alumina powder will form a 125μm drop primitive . Then, if primitives are overlaid on each other every 20μm, they will form a 200μm wide line. Hence, texture can be produced as protrusion (positive) features as small as 200 μm. On the other hand, cavity or negative features need to be large enough to let the trapped unbound ceramic to be removed easily from cavity. As a rule of thumb, the cavity should be at least as large as four or five ceramic grain size, which is in our case approximately 120-150μm for 30 μm alumina powder.

Figure 5 shows an alumina mold produced for investment casting of a texture. It reveals detailed features in the size range of 375μm, and it should be noted that positive feature size is about twice as big as the primitive size in order to sustain the pouring stresses caused by the liquid metal rushing into the mold. Negative features or cavities are also slightly bigger than the minimum admissible size (≈120μm) to prevent misrun or incomplete mold filling due to metal surface tension.

Machine Accuracy

The ability to reproduce fine textures relies heavily on the machine accuracy. 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, is done within an error budget. An error budget is a system analysis tool, used for prediction and control of the total error of a system when accuracy is an important measure of performance[6]. To find and organize the different types of error contributors into a budget, one considers the chain of all elements connecting the tool (printhead) to the workpiece (powder bed) through out the machine. This chain consists of all machine elements which provide mechanical support for the printhead and powder bed, and components which measure or control the position of the printhead. This structural chain, referred as a metrology loop[7] is showed for the 3D Printing machine (figure 8). All the error sources are combined selectively for the three axes into a final number representing the achievable accuracy in terms of surface finish, form and size of the produced 3D printed part. A preliminary analysis of the 3D printer error budget showed that a large fraction of errors originate from just a few components of the machine, most notably the electrostatic printhead.

Printhead Accuracy; Simulation and Experiment

One of the major contributors to drop placement error is the electrostatic printhead and the various secondary effects related to it[5]. The electrostatic printhead (figure 6) consists of a continuous jet of droplets printed in either binary or proportional deflection mode. In the binary mode, selected drops can either be fully charged or neutral, in order to be either deflected away in a drop catcher or printed on the powder. In the proportional deflection mode, droplets are partially charged in order to be positioned proportionally to their charge, on either side of the stream axis (figure 6) .

Potential deflection errors are determined from two basic disturbances affecting the droplet charge and speed; electrostatic interaction between drops and aerodynamic forces[5]. The exact charge carried by each drop determines the final proportionally deflected position. Any secondary effects changing the initial desired charge or speed will generate subsequent droplet positioning error.

As mentioned, positioning error is also caused from drag forces acting on the jet stream by slowing down the initial drop velocity along their path. A simulation of this effect has been conducted to determine the distance from the charging electrode where drag forces make the leading drop merge with the subsequent drops. (figure 7). In this process, merged drops are regarded as unacceptable for accurate printing. Experimentation on a train of drops in still air confirmed the results obtained in the simulation where the first merge occurred at about 15 mm from the charging electrode. Fortunately, most of the drag forces can be counteracted with software compensation by removing problematic drops, modifying charging pattern or printing closer to the powder bed.

Analytically describing the combination of all the drops interaction in the printhead becomes extremely complex. Therefore, most of the error compensations incorporated in a software algorithm will be based on experimental data in the process of being compiled for now.

CONCLUSION

3D Printing has been used to create complex surface textures with overhangs and undercuts. Such textures have been fabricated on ceramic molds and transferred to castings of tin-lead and high melt temperature CoCr alloys. The resulting textures, intended for use as bone ingrowth surfaces for orthopaedic implants, have 40% porosity with an average pore size of 350μm. The 3D printed ceramic molds were generated directly from a CAD model with minimal software error compensation. Research is under way to compile an error compensation scheme that will improve even more the actual accuracy and surface finish of 3D printed parts. This will lead to eventually print a full size ceramic mold to produce functional casting of orthopaedic prosthesis with bone ingrowth surface texture.

The current 3D Printing machine design produces minimum feature size in the range of 175 μm diameter (on alumina powder) which can be positioned on the powder bed with an approximate accuracy of ±5 to 25 μm depending on the part orientation. The formulation of an error budget will help to elucidate the most important factors influencing accuracy and guide future designs and developments of the machine. Research in powder and binder materials is under way in order to better understand and improve our dimensional control over the primitive size.

Many applications will benefit from the use of 3D Printing for its flexibility and fast turnaround time. Moreover, it opens new fields of applications requiring enhanced surface features, such as protrusions, cavities, overhangs and undercuts in the millimeter or sub-millimeter range. Finally, designers now have access to a new process likely to be used for production, as well as a design of experiment tool. Different conceptual product variations could now be compared to optimize functionality, cost effectiveness or other issues.

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FIGURES

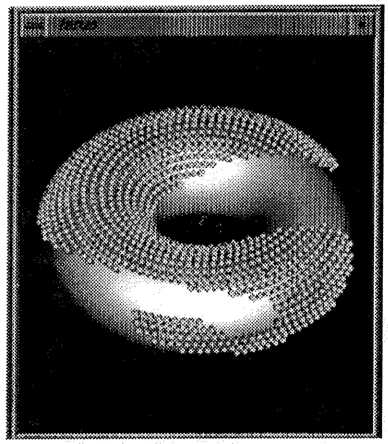

Figure 1a): CAD model of a torus shape with mushroom surface.

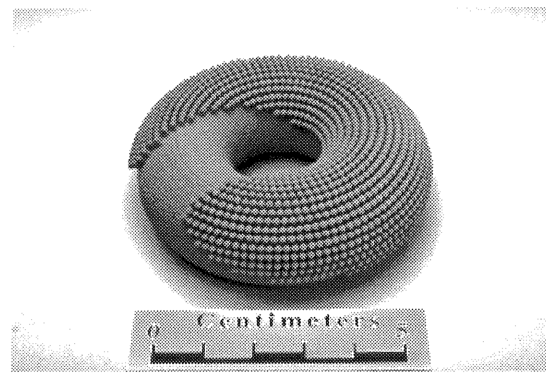

Figure 1b): 3D printed torus of CAD model of figure 1atexture.

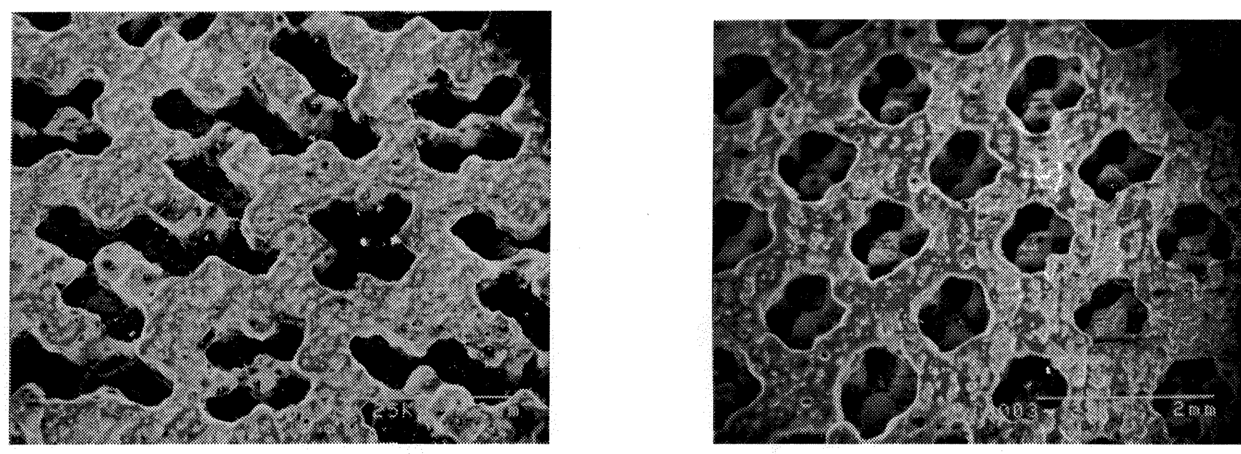

Figure 2: Tin-lead castings of 2 different textures cast from an Aluminum Oxide mold featuring textures (≈400 μm size) generated from macro-cavities directly printed onto the mold surfaces.

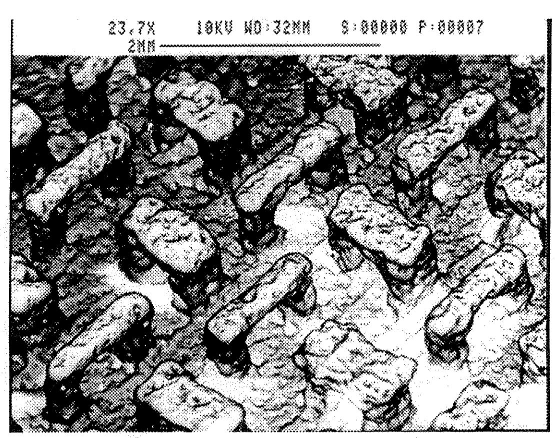

Figure 3: SEM of "Velcro" tin-lead casting. (arches are 1.2mmL x 0.35mmW)

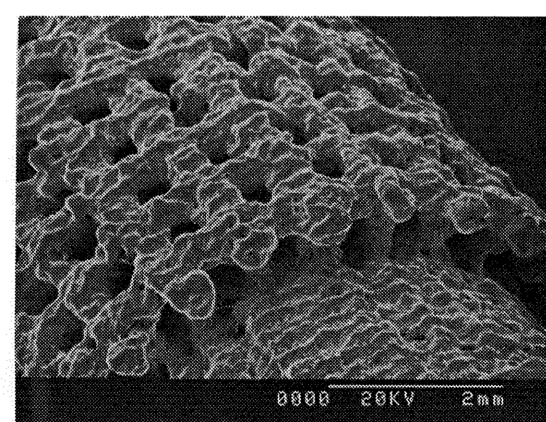

Figure 4: SEM of CoCr texture on a 6mm dia cylinder.

Figure (cont'd)

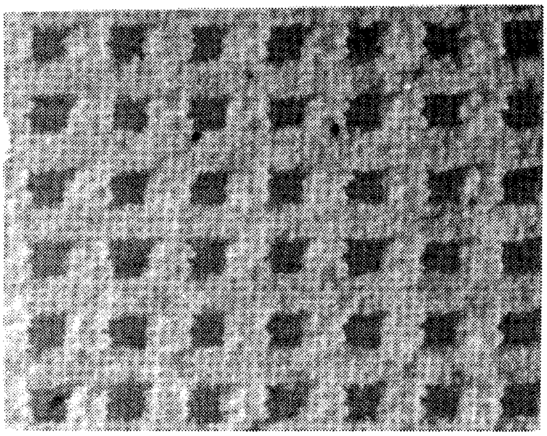

Figure 5: Alumina mold for investment casting of a surface textured part (each line is 350µm wide).

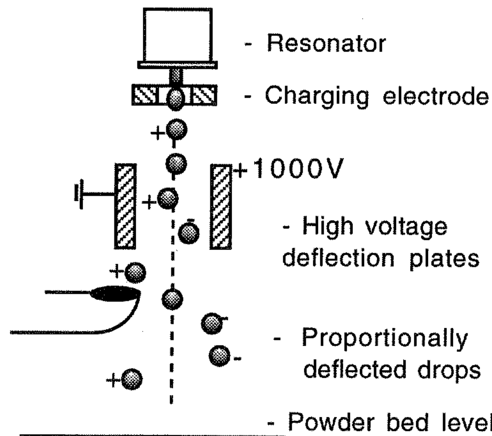

Figure 6: Electrostatic printhead schematic.

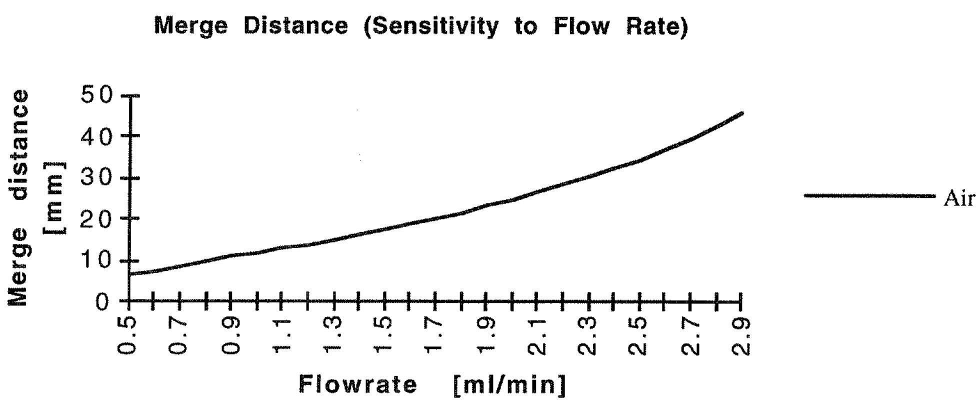

Figure 7: Simulation of drop merge distance in still air as a function of flow rate.

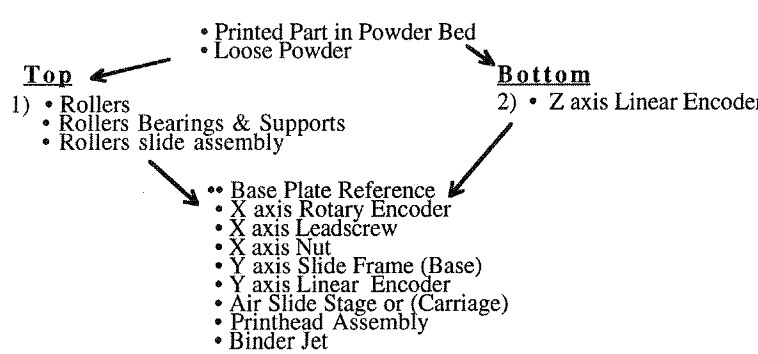

Figure 8: 3D Printing metrology loop.