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Incorporation of Fractal Textures to 3D CAD: Towards an Enhanced Control of Surface Topography

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ABSTRACT

The possibility of designing and manufacturing textured materials and objects, with surface properties controlled from the design stage, instead of being the result of machining processes or chemical attacks, is a key factor for the incorporation of advanced functionalities to a wide set of products. Recently developed high-precision additive manufacturing technologies, together with the use of such textured designs, may promote a precise definition and control of final surface properties and have potential applications in relevant research fields, including tissue engineering and implant technology, optics and optoelectronics, materials science, micro- and nano-systems engineering or tribology, to cite just a few. In this work we present an enhanced design process for incorporating controlled textures to the three-dimensional geometries of computer-aided designs. The process is based on adequately modifying the positions of the vertices of tessellated geometries, stored in form of .stl (standard tessellation language) files, and stands out for the possibility of texturing very complex three-dimensional objects. Some cases of study, including spheres, screws, dental implants and expandable stents, all of which may benefit from the special tribological or biological effects induced by the introduction of textures, are presented to show the potential of the proposed design process.

Keywords: surface topography, material texture, materials design, CAD, fractals.

1. INTRODUCTION

Material surface topography has a direct influence on several relevant properties, linked to its final performance, such as friction coefficient [1], wear resistance [9], self-cleaning ability [2], biocompatibility [10], optical response [5], touch perception, overall aesthetic aspect and even flavour [7]. Therefore it also plays a determinant role in material selection in engineering design, especially in the field of micro and nanosystem development, in which the effects of topography on the incorporation of advanced properties are even more remarkable.

Normally material surface topography is consequence of material's natural state or the result of machining processes, chemical attacks or post-processes used for the manufacture of a device or product. Several strategies for modifying material topographies and surface properties have taken advantage of conventional surface micromachining [27], laser ablation [11], micromolding [29], biomimetic templating [34], physical and chemical vapor deposition processes [24], sol-gel procedures [23] and molecular self-assembly [35]. All these processes require enormous hands-on expertise and final result depends on several control parameters, whose interdependencies are normally complex to understand, characterize, model and master [18]. As can be seen from the previously cited documents, top-down and bottom-up approaches for controlling surface properties co-exist and in many cases complement each other [30], the former being more focused on mass-production (as it derives from the microelectronic industry), the latter providing remarkable geometrical versatility. Combinations of top-down and bottom-up approaches are frequent and have usually focused on manufacturing the larger micrometric features by means of top-down processes (micromachining, etching ...) and the smaller nanometric details by using bottom-up techniques (CVD, PVD, sol-gel ...).

Advances in computer-aided design and in high-precision additive manufacturing technologies, based on layer-by-layer deposition or construction, are opening new horizons for controlling surface topography from the design stage and in a very direct way, even allowing for biomedical interactions at a cellular level [31,41]. Even though conventional

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computer-aided design programs usually handle Euclidean geometries and mainly rely on simple operations (sketch based operations, extrusions, pads, holes, circular grooves . . .) for obtaining "soft" solids and surfaces, recent approaches resorting to the use of matrix-based programming have already proved to be useful for designing rough surfaces and textured objects adequately described by fractal geometries [16,28]. In parallel, the continued progress on additive manufacturing technologies (also called "solid free-form fabrication" due to the complex geometries attainable), has increased the range of materials capable of being additively processed and greatly promoted their precision, even down to nanometric features, with implications in the development of advanced multi-scale materials and metamaterials [8,37,41].

The possibility of obtaining micro-textures and micro-architectures on conventional 3D design files (for instance for controlling the surfaces of medical devices, in order to promote osseointegration by design, among other positive effects, including the incorporation of visual effects) is being addressed by computer-aided design companies and has led to the recent development of interesting software, such as Within Medical Software [44] (http://www.within-lab.com) or MeshLab (http://meshlab.surceforge.net). The possibility of linking such designs, including complex features for improved performance, with the world of additive or layer-by-layer manufacturing, opens up new horizons in several fields, such as architecture, automotion and aeronautics, biomedical engineering, materials science and engineering, product design and art, among others.

In fact, the control of surface topography from the design stage and the possibilities of using computer-aided multi-scale materials for product development have been subject of recent methodical analyses [22] what helps to highlight the relevance and present impact of advances linked to the topic of present study. Some of the most interesting and successful strategies for texturing and controlling the surface topography of computer-aided designs are mentioned under these lines. In the case of Within, the process is based on the optimization of latticed microstructures and on the use of variable density surface skins for promoting bio-inspired and personalized designs, adapted to desired weight requirements, to allowable maximum displacements and to required stiffness [13, 44]. Other approaches resort to the use of mesh-based operations for the incorporation of random or fractal perturbations to the conventional "soft" surfaces of computer-aided designs [42] or benefit from the use of repeated Boolean operations or functions at different scales for the inclusion of details to product surfaces, pursuing multi-scale designs, also leading to fractal-like surfaces [19].

From an historical perspective, it is also interesting to note that some decades ago, the initial studies trying to incorporate textures to computer-aided designs mainly focused on creating textured renderings of architectural designs, after texture samples and details extracted from digital images of color photographs of the actual materials [17]. Regarding physical 3D textures, well before the generalization of additive manufacturing, machinable textures for CAD/CAM machining systems was also addressed by means of two- and three-dimensional scanned textures and incorporated into the ArtCAM design and manufacturing system [46] (http://www.artcam.com), with implications in jewelery, furniture and sculpture, between other artistic fields. More recently, the creation of enhanced bas-reliefs has also been addressed [6].

In this work we present an enhanced design process for incorporating controlled textures to the three-dimensional geometries of computer-aided designs. The process is based on adequately modifying the positions of the vertices of tessellated geometries, stored in form of .stl (standard tessellation language) files, and stands out for the possibility of texturing very complex three-dimensional objects. Previous research from our team had focused on the modification of planar surfaces and other simple geometries, such as spheres, cylinders or cones [12, 13], but here we improve the procedure for incorporating textures to any 3D CAD file. In such prior studies we presented the incorporation of textures to planar objects, in which only the height of each point of the working grid had to be changed.

The shift towards three-dimensional texturing, working upon .stl files, has to face several challenges, including the need to act just once on each vertex, so as to avoid mesh openings and surfaces with "holes", which makes automation of the process more complex and requires the incorporation of a control vector for controlling the already modified vertex, and the modification of three different coordinates at once, instead of just changing the height of each point of the working grid.Some cases of study, including screws, dental implants and expandable stents, all of which may benefit from special tribological and biological effects induced by the introduction of textures, are presented to show the potential of the proposed design process and three-dimensionally textured for the first time using the proposed approach.

2. DESIGN METHODS

Even using conventional CAD resources; mainly pattern operations, scaled copies, symmetries and Boolean operations, multi-scale fractal-like designs of textured materials can be obtained and the benefits of using parametric design tools, typical of any CAD program, are evident, as just by changing the value of one parameter the whole structure and properties of a textured material or design can be changed, an even linked to more general control parameters like the fractal dimension [39]. However the incorporation of other fractal features, such as textures and other micro-architectures, to computer-aided designs, requires alternative processes. The design process detailed here is a generalization of previous research, linked to the generation of simple geometries, stored in form of matrices in the form [X, Y, Z(x, y)], being X and Y column vectors, storing the x and y components of the working grid, and Z(x, y) a column vector, whose components were the height values for each (x, y) couple. Subsequently, fractal features could be introduced, for the incorporation of controlled random textures to the initially regular meshes, typically corresponding to two-dimensional objects [13]. In previous works we used fractional Brownian surface models [16], for incorporating the desired fluctuations of height by means of the following equation:

$$z(x,y) = z_0 + m \cdot \cdot \sum_{k=1}^{\infty} C_k \cdot \lambda^{-\alpha k} \cdot \sin(\lambda^k [x \cdot \cos(B_k) + y \cdot \sin(B_k) + A_k]) \tag{1}$$

Such model used several random functions (A_k, B_k, C_k), several control constants (λ, α, m) and an initial height function "z_0" could also be introduced. It is interesting to note that, in fractional Brownian models [16], fractal dimension can be related to the exponent α, being $D = 3 - \alpha$, with $0 < \alpha < 1$. Therefore, higher values of "alpha" lead to more "planar" surfaces and lower values of "alpha" lead to more "three-dimensional" or spiky surfaces. In present study we use the random functions proposed by Falconer [16], being C_k a normal distribution with mean = 0 and standard deviation = 1 and being A_k and B_k uniform distributions in the interval (0.1). By truncating the aforementioned sum of infinite terms, basic fractal geometries could be obtained in matricial form and further converted into recognizable CAD formats, typically .stl, .igs or .dwx. The use of additional "mesh to solid" converters led to final solid files, which could be used as normal CAD parts for further design, simulation and computer-aided manufacturing tasks.

The process detailed here constitutes an adaptation of such procedure to the three-dimensional surfaces of any computer-aided design. For present study we have started using spheres, for process adjustment, and also applied the procedure to several cases of study linked to different complex three-dimensional objects to show the versatility of the proposed approach. The process starts from different un-textured conventional CAD geometries designed with the help of NX-8.5 (Siemens PLM Solutions). Once the initial CAD geometries are obtained, we store them in .stl (standard tessellation language) format, in its binary version (as the ASCII .stl files can become very large). A binary STL file has typically an 80 character header (generally ignored, but which should not begin with the word "solid" because that will lead most software to assume that it is an ASCII .stl file). Following the header, a 4 byte unsigned integer indicates the number of triangular facets in the file. After that integer, each triangle is described by twelve 32-bit-floating point numbers: three for the normal vector and then three for the Cartesian coordinates of each vertex.

The number and size of triangles of the tessellated CAD geometries depends on the precision and related options selected, when exporting the initial geometry to a .stl file. Some computer-aided design resources, such as SolidWorks (Dassault Systèmes SolidWorks Corp.), allow for the introduction of a fixed triangle size; other programs, such as Solid Edge and NX-8.5 (both Siemens PLM Solutions) allow for the introduction of a desired precision, while the final size of each triangle depends on external surface curvature.

After conversion of the CAD files to .stl format, we apply the textures by opening the different binary .stl files and introducing random fractal-based perturbations to the Cartesian coordinates of the different vertices. For re-writing the .stl files we have developed a Matlab (The Mathworks Inc.) program for obtaining a matrix of vertices, systematically modifying their positions and finally storing the new coordinated in the ASCII .stl file. After re-writing the .stl files, most CAD resources can be used for viewing final result and the files can even be linked to automated manufacturing technologies, especially those working using additive approaches, for obtaining final devices or the related production tools.

In our examples, best results are obtained when the displacements introduced to the different vertices are of a similar order of magnitude or one order lower than the initial triangle size, otherwise the surfaces change dramatically and final results are too spiky. The introduction of displacements is schematized in the following equation, where Z_t is the matrix listing the (x, y, z) coordinates of the vertices of all triangles (n triangles, and therefore 3n lines in each matrix) after modifying their positions, Z is the matrix listing the (x, y, z) coordinates of the initial vertices and ΔZ is the perturbance matrix:

$$Zt = Z + \Delta Z;$$

$$\begin{pmatrix} x_{1t} & y_{1t} & z_{1t} \\ x_{2t} & y_{2t} & z_{2t} \\ \vdots & \vdots & \vdots \\ x_{(3\cdot n-1)t} & y_{(3\cdot n-1)t} & z_{(3\cdot n-1)t} \\ x_{(3\cdot n)t} & y_{(3\cdot n)t} & z_{(3\cdot n)t} \end{pmatrix}$$

$$= \begin{pmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \\ x_{(3\cdot n-1)} & y_{(3\cdot n-1)} & z_{(3\cdot n-1)} \\ x_{(3\cdot n)} & y_{(3\cdot n)} & z_{(3\cdot n)} \end{pmatrix}$$

$$+\begin{pmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ \vdots & \vdots & \vdots \\ a_{(3\cdot n-1)} & b_{(3\cdot n-1)} & c_{(3\cdot n-1)} \\ a_{(3\cdot n)} & b_{(3\cdot n)} & c_{(3\cdot n)} \end{pmatrix} \quad (2)$$

With:

$$\Delta Z\,(\mathrm{i,j}) = \sum_{k=1}^{10} C_k \cdot \lambda^{-\alpha k} \cdot \sin(\lambda^k[i \cdot \cos(B_k) + j \cdot \sin(B_k) + A_k]); \quad (3)$$

using several random functions (A_k, B_k, C_k) and several constants (λ, α), according to the typical fractional Brownian fractal models [16], in our case with $\lambda = 10$, which leads to amplified textures for visual purposes, and controlling final texture with the control parameter α, with values from 0 to 1, usually corresponding to fractal dimensions from 3 to 2, respectively. For the three-dimensional model we have used again the random functions proposed by Falconer [16], which are easily generated with the help of Matlab functions, being C_k a normal distribution with mean = 0 and standard deviation = 1 and being A_k and B_k uniform distributions in the interval (0.1). The use of the random functions may lead to slightly different CAD models, when reproducing the process with different computers, but main surfaces characteristics and roughness, which are connected to the fractal dimension, will still be similar.

It is important to note that a vertex in a .stl file typically belongs to four different triangles meeting together, so each line (vertex) of "Z" matrix is repeated four times, storing the Cartesian coordinates of a single vertex. If "ΔZ" matrix is constructed without taking the aforementioned issue into account, different lines of "Z_t" matrix corresponding to the same vector in different triangles end up with different coordinates, hence leading to a final open mesh. The fact that the vertex of .stl files typically belong to four different triangles incorporates the additional difficulty of defining a normal vector to the surface being modified, so instead of using normal displacements our process incorporates random movements to the different vertex, but working just once on each vertex belonging to different triangles to avoid the hole generation presented in Fig. 1a.

Therefore it is necessary to use an additional control column vector, as an aid to construct the perturbance matrix (initially null). Step-by-step the components of the control vector take a value of "1", for those positions where the vertex being modified appears, and a value of "0", for the remaining vertices. The positions stored in the control vector recall us which lines of the perturbance matrix have to be introduced at once and with the same values. Using this strategy, each vertex position is modified just once, in spite of belonging to different triangles.

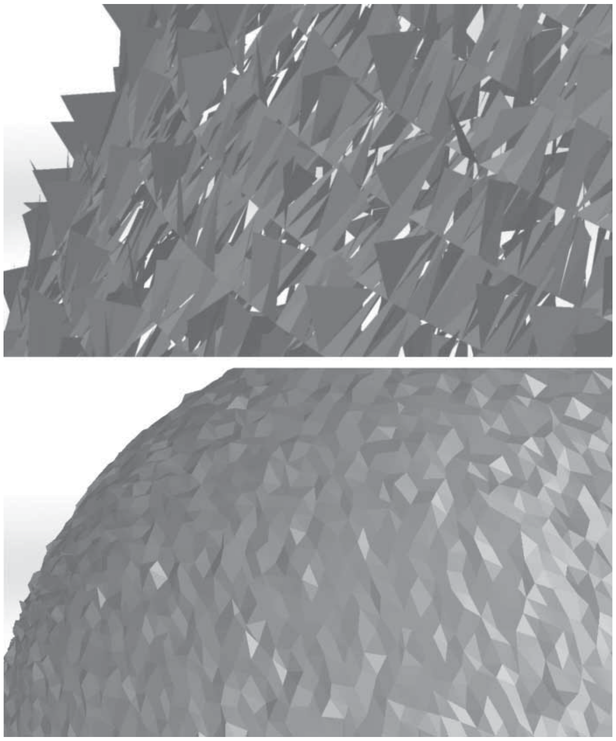

Fig. 1: Incorporation of controlled textures to a tessellated sphere: Process evolution. a) Wrong open mesh, due to modifying the positions of the different vertices more than once. b) Adequate closed mesh, after the introduction of a counter for controlling the already modified vertices.

Fig. 1 helps to highlight the relevance of the mentioned problem, when applying the design procedure to a spherical 3D probe: the upper image shows a wrong open mesh, due to modifying the positions of the different vertices more than once; while the lower image shows an adequate closed mesh, after the introduction of a counter for controlling the already modified vertices. Closed meshes are necessary for further rapid prototyping procedures, so that conventional slicing software of the associated layer-by-layer manufacturing machines work properly, as well as for using these geometries for finite element based simulations. Additional design implications, details and results linked to the different cases of study are included in the following section.

3. CASES OF STUDY, RESULTS AND DISCUSSION

In order to address the influence of control parameter "alpha" on surface texture and its impact on global part volume, overall surface and surface to volume ratio, we have designed a spherical probe, converted it into a binary .stl file (in this case without using a very fine tessellation to avoid excessive file sizes and processing times) and applied different fractal textures, using the values of alpha included in

α	*Surface (mm^2)*	*Volume (mm^3)*	*S/V*
0.9	11659737.8000	3726291218.4160	0.00312905
0.8	11676750.3000	3726421029.6390	0.0031335
0.7	11711155.8100	3727778811.1940	0.00314159
0.6	11760379.1400	3727295217.5490	0.0031552
0.5	11828523.0600	3725085670.4260	0.00317537
0.4	11998017.5700	3724918159.9600	0.00322102
0.3	12269358.5200	3726996649.8110	0.00329202
0.2	12876341.3200	3722746182.1170	0.00345883
0.1	14400398.7000	3713786962.1680	0.00387755

Tab. 1: Influence of control parameter alpha on the final surface, volume and surface to volume ratio.

Tab. 1. Visual examples of the influence of control parameter on surface aspect are incorporated below in Fig. 2. Decreasing values of alpha (0.9; 0.7; 0.5; 0.3 and 0.1) lead to rougher surfaces, which are in fact surfaces with a higher fractal dimension (more three-dimensional).

Parameter "lambda" may be used as an additional control parameter, although in this study we have used the fixed value $\lambda = 10$ for visual purposes. For researchers wishing to take advantage of both control parameters, we propose to use a fixed value of lambda, with which the order of magnitude of surface roughness can be tunes, and further introduce variations by changing alfa, which according to Falconer and to our previous results [17], helps to modify the fractal dimension of the surfaces and to change the values of roughness in a controlled way, without changing their order of magnitude.

Total volumes and surfaces of the different textured spheres obtained have been measured with the help of the analysis tools of NX-8.5 (Siemens PLM Solutions). Fig. 3 shows the evolution of total part volume (spheres in these examples), total surface and surface to volume ratio, when varying control parameter alpha. In short, lower values of alpha lead to rougher parts, larger surfaces and a remarkable increase of surface to volume ratio. The possibility of controlling texture from design is interesting for several tribological purposes; while the option of improving the surface to volume ratio has several chemical and biological implications, as the speed of chemical reactions typically increases with the amount of exposed surface. Other mechanical (i.e. heat dissipation) and contact phenomena (i.e. adhesion) can also benefit from designs including enhanced surface to volume ratios, as well as other options discussed in the conclusions section.

The results shown, by using the textured spheres as initial examples, help to validate the aforementioned possibility of precisely controlling the texture of three-dimensional objects from the design stage. Prototype manufacture by means of additive rapid prototyping is direct and beyond the purpose of present study, although we expect interesting forthcoming results, especially by using supportless technologies, including selective laser sintering, selective laser melting, direct laser writing and digital light processing. Other interesting possibilities are detailed further on, by means of different cases of study, mainly linked to biomedical devices; although many other areas of study may benefit from similar approaches, as discussed in the conclusions section when detailing some additional possible future directions.

In the field of biomedical engineering, combined advances in the computer aided design of complex biomimetic geometries and high-precision additive manufacturing is providing interesting results of interacting at a cellular level. Currently the highest precision can be obtained by using additive technologies (high precision laser stereolithography or direct laser writing) working with photopolymers. Their precision reaching some hundreds of nanometers, combined with recent developments in the field of bio-photopolymers and bio-photoelastomers, open new horizons for such mentioned interactions at a cellular level. In addition, even ceramic and metallic devices may be obtained using such technologies and photopolymers with metallic or ceramic loadings. Interesting groundbreaking research in the field of additive manufacturing with biomaterials may be consulted for additional details [3,4,31,40,41]. For instance the effects of controlling surface topographies, towards final osseointegration and implant viability, have already been addressed in dental implants, by means of computer-aided designs and rapid prototypes (for in vitro trials) obtained by direct laser writing, at present the most precise additive manufacturing technology [45]. The micro and nanostructures usually obtained, upon the surfaces of such experimental implants, are composed mainly of rigid posts and flexible rods, resembling the typical wood-pile structures of scaffolds for tissue repair. Such designs can be easily obtained with the help of CAD tools and can be used as standards for comparison, but are not biomimetic and their final impact on cell behavior still needs to be improved. Previous research

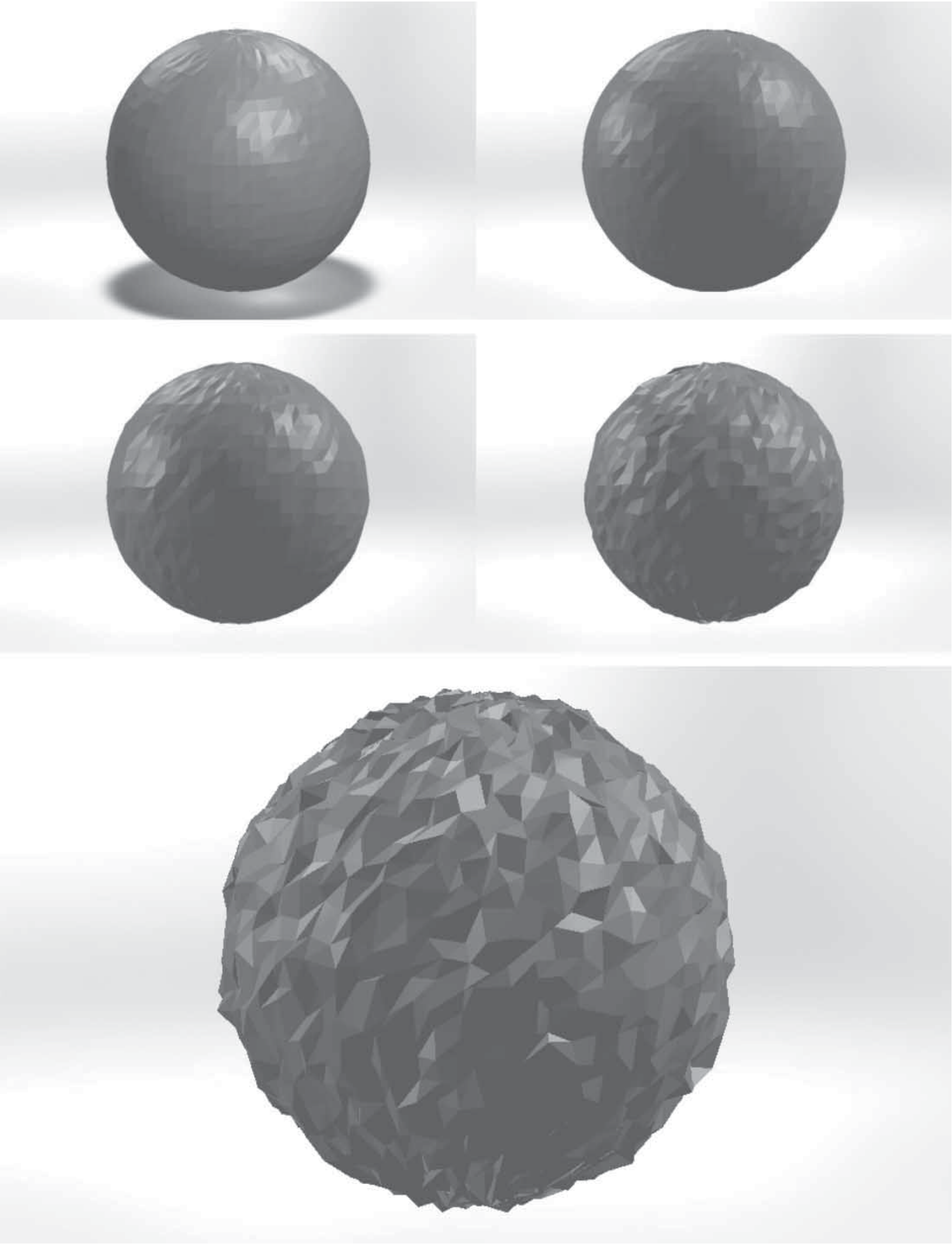

Fig. 2: Influence of control parameter alpha on final texture. Decreasing values of alpha (0.9; 0.7; 0.5; 0.3 and 0.1) lead to rougher surfaces or to surfaces with higher fractal dimension.

[14] has also helped to address the positive effects of computer-aided designed and manufacture fractal surfaces on cell growth and aggregation upon scaffolds for tissue repair and engineering. In this case of study we have focused on a more complex three-dimensional image, aimed at obtaining textured dental implants.

A couple of approaches are compared and explained further on. First of all we construct a thread using conventional CAD tools and save the three-dimensional geometry as .stl file. Upon the .stl file we apply the desired fractal texture to the thread and finally we use Boolean operations to incorporate a cylindrical nucleus and obtain a screw with textured threads, as shown in Fig. 4. Several implantable screws can be designed on the basis of a similar procedure.

An alternative option is to apply the texture to a whole conical screw previously designed and stored in form of .stl file and, subsequently, use Boolean operations to add other common features of more advanced dental implants, as Fig. 5 shows. Recent studies have also shown the potential of fractal

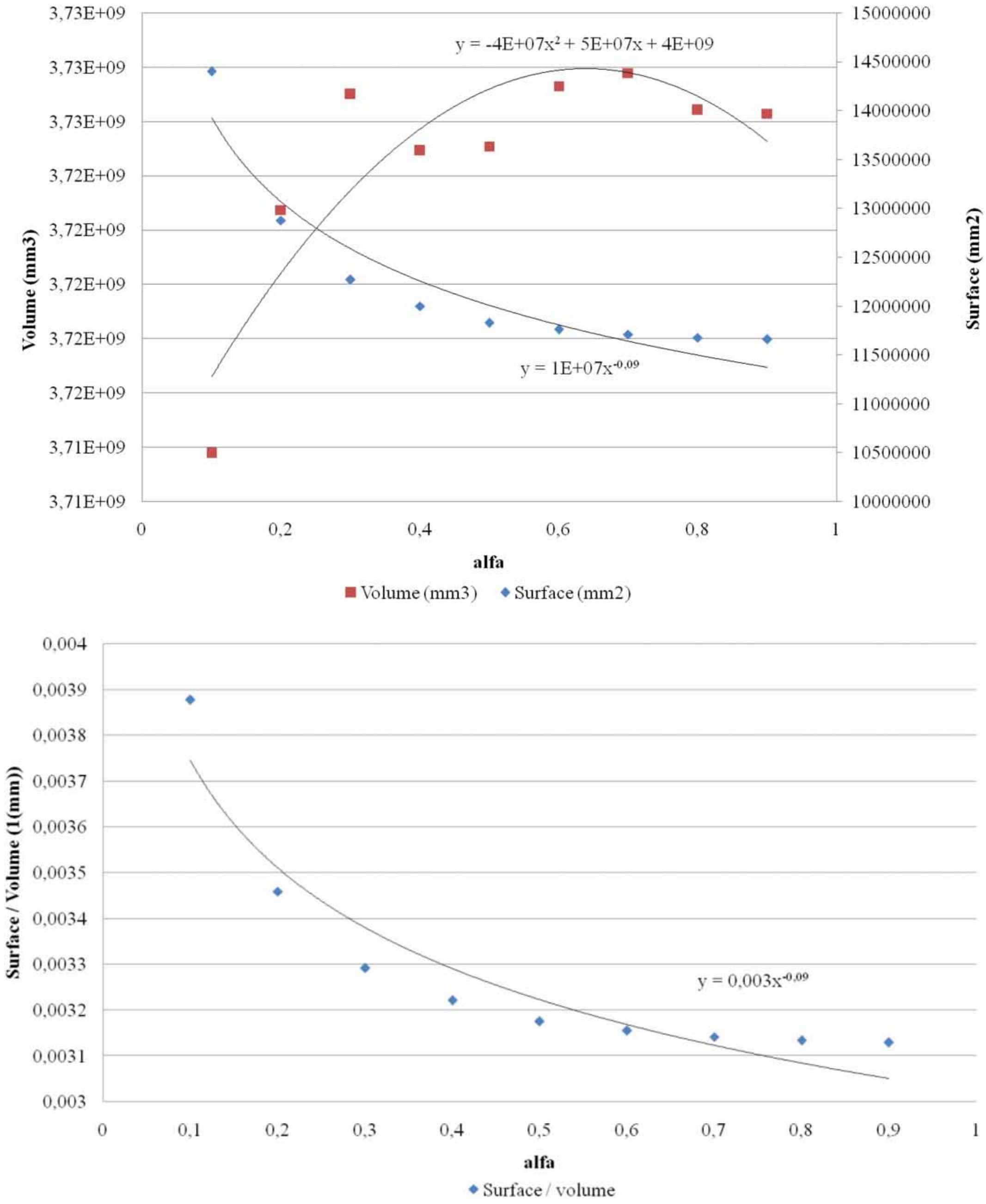

Fig. 3: Evolution of part volume, surface and surface to volume ratio when varying control parameter alpha. Lower values of alpha lead to rougher parts, with a remarkable increase of surface to volume ratio.

diffusion limited aggregation models for incorporating textured surfaces to enhance dental implant thread designs and for obtaining surfaces with a fractal appearance similar to different bone qualities, thus opening horizons to medical device personalization through fractal-based image analysis of patient bone or tissue of interest and the subsequent incorporation of biomimetic texture to the implant design [25]. The commercial interest of the process has even led to a patent application [26]. The possibility of obtaining micro-textures and micro-architectures on conventional 3D design files for controlling the surfaces of medical devices and promoting osseointegration by design (among other positive effects, including the incorporation of visual effects) has also been addressed by computer-aided design companies and has led to the recent development of interesting software, such as Within Medical Software (http://www.within-lab.com). Possible examples include acetabular cups, tibial trays and other cases of studies included in their website [44]. The procedure presented in this study will hopefully be

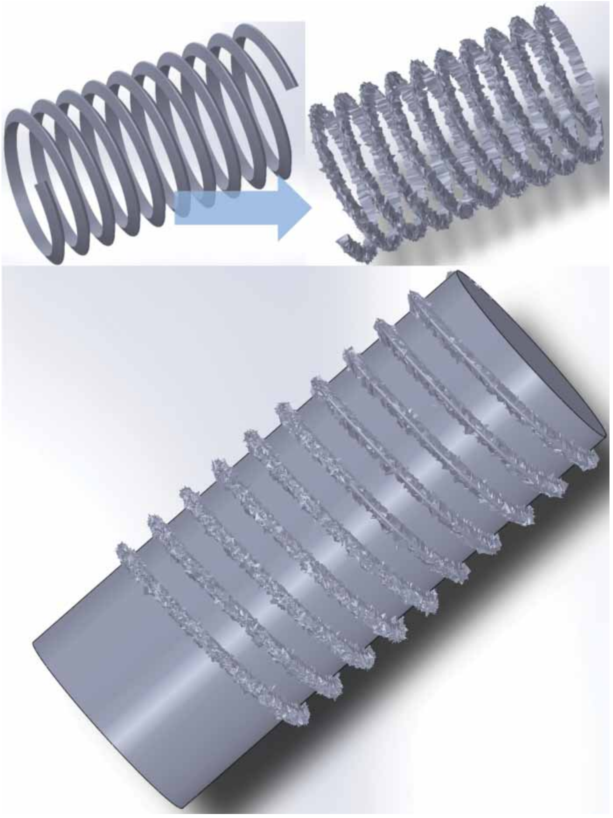

Fig. 4: Application of fractal texture to a screw thread and use of Boolean operations towards a final 3D screw with textured threads for different potential applications, including improvement of osseointegration in implantable screws and easier penetration in different materials.

an interesting complement to the aforementioned approaches.

Another interesting bioengineering challenge, connected with the improvement of surface properties, is the improvement of stent adhesion to the surfaces of patients' tissues. Typical complications of stenting procedures include perforation, migration, bleeding, occlusion and pain [32]. Stent migration can occurs in around 10% of implanted stents, either gastrointestinal of vascular, and require an additional surgical procedure for being replaced. As another case of study, Fig. 6 includes a vascular stent, again designed with conventional CAD resources, before and after the application of texture, following the aforementioned procedure, for potentially improving its attachment to the vascular tissue and preventing stent migration. The presented stent design is just a proof of concept, which should be in vitro validated after adequate manufacture using some of the aforementioned technologies, so as to analyse the real impact on cell adhesion. In addition, the design process should be additionally improved, as the textures should be applied only in the regions contacting the surrounding tissues, to which the stent is expected to attach, but not in the zones exposed to blood flow, so as to prevent thrombogenesis. Boolean operations can be further easily applied to eliminate the inner textures. In vitro addressing the effectiveness of the proposed approach is subject to forthcoming research, once we can access some of the proposed manufacturing technologies, but several references dealing with the positive effects of textures in biodevices can be found in [15].

For visual purposes we have used parameter lambda = 10 in the whole study and controlled surface properties with parameter alpha, which normally is the most relevant for obtaining a desired fractal dimension and for overall control of surface to volume ratio. The effect of alpha has been appreciated in Figs. 2 and 3. Due to our CAD software limitations when measuring the surface and volumes of more complex examples, as those from Figs. 4–6, we have just selected parameter values useful for visualizing the possibility of incorporating textures to the more complex geometries of dental screws and stents. With forthcoming additional capabilities, we expect

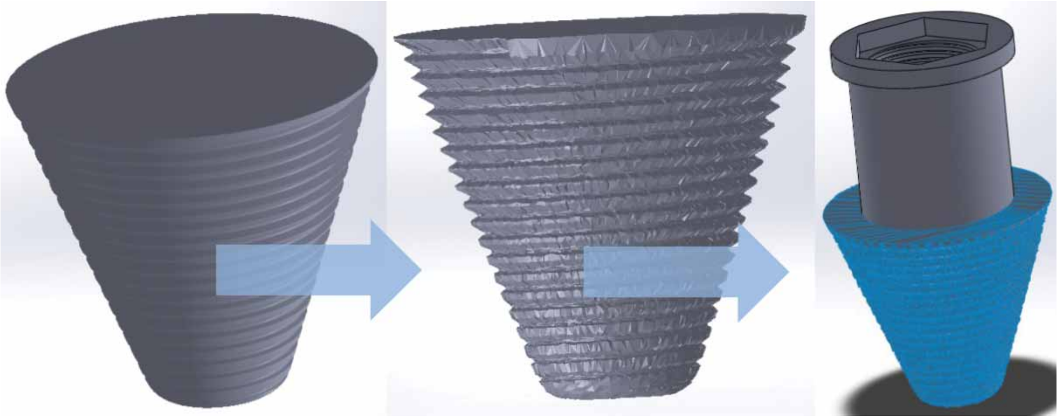

Fig. 5: Application of fractal texture to a conical screw thread and use of Boolean operations towards a final implantable dental screw with textured threads for potential improvement of osseointegration.

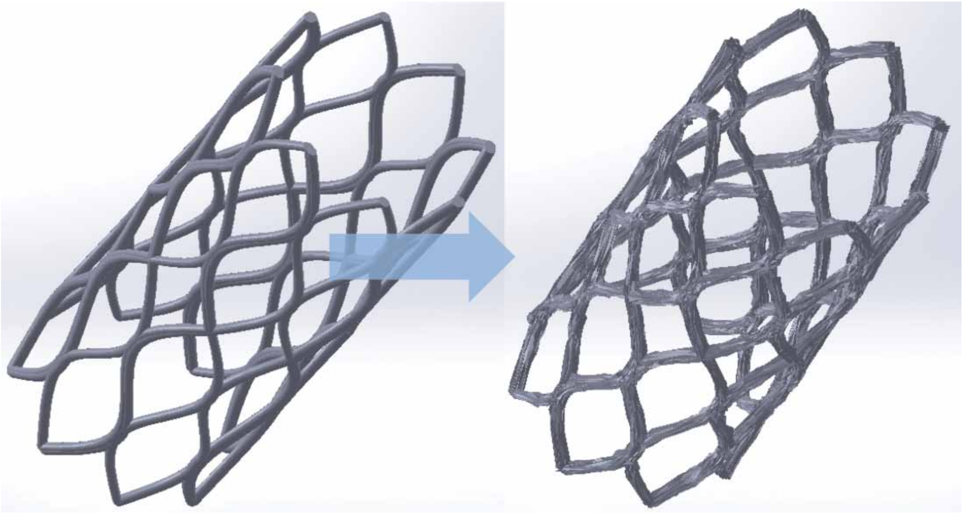

Fig. 6: Case of study: Vascular stent before and after the application of texture for potentially improving its attachment to the vascular tissue and preventing stent migration.

to address more systematically the effect of parameter change on the final surface properties of more complex geometries, such as those from Figs. 4–6, but we hope that the provided information serves as a proof of concept and serves as basis for forthcoming research.

4. CONCLUSIONS

We have presented an enhanced design process for incorporating controlled textures to the three-dimensional geometries of computer-aided designs. The process is based on adequately modifying the positions of the vertices of tessellated geometries, stored in form of .stl (standard tessellation language) files, and stands out for the possibility of texturing very complex three-dimensional objects. The process is in fact much more versatile than previous processes developed by our team and is in line with recent tendencies linked to multi-scale computer-aided design and to the incorporation of non-Euclidean geometries to product design, as has also been detailed. Some cases of study, including spheres (for instance for the cups of artificial hip prostheses), screws, dental implants and expandable stents, all of which may benefit from special tribological and biological effects induced by the introduction of textures, have been detailed, so as to show some potentials of the proposed design process.

We believe this process may be a good complement to other recent excellent approaches aiming at the representation of subdivision meshes with arbitrary topology [43], at the synthetic modeling using voxel-by-voxel methods [21], and at the modeling and rapid manufacture of irregular microstructures [33, 36], which allow for the generation of complex geometries directly from CAD, as alternative procedures to those approaches based on 3D digitalization from physical objects [20, 38]. Combining volumetric and surface-based procedures may increase the attainable degree of complexity and help towards enhanced biomimetic or bio-inspired designs.

In future studies we think it will be important to focus on exploring in depth the possible applications of design-controlled textured surfaces or materials; and to validate them with real prototypes, obtained by means of high-precision additive manufacturing technologies (i.e. direct laser writing via two-photon polymerization). We foresee relevant implications for areas including: tribology, due to the potential promotion of adhesion using fractal textures; microfluidics, due to the possibility of controlling the hydrophobicity and hydrophilicity of surfaces by acting on their topography; optics, due to the option of changing surface reflection properties and overall aesthetic aspect; biomedical engineering, for the promotion of biomimetic designs; sport and textile industry, for improving the adherence of shoe soles and garments; inner architecture, for enhancing the adherence of bathroom tiles; and even chemistry for the possibility of improving surface to volume ratios in materials used for catalysis. Currently we are improving the design process for enabling the introduction of controlled texture gradients and different kinds of texture variations, within the surfaces of interest, for additional versatility.

It is also important to highlight that texturing materials, which may be useful for tribological, optical and even aesthetical reasons, may have a relevant impact on other material properties, such as impact resistance, crack propagation, fatigue behavior, and importantly affect final device performance. In consequence, designs incorporating textures using the procedure proposed here should be adequately assessed, especially from a mechanical point of view, at least by means of adequate performance simulations, but even better by resorting to mechanical testing upon real prototypes. Regarding simulations, FEM modelling may be very well-suited for such purpose, although it is necessary to note that most commercial FEM simulation resources are unable to handle the .stl files, in which our designs are stored. Even if relying on some exceptional resources (i.e. Ansys) capable of working with .stl meshes for further simulations using solid elements, the complex geometries shown in the examples from Figs. 4–6 may require computational resource, which are currently beyond our reach. For future studies we propose to analyse the influence of the different design parameters (and consequent texture incorporation) on the mechanical properties of simpler geometries.

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