Int J Adv Manuf Technol
DOI 10.1007/s00170-014-6333-2

ORIGINAL ARTICLE

Toward mass production of microtextured microdevices: linking rapid prototyping with microinjection molding

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Received: 18 March 2014 / Accepted: 1 September 2014

Abstract The possibility of manufacturing textured materials and devices, 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 micro- and nanosystems. Recently developed high-precision additive manufacturing technologies, together with the use of fractal models linked to computer-aided design tools, allow for a precise definition and control of final surface properties for a wide set of applications, although the production of larger series based on these resources is still an unsolved challenge. However, rapid prototypes, with controlled surface topography, can be used as original masters for obtaining micromold inserts for final large-scale series manufacture of replicas using microinjection molding. In this study, an original procedure is presented, aimed at connecting rapid prototyping with microinjection molding, for the mass production of two different microtextured microsystems, linked to tissue engineering tasks, using different thermoplastics as ultimate materials.

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Keywords Fractals · Surface topography · Material texture · Materials design · Computer-aided design · Additive manufacturing · Microinjection molding · Mass production

1 Introduction

Material (and device) surface topography has a direct influence on several relevant properties, linked to its final performance, such as friction coefficient [1], wear resistance [2], self-cleaning ability [3], biocompatibility [4], optical response [5], touch perception, overall esthetic aspect, and even flavor [6]. 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, a device surface topography is a consequence of its 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 [7], laser ablation [8], micromolding [9], biomimetic templating [10], physical and chemical vapor deposition processes [11], sol-gel procedures [12], and molecular self-assembly [13]. 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 [14]. As can be seen from the previously cited documents, top-down and bottom-up approaches for controlling surface properties coexist and, in many cases, complement each other [15]; the former being more focused on mass production (as it derives from the microelectronic industry) and 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, etc.) and the smaller nanometric details by using bottom-up techniques (CVD, PVD, sol-gel, etc.).

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, of materials and devices, from the design stage and in a very direct, rapid, and easy way. Even though conventional computer-aided designs are only capable of handling Euclidean geometries and mainly rely on simple operations (sketch-based operations, extrusions, pads, holes, circular grooves, etc.) for obtaining "soft" solids and surfaces, recent approaches relying on 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, 17]. In parallel, the continued progress on additive manufacturing technologies (also called "solid free-form fabrication" due to the complex geometries attainable), especially during the last decade, 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 materials, metamaterials, and devices based on them [18, 19].

It is important to note that rapid prototyping, based on additive manufacturing processes, is typically very well suited for single prototypes with complex geometries, but inadequate for mass production, due to the excessive cost and time involved, in comparison with replication technologies, such as injection molding and compression molding. In addition, the polymers used in the most precise rapid prototyping technologies, which are based on photopolymerization processes, are typically toxic or inadequate for biomedical applications, what limits enormously the span of final applications. For instance, common thermoplastics used for the mass production of medical devices, including poly(methyl methacrylate) (PMMA) or polycarbonate (PC), cannot be processed using conventional additive manufacturing technologies. Recent research has achieved groundbreaking improvements in the biocompatibility of rapid prototyping materials [20, 21] and dramatically helped to increase the manufacture speed and the attainable precision of these technologies [22]. However, for efficient and economic mass production of polymeric microdevices, especially for the medical industry, mass replication technologies still have no rival. Other moldable thermoplastics can be of interest for further specific applications in mechanical engineering, aeronautics, electronics, etc. taking advantage of engineering polymers with enhanced thermal, electrical, or mechanical behaviors, which cannot be found among the typical properties of rapid prototyping polymers.

Exploring cooperative strategies, for taking advantage of the complexity of geometries attainable via rapid prototyping, while also benefiting from the possibility of manufacturing large low-cost series using mass replication techniques, is a relevant industrial need and can be a source of novel procedures for supporting research and innovation in several fields. Among mass production technologies, microinjection molding provides a high efficiency concerning the replication of micro- or even nanosized structures. Description of the so-called microinjection molding process and its advantages can be found in previous references [23–25], which highlight the possibilities of obtaining multicomponent and multimaterial microsystems.

The interesting work of Bissacco and colleagues [26] describes different sequential processes, depending on the number of parts needed, for obtaining microinjection molding and hot-embossing tools. Typically, such procedures include combinations of photolithography, etching, laser ablation, high-precision milling, or electrical discharge machining (EDM) milling upon soft surfaces, and subsequent electroforming or electrodeposition processes (by chemical or physical vapor deposition or electroplatting) for obtaining the mold insert. Regarding precision, probably the most precise approach toward fabrication of microinjection molding tools is the LIGA process, whose high aspect ratio is also noteworthy (real 3D parts can be obtained, while processes based on surface micromachining by chemical etching typically lead to 2D 1/2 features), but its use is limited due to the expensive hard X-ray radiation needed during the process [14].

In this work, an original alternative procedure is presented, for connecting rapid prototyping with microinjection molding, for the mass production of two different microtextured microsystems linked to tissue engineering tasks (a textured cell culture platform and a textured microdevice for studying cell motility), using, in this case, different thermoplastics (PMMA and PC) as ultimate materials. The procedure starts from additively manufactured rapid prototypes, continues with a thin-film deposition technique for improving surface conductivity, follows with an electroplating process for obtaining mold inserts, and ends up with mold adjustment and mass production using microinjection molding.

The proposed process stands out for the attainable degree of detail, for the versatility of final materials, for the manufacturing speed, and for the possibility of obtaining final low-cost replicas. The following section explains the methods and materials used, before paying attention to the main results obtained, proposing some future directions, and detailing our concluding remarks. The process is aimed at rapidly connecting the complex geometries attainable by additive technologies with mass production procedures.

2 Materials and methods

2.1 Design process

The first application example (shown in the different left images of Fig. 1) is a microtextured fractal surface-based cell culture platform or tissue engineering scaffold, with an improved level of detail, for more adequate interactions at a cellular level than previous preliminary prototypes [27]. Its upper surface includes a fractal texture with a typical peak height between 50 and 750 μm.

The second application example (shown in the different right images of Fig. 1) corresponds to a microsystem for studying cell motility and addressing the effect of surface texture on cell migration and overall behavior, as previously detailed [28]. The system includes a couple of microchambers connected by several microchannels, for guiding cell movement, each of them with a different texture at its bottom. A typical cell motility experiment should begin with the incorporation of cells to one of the chambers and of growth factors to the other one, so as to promote cell movement from one chamber to another. Channels are 300 μm in width and 3 mm in length and the roughness of the different channels (maximum peak height) reaches values around 25, 50, 75, 100, 125, and 150 μm.

Both microsystems are based on a design procedure firstly described by our team [27] combining different steps, including (a) the generation of fractal textures using fractional Brownian surface models with the help of Matlab (The Mathworks Inc.); (b) the conversion of the fractal surfaces into .stl format for further manipulation with computer-aided design programs; (c) the incorporation of thickness to the fractal surfaces using conventional computer-aided design (CAD) modeling tools; and (d) the combination, by means of Boolean operations, of the textured zones with other solids previously designed, in order to obtain more complex microsystems or to adjust final size and external shape.

Our preliminary in vitro trials with both microsystems were carried upon rapid prototypes adequately coated with diamond-like carbon, to avoid the toxic effects of the acrylic resin, and upon some rapid copies obtained using PDMS casting, as previously detailed [27, 28], and showed promising results regarding the beneficial effects of textures on cell culture. However, for additional systematic evaluations, taking into account several parameters of influence, the number of prototypes required increases dramatically and the mentioned rapid prototyping processes, together with the post-processes needed for improving their biological interactions, result inefficient.

As detailed below, the procedure for connecting the initial rapid prototyping technologies with other mass replication resources is a key for rapidly obtaining larger series, hence helping to promote more systematic studies, to send complimentary copies to colleagues and possible industrial partners, and even to directly launch the production stage.

2.2 Additive manufacture of masters of "green parts"

The master models or "green parts" are manufactured using digital light processing, a high-precision rapid prototyping technology working on an additive approach that projects, layer by layer upon a photopolymer, images corresponding to the slices of the three-dimensional objects being built. For that purpose a Perfactory SXGA machine (EnvisionTec GmbH) has been used, together with the R11 EnvisionTec acrylate-based photoresin. Figure 1 includes the master prototypes (red-orange resin) directly obtained from the three-dimensional geometries stored in the computer-aided design files.

2.3 Mold inserts fabrication

The polymeric masters (size cell culture platform, 10 mm in diameter, 2 mm in height; size microdevice, $1 \times 6 \times 2$ mm^3) had to be transferred into a cavity of a metallic mold inserts by electroforming at Institute for Microstructure Technology (IMT). First, the masters, made in acrylic resin, were glued on a thick copper substrate ($84 \times 54 \times 8$ mm^3) [29]. In an evaporation process, master and substrate were coated with layers of 7-nm chromium and 50-nm gold. The chromium layer serves as an adhesive layer and the gold layer as a conductive plating base. These metallic layers support a precise metal deposition along the microstructures on top of the master. The copper substrate was fixed to a special plating holder that was immersed into the galvanic bath. The nickel electroplating system with a boric acid-containing nickel sulphamate electrolyte (T=52 °C, pH 3.4…3.6) was developed especially for the electroforming of microstructures at IMT [30, 31]. To ensure a slow growth of the nickel layer and to achieve a defect-free filling of the microstructured areas, the current density was adjusted to $0.25 \cdot 10^2$ A/m^2 at the beginning of the plating process and was subsequently increased up to $1.8 \cdot 10^2$ A/m^2. Electroforming was continued until the nickel layer has reached a thickness of 6 mm.

This process leads to a stiff homogenous metal block which can withstand the forces applied in the injection molding process. The electroplated nickel block was separated from the substrate and processed to the desired outer dimensions ($19.9 \times 19.9 \times 4.0$ mm^3) by wire-cut EDM. The acrylic master was removed from the mold insert cavity in a novel wet-chemical process using a specific cleaning agent using ultrasonic agitation at 80 °C. Finally, rinsing steps with ethyl acetate and acetone complete the nickel mold insert fabrication. Structure characterization was done by SEM (Fig. 2).

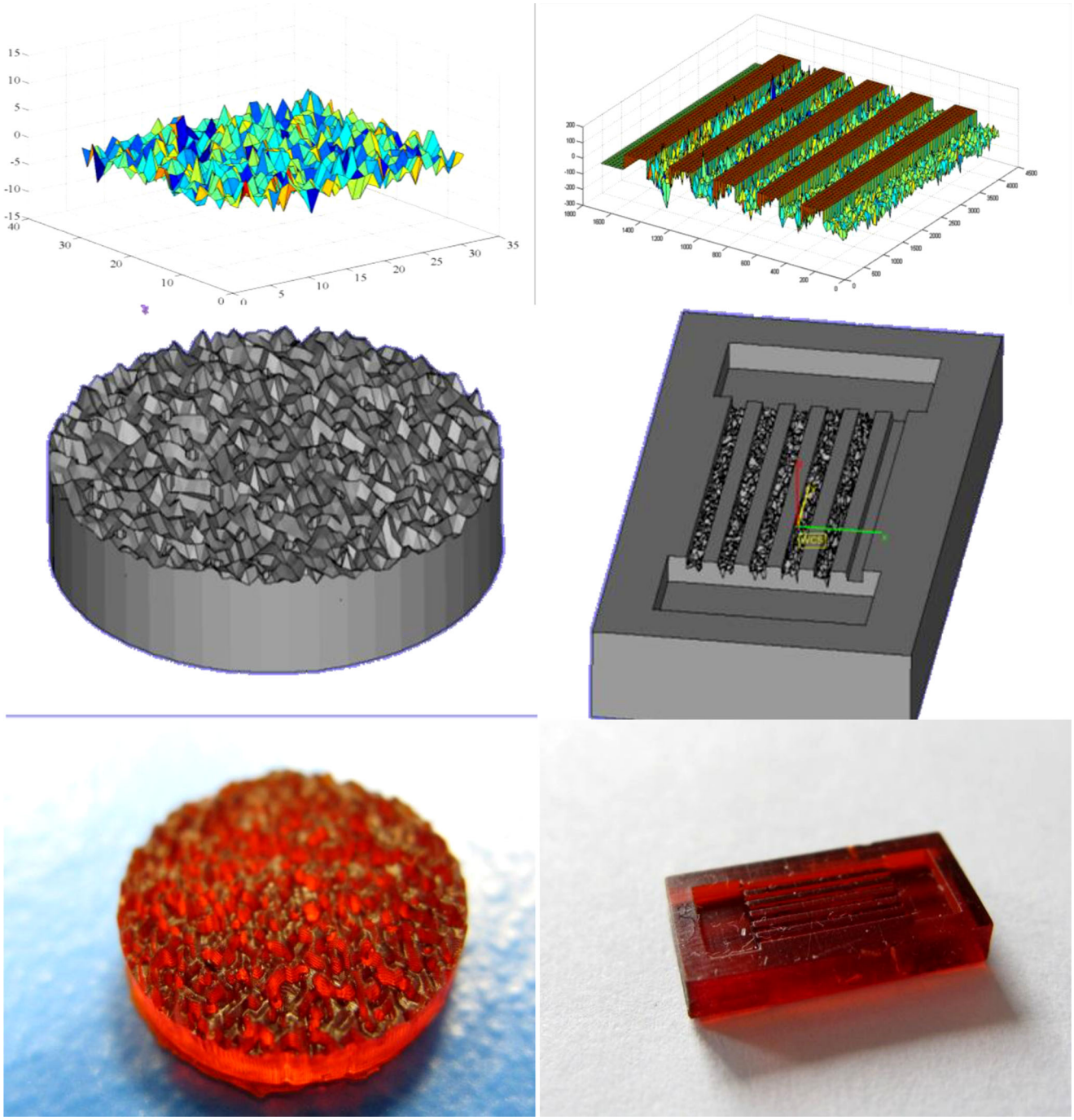

Fig. 1 Incorporation of fractal texture to computer-aided designs and rapid prototypes obtained in acrylic resin using digital light processing for their use as "green parts" (*left* a textured cell culture platform, *right* a textured microdevice). We acknowledge Prof. Dr. Jürgen Stampfl, from the Technical University of Vienna, for the access and help when using their digital light processing machine. Adapted from the Handbook of Advanced Design and Manufacturing Technologies for Biodevices [24]

2.4 Mold manufacture and replication by microinjection molding

First action before starting the injection molding trials was the adjustment of the electroplated nickel mold inserts (see example in Fig. 3a) to one of the standard molds at IAM-WPT. For this purpose, a special adapter has been machined (see Fig. 3b). As no further molding tool modification was planned the samples had been replicated on a base plate which forms the runner as well as acts as an auxiliary feature for safe demolding.

The replication trials have been performed on a Ferromatik Elektra 50S injection molding machine (see Fig. 3c) which is equipped with necessary features like tool evacuation and

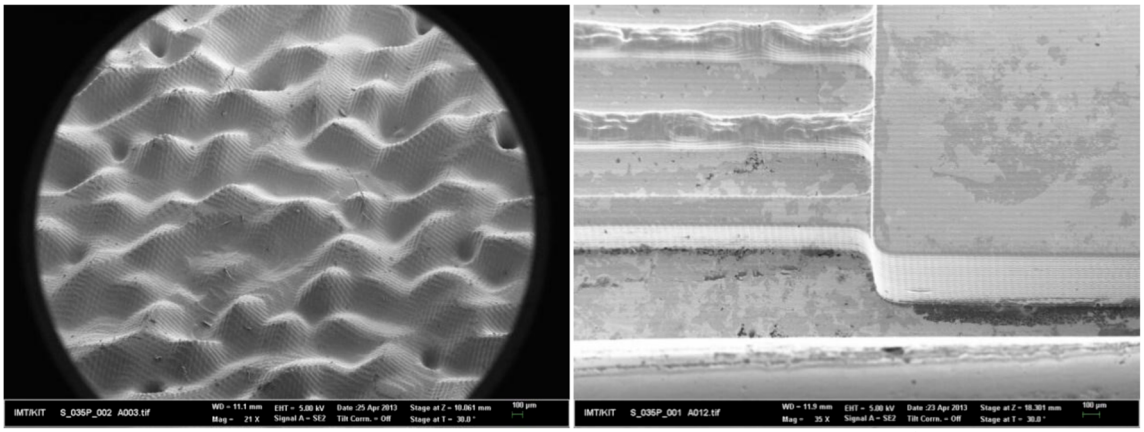

Fig. 2 SEM images of nickel mold inserts (*left* a textured cell culture platform, *right* a textured microdevice). *Green bars* 100 μm

vario-thermal-temperization. The latter means that the core of the molding tool is heated up prior to the material injection. After filling, the tool core is cooled down to a temperature which secures safe demolding without damaging the microstructured part. This procedure allows for the replication of very fine structures with outstanding surface qualities. Main injection molding parameters are given by Table 1.

Using these parameters and equipment, more than 200 parts of each of the aforementioned microsystems have been produced, using both PMMA and PC as interesting thermoplastics for the medical appliances. Several additional replicas can be manufactured if needed, as the mold inserts have not been damaged during the microinjection process.

3 Results

Figure 4 shows some replicas of the two different microsystems obtained by microinjection molding and a detailed optical microscopy view of the microtextured channels present in the second microsystem. Repeatability is outstanding and final parts are compact, without some typical injection molding problems such as the presence of pores or warping, in spite of the precise dimensions of interest. The accuracy is remarkable and even micrometric details, such as the presence of succinct longitudinal lines consequence of the initial additive process and of the separation between layers in the original acrylic prototypes/masters, can be perfectly replicated and appreciated in the detailed views. Figure 5 includes additional SEM images of the replicated microtextured fractal surfaces, which help to show the attainable level of detail.

The replicas obtained present several advantages, when compared with the original acrylic rapid prototypes. They are made of bioinert polymers typically used in the medical industry (polycarbonate and poly(methyl methacrylate)), hence adequate for in vitro trials; they are transparent, what constitutes an enormous help for cell culture processes and related fluorescent microscopy tasks; and their manipulation is easier thanks to the presence of a supporting structure. Figure 6 shows a final view of the microinjected cell culture microsystem, together with the mold insert, for showing the adequate state of the mold insert after the microinjection of 200 parts. After manufacture of such 200 parts, the mold inserts continue in perfect conditions and larger series can be manufactured. Future studies will be devoted to the resistance of the electroplated mold inserts, when compared with traditional inserts.

Regarding production time and cost, it is important to compare the proposed process, which combines the additive manufacturing of rapid prototypes and a subsequent electroplating for obtaining a mold insert, with the more traditional manufacturing of mold inserts by electroerosion or by computed numerical control machining (CNC). First of all, it is necessary to highlight that the geometrical complexity and degree of precision attainable with current additive manufacturing technologies based on photopolymerization processes [17, 18] cannot be achieved by traditional electroerosion or CNC processes. Besides, producing the master prototypes is fast, as they can be ready in just 4 h, and cheap, as enterprises (i.e., iMaterialise) providing additive manufacturing services would require less than 300€ for obtaining similar master prototypes. The electroplating process needs more detailed adjustment and is more cost intensive, although we estimate 1 week of time for obtaining the mold inserts and a related cost of 2000€. Therefore, production time and cost are in the same order of magnitude as traditional one-step processes and, for especially complex geometries, there may not be another option than linking the rapid prototypes with microinjection molding.

In order to provide some additional quantification of the results obtained, the surfaces of the microinjected prototypes were digitized with the help of the Infinite Focus SL 3D surface profiler from Alicona, which also enables conversion of the 3D surfaces obtained to .stl format for further prototyping tasks and reverse engineering procedures. Figure 7

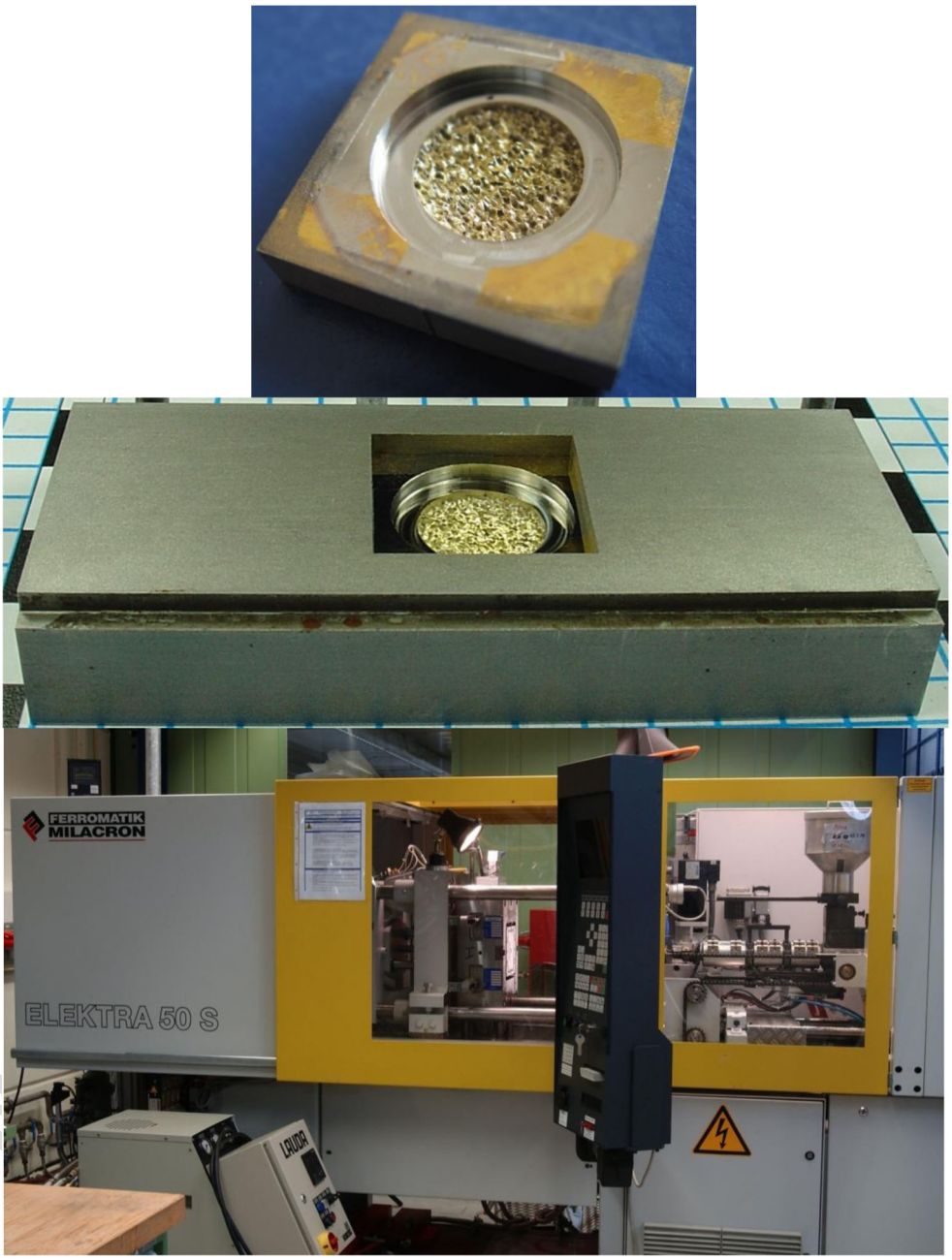

Fig. 3 **a** Electroplated nickel mold insert for fractal cell culture platforms (*above*). **b** Adapter for mounting the electroplated masters in a standard injection molding tool (*middle*). **c** The Elektra 50S microinjection molding machine used for the replication trials (*bottom*)

shows the optical reconstruction of the microtextured fractal cell culture platform (upper image) and of the microsystem with fractal channels for studying cell motility (lower image). Figure 8 presents a visual comparison between the original

Table 1 The main parameters of the replication trials, here using PC (polycarbonate) as molding material. PC and PMMA optimal parameters are quite similar

	Unit	Cell culture platform with microtextured fractal surface	Biodevice with microtextured channels
Injection pressure	Bar	1300	1300
Injection speed	mm/s	33	33
Max. material temperature	°C	292	295
Tool temperature at injection	°C	130	130
Tool temperature at demolding	°C	65	65
Back pressure	Bar	1050	1050

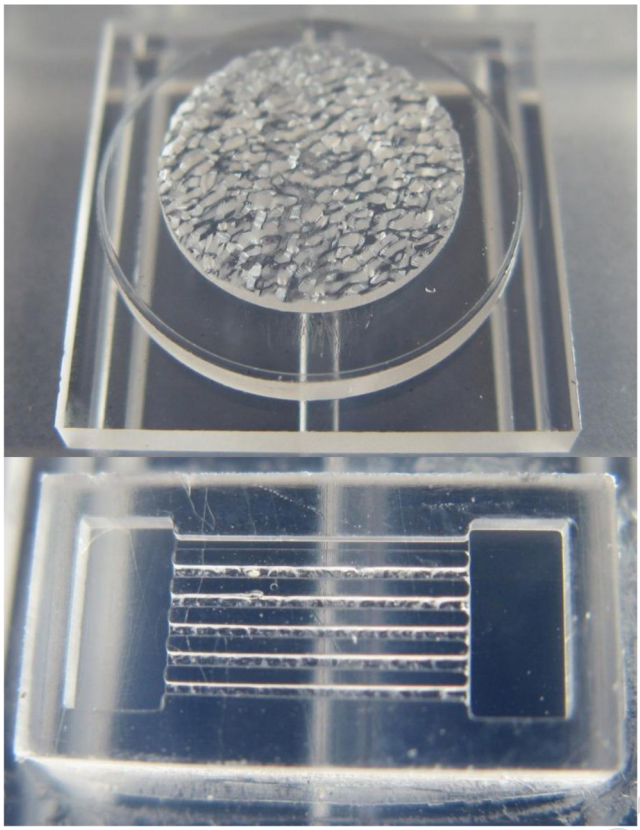

Fig. 4 Replicas obtained by microinjection molding. Two different microsystems, a microtextured fractal cell culture platform (or scaffold) and a microdevice for studying cell motility along different microtextured channels, both manufactured using PMMA and PC

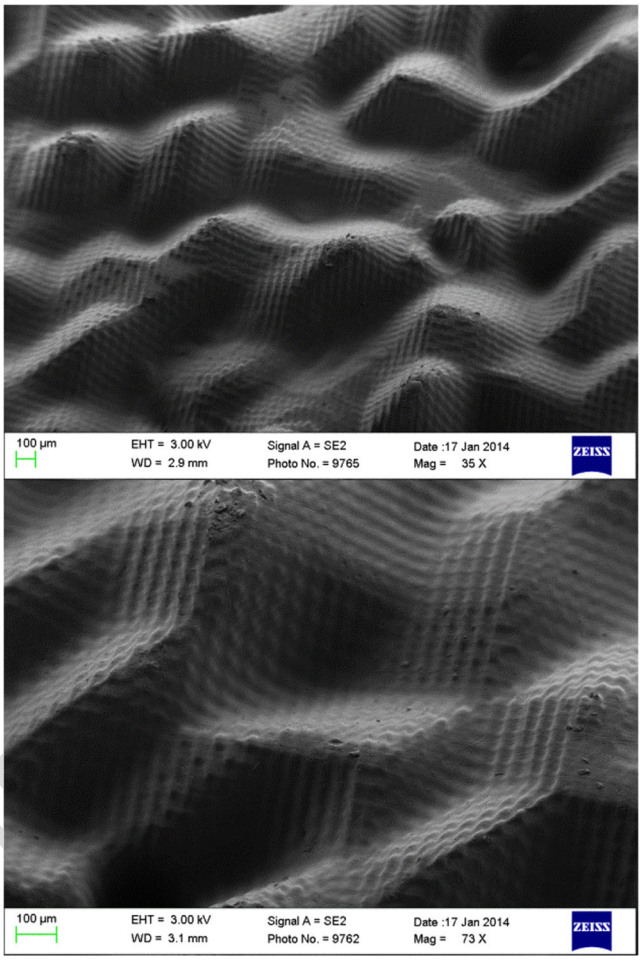

Fig. 5 SEM image of the replicated microtextured fractal surfaces of the cell culture platform, here in PMMA. Similar results are obtained with PC

CAD design (upper image) and the .stl reconstruction of a final microinjected prototype of the fractal cell culture platform (lower image). It can be appreciated that the spikiest features of the original design are lost through the prototyping and replication process, which is a consequence of different limitations of the prototyping and replication steps and will be analyzed further on. In any case, qualitatively, the overall fractal aspect of the surfaces is maintained from the design stage, through the prototyping, to the final replication step by microinjection molding, and the whole process is adequate for obtaining microtextured devices, apt for in vitro trials, and with controlled modifications of surface topography, as the microsystem with the different textured channels shows. Figure 8 helps to show that the number of irregular spiky features is maintained from the design to the final microinjected devices, although the quality of the tessellation decreases.

It is important to note that, being the surfaces fractal and obtained by random design process (originally described in [27]), once the prototypes are obtained, it is complex to exactly the same section in the design and in the parts obtained for quantitative roughness evaluation for systematic comparison. Trying with contact measurement procedures is not viable, as the measurement tip gets stuck to the surfaces due to the magnitude of the designed spikes and to the sudden changes of direction that the tip suffers. Most of such

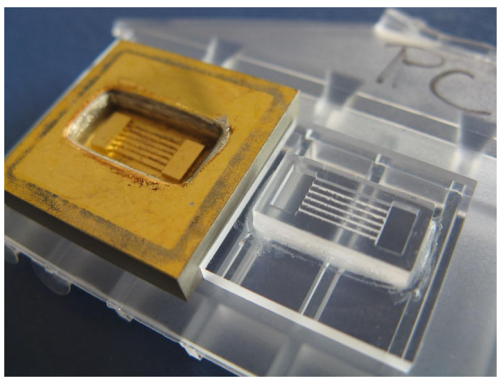

Fig. 6 Microinjected microsystem together with the mold insert used for its fabrication and obtained by electroplating upon the original acrylic rapid prototypes Q6

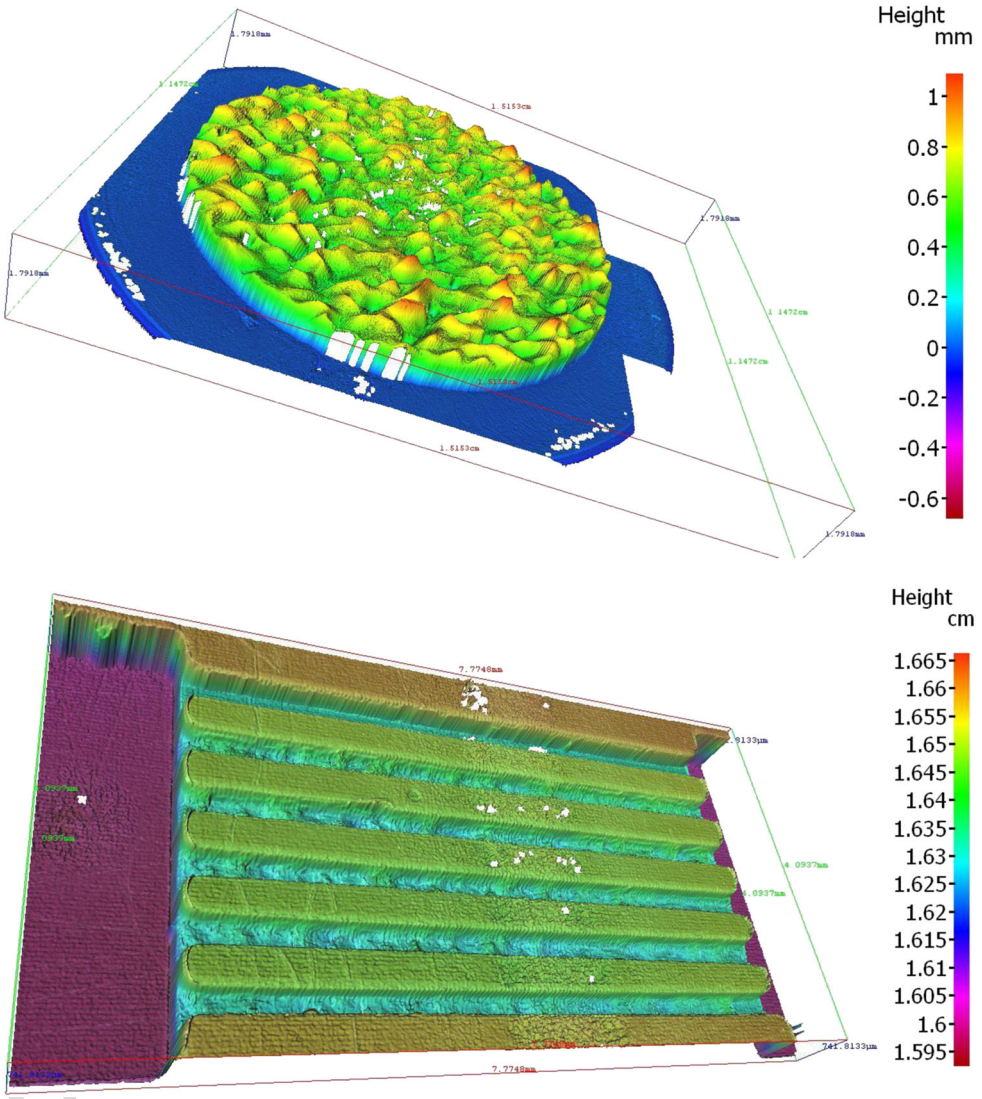

Fig. 7 Optical reconstruction of the microtextured fractal cell culture platform (*upper image*) and of the microsystem with fractal channels for studying cell motility (*lower image*)

Q6

contact measurement techniques are focused on the measurement of micro- (normally <10 μm) and nanofeatures and the magnitude of our artificially incorporated textures goes from 100 to 800 μm. As the layer manufacturing process used for the original masters has a layer depth of 25 μm and movement precision in the XY plane of 25 μm, adequate structuring of the surfaces is based on design feature sizes implying the use of at least 4–5 layers, so as to obtain features (spikes) clearly visible and to minimize the relative effect of the typical-stepped geometries obtained in additive processes. Such dimensions prevent contact characterization and optical 3D surface profilers are needed (which have been of help to obtain the images from Figs. 7 and 8). In addition, during the manufacturing process, the master rapid prototypes are lost after metallization and, currently, only the original CAD geometry and the final microinjected devices can be adequately compared. Forthcoming studies will be focused on manufacturing ad hoc probes for specifically characterizing the precision of each step, but based on our available data, some additional interesting data on the whole process precision can be provided.

For instance, a direct consequence of the additive manufacture machine precision is the obtaining of master prototypes, in which the last 25 μm of the spiky textures are lost, thus leading to somewhat softer surfaces than those from the original CAD files. For most applications of microtextured surfaces, such softer results may even be positive, as the devices will be a bit softer to the tact and more resistant, as fine needle-like details of 25 μm would anyway break down under the slightest mechanical request. Besides, having a look at the cell culture platform (Fig. 7), a maximum profile

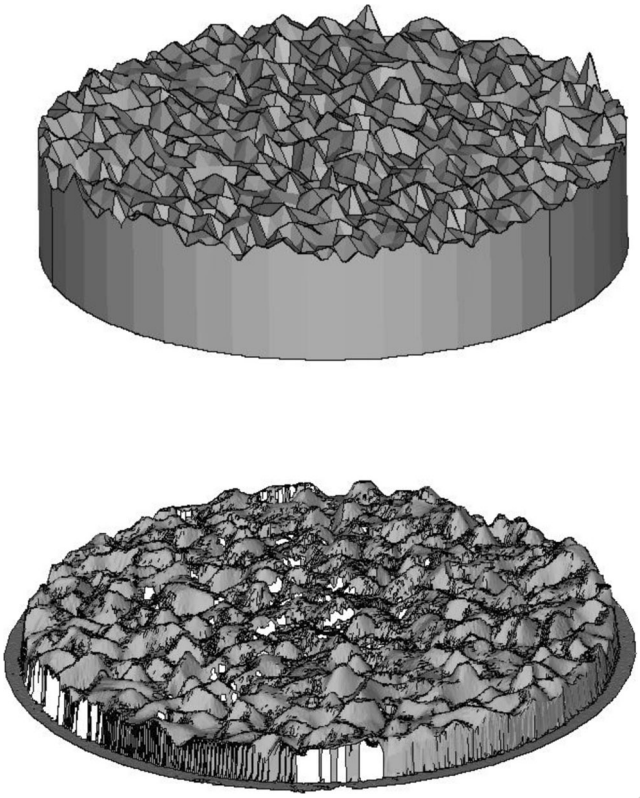

Fig. 8 Visual comparison between the original CAD design (*upper image*) and the .stl reconstruction of a final microinjected prototype of the fractal cell culture platform (*lower image*). It can be appreciated that the spikiest features of the original design are lost through the prototyping and replication process

height of 700 μm (R_t=700 μm) can be seen, while R_t of the original CAD design reaches a value of 750 μm. The difference can be explained considering not only the loss of the last portion of the spikes during additive manufacture but also due to a valley depth decrease during metallization and injection, as possibly the material does not perfectly replicate the mold details. Finally, some contraction during cooling down, after the microinjection process, may lead to around 3–5 % smaller features in the final parts, when compared to the mold inserts. Additional in vitro validations of the performance of the designed devices and further studies for more systematically addressing the manufacturing precision of the different steps of the proposed process may help to improve its applicability.

4 Conclusions

In this work, an original procedure has been presented, aimed at connecting rapid prototyping with microinjection molding, for the mass production of two different microtextured microsystems linked to tissue engineering tasks, using different thermoplastics (PMMA and PC) as end materials. The procedure starts from additively manufactured rapid prototypes used as "green parts" or master models, continues with a thin-film deposition technique for improving surface conductivity and simplifying further metallic deposition, follows with an electroplating process for obtaining long-lasting mold inserts, and ends up with the mold adjustment and the mass production using microinjection molding.

The proposed process stands out for the attainable degree of detail, for the versatility of final materials, for the manufacturing speed, and for the possibility of obtaining final low-cost replicas of textured microsystems, which are quite complex to manufacture using conventional micromachining technologies. The additive manufacturing process supplies geometrical complexity and high initial precision, while the microinjection molding enables the rapid and low-cost production of larger series of accurate replicas and provides the possibility of using several types of thermoplastics for a wider set of applications. In the examples presented, the focus has been put on biomedical microsystems and the PMMA and PC used are adequate for further in vitro trials.

Regarding future studies, it will be important to focus on exploring in depth the possible applications of design-controlled-textured surfaces and related mass-produced devices. 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 esthetic; and biomedical engineering, for the promotion of biomimetic designs. Currently, 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, is being improved.

Acknowledgments This work was carried out with the support of the European Community. We appreciate the support of the European Research Infrastructure EUMINAfab (funded under the FP7 specific program Capacities, Grant Agreement Number 226460) and its partner the Karlsruhe Institute of Technology. We are also grateful to Dr. Dieter Maas and to Dr. Thomas Schaller for their kind help and support to the EUMINAfab 1099 proposal on "Replication of advanced scaffolds with biomimetic fractal features." This work was partly carried out with the support of the Karlsruhe Nano Micro Facility (KNMF, www.knmf.kit.edu) and the Helmholtz Research Infrastructure at Karlsruhe Institute of Technology (KIT, www.kit.edu). We acknowledge Prof. Dr. Jürgen Stampfl, Head of the Additive Manufacturing Laboratory from the Technical University of Vienna, for the access to the digital light processing machine and for his support for obtaining the initial master models.

We also acknowledge reviewers' positive comments and proposals for improvement, which have helped us to improve paper quality, to incorporate relevant references of interest for the readers, and to present our results in a more adequate form.

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