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A Review on Micro Fabrication Methods to Produce Investment Patterns of Microcasting

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Abstract

Microcasting is one of the key technologies enable the manufacture of small structures in the micrometer range or of larger parts carrying microstructures by using a metal melt which is cast into a microstructured mold. Microcasting, is generally identified with the investment casting process, which is known as the lost-wax, lost-mold technique. A main step in micro investment casting is making disposable patterns which have sufficient mechanical strength and dimensional accuracy. In this study a review on available microfabrication methods to produce such patterns has been down and possible processes have been compared in order to select the best process.

Keywords: micro investment casting, plastic pattern, micro manufacturing techniques

1. Introduction

Microcasting is one of the key technologies enable the manufacture of small structures in the micrometer range or of larger parts carrying microstructures by using a metal melt which is cast into a microstructured mold. This technology has been successfully applied for manufacturing of instruments for surgery and dental devices, instruments for biotechnology and miniaturized devices for mechanical engineering. Microcasting, is generally identified with the investment casting process, which is known as the lost-wax, lost-mold technique (Baltes *et al.* 2005). Figure 1 shows the micro investment casting process steps. First the plastic or wax pattern is made and embedded in a ceramic slip. After drying the ceramic mold is heated and sintered and the pattern will be lost during this process due to melting and burning. Finally the preheated ceramic mold is filled with metal melt by vacuum-pressure or centrifugal casting. After solidification, the ceramic mold is mechanically removed without destroying or influencing the cast surface. Depending on the casting alloy and the ceramic mold material, additional chemical cleaning processes may be sometimes necessary. Finally, the single parts are separated from the runner system.

Mechanical removing of the ceramic mold after casting, offers the chance to produce metallic parts even with undercuts. The key point in producing such parts is fabrication of pattern with undercut. Also pattern fabrication technique directly influence on surface roughness and dimensional accuracy of the pattern which are of importance in final surface quality and dimensional accuracy of the cast part. Common approach in fabricating investment patterns is micro injection molding (Baltes *et al*, 2005; Baumeister et al. 2002, 2004; Qin 2010, Chuang et al. 2009; Thian et al. 2008; Rath *et al*. 2006), that has some disadvantages and limitations. In this study other possible methods to fabricate these patterns has been introduced and compared with each other.

2. Investment Casting Patterns

The type of pattern used also has a significant effect on the casting tolerances that can be obtained and maintained. In general, final casting tolerances can be held within tighter limits as the rigidity and durability of the pattern equipment increase. Traditional investment casting usually uses wax and sometimes plastic, for pattern material and wax or plastic patterns are almost injection-molded. When wax is used, the molds can be inexpensive, being made from a low-temperature alloy sprayed or cast around a master-part pattern. The pattern is made with an allowance for shrinkage (Stefanescu *et al*. 1992).

In micro investment casting the patterns should guarantee a higher strength and are thus of advantage when assembling microstructures thus in contrast to the wax patterns used there, microtechnology mostly works with plastic patterns which have much higher mechanical strength. The patterns usually are made of thermoplastic like PMMA or POM which shows much higher strength than wax made structures (Baumeister *et al*. 2004). The improved mechanical properties permit easier handling and assembling of the pattern during the manufacturing process. The feeding system can be made of wax. Figure 2 shows a PMMA pattern with runner system made of wax, used for investment casting (Baltes *et al*. 2005).

2.1 Influence of Pattern on Surface Roughness and Dimensional Accuracy

By far the most significant factor influencing the dimensional accuracy of micro investment castings is the dimension of pattern and shrinkage of the materials used as they change from the molten to solid state. The wax or plastic pattern, the investment material, and the cast metal all exhibit this characteristic to some degree. Like patterns for macrocasting, patterns for microcasting should be constructed according to the well-known design rules for casting. Manufacturing method of the pattern should be able to produce the pattern with required tolerance.

3. Microfabrication Methods to Produce PMMA Patterns

Today's technology gives various processes for microfabricating of polymer and plastic materials. To select the suitable process, it is necessary to compare these processes based on availability, manufacturing aspects and economical points of view.

3.1 Micro Mechanical Cutting

Micro-cutting is one of the key technologies to enable the realization of micro-products. Similarly to the conventional cutting operation, in micro-cutting the surface of the workpiece is mechanically removed using tools, but the depth of cut is normally at the level of a micrometer or less (Dornfeld *et al*. 2006). This process brings many potentialities to the fabrication of miniature and micro-products components with arbitrary geometry. The micro cutting process is particularly suitable for the manufacture of individual personalized components rather than large batch sizes, which is largely indispensable for customized and vibrant markets.

With the high level of machine accuracy of ultra-precision machine tools, good surface finish and form accuracy can be achieved. Micro- cutting is also capable of fabricating 3D free-form surfaces. The high machining speed of micro-cutting is another advantage over other micro manufacturing technologies. Unlike micro-laser beam machining and lithographic techniques, it does not require a very expensive set-up, which enables the fabrication of miniatures at an economically reasonable cost (Qin 2010).

Established methods of micromachining by turning, drilling, milling, and grinding have already been applied to polymethylmetacrylate (PMMA) plastics (geough 2002).

3.1.1 Micro-turning

Various Swiss-type machine tools, ultra-precision lathes for diamond turning and miniature desktop machines, are used to perform micro-turning operations on parts made of different materials like plastics. The next application group of micro-turning operations with ultra precision mode makes it possible to machine materials from a few microns to sub micron. Such a machining process is easily able to produce mirror surfaces of less than 10 nm surface finish and form error of less than 1 nm on some diamond turnable materials (geough 2002).

3.1.2 Micro-milling

Micro-milling is a classical form of tool-based micromachining, in which miniaturized milling cutters are used to achieve the material removal in the form of chips. This micromachining technique is able to produce three-dimensional high aspect ratio functional parts with high accuracy and surface quality. During the stepping zone itself, micro-milling operation is suggested for a wide variety of medical and engineering applications (Sooraj & Mathew 2002).

The micro-milling process is characterized by milling tools that are currently in the range from 10-100 pm in diameter and made by the focused-ion beam machining process (Craig *et al*. 1996). the most usual meaning of a micro-milling machine refers to ultra precision milling machines, with submicron accuracies, that is, accuracies under 1 micron or less, usually one tenth of a micron. Machine tools capable of such extreme accuracy may be applied to microscopic workpieces (micromachining), but they are more typically applied to workpieces with features and details measurable in submicron increments or even in the mesoscale.

The two main advantages of micro-milling in relation with other micro technologies are its apparent similarity with conventional milling (which enables user to tackle the process from a position of in-depth knowledge) and the fact that it enables intricate parts with 3D forms to be machined (molds, electrodes, etc.) in a large range of materials (Lopez *et al*. 2009).

3.2 Laser Machining

Laser micromachining has been widely applied in the fabrication, production and manufacturing of Micro Electro Mechanical Systems (MEMS). It uses photo thermal melting or ablation to fabricate a microstructure (Neda *et al*. 2011).

In the production of micro-scaled products, laser ablation is able to generate structure sizes in the range of 10– 100 micro-meter, not only in metals and polymers like PMMA but also in hard and ultra-hard materials such as tungsten carbide and ceramics. Especially for micro-machining, laser processes qualify for a wide range of materials, from semiconductors in the field of micro-electronics, to hard materials such as tungsten carbide for tool technology, to very weak and soft materials such as polymers for medical products. In comparison to the classical technologies, laser processes are generally used for small and medium lot sizes but with strongly increased material and geometric variability.

Using ultra-short pulsed lasers with durations of 10 ps in bursts of several pulses with a time spacing of 20 ns each and adapted pulse energies, the surface quality of metal micro-ablation has been increased significantly and allows the production of tools and parts with Ra values of less than 0.5 mm.

Laser manufacturing of parts and tools can be performed without additional working tools in reasonable times directly from the CADCAM system.

Material removal on polymers like PMMA can be obtained using low power lasers. Depending on the interaction time, radiation intensity and polymer properties, the material is rapidly heated to become molten and then burned or even vaporized. High energy density associated with the focused laser spot allows a relevant resolution during cutting. This procedure can provide very small details or radii, which are difficult to achieve if conventional milling process is used (Romoli *et al*. 2011). For this reason lasers are retained to be flexible and precise “thermal tools” for the fast production of micro plastic patterns.

Unfortunately Distortion of the material is one of the negative effects of laser ablation, especially for polymers. During laser cutting of polymers, bulges are formed mainly due to resolidification of molten material in the working zone and temperature difference between the heat affected zone and the heat unaffected zone. In order to prevent the creation of such defects it is necessary to choose laser machining parameters like laser power accurately.

Commonly, PMMA are highly absorptive at the CO2 laser wavelength and transparent to the visible and near-infrared spectra (Neda *et al.* 2011). Figure 3 shows a CO2 laser machine for fabrication PMMA micro parts.

3.3 Micro Injection Molding

Microinjection molding (µIM) appears to be one of the most efficient processes for the large-scale production of thermoplastic polymer microparts like patterns for micro investment casting. The micro-injection molding process steps are the following (see Figure 4):

1. Plastic pellets are plasticized by the fixed extruder screw and fed into the metering chamber.

2. The shut-off valve closes in order to avoid backflow from the metering chamber.

3. After the set volume has been achieved, the plunger in the dosage barrel delivers the shot volume to the injection barrel.

4. The injection plunger then pushes the melt into the mold.

5. Once the plunger injection movement is completed, a holding pressure may be applied to the melt. This is achieved by a slight forward movement (maximum 1 mm) of the injection plunger.

The independent system for melting the polymer allows a limitation of the cycle times. The polymer flows through small sized runners and gates using high speed and high pressure, which can favor its degradation. The fabrication of high aspect ratio micro features can be achieved by using a mold temperature close to the softening temperature of polymer, with structure sizes in the nanometer range (Giboz *et al*. 2007).

Nearly every commercially available thermoplastic – unfilled or filled – can be used for the microinjection molding of plastic micro-components. In contrast to the injection molding of macroscopic parts, some modifications of the process have to be developed to achieve complete mold filling and damage-free demolding even for patterns down to the submicrometer regime (Baltes et al. 2005).

Mold inserts are required to produce microstructured plastic parts. Their micrometric dimensions and tolerances require specific methods for the mold inserts realization, such as:

(i) LIGA based (lithography, electroplating, molding) technologies (LIGA, UV-LIGA, IB-LIGA, EB-LIGA);
(ii) 3D micro machining regrouping micro electrical discharge machining (µEDM), micro mechanical milling and electrochemical machining (ECM) using ultra-short pulses;
(iii) silicon wet etching (or silicon wet bulk machining);
(iv) deep reaction ion etching (DRIE);
(v) thick deep UV resists;
(vi) excimer and ultra-short pulse laser ablation

Compared with the µIM, the classical IM process uses ablation techniques of material, such as milling, turning or EDM (Giboz *et al*. 2007).

3.4 Rapid prototyping

To reduce the product development time and reduce the cost of manufacturing, the new technology of rapid prototyping (RP) has been developed, which offers the potential to completely revolutionize the process of manufacture. This technology encompasses a group of manufacturing techniques, in which the shape of the physical part is generated by adding the material layer-by-layer. Many of these techniques are based on either the selective solidification of the liquid or bonding solid particles (Rosochowskia & Matuszakb 2000).

The most established and widely distributed technology is stereolithography with the direct layer-by-layer transformation of computer-aided design data into a 3-D mold using the photopolymerisation of reactive polymer resins with a focused UV beam (Volker Piotter & Thomas Hanemann 2011).

Micro-stereolithography (MicroSL) , is a novel micro-manufacturing process which builds the truly 3D microstructures by solidifying the liquid monomer in a layer by layer fashion. The basic principle of stereolithography is schematically shown in figure 5. A 3D solid model designed with CAD software is sliced into a series of 2D layers with uniform thickness. The NC code generated from each sliced 2D file is then executed to control a motorized x–y stage carrying a vat of UV curable solution. The focused scanning UV beam is absorbed by an UV curable solution consisting of monomer and photoinitiators, leading to the polymerization, i.e., conversion of the liquid monomer to the solid polymer. As a result, a polymer layer is formed according to each sliced 2D file. After one layer is solidified, the elevator moves downward and a new layer of liquid resin can be solidified as the next layer. With the synchronized x–y scanning and the Z-axis motion, the complicated 3D micro part is built in a layer by layer fashion. The MicroSL shares the same principle with its macroscale counterpart, but in different dimensions. Submicron resolution of the x–y–z translation stages and the fine UV beam spot enable precise fabrication of real 3D complex microstructures (Zhang *et al.* 1999).

A promising three-dimensional microfabrication method that has recently attracted considerable attention is based on two-photon polymerization with trashort laser pulses. When focused into the volume of a photoresistive material like PMMA, the pulses initiate two photon polymerization via two photon absorption and subsequent development (e.g. washing out the non illuminated regions) the polymerized material reminds in the prescribe 3-D form. This allows fabrication of any computer generated structure by direct laser recording into the volume of a photosensitive material. Figure 6 shows some micro components fabricated via mentioned method. Because of the threshold behavior and non linear nature of the process, a resolution beyond the diffraction limit can be realized by controlling the laser pulse energy and the number of applied pulses. As a result the technique can provide much better resolution than micro-stereolithography. The achieved resolution can be 100 nm or better (Ostendorf & Chichkov 2011).

5. Conclusion

As seen above, today's industry has provided various techniques to fabricate micro investment casting patterns from PMMA. Comparison of these techniques based on important manufacturing criteria is beneficial for selection of the best process to fabricate the patterns. Table 1 shows a comparison between mentioned micromanufacturing techniques based on cost, aspect ratio, geometric freedom based on existing of undercut, surface roughness and accuracy.

From table 1 it is obvious that in mass production the best process for pattern fabrication is microinjection molding. A complete review of this technique can be found in (Giboz et al. 2007). For one-off and batch production, microcutting, laser machining, micro steriolithography and two photon polymerization technique respectively can be chosen. Complicate shapes with undercut may be producible only by steriolithography and two photon polymerization.

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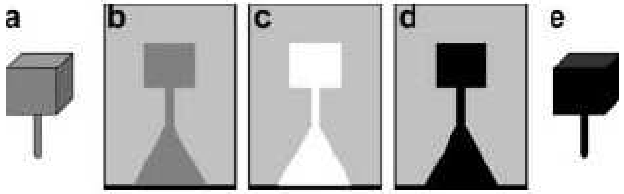

Figure 1. Micro investment casting process, **a** plastic pattern, **b** embedded in ceramic slip, **c** hollow form, **d** gold filled mold, **e** cast part

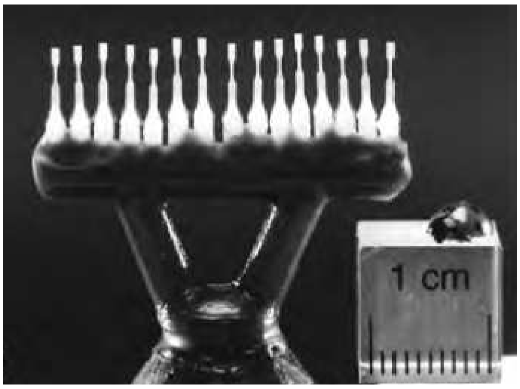

Figure 2. Pattern with 15 injection-molded specimens fixed on a runner system made of wax (Baltes et al. 2005).

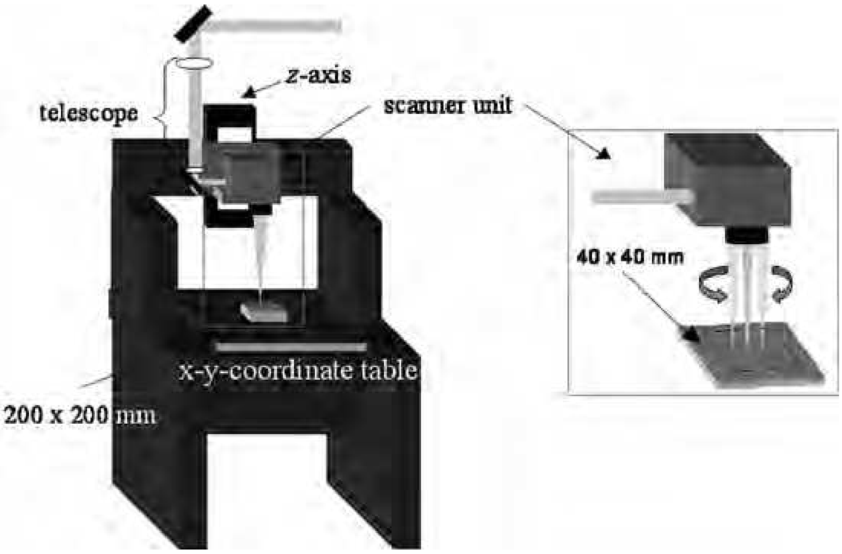

Figure 3. Laser micro machining of PMMA (Neda et al. 2011).

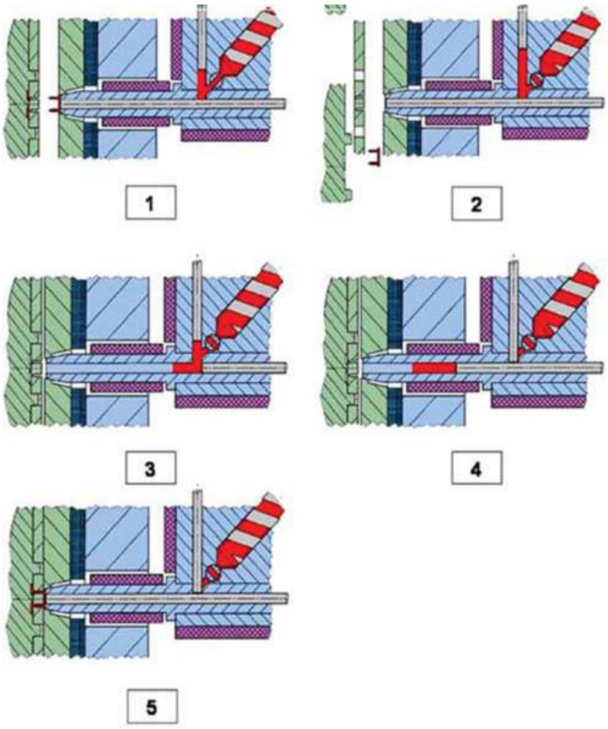

Figure 4. Schematic drawing of the injection molding process (Giboz et al. 2007).

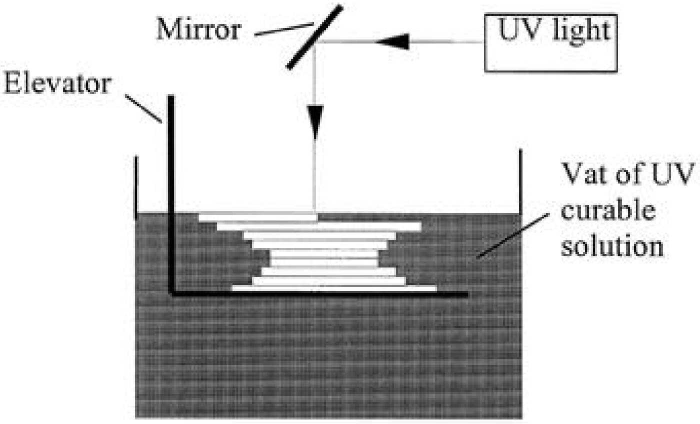

Figure 5. The principle of stereolithography (Zhang et al. 1999).

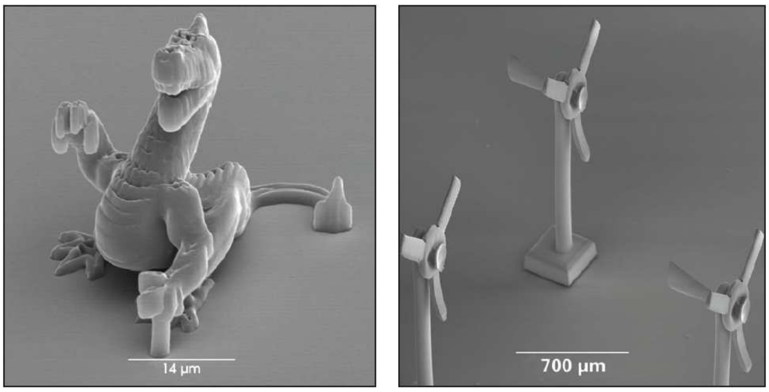

Figure 6. The SEM image shows a micro-scale dragon (left) and a movable windmill (right) fabricated by two-photon polymerization (Ostendorf & Chichkov 2011).

Table 1. comparison between mentioned methods for fabrication PMMA patterns (Baltes et al. 2005; Baumeister et al. 2002; Giboz et al. 2007; Ostendorf. A. & Chichkov, B.N. 2006; Choudhury, I.A, & Shirley, S. 2010; Hansen,H.N, et al, 2011; Leea, K.S et al. 2008; Bertsch, A. et al 1999).

technique	Workpiece dimension	accuracy	Surface roughness	Geometrical freedom	Aspect ratio	cost
microcutting	Higher than50 µm	~2 µm	<100 nm	low	Medium To Low 10-50	medium
Laser machining	Higher than 3 µm	~30 µm	~ 1 µm	low	low 1-10	high
Micro injection molding	Higher than 20 µm	Higher than 1 µm	10 nm to 100 µm	medium	Medium To low ~20	Low to high
MicroSL	Higher than 1 µm	~ 5 µm	~ 5 µm	high	high	high
Two photon polymerization	Higher than nano meter	100nm to µm	~ 40nm	high	high	high

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