Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 132 (2015) 655 – 662

Procedia Engineering

www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2015

Electroforming applied to manufacturing of microcomponents

P. Hernández[a,*], D. Campos[a], P. Socorro[a], A. Benítez[a], F. Ortega[a], N. Díaz[a], Mª D. Marrero[a]

[a]University of Las Palmas de Gran Canaria. Fabricación Integrada y Avanzada Research Group. Edificio de Fabricación Integrada. Campus de Tafira. Las Palmas de Gran Canaria 35017. Spain.

Abstract

Nowadays, there is an increased demand for micro-products and micro-components in many industry sectors therefore development of advanced manufacturing technologies and metrological instrumentation in this range, have thus become a critical issue and an engineering challenge. If a product cannot be measured, although it might be manufactured, it would not be possible to analyse its design in order to improve its functionality. Electroforming could be defined as the highly specialized use of electrodeposition for the manufacturing of metal parts. Due to progress in materials, processes and equipment, electroforming has shown considerable development. Consequently, electroforming is increasingly combined with other micro-manufacturing technologies, giving rise to other processes such as LIGA and UV-LIGA. Thanks to the accumulated experience of Fabricación Integrada y Avanzada research group, of the University of Las Palmas de Gran Canaria in the electroforming process focused on macro-scale, as well as specific equipment available, this paper aims to analyse the potential of electroforming process for micro-injection mould manufacturing.

Peer-review under responsibility of the Scientific Committee of MESIC 2015

Keywords: Electroforming, Micro-metrology, Micro-injection moulding.

1. Introduction

In recent years, there is an increasing demand for small and even micro-scale parts and this trend towards miniaturization makes the micro-system technologies of growing importance. Micro-manufacturing process

* Corresponding author. Tel.: +34-928-458604; fax: +34-928-451484.
E-mail address: pedro.hernandez@ulpgc.es

Peer-review under responsibility of the Scientific Committee of MESIC 2015
doi:10.1016/j.proeng.2015.12.544

capabilities should expand to encompass a wider range of materials and geometric forms, by defining processes and related process chains that can satisfy the specific functional and technical requirements of new emerging multi-material products, and ensure the compatibility of materials and processing technologies throughout these manufacturing chains. Example technologies to be investigated either individually or in combination are technologies for direct or rapid manufacturing, energy assisted technologies, micro-replication technologies, qualification and inspection methods, functional characterisation methods and integration of "easy and fast" on-line control systems [1].

The processes should demonstrate significantly high production rates, accuracy and enhanced performance or quality, creating capabilities for mass manufacture of micro-components and miniaturised parts incorporating micro- or nano-features in different materials. Processes should also provide high flexibility and seamless integration into the new micro- and nano-manufacture scenario. Micro- and nano-manufacturing technologies can provide the basis of the next industrial revolution that could dramatically modify the way in which businesses are setup, run and marketed. Electroforming process has great advantages in this range, such as high dimensional accuracy, precise reproduction of surface detail, production of complex-shaped and thin-walled components and assisting other mass production processes. When exacting tolerances are required, complexity, lightweight and miniature geometry, electroforming is a serious contender and in certain cases may be the only possible or economically viable manufacturing process [2].

This work is included in a new research line, which will be focused in mould-making applications, based on the experience obtained by use of electroforming process in macro-scale. The first section of this paper provides a brief review of micro-manufacturing processes focusing on the electroforming process as well as their applications, capabilities and limitations at micro-scale. Special mention is made to the applications of electroforming for micro-injection moulding. Furthermore, metrological needs to fulfil the requirements demanded in micro-manufacturing are analysed by comparing characteristics and limitations of current measurement equipment. In the section of experimental methodology, the manufacturing of an electroformed part making use of an aluminium pattern is described. This pattern or model and the final electroformed part are measured by optical digital microscopy, at the Laboratory of Metrología y Calibración from University of Las Palmas de Gran Canaria (ULPGC). A summary of this measurement process is also presented in this section.

2. Micro-manufacturing processes

New complementary micro-manufacturing technologies are necessary to produce micro-components in a multiplicity of materials and also enable length-scale integration in products [1]. Special attention is given to investigations into tool/master-making technologies, electro discharge machining (EDM), laser machining, micro-milling, and focussed ion beam (FIB) machining, together with replication processes for serial manufacture, in particular, micro-injection moulding (MIM), nano-imprint lithography (NIL), hot embossing and electroforming.

Some technologies such as EDM, laser milling, and FIB are essential for the successful development of high throughput micro-manufacturing process chains due to their tool/master-making capabilities. In particular, the quality and performance of a replicated micro-part is directly dependent on the quality of the corresponding micro-mould [3]. In general, micro-milling has the highest material removal rate, and it can machine materials such as titanium, copper, aluminium, brass, polymers, ceramics and glass. Laser milling can process the widest range of materials. Among the four processes mentioned, the highest aspect ratio can be obtained with micro-EDM. For instance, micro-EDM drilling can produce holes with an aspect ratio of up to 25. FIB is a process that allows sub-micrometre features to be produced, but at the same time, its material removal rate is extremely low in comparison with the other three processes. MIM and hot embossing can process any thermoplastic polymer and are considered important complementary technologies to MEMS processes. When micro-structured surfaces have to be produced in large quantities, MIM is the preferred method due to cycle times typically in the order of seconds and, hence, high throughput and relatively low cost per part. At the same time, hot embossing is considered as a complementary technology to MIM due to its different cost-effective processing window, in particular cycle times in the order of minutes and relatively low complexity and cost of the replication masters in comparison to the MIM tools. Electroforming, micro-injection moulding, and metrological needs will be described in the next subsections.

2.1. Electroforming

Electroforming technology develops on the basis of the principle of electroplating. Anode, electrolyte, workpiece model for plating and power supply, constitutes the basic elements of this process. The metal anions from metal salt solution are made to migrate to cathode by the electric field force and turn into atoms and deposit on the surface of the cathode model cousin. In the process of deposition, there are no space exits between ion and core model surface, and it does not cause any damage to its surfaces [2]. The difference between electroforming and electroplating lies in the purpose of use for the deposited metal. Electroplating is concerned with taking an existing part and applying a metallic coating to provide a decorative and/or protective surface. An electroforming product, however, is a metallic object that has been created by utilising the electroplating process to deposit a metal on or against a master form. Its purpose is to serve functionally as a separate entity.

In general, the model materials for electroplating must to be conductive on active surfaces. As for electroforming, the choice is quite multitudinous: conductor, non-conductor and light resistance material can be used as the master form. Electroforming products mainly emphasize the functional properties that can achieve: high hardness, great tensile strength, and other mechanical properties. Therefore, the solution composition and operating conditions of them are quite different. Electroforming process is an accumulation process atom by atom theoretically, so it could copy the surface details of the model accurately. Electroforming accuracy completely depends on the design accuracy of the master part, its replication precision can achieve sub-micron grade. It is the reason why electroforming can be defined as a precise replication technique. Consequently, it needs to control electroforming process parameters properly during the process: plating solution composition, pH, temperature, additives and impurity. Due to the high replication precision, repeatability and conveniently controllability you can directly change the process parameters to adjust the performance electroforming products, this process must be considered as a tool or intermediate process in a process chain that allows mass production [2].

The characteristics of electroforming in comparison with traditional metal forming processes give rise to a significant advantage. By electroforming, components can be manufactured which would be difficult or in some cases impossible to produce by conventional methods of fabrication. Its main advantages are [4, 5]: high dimensional precision, precise reproduction of surface detail, production of complex-shaped and thin-walled components, extensive range of size. Electroforming process has certain limitations, which may hinder its use as a viable production process. Its main engineering limitations are [4]: long deposition times, material restrictions, non-uniform thickness, electroform/mandrel separation, and internal stress. Nickel, copper, iron, silver, gold, and a few other alloys are the materials used primarily for electroforming. At present, electroforming has become one of the important technologies in micro-manufacturing field in comparison with other viable processes. For this reason, a lot of scientific and technical personnel and enterprises have to pay attention to it. Electroforming is mainly applied to the following products [4]: conventional record stampers, roughness standard simples, metal foil and metal mesh, perforated products like screen printing cylinders, filters, sieves, waveguides, reflectors, optical beam-bounding diaphragms, components for semiconductors and micro-systems technology, mini- and micro-housings for shielding in electronics applications, and many others. In mould manufacturing mainly including plastic mould and die, stamping dies, Ni-Co alloy electroforming moulds, and EDM electrodes.

In recent years, research on electroforming has mainly concentrated on two aspects. On the one hand, the refining grain size to improve surface quality and micro-structure; on the other hand, electroforming combined with the other advanced manufacturing technology. In this context, the importance of this technology in LIGA process should be noted, as well as use of electroforming for Rapid Prototyping techniques. Due to the results obtained, jet electroforming technology needs to be focused on. In the process of nickel jet electroforming, the plating rate is up to 90 times as fast as conventional electroforming, by using a current density up to 380 A/dm^2. Moreover, electroforming alloy and composite electroforming is an important development direction of the electroforming technology [2].

Main advanced developed in recent years by different authors are mentioned in this paragraph. Huang et al. [2] described widely the basic principles and technological methods of electroforming. Yang et al. [6] developed an effective method to improve thickness uniformity in nickel electroforming for the LIGA process. Zheng y Zhu [7, 8] investigated the several important factors on nickel-iron plating composition and electromagnetic property. The influences of current density, nickel and iron ion concentration, solution, pH, temperature, were evaluated in this study. Chen et al. [9] carried out an experimental research on jet electroforming oriented to Rapid Manufacturing. Du et al. [10] investigated the effects of pulse-reverse current on uniformity in micro-electroforming. Sun et al [11] fabricated micro-gears with new technologies, like electroforming. Excellent properties concerning hardness and resistance against wear and friction have also been obtained. Sawa et al. [12] fabricated a high hardness micro-mould using double layer nickel electroforming. Hussain [5] realised a study of electroforming process in the synthesis of nano-crystalling nickel by very high speed movement of the electrolyte. Li et al. [13] studied bipolar pulse electroforming on micro-optical aspheric mould manufacturing. Ming et al. [14] fabricated micro-precision sieves with high open area percentage using micro-electroforming technology. Liu et al. [15] fabricated a low deformation mould by optimizing micro-electroforming process parameters.

2.2. Micro-injection moulding

Polymeric micro-components are mainly manufactured today by Micro-injection moulding process to transfer micron features through metallic moulds. This process will play a fundamental role in future to produce miniature components in several sectors like biomedical, optical and IT technologies for these reasons [16]: the ability of low cost and short cycle times process, useful for mass production; the increasing capacity to achieve components of high aspect ratio and micro-dimensions with demanding fabrication tolerances; the ability of processing polymers with a wide range of properties according to the functionality requested.

Some limitations, however, need to be overcome before this process can realize the wide-scale manufacturing of micro-components. In particular, the nature of end-shape processes puts constraints on the allowed geometrical designs to achieve easy demouldability. Moreover, the analysis and optimization of the process parameters are imperative for producing parts with acceptable quality. The variables, that affect the quality, can be classed into four categories: mould and part design, injection machine, material, and processing parameters [17]. The aspect ratio of a shape is essential for micro-manufacturing processes. It´s defined as the ratio of its longer dimension to its shorter one, and it constitutes a constraint in applying injection moulding. Many applications require High Aspect Ratio (HAR) components and therefore have to be investigated to improve limits in miniaturization. There are limitations which are a function of the geometry of the micro-features, their position on the part, the polymer type and the process conditions [18]. Polymeric materials with minimum wall thickness of 10 μm, structural details in the range of 0.2 μm, and surface roughness of about $Rz < 0.05$ μm have been manufactured [19].

Many design rules commonly applied for conventional injection moulding, can't be directly used to micro-moulded parts. An important point to take into account in mould cavity design is related to the fact that many micro-components have a large surface to volume ratio, which leads to fast cooling of the injected melts into tools. The evacuation of the air from the mould cavity, the design of the cooling system and the ejection mechanism, require different solutions because of the mould dimensions. The use of inserts fitted in the main mould body, is very common and important in micro-injection moulding. The main objective of using mould with changeable inserts is in the ability to test different micro-part geometries, through removable cavities, without discarding the basic structure of the mould, specifically designed for micro-components injection [20]. The use of moulds with inserts reduces the overall cost of process setup, where the finalized mould design is produced by a number of iterative steps in which parts are injected and the mould design is changed. The concept of replaceable cavities can be applied in design of mould for different applications and the efficiency of the product development stage is greatly improved. The inserts allow easy testing of the design prototypes especially in those products where clear design guidelines are not available. Another advantage of using inserts is related to the material with which they can be manufactured. In fact, the material can be different from the one used for the mould, usually made of steel, and it can depend on the manufacturing technology available and on costs.

Also the interaction with process of the surface roughness of the mould is of paramount importance. Griffiths et al. [21] studied the factors affecting the flow behaviour in the interaction between the melt flow and the tool surface and three polymers were employed to perform moulding tests using cavities with the same geometry but different surface finish. It was found that there is a relationship between the tool surface finish and the level of turbulence in the melt flow. For this last reason, electroformed inserts present excellent properties to apply for micro-injection moulds.

2.3. Metrological needs

Metrology techniques for micro-components demand a combination of high accuracy, precision and reliability, and the flexibility to create a turnkey solution for the application at hand. In the case of micro- mechanical parts the absolute dimensions are small and so are the tolerances. These facts result in at least two challenges: finding a suitable measurement method to measure the components; and ensuring that the measurement uncertainty is sufficiently small to actually be able to verify the tolerance. The consequence in all cases usually is that the measurement uncertainty becomes larger compared to the tolerance interval leaving a much smaller conformance zone for process variations and the relationship between tolerance, processing capability and metrology methods is particularly challenging in micro- technology [22]. The generic measurement tasks to be performed in micro-metrology are distance, width, height, geometry (or form), texture and roughness, thickness of layers and aspect ratio [23].

In micro-manufacturing, the complexity will increase when going from 2D to 2½D and subsequently 3D measurement tasks. Moreover, the smaller the absolute scale the more challenging the measurement task. Features with aspect ratios below 1, will be referred to as 2D techniques. Measurement of features with aspect ratios of one or bigger is referred to as 2½D and measurement of undercuts, freeforms or features within cavities, will be described as 3D measurement tasks. In general a variety of 2D and 2½D metrology systems are currently available and its associated uncertainties completely determined. However, there are few truly 3D metrology systems in this domain. Full three dimensional characterization in the mm regime is not possible through the use of any of the reviewed techniques in this paper. Methods for dimensional micro- and nano-metrology can be divided into the following categories, though a clear border line between them is not always possible to draw [23]: technologies based on interferometric solutions, micro-topography measuring instruments, optical microscopy, scanning electron microscopy (SEM), scanning probe microscopy (SPM), micro-coordinate measuring machines (micro-CMMs), other techniques, such as digital holography and micro-computed tomography.

Needs for dimensional micro- and nano-metrology are evident, and as critical dimensions are scaled down and geometrical complexity of objects increased the available technologies appear not to be sufficient. Major research and development efforts have to be undertaken in order to answer these challenges. The developments of course have to include new measuring principle and instrumentation, but an equally important issue is linked to tolerance rules and procedures. Finally the issue of traceability and calibration is of upmost importance if the micro- and nano-technologies have an ambition of developing into industrial environments.

3. Experimental Methodology

In this section, the electroforming process of a self-designed component with micro-features is presented and discussed as a case study developed by this research group. The experimental work was divided into three steps: a machining phase, an electroforming and extraction phase and finally an additional step that involves specimen preparation and measurement. To put this work into practice, it was necessary first of all to manufacture an aluminium pattern, with the resources available in our laboratories and representative for micro-manufacturing because it has features in the order of microns. Its design is based on characteristics of calibration standards for microscopes and features typical of electroformed micro-components, as a succession of holes with different diameters in two perpendicular axes, and V-grooves with different width.

This aluminium model part was manufactured in a high-speed vertical CNC machining centre (MAZAK VTC 300 C II) with a conical engraving tool (diameter of 6 mm and angle of 60^o) and one end mill tool (diameter of 1 mm). In the same raw part two patterns were machined to allow the comparison of two electroformed nickel shells. The overall dimensions are the same as the other electroformed nickel part to apply and insert for injection moulding to obtain micro polymeric samples for tensile tests. The geometry and dimensions of this model part are illustrated in Fig. 1. After it was machined, it was necessary to prepare this model isolating non-active surfaces with an easilt removed protective varnish. The electroforming process was applied using simple laboratory equipment with nickel sulfamate electrolytic bath. The current density used was of 2 A/dm2 during 48 hours, and the nickel shells obtained are showed in Fig. 2.

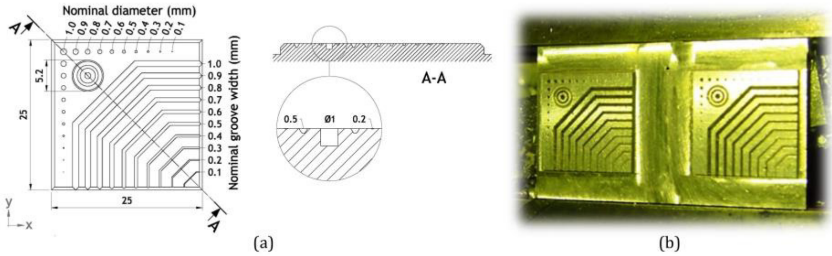

Fig. 1. (a) Sketch of model; (b) aluminium pattern with two models.

Before shells separation, it was decided to strengthen them using an epoxy resin used as a holder to allow safe removal by mechanical means and avoid potential damages that change any part features. Also this epoxy filler achieved good reference surface by milling, high parallelism to opposite side with active surfaces of the aluminium pattern, which is very important for the next phase of measurement. The demoulding phase was relatively easy because the protective varnish helped to prevent adhesion with the aluminium, and the model part was not harmed and it could be used to repeat electroforming process.

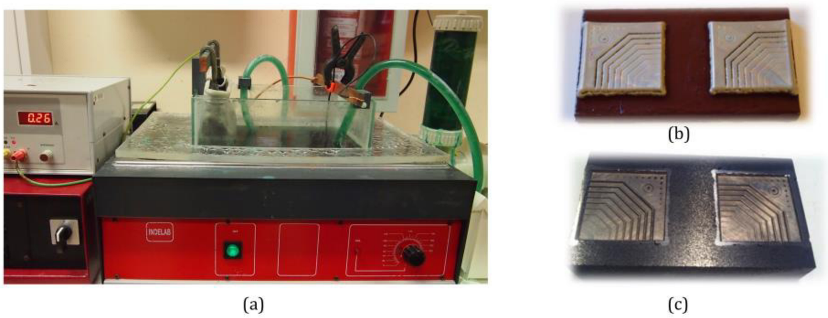

Fig. 2. (a) Electroforming lab equipment; (b) back surface of eletroformed parts; (c) functional surface of nickel parts inside epoxy filler.

To measure the nickel shells it was necessary to prepare the combined part by milling of the outer sides, parting off in diagonal section one of the shells, and grinding this surface to evaluate the thickness distribution. Finally, the aluminium pattern and nickel shells were measured in detail by optical microscopy with Olympus BX51+BXRLA2 microscope provided with UIS optical system and Olympus DP72 digital camera. This equipment's research group is located in the Laboratory Metrología y Calibración of Mechanical Engineering Department of ULPGC, Fig. 3.

This measuring process has guaranteed the traceability of its calibration carried out to references of the CEM (Spanish Centre of Metrology), and its calibration uncertainty is 0.34 µm. The expand measurement uncertainty is obtained by multiplying the standard uncertainty of measurement by the coverage factor k=2 that for a normal distribution corresponds to a coverage probability of approximately 95%. The global uncertainty of the measurement process has been determined according to the document EA-4/02, and it was estimated to be 0.57 µm, after applying the corresponding measurement corrections.

Measurement of parts was carried out in order to evaluate the accuracy of the process, for example linearity, parallelism, concentricity and angularity. Obviously aluminium pattern was measured before electroforming was applied to it. An accurate reproduction of machining process surface details was achieved by means of electrodeposition. It can be seen clearly by comparing in Figure 3. From all measurements the deviations between the aluminium mould and the electroformed parts were calculated and shown in the following table. Differences in work pieces measurement are also shown to justify the degree of repeatability, Table 1.

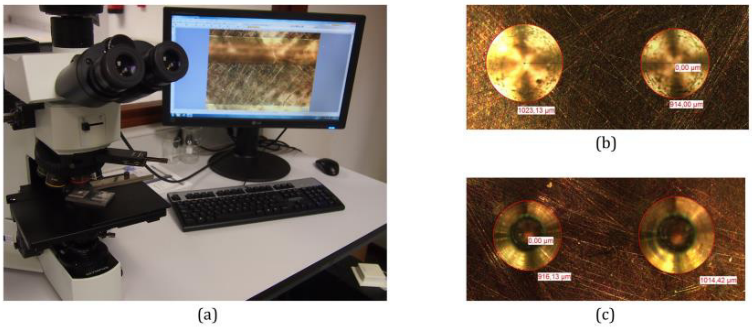

Fig. 3. (a) Microscopy Olympus BX51; (b) features in aluminium model; (c) features in nickel part.

Table 1. Summary of measurement results.

Average deviations		Left Part	Right Part
Grooves (µm)	X	1.04	3.44
	Y	1.32	2.46
Angle (degrees)		0.64	1.08
Holes (µm)	X	1.03	1.27
	Y	2.15	3.04
Centre distance (µm)		1.66	1.17
Parallelism (µm)		2.15	3.84

Two measures in axes X and Y were carried out in those features which required such grooves or holes. Measuring thickness was performed in the diagonal as shown in Figure 4. The data set obtained is shown in the following plot. Taking into account all the data obtained by measuring parts, special mention should be made of the high degree of reproducibility and repeatability of the process, being both from 1 to 5 micros. The great potential of this process to work at this level is justified by the measurements obtained. Electroforming is capable of reproducing superficial details very difficult to measure with available equipment, by meeting the requirements demanded in micro-manufacturing even at submicron range. The degree of accuracy is such that it substantially exceeds the capability of the measurement equipment employed.

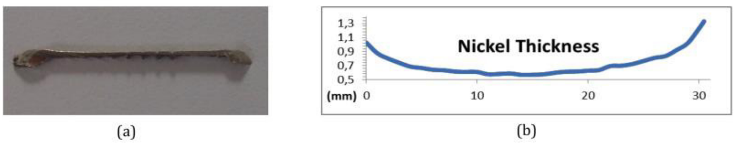

Fig. 4. (a) Cross-section of nickel part; (b) Thickness distribution

4. Conclusions

There is not a micro-manufacturing process to prevail over others, in order to attend the growing demand for micro-components. At present there is a tendency to develop hybrid processes focused on developing specific products. The electroforming is a process that has been known for a long time, which is gaining a renewed capacity to meet the needs required in the area of interest micro-manufacturing. One of its main applications is in the manufacture of micro-tools, being the micro-injection process where electroforming is receiving increased interest, as this is key to the development of micro-components for its high production rates and low cost process.

This work has allowed identifying real capabilities by this research group in applications to micro-manufacturing of electroforming. One of the main limitations identified has been manufacturing a component with micro-geometric features, because there is not specific equipment available for these applications. It would be convenient to use conductive materials for models, because the processes for conducting the active surfaces of non-conductive models, may determine the quality and precision of the surfaces of the final electroformed parts.

Also with the metrological equipment available we only evaluate 2-D features, and it is not capable of measuring geometric details that electroforming has been able to reproduce. It has been found that electroforming with the available equipment, and the electrolytic baths used, one can achieve the manufacture of micro-components.

References

[1] E. B. Brousseau, S. S. Dimov and D. T. Pham. Some recent advances in multi-material micro- and nano-manufacturing. Int J Adv Manuf Technol 47(1-4), pp. 161-180. 2010. . DOI: 10.1007/s00170-009-2214-5.

[2] C. Huang, H. -. Li, M. -. Zhu and M. -. Yu. Present research situation and new trends of electroforming. Appl. Mech. Mater. 278-280pp. 401-405. 2013. . DOI: 10.4028/www.scientific.net/AMM.278-280.401.

[3] L. Uriarte, A. Herrero, A. Ivanov, H. Oosterling, L. Staemmler, P. T. Tang and D. Allen. Comparison between microfabrication technologies for metal tooling. Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci. 220(11), pp. 1665-1676. 2006. . DOI: 10.1243/09544062JMES220.

[4] J. A. MacGeough, M. C. Leu, K. P. Rajurkar, A. K. M. De Silva and Q. Liu. Electroforming process and application to micro/macro manufacturing. CIRP Ann. Manuf. Technol. 50(2), pp. 499-514. 2001.

[5] M. S. Hussain. Electroforming a process for macro/nano manufacturing. Int. J. Nanomanufacturing 6(1-4), pp. 324-333. 2010. . DOI: 10.1504/IJNM.2010.034794.

[6] H. Yang and S. -. Kang. Improvement of thickness uniformity in nickel electroforming for the LIGA process. Int. J. Mach. Tools Manuf. 40(7), pp. 1065-1072. 2000.

[7] X. Zheng and D. Zhu. Research on electroforming ni-fe alloy for MEMS. Presented at International Technology and Innovation Conference 2006, ITIC 2006. 2006, . DOI: 10.1049/cp:20060944.

[8] Z. Xiaohu and F. Gu. Experiment on electroforming ni-fe property for micro fabrication. Adv. Mater. Res. 658pp. 213-216. 2013. . DOI: 10.4028/www.scientific.net/AMR.658.213.

[9] J. -. Chen, Y. -. Huang, Z. -. Liu, Z. -. Tian and Y. -. Zhao. Experimental research on jet electroforming oriented by rapid manufacturing. Huanan Ligong Daxue Xuebao/Journal of South China University of Technology (Natural Science) 34(11), pp. 16-19+24. 2006.

[10] L. Du, H. Liu, C. Liu, S. Zhu and J. Qin. Study on the uniformity of micro electroforming mold insert used in micro fluidic-chip fabrication. Presented at Proceedings of the International Conference on Integration and Commercialization of Micro and Nanosystems 2007. 2007, .

[11] S. Sun, Z. Li, P. Wang and W. Huang. Fabrication of micro gear with new technologies. Presented at 2009 IEEE International Conference on Mechatronics and Automation, ICMA 2009. 2009, . DOI: 10.1109/ICMA.2009.5246659.

[12] Y. Sawa, K. Yamashita, T. Kitadani and T. Hattori. Fabrication of high hardness micro metal mold by double layer nickel electroforming. Nihon Kikai Gakkai Ronbunshu, C Hen/Transactions of the Japan Society of Mechanical Engineers, Part C 75(759), pp. 3076-3081. 2009.

[13] H. Li, C. Huang, H. Zeng and K. Jiang. Experimental study of bipolar pulse electroforming on micro optical aspheric mold manufacturing. Advanced Materials Research 154-155pp. 806-809. 2011.

[14] P. Ming, Y. Li, Y. Wang and W. J. Jiang. Fabrication of micro-precision sieves with high open area percentage using micro-electroforming technology. Advanced Materials Research 426pp. 64-68. 2012.

[15] C. Liu, X. Ke, J. Li and Y. Duan. Optimization of micro electroforming process for fabrication of low deformation nickel mold. Nami Jishu Yu Jingmi Gongcheng/Nanotechnology and Precision Engineering 11(3), pp. 271-276. 2013.

[16] R. Surace, G. Trotta, V. Bellantone and I. Fassi, The micro injection moulding process for polymeric components manufacturing. New Technologies-Trends, Innovations and Research, C. Volosencu, Ed. 2012.

[17] B. H. Min. A study on quality monitoring of injection-molded parts. J. Mater. Process. Technol. 136(1-3), pp. 1-6. 2003.

[18] M. Heckele and W. K. Schomburg. Review on micro molding of thermoplastic polymers. J Micromech Microengineering 14(3), pp. R1-R14. 2004.

[19] V. Piotter, K. Mueller, K. Plewa, R. Ruprecht and J. Hausselt. Performance and simulation of thermoplastic micro injection molding. Microsystem Technologies 8(6), pp. 387-390. 2002.

[20] J. J. Marquez, J. Rueda and M. L. Chaves. Design and manufacturing of a modular prototype mold to be employed in micro injection molding experiments. Presented at AIP Conference Proceedings. 2009.

[21] C. A. Griffiths, S. S. Dimov, E. B. Brousseau and R. T. Hoyle. The effects of tool surface quality in micro-injection moulding. J. Mater. Process. Technol. 189(1-3), pp. 418-427. 2007.

[22] G. Tosello, H. N. Hansen and S. Gasparin. Applications of dimensional micro metrology to the product and process quality control in manufacturing of precision polymer micro components. CIRP Ann Manuf Technol 58(1), pp. 467-472. 2009. . DOI: 10.1016/j.cirp.2009.03.027.

[23] H. N. Hansen, K. Carneiro, H. Haitjema and L. De Chiffre. Dimensional micro and nano metrology. CIRP Ann. Manuf. Technol. 55(2), pp. 721-743. 2006. . DOI: 10.1016/j.cirp.2006.10.005.