Micro Manufacturing – Process and Part Quality Control

H.N. Hansen

Department of Mechanical Engineering, Technical University of Denmark, Denmark

Abstract – This paper presents the challenges related to process and part quality control in micro manufacturing. The use of dimensional metrology is discussed with focus on precision and uncertainty estimation. Tolerance verification and process qualification is depending upon measurements uncertainty, and in micro manufacturing the ratio U/T is often large compared to conventional scale manufacturing. The challenges are presented using a number of cases, and various approaches to their solution are suggested.

Key Words: Micro manufacturing, metrology

1 INTRODUCTION

Micro manufacturing is a common term used for production of products and components with critical dimensions in the sub-mm range. Different definitions have been proposed over the years trying to be more specific [1-4]. Currently research in the micro manufacturing is focused on single manufacturing processes and their interaction with the materials being processed. Focus is given to size effects [5-7], process capabilities [8-10] and to some extent components quality [11-13]. The establishment of coherent process sequences, to cover all necessary processing steps from tooling over replication to assembly processes is necessary for the industrial implementation. When integrating single processes into production systems issues as material compatibility, relative accuracy, alignment precision etc. become critical. The necessary actions related to quality control comprise process validation and verification of tolerances as specified in the design. This paper discusses challenges and possible solutions related to this problem complex and presents selected cases for illustration.

2 PROCESS VALIDATION AND METROLOGICAL CAPABILITIES

In micro manufacturing, like in ordinary scale manufacturing, it is important to control product characteristics such as dimensions, geometry, surface roughness, material properties etc. This implies methods, procedures and instrumentation that can be applied in such a way that results are meaningful and applicable in quality and process control. Basic boundary conditions include:

- Capability of measuring critical dimensions on the µm or even nm scale → requirements regarding instrument resolution, traceability, measurement uncertainty
- Capability of measuring and/or combining dimensions across several orders of magnitude on the same item → requirements regarding measurement range and resolution, measurement principle
- Possibility to verify product tolerances on the µm scale → measurement uncertainty must be determined and extremely low
- Process precision/accuracy/variation very high → similar or lower measurement capability required

Due to these boundary conditions it is necessary to apply metrological sound methods only. For the verification of tolerances the challenges are manifold [12-13]: tolerance zones are reduced as absolute dimensions are scaled down; measurement uncertainties are not reduced at the same rate leaving a smaller conformance zone for the verification (Fig. 1). This link to the design and specification of components is a key point in bringing micro manufacturing from the laboratory to industrial applications. According to ISO 14253 [14] the measurement uncertainty (U) must be subtracted from the tolerance (T) in order to establish the so-called conformance zone (Fig. 1). If the ratio U/T is close to 1, then a very little conformance zone is present, and the consequence is a very little allowable interval of variation for the manufacturing processes. The so-called 'golden rule of the gauge maker' expresses that if U/T < 0.1, then you are on the safe side. In micro manufacturing U/T almost never is on that level. It is far more likely to see 0.5<U/T<1, and of course in this case verification becomes critical.

Fig. 2 illustrates this connection in a different way. Variations due to measuring instrument, chosen measurement procedure etc. should be smaller than the expected process variation if the measurements are used for process analysis.

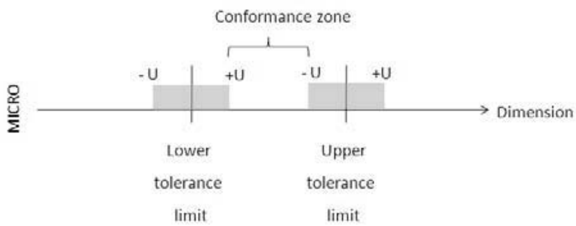


Fig. 1. Illustration of tolerance zone and measurement uncertainty.

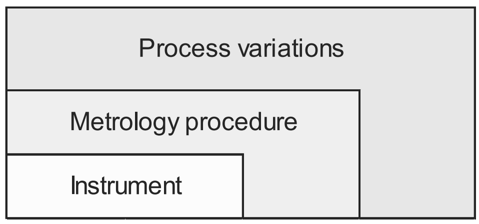


Fig. 2. Illustration of variations.

3 MICRO FLUIDICS

Micro fluidic systems are used to analyse small amounts of liquids in the bio-chemical area. Such systems are characterised by micro channels and other geometries of this order of magnitude. Dimensional accuracy of micro channels is of great importance in micro fluidic systems. Fundamental measuring tasks to be performed in quality control of micro fluidic systems are the width (define as the distance between two opposing surfaces) and the depth (defined as the distance between two surfaces of same orientation but placed in a vertical direction) of a micro channel [2]. A micro channel's width and depth must comply with the dimensional specifications in order to be able to contain the correct volume of reagents and biological fluids to be analysed and to convey the requested flow rate designed for the function to be delivered. Surface topography is also of great importance in polymer micro fluidics, hence the replication capability of the process and the surface quality of the tool has to be evaluated and possibly optimized. The surface finish on micro fluidics has different roles, depending on the location on the surface device. Firstly, low roughness is required to allow assembly by for example laser welding or thermal bonding of a lid on top of the micro fluidic unit for sealing purposes and, secondly, to diminish the interaction between the bio-fluid to be analysed and the channel/reservoir surfaces [15].

The micro fluidic system presented in this paper was designed to separate red blood cells from plasma [16]. The process chain for manufacturing was rather complex and involved micro electrical discharge machining of a Silicon wafer (to create the master geometry), followed by PVD and electroforming of a Ni counterpart. This Ni shim was finally used as an insert in an injection moulding process to create polymer micro fluidic systems. Fig. 3 illustrates the process sequence of creating the Ni shim.

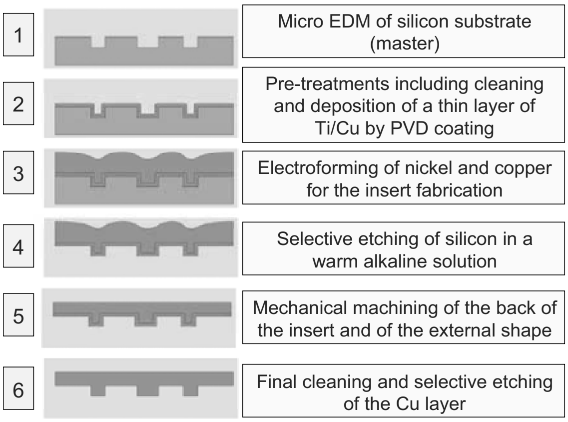
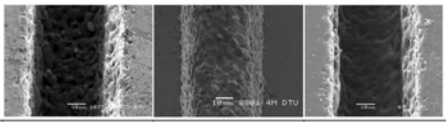


Fig. 3. Process chain for making the Ni shim for the micro fluidic device [17].

The precision moulding of a microfluidic system for blood analysis was analysed and validated by using a metrological approach applied to both micro channels dimensions (width and depth) and to surface topography on a reservoir chamber and on the microfluidic substrate surface. Dimensions were measured using an optical coordinate measuring machine (CMM); optical profilometry such as white light interferometry (WLI) was used for topographic characterization of polymer surfaces. Optical techniques provide fast non-contact measurements, which are in general recommendable when in-line process controls are needed on soft materials and when sample contaminations are to be avoided. Careful calibration of the instruments was performed and the measurement uncertainties determined. In this respect, the replication process involves a mirroring of the structure in such a way that an indent on the shim is seen as a protrusion on the replicated part adding the complication of establishing comparable measurement strategies. In particular, the relocation of corresponding measuring points on different specimens is key issue [16] that adds to the achievable lower measurement uncertainty. Fig. 4 shows a reasonably good agreement between the different steps of the process chain – and consequently a conclusion is that the replication of these features throughout the process chain is acceptable. However, the nominal width was not met (Fig. 4) mainly due to problems with the micro electrical discharge process and the control hereof.

Surface roughness results are shown in Fig. 5 and 6. Two areas were analysed: reservoir chamber surface and micro fluidic platform surface. The two levels of roughness are significantly different.



Width (nominal = 20μm)	(38±3)μm SEM image processing	(38±3)μm SEM image processing	(37±3)μm SEM image processing
Depth (nominal = 90μm)	(108± 3)μm Autofocus 3D laser profilometer	(110± 1)μm 3D mechanical stylus roughness tester	(110± 6)μm Autofocus 3D optical CMM

Fig. 4. Examples of channel width and height measurement of micro fluidic system: Si master, Ni shim and polymer part (from left to right) [16].

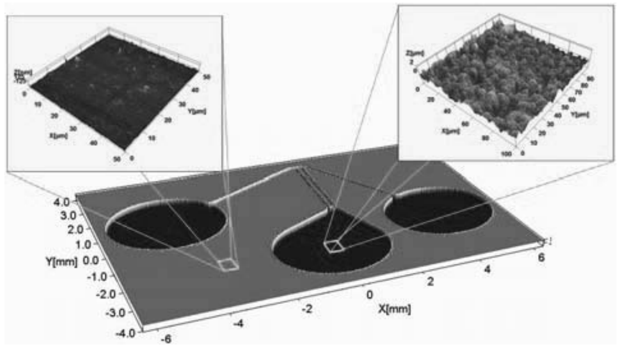


Fig. 5. Surface roughness analysis using WLI on micro fluidic system [15].

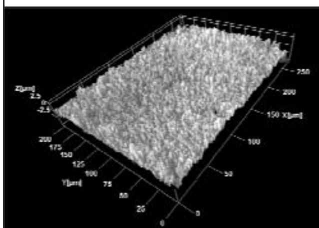
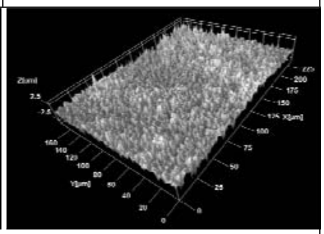
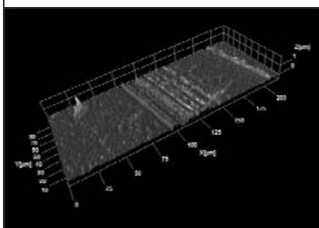
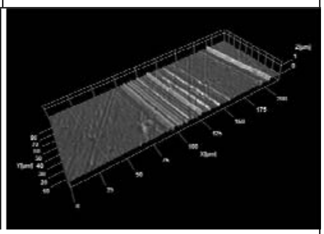
Reservoir chamber surface	
Micro tool surface (Nickel) Ra = 448 nm (U = 27 nm)	Moulded part (PP) Ra = 301↔362 nm (U = 11 nm)
	
Microfluidic platform surface	
Micro tool surface (Nickel) Ra = 71 nm (U = 5 nm)	Moulded part (PP) Ra = 28↔48 nm (U = 2 nm)
	

Fig. 6. Comparison of surface roughness values on tool and moulded part [15].

The results discussed above are interesting from two viewpoints. First they can be seen as a verification of the part quality. In this case measurement results have to be compared with the tolerances taking measurement uncertainty into account as already discussed. The other application is to use the results for process analysis and process optimisation. In the current case investigations were performed to analyse the injection moulding process based on a statistical design of experiments. The purpose of these investigations was to find optimal settings of process parameters based on the influence of these process parameters on achievable dimensions and surface roughness. Fig. 7 illustrates how the process parameters melt temperature, mould temperature and injection speed influences the depth of the channels when varied between a “low level” and a “high level” (two level factorial design). It can be seen that there are differences between the observed channel depths when changing process parameters. It can also be seen that the maximum differences are of the order of some µm and the measurement uncertainty is determined to be of the order of ±5 µm. In this case, the observed changes are not significant compared to the measurement uncertainty. Fig. 7 also contains the dimension of the tool (measured as the height of a protrusion that results in a channel during moulding). A typical observation is that the tool dimensions usually can be determined with a lower uncertainty than the polymer parts. This is partly due to material properties (the parts are measured using optical methods), partly due to the mirroring of the geometries during replication.

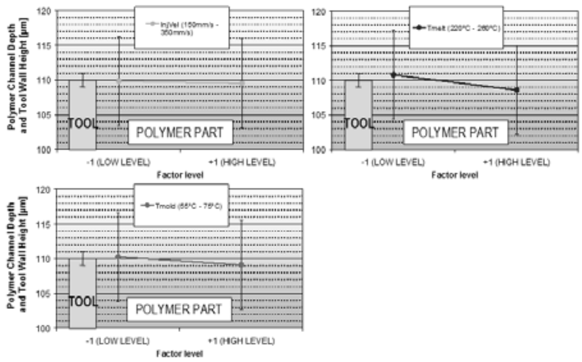


Fig. 7. Process optimization based on statistical design of experiments [15].

The diversity of features (e.g. channels, reservoirs) and their dimensions (e.g. from 50 nm to 500 µm) makes the measurement situation quite challenging. For each device, in principle you must develop a specific procedure and this will ultimately affect the obtainable measurement uncertainty. So for the sake of process optimization and process control we have suggested the introduction of the so-called process fingerprint [18]. The fingerprint contains a variety of features that cover a certain dimensional range (see Fig. 8) and therefore can represent typical features of a variety of real micro fluidic systems. The fingerprint should be put on the microfluidic system in a position that does not influence functionality. This requires the fingerprint to have a small footprint. By analysing certain parts of the fingerprint most relevant to a specific micro fluidic system it is possible to optimise the process. Fig. 8 illustrates a process fingerprint layout based on crosses of various widths (10 µm, 2 µm and 500 nm respectively) and same nominal depth (60 nm).

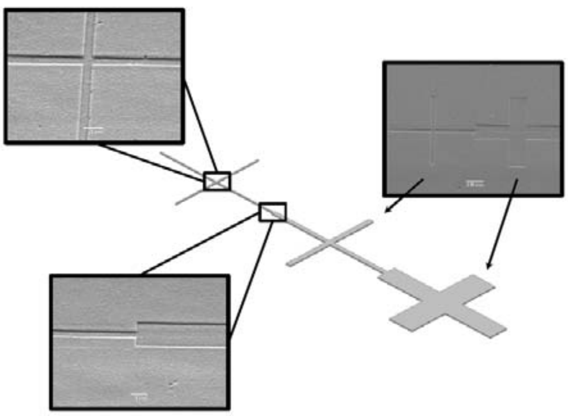


Fig. 8. Process fingerprint for nano scale features [18].

4 MICRO OPTICS

In a second case a process chain for production of polymer micro optics was investigated. A mould geometry has been machined using ultra high precision machining techniques with a resulting surface roughness of optical quality (Fig. 9 Top). These inserts were mounted in an injection moulding machine (Fig. 9 Middle) and the resulting polymer micro lenses are seen in Fig. 9 Bottom. Two moulds were made and one was coated with TiN coating [19]. Polymer micro structured optical Fresnel lenses were injection moulded using a commercially available optical grade highflow polycarbonate (Makrolon 2405 by Bayer MaterialScience). Injection mouldings were executed on a conventional injection moulding machine with a reciprocating screw of diameter of 35 mm and a clamping force of 60 kN.

The dimensions of the tool inserts micro structures were investigated at different production stages to evaluate the tool wear. However, the characterization of highly reflective surfaces with nanometer surface finish is a challenging task to be performed. On one hand, tactile instruments could damage the surface itself, and on the other hand, measurements carried out with optical instruments could be hampered by the high reflectivity of the surface limiting their accuracy. Also, the inserts have to be dismounted at each quality control step of the quality control process to be positioned on the measuring instrument, making the whole procedure lengthy and cumbersome. For these reasons, an indirect surface metrology method based on surface replication was developed and applied directly on the tool using a soft replica material (polydimethylsiloxane, PDMS) curing at room temperature. A replication mould device that could be easily mounted and removed from the mould was designed and manufactured to solve the issue of disassembling the inserts from the injection moulding tool (Fig. 9 Middle) [19].

The tool wear was investigated by means of dimensional measurements and scanning electron microscopy. A total number of 24500 injection moulding cycles were run. Dimensional measurements were carried out with the replica technique each 1000-2000 cycles with the tool inserts mounted on the mould during production. Fig. 10 illustrates the observed deviations of selected rib heights over 24500 mouldings. Deviations are smaller than 1 µm, and therefore measurement uncertainty becomes critical. Furthermore measurements are performed on a replica of the mould, and the variation of this replica process in combination with the stability of the rubber material over a short-medium period will influence measurement uncertainty. Assuming that absolute traceability is of less importance because we want to observe relative changes over time, still we need to assure stability of measurement procedure over time.

5 CONCLUSION AND OUTLOOK

The paper has described the challenges related to process and product quality control in micro manufacturing. When absolute dimensions are scaled down, so are the tolerances, but usually at a lower rate. This means that the ratio between measurement uncertainty (U) and tolerance interval (T) becomes larger than in ordinary scale manufacturing. This implies that care must be taken to determine measurement uncertainties and to reduce their sizes as much as possible. For process control metrological solutions must be able to determine critical process fluctuations, and this again requires small measurement uncertainties and establishment of traceability. These challenges have been illustrated with two typical cases: a micro fluidic system and micro optics.

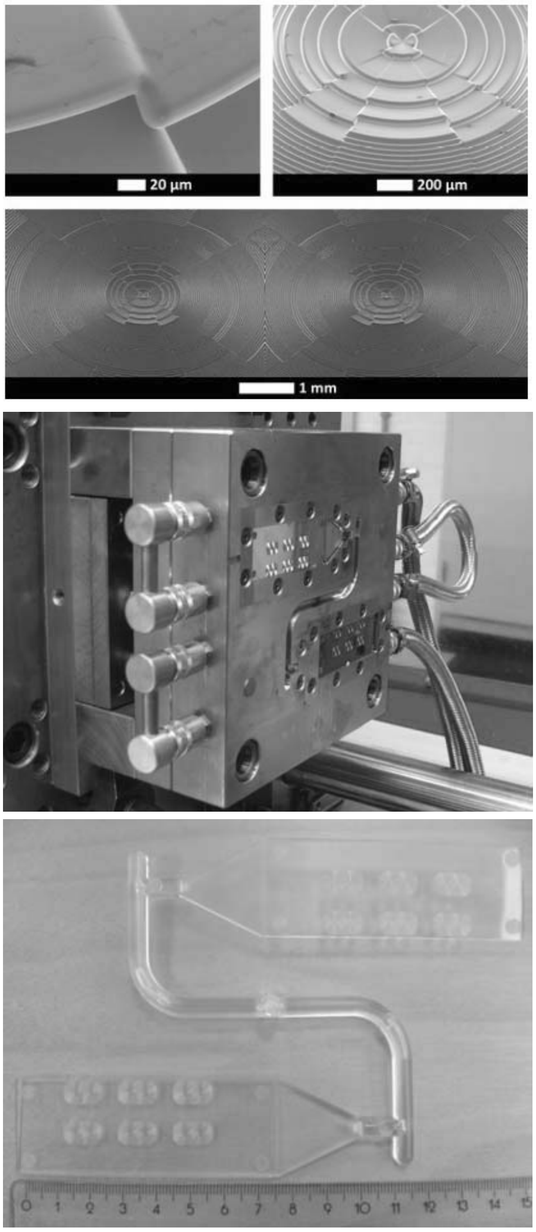


Fig. 9. Tool and polymer parts for micro optical elements [20].

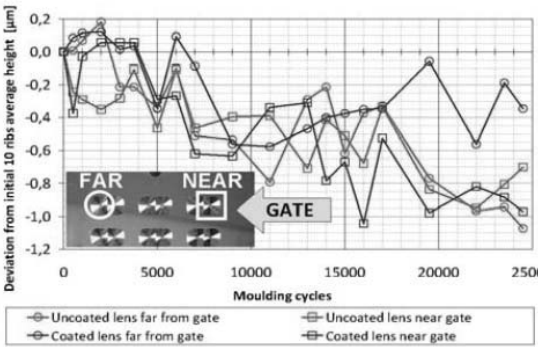


Fig. 10. Investigation of wear phenomena in micro injection moulding [19].

6 REFERENCES

[1] Alting L., Kimura F., Hansen H.N., Bissacco G., Micro engineering, Keynotepaper, Annals of the CIRP, Vol. 52/2 (2003), p. 635-658.

[2] Hansen H.N. et al, Dimensional micro and nano metrology, Keynote paper, Annals of CIRP Vol. 55/2 (2006), p.721-744.

[3] Masuzawa, T., 2000, State of the art of micromachining, Annals of the CIRP, 49/2:473-488.

[4] Brinksmeier E. et. al, 2001, Machining of precision parts and microstructures, Proc. of the 10th ICPE, p.1-9.

[5] Geiger M. et al, 2001, Microforming, Keynote paper, Annals of the CIRP, 50/2:445-462.

[6] Vollertsen F. et al, Size effects in manufacturing of metallic components, Keynote paper, Annals of CIRP Vol. 58/2 (2009), p. 566-587.

[7] Bissacco G. et al, Modelling the cutting edge radius size effect for force prediction in micro milling, Annals of CIRP Vol. 57/1 (2008), p. 113-116.

[8] Hansen H.N. et al, Complex process chains for manufacturing of invisible displays integrated in bulk metal panels, Annals of CIRP Vol. 56/1 (2007), p.237-240.

[9] Islam A. et al, Process chains for the manufacture of molded interconnect devices, International Journal of Advanced Manufacturing Technology, Volume 42 (9-10), (2009), p. 831-841.

[10] Hansen H.N. et al, Precision tooling technologies for micro forming, Invited paper, 2nd International Conference on New Forming Technology, Bremen, September 20-21, 2007, p. 157-165.

[11] Hansen H.N., Dimensional metrology in micro manufacturing, Keynote paper, 3rd International Conference on Multi-Material Micro Manufacture (4M2007), Borovets (Bulgaria), 3-5 October 2007, p. 29-35.

[12] Hansen H.N. et al, Tolerancing issues in micro manufacturing, 10th Anniversary International Conference of the European Society for Precision Engineering and Nanotechnology (Euspen), Zurich (Switzerland), 18-22 May 2008, Vol. II, p.317-320.

[13] Tosello G. et al, Applications of dimensional micro metrology to the product and process quality control in manufacturing of precision polymer micro components, Annals of CIRP Vol. 58/1 (2009), p. 467-472.

[14] ISO 14253-1:1998 Geometrical Product Specifications (GPS) – Inspection by Measurement of Workpieces and Measuring Equipment – Part 1: Decision Rules for Proving Conformance or Non-Conformance with Specifications, International Organization for Standardization, pp. i–v, 1–15.

[15] Tosello G., Marinello F., Hansen H.N., Characterization and analysis of micro channels and sub-micron surface roughness of injection moulded microfluidic systems using optical metrology, Polymer Process Engineering ‘09 Conference (PPE’09), Bradford (United Kingdom), 27-28 October 2009, pp.199-232, ISBN 13 978 1 85143 262 2

[16] Tosello G., 2008, Precision Moulding of Polymer Micro Components – Optimization, Simulation, Tooling, Quality Control and Multi-Material Application, Ph.D. Thesis, Technical University of Denmark, Department of Mechanical Engineering, pp.1-242, ISBN: 978-87-89502-77-9.

[17] Tosello G. et al, High aspect ratio micro tool manufacturing for polymer replication using µEDM of silicon, selective etching and electroforming, Microsystems Technology (2008) 14:1757-1764.

[18] Calaon M. et al, 2012, Production quality control of microfluidic chip designs, Proceedings of the 3rd European Conference on Microfluidics - Microfluidics 2012 - Heidelberg, December 3-5, 2012.

[19] Tosello G. et al., Surface wear of TiN coated nickel tool during the injection moulding of polymer micro Fresnel lenses Annals of CIRP, Vol. 61/1 (2012), 535-538

[20] Gasparin S., 2012, Verification of Tolerance Chains in Micro Manufacturing, Ph.D. Thesis, Technical University of Denmark, Department of Mechanical Engineering, pp.1-232.