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MEASUREMENT DESIGN FOR DIMENSIONAL CONTROL OF FUNCTIONAL MICRO-SCALE FEATURES ON MICROFLUIDIC MOULDS

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Abstract. *Manufacturing-related technologies and machine tools for micro-machining have experienced enormous advances in recent years due to the increasing demand for micro-structured parts with optical functional surfaces in industry and research. Micro-milling operations have been tested for manufacturing microfluidic moulds using different strategies in the project Micro-Milling Process Optimization - Micro-O, operated under the BRAGECRIM program. Focusing specifically on the micro-scale product development loop, metrology plays a vital role as it generates information and knowledge for manufacturing optimization. The matter of defining suitable measuring techniques for microfluidic mould features, particularly for micro-scale features of size and surface roughness, is addressed in this work. Design needs for surface roughness disable classical roughness testers for the measuring task. Thus two measuring systems based on different working principles are evaluated under the uncertainty perspective; the main findings are reported and discussed. For features of size (FOS) such as micro-channel width and height, coordinate measuring machines with multisensor capabilities are chosen. Considering the so-called integrative framework proposed in previous researches, the experimental approach specified in ISO 15530-3 is applied to enhance measurement knowledge and therefore to estimate the measurement uncertainty. The measurement setup, tests and results are detailed in this paper.*

Keywords: *micro-scale FOS, surface roughness evaluation, measurement uncertainty, experimental approach*

1. INTRODUCTION

Manufacturing-related techniques and machine tools for producing micro-scale products have experienced huge developments in recent years, in part explained by the growing need for micro-structured parts with optical functional surfaces in industry and research. The realization of micro-scale parts, features and specifications can be attained by implementing conventional cutting processes under appropriate conditions with regard to cutting tools, machine tools and thermal environments. Nevertheless, miniature cutting tools commonly used can be subjected to larger deflection and higher stress during machining than regular cutting tools, due to size effect and reduced stiffness (Bodziak et al., 2014). Vibrations can influence the tool's lifetime and the dimensional quality of the machined part. Because of the small size, it is more difficult to detect wear on the cutting edges that may lead to tool breakage and non-conformity of part tolerances and surface quality (Malekian et al., 2009).

The efficient improvement of micro-milling processes implies the application of advanced analysis and modeling techniques. Micro-milling operations have been tested for manufacturing microfluidic moulds using different strategies in the research project titled Micro-O, short for Micro-Milling Process Optimization, operated under the BRAGECRIM (Brazilian-German Collaborative Research Initiative on Manufacturing Technology) program. Since surface quality and dimensional accuracy are critical factors in parts with micro features regarding functionality, this research project aims at investigating how the generated NC (Numerical Control) tool paths can impact micro-milling processes and how they can be improved in some aspects, such as reduced process time and better dimensional quality.

Focusing specifically on the micro-scale product development loop, metrology plays a vital role as it generates information and knowledge for manufacturing optimization. The matter of defining suitable measuring techniques for microfluidic mould features, particularly for datum-dependent features (*i.e.* step height and line distance) and datum-independent features (*i.e.* roughness), is addressed in this work. For features of size, coordinate measuring machines with multisensor capabilities have been chosen and the experimental approach specified in ISO 15530-3 employed to enhance measurement knowledge and therefore to estimate the measurement uncertainty. Design needs for surface roughness make classical roughness testers unable for the measuring task; for this reason, two first-class measurement instruments that operate under different working principles have been evaluated under the uncertainty perspective. The measurement setup, tests and main findings are reported and discussed in this paper.

2. MICRO-SCALE TEST SAMPLES

Micro-scale products have been defined in published literature as components having at least two critical dimension in the sub-millimeter range (Tosello et al., 2009), or as components whose feature has at least one critical dimension significantly smaller than 0.1 mm, typically with tolerance ranges of a few micrometers, while the whole component may have larger dimensions (Petz et al., 2012). For the purpose of this work, both definitions extracted from literature are acknowledged.

Improvement of cutting conditions of micro-scale parts, *e.g.* using bigger cutting depth and width with lower feed, which save time without jeopardizing surface quality, is one of the objectives of the research project Micro-O. For this purpose, stair samples made of brass and steel were designed and experimentally machined; each stair sample contains 36 steps, and for each step the cutting parameters were varied in order to study their impact on surface roughness and cutting forces (the latter is not covered in this paper). The cutting parameters and the test samples are shown in Tab. 1. The cutting experiments are full factorial, as evidenced in Tab. 2 and Tab. 3. For CuZn39Pb stair sample, spindle speed of n = 30000 rpm was set on steps 1 to 18 and of n = 50000 rpm on steps 19 to 36, where the cutting parameters were varied in the same order as in Tab. 2. For X40CrMoV5-1 stair sample, spindle speed of n = 15000 rpm was set on steps 1 to 18 and of n = 30000 rpm on steps 19-36, where the cutting parameters were varied in the same order as in Table 3.

Table 1. Cutting parameter setup, tool properties and sample material for experimental investigation of varying cutting parameter impact on surface roughness.

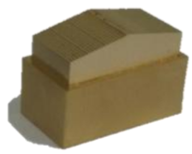
Parameter	Setup 1	Test Sample 1	Setup 2	Test Sample 2
Cutting depth, ap	4, 40, 80 µm		4, 10, 20 µm	
Cutting width, ae	100, 200 µm		20, 40 µm	
Feed per tooth, fz	4, 20, 40 µm		4, 10, 20 µm	
Spindle speed, n	30000, 50000 rpm		15000, 30000 rpm	
Tool	Flat micro-end mill		Flat micro-end mill	
Tool diameter, d	400 µm		400 µm	
Material	CuZn39Pb		X40CrMoV5-1	

Table 2. Cutting parameter test setup for micro-milling of CuZn39Pb sample (values in micrometers).

	Stair Sample Step																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Cutting depth, ap	80	80	80	80	80	80	40	40	40	40	40	40	4	4	4	4	4	4
Feed per tooth, fz	4	4	20	20	40	40	4	4	20	20	40	40	4	4	20	20	40	40
Cutting width, ae	200	100	200	100	200	100	200	100	200	100	200	100	200	100	200	100	200	100

Table 3. Cutting parameter test setup for micro-milling of X40CrMoV5-1 sample (values in micrometers).

	Stair Sample Step																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Cutting depth, ap	20	20	20	20	20	20	10	10	10	10	10	10	4	4	4	4	4	4
Feed per tooth, fz	4	4	10	10	20	20	4	4	10	10	20	20	4	4	10	10	20	20
Cutting width, ae	40	20	40	20	40	20	40	20	40	20	40	20	40	20	40	20	40	20

The study of the generated NC tool paths influence on the micro-milling process is also under the project scrutiny, and, for this reason, exemplary moulds for microfluidic devices were designed and experimentally machined using the parameter set with the best surface roughness to productivity ratio. The manufacturing process realization is illustrated in Fig. 1, from the technical drawing to the virtual and physical machined mould. The dimensional content of the mould is composed of channel heights and some features of size (*i.e.* inlet hole diameter and channel width), as shown in the technical drawing of Fig. 1 (left). Those features have been suitable for checking the simulation model prediction of the dimensional content of the test sample, which is one of the main goals of the research project.

Experimental cutting tests were conducted on the ultra-precision machining center KERN EVO installed at IPT's BioNanoManufacturing laboratory. Cutting tool diameter and length were measured using the inbuilt tool setter BLUM Laser Control Nano NT (type: P87.0634-015). The test sample referencing was done by scratching in z-direction while monitoring the contact area with the inbuilt high sensitivity CCD camera (model: WAT-231S2), in order to detect the first contact between the cutting tool and the test sample surface. Referencing in x- and y-direction was performed using an infrared touch trigger probe (model: M&H 32.00-MINI HDR). Micro-end mills with distinct diameters were selected to machine the exemplary moulds.

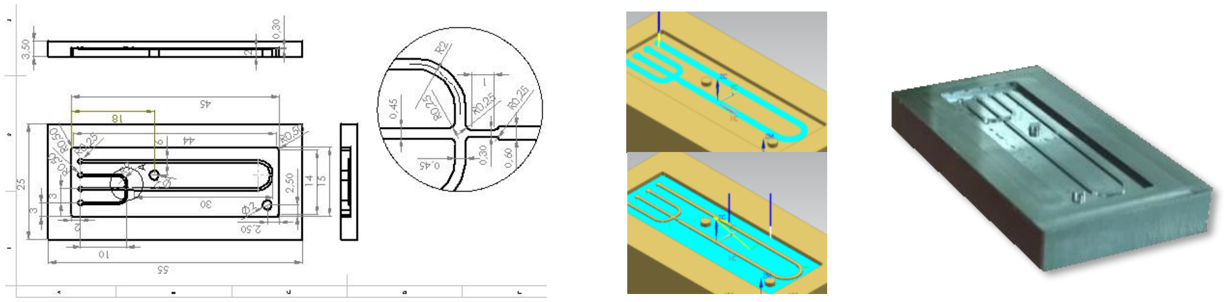


Figure 1. Manufacturing process realization: (a) technical drawing of a mould with micro features; (b) CAM tool path generation of finishing operations; (c) machined mould.

3. MEASUREMENT DESIGN

Considering the measurement needs for the test samples just described, this section outlines the measurement setup designed for inspecting both surface roughness (Subsection 3.1) and micro-scale dimensional features (Subsection 3.2) of micro-milled test samples.

3.1. Surface roughness investigation

Line roughness parameters, *i.e.* arithmetic average - Ra, mean depth - Rz (mean over five consecutive sections) and maximum depth - Rt, were considered. Surface texture parameters were chosen in accordance with ISO 4288:1996 (*e.g.* tip radius for contact measurements and cutoff wavelength value). To separate long wavelength components from short wavelength components, the Gaussian regression filter was applied to all roughness evaluations. In order to validate the proposed strategy for each measurement task, the substitution method was conveniently employed and the uncertainty associated with the measurement result used as a decision factor.

Two measurement systems based on different working principles were put into scrutiny. The first instrument was a stylus profiler (BRUKER DEKTAK XT) that scans the test sample surface by sensing the deflection of a fine stylus that is raster scanning over features ranging in height from about 1 mm down to 5 nm; thus, it is capable of measuring both step height and surface roughness. Figure 2 shows the stylus profiler during roughness evaluation of a machined sample (the measuring device is housed in a clean room at IPT's BioNanoManufacturing laboratory). The second instrument was a non-contact optical profiler (TAYLOR-HOBSON CCI) that uses a correlation algorithm to find the coherence peak and phase position of an interference pattern produced by a precision optical scanning unit; for this reason, it has dimensional and roughness measuring capability.

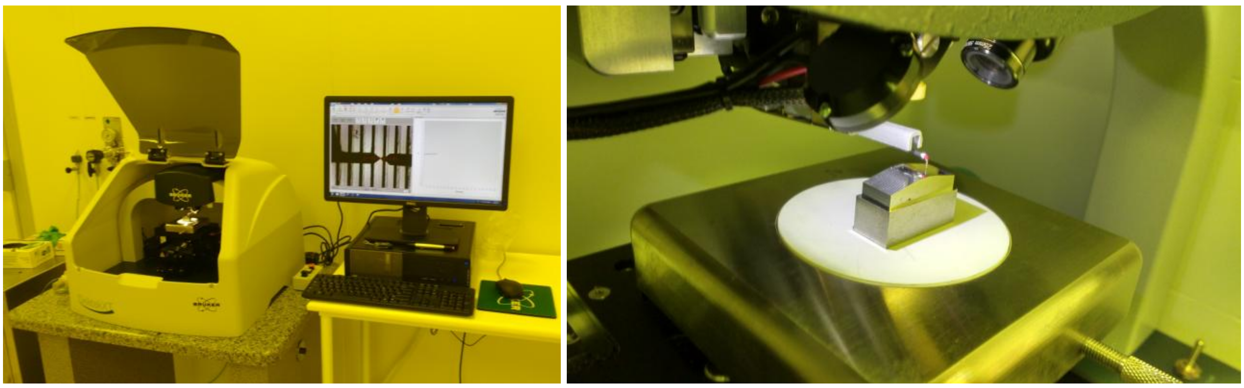


Figure 2. Stylus contact profiler (left picture) used for measuring step height and surface roughness on test samples machined on the ultra-precision machining center (right picture).

In order to investigate the measurement performance of both instruments for surface roughness evaluation, optical flats and steel gauge blocks were used as reference standards. The manufacturers specify a root-mean-square roughness (Rq) parameter less than 5 nm for the optical flats and an arithmetic average roughness (Ra) parameter less than 25 nm for the gauge blocks, which are values considerably below the expected surface roughness of the micro-machined test samples, and thus appropriate for testing the proposed measuring instruments with regard to the actual measurement application.

Despite the very smooth surface of the reference standards, on each standard n = 5 positions and k = 3 independent repeated measurements were carried out, to detect and remove outliers stemming from surface scratches and pits. Due to surface reflectivity issues related to the optical profiler, significant bias between the measurement systems was found, *i.e.* greater than the background noise, and larger measurement variability of the optical profiler was observed, in particular for the steel gauge blocks. The signal-to-noise ratio for the stylus profiler was calculated (about twice the ratio calculated for the optical profiler) and used as basis for selecting it as the reference measurement system for the actual application. Based on this measurement setup, an instrumental uncertainty of U-Ra = 5 nm (k = 2) and U-Rz = 30 nm (k = 2) was estimated, mostly dominated by the measurement bias between the two systems, though sufficient for inspecting the test samples.

3.2. Dimensional content investigation

The features of size of the microfluidic device were inspected on a multisensor coordinate measuring machine (WERTH VIDEOCHECK IP 400 3D CNC) using an inbuilt image processing unit (CCD camera), as shown in Fig. 3. The machine is housed in a temperature-controlled laboratory kept within (20 ± 1) °C at IPT's BioNanoManufacturing laboratory, thus minimizing temperature effects on the mould measurements. Diameters were realized by associating ideal features of type circle to the scanned points using the least-squares association method. Channel widths were realized by associating ideal features of type line to the scanned points on both opposite sides of the channel using the least-squares association method. In order to estimate the measurement uncertainty and hence validate the measurement setup, again the substitution technique was selected. For example, the channel width was experimentally simulated by an arrangement of gauge blocks that resemble the actual mould feature of size. Using this setup, an expanded uncertainty of U = 1 µm (k = 2) was estimated and regarded as satisfactory for the specific measuring task.

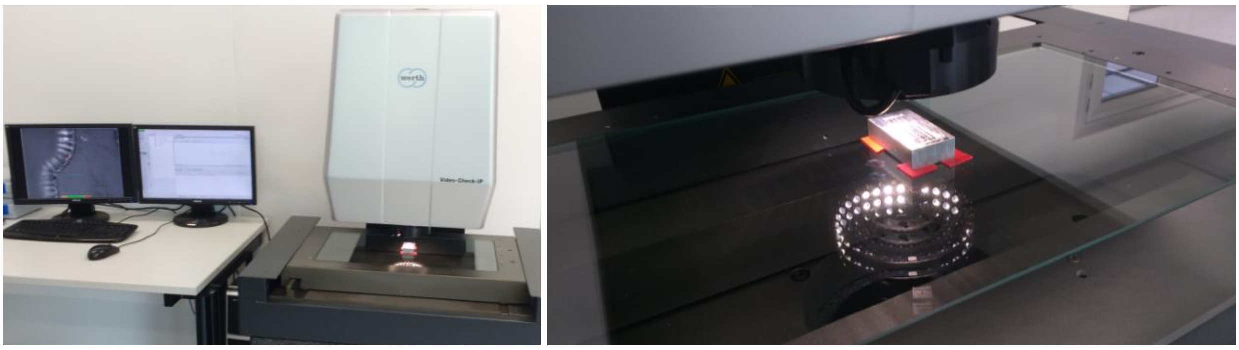


Figure 3. Multisensor coordinate measuring machine (left picture) used for checking the dimensional content of the microfluidic mould (right picture).

Regarding the channel height, preliminary tests using another arrangement of gauge blocks were performed on the same multisensor coordinate measuring machine, but employing the autofocus feature of the image processing unit. The test outcomes were not acceptable for the measuring task due to the intrinsic measurement variability and bias of the optical sensor. In fact, they just confirmed the remark made by Fleischer and Behrens (2005), who mention that the autofocus feature of optical sensors offers lower accuracy owing to dependence on the optical properties of the material. Being not able to reference the mould floor with a conventional touch probe, the stylus surface profiler was chosen to inspect the mould channel height, with uncertainty in the submicrometer range.

4. EXPERIMENTAL RESULTS

This section summarizes the experimental arrangement and the most significant findings for each measurement task previously described. Particular attention is given to the uncertainty associated with the measurement result. Subsection 4.1 describes the roughness evaluation of the stair sample surface; Subsection 4.2, the mould channel height evaluation; Subsection 4.3, the mould functional surface roughness.

4.1. Roughness evaluation of the stair sample surfaces

To identify and quantify individual random effects in a measurement so that they may be appropriately taken into account when the uncertainty of the result of the measurement is evaluated, analysis of variance (ANOVA) was used. A balanced, one-stage nested design was chosen because there is one level of nesting of the observations with one factor, the position on which points were sampled, being varied in the measurement.

On each of n = 36 steps of the stair samples, r = 3 independent repeated measurements were performed keeping the stylus profiler tip in the same position (*i.e.* without any relative transverse movement between the stylus tip and the test sample) and k = 5 measurements with minor incremental transverse movement of the stylus relative to the test sample. Measurements carried out in the same transverse position define the within-track variation; measurements carried out in different positions define the between-track variation. The consistency of the within-track variation and between-track variation of the observations could be checked by comparing two independent estimates of the within-track component of variance. The first estimate was obtained from the observed variation of the (five) within-track averages; the second, from the individual variances of (three) observations made on each track.

For the steel stair sample, the existence of between-track effect was rejected because the difference between the two estimates of the within-track variance was not viewed as statistically significant. The graph with both within-track and between-track variation is shown on the left of Fig. 4 for the mean roughness depth Rz, which clearly demonstrates the within-track variation as the dominant component. For the brass stair sample, however, the existence of between-track effect was accepted and assumed to be random. The graph with both within-track and between-track variation is shown on the right of Fig. 4, also for the mean roughness depth Rz, which clearly indicates the predominance of the between-track component of variation (within-track variation negligible).

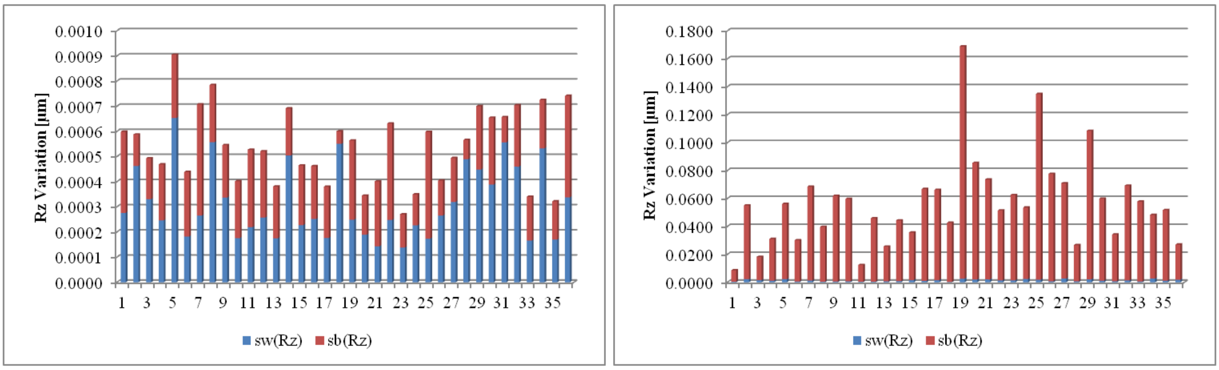


Figure 4. Within-track variation (in blue) and between-track variation (in red) estimated for each stair step - steel sample on the left plot, brass sample on the right plot. Very dissimilar variation behavior observed for each sample material. Note that the graph scales are different. Vertical axis values in micrometers.

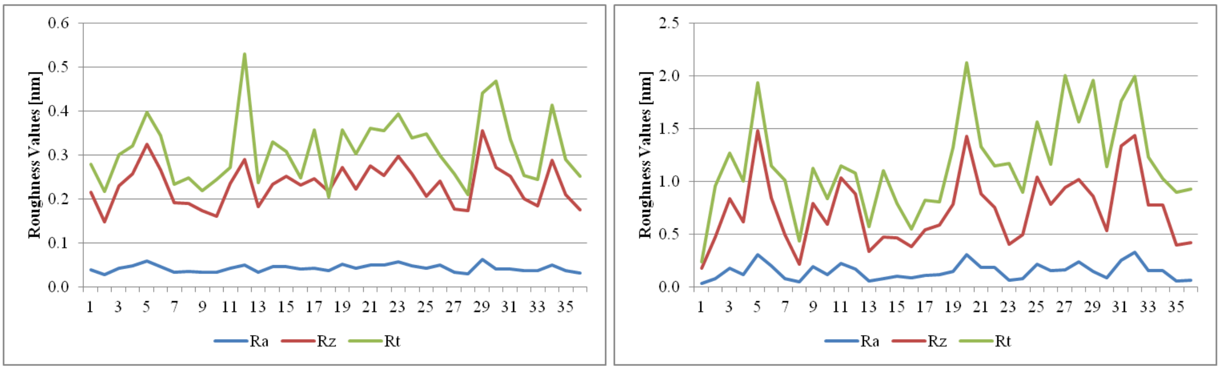


Figure 5. Line roughness parameters estimated for each steel stair sample step (left plot) and for each brass steel stair sample step (right plot); roughness values in micrometer for all 36 steps. Note that the graph scales are different. Vertical axis values in nanometers.

The best estimate of each roughness parameter for each stair sample step was determined as the arithmetic mean of all corresponding measurements; the expanded uncertainty, as the combination of the within-track and between-track standard uncertainties in a root-sum-of-squares (RSS) manner. The arithmetic average roughness Ra, mean roughness depth Rz and maximum roughness depth Rt calculated for each stair sample step are plotted on the graph shown in Fig.

5. On the left plot the results for the steel stair sample are displayed; on the right, for the brass stair sample. Note that the values for the brass stair sample are approximately five times larger than for the steel stair sample.

This latter information was very important for setting optimally the cutting conditions of the micro-milling process. Despite setting identical cutting parameters and the same micro-end mill, completely dissimilar variation behavior could be evidenced for stair test samples made of different materials. That surely needs to be conveniently handled by the simulation model for predicting the final quality of micro-milled products in terms of dimensional accuracy and surface quality.

When comparing the n = 36 steps of the stair sample, even using the arithmetic average roughness Ra the variation in roughness as changing the cutting conditions could be observed in the steel stair sample. For the planned experiment arrangement, the estimated expanded uncertainty for Ra was equal to 1 nm or 1% (indeed, Ra filtered out most the measurement variability). The other two line roughness depth parameters (*i.e.* Rz, Rt) showed more clearly the surface texture variation as varying the cutting conditions (range of about 0.3 µm), despite the higher associated uncertainty (equal to 20 nm or 5%). The same conclusions drawn for the steel stair sample were valid for the brass stair sample but with a different factor. The roughness variation for different steps was much higher than that observed for the steel stair sample. For instance, Rz and Rt results varied within a range of approximately 2 µm. Taking into account both the within-track variation and between-track variation, an expanded uncertainty of 0.4 µm or 30% could be associated with the results, which was greatly influenced by the between-track variation present on each stair sample step.

4.2. Dimensional evaluation of the mould features

With regard to microfluidic mould dimensional features, which could not be characterized with classical coordinate measuring machines with touch probes, due to the size limitation of the probing element, multisensor capabilities were explored. The image processing unit was applied to control the micro-channel width, as mentioned in Section 3. The major uncertainty contribution was the surface form variation, directly associated with the machining process, and much beyond the other uncertainty components (*i.e.* substitution method and actual experimental procedure, thus including influence factors such as machine scale errors, temperature effects on the machine and on the test sample, measurement repeatability). The large form error was an important finding of this measurement task, which was reported to the machine shop staff for adjusting the cutting parameters.

For inspecting the micro-channel height (nominal value of 300 µm), transverse tracks were sampled with the stylus contact profiler, as illustrated in Fig. 6 (four height estimates for positions P1 and P2, two height estimates for positions P3 and P4). For each track, a large amount of points were sampled on the lower surface (channel floor) and on the upper surface; the distance between the two ideal features of type straight line associated using the least-squares method was taken as the channel height. The graph shown in Fig. 6 indicates an overall height variation lower than the estimated expanded uncertainty associated with each average height - U = 1 µm (k = 2), which took into account the instrumental uncertainty and the measurement repeatability.

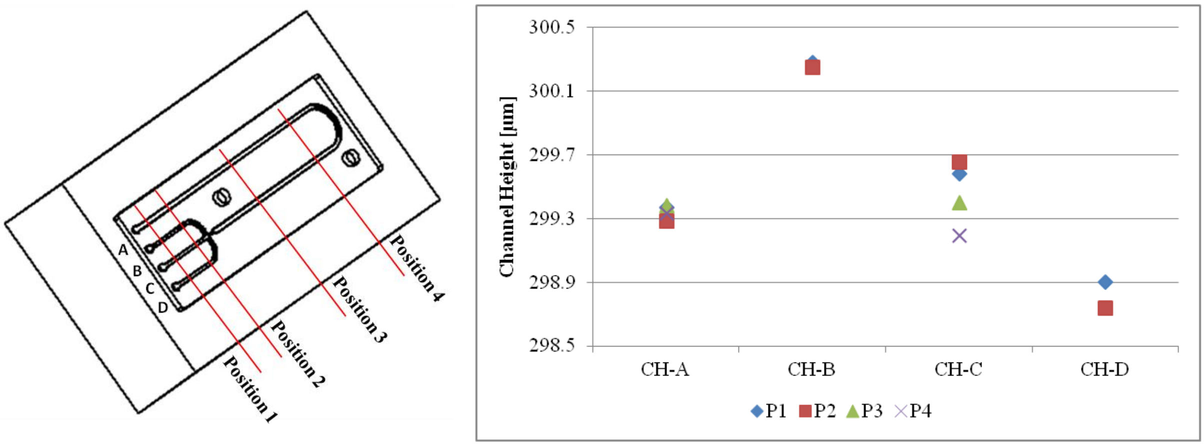


Figure 6. Designated positions for the mould channel height measurements on each channel (sketch on the left) and measurement results in each position (right plot), with expanded uncertainty of 1 µm. Vertical axis values in micrometers.

4.3. Roughness evaluation of the mould functional surfaces

Similarly to the measurement problem described in Subsection 4.1, analysis of variance was employed to determine the measurement variability. A balanced, one-stage nested design was chosen since there is one level of nesting of the observations with one factor, the location on which points were sampled, being varied in the measurement design. On each functional surface, *k* = 5 different locations and *r* = 3 independent repeated measurements were carried out using the stylus profiler. The consistency of the within-location variation and between-location variation of the observations could be investigated by comparing two independent estimates of the within-location component of variance. The first estimate was obtained from the observed variation of the (five) within-location means; the second, from the individual variances of (three) observations made on each location.

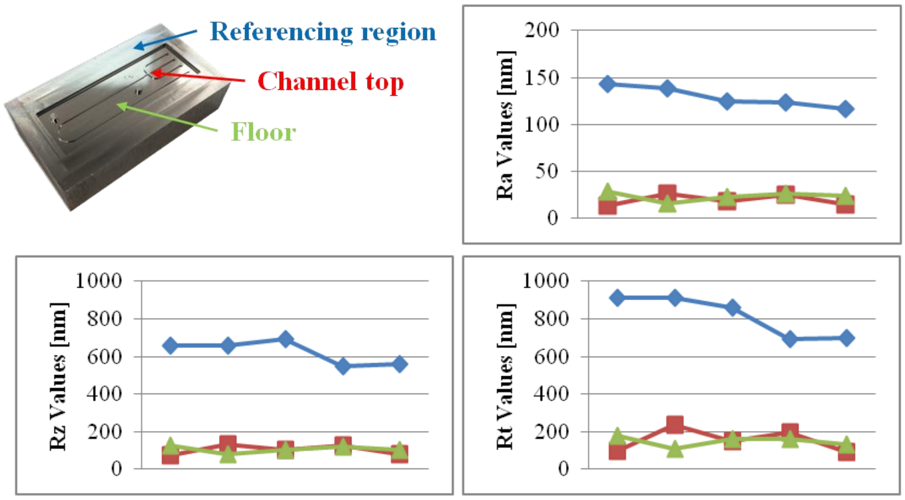


Figure 7. Roughness results for five different tracks within each of the three distinct zones of the steel mould: referencing region in blue, channel top in red, mould floor in green. Vertical axis values in nanometers.

The between-location roughness variation was much larger than the pure repeatability, which implies significantly change of cutting conditions during machining; the F-test (Montgomery et al., 2013) was used to test and confirm this statistical assumption in the referencing region, channel top and mould floor. Concerning the measurement setup, for the referencing region, the cutoff wavelength value was chosen as 0.25 mm (sampling length of same value); evaluation length and traverse length respectively as 1.25 mm and 1.50 mm. For the channel top and the mould floor, the cutoff wavelength value was selected as 0.08 mm; evaluation length and traverse length respectively as 0.40 mm and 0.48 mm. The arithmetic average roughness Ra, mean roughness depth Rz and maximum roughness depth Rt calculated for each mould zone position are plotted on the graphs shown in Fig. 7 (each marker represents the arithmetic mean of three repeated measurements). Finally, the best estimate of each roughness parameter for the mould regions was estimated as the arithmetic mean of all corresponding parameter values; the expanded uncertainty, as the combination of the within-location and between-location standard uncertainties in a root-sum-of-squares (RSS) manner (see Tab. 4).

Table 4. Expanded uncertainties (k = 2) associated with each roughness parameter average calculated for the mould regions shown in Fig. 7.

Mould region	U-Ra	U-Rz	U-Rt
Referencing region	10 nm (or 10%)	60 nm (or 10%)	100 nm (or 10%)
Channel top	5 nm (or 25%)	25 nm (or 20%)	60 nm (or 30%)
Mould floor	5 nm (or 20%)	15 nm (or 15%)	25 nm (or 15%)

5. CONCLUDING REMARKS AND OUTLOOK

This paper outlined the design and validation of measurement methods for assessing critical features on micro-scale components. For surface roughness evaluation, two measurement technologies were tested and their results compared using reference dimensional standards. The stylus contact profiler was preferred to the interferometer-based profiler because of improved overall measurement performance (*i.e.* measurement uncertainty and throughput) for the particular tasks. Outputs for both test samples, *i.e.* stair sample and microfluidic mould, were not significantly influenced by the pure repeatability, but mainly by the within-sample texture variation. That means that attention should be paid to the influence factors of the micro-milling cutting process in order to reduce that within-sample variation, particularly in the brass stair sample and steel mould.

For the dimensional content of the machined microfluidic mould, features of size such as mould channel width could be characterized on the multisensor coordinate measuring machine with good enough measurement uncertainty. However, that was not the case for the channel height, because the autofocus feature of the image processing unit could not provide reliable results (experimentally investigated with an arrangement of gauge blocks that resembled the actual measuring task), and conventional tactile sensors could not make physical contact with the mould surfaces. The stylus profiler was again identified as a possible alternative to measuring the channel height. Experiments with gauge blocks were important to validate the measurement strategy and provide robust information for estimating the uncertainty. Therefore, reliable measurement data could be supplied for micro-milling process diagnostics and improvements in the milling process have been examined to reduce surface form errors (*e.g.* by reducing tool movement spacing) and burrs along the functional geometries.

Despite the acceptable measurement accuracy of all definitive measurement strategies presented in this paper, there is room for advancement particularly with regard to the measurement throughput for dimensional features of the mould. For this reason, new measurements have been designed considering another multisensor coordinate measuring machine (WERTH VIDEOCHECK UA 400 3D CNC) outfitted with an image processing unit and fiber probe 3D (tip diameter as smaller as 20 µm), which enables nearly non-contact measurements due to extremely low probing forces. Using the full multisensor capability of that machine, reliable results could be obtained for all mould features in considerably less measuring and evaluation time. CNC programming of such a multisensor machine would be beneficial for diminishing measuring effort. Last but not least, the instrumental uncertainty would be in the order of 0.15 µm for such diminutive features as those specified for the microfluidic mould.

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