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Computed tomography as a tool for tolerance verification of industrial parts

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Abstract

Computed tomography (CT) is becoming an important technology for industrial applications, enabling fast and accurate control of manufactured parts. In only a few minutes, a complete 3D model of a part may be obtained, allowing measurements of external and internal features. This paper presents results of tolerance verification of a plastic housing for an insulin pen manufactured by Novo Nordisk A/S. Calculation of measuring uncertainties was taken into account in decision making regarding the specified tolerance limits. Variables in terms of CT systems, data sets, and evaluation software are considered in this study.

Keywords: computed tomography; measuring uncertainty; tolerance verification; Voxel model; STL model

1. Introduction

The complexity of industrial parts is increasing, while development times must be minimised. In order to meet such a requirement, a high degree of quality assurance is needed [1]. A manufacturer asks whether machined parts, or parts produced by other means, are within the specified tolerances. The results of measurements, along with stated uncertainty, form the basis for decision making regarding manufactured products. Knowledge of the measuring uncertainty is an important parameter describing the quality and the reliability of the measurement result [2, 3].

Computer tomography (CT) has recently become an accepted inspection tool for a large number of industrial applications. Using CT scanning, one can measure and examine the internal structures of

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products without destroying them. This makes the imaging technique unique and in many cases preferable to commonly used tactile or optical coordinate measuring machines (CMMs). A single CT scan yields high information density compared to any other measuring instruments, e.g., tactile CMMs. A common means of quality assurance for newly manufactured parts is a 3D geometry comparison (a so-called actual/nominal comparison), where the actual measurement of geometry by CT is compared with reference data and/or CAD data. The reference data can be obtained from measurements from a more precise measuring instrument (e.g., tactile CMM) and nominal data from a CAD model of the inspected part (see the example in Fig. 1). As a result, detailed deviations of the product are visualised. As mentioned in [4], a problem with comparisons between CT data and CAD data is that it is not known whether the deviations are associated with inaccuracies in the manufacturing process or with the CT scan itself. Therefore, calibration of the parts using a traceable measuring instrument is necessary.

The objective of the present work is to perform measurements on an industrial part using CT scanning technology. Different types of CT systems are being manufactured, each yielding different performance characteristics and, therefore, suitable for different applications (some CT systems are preferable for small parts rather than big ones, and low-density materials do not require high-power X-ray sources compared to high-density materials, and so on). It is, therefore, of interest to investigate the influence of the CT systems employed in the present work.

After the part is scanned and a 3D model reconstructed, the question of which software to use for data evaluation arises. Different software packages offer different approaches for fitting geometrical primitives, and, therefore, an assessment of measuring strategy plays a major role. Another consideration is whether the measurement should be performed on a voxel model or a surface model (also called STL). The latter generally yields poorer quality and therefore results in measuring impressions [5]; however, data saved in STL format can be easily handled by many software packages for point cloud and surface model inspection.

Due to these influencing factors in terms of machine, software, and data, the specific aims of the present investigation are assessed as follows:

- Comparison of voxel models from two CT systems (→ CT system performance comparison)
- Comparison of voxel model and STL model from each of the scanners (→ data format comparison)
- Comparison of voxel model from one CT system evaluated in two different software packages (→ software comparison)

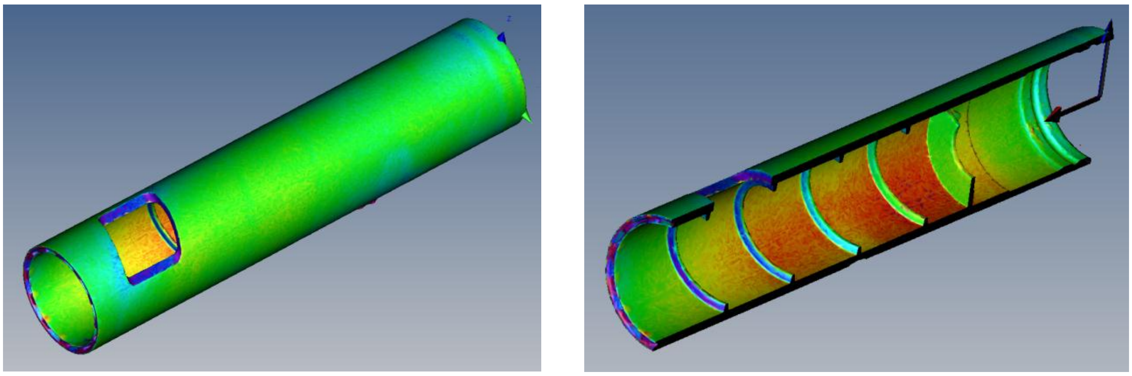


Fig. 1. A typical representation of results using the Actual/Nominal comparison using a CAD model of (a) a whole part and (b) a cut-out to identify variations inside the part

The paper is organised in the following way: a case description is presented in section 2, including a selection of measurands and variables employed in this work; section 3 describes in detail the measuring procedure for both tactile and CT measurements; the process chain for data evaluation and definition of measuring strategies is indicated in section 4; uncertainty budgets are assessed in section 5; the results are discussed in section 6; and a summary and outlook for future work are drawn in section 7.

2. Case description

2.1. Test object

The test object under investigation is the housing part of an insulin pen manufactured by Novo Nordisk A/S. As the name indicates, it houses other parts that are needed for complete function of the insulin pen as a whole. The housing was produced by injection molding and is made of polypropylene (PP). It is a medium-sized object made of material highly suitable for micro CT scanning due to its low density and, therefore, high penetrability rate (= low attenuation). Five measurands (three dimensional and two geometrical) were defined and are indicated in Fig. 2. These are: outer diameter of the housing (D) defined on the external surface of the part, inner diameter of the flange (d), distance (L) defined between the flange and the end of the housing, coaxiality (C) defined between the circular part of the flange and a cylindrical surface on the inner thread, and parallelism (P) of the flat surface on the window and a datum plane defined on the inner grooves. Nominal dimensions and related tolerances are as follows: D = 15.35 ± 0.05 mm, d = 6.4 ± 0.05 mm, L = 52.5 ± 0.05 mm, C = 0.1 mm and P = 0.2 mm. Due to a confidentiality agreement with the company, all presented tolerances are virtual and do not reflect the real tolerances of the part.

2.2. Variables

Two cone beam CT systems, Nanotom CT scanner from GE/Phoenix|x-ray and Metrotom 1500 CT scanner from Zeiss, were used for tolerance verification of the housing. Two commercial software packages, VGStudio MAX from Volume Graphics and Calypso CT from Zeiss, were used for data evaluation. Measurements in Calypso CT were performed on a voxel model, whereas measurements in VGStudio MAX were performed on both voxel and STL models. An overview of software packages and CT systems along with the acronyms used in the present investigation is provided in Table 1.

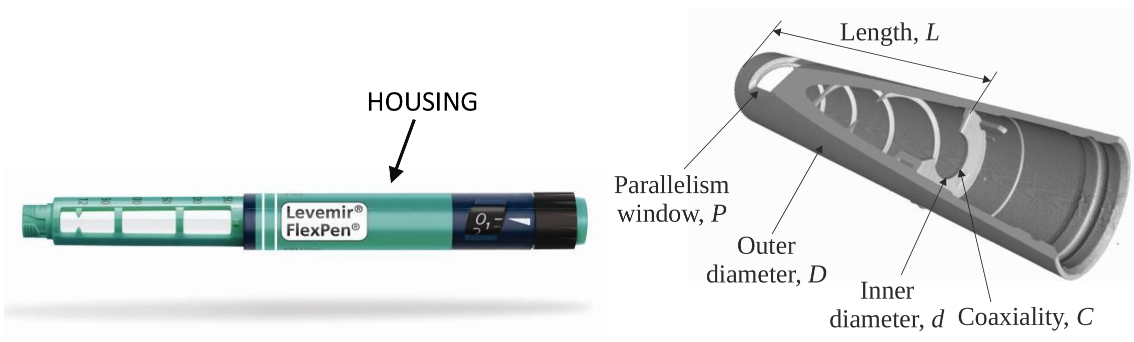


Fig. 2. (a) Insulin pen; (b) Definition of measurands

Table 1. An overview of CT systems and software packages used in the present investigation

	CT system		Software name and version	
	Nanotom	Metrotom 1500	VGStudio MAX 2.1	Calypso CT 4.10
Producer	GE/Phoenix|x-ray	Zeiss	Volume Graphics	Zeiss
Acronym	CT1	CT2	SW1	SW2

3. Measuring setup for tactile and CT measurements

The part under investigation was first measured using a tactile CMM, ensuring traceability to the unit of metre, and then CT scanned using two commercial CT scanners. Results of uncertainty calculations from reference measurements were taken into account when calculating the uncertainty from CT measurements. Results from CMM and CT measurements were not compared with each other, because two completely different measuring approaches, described in sections 3.1 and 3.2, were used. Tolerance verification, i.e., a conformity check, of the part was carried out for both tactile and CT measurements according to ISO 14253-1 [6].

3.1. Tactile reference measurements

The tactile measurements of the housing were performed using a Zeiss OMC 850 CMM. Measurements performed on the CMM were considered as reference measurements. Measurements were performed in a temperature-controlled laboratory at a temperature of 20 ± 0.5 °C. A specially built probe configuration was used, consisting of eight styli with a corresponding number of probes, including cylindrical probes, with nominal dimensions in the range 0.6 to 6.0 mm. Such a probe configuration enables measurements of difficult-to-reach features without repositioning the part. A probe of suitable size and shape was carefully assigned to a specific feature depending on the part's material, surface roughness, Young's modulus, desired resolution, and uncertainty. A total of 16 randomly chosen specimens from the production batch were measured, each part only once. As a batch, a mould consisting of 32 cavities for the housing was considered. This was done to check variation due to the manufacturing process. The data evaluation was accomplished using the Calypso 4.8 software from Zeiss.

3.2. CT measurements

Three reproduced CT measurements were realised using CT1 and CT2 on only one randomly chosen part from a production batch. The part was freely placed on polystyrene (PS), which is often used as a fixture. This is because the material's low density enables easy penetration of X-rays and does not influence the attenuation of the scanned part. However, the object has to be firmly attached to the fixture so that it does not move during rotation.

Scanning parameters, which were carefully chosen by two different operators for the two CT systems, are shown in Table 2. It can be seen from the table that both systems yield different performances. Different setting parameters are also chosen due to the scanners' distinctive designs. In particular, due to the large size of the sample, in CT1, a detector feature called "Shifting Detector" was used to enlarge the measuring area. The detector was moved in a horizontal direction to acquire two images and combine them into one, which enabled the sample to fit in the central detector area.

Table 2. An overview of scanning parameters

Parameter	Unit	Nanotom	Metrotom 1500
Voltage	kV	100	150
Current	µA	100	200
Magnification	-	2.0	3.0
Voxel size	µm	50	134
Focal spot size	µm	9.3	32.5
Integration time	ms	500	1000
No.of projections	-	720	800
Detector matrix	pixel	1152 x 1152	1024 x 1024
Pixel size	µm	100	400

Due to anisotropies in the measuring volume of the scanner, errors occur on the reconstructed model. In particular, geometrical errors from the manipulator, focus spot drift, and scaling errors of the 3D image lead to errors in voxel size and systematic length measurement. Such errors can be corrected using calibrated ball bars with known distances between sphere centres. In this case, the ball bar was scanned after each scan of the housing using the same setting parameters. The correction method using the ball bar was only carried out in connection with CT1. CT2 performs the correction of voxel size automatically.

4. Process chain for data evaluation and definition of measuring strategies

A schematic representation of the process chain for measurement of the part for the voxel model and STL model is shown in Fig. 3. The evaluation method used to fit all geometrical primitives is the least square method (also called Gaussian best fit).

After the part is scanned and reconstruction of projection images completed, a 3D voxel model is visualised using specific software. Using SW1, the surface is extracted on the part using a local adaptive threshold method. After this, measurements on the voxel and surface models are performed by defining measurands directly on the 3D models. An STL obtained from CT1 yields approximately 2 million triangles, whereas from CT2 approximately 800,000 triangles were generated using the same STL extraction method. In SW2, a CAD model with already defined measuring strategies for selected measurands is imported and aligned with the voxel model using a best fit method. The alignment is run several times to achieve a good fit. Then, the program is run in a CMM mode and results are obtained. The reconstructed voxel model from CT1 is corrected for scale errors by scanning a ball bar, with calibrated sphere-to-sphere distance. Since CT2 corrects the measuring errors automatically, no scanning of the ball bar is necessary. Symbols A–E in Fig. 3 represent combinations of variables (CT system, data set, and software), which are compared among each other according to the objectives outlined in section 1.

Due to the use of different approaches for fitting geometrical primitives on the 3D features of the part, the two software packages offer different measuring strategies. Measuring strategy is an important factor, since knowledge of number of points, measured positions, measurand definition, and fitting element is needed for a more precise interpretation of results. The influence of measuring strategies is pointed out in [7]. Table 3 presents an overview of measuring strategies used for assessing selected measurands. It can be seen that both diameters, *d* and *D*, are defined by fitting circles in SW2 and by cylinders in SW1.

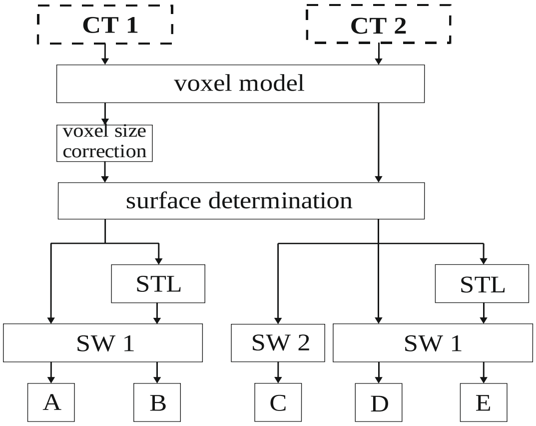


Fig. 3. Measuring procedure for data evaluation

5. Uncertainty assessment

Measuring uncertainties for both measuring instruments were calculated according to ISO 14253-2 [8].

5.1. Uncertainty estimation for tactile measurements

The measuring uncertainty for the housing was calculated according to equation 1 as follows:

$$U_{ref} = k\sqrt{u_i^2 + u_b^2 + u_e^2} \tag{1}$$

where U_{ref} is expanded uncertainty of the housing measurements by the tactile CMM, k is coverage factor ($k = 2$ for a confidence interval of 95%), u_{i} is standard uncertainty of the measuring instrument, taking into account the maximum permissible error (MPE) of the machine stated by the manufacturer $\mathrm{MPE_{CMM}}$ = 3 + L/250 µm (L in mm) (u_i = MPE/2), u_{b} is standard uncertainty of the production batch, calculated as $u_{\mathrm{p}} = s/\sqrt{n}$, where s is standard deviation of 16 randomly chosen specimens from the batch and n is number of measurements ($n = 16$), and u_{e} is temperature-related standard uncertainty calculated for a deviation of ±0.5 °C and using a coefficient of linear expansion for PP 90 x 10^{-6} °C^{-1}.

Calculation of uncertainty using MPE specification is unreliable, especially for form measurements; however, we applied an industrial approach to this task, where no calibration master piece was used.

Table 3. An overview of fitting elements for measurand assessment. Fitting elements in the brackets are assigned to datum features with respect to which the geometrical tolerances were verified

Measurand	Fitting element		
	CMM / Calypso	CT2 / SW2	CT1 / SW1
P	Plane (Plane)	Plane (Plane)	Plane (Plane)
C	Circle (Cylinder)	Circle (Cylinder)	Cylinder (Cylinder)
L	Plane - Plane	Plane - Plane	Plane - Plane
d	Circle	Circle	Cylinder
D	Circle (2x)	Circle (2x)	Cylinder

Table 4. Uncertainty budget for geometrical and dimensional CMM measurements of the housing

Uncertainty component	Symbol	Standard uncertainty [mm]				
		P	*C*	*L*	*d*	*D*
Instrument	u_i	0.002	0.002	0.002	0.002	0.002
Batch	u_b	0.008	0.004	0.004	0.002	0.001
Temperature	u_e	6.9E-06	3.3E-06	3.3E-03	4.0E-04	9.7E-04
Expanded uncertainty [mm]	$U_{ref}(k=2)$	0.016	0.009	0.011	0.006	0.004

The uncertainty budget for tactile measurements of selected geometrical and dimensional tolerances is shown in Table 4.

5.2. Uncertainty estimation for CT measurements

The measuring uncertainty for CT measurements was calculated as follows:

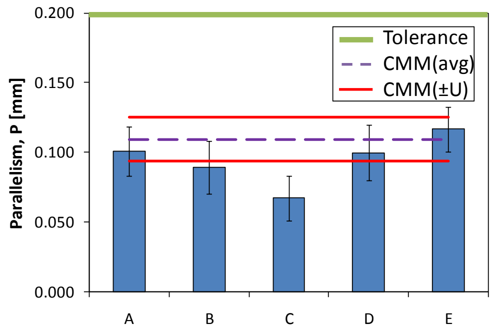
$$U_{CT} = k\sqrt{u_{ref}^2 + u_p^2 + u_e^2} \tag{2}$$

where U_{CT} is expanded uncertainty of the housing measured by the CT scanner for each measurand, k is coverage factor ($k = 2$ for a confidence interval of 95%), u_{ref} is standard uncertainty previously calculated from measurements on the tactile CMM ($u_{ref} = U_{ref}/k$), u_p is standard uncertainty of the measuring procedure for each measurand, calculated as $u_p = h(s/\sqrt{n})$, where h is safety factor ($h = 2.3$), s is standard deviation of three reproduced measurements and n is number of measurements ($n = 3$), and u_e is temperature-related standard uncertainty calculated for a deviation of ± 0.5 °C and using a coefficient of linear expansion for PP 90 x 10^{-6} °C^{-1}.

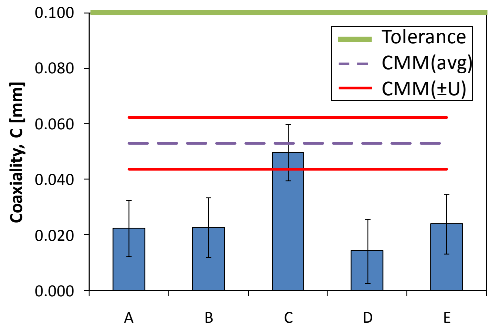
Due to the fact that a real calibration of the part was not performed, but rather an industrial approach was applied, i.e., measurements of parts from the batch without repetitions, it turned out that resulting uncertainty from the CT measurements was mainly influenced by the uncertainty component u_{ref} and was significantly higher than uncertainty of the measuring procedure in terms of reproducible measurements.

6. Results and discussion

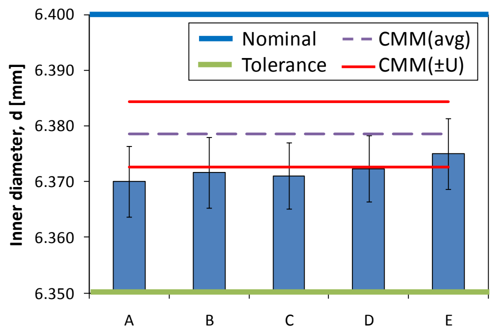
Results from measurements of the housing using CT scanning are presented in this section. The conformity check of selected tolerances was realised by measuring individual features using selected software. Results of geometrical and dimensional tolerances of the housing are plotted in Fig. 4. Each column in the figure represents an average value of three reproduced CT measurements. The error bars represent expanded uncertainty calculated according to equation 2. The designation of symbols A–E is explained in Fig. 3 and refers to a combination of variables employed in this investigation. The violet dashed lines are average values measured by the CMM on 16 randomly chosen parts from a production batch, and the red full lines show the range of expanded uncertainties calculated according to equation 1. Relatively high uncertainties were calculated for measurements of the part using CMM, with uncertainty from process variation being the dominant uncertainty component (see Table 4). On the other hand, CT measurements correspond to only one randomly chosen part (out of 16), where three reproduced measurements were carried out.



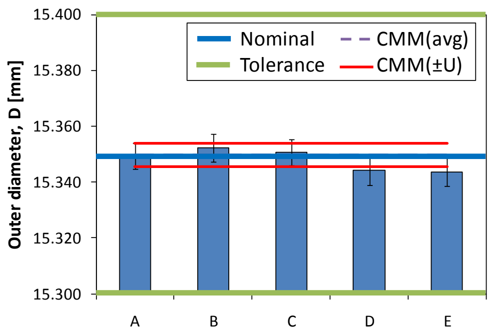
a) Parallelism



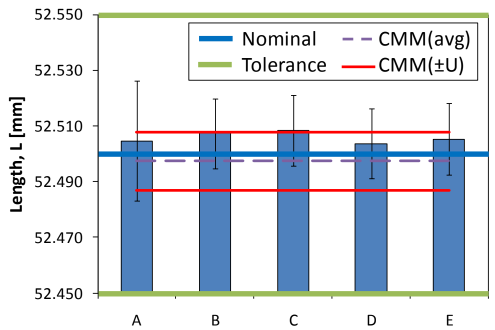
b) Coaxiality



c) Inner diameter



d) Outer diameter



e) Length

Fig. 4. Results of geometrical and dimensional tolerance analysis. Each column represents an average value of three reproduced CT measurements. The error bars represent expanded uncertainty for CT measurements at 95% confidence interval. The designation of symbols A–E is explained in Fig. 3 and refers to a combination of variables employed. The violet dashed lines are average values measured by the CMM on 16 randomly chosen parts from a production batch, and the red full lines show the range of expanded uncertainties at 95% confidence interval.

As can be seen in Fig. 4, variation of results is evident and is dependent on the chosen combination of CT system, data set, and software. Measurements of parallelism and coaxiality are totally different for voxel data processed in SW2 compared to measurements in SW1. Parallelism tolerance is found to be smaller in SW2, whereas coaxiality is much higher. The fact is that the same probing points used for measurements of the part on the CMM are also used on the voxel model in SW2. In this case, parallelism tolerance was defined by only few points taken on a flat surface in the housing window and a datum plane defined on the flat surfaces of two grooves. In contrast, coaxiality tolerance was defined by tactilely taking hundreds of points on the inner surface of the flange and a cylindrical datum surface of the inner thread using a scanning probe. Measurement of geometrical features is, therefore, considered more difficult compared to dimensional measurements.

The three specific objectives of this investigation, as they are described in section 1, are presented as follows:

- Considering the performance of both scanners (columns A and D in Fig. 4), i.e., quantitative comparison of measurements performed on the voxel models and evaluated in SW1, slightly higher values of all measurands were obtained from CT1, except for inner diameter. However, the difference was not significant; maximum deviation of approximately 5 µm was observed for outer diameter.
- Considering the comparison of two data sets, voxel model and STL model, from each of the scanners (columns A and B, and D and E in Fig. 4), all evaluated in SW1, slightly higher values of all measurands for both CT systems were obtained by measuring on the STL model. However, again, the difference was not significant; maximum deviation was observed for measurements of geometrical tolerances, namely coaxiality tolerance of approximately 17 µm. As mentioned in section 4, data sets evaluated in STL format can yield poorer quality due to the fact that measurements are performed on a triangulated surface, in contrast to measurements on the original voxel data. However, this cannot be fully concluded in this case, since there is a fairly good agreement between the two data sets.
- A quantitative comparison of the data set from CT2 evaluated in SW1 and SW2 (columns C and D in Fig. 4) resulted in significant deviations for geometrical measurements and rather small deviations for dimensional measurements. Maximum deviations of approximately 7 µm were found for the latter, resulting in a good agreement between the two software packages. One has to be aware of the fact that both SW1 and SW2 use different approaches for fitting geometrical primitives, and so individual measurands are defined differently: SW1 takes full advantage of the CT scanner capabilities, i.e., geometrical elements like cylinders, spheres, planes, and so on are fitted on the whole model surface. On the other hand, SW2 uses an approach applied to CMM, for example, a cylinder can be fitted by use of a number of circles or spirals.

Both CMM and CT measurements of the housing satisfied the manufacturer's specifications. Geometrical tolerances were found below the specified tolerance limits, and dimensional tolerances were in the tolerance range.

Measuring uncertainties were calculated generally in a range that is acceptable for CT measurements. Namely, outer diameter *D* yielded average expanded uncertainty of 5 µm, taking into account measurements using the two CT scanners, measurements performed on two data sets, and evaluation in two different software packages. Inner diameter *d* yielded expanded uncertainty of 6 µm, length, *L*, of 14 µm, parallelism, *P*, of 18 µm, and coaxiality, *C*, of 11 µm.

7. Conclusions

7.1. Summary

This paper discusses results of tolerance verification of a plastic housing for an insulin pen manufactured by Novo Nordisk A/S. Calculation of measuring uncertainties was taken into account for decision making regarding the specified tolerance limits. It was found that measurements from CMM, including 16 specimens from the production batch measured once, and CT measurements, including three reproducible measurements on a single part, fulfilled the tolerance specifications for all selected geometrical and dimensional tolerances for a number of variables applied in this work. The notion that measurement of geometrical features is more difficult and yields bigger variations was also investigated.

7.1 Outlook

In this case, i.e., in mass production where thousands of parts are produced from a single mould, calibration should be performed on a specially developed master piece, where measurements of individual features are the same as, or similar to, a real product. This approach is in accordance with procedures described in ISO 15530-3 [9], where a number of repeated measurements are performed on the calibrated workpiece, enabling the manufactured parts to be traceably verified using a CMM integrated within the production. For example, such a calibrated part was used in [10] for a number of metrological investigations. This piece is dismountable and its segments can be registered by means of regular geometries. In [11], a procedure using a calibrated aluminium test part was applied to document the effects of several system parameters, which can be influenced by the operator.

Future work will be focused on calibrated workpieces (master pieces) to investigate CT-related uncertainty contributions directly.

Acknowledgement

This paper discusses an investigation that was undertaken in the context of the Danish project "CIA-CT – Center for Industrial Application of CT scanning". The authors would like to thank Novo Nordisk A/S for kindly providing the CT scanners and use of software.

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