Distance measurements on compound workpiece with industrial computed tomography

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Abstract. More recently, the industrial CT equipment is used not only for non-destructive analysis but to perform geometrical size evaluations. The three dimensional, optical measurements made by CT are popular because the measurement time is much more less than by using traditional 3D measurement machines, furthermore the inner geometries can be determined by non-destructive manner. In this article the measurement error and uncertainty are investigated in a particular case where the test piece consists of two materials, aluminium and polymer.

1. Introduction
Dimensional metrology has an important role in the quality control of manufactured (cut, milled or turned) parts. The tolerances of the characteristics (i.e. diameter or length) of these parts are usually within the range of 0.003 mm to 0.01 mm. There are several dimensional measurement equipments which are good for the control of these specifications such as simple devices (e.g. micrometer, dial calliper) or CMM machines with tactile or optical probes. Nowadays new technologies have been developed for dimensional measurements. One of them is industrial computed tomography (iCT) metrology using X-rays [1]. The advantages of CT technique are as follows: non-contact, capability of measuring both internal and external geometries, fast scanning time [2]. Due to the automation of the measurements and the requirements concerning faster measurement processes the dimensional measurements are preferred to apply CT equipments in industrial practice [2].

The use of iCT on dimensional metrology has a lot of advantages, but it has many disadvantages [3][4]. One of the main advantages of CT is to use non-destructive dimensional testing of parts and products. In the field of metrology this non-destructive measuring technology can be used to measure internal and external dimensions that can not be achieved with traditional coordinate measuring machines without cutting the test piece. CT measurements may in some cases be faster than touch probe measurements.

There are some problems with the calibration process of dimensional iCTs. The traceability of measurement results is not standardized [5]. There are some guidelines which refer to the use of iCTs for dimensional measurements [6][6]. The disadvantages of using iCT for dimensional measurements are as follows:

- there are no accepted, uniform test procedures;
- there are complex and countless influencing factors for measurements [11];
- due to measurement errors, reduced shape measurement capability [8];
- measurement uncertainty is unknown in most cases [9] [10][12];
- there are problems to test products with compound workpieces composed of different materials [4].

Industrial CT equipments are increasingly used to determine the dimensions of geometric features (e.g. diameter, position, cylinder) in the industry. The pieces typically consist of some metal and polymers, such as a hybrid car control unit consisting of an external pressure-resistant aluminium workpiece including electronic devices. There are problems with iCT dimensional measurements performed in case of internal dimensions where two materials meet. Within this research the performance, the measurement errors and uncertainty are investigated by using compound test workpieces constructed by us.

2. Materials and methods

2.1. Test workpieces

When selecting the materials of the test piece, the main criterion was to have two types of materials that can be scanned simultaneously and separately with CT. The two types of materials chosen were aluminium and POM (polyoxymethylene). Aluminium is advantageous for testing, because it has a small beam absorption factor during the use of X-ray and is used in a lot of applications in industrial practice. The AlMgSi1 alloy was chosen because of its easy machinability, availability. The other material was POM, which is a general technical plastic, widely used in industry and is easily obtainable. The POM can be used as gears, control cams, heavily loaded sliders, as various precision gauges in the machine industry, as an insulator in electrical engineering.

The design of the aluminium part is shown in Fig. 1. It contains three cylinders with 15 mm diameter and three cylinders with 20 mm diameter. These holes were prepared by H7 reamer process.

![Figure 1. CAD model of aluminium test piece (the grid scale is in (mm))](image)

During the design of the six plastic taps the main point was that the POM taps located in the aluminium body holes should be small, but not overlapped. The tolerance is thus 0 / -0.03 mm, which can be achieved even during turning manufacturing process.

2.2. Reference measurements

The reference measurements were performed at the Dimensional Metrology Lab , Óbuda University. The measurement device was Mitutoyo Crysta Plus 544, the diameter of the probe was 5 mm (Fig. 2). The recorded measurement points were 18, 36 and 72 for each holes and taps, respectively. The measurement points were equally distributed at 3 sections parallel to the z axis.
2.3. iCT measurements

Two types of industrial CTs were used during the experiments: GE phoenix v|tome|x m (at Continental Hungary Ltd.) and Werth HV-500 (Enerswiss Hungary Ltd.). The setting parameters are in Table 1. Measurements of the GE CT data were carried out using software VGStudio Max 2.2.2 from Volume Graphics, and were calculated on voxel data. The STL file was generated by GOM 2016 software from this scanned, reconstructed image. The output of the measurements performed by Werth CT was STL file. The philosophy of Werth does not allow us to examine the voxel data, only the generated STL files as in case of other 3D measurement techniques.

The purpose of this research is to compare the performance of the two iCT, and determine the measurement error. Therefore the same type of outputs is advantageous for comparison.

![Reference measurements: a) for aluminum piece and b) for POM piece](image)

**Figure 2.** Reference measurements: a) for aluminum piece and b) for POM piece

| iCT | Materials | U (kV) | I (µA) | t_{exp} (ms) | No\_scan. |
|-----|-----------|--------|--------|--------------|-----------|
| GE  | Al        | 280    | 260    | 500          | 1800      |
|     | POM       | 250    | 250    | 500          | 1620      |
| Werth | Al    | 190    | 450    | 1000         | 800       |
|     | POM       | 120    | 250    | 1000         | 800       |
|     | Al+POM    | 190    | 450    | 1000         | 800       |

2.4. Design of experiments and evaluation method

During experiments three different measurements were performed:
- measurement of one POM tap by GE and Werth CT three times, respectively
- measurement of the aluminium test piece by GE and Werth CT
- measurement of the aluminium and POM taps assembled by Werth CT (Fig. 3)
Figure 3. Measurement of the assembled test piece by Werth iCT

The outputs of measurements are given in STL files representing results about the geometry of the taps and holes. In order to determine the measurement error of the iCT dimensional measurements it is needed to make comparisons with the reference values. During the reference measurements the diameters of the holes and taps were determined in several ways.

- In case of holes (aluminium test piece) two evaluation methods were used to calculate the diameters of the cylinders: LSC (least square or Gaussian circle) and MIC (maximum inscribed circle) evaluations.

- In case of taps (POM test piece) similarly two evaluation methods were used for the diameters of the cylinders: LSC and MCC (minimum circumscribed circle) evaluation.

These evaluation methods were used in all cases. The dimensional measurements and calculation of the diameters were evaluated by Kotem SmartProfile software. This software is able to handle the measurement points independently from the measuring device. One example for the output of the SmartProfile software is illustrated in Fig. 4.

Figure 4. Results of the evaluation by SmartProfile (Werth CT measurement for the aluminium test piece, the evaluation method is LS, the diameters and the cylindricities are given)
The reference values for the diameters of the holes and taps were determined on the basis of 18, 36 or 72 touched measurements points. For each diameter calculation two types of evaluation methods (LS and MI; or LS and MC, respectively) were used. Therefore each diameter has 6 reference values.

Additionally, the purpose of this investigation was to determine the measurement error of the iCT measurements. For this, it was necessary to calculate the iCT measured diameter minus the reference value. With the use of Smartprofile the diameters can be calculated from the STL data originated from CT scanning process. The Smartprofile software do not use all the scanned points (which is 241934 points for a certain STL file, see Fig. 5), only some of them elaborated by CMM-like sampler. This means that during the calculation and evaluation process a limited amount of the measurement points are used. For the calculation of the diameters the CMM-like sampler points were the points from the reference measurements. From this data it is possible to determine the measurement errors for the diameters, i.e. iCT measured diameter minus reference diameter (for each measurement points: 18, 36 or 72 and evaluation: LSC, MIC or MCC).

![Figure 5. Fitting of the scanned iCT point cloud to the CAD model](image)

3. Measurement results

3.1. Measurement of POM tap

The POM tap No. 6. was measured three times with GE and Werth CT. Three factors were taken into consideration, such as type of CT (two levels), number of measurement points (3 levels) and type of fitting (two levels). The main effects plot for the measurement error is shown in Fig. 6. It can be stated, that the measurement error is larger in case of GE CT comparing to Werth CT. Moreover, the type of the fitting method has a large impact on the measurement results.

The ANOVA analysis shows (Table 2) that the type of CT and the method of Fitting have large, significant impact on the measurement result, on the measurement error.

3.2. Measurement of aluminium holes

The aluminium test workpiece was measured by two CT equipments. The following factors were systematically changed during the experiments: diameter of the hole (at two levels: 15 or 20 mm nominal); type of iCT (GE and Werth); number of measurement points (for the reference measurement; 3 levels); fitting method (least squares of maximum inscribed circle). The results show (Fig. 7.) that there are negative measurement results in all cases, i.e. the measured value by the CT is less than the reference value. As a result of ANOVA analysis it is stated, that the type of CT and the fitting method have significant effect on the measurement error.
3.3. Measurement of the compound workpiece (aluminium and POM)
Finally, the diameters of the aluminium workpiece were measured in a case where the POM taps were within the holes (only in case of Werth CT). The comparison of the together (i.e. Al+POM) and the separately (only Al, previously mentioned case) measured results is given in Fig. 8. It is seen that there are large differences between the measurement error. The separate measurements have given much better results as the assembled version. It has to be emphasized that the measurement errors are up to 160 µm.

Table 2. ANOVA results for the POM tap measurement

| Source                          | DF | Adj SS    | Adj MS    | F-Value | P-Value |
|--------------------------------|----|-----------|-----------|---------|---------|
| CT                             | 1  | 0.020259  | 0.020259  | 40.52   | 0       |
| No. of meas. points            | 2  | 0.002319  | 0.00116   | 2.32    | 0.118   |
| Fitting                        | 1  | 0.008281  | 0.008281  | 16.56   | 0       |
| CT*No. of meas. points         | 2  | 0.001518  | 0.000759  | 1.52    | 0.238   |
| CT*Fitting                     | 1  | 0.008464  | 0.008464  | 16.93   | 0       |
| No. of meas. points*Fitting    | 2  | 0.002278  | 0.001139  | 2.28    | 0.122   |
| Error                          | 26 | 0.012998  | 0.0005    |         |         |
| Lack-of-Fit                    | 2  | 0.00109   | 0.000545  | 1.1     | 0.349   |
| Pure Error                     | 24 | 0.011908  | 0.000496  |         |         |
| Total                          | 35 | 0.056118  |           |         |         |
Figure 7. Main effects plot of the measurements of aluminum test piece

Figure 8. The diameters of the holes of Al test piece with Werth CT alone (separately) and together with the POM taps
4. Conclusion
During this study some preselected parameters were examined from the iCT dimensional measurement process in case of compound workpieces. From the investigations the following conclusion can be drawn:

- there are large differences between iCT equipments related to the accuracy;
- the fitting method has significant effect on the measurement error in case of tap and hole diameter measurements;
- the number of touched points for the reference measurements has not significant effect on the iCT dimensional measurement error;
- there are large difference in the measured diameter values depending on the type of test workpieces (one material or two materials).

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