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A testpart for interdisciplinary analyses in micro production engineering

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Abstract

In 2011, a round robin test was initiated within the group of CIRP Research Affiliates. The aim was to establish a platform for linking interdisciplinary research in order to share the expertise and experiences of participants all over the world. This paper introduces a testpart which has been designed to allow an analysis of different manufacturing technologies, simulation methods, machinery and metrology as well as process and production planning aspects. Current investigations are presented focusing on the machining and additive processes to produce the geometry, simulation approaches, machine analysis, and a comparison of measuring technologies. Challenges and limitations regarding the manufacturing and evaluation of the testpart features by the applied methods are discussed.

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Keywords: Micro Production Engineering; Testpart; Round Robin; Micro Milling; Additive Manufacturing; Metrology; Computed Tomography

1. Preface

Within the Research Affiliate network of the International Academy for Production Engineering, CIRP, a round robin test was initiated in 2011 and started in 2012, involving participants from all over the world. The goal of this initiative is to join interdisciplinary research activities and to provide a framework for the collective development and comparison of technologies. For this round robin test, a testpart was proposed which can be used to investigate various manufacturing processes (also regarding different part materials and sizes), machinery, simulation approaches, monitoring strategies, and metrology. It can also be applied for the comparison of different technologies with respect to energy consumption and resource efficiency. Starting with the task of programming the considered processing operations and ending up with the need to measure the features of interest, this testpart implicates some challenges which have to be solved with individual approaches.

This paper introduces the *pc-testpart* and describes current collaborative work using this testpart for several

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investigations with respect to micro production engineering.

2. Introduction of the pc-testpart

The geometry of the testpart (22.6 mm x 15 mm x 3 mm) is shown in Fig. 1. The elements of the testpart partly consist of thin-walled sections with a thickness of 0.1 mm and grooves having a width of 0.6 mm.

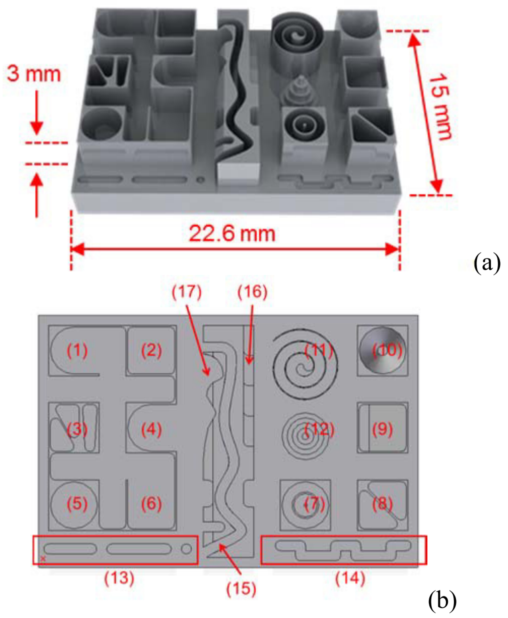


Fig. 1. (a) CAD model of testpart; (b) top view with numbered features

Different process technologies (e.g. 2½D or 3D milling, EDM, generative processes) can be applied for manufacturing the testpart. The analysis of how to produce the part starts with process planning, programming and simulation. It includes process characteristics as well as workpiece and machine behavior. Finally, measuring strategies have to be developed for accuracy and surface assessment. The following criteria are observed in the round robin test:

- Ability to produce the testpart features
- Shape of the elements and geometric part accuracy
- Surface quality
- Machine and process influences
- Time needed for manufacturing
- Time and effort for process setup
- Energy consumption
- Repeatability of the manufacturing result
- Time, effort and accuracy of measuring methods
- Additional effects (e.g. burr formation)

When machining the testpart elements, some technical challenges occur, which at the same time constitute objects of investigation (table 1).

Table 1. Elements of the testpart and aspects for milling

1-10	basic cubes are arranged regularly; machine accuracy can be assessed by a deviation grid
1-11	thin-walled elements tend to vibrate; open and closed profiles behave differently
1, 4, 5, 7, 10, 12	circular interpolation can be used; circularity deviation can be compared
2, 3, 5, 7, 8, 9, 10	appropriate immersion strategies are necessary
2, 3, 8, 9	different and difficult engagement situations occur
9, 10	machining of datum plane is challenging; beveled geometry can be machined with different strategies
11	archimedean spiral requires special programming, interpolation and dynamic path accuracy
12	pyramid planes can either be machined consecutively or interrupted by other machining tasks to investigate repeatability and thermal influences (see also 16)
13, 14	grooves require immersion and path accuracy
11-17	acceleration and deceleration behavior of the machine can be analyzed
15	sine sweep requires special programming and dynamic path accuracy
16	steps can be used to analyze positioning accuracy, repeatability and thermal influences
17	outer profile can be used to analyze acceleration and deceleration behavior of the machine; different engagement situations occur

An application of semantic associative GD&T conforming to the latest STEP AP242 data format and the GPS standards to describe the testpart has been performed using IDA-STEP software (by LKSoftWare GmbH) at KTH Stockholm, Sweden (Fig. 2).

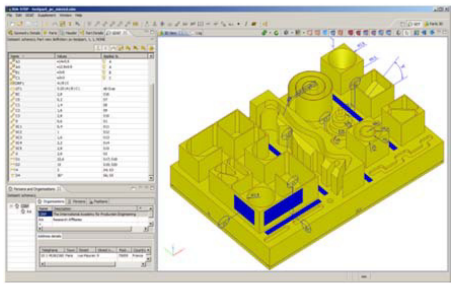


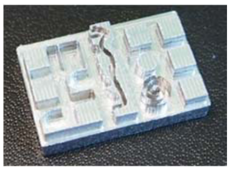
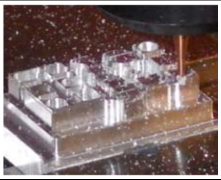
Fig. 2. ISO 10303-242 STEP based integration of semantic GD&T, lightweight shape tessellation, process plan and inspection results.

3. Micro part production

In this paper, investigations with respect to micro production engineering are presented. In particular micro milling and additive manufacturing are analyzed. For this, different equipment is applied. An analysis of produced parts and a comparison of computed tomography (CT) measurements are conducted.

3.1. Micro milling

Micro milling was applied by ISF, IFQ and Sabanci Univ. (Fig. 3). Mainly Al7075 was chosen but also other workpiece materials were used.

ISF (a)		
	Al7075	HS steel (1.3343, 63HRC)
	a_p = 0.02 to 0.05 mm a_e = 0.025 to 0.1 mm f_z = 0.01 mm v_c = 78 to 157 m/min n = 50,000 min^{-1}	a_p = 0.008 to 0.025 mm a_e = 0.015 to 0.6 mm f_z = 0.006 to 0.025 mm v_c = 80 to 120 m/min n = 50,000 min^{-1}
	KERN HSPC 2522, Heidenhain iTNC 530, (Ball)-end milling cutter, d = 1 and 0.5 mm, z = 2, HC, TiAlN, down milling, oil	
IFQ (b)		
	Ureol	Al7075
	$a_{p,max}$ = 0.6 mm a_e = 0.3 – 0.6 mm v_f = 420 mm/min n = 42,000 min^{-1}	a_p = 0.1 mm $a_{e,max}$ = 0.5 mm v_f = 100 mm/min n = 42,000 min^{-1}
	Mikron HSM700, Heidenhain; nano-coated solid carbide tool: z = 2, d = 0.6 mm, dry	µ-milling test rig, air spindle, transl. stages PI-M605 (int. contr.); dry, z = 2, d = 0.5 mm
Sabanci Univ. (c)		
	Al7075, KERN Evo, Heidenhain iTNC 530	

	Roughing		Finishing	
tool	Solid Carbide		Solid Carbide	
z	2	2	2	2
d (mm)	1.5	1	1.5	1
coolant	wet	wet	wet	wet
a_p (mm)	0.075	0.05	0.075	0.05
a_e (mm)	0.3	0.3-1	0.3	0.3-1
v_f (mm/min)	1040	480	1040	480
n (min^{-1})	26,000	20,000	26,000	20,000

Fig. 3. Exemplary testparts produced by micro milling

Sensitive milling tools with diameters down to 0.5 mm were applied. Due to the different stiffness values of the workpiece features, bending of the tools or deflections of the workpiece could lead to geometric deviations of the final part. A high precision regarding the concentric run-out of the milling spindle is necessary. Otherwise the thin-walled elements of the part are destroyed. Chip removal also has a significant influence on the integrity of the workpiece elements. Due to the high penetration depth, insufficient chip removal also provokes extensive process forces and tool breakage. Depending on the milling strategy and tool wear condition, burr formation but also burst occur at the upper edges of the features. The interpolation and path accuracy affects the complex curved thin-walled elements, especially the spiral.

An additional experiment was implemented at the IFT in Vienna in terms of the ultrasonic assisted machining of a testpart in glass (Fig. 4).

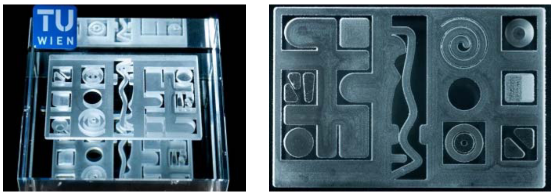


Fig. 4. Glass testpart, produced by ultrasonic assisted machining

3.2. Additive manufacturing

Univ. of Twente (a)		Berkeley (b)	
KU Leuven (c-g)	Stratasys Dimension SST 1200es, CAD/CAM: CatalystEX scale 1:5	 (c)	
	Stratasys Dimension SST 1200es, CAD/CAM: CatalystEX scale 1:1	 (d)	
	Thing-O-Matic, CAM: ReplicatorG, scale 1:5, layer resolution 0.3 mm, errors due to software	 (e)	
	Replicator 2x, CAM: ReplicatorG, scale 1:5 layer resolution 0.2 mm, improved slicing and hatching software leads to better result	 (f)	
	Replicator 2x, CAM: ReplicatorG, scale 1:5 layer resolution 0.1 mm, a double number of layers improves the part resolution	 (g)	

Fig. 5. Testparts produced by additive manufacturing

Various micro testparts were produced by KU Leuven, Univ. of Twente and the Joint Center for Artificial Photosynthesis Lawrence Berkeley using additive manufacturing (AM) processes. In particular Selective Laser Melting (SLM) and Fused Deposition Modeling (FDM) with ABS (thermoplastic polymer) were applied. A testpart made of Ti6Al4V was generated utilizing a SLM280HL machine (SLM Solutions GmbH) at the Dutch National Aerospace Laboratory. This testpart is inclined by 45° and built with a layer thickness of 50 µm (Fig. 5a). Regarding FDM, several machines are tested and compared: a STRATASYS Dimension SST1200es with a typical layer resolution of 0.254 mm, a MAKERBOT Thing-O-Matic and a MAKERBOT Replicator 2X, both with a typical layer resolution of 0.3, 0.2 or 0.1 mm (Fig. 5c-g). Due to the limited resolution, the testpart has to be scaled up by a factor of five to allow its manufacturing by FDM. For the AM-FDM systems, the CAD data is converted into the STL format. Limits regarding the capability to produce the thin-walled features appear mostly due to the resolution in the plane.

4. Simulation of the milling process

Additional to the real manufacturing of the testpart, the micro milling process was also simulated within this round robin test. In Fig. 6a the deviations of the aluminum workpiece shown in Fig. 3a measured by metrological CT scanning at University of Padova (see chapter 6) is presented. Most of the elements were machined in a suitable quality (see green color in Fig. 6a), but there were problems during the machining of the marked feature (red and blue). Within the round robin test, a primary analysis was conducted to evaluate the machining of this workpiece element (Fig. 6b).

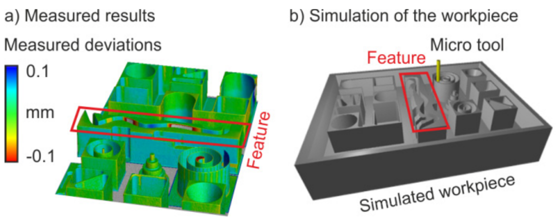


Fig. 6. (a) Measured results of the Al part; (b) Simulated workpiece

The used time-domain simulation system [1] was developed at the Institute of Machining Technology (ISF, Dortmund, Germany). This system is able to model the material removal process using the Constructive Solid Geometry (CSG) technique [2] in order to calculate the chip shape. Based on the analysis of the determined chip thicknesses, the cutting forces can be predicted using an empirical force model [3]. For the visualization of the workpiece surface, an additional dexel-based modelling technique is used. Taking modal parameters of the tool, workpiece, or machine into account, the simulation system is also capable of analysing the process dynamics during the NC milling process.

In Fig. 7 and Fig. 8, measured and simulated results of the feature marked in Fig. 6 are presented. The measurement results show that there is a relatively good machining quality on side 1 (Fig. 7a), but there are machining errors on side 2 of the element (Fig. 8a).

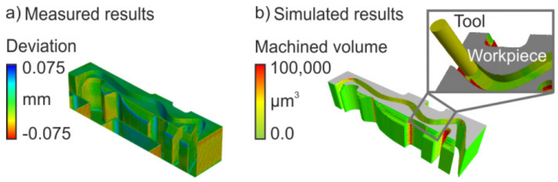


Fig. 7. Comparison of measured and simulated results of side 1.
(a) Measured deviations; (b) Visualization of the simulated machined volume

In order to analyze these effects, the machined volume simulated by the time-domain milling simulation is visualized directly onto the workpiece surface using different colors on the dexelboards (Fig. 7b, Fig. 8b).

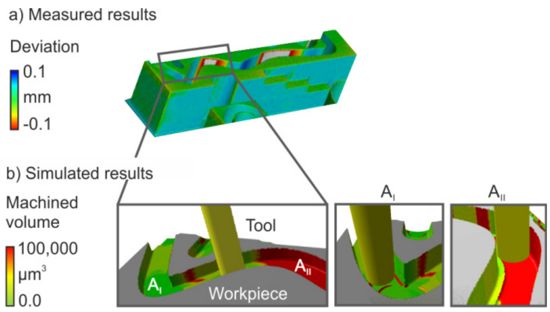


Fig. 8. Comparison of measured and simulated results of side 2.
(a) Measured deviations; (b) Simulated engagement situations.

It is clearly visible that the machined volume per tooth feed is much higher on side 2 than on side 1. Looking at the engagement conditions, side 2 is – in contrast to the machining of side 1 – machined with a fully immersed milling tool (A_{II} in Fig. 8b). This corresponds directly to higher cutting forces during the machining of side 2 and, therefore, resulting in the measured machining errors. This information can be used in order to optimize the milling process by adapting the NC programs and, thus, the machining outcome.

5. Machine analysis

The testpart can also be used to investigate the controlled kinematic accuracy of the applied machine tool and to observe thermal influences in terms of indirect testing. For this, the assessment of the testpart features at different steps of the overall machining process is essential. Whereas milling of the stepped features provides information about thermal effects, the compliance of the tool and the changing stiffness of the workpiece elements have to be considered when analyzing the produced part geometry. Shape deviations can result from the machine and control behavior (Fig. 9b), tool bending and part deflection. The process simulation described above can provide the necessary information to separate these effects and to identify the machine influence. The arrangement of the workpiece elements as evenly distributed cubes (Fig. 9a and b) together with measurement results regarding a displacement, rotation and tilting of these cubes allows gathering machine calibration information with respect to volumetric error compensation and calibration model parameter identification.

For machining the aluminum part shown in Fig. 3b a micro milling test rig presented in Fig. 9 was used. A calibration model for such a device can e.g. be obtained by splitting the kinematic structure and representing each machine axis by a local coordinate system CS_i (where CS_0 is the base coordinate system) as shown in Fig. 9c. The relative positions of the local coordinate systems among themselves and referred to CS_0 can be described by transformation matrices containing translational displacements and rotational matrices. By parameterizing these transformations, error influences can be computed and the resulting path and machining inaccuracy can be calculated (Fig. 10). Vice versa, measured deviations at the testpart can be used to identify the model parameters which describe the real behavior of the machine.

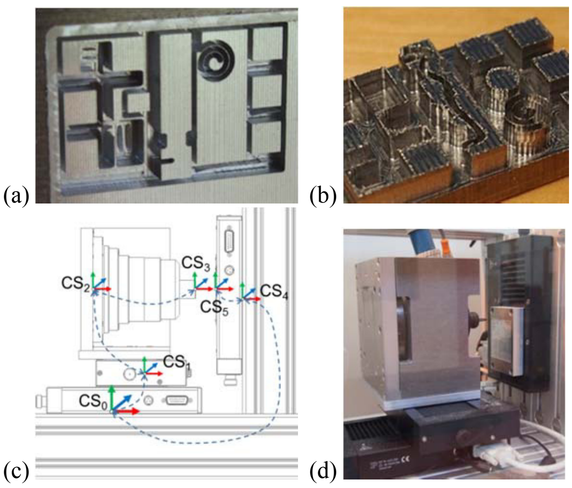


Fig. 9. (a) machined features manually programmed; (b) features machined by primary MATLAB-based CAM interpretation; (c) machine model; (d) micro milling test rig

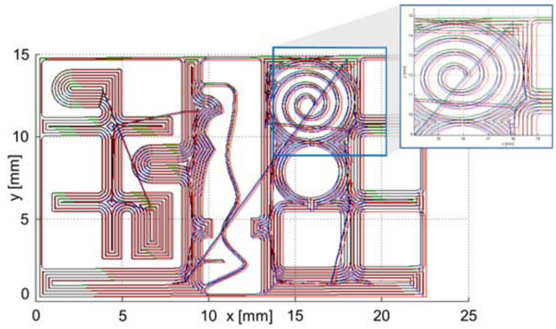


Fig. 10. Calculated path deviations (the colored paths show the influences of different error parameter settings)

6. Metrology and measuring of produced parts

The complex geometries of the parts and its micro features make it especially challenging in terms, not only of manufacturing, but also of measurement and dimensional evaluation. The features to be evaluated are in the range of a few millimeters or even below that, with access difficulties and, in some cases, with parts made of soft materials that could be deformed by tactile measurement. Moreover, the different materials and surface characteristics of the parts (ranging from reflective metals to rough and translucent surfaces) are not suitable for optical measurement techniques in most cases. All this makes Computed Tomography (CT) a very appropriate technology for the measurement of the parts produced in this study.

6.1. Materials and methods

As explained before, different parts from different materials and by different processes were manufactured for this study. Some of these micro parts (detailed in table 2) were measured by CT techniques in order to evaluate some of their dimensions. Two different CT measuring systems were used to measure the parts: (1) one placed at the University of Padova and (2) another one at the University of Zaragoza.

(1) The CT-Padova machine is a high accuracy metrological CT system, Nikon MCT225, with a maximum X-ray source voltage of 225 kV, an X-ray spot resolution of 3 µm (micro focus), a temperature controlled enclosure (20±1 ºC), high precision linear guideways and metrological characteristics monitored according to VDI/VDE guidelines [5].

(2) The CT-Zaragoza machine is a General Electric eXplore Locus SP cone-beam micro-CT machine. Its X-ray source voltage range is between 50 and 90 kV, the maximum resolution or minimum voxel size of 8 µm. During the scanning of the working part the temperature is recorded inside the machine, obtaining a temperature

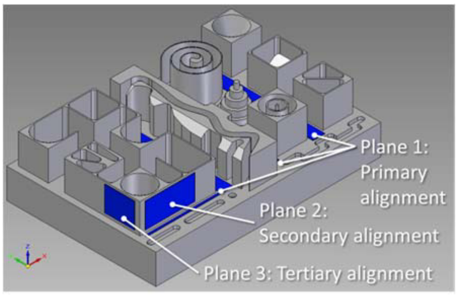
range of 20±2 ºC. In the measurements taken with CT-Zaragoza two different techniques were applied for the surface extraction to perform the measurements: (a) CT1, based on the local threshold method [6]; (b) CT2 based on the 3D Canny method [7]. The maximum permissible errors (MPE) obtained for CT1 and CT2 are respectively: MPE_{CT1} = 7.2 µm + (L/6.8) µm (L in mm) and MPE_{CT2} = 7.0 µm + (L/5.7) µm. In table 2 the distribution of the parts measured by each of these machines is shown.

Table 2. Distribution of parts measured

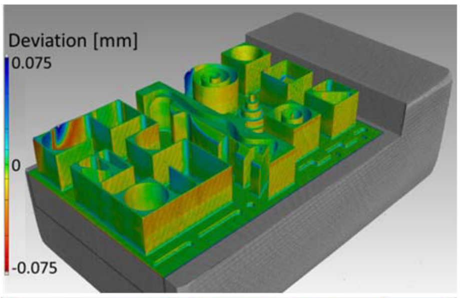
Part code: material (manufacturer)	CT-Padova	CT-Zaragoza
UR1: Ureol 1 (IFQ)	X	
UR2: Ureol 2 (IFQ)	X	X
AL1: Aluminum thick (ISF)	X	X
AL2: Aluminum thin (Sabanci U.)	X	X
AM1: Additive Manuf. Ti (U. Twente)	X	X
AM2: Additive M. FDM/ABS (Leuven)	X	

6.2. Datum, features and dimensions

(a)



(b)



(c)

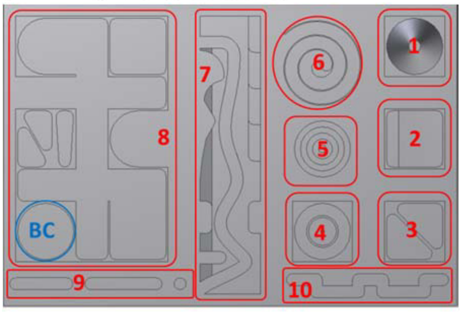


Fig. 11. (a) Reference surfaces of the CAD model for aligning the entire part; (b) Example of CAD comparison with the global alignment on datum reference surfaces; (c) Features coding

All measured parts are compared to nominal CAD in two different ways: firstly, a global alignment of the entire part, using the datum reference planes defined in Fig. 11a. This alignment allows a global overview of the part accuracy. Secondly, an alignment of each single feature to the corresponding CAD portion representing the single nominal feature. This second alignment allows better evaluation of the accuracy of each single feature (independently from the relative position of the features). The features of the part are coded as shown in Fig. 11c. Some of them are selected for evaluation of their dimensions:

- Feature 1 (cone): base diameter (D); top diameter (d); height (H).
- Feature 2 (tilted plane): angle (A).
- Feature 4 (four cylinders): diameters (C0, C1, C2, C3), being C0 the smaller (external), and C3 the larger (internal).
- Feature 5 (five step cylinder): diameters (SC1 to SC5), being SC1 the smaller (on the top) and SC5 the larger (at the bottom).
- Feature 8 (cylindrical hole): diameter (BC)

6.3. CT measuring results

The dimensions were measured by the CT-Padova, and the CT-Zaragoza using CT-1 (i.e. segmentation based on local threshold) and CT-2 (i.e. segmentation based on Canny adapted). The results obtained by these three systems are compared, both to the CAD, in order to check possible manufacturing errors, and between them, in order to check the robustness of the measurements. In table 3 the results for part AL1 are shown as an example.

Table 3. Measuring deviations with respect to the nominal values (bias) of the dimensions of AL1 as a percentage of the nominal value

Measurand	CAD nominal value (mm)	CT-Padova Error (%) w.r.t. CAD	CT-Zaragoza CT-1 Error (%) w.r.t. CAD	CT-Zaragoza CT-2 Error (%) w.r.t. CAD
D	0,600	-1.7%	-7,0%	2,0%
d	2,800	0.0%	-0,3%	-1,5%
H	3,000	0.0%	-1,1%	-0,3%
SC1	0,400	-2.6%	-15,0%	-2,7%
SC2	1,000	-0.4%	-1,5%	-0,7%
SC3	1,600	0.0%	-0,1%	-0,3%
SC4	2,200	-0.2%	-0,3%	-0,4%
SC5	2,800	-0.1%	-0,4%	-0,3%
C0	0,200	-6.4%	-20,5%	-7,2%
C1	1,400	-1.5%	-0,9%	-0,5%
C2	1,600	0.1%	-0,9%	0,2%
C3	2,800	-0.6%	-0,9%	-0,4%
BC	2,800	-0.4%	0,4%	-0,9%
A (º)	36,000	0.0%	-0,5%	0,1%

Differences between the CT measurement results obtained by the different CT systems are due to several reasons. A first cause is the different metrological capabilities of the CT systems used: while CT-Padova is a metrological system, CT-Zaragoza is a conventional scanner, which can anyhow reach sufficiently accurate results thanks to fundamental correction methods [8]. A second reason is due to the different techniques used for surface extraction. Other reasons for CT measurement uncertainty are reported for example in [9].

Most of the manufacturing errors (difference between measured and nominal dimensions) are below 1% the nominal value of each dimension. Just in some cases these errors are sensibly higher, especially in SC1 and C0. Both measurands correspond to very thin and slim micro features difficult to manufacture. In both cases large form errors can also be observed. In Fig. 12b the case of C0 is shown as an example of this fact, where it can be observed the form error of the cylinder (thicker at the bottom and thinner on the top). As another example of the ability of CT techniques to evaluate dimensions and form errors in this sort of micro parts Fig. 12c and Fig. 12d show the results obtained for C0 in the AM1 part. This part was made out of Titanium by additive manufacturing. In this case the CT techniques clearly show the lack of uniformity in the surface, form and dimensions obtained.

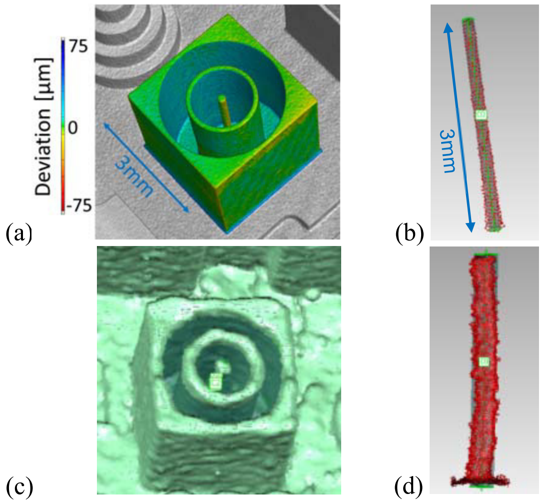


Fig. 12. (a) AL1 part measured by CT-Padova: feature 4 (including C0) local CAD alignment; (b) AL1 part measured by CT-Zaragoza: points cloud obtained from the CT scan that shows the form error of C0; (c) AM1 part measured by CT-Zaragoza: feature 4 (including C0) 3D volume reconstructed; (d) AM1 part measured by CT-Zaragoza: point cloud obtained from the CT scan that shows the form error of C0.

7. Summary and outlook

This paper presents a testpart for a round robin test within the CIRP Research Affiliate network and its application for investigations with respect to micro production engineering. The testpart provides some challenging features regarding the ability of different manufacturing technologies to achieve an acceptable part shape. The performance of the analyzed additive processes is limited regarding the necessary resolution. On the other hand, in micro milling tool and workpiece deflections occur depending on the local workpiece stiffness and the material to be removed. These deflections become visible by geometric deviations of the part features. Machine accuracy and control quality can also be analyzed. A combination of simulations, machine analysis and appropriate measuring allows a separation and identification of the influences. CT measurements show their capability to evaluate the testpart comprehensively. However, also limits of the applied devices and strategies can be observed.

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