The application of micro computed tomography to assess quality of parts manufactured by means of rapid prototyping

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Abstract: In the paper a possibility of using a metrology micro computed tomography (CT) to assess quality of parts made by rapid prototyping technique was presented. Additive manufacturing techniques dramatically change the approach to manufacturing process. Not long ago they allowed solely for obtaining a spatial model of a part in order to visualize its features. Nowadays, it is possible to produce elements and assembly groups with properties that make it possible to replace many parts manufactured using traditional casting or injection techniques. Polymer components created by means of 3D printing can be generated one layer of material after another. In many cases inner spaces (sections) are not fully filled in (solid), they are rather replaced by a specially selected structure. Thanks to this it is possible to save material and reduce weight. To control these structures and to inspect joints between particular layers using a non-destructive method it is necessary to use a metrology micro CT. In the paper an application of X-ray computed tomography and assessment of measurement uncertainty regarding elements manufactured with fused deposition modeling (FDM) method using ABS 3D printing on UP! printer was presented. Inspection of both: inner structure and outer shapes as well as joints between them was performed basing on computer aided design (CAD) model.

Keywords: computed tomography, uncertainty of measurements, rapid prototyping.

Zastosowanie tomografii komputerowej do oceny jakości elementów wykonanych metodą szybkiego prototypowania

Streszczenie: W pracy przedstawiono możliwość zastosowania pomiarowej tomografii komputerowej (CT) do oceny jakości elementów wykonanych techniką szybkiego prototypowania. Techniki wytwarzania addytywnego rewolucjonizują podejście do technik wytwarzania. Jeszcze niedawno pozwalały jedynie na uzyskanie przestrzennego modelu w celu jego wizualizacji. Obecnie możliwe jest uzyskanie gotowych elementów o właściwościach pozwalających na zastąpienie wielu wyrobów wykonywanych tradycyjnymi technikami odlewania lub wtryskiwania. Elementy polimerowe uzyskiwane za pomocą druku 3D wytwarzane są przez nakładanie kolejnych warstw materiału. W wielu wypadkach wewnętrzne przestrzenie (przekroje) elementu nie są całkowicie wypełnione, ale są zastępowane przez odpowiednio dobraną strukturę wewnętrzną. Pozwala to na oszczędność materiału i redukcję masy elementów. Kontrola jakości tych struktur, jak i połączeń pomiędzy poszczególnymi warstwami, jest możliwa w sposób nieniszczący jedynie za pomocą pomiarowej tomografii komputerowej. Metodę rentgenowskiej tomografii komputerowej zastosowano do oceny niepewności pomiaru elementów wykonanych z ABS techniką osadzania topionego materiału (FDM) z zastosowaniem drukarki UP! 3D. Dokonano badania i oceny na podstawie modelu projektowanego ze wspomaganiem komputerowym (CAD) z uwzględnieniem zarówno powierzchni zewnętrznych, jak i wewnętrznej struktury oraz połączeń pomiędzy poszczególnymi elementami.

Słowa kluczowe: tomografia komputerowa, niepewność pomiarów, szybkie prototypowanie.

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Coordinate measuring technique has been continually developed for about fifty years. It comprises different techniques and measurement devices, operating in 2D and 3D. A two-dimensional measurement is possible for example on a measuring microscope or optical machines. The most widely used are instruments that enable to inspect parts in three dimensions (space). Here, the best known are coordinate measuring machines (CMM) and measuring arms [1, 2]. For about 15 recent years optical devices are more and more commonly applied (*e.g.*, scanners using different light patterns). All these instruments have a common feature – they are suitable for measuring elements, where it is possible to make contact with a surface (tactile methods) or to observe it (contactless method). Still, they do not allow to inspect geometry of inside – invisible elements, without destroying the part [3–5]. An alternative device to that is an X-ray tomograph. In medicine they are known from 70-ties of XX century, but in mechanical engineering applications they are used for last couple of years. Apart from surface that can be measured with more traditional instruments they allow to inspect closed spaces as well as assess quality of assembly and functionality of groups in ready mechanisms [4, 6].

COMPUTED TOMOGRAPHY

An expression tomography comes from Greek words "tomé" (section) and "gráfein" (write). As a combination of projections of a measured object executed from different directions it is possible to create section images (2D) and spatial images (3D). Analysis and working out of particular projections is performed by means of a computer – hence the name computed tomography (CT). Mathematical bases of this invention were made by an Austrian mathematician Johann Radon, who in 1917 proved that an image of two- and three-dimensional object can be reconstructed in a total from infinite number of projections of the same part [7].

Metrology tomography is a kind of X-ray tomography. The first computed tomograph enabling to obtaining an image of inner structure was elaborated between 1969 and 1972 by Godfrey Newbold Hounsfield. Its production version was released to the market in 1973 and – due to a company that sponsored the whole project – is known as EMI Scanner. Hounsfield was given a Nobel Prize in medical sciences for his achievements in 1979 [8–10].

A basic way of inspection is to focus an X-ray beam onto an object and registering its intensity on a detector on the other side. X-ray beam, crossing an inspected object, loses its power, and this weakening is a function of radiation energy as well as the kind and thickness of the inspected material. The volume of material is divided into small elements, called voxels, in which linear coefficient of radiation absorption is the same. A reconstructed section image is a quantitative map of a linear radiation absorption coefficient in voxels, being a part of a scanned layer. Creation of a tomographic image is illustrated in Fig. 1.

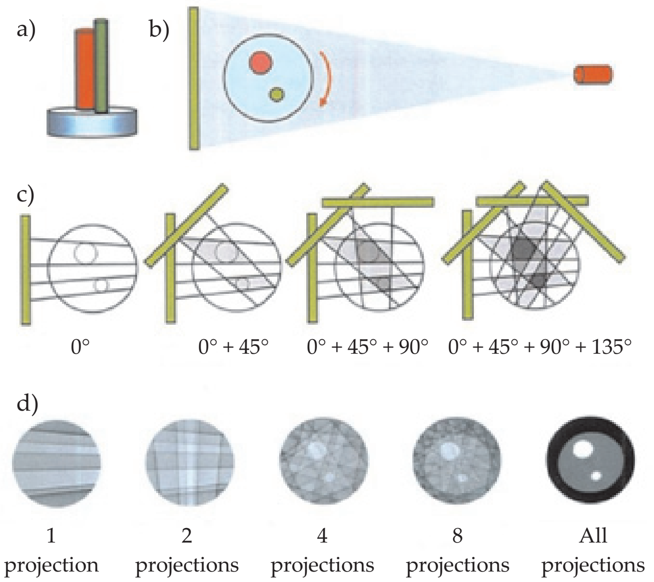


Fig. 1. The idea of a tomographical image: a) measured object, b) X-ray radiation beam for a single measurement projection, c) a rule of connecting results of single projections, d) a result of a reconstruction of a real object measurement for various numbers of projections (according to [11])

An X-ray radiation source in measurement tomographs is an X-ray lamp. The first commercial X-ray lamp was constructed in 1913 by W.D. Coolidge. He used a heating of a tungsten fiber to form an electron beam in a glass pipe with vacuum. In contemporary systems two basic types of lamps are used: transmission and directional. Both types are presented in Fig. 2. A transmission lamp enables to reach a higher magnification, while a directional lamp is used when a greater power is needed [7, 12, 13].

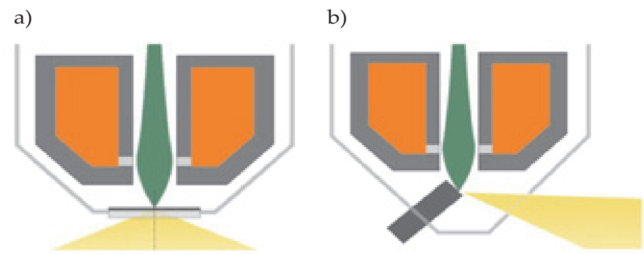


Fig. 2. Types of lamps used in metrology tomographs: a) transmission, b) directional (according to [14])

In order to obtain better resolution of a measured image two kinds of lamps are used: microfocus and nanofocus. Particularly the latter one, additionally equipped with a special pinhole and voltage stabilization, makes it possible to reduce a spot in focus to a very small size, even below 1 micrometer [14].

UNCERTAINTY OF MEASUREMENT

Uncertainty of measurement is defined as a non-negative parameter attributed to the measured quantity that is characterizing dispersion of measured values. Thus uncertainty reflects incomplete knowledge of the measured quantity [15–19]. A proper evaluation of uncertainty is a very complex and time consuming process, because of a large number of sources and factors influencing its value. Generally, there are two methods to evaluate measurement uncertainty. Type A is based on statistical analysis while type B is used when applying statistics is not possible or justified. In type A, it is often assumed that a distribution best describing an input quantity is a Gaussian one, or – when a number of measurements is small – a Student's t-distribution. Depending on the phenomenon other distributions apply as well.

For a type B evaluation, regardless of the lack of statistical knowledge, it is also possible to use a distribution. As the only information we have is that a value lies within a specified interval, a rectangular probability distribution can be used, characterized by interval limits. If there is more information available, another probability distribution that comply with that information can be used.

In description of measurement uncertainty evaluation of a standard uncertainty u was introduced, expressed by means of standard deviation, as well as extended uncertainty U, considered as a quantity defining an interval dependent on assumed confidence level and expressed by a formula:

$$U = k \cdot u \tag{1}$$

where: U – extended uncertainty, u – standard uncertainty, k – extension coefficient, dependent on assumed confidence level p, where in practice it is assumed that $k = 2$, what corresponds to confidence level $p = 95$ %.

Evaluation of type A uncertainty is based on a series of repeated measurements of certain quantity what is done by experiment. Standard deviation s_x is considered as a standard uncertainty u:

$$u(x) \approx s_x = \sqrt{\frac{\sum_{1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{2}$$

where: $u(x)$ – standard uncertainty of a measurement, s_x – standard deviation, x_i – value in a data set, $\bar{x}$ – arithmetical mean value from a data set, n – number of elements in a set.

Standard deviation of sample distribution based on measured values s_x is an assessment of a standard deviation regarding distribution σ. Mean value $\bar{x}$ from a certain number n of measurement results x_i is an assessment of a correct mean value of the distribution.

Reducing the obtained value of standard uncertainty is possible by means of calculating $\bar{x}$ value from a series of measurements. In that case measurement uncertainty is $\sqrt{n}$ times smaller than standard uncertainty of a single measurement:

$$u(\bar{x}) = \frac{u(x)}{\sqrt{n}} = \sqrt{\frac{\sum_{1}^{n}(x_i - \bar{x})^2}{n(n-1)}} \tag{3}$$

where: $u(x)$ – uncertainty obtained from calculation of the mean value from a series of measurements.

In industry reality because of a necessity to reduce measurement time it is very seldom possible to have enough time to do a large number of measurements in order to obtain a reasonable mean value. Another issue is to maintain constant measurement conditions and repeatability of the process.

MICRO CT USED FOR RESEARCH

For research purposes a metrology micro CT was used. GE Phoenix v|tome|x s240 device, shown in Fig. 3, is equipped with two X-ray lamps. A directional lamp with large power enables working with voltages up to 240 kV and obtaining X-ray beam power up to 320 W and maximum magnification of the measured object up to 100 times. The second lamp is a transmission nanofocus one. It works with much less power, maximum 15 W, but its construction makes it possible to obtain much smaller focal spot size and magnifications up to 200 times. Thanks to this lamp it is possible to detect details as little as 0.5 μm. The measurement space of a CT enables to measure parts, with diameter up to 260 mm and 420 mm in length. Still, it is crucial to remember that the greater the density of a measured material, the smaller is a total thickness of walls that can be penetrated by X-ray radiation.

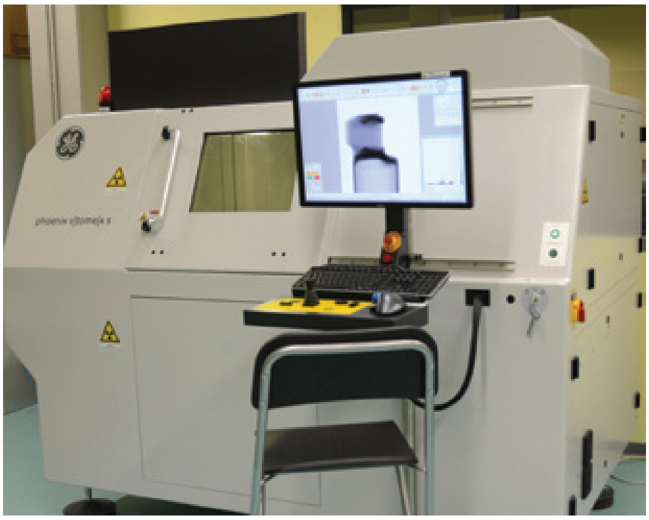


Fig. 3. Micro CT equipment type GE Phoenix v|tome|x s240 used for research

CREATION OF A REAL MODEL BY MEANS OF A MEM ADDITIVE MANUFACTURING TECHNIQUE

A 3D model of a piston engine is presented in Fig. 4. The real model composed of: engine block, piston, crankshaft, and a pin was made using fused deposition modeling (FDM) method on an UP! 3D printer, shown in Fig. 5. A working space of a 3D printer was equal to 140 x 140 x 135 mm, what made it possible to print all el-

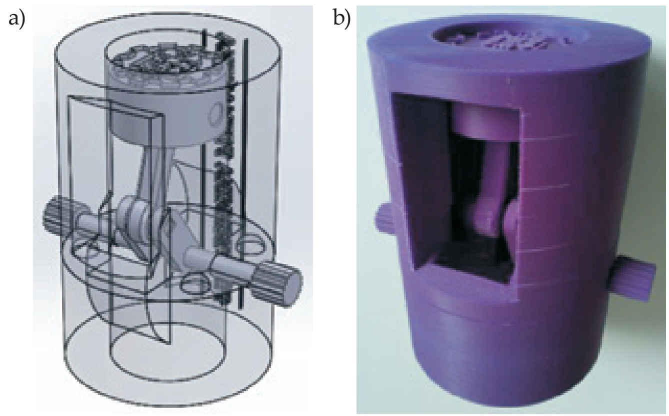


Fig. 4. A simplified model of a reciprocating engine: a) CAD model, b) element manufactured by means of a 3D printing

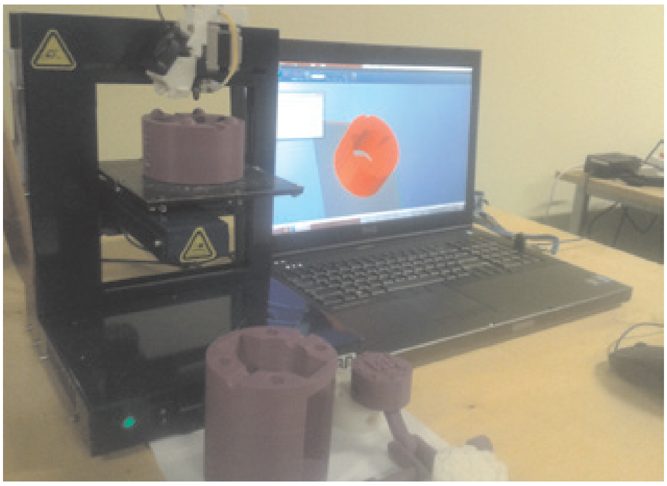


Fig. 5. Part on the printer UP! 3D used in this study

ements in 1:1 scale. A material used in the process was acrylonitrile-butadiene-styrene (ABS) terpolymer, having properties consistent with those listed in Wholers Report from March, 2011 [20].

In order to realize a printing process of elements it was necessary to convert all the files to a format that could be supported by a rapid prototyping (RP) device. In most cases the models have to be saved as STL files. A file conversion process is based on describing shape geometry by means of mesh of triangles with respectively accurate degree of density.

The first step to start the printing process was retrieving an in advance prepared STL file using printer software and placing models in 3D space of a printer. Because of a complex geometry of printed elements, printing resolution in Z axis equal to 0.15 mm was selected. It makes possible to obtain possibly the most accurate surface reconstruction. A maximum filling degree was also selected. Apart from basic layer model parameters, the parameters of supports (support layers) were defined. Depending on the shape of model and its location on a working platform, the amount of supporting material used to build the whole element varies. Complex geometries often enforce using large number of supporting layers. This is a factor making processing of the whole element more difficult.

After finishing of 3D printing obtained real models were dismounted and redundant supporting material was removed.

Connecting computer aided design/computer aided engineering (CAD/CAE) systems with RP methods makes it possible to shorten time from elaboration of a project of a device to its physical creation [21].

RESEARCH AND DISCUSSION

ASSESSMENT WITH CT METHOD OF QUALITY OF MANUFACTURED ELEMENTS

For research a simplified model of a reciprocating engine by means of 3D printing was made. It consists of an engine block, piston, connecting rod, crankshaft, and pin. Each of these elements was measured separately in order to confirm its correct manufacturing [22, 23].

An example of measurement of a piston is shown in Fig. 6. The obtained values were presented in a form of a color map of dimensional deviations of a real part from a CAD model. Measurement results analysis was per-

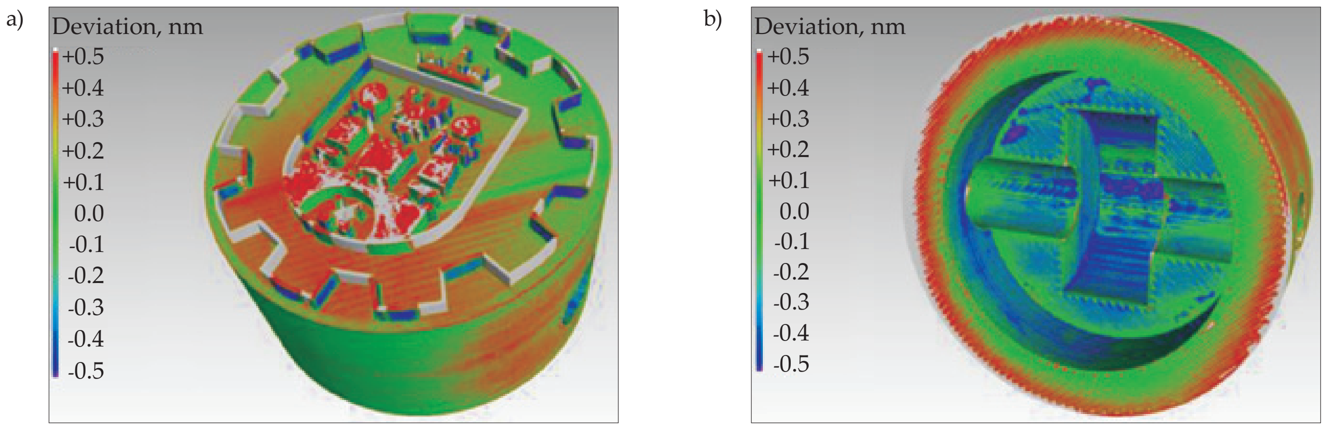


Fig. 6. Color map of dimensional deviations of reciprocating engine made of ABS by means of 3D printing in comparison to a CAD model: a) top view, b) bottom view

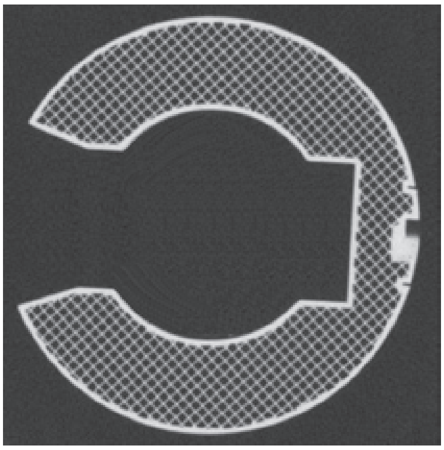


Fig. 7. A section through an engine block showing a structure inside the element

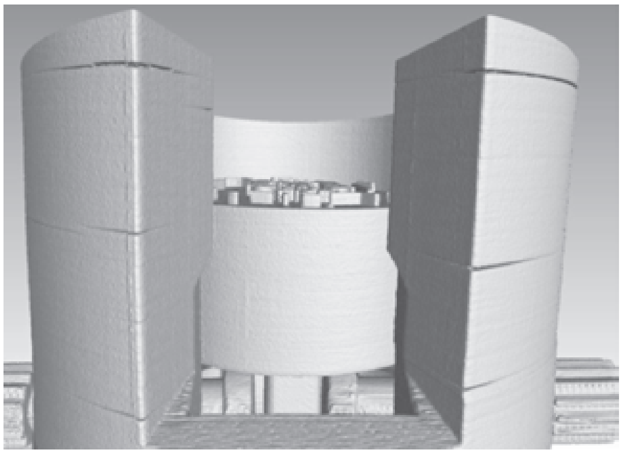
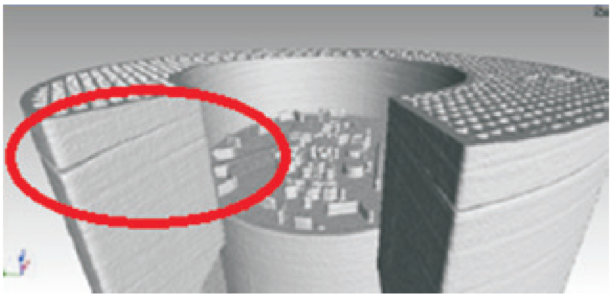


Fig. 8. A view of an engine block showing dissection

formed using Volume Graphics Studio MAX software. It enables to perform geometrical analysis of inspected element, in comparison with CAD model, as well as detection of pores and analysis of wall thickness [22–24].

The outer shape of the part (shown in Fig. 5) was measured on a CT. Such measurements naturally can be made for a number of various devices. Still only CT makes it possible to assess the inside structure of the element without destroying it. A section of an engine block is

a)



b)

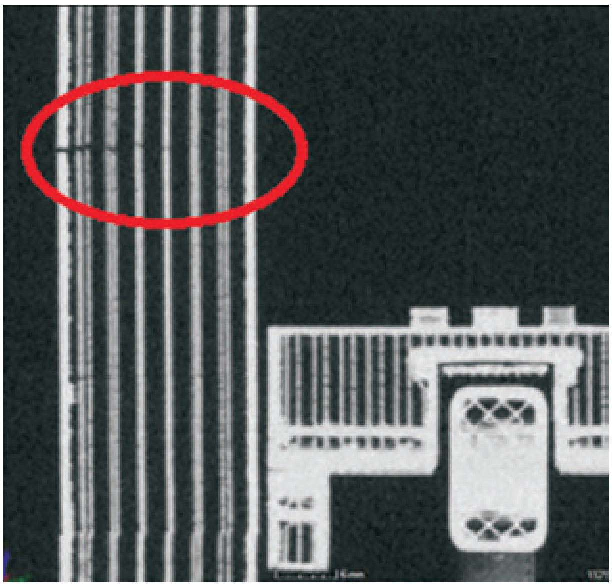


Fig. 9. A view (a) and section (b) of an engine block with visible dissection penetration inside the element

presented in Fig. 7. The inner structure of the element is clearly visible as a net filling the inside of the body. Thanks to such images full inside geometry analysis is possible including all the reinforcements, their thickness as well as continuity across the whole section of the element – in all directions.

In the upper part of the engine block some dissections are present. They can be seen with a naked eye and also in the photo shown in Fig. 8. Still only CT measurement gives possibility to assess the magnitude of that crack and its influence on the inner structure of the part.

Defects in part were presented in Fig. 9. These cracks and discontinuities are possible to detect thanks to some options of measured data analysis. On 2D section one can clearly see how deep this dissection penetrates into the inspected element. It allows a user to decide whether the part can be accepted for use or not. Additionally it makes possible to introduce modifications in the technological process to eliminate such defects in following elements.

Computed tomography makes also possible to assess quality of assembly, location, and cooperation of particular elements in a ready mechanism. A section of inspected engine model in the lowest position of the piston was shown in Fig. 10. Using volume graphics software it is possible to prepare a 3D view and 2D sections.

Computed tomography enables to measure a mechanism in several places, important for its functionality. In that case it is possible to assess geometrical changes and deformations of each single element.

MEASUREMENT UNCERTAINTY ANALYSIS ON CT

Measurement uncertainty is one of the quantities that helps to find out whether the results are useful or not. In this case the uncertainty was assessed for characteristic features of a piston. Results obtained as an effect of that analysis were shown in Table 1. Uncertainty was evaluated according to type A and the expansion coefficient

T a b l e 1. Uncertainty results for characteristic features of piston

Element	Measured	Nominal dimension mm	Mean value mm	Measurement uncertainty U_{95}, mm
Outer cylinder	diameter	49.650	49.631	0.0113
	cylindricity deviation	0	0.203	0.0015
Hole for pin	diameter	10.000	9.744	0.0074
Inner cylinder	diameter	35.700	35.682	0.0170
	runout	0	0.016	0.0079
Front surface	flatness	0	0.200	0.0042
	distance from pin axis	17.000	16.945	0.0151

was assumed as $k = 2$. Analyzing the results presented in the table one can observe that the measurement uncertainty $U_{95} \leq 0.017$ mm. This value shows that a computer tomograph is an accurate measurement system, bearing in mind, that among most of the inspected features the measurement uncertainty does not exceed 0.008 mm.

a)

b)

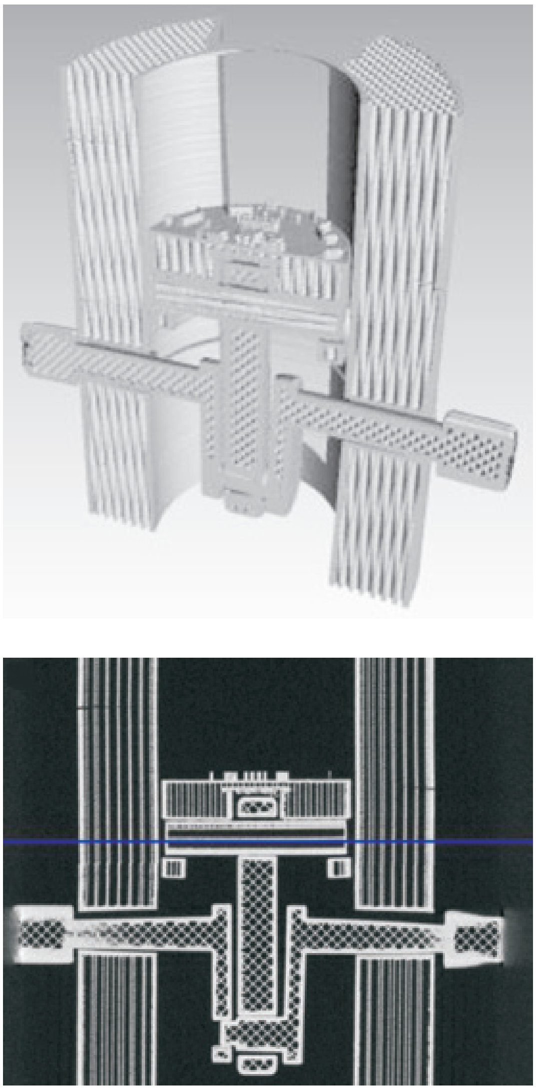


Fig. 10. An assembly model of the engine block: a) 3D view, b) 2D section along the cylinder axis

CONCLUSIONS

Metrology computer tomographs are the most modern devices used in contemporary coordinate measuring technique. They allow to conduct research in a very wide range of applications, including inspection of part geometry (dimensions) and checking its inner structure. Data obtained as a result of measurement can be also analyzed from pores and discontinuities point of view, as well as to view changes of wall thickness.

A measurement performed with a CT method is a contactless one, what makes it possible to inspect surfaces with any shape. Still, it does not have drawbacks of optical systems where it is often not possible to check narrow gaps or holes. The greatest limitation of that technique is possibility of penetration of measured object, dependent on the material density and total wall thickness in the examined object. As far as plastic elements are concerned this is very seldom the case limiting inspection possibilities. However, it is important to remember that as the power of lamp increases, the measurement accuracy decreases. It is connected with a size of a focal spot.

At present CT method is not very popular, particularly in industry applications. One of the reasons is the fact that the technique is very young, another issue is high price of such devices. There are however opinions that during next 10–15 years even 20 % of dimensional measurements will be performed with CT methods, as inspection possibilities look very promising.

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