Shaping and Geometrical Analysis of the Ring-type Test Samples Used in Dimensional Measurements by a Bench-Type Multisensor CMM

Wojciech Kapłonek[1] and Krzysztof Nadolny[2,*]

[1]Subject Group of Metrology and Quality, Faculty of Mechanical Engineering, Koszalin University of Technology, Racławicka 15-17, 75-620 Koszalin, Poland

[2]Department of Production Engineering, Faculty of Mechanical Engineering, Koszalin University of Technology, Racławicka 15-17, 75-620 Koszalin, Poland

Abstract: The routine measurements of various geometrical quantities in industrial applications are realized by use of a range of optical methods. Optical metrology is a dynamically developing area of the modern science and technology using a hardware solution from simple sensors to advanced computer-controlled measurement systems. In many specific applications dedicated measurement systems are required, which are characterized by much better metrological parameters and wider measuring capabilities than typical systems. Testing of such systems must be carried out on objects with similar properties as the actual objects produced in industrial conditions. The hybrid system for non-contact simultaneous assessment of the surface texture and dimension developed in Koszalin University of Technology (Koszalin, Poland) specially produced sets of ring-type samples with a variable external diameter ϕ_z =20.5-30±0.2 mm.

This paper presents the progress of works related to the design, production and analysis of the geometrical dimensions of such sets of test samples prepared for dimensional assessment by using laser triangulation methods. All the stages of this work are all so described and detailed in this paper. These stages included: the determination of assumptions for the preparation of samples, the choosing and characterising of the materials used for samples, the machining with a specialized bench-type lathe SK-1, as well as the dimensional measurements used by simple hand measuring instruments and the advanced bench-type coordinate measuring machine Video-Check® -IP 250 produced by Werth Messtechnik GmbH. The results obtained, which were presented in the form of bar diagrams and detailing already discussed, confirmed the dimensional correctness of the machining that was carried out.

Keywords: Ring-type test samples, machining, dimensional measurements, coordinate measuring machine (CMM).

1. INTRODUCTION

Optical metrology [1-3] has for many years played a dominant role in the measurement of various geometrical quantities in applications covering such areas of modern science and technology as, among others, mechanics, mechanical engineering, mechatronics and electronics. A large part of modern measurement solutions relates to the control of the manufacturing process and production conditions. The manufacturing processes of various non-contact instruments utilised during in-process (in-line) inspection [4] have largely achieved saturation levels within optical metrology. These instruments, depending on the complexity of measurement tasks, may include simple sensors [5] or more complex high accuracy computer-controlled measurement systems [4].

The inspection of the dimensional accuracy of manufactured parts is one of the major tasks realized by the aforementioned instruments. It usually takes place during the movement (rotational or progressive) [6,7] of the test object by means of triangulation-based methods [8,9], which use a laser radiation (within the visible and IR ranges). The range and accuracy of triangulation measurements depends on the specific requirements of a given application. In this respect the selection of appropriate measuring instruments, such as portable or integrated triangulation sensors, are also important [10].

Many specific applications require dedicated measurement systems with much better metrological parameters and wider measuring capabilities. Their development is often associated with a number of activities from the fields of research and development carried out in large corporations and companies, as well as from the measurement branches of many academic canters. For many years such works have been carried out at the Koszalin University of Technology (Koszalin, Poland). They are related to the development of the basics of measurement methods using laser radiation to assess the surface texture and dimensions of machine components and their implementation in a number of hardware solutions. A hybrid system for non-contact simultaneous

*Address correspondence to this author at the Department of Production Engineering, Faculty of Mechanical Engineering, Koszalin University of Technology, Racławicka 15-17, 75-620 Koszalin, Poland; Tel: +48 943478412; Fax: +48 943478440; E-mail: krzysztof.nadolny@tu.koszalin.pl

E-ISSN: 2409-9848/14

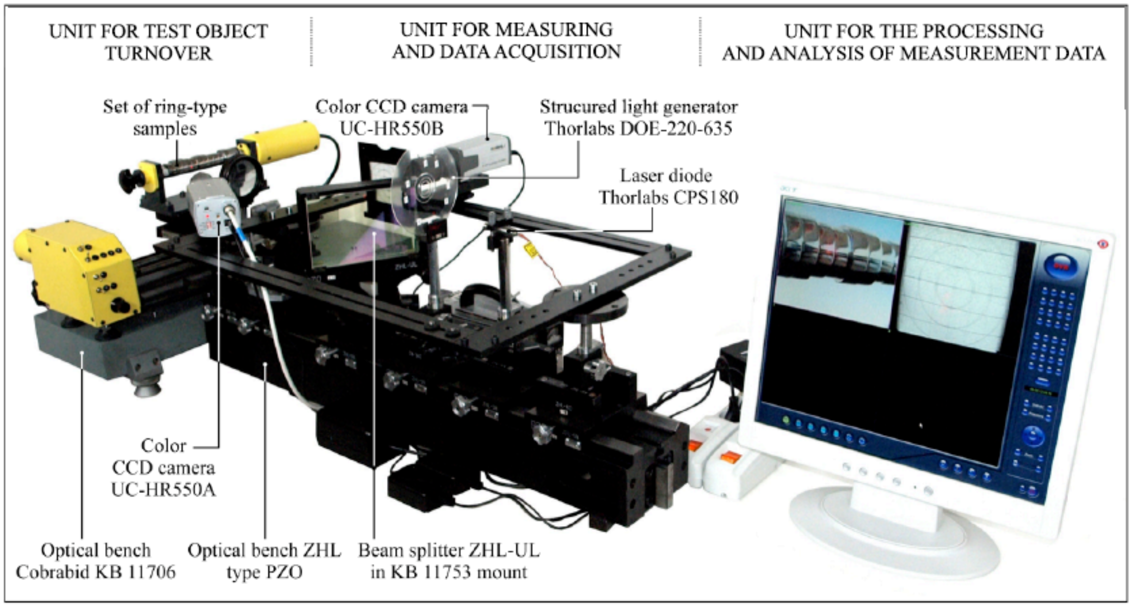


Figure 1: General view of the hybrid system for non-contact simultaneous assessment of the surface texture and dimension during the movement of the test object developed in Koszalin University of Technology (Koszalin, Poland).

assessment of the surface texture and dimensions of a test object were developed as part of this work. In this system, described in the work [11], three laser measurement methods were integrated:

- ARS (*Angle-Resolved Scatter/Scattering*) method, based upon a light scattering phenomenon and used in the assessment of surface roughness by analysis of the angular distribution of scattered light intensity,
- triangulation method, using laser radiation for the assessment of dimensions on the basis of the displacement of the light spot on the test object,
- a structured light method which uses a projection of the optical patterns used for assessment of surface shape on the basis of the geometric distortion of the patterns.

The values of surface roughness (*Ra* parameter) assessed by this system are in the range of 0.02 μm to 1μm, whereas the geometrical dimensions can be measured from 10 to 250 mm, at a relatively small error value of approximately 1-1.3%. A general view of the system is presented in Figure **1**.

A series of tests to confirm the compliance of the system with the established metrological parameters were compared with the measurement of appropriate test objects that exhibit similar characteristics to standard manufactured elements. As a result of these tests a prototype set of samples were designed and produced which simulated the processes of mass production. These prototypes were in the form of four sets of rings with different outer diameters.

This paper describes work related to the design, production and analysis of a set of test samples used for the assessment of geometrical dimensions through the application of the laser triangulation method presented. In Section 2, a detailed description of assumptions about the preparation of samples (Section 2.1), the characteristics of the materials used for samples (Section 2.2), and the complete process of their production using a specialized bench-type lathe SK-1 (Section 2.3) were given. Additionally in Section 2.4, the hand measuring instruments and bench-type coordinate measuring machine (CMM) used for assessment of the ring-type samples were described. The most important measurement results are presented alongside a detailed discussion in Sections 3 and 4.

2. MATERIALS AND METHODS

2.1. ASSUMPTIONS FOR THE PREPARATION OF THE SAMPLES

The work related to the production of a sets of samples was preceded by the preparation of an appropriate group of assumptions concerning the selection of the shape and type of surface machining. Analysis of the required sample features are given in Table **1**.

Table 1: The Most Important Features Required of the Samples

Group of features	Feature	Proposed solution	Solution advantages	Adopted solution
Design features	Shape	Cylindrical surfaces, flat surfaces	Possibility of realizing the measurements in motion	A set of cylindrical surfaces in the form of rings
	Dimension	Variable outer diameter	Possibility of realizing the dimension measurements	Variable diameter
	Material type	Various materials	Possibility of realizing the tests for various materials	Aluminium, brass, cast iron, steel
Other features	Machining type	Turning and abrasive machining	Obtaining a surface with characteristics similar to the real surfaces of the precisely machined machine parts	Grinding and polishing
	Surface roughness parameters	Various	A complete assessment of the surface roughness	*Ra*=0.05-0.5 µm*
	Gloss	Various	The possibility of testing for surfaces with different reflectivity**	Surfaces with a limited, but high gloss

Note: *typical range for height of the surface irregularities acceptable in production of precision elements, **important in case of the use of laser methods.

Table 2: The Most Important Physical and Mechanical Properties of Aluminium EN AW-6082

Physical Properties					
Density	Melting point	Modulus of elasticity (Young's modulus)	Resistivity (specific resistance)	Thermal conductivity	Thermal expansion
[g/cm^3]	[°C]	[GPa]	[Ωm]	[W m^{-1} K^{-1}]	[1/K]
2.7	555	70	0.038×10^{-6}	180	24×10^{-6}

Mechanical Properties				
Variety of alloy after annealing	Yield point	Tensile strength	Shear strength	Vickers hardness
	[MPa]	[MPa]	[MPa]	[HV]
O	60	130	85	35
T4	170	260	170	75
T6/T651	310	340	210	100

The Chemical Composition and the Percentage of Elements*								
Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
0.7-1.3	0.5	0.1	0.4-1.0	0.6-1.2	0.2	0.1	0.25	residual

Note: *in accordance with [12].

2.2. Characteristics of Materials Used for Sample Production

The starting material for the preparation of the samples was a set of four cylindrical bars with dimensions: outer diameter ϕ_z=40 mm, length l=150 mm. The bars were made of the following materials: aluminium EN AW-6082 (aluminium alloy), brass EN CW612N (lead brass alloy), cast iron EN GJL150 (gray cast iron) and steel EN C45 (structural steel). The characteristics of these materials are given in Tables **2-5**.

2.3. Machining of the Samples

The pre-machined processing of the samples were carried out using a lathe SK-1, designed and constructed by S. Kapłonek. This was a bench-type lathe used in the machining of a small-sized elements made of metal, wood and plastic. The drive of the lathe was a 3-phase AC induction motor with a power of 370W, manufactured by CET (Czech Republic). The use of the shift wheel and the proper manual combination of v-belt settings enabled the acquisition of three rotational speeds: n_w=675 min^{-1}, n_w=1370 min^{-1} and n_w=2740 min^{-1} (for the left and right rotation). The workpieces were mounted in the self-centring three-jaw chuck PUTm (nominal size of 80 mm) using a manual clamping (type 3204), produced by Bison (Poland).

Cutting tools, in the form of turning clutch tools (not to exceed the cap section 16×16 mm), were fixed in the tool holder. The traverse of the cross slide was 1mm^{-1} in the range of 60 mm. Displacement of the cross slide

Table 3: The Most Important Physical and Mechanical Properties of Brass EN CW612N

Physical Properties						
Density	Melting point	Modulus of elasticity (Young's modulus)	Conductivity (specific conductance)	Thermal conductivity		
[g/cm^3]	[°C]	[MPa]	[S/m]	[W m^{-1} K^{-1}]		
8.44	<1000	102	13.9×10^6	109		
Mechanical Properties						
Material state	Yield point	Tensile strength	Elongation at rupture	Vickers hardness		
	[MPa]	[MPa]	[%]	[HV]		
Soft	180	390	35	95		
Hard	500	560	3	150		
The Chemical Composition and the Percentage of Elements						
Cu	Pb	Sn	Al	Fe	Ni	Zn
[%]	[%]	[%]	[%]	[%]	[%]	[%]
59-60	1.6-2.5	≤0.3	≤0.05	≤0.3	≤0.3	residual

Table 4: The Most Important Physical and Mechanical Properties of Gray Cast Iron EN GJL 150

Physical Properties					
Density	Melting point	Modulus of elasticity (Young's modulus)	Resistivity (specific resistance)	Thermal conductivity	Thermal expansion
[g/cm^3]	[°C]	[MPa]	[Ωm]	[W m^{-1} K^{-1}]	[1/K]
6.8-7.25	1150-1250	25-35	2-5×10^{-6}	52.5 (100 °C)	–
Mechanical Properties					
Material state	Yield point	Tensile strength	Elongation at rupture	Brinell hardness	
	[MPa]	[MPa]	[%]	[HB]	
Soft	98	150	0.8	135	
Hard	165	250	0.3	200	
The Chemical Composition and the Percentage of Elements					
C	Si	Mn	P	S	
[%]	[%]	[%]	[%]	[%]	
3.5	2.3	0.6	0.01	<0.2	

Table 5: The Most Important Physical and Mechanical Properties of Steel EN C45

Physical Properties							
Density	Melting point	Modulus of elasticity (Young's modulus)	Thermal conductivity	Thermal expansion			
[g/cm^3]	[°C]	[GPa]	[W m^{-1} K^{-1}]	[1/K]			
7.85	1540	210	50	11.7×10^{-6}			
Mechanical Properties							
Material state	Yield point	Tensile strength	Elongation at rupture	Impact strength			
	[MPa]	[MPa]	[%]	[J/cm^2]			
Soft	340	600	16	50			
Hard	400	800					
The Chemical Composition And The Percentage Of Elements							
C	S	P	Si	Mn	Cr	Ni	Cu
[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
0.5	0.04	0.04	0.37	0.8	0.3	0.3	0.3

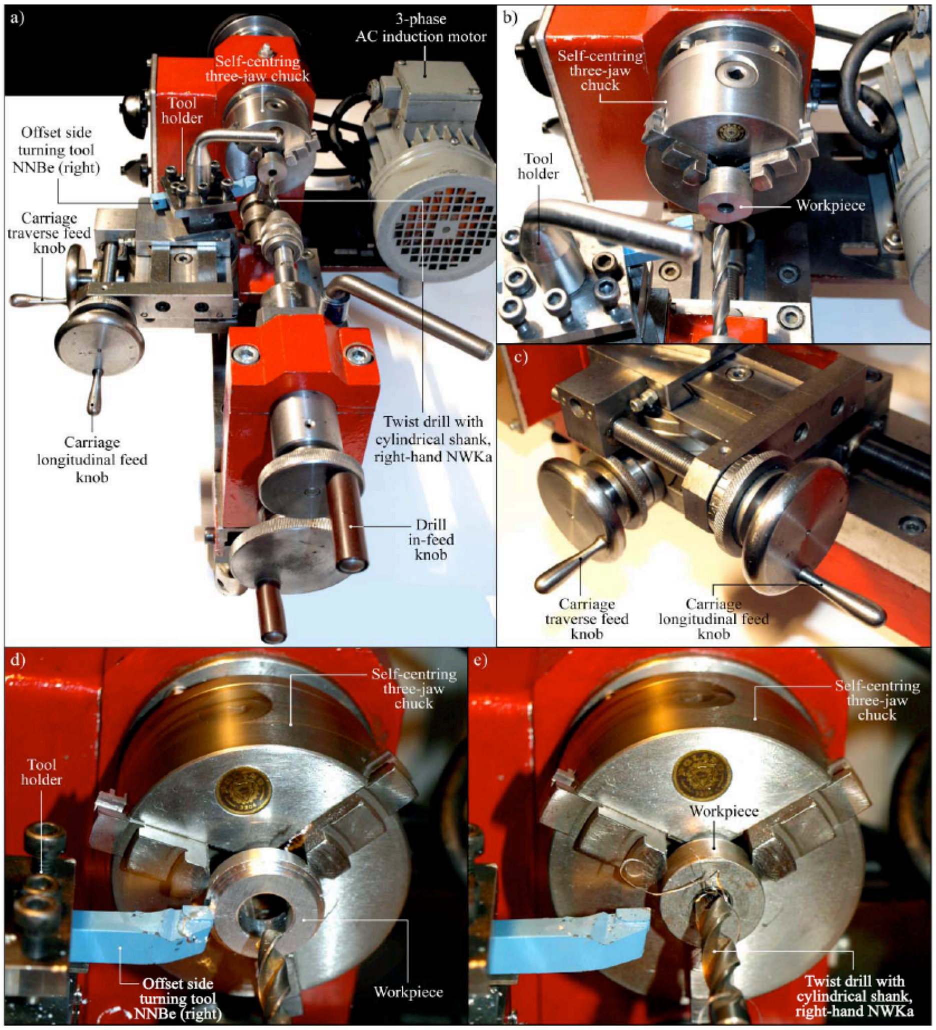


Figure 2: Bench-type lathe SK-1: a) general view of the machine, b) close-up of the 3-jaw self-centering chucks with fixed sample, c) close-up of the handwheel for lateral and longitudinal movement of slide, d) rough turning of aluminium AW-6082 sample, e) drilling a hole ϕ=13 mm in the cast iron EN GJL 150 sample.

(in *x* axis) was realized through the use of a leadscrew with a pitch of 1.5 mm. The turning length was 150 mm, whereas the turning diameter was 80 mm. Cutting tools for drilling (not exceeding the diameter 15 mm) were mounted in the tailstock holder. The machine consisted of the following compact dimensions: length 650 mm, width 400 mm, height 320mm. The weight of the lathe was approx. 25 kg. A general view of the bench-type lathe SK-1, with details of its construction as well as the examples of the machining processes, are presented in Figure **2**.

For the machining of the samples the following cutting tools were used:

- offset side turning tool NNBe (right) by Pafana (Poland),
- parting-off tool NNPa (right) by Pafana (Poland),
- twist drill with cylindrical shank, right-hand NWKa by Baildon (Poland),
- rough machine reamer with Morse taper shank, NRTa by Dolfamex (Poland),
- finish machine reamer with Morse taper shank NRTc by Dolfamex (Poland).

The works began with the initial preparation of the surface of each cylinder. After planing of the front, the cylinders were roughly turned to the external diameter ϕ_z=31 mm, and then they were precisely turned to the external diameter ϕ_z=30$\pm$0.2 mm (offset side turning tool NNBe, n_w=685 min^{-1}, manual feed). By using the parting-off tool NNPa, each cylinder was cut into 11 samples, each one having a width h=10 mm (n_w=685 min^{-1}, manual feed). Then each sample was machined separately to an established external diameter ϕ_z, incremented for each of the following samples by 0.5 mm (offset side turning tool NNBe, n_w=685 min^{-1}, manual feed).

After the machining process, holes were drilled in each of the samples, with an internal diameter of ϕ_w=14 mm. This process was begun by drilling a hole with a diameter of ϕ =13 mm (twist drill with cylindrical shank, right-hand NWKa, n_w=685 min^{-1}, manual feed). Next the hole was roughly drilled to the diameter of ϕ=13.8 mm, then precisely to the diameter of ϕ=14 mm (rough/finish machine reamer with Morse taper shank, NRTa/NRTc respectively, n_w=685 min^{-1}, manual feed).

The general view of a single ring-type sample with dimensions, as well as various sets of samples in measurement configuration, are presented in Figure **3**.

As a result of the above described work four sets of ring-type samples with variable external diameter ϕ_z=20.5-30±0.2 mm and a constant internal diameter ϕ_w=14 mm were produced. Each set contained 11 ring-type samples. The total number of all ring-type samples was 44.

2.4. Measurement of External Dimensions of the Samples

After the machining of the samples an assessment of all the samples with regard to dimensional correctness was conducted. The measurements of external dimensions were carried out using a simple hand measuring instruments and advanced bench-type coordinate measuring machine (CMM) Video-Check® - IP 250 produced by Werth Messtechnik GmbH (Germany). The characteristics of the simple measuring instruments are given in Table **6**.

The results obtained using the simple hand measuring instruments were compared with measure-

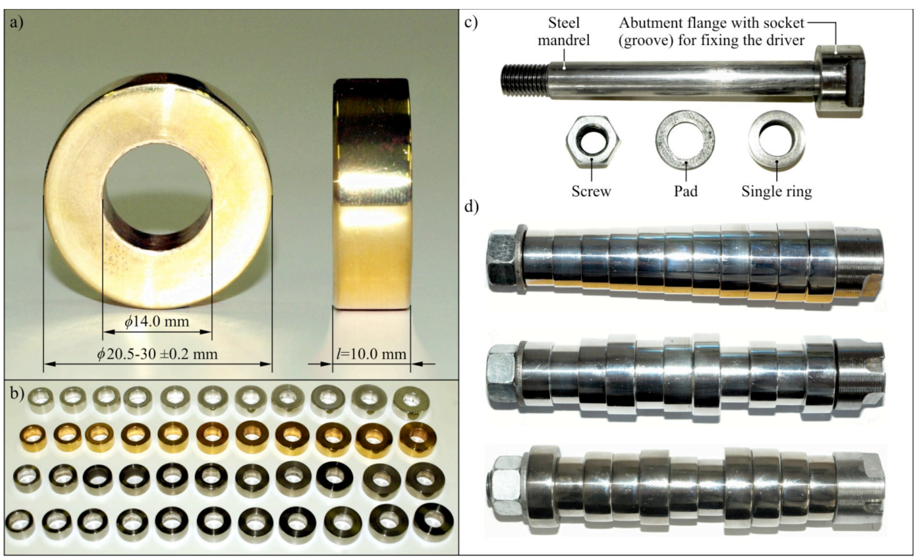


Figure 3: Ring-type sample: (**a**) general view and basic dimensions of a single sample, (**b**) 4 sets of the samples made from aluminium EN AW-6082, brass EN CW612N, gray cast iron EN GJL 150 and steel EN C45, (**c**) steel mandrel for the mounting of ring-type samples, (**d**) final configurations of the samples prepared for dimensional measurements by use of the laser triangulation method.

Table 6: The Characteristics of the Simple Hand Measuring Instruments Used for Assessment of External Dimensions of Ring-Type Samples

Instrument	Designation	Producer	Measuring range, mm	Value of scale interval, mm	Material
One-side caliper with internal jaws, depth probe and locking screw	MAUf	Luna (Poland)	0-190	0.05	Stainless steel, hardened
One-side digital caliper	MAUa-E1	VIS (Poland)	0-150	0.01	Stainless steel, hardened
External micrometer with flat measuring surfaces	MMZa		0-25	0.01	Tool steel
External micrometer with flat measuring surfaces (heavy)	MMZc		25-50	0.01	Tool steel

ments carried out using advanced CMM Video-Check® -IP 250. This CMM was a bench-type multisensory machine [13] designed for laboratory [14-16] and industrial [17] precision measurements of 2D/3D geometric quantities. These are the measurements of both finished machine parts, as well as their prototypes, produced by the modern rapid prototyping technologies. The measuring system was characterized by a modular structure, which enabled it to adapt to specific applications.

Video-Check® -IP 250 was built with two main modules – a measuring Table moving on mechanical bearings with magnetic mount and a vertical travel column with the measuring (vision) head. In the head was mounted the Video sensor IP, which enabled the automatic measuring of basic elements in incident and transmitted light at an optical zoom range from 50× to 150×. The image of the measured parts was acquired by a high-resolution CCD camera and was then processed to detect the contours of these objects. All measurements were carried out in automatic mode

Table 7: The General Characteristics of Bench-Type Multisensor Coordinate Measuring Machine Video-Check® -IP 250 Produced by Werth Messtechnik GmbH (Germany)

General	
Measuring technique	Coordinate measuring technique
Machine type	Bench-type multisensor coordinate measuring machine
Type of optical head	Video IP
Modes of operating	Continuous path control
Software	Measuring program WinWerth® 6.21
Dimensions and Weights	
Measuring range	x=to 250 mm, y=to 125 mm, z=to 200 mm
Min. installation area (width/height/depth)	1600×1860×950 mm
Weight	to 380 kg
Workpiece weight	m_{max}=30 kg
Parameters of Measurement System	
Resolution	0.0001 mm
Positioning speed	200 mm/s
Acceleration	300 mm/s^2
Range of zoom	(9 selective degrees) from 50× to 150×
Measurement time	Depends on type of measurement

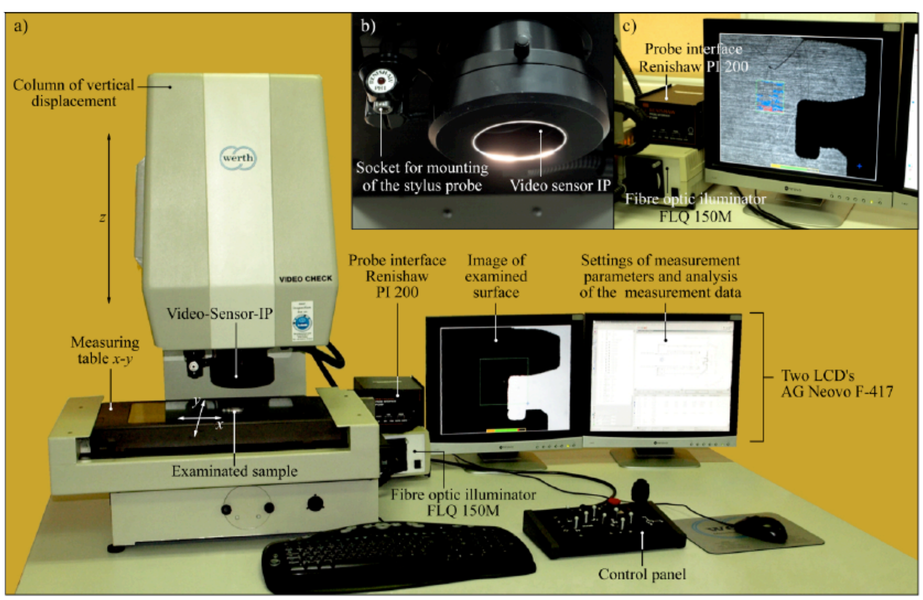


Figure 4: The general view of bench-type multisensor coordinate measuring machine Video-Check® -IP 250 produced by Werth Messtechnik GmbH (Germany): a) general view of the measuring machine, b) detail of multisensory system, c) detailed view of the external illuminating system and LCD screen during the measurement.

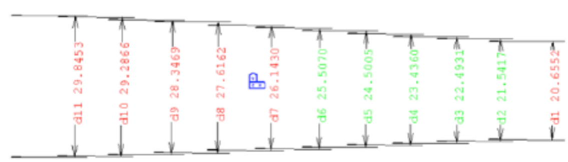
utilising the measuring program *Dimension_1* prepared with dedicated software WinWerth® 6.21.

The general characteristics of the bench-type CMM used are given in Table **7**, whereas the general view of the machine is presented in Figure **4**.

3. RESULTS

This section will present the results of measurements carried out using simple hand measuring instruments and a bench-type CMM. In the case of the instruments, described in Table **6**, the measurement process consisted of 5 measurements, provided at selected areas of each of the samples. An average of the values obtained for each sample, during the measurements conducted, was then compiled. All results were presented in the form of light gray bars in Figure **6**. Dark gray bars on the same Figure show the results obtained by Video-Check® -IP 250, whereas white bars indicate the nominal diameters for each ring-type sample indicate the nominal obtained for a set of ring-type samples made for aluminium EN AW-6082 by Video-Check® -IP 250 is presented in Figure **5**

a)



b)

BITMAP:C:\WMT7\BITMAP\LOGO.BMP

PRIMA BILAVCIK s.r.o.
RAPORT
19-09-2014
688 01 Uhersky Brod

Client : Wojciech Kaplonek — Date : 19-09-2014
Workpiece : Polished rings — Hour : 09:37:13
Workpiece no. : Aluminium
Program : Dimension_1
Controler : Lab Metrology 11E
Notes : ______________

Dat09-20147 / Page: 1

SYM	ACT	NOM	TOLup	TOLlow	DEV	<>TOL	+/-	PROJ
Dim	20.4994	20.5000	0.1000	-0.1000	-0.0006		-	d1
Dim	21.4144	21.5000	0.1000	-0.1000	-0.0856		----	d2
Dim	22.4244	22.5000	0.1000	-0.1000	-0.0756		----	d3
Dim	23.4607	23.5000	0.1000	-0.1000	-0.0393		--	d4
Dim	24.5041	24.5000	0.1000	-0.1000	0.0041		+	d5
Dim	25.2523	25.5000	0.1000	-0.1000	-0.2477	-0.1477	<<<<	d6
Dim	26.4564	26.5000	0.1000	-0.1000	-0.0436		--	d7
Dim	27.4127	27.5000	0.1000	-0.1000	-0.0873		----	d8
Dim	28.3718	28.5000	0.1000	-0.1000	-0.1282	-0.0282	<<<<	d9
Dim	29.3648	29.5000	0.1000	-0.1000	-0.1352	-0.0352	<<<<	d10
Dim	30.1226	30.0000	0.1000	-0.1000	0.1226	0.0226	>>>>	d11

Figure 5: Measurement report obtained for a set of ring-type samples made for aluminium EN AW-6082 by bench-type multisensor coordinate measuring machine Video-Check® -IP 250 produced by Werth Messtechnik GmbH (Germany): a) visualization of measurement results including values of calculated dimensions, b) obtained real values and referred to nominal values, with calculated upper/lower tolerance and deviation.

4. DISCUSSION

This paper presents work from the contemporary fringes of technology and, more specifically, metrology. The work conducted has revealed a number of issues related to the accuracy in the development, production and assessment of geometric ring-type samples made from a variety of materials. Due to the fact that the produced samples were used to test the higher accuracy of a laser method supported by image processing and analysis techniques, and that the measurements were carried out whilst the samples were in motion, it was crucial to obtain samples with accurate rendered external dimensions. Work in a range of machining types was carried using a specially designed and developed bench-type lathe SK-1, described in detail in Section 2.3. This lathe was purpose-built for this type of machining. Results of these works should be assessed as satisfactory (Figure **6**).

For all produced ring-type samples the value of dimension was correct and did not extend under the tolerance. However, it should be emphasized that with the different methods used there were significant differences in the diameter values measured. These values differed by more than 0.4 mm (sample No.11 from steel EN C45 – Figure **6d**). The difference when taking into consideration the measurements carried out by simple hand measuring instruments and CMM, were, in this case, more than the expected dimensional tolerances (±0.2 mm). As a result it would clearly seem to be the case that the adequacy of the measurements, with regard to measuring methods (such as the aforementioned laser triangulation), is dependent upon the use of an at least one order higher reference dimension. The use of CMM, in this case, allows for the satisfying of this condition.

5. CONCLUSION

Preparation of samples with given properties related to shape and dimension, as well as appropriate parameters of surface texture, that correspond to characteristics of the real machine parts produced, as well as mechanical components, is a fairly complex task. For samples with a special shape or unique

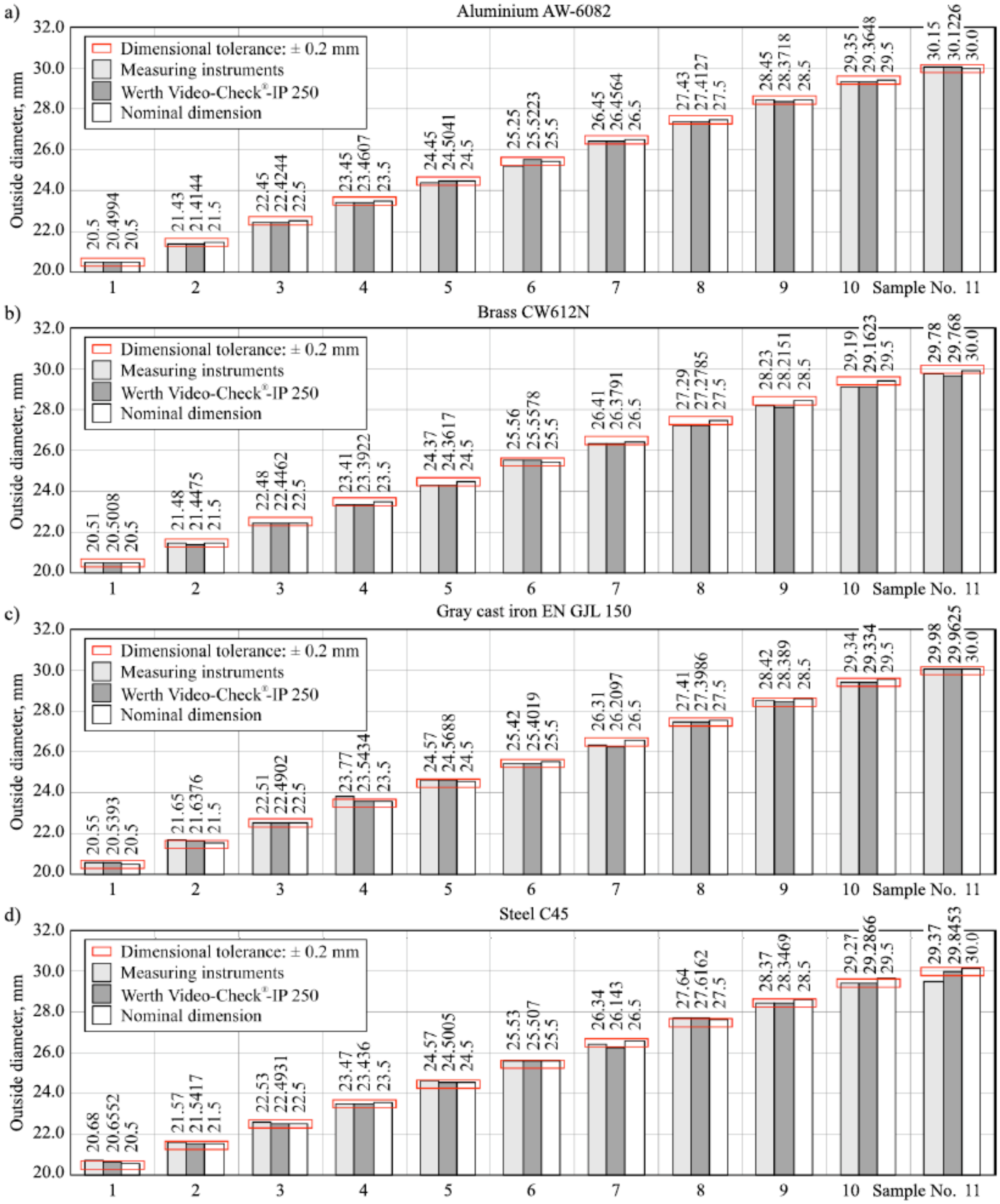


Figure 6: Results of dimensional measurements of a set of ring-type samples using a simple hand measuring instruments (light gray bars) and bench-type multisensor coordinate measuring machine Video-Check® -IP 250 produced by Werth Messtechnik GmbH (Germany) (dark gray bars) obtained from: (**a**) aluminium EN AW-6082 (aluminium alloy), (**b**) brass EN CW612N (lead brass alloy), (**c**) cast iron EN GJL150 (gray cast iron), (**d**) steel EN C45 (structural steel).

surface properties dedicated to a narrow field of geometric measurements, it is required to take a number of works of a technical and metrological nature. Some of these works were presented in the paper. This paper's methods can be treated as an example, and can be applied to the development of other similar cylindrical or ring-type test objects.

ACKNOWLEDGEMENTS

The Authors wish to thank Stanislaw Kapłonek MSc, BSc from the Department of Precision Mechanics at Koszalin University of Technology (Poland) for providing the bench-type lathe SK-1 used for production of sets of the ring-type samples. They also wish to thank Mr. Krzysztof Maciejewski from the Laboratory of

Metrology and Measurement Systems at Koszalin University of Technology (Poland) for conducting measurements carried out by multisensor bench-type CMM Video-Check®-IP 250.

REFERENCES

[1] Hocken RJ, Chakraborty N, Brown C. Optical Metrology of Surfaces. CIRP Ann-Manuf Techn 2005; 54(2): 169-183. http://dx.doi.org/10.1016/S0007-8506(07)60025-0

[2] Yoshizawa T (Ed.). Handbook of Optical Metrology: Principles and Applications. CRC Press: Boca Raton 2009.

[3] Harding K (Ed.). Handbook of Optical Dimensional Metrology. CRC Press: Boca Raton 2013.

[4] Vacharanukul K., Mekid S. In-process Dimensional Inspection Sensors. Measurement 2005; 38(3): 204-218. http://dx.doi.org/10.1016/j.measurement.2005.07.009

[5] Zhang H, Katz R, Agapiou JS. In-process Inspection of Internal Threads of Machined Automotive Parts Proc SPIE 2009; 7432:74320D.

[6] Sotnikov VV. Signal Processing in Laser Triangulation Sensors for Geometric Parameters of Moving Objects. Optoelectronics, Instrumentation and Data Processing 2009; 45(6): 531-538. http://dx.doi.org/10.3103/S8756699009060077

[7] Zeng L, Yuan F, Song D, Zhang R. A Two-beam Laser Triangulation for Measuring the Position of a Moving Object. Opt Laser Eng 1999; 31(6): 445-453. http://dx.doi.org/10.1016/S0143-8166(99)00043-3

[8] Rejc J, Činkelj J, Munih M. Dimensional Measurements of a Gray-iron Object using a Robot and a Laser Displacement Sensor. Robot Cim-Int Manuf 2009; 25(1): 155-167. http://dx.doi.org/10.1016/j.rcim.2007.11.001

[9] Brosed FJ, Santolaria J, Aguilar JJ, Guillomía D. Laser Triangulation Sensor and Six Axes Anthropomorphic Robot Manipulator Modelling for the Measurement of Complex Geometry Products. Robot Cim-Int Manuf, 2012; 28(6): 660-671. http://dx.doi.org/10.1016/j.rcim.2012.04.002

[10] Blais F. Review of 20 Years of Range Sensor Development. J Electron Imaging 2004; 13(1): 231-240. http://dx.doi.org/10.1117/1.1631921

[11] Kaplonek W, Lukianowicz Cz. Non-Contact Optical Metrology for Automated In-Process Inspection of Machined Surfaces. Proceedings to the 11th IMEKO TC14 Symposium on Laser Metrology for Precision Measurement and Inspection in Industry (ISCQM2013), Krakow-Kielce, Poland 2013. International Measurement Confederation (IMEKO) 2013; pp.36-39.

[12] BS EN 573-3:2013. Aluminium and aluminium alloys. Chemical composition and form of wrought products. Chemical composition and form of products. CEN-CENELEC Management Centre: Brussels 2013.

[13] Grebe W. Up to the New Horizons. Inspect 2004; 2: 54-55.

[14] Raimondi MT, Pietrabissa R. The In-Vivo Wear Performance of Prosthetic Femoral Heads with Titanium Nitride Coating. Biomaterials 2000; 21(9): 907-913. http://dx.doi.org/10.1016/S0142-9612(99)00246-X

[15] Kaplonek W, Zurawski L. Assessment of the cutting tools geometry by used of bench-type coordinate measuring machine Werth Video-Check®-IP 250. Measurement Automation and Monitoring 2011; 57(9): 1067-1070. (in Polish)

[16] Nadolny K, Kapłonek W. Design of a Device for Precision Shaping of Grinding Wheel Macro- and Microgeometry. J Cent South Univ 2012; 19(1): 135-143. http://dx.doi.org/10.1007/s11771-012-0982-9

[17] Pacurar R, Balc N, Olimpia R. Improving the Accuracy of the SLS Metal Parts Using the Finite Element Method. International Journal of Modern Manufacturing Technologies 2010; 2(1): 61-66.

Received on 02-12-2014 Accepted on 12-12-2014 Published on 23-01-2015

DOI: http://dx.doi.org/10.15377/2409-9848.2014.01.02.3