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Analysis of Accuracy in Different Positioning Schemes Using Statistical Methods

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***Abstract*— The choice of fixtures, the type of clamping, and the clamping force are key criteria for minimizing adverse effects that lead to deterioration in the geometric characteristics of the machined surfaces. This article examines the accuracy of cylindrical and conical surfaces under different clamping schemes—in a chuck (three-jaw self-centering) and between a chuck and a center. The accuracy of the machined surfaces has been analyzed and evaluated using statistical methods, with a comparative analysis performed between the mathematical expected value and the variance for the two clamping schemes.**

Keywords*— *accuracy, cylindrical surfaces, conical surfaces, geometric characteristics, machined surfaces.

I. Introduction

With the advance in the technological development, mechanical and device engineering are facing a number of tasks, one of which is to maintain a balance between quality and high productivity.

The implementation of computer numerically controlled (CNC) machine tools satisfies the requirement for productivity. By refinement of the modes of cutting, conditions are created to increase productivity while sufficing the durability of the tools, taking part in the cutting process. Geometric accuracy is a fundamental parameter, required for the proper operational characteristic of a given part. In the process of machining through chip removal, conditions are created for violating the tolerances, one of the factors for this being the way the product is positioned during cutting.

The generated geometric errors in the process of machining exert a significant influence on the accuracy of the machined surfaces. The accuracy depends on various factors, including shape-forming errors, deformations caused by the cutting force, thermal errors, part positioning errors, etc. In turn, geometric accuracy includes dimensional errors, shape errors, and positioning errors [1], [2], [3].

A number of authors [1], [4], [5], [6] have considered the topical problem, related to measuring the deviations from a proper geometric shape in the process of turning, by modeling the influence of the geometric errors of the machines and the tool wear on the accuracy of the machined surfaces.

Paper [7] defines the technological tasks and the modern approaches to achieving the specified accuracy when processing parts on CNC machine tools. The need for automation of the functions, performed by an operator, including the control on his/her side, in order to increase the efficiency of the technological processes has been argumentized. Approaches for automation, as well as for selecting appropriate schemes of tool setting have also been proposed in [8], [9], [10]. In [11], a new approach is discussed for predicting and compensating for the deviations of the surfaces, machined by turning, taking into account the stages of planning before machining, A model

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is proposed for determining the allowable value of deviations from dimensions and geometric shape, which is used to set appropriate operating conditions.

Yousefi et al. [12] have studied the dependence between dimensional accuracy, on the one hand, and vibration, cutting forces and tool wear, on the other. They establish that feed is the main factor, influencing the roughness of the machined surfaces. However, the depth of cut and cutting speed have the greatest influence on dimensional accuracy, while the radius at the tool tip does not have a significant effect.

There are studies, focused on the possibility for error compensation, aiming at improving machining accuracy. By compensating for transportation errors, Gao et al. [13] achieve reduction of the deviation from flatness from 0.27 μm to 0.12 μm. Kong et al. [14] have studied the influence of X and Z axis straightness when carrying out facing, tapering and spherical turning. They have proposed a method to compensate for a software error, and the method is applied by changing the tool trajectory while taking into account changes in the kinematics of the process.

Studies, related to machined surface accuracy have been conducted by Peterka at al [15]. The authors analyze the shape errors and the roughness of parts, made of heat-treated steel DIN EN 1.2842 (ISO 90MnCrV8) with a hardness of 58 HRC. Dimensional deviations, as well as errors in cylindricity and parallelism of hole generatrices in transmission parts serial production have been studied by Kundrák et al. [3].

The existing research, related to ensuring accuracy of dimensions and shape of machined surfaces concerns specific operating conditions. It has been established that the choice of fixtures, type of clamping and clamping force are key criteria for reducing the adverse effects, leading to deterioration in the geometric characteristics of the machined surfaces. In this regard, the present paper studies and analyzes, by applying statistical methods, the accuracy of cylindrical and conical surfaces when clamping under different schemes – in a chuck (three-jaw self-centering) and between a chuck and a center.

II. MATERIAL AND METHODS

Two series of 10 parts with shape, dimensions and accuracy presented in Fig. 1, were machined for the analysis of the geometric parameters. The material under machining was steel 45 (1.0503) with chemical composition and mechanical properties, complying with the standard EN 10277-2-2008 (Table 1).

The selected steel is medium-carbon structural steel, occupying a significant share among structural carbon steels (approximately 22%), used in machine building, and its main uses being for manufacturing shafts, axles, gears, fasteners and others.

The studied parts were machined on a RAIS T200 computer-controlled lathe, the working space of which is shown in Fig. 2. Two schemes of clamping were used – in a three-jaw self-centering chuck and between a chuck and a rotating center.

The processing of the parts was carried out under the following cutting mode: cutting speed V_c = 100 m/min; depth of cut a_p = 0.83 mm; feed f = 0.1 mm/rev. A lathe turning tool DDJNR2525JM15 was used as a cutter (designation according to ISO 5608:2012) with a P25 cermet insert with a wear resistant titanium nitride (TiN) coating and a designation according to ISO 1832:2017 DNMG 150604.

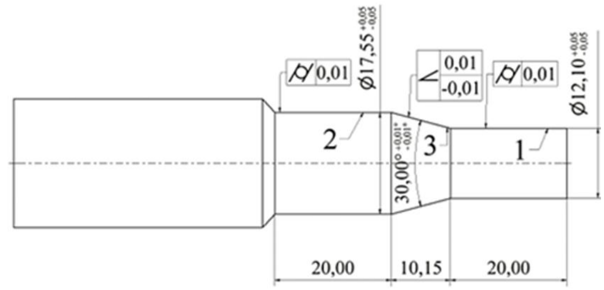


Fig.1 Shape, dimensions and accuracy parameters of the machined part .

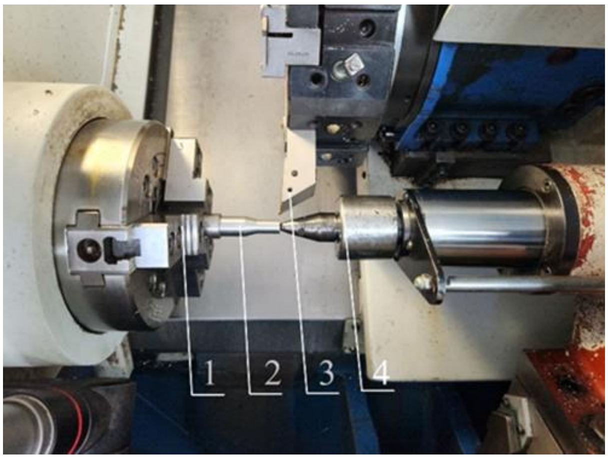


Fig.2 Workspace of a computer-controlled lathe. 1-self-centering chuck, 2- workpiece, 3- cutting tool, 4- rotating center.

The geometry of the cutting tool was: tool back race angle γ_p = -6°; tool major cutting edge angle κ_r = 93°; tool minor cutting edge angle κ_r' = 32°; rake angle of the main cutting edge λ_s = -7°; tool tip radius r_ε = 0.4 mm.

In order to compare the accuracy of the machined parts in the two schemes, the following parameters were measured: the diameters of the cylindrical surfaces 1 and 2 - d_i = 12.10 mm and D_i = 17.55 mm; the deviation from cylindricity of surfaces 1 and 2 - $\Delta_{i,d}$ and $\Delta_{i,D}$; the angle of the cone of surface 3 - δ_i ($i = 1,2$, respectively, when clamping in a chuck and in a chuck and center).

A DEA Global Performance coordinate measuring machine was used to measure the specified parameters (Fig. 3).

The measurement of the diametric dimensions of cylindrical surfaces 1 and 2 was carried out at 5 points across 72°.

The cone angle of surface 3 was measured in three cross-sections spaced 3 mm apart, with measurements taken at 5 points across 72° in each cross-section.

TABLE I. CHEMICAL COMPOSITION AND PHYSICO-MECHANICAL PROPERTIES OF THE STUDIED MATERIALS

Machined material	Hardness HB	Tensile strength MPa	Yield strength $Rp_{0,2}$, N/mm^2	Relative elongation A, %	Chemical composition, %
C45	170-210	600-800	300-450	16-20	C-0.48; P-0.022; Mn-0.6; S-0.1; Si-2.1

The deviation from cylindricity of surfaces 1 and 2, was estimated by using the transverse cross-section method. The measurements were performed in four cross-sections, spaced 6.2 mm apart, with measurements taken at 5 points in each of the cross-sections.

Fig. 3 DEA Global Performance coordinate measuring machine

The deviation from cylindricity of surfaces 1 and 2, was estimated by using the transverse cross-section method. The measurements were performed in four cross-sections, spaced 6.2 mm apart, with measurements taken at 5 points in each of the cross-sections.

Statistical analysis, comprised of testing two statistical hypotheses – for equality of two mathematical expectations; and for equality of two variances – was conducted in order to compare the results, concerning the accuracy of the surfaces, machined when fixed in a chuck or between a chuck and a center. Statistical hypothesis testing is a method by which a number of comparison and evaluation tasks are solved in engineering practice. At the heart of the method is a statistical criterion, determining the rules by which the formulated null hypothesis is accepted or rejected.

The verification of the statistical hypotheses was carried out in accordance with the methodology, presented below in the following sequence [16]:

1. Determining the arithmetic mean values of the studied parameters: diameter d_i (mm); diameter D_i (mm); deviation from cylindricity of a surface with a diameter $d_i - \Delta_{i,d}$ (mm); deviation from cylindricity of a surface with a diameter $D_i - \Delta_{i,D}$ (mm); cone angle δ_i (grad):

$$\bar{X}_i = \frac{\sum_{u=1}^{n} X_{iu}}{n}, \quad (1)$$

where $X_i = d_i;\ D_i;\ \Delta_{i,d};\ \Delta_{i,D};\ \delta_i$; $n = 10$ – number of observations in each experiment.

2. Determining the estimates of the variances of the studied parameters X_i:

$$S_{X_i}^2 = \frac{\sum_{u=1}^{n} (X_{iu} - \bar{X}_i)^2}{n-1}. \quad (2)$$

3. Testing the hypothesis for equality of variances of the studied parameters when fixing in a chuck and a center, using the Fisher criterion, the empirical values of which are determined by the dependence:

$$\widehat{F_X} = \frac{S_{X_1}^2}{S_{X_2}^2}. \quad (3)$$

If $\widehat{F_X} \leq F_{\alpha,k_{X_1},k_{X_2}}$ ($F_{\alpha,k_{X_1},k_{X_2}}$ - Fisher's quantile, α=0.05 – significance level; $k_{X_1} = k_{X_2} = n - 1$), then it is assumed that the compared parameters have equal variances. Otherwise, this hypothesis is rejected, i.e., the variance of the studied parameter X_1 is greater than that of the parameter X_2.

4. Testing the hypothesis for equality of the mathematical expectations of the studied parameters in the case of clamping in a chuck and a center, using the Student's criterion, the empirical values of which are determined by the dependence:

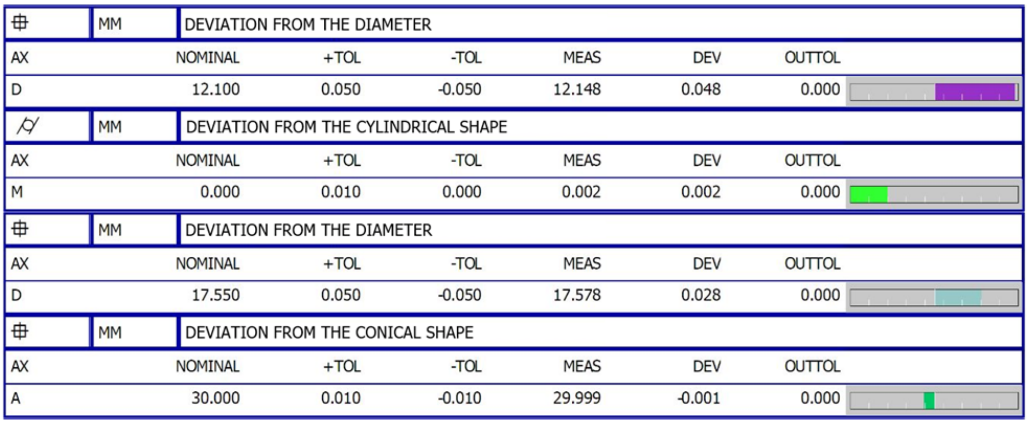
$$\hat{t}_X = \frac{|\overline{X_1} - \overline{X_2}|}{\sqrt{S_{X_1}^2 + S_{X_2}^2}} \sqrt{n}. \quad (4)$$

If $\widehat{t_X} \geq t_{\frac{\alpha}{2},k}$ ($t_{\frac{\alpha}{2},k}$ – Student's quantile, $k = n + n - 2$), the mean value of the studied quantity X_1 is greater than that of the studied quantity X_2. Otherwise, the mean values of the two quantities do not differ.

III. Results and Discussion

The results from the measurements of the studied parameters – diameter d_i; diameter D_i; deviation from cylindricity $\Delta_{i,d}$ of the surface with a diameter d_i; deviation from cylindricity $\Delta_{i,D}$ of a surface with a diameter D_i; cone angle δ_i – are presented in Tables 2 - 6. Part of the protocol of the performed measurements is shown in Fig. 4.

In accordance with the methodology presented in Section II and with the help of the QstatLab [17] software product, a statistical analysis of the experimental data was conducted (Tables 2 – 6), the results of which are presented in Table 7



	MM	DEVIATION FROM THE DIAMETER					
AX		NOMINAL	+TOL	-TOL	MEAS	DEV	OUTTOL
D		12.100	0.050	-0.050	12.148	0.048	0.000
	MM	DEVIATION FROM THE CYLINDRICAL SHAPE					
AX		NOMINAL	+TOL	-TOL	MEAS	DEV	OUTTOL
M		0.000	0.010	0.000	0.002	0.002	0.000
	MM	DEVIATION FROM THE DIAMETER					
AX		NOMINAL	+TOL	-TOL	MEAS	DEV	OUTTOL
D		17.550	0.050	-0.050	17.578	0.028	0.000
	MM	DEVIATION FROM THE CONICAL SHAPE					
AX		NOMINAL	+TOL	-TOL	MEAS	DEV	OUTTOL
A		30.000	0.010	-0.010	29.999	-0.001	0.000

Fig. 4. Protocol of measurement of the machined parts

TABLE II. DIAMETERS OF SURFACE 1

№	Setting in a 3-Jaw self-centering chuck				Setting in a 3-Jaw self-centering chuck and a center			
	d_1 (mm)	*d_1 (min)*	*d_1 (max)*	*Measured deviation*	*d_2 (mm)*	*d_2 (min)*	*d_2 (max)*	*Measured deviation*
1	12.148	12.142	12.156	0.048	12.092	12.087	12.097	-0.008
2	12.146	12.141	12.153	0.046	12.089	12.080	12.095	-0.011
3	12.148	12.143	12.158	0.048	12.088	12.075	12.096	-0.012
4	12.149	12.143	12.157	0.049	12.084	12.077	12.092	-0.016
5	12.147	12.141	12.154	0.047	12.086	12.079	12.094	-0.014
6	12.144	12.141	12.150	0.044	12.089	12.082	12.096	-0.011
7	12.147	12.142	12.153	0.047	12.091	12.084	12.102	-0.009
8	12.147	12.142	12.153	0.047	12.084	12.074	12.091	-0.016
9	12.147	12.142	12.153	0.047	12.094	12.081	12.112	-0.006
10	12.145	12.141	12.152	0.045	12.090	12.082	12.097	-0.010

TABLE III. DIAMETERS OF SURFACE 2

№	Setting in a 3-Jaw self-centering chuck				Setting in a 3-Jaw self-centering chuck and a center			
	D_1 (mm)	*D_1 (min)*	*D_1 (max)*	*Measured deviation*	*D_2 (mm)*	*D_2 (min)*	*D_2 (max)*	*Measured deviation*
1	17.578	17.576	17.58	0.028	17.543	17.54	17.547	-0.007
2	17.577	17.574	17.58	0.027	17.54	17.537	17.545	-0.01
3	17.577	17.573	17.587	0.027	17.54	17.536	17.545	-0.01
4	17.577	17.575	17.579	0.027	17.536	17.531	17.545	-0.014
5	17.577	17.575	17.582	0.027	17.539	17.535	17.543	-0.011
6	17.573	17.571	17.578	0.023	17.541	17.538	17.545	-0.009
7	17.577	17.575	17.581	0.027	17.54	17.535	17.55	-0.01

8	17.576	17.574	17.578	0.026	17.537	17.532	17.544	-0.013
9	17.576	17.574	17.579	0.026	17.545	17.532	17.562	-0.005
10	17.574	17.572	17.577	0.024	17.542	17.536	17.547	-0.008

TABLE IV. DEVIATIONS FROM CYLINDRICITY OF SURFACE 1

№	Setting in a 3-Jaw self-centering chuck				Setting in a 3-Jaw self-centering chuck and a center			
	$\Delta_{1,d}$ (mm)	$\Delta_{1,d}$ (min)	$\Delta_{1,d}$ (max)	*Measured deviation*	$\Delta_{2,d}$ (mm)	$\Delta_{2,d}$ (min)	$\Delta_{2,d}$ (max)	*Measured deviation*
1	0.007	-0.003	0.004	0.007	0.005	-0.003	0.002	0.005
2	0.006	-0.002	0.004	0.006	0.008	-0.004	0.003	0.008
3	0.008	-0.003	0.005	0.008	0.011	-0.006	0.004	0.011
4	0.007	-0.003	0.004	0.007	0.007	-0.003	0.004	0.007
5	0.007	-0.003	0.004	0.007	0.008	-0.004	0.004	0.008
6	0.005	-0.002	0.003	0.005	0.007	-0.003	0.004	0.007
7	0.005	-0.002	0.003	0.005	0.009	-0.004	0.006	0.009
8	0.006	-0.002	0.003	0.006	0.008	-0.005	0.004	0.008
9	0.006	-0.003	0.003	0.006	0.016	-0.006	0.009	0.016
10	0.005	-0.002	0.003	0.005	0.008	-0.004	0.004	0.008

TABLE V. DEVIATIONS FROM CYLINDRICITY OF SURFACE 2

№	Setting in a 3-Jaw self-centering chuck				Setting in a 3-Jaw self-centering chuck and a center			
	$\Delta_{1,D}$ (mm)	$\Delta_{1,D}$ (min)	$\Delta_{1,D}$ (max)	*Measured deviation*	$\Delta_{2,D}$ (mm)	$\Delta_{2,D}$ (min)	$\Delta_{2,D}$ (max)	*Measured deviation*
1	0.002	-0.001	0.001	0.002	0.004	-0.002	0.002	0.004
2	0.003	-0.002	0.001	0.003	0.004	-0.002	0.002	0.004
3	0.007	-0.002	0.005	0.007	0.004	-0.002	0.003	0.004
4	0.002	-0.001	0.001	0.002	0.007	-0.002	0.004	0.007
5	0.003	-0.001	0.002	0.003	0.004	-0.002	0.002	0.004
6	0.004	-0.001	0.002	0.004	0.003	-0.001	0.002	0.003
7	0.003	-0.001	0.002	0.003	0.008	-0.003	0.005	0.008
8	0.002	-0.001	0.001	0.002	0.006	-0.003	0.003	0.006
9	0.003	-0.001	0.002	0.003	0.015	-0.006	0.008	0.015
10	0.002	-0.001	0.001	0.002	0.005	-0.003	0.003	0.005

TABLE VI. CONE ANGLE OF SURFACE 3

№	Setting in a 3-Jaw self-centering chuck				Setting in a 3-Jaw self-centering chuck and a center			
	δ_1 (grad)	δ_1 (min)	δ_1 (max)	*Measured deviation*	δ_2 (grad)	δ_2 (min)	δ_2 (max)	*Measured deviation*

1	29.999	29.999	29.999	-0.001	30.013	30.013	30.013	0.013
2	30.006	30.006	30.006	0.006	30.059	30.059	30.059	0.059
3	30.009	30.009	30.009	0.009	30.074	30.074	30.074	0.074
4	30.014	30.014	30.014	0.014	30.052	30.052	30.052	0.052
5	30.001	30.001	30.001	0.001	30.058	30.058	30.058	0.058
6	30.016	30.016	30.016	0.016	30.06	30.06	30.06	0.06
7	30.021	30.021	30.021	0.021	30.043	30.043	30.043	0.043
8	30.024	30.024	30.024	0.024	30.05	30.05	30.05	0.05
9	30.003	30.003	30.003	0.003	30.055	30.055	30.055	0.055
10	30.025	30.025	30.025	0.025	30.053	30.053	30.053	0.053

TABLE VII. STATISTICAL ANALYSIS OF THE STUDIED PARAMETERS

Studied parameter	Arithmetic mean values		Variances		Fisher criteria		Student's criteria	
	$\overline{X_1}$	$\overline{X_2}$	$S^2_{X_1}$	$S^2_{X_2}$	$\widehat{F_X}$	$F_{\alpha,k_{X_1},k_{X_2}}$	$\widehat{t_X}$	$t_{\frac{\alpha}{2},k}$
d_i (mm)	12.1468	12.0887	$2.25.10^{-6}$	$10.89.10^{-6}$	4.84		50.68	
D_i (mm)	17.5762	17.5403	$2.25.10^{-6}$	$7.29.10^{-6}$	3.24		36.76	
$\Delta_{i,d}$ (mm)	0.0062	0.0087	$1.\ 10^{-6}$	$2.25.10^{-6}$	2.25	3.18	4.23	2.101
$\Delta_{i,D}$ (mm)	0.0031	0.006	$9.\ 10^{-6}$	$12.25.\ 10^{-6}$	1.36		1.99	
δ_i (grad)	30.0118	30.0517	$92.16.10^{-6}$	$249.6.\ 10^{-6}4$	2.70		6.83	

The conducted statistical analysis shows that the scheme of basing exerts different influence on the studied accuracy parameters of the machined surface.

The comparison of the arithmetic mean values of the diametric dimensions of cylindrical surfaces 1 and 2 shows a systematic displacement of the mathematical expectation for the second scheme (a chuck and a center), where the dimensions are smaller but the variance is significantly larger. The estimates of the mathematical expectation for the diameters d_i and D_i ($\widehat{t_d} = 50.68 > t_{\frac{\alpha}{2},k}$ =2.101; $\widehat{t_D} = 36.76 > t_{\frac{\alpha}{2},k} = 2.101$) confirm the presence of a systematic difference between the two groups of dimensions. The Fisher criterion confirms the inhomogeneity of the variances ($\widehat{F_d} = 4.84 > F_{\alpha,k_{X_1},k_{X_2}} = 3.18$; $\widehat{F_D} = 3.24 > F_{\alpha,k_{X_1},k_{X_2}} = 3.18$), with the accuracy for the cantilever type of setting being on average 70% higher.

The test of the hypothesis of equality of variances of the deviation from cylindricity and the conc angle for both setting schemes shows commensurability of the variances of the studied parameters ($\widehat{F_{\Delta_d}} = 2.25 < F_{\alpha,k_{X_1},k_{X_2}} = 3.18$; $\widehat{F_{\Delta_D}} = 1.36 < F_{\alpha,k_{X_1},k_{X_2}} = 3.18$; $\widehat{F_\delta} = 2.7 < 3.18$). The mathematical expectations of the deviations from cylindricity of surface 2 when basing in a chuck and in a chuck and a center, are also commensurable ($\widehat{t_{\Delta_D}} = 1.99 < t_{\frac{\alpha}{2},k}$ =2.101).

The introduction of a second support (a center) deteriorates both the diametric accuracy and the correctness of the geometric shape of surface 1 and surface 3 ($\widehat{t_{\Delta_d}} = 4.23 > t_{\frac{\alpha}{2},k}$ =2.101; $\widehat{t_\delta} = 6.83 > t_{\frac{\alpha}{2},k}$ =2.101).

This is probably due to accumulated errors from lack of coaxiality in the technological system or from part deformation under the action of the pressing force of the center.

IV. CONCLUSIONS

The accuracy of the cylindrical and conical surfaces of parts, made of C45, has been studied after turning, depending on the setting scheme. It has been established that the choice of fixture and type of clamping is a fundamental criterion, influencing the geometric characteristics of the machined surfaces.

The accuracy of the machined surfaces has been analyzed and assessed by applying statistical testing of parametric hypotheses, while making a comparative analysis between the mathematical expectation and the variance of the diametric dimensions, the deviation from cylindricity and the cone angle for the two setting schemes (in a three-jaw self-centering chuck and between a chuck and a center).

It has been found that the setting scheme has the greatest impact on the accuracy of the diametric dimensions, as well as on their variance.

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