Determination of error of sector location of subterrene stabilizing section based on coordinate control data

A V Valter¹, V V Aksenov²,³,⁴, V Yu Beglyakov⁵,¹,⁶, P A Chazov¹ and A B Efremenkov⁷

¹Yurga Technological Institute, Branch of the National Research Tomsk Polytechnic University, Yurga, Russian Federation
²Scientific Research Center OOO (Limited Liability Company) Sibirskoe NPO, Kemerovo, Russian Federation
³Institute of Coal FITs UUKh SO R AN (the Federal Research Center for Coal and Coal Chemistry of the Siberian Branch of the Russian Academy of Sciences), Kemerovo, Russian Federation
⁴T.F. Gorbachev Kuzbass State Technical University, Branch in the city of Prokopyevsk, Prokopyevsk, Russian Federation
⁵T.F. Gorbachev Kuzbass State Technical University, Kemerovo, Russian Federation
⁶National University of Science and Technology MISIS, Gubkin Branch, Gubkin, Russian Federation
⁷Yaroslav-the-Wise Novgorod State University, Veliky Novgorod, Russian Federation

E-mail: awalter@tpu.ru, 55vva42@mail.ru, begljakov@rambler.ru, abe@novsu.ru

Abstract. Results of the study of actual accuracy of the stabilizing section shell of the prototype subterrene are presented. The problem of experimental verification of the assumptions made in modeling is formulated. The research described in the article was carried out on the basis of experimental data obtained by coordinate control of the shell of the prototype subterrene. Data analysis was carried out by mathematical modeling of the surface of the stabilizing section as a whole and the surfaces of each individual sector. The obtained mathematical models are based on the approximation of sets of points obtained in the process of coordinate control by cylindrical surfaces. The article shows that at least a significant part of the deviations of the geometric shape of the section shell (from 30.3 to 52.3%) is explained by errors in the location of the sectors and errors in their radii. On the basis of the performed modeling, absolute values of the corresponding errors and actual values of the dimensions and deviations were determined. Studies confirmed the possibility of ensuring the specified accuracy of the shell surface when implementing the assembly technology used in a pilot production. At the same time, the proximity of actual deviations to maximum permissible values can lead to problems in ensuring the stable quality of subterrene products in mass production. Correlation analysis of coordinate control data and statistical analysis of the series of residuals of developed models were carried out. Correlation analysis confirmed the dependence of deviations of experimental points on their cylindrical coordinates, which confirms the significance of the error in the location of the sectors in deviations from the geometric accuracy of the shell.

1. Introduction

The subterrene case [1] is the most important component of the apparatus, which serves as a basic
product for the installation of most of the subterrene systems and separates the inner working space of the apparatus from the geo-environment. During operation, the subterrene case is exposed to serious loads both from the surrounding rock mass and from mechanisms located in the apparatus [2]. In this regard, increased requirements are imposed on the design of the case and the quality of its manufacture. One of the most important aspects of these requirements is the geometric accuracy of the shell (outer surface), which directly affects the energy efficiency of the machine and the resource of its main systems [3].

Subterrene cases are classified as circular segment products, and one of the most significant factors complicating the manufacturing technology of them is their separability [4]. Each of the case consists of several sectors connected to each other using detachable connections (Figure 1). So, the geometric version is given in the work [5], and the version of the model extended to three-dimensional space is presented in the work [6].

At the same time, the practice of mechanical engineering technology shows that the significance of certain factors for errors arising in the technological process can be reliably identified only as a result of the implementation of the technology under study [7]. This is explained not only by the complexity of the analytical description of the influence of various factors on accuracy, but also by the complex nature of the interaction of errors. The vector and probabilistic nature of errors leads to complex mechanisms for their summation, in which one error can be absorbed or compensated for by another. In this regard, in many works devoted to the issues of accuracy, the regularities of the formation of errors are investigated on the basis of control data of products manufactured using the analyzed technology. A similar approach, applied to circular segment products, is demonstrated in the work [8]. In this work, as in a number of others, the control of the geometric accuracy of products is based on the principle of coordinate control [9]. This is due to the fact that it is coordinate control that makes it possible to obtain a sufficiently wide set of data for further analysis of accuracy and to reveal the nature of errors [10].

In a significant part of the works concerning the accuracy of circular segment products, the error of the relative position of component parts of the product is considered as the main (often the only) factor in the formation of errors [5, 6]. This approach is not indisputable and requires experimental verification. In addition, the recent production experience in the manufacture of the stabilizing section of the prototype subterrene shows that, in all likelihood, factors such as deformations of case parts caused by welding and pressure treatment processes can be significant.

All of the above allows us to formulate the research problem as follows:
- establishing the magnitude and nature of the error in the position of the stabilizing section of the subterrene based on the coordinate control data, assessing the significance of this error and the possibility of considering it as a prevailing factor that forms deviations from the geometric accuracy of the shell.

2. Technique of coordinate control
The case of the stabilizing section of the subterrene, manufactured in a pilot production, was subjected to control. The FARO Arm Edge 9 coordinate measuring machine (CMM) of the “artificial arm” type
was used as a means of coordinate control (the main characteristics are given in Table 1). The choice of this type of equipment is primarily due to the significant dimensions of the case (diameter - 3200 mm, length - 1790 mm), which do not allow the use of most stationary CMMs for inspection, and also complicate the use of optical and laser 3D scanners.

Table 1. Coordinate measuring machine specifications.

| Specification description                              | Value   |
|--------------------------------------------------------|---------|
| Working area size, mm                                  | 2700    |
| Number of freedom degrees                              | 7       |
| Linear measurement error (according to ISO 10360-2: 2009), mm | ±0.041  |
| Repeatability (according to ISO 10360-2: 2009), mm     | 0.029   |
| Measurement type                                       | Contact |

In the process of testing, the case is installed vertically on the control plate. The CMM is based on the same plate. The control is carried out for four CMM positions, one for each sector of the case. To obtain the coordinates of the fixed points in a single coordinate system, the CMM snapping along the reference cones is used. For each of the sectors, coordinates are taken from 71 to 90 points on the surface of the shell (depending on the state of the surface).

The primary processing of the control data was carried out in the PowerINSPECT software package. The coordinates of the shell points fixed in the process of control were presented in the coordinate system associated with the plane of the control plate. For this, nine points were fixed on the control plate using the CMM. The origin of the coordinate system was set by the center of a circle, which was a section of a cylinder circumscribed around all fixed points of the shell (adjacent cylinder) in the plane of the control plate. The results of the primary processing of the shell control data are given in table 2. It should be noted that the values of deviations in the dimensions and shape of the shell obtained as a result of measurements meet the requirements of the design documentation.

Table 2. Results of primary processing of coordinate control data.

| Name of value                                      | Symbol | Value   |
|----------------------------------------------------|--------|---------|
| Adjacent cylinder diameter, mm                     | $D$    | 3195.934|
| Deviation from cylindricity, mm                    | $\Delta C$ | 9.463  |
|                                                    | $a_x0$ | 0.00146 |
| Coordinates of direction vector of axis of adjacent cylinder in base coordinate system | $a_y0$ | 0.00040 |
|                                                    | $a_z0$ | 1.00000 |

3. Coordinate control data analysis

The data were imported into a specially developed program for a detailed analysis and determination of the values of the sector position errors. The functioning of the program is based on the creation of regression models of cylindrical surfaces (models of the shell of the case as a whole - MSCW, and models of individual sectors - MIS) and their subsequent study [11]. The sequence of the performed analysis is shown schematically in Figure 2.
At the first stage of the analysis, a regression model of the case shell as a whole was developed, based on the approximation of points by a cylindrical surface. The model is formulated by the following system of equations:

\[
\sqrt{A^2 + B^2 + C^2} - r + \varepsilon_i = 0;
\]
\[
A = -a_y z_i - \sqrt{1 - a_x^2 - a_y^2} (y_0 - y_i);
\]
\[
B = \sqrt{1 - a_x^2 - a_y^2} (x_0 - x_i) + a_x z_i;
\]
\[
C = a_x (y_0 - y_i) - a_y (x_0 - x_i),
\]

where \(x_i, y_i, z_i\) are coordinates of points to be approximated; \(a_x, a_y, x_0, y_0\), \(r\) are unknown regression coefficients with the following geometric significance: \(a_x, a_y\) are coordinates of the direction vector of the axis of the approximating cylinder; \(x_0, y_0\) are coordinates of the point through which the axis of the approximating cylinder passes; \(r\) is radius of the approximating cylinder (AC); \(\varepsilon_i\) is regression residual.

The direction vector of the axis of the approximating cylinder was taken to be unit, and the point of the axis was taken to lie in the plane \(XY\), i.e.

\[
a_z = \sqrt{1 - a_x^2 - a_y^2};
\]
\[
z_0 = 0.
\]

Regression coefficients were determined using the least squares method [12]. The results of creating the regression model are shown in Table 3. Figure 3 shows the approximating cylinder and the points fixed during the control.

In order to compare the points obtained during the control with the approximating cylinder, their coordinates were transformed into a coordinate system associated with its axis, and subsequently converted into a cylindrical coordinate system \(Z-\theta-p\). In this case, the angular coordinates \(\theta\) for each
sector were transferred to the first quarter. Figures 4 and 5 show the dependences of the radius \( \rho \) on the polar coordinates \( Z \) and \( \theta \). As follows from the graphs, in many cases there is a pronounced regularity of the change in the radius \( \rho \) with a change in the cylindrical coordinates \( Z \) and \( \theta \). The same is indicated by the data of the correlation analysis, presented in Table 4.

### Table 3. Characteristics of regression surface models.

| Name of value                                      | Symbol | Common cylinder | Sector 1  | Sector 2  | Sector 3  | Sector 4  |
|---------------------------------------------------|--------|-----------------|-----------|-----------|-----------|-----------|
| Radius of approximating cylinder, mm              | \( r \) | 1595.254        | 1595.015  | 1591.890  | 1604.451  | 1610.183  |
| Coordinates of axis point of approximating cylinder, mm | \( x_0 \) | –1.210          | –4.849    | –7.02070  | –9.36417  | 16.551    |
|                                                   | \( y_0 \) | 0.652           | 2.585     | –8.01030  | –7.89340  | –8.622    |
|                                                   | \( z_0 \) | 0               | 0         | 0         | 0         | 0         |
| Coordinates of direction vector of axis of approximating cylinder | \( a_x \) | 0.00128         | 0.00440   | 0.00637   | 0.00372   | –0.00003  |
|                                                   | \( a_y \) | –0.00006        | –0.00185  | 0.00257   | 0.00107   | 0.00271   |
|                                                   | \( a_z \) | 0.99999         | 0.99999   | 0.99998   | 0.99999   | 0.99999   |
| Standarddeviation, mm                             | \( \sigma \) | 2.10460        | 1.42102   | 1.11303   | 1.32553   | 0.99011   |
| Maximumdeviation, mm                              | \( \varepsilon_{\text{max}} \) | 5.25217     | 2.75851   | 2.84905   | 3.23230   | 1.83216   |
| Minimumdeviation, mm                              | \( \varepsilon_{\text{min}} \) | –4.49901    | –4.03908  | –3.09642  | –3.32721  | –2.81700  |
| Totaldeviation, mm                                | \( \varepsilon_f \) | 9.75118      | 6.79759   | 5.94547   | 6.55951   | 4.64916   |
| Share of deviations unexplained by model (in percent from total deviation of common cylinder) | \( q \) | 100 %           | 69.7 %    | 61.0 %    | 67.3 %    | 47.7 %    |

**Figure 3.** Result of approximation of a set of points.

Thus, it can be assumed that the deviations of the radius \( \rho \) from the MSCW are of systematic nature. To identify the nature of deviations from the regression model, a number of residuals \( \varepsilon \) were studied (Table 5). We carried out analyses of the correspondence of a number of residuals to the law
of normal distribution according to the Epps-Pally criterion [13], of the presence of a trend in the series $\varepsilon (\theta)$ and $\varepsilon (Z)$ according to the criterion of turning points [14], and of the presence of autocorrelation in the series $\varepsilon (\theta)$ and $\varepsilon (Z)$ by the Durbin–Watson criterion [15]. The analysis showed that a number of MSCW residuals were not random.

Figure 4. Dependence of radius of points on cylindrical coordinate $Z$ (in coordinate system associated with MSCW axis).

Figure 5. Dependence of radius of points on cylindrical coordinate $\theta$ (in coordinate system associated with MSCW axis).
Table 4. Correlation analysis data.

| Name of value                                      | Common cylinder | Sector 1 | Sector 2 | Sector 3 | Sector 4 |
|---------------------------------------------------|-----------------|----------|----------|----------|----------|
| Correlation coefficient ρ(Z)                      | 0.1261          | -0.2688  | 0.3687   | 0.7075   | 0.2633   |
| Level of correlation significance ρ(Z)            | 0.0237          | 0.0159   | 7.6×10⁻⁴ | 5.3×10⁻¹² | 0.0117   |
| Correlation coefficient ρ(θ)                      | -0.1683         | -0.4562  | -0.7387  | 0.4235   | 0.1330   |
| Level of correlation significance ρ(θ)            | 0.0024          | 2.1×10⁻⁵ | 5.2×10⁻¹⁵| 2.3×10⁻⁴ | 0.2087   |
| Number of points                                  | 322             | 80       | 80       | 71       | 91       |

Table 5. Residual series analysis data.

| Name of value                                      | Common cylinder | Sector 1 | Sector 2 | Sector 3 | Sector 4 |
|---------------------------------------------------|-----------------|----------|----------|----------|----------|
| Epps-Pally statistics                             | 0.9053          | 0.3363   | 0.6347   | 0.1949   | 0.7006   |
| Critical value (significance level α = 0.05)      | 0.3803          | 0.3754   | 0.3754   | 0.3751   | 0.3757   |
| Conclusion on correspondence of residuals to law of normal distribution | Does not correspond | corresponds | Does not correspond | corresponds | Does not correspond |
| Number of turning points in series ε(θ)           | 211             | 51       | 51       | 44       | 57       |
| Conclusion on presence of a trend in a series ε(θ)|                |          |          |          |          |
| Number of turning points in series ε(Z)           | 204             | 57       | 52       | 42       | 62       |
| Conclusion on presence of a trend in series ε(Z)  |                |          |          |          |          |
| Critical number of turning points (significance level α = 0.05) | 198.5         | 44.7     | 44.7     | 39.1     | 51.5     |
| Durbin – Watson statistics for series ε(θ)        | 0.6454          | 0.7655   | 0.9767   | 0.7242   | 1.18     |
| Conclusion on presence of autocorrelation in series of residuals ε(θ) |                |          |          |          |          |
| Durbin – Watson statistics for series ε(θ)        | 1.8416          | 1.9726   | 1.9843   | 2.0224   | 1.9245   |
| Conclusion on presence of autocorrelation in series of residuals ε(θ) |                |          |          |          |          |
| Conclusion on presence of autocorrelation in series of residuals ε(θ) |                |          |          |          |          |
|Conclusion on presence of autocorrelation in series of residuals ε(θ) |                |          |          |          |          |
Conclusion on presence of autocorrelation in series of residuals:

\( \varepsilon(Z) \)  

No autocorrelation

| Significance intervals for Durbin-Watson statistics (significance level \( \alpha = 0.05 \)) |
|---------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
|                                 | Sector 1                                        | Sector 2                                        | Sector 3                                        | Sector 4                                        |                                                 |
|                                 | 1.5488                                          | 1.4650                                          | 1.4650                                          | 1.4330                                          | 1.4989                                          |
|                                 | 1.6154                                          | 1.5140                                          | 1.5140                                          | 1.4884                                          | 1.5433                                          |
|                                 | 2.3846                                          | 2.4860                                          | 2.4860                                          | 2.5116                                          | 2.4567                                          |
|                                 | 2.5142                                          | 2.5350                                          | 2.5350                                          | 2.5670                                          | 2.5011                                          |

Further, the models of each of the four sectors were determined according to the equations and using a methodology similar to that used to determine the MSCW. The results of the approximation of the sectors by cylindrical surfaces are given in Table 3. Based on the data on the coordinates of the axes, the deviations of the location of the sectors were calculated. Figure 6 shows images of the location deviations. Table 6 gives the characteristics of the deviations.

**Figure 6.** Approximating sectors (deviations increased by 5 times).

**Table 6.** Characteristics of deviations in location of sectors.

| Name of value                        | Symbol | Sector 1  | Sector 2  | Sector 3  | Sector 4  |
|--------------------------------------|--------|-----------|-----------|-----------|-----------|
| Displacement in plane XY, mm         | \( d \) | 4.12      | 10.43     | 11.81     | 20.04     |
| Displacement direction angle, degrees| \( \psi \) | 152.024   | -123.851  | -133.655  | -27.57    |
| Sector tilt angle, degrees           | \( \alpha \) | 0.206     | 0.328     | 0.154     | 0.175     |
| Tilt direction angle, degrees        | \( \varphi \) | -29.888   | 27.256    | 24.828    | 115.342   |

To find out how completely the error in the shape of the shell of the stabilizing section can be explained by the error in the relative position of the sectors, the coordinates of the points were converted into coordinate systems associated with the axes of the corresponding cylindrical surfaces.
approximating the sectors, using a technique similar to that given in [16].

Similarly to the MSCW, a correlation analysis (Table 4) and an analysis of residual series (Table 5) were performed for each of the MIS.

4. Results and discussion

The study of the regression model of the shell of the case as a whole showed that the deviations of the monitored points correspond to the accuracy requirements set for the stabilizing section. At the same time, the deviations are close to the boundaries of the tolerance fields, which can lead to a violation of the requirements for product quality in mass production. Thus, the task of increasing the geometric accuracy of the shells of subterranean cases can be recognized demanded.

The correlation analysis of the dependences of the radius of the monitored points relative to the axis of the common cylinder showed that there was a statistically significant relationship between the polar coordinates of the points and the radius (see Table 3). This connection is especially pronounced if we consider sets of points separate for each of the sectors, as shown in Figure 4 and 5. The most natural reason for this phenomenon may be deviations in the relative location of individual sectors.

The study of a number of the MSCW residuals showed that the deviations from the model were systematic. This is confirmed by the discrepancy between a number of residuals and the law of normal distribution (see Table 5), as well as the presence of autocorrelation in the series of residuals \( \varepsilon(\theta) \). This means that the deviations are caused by one or more prevailing factors. In the study, the deviations of the relative positions of the sectors and the errors of the radii of each of the sectors, which are complexly interrelated with them, were considered as the prevailing factor, which is associated with a number of previously conducted theoretical studies (see [16]).

The characteristics of the models of individual sectors show that the sectors have significant positional deviations relative to the shell as a whole, both in orientation angles and in linear displacements (see Table 6). In particular, linear displacements reach 20.04 mm, i.e., they exceed the size of the tolerances for the geometric accuracy of the shell. However, as noted above, the shell generally meets the accuracy requirements. This is due to the compensation of the sector radius error by the way of its displacement. The latter is also confirmed by the fact that the displacement values increase with an increase in the deviation of the actual sector radius relative to the nominal one (see Table 3). This phenomenon is described and theoretically substantiated in the work [16]. Thus, in the manufacture of subterranean sections, the approach of compensating for errors in the course of various stages of the production process or the selection of the optimal combination of component parts and their location in the assembly [17] can be used.

The study of the values of deviations from the MIS shows that the models describe a significant proportion of deviations - from 30.3 to 52.3% of the total deviation of the common cylinder. At the same time, a significant share of deviations is not explained only by errors in the relative position of the sectors and errors in the radii of the sectors.

The study of the series of residuals of the models of the shells of the sectors (see Table 5) showed that deviations from the models were systematic. The latter is confirmed by the presence of autocorrelation in the series of residuals \( \varepsilon(\theta) \). In addition, for sectors 2 and 4, there is a discrepancy between the series of residuals and the law of normal distribution. This allows us to say that in the production process there are other factors that appear in the form of an error in the shape of individual sectors and have a significant impact on the accuracy of the shell as a whole. Moreover, among these factors there are prevailing ones that cause systematic deviations from the geometric accuracy of the shell.

5. Conclusions

The conducted research allows us to draw the following conclusions.

1. Deviations from the geometric accuracy of the shell of the stabilizing section of the prototype subterranean system are systematic, from which it follows that the formation of errors is associated with the presence of several prevailing factors, the nature of the influence of which can be revealed by developing and
studying the corresponding mathematical models.

2. A significant role in the formation of deviations is played by errors in the relative position of the sectors of the stabilizing section and their radii. The deviations are significant and can explain about 30 ... 50% of the total error.

3. The complex nature of the combined effect of errors in the relative position of the sectors and their radius on the accuracy of the shell as a whole is confirmed. The results of the analysis of coordinate control show the practical possibility of compensating for the inaccuracies of individual sectors by displacing them relative to the nominal position.

4. Deviations in the location of the sectors and errors in their radii cannot be considered as the only significant factors causing the formation of shell inaccuracies. In addition to them, in the production process, there are other, currently not revealed, mechanisms for the formation of systematic errors in the geometric accuracy of the shell.

References
[1] Aksenov V V, Beglyakov V Yu and Kapustin A N 2014 Analysis of supporting structures (cases) of known technical systems applicable as a case (carrier) of a subterrene Bulletin of Kuzbass State Technical University 6 (106) 34–6
[2] Aksenov V V, Valter A V and Beglyakov V Yu 2014 Ensuring the geometric accuracy of the shell when assembling the subterrene sections Metal Processing (Technology, Equipment, Tools) 4 (65) 19–28
[3] Aksenov V V, Valter A V and Lagunov S E 2015 Setting the position of the supports using the triangulation method when assembling subterrene sections Technologies and Materials 1 31–6
[4] Saunders P, Wilson P A, Orchard N, Tatman N and Maropoulos P2014 An exploration into measurement consistency on coordinate measuring machines Procedia CIRP 25 19–26 DOI:10.1016/j. procir.2014.10.005
[5] Durbin J and Watson GS 1971 Testing for serial correlation in least squares regression. III Biometrika 58 (1)1–19
[6] Efremenkov A B 2011 Forming the subterranean space by means of a new tool (geohod) Proceedings of the 6th International Forum on Strategic Technology (IFOST–2011) Harbin, 22–24 August 2011.1 pp348–50 DOI: 10.1109/IFOST.2011.6021037
[7] Jiao Y and Djurdjanovic D 2011 Compensability of errors in product quality in multistage manufacturing processes Journal of Manufacturing Systems 30 (4) 204–13 DOI: 10.4028/www.scientific.net/AMM.770.439
[8] Kendall M G and Stuart A 1968 The advanced theory of statistics Vol 3 Design and analysis, and time-series 2ned (London: Charles Griffin) p 567
[9] Lovth S and Axinte D A 2014 An assessment of “variationconscious” precisionfixturing methodologies for the control of circularity within large multi-segmentannular assemblies Precision Engineering 38 379–390 DOI:10.1016/j.precisioneng.2013.12.004
[10] Memon M, Hussain T and Memon Z A 2012Minimizing assembly errors by selecting optimum assembly sequence in the assembly of a rigid circular structure Mehran University Research Journal of Engineering &Technology 31 (4) p743–54
[11] Mian SH and Al-Ahmari A 2014 Automation of determination of optimal

[12] LemeshkoB Y, Lemeshko S B, Nikulin M S and Saaidia N 2010 Modeling statistic distributions for nonparametric goodness-of-fit criteria for testing complex hypotheses with respect to the inverse Gaussian law Auto- mation and Remote Control 71 (7) 1358–73 DOI: 10.1134/S000511791007009X
[13] Nievergelt Y 2013 Fitting cylinders to data Journal of Computational and Applied Mathematics 239 250–69
[14] Shilin A N, Petrov S A and Zayarny V P 2010 Automation of determination of optimal
conditions for assembling oil and gas equipment casings Assembly in Mechanical Engineering, Instrument Making 6 (119) 10–14

[15] Hussain T, Yang Z, Popov A A and McWilliam S 2011 Straight-build assembly optimization: a method to minimize stage-by-stage eccentricity error in the assembly of axisymmetric rigid components (two-dimensional case study) Journal of Manufacturing Science and Engineering 133 (3) 031014 DOI: 10.1115/1.4004202

[16] Bezyazchny B F and Nepomiluev V V 2009 Some problems of modern assembly production and prospects for overcoming them Assembly in Mechanical Engineering, Instrument Making 8 (109) 18–25

[17] Lin Zone-Ching and Wu Wen-Jang 1999 Multiple linear regression analysis of the overlay accuracy model IEEE Transactions on Semiconductor Manufacturing 12 (2) 229–37 DOI: 10.1109/66.762881