THE MEASUREMENT OF SHELL'S ELASTIC OVALITY AS ESSENTIAL ELEMENT OF DIAGNOSTIC OF ROTARY DRUM'S TECHNICAL STATE

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Summary

In the article the author carries out classification of the typical rotary drum shell's deformations. He shows the cyclic elastic distortion of shell's cross-section as one of the most essential and particularly important from the fatigue life and from the durability of plant's internal lining point of view. He describes the method and device to measurement it and he characterizes basic diagnostic parameters, such as degree of shell section's elastic ovality and curve of ovality. On example of data received from two rotary kilns' measurements, he shows possibilities and the effectiveness of the method in the range of finding the basic damages' symptoms concerning drum's main elements, i.e. its support system and its shell.

Keywords: elastic deformation, ovality, rotary drum, shell.

POMIAR SPRĘŻYSTEJ OWALIZACJI PŁASZCZA JAKO ISTOTNY ELEMENT DIAGNOSTYKI STANU TECHNICZNEGO WALCZAKA OBROTOWEGO

Streszczenie

Autor w artykule dokonuje klasyfikacji odkształceń płaszcza typowego walczaka obrotowego. Wskazuje cykliczne deformacje sprężyste przekroju płaszcza za jedne z najbardziej istotnych i szczególnie ważnych z punktu widzenia zmęczeniowej trwałości powłoki oraz z punktu widzenia trwałości wewnętrznej wykładziny obiektu. Opisuje metodę i urządzenie do ich pomiaru oraz charakteryzuje podstawowe parametry diagnostyczne, takie jak stopień sprężystej owalizacji przekroju i krzywa owalizacji. Na przykładzie danych pozyskanych z pomiarów dwóch obrotowych pieców, wskazuje możliwości i skuteczność metody w zakresie wychwytywania symptomów podstawowych uszkodzeń, dotyczących kluczowych elementów walczaka, tj. jego układu nośnego i jego płaszcza.

Słowa kluczowe: sprężyste odkształcenia, owalizacja, walczak obrotowy, płaszcz.

1. INTRODUCTION

The shell, in the form of the thin-walled steel pipe with horizontal or close to horizontal location of axis, is the basic component of typical rotary drum. The rotation is the main movement of this object, including its shell. This movement is realized thanks to the rings, which together with the pipe placed in them, roll on the pairs of rollers - subordinated to each ring. It constitutes something of the support system for the shell and simultaneously it is the stiffener of this relatively flexible construction.

The amount of the pairs of rollers equals the amount of rings and holds in the scope from 2 to 4 - the most often. The length of the pipe (shell) achieves a few dozen, and its diameter - several meters. The general scheme of this type object is presented in figure 1.

The production tasks, which rotary drums realize, were listed in the study [4]. They are very essential. In the case of many enterprises we can judge them as the core of activity.

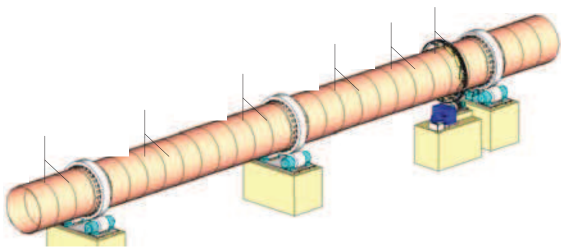

Fig. 1. General scheme of 3-piers (rings) rotary drum:
1 – support system (rings and support rollers),
2 – shell (coat),
3 – drive section (motor, reducer and open gear)

Cement plants and kilns for production of clinker situated there, are distinct example of this situation. Both, from this important reason, as well as taking the high costs of repairs into consideration, the this type machines should be subjected to increased discipline of technical supervision, and the evaluation techniques of their technical state should include as wide as possible spectrum of effective diagnostic methods and data.

Unfortunately, because of the low rotational speed (only up to several revolutions per minute), considerable dimensions and more than once very high temperature of the external surface of the drum's shell (even up to 350^{0}C), diagnostic tools - applied universally - have strongly limited application in this case. All activities aiming both to the adaptation of classic diagnostic methods (in the field of vibro-diagnostic analysis or in the field of measurements of geometrical parameters) and to the study of completely new ways and measurement-analytic tools, are very desirable and particularly expected by operators of these big machines.

This article presents the description of the one of such innovatory methods and exactly the way, which was worked out by Swedish diagnostician - the most probably in fiftieth years the 20-th century [6]. However this method did not gain in common acceptance in the industry then. Attempts of device's implementation of prototypes basing on this way, undertook in the farther future, also in Poland [1], did not meet with the positive market response.

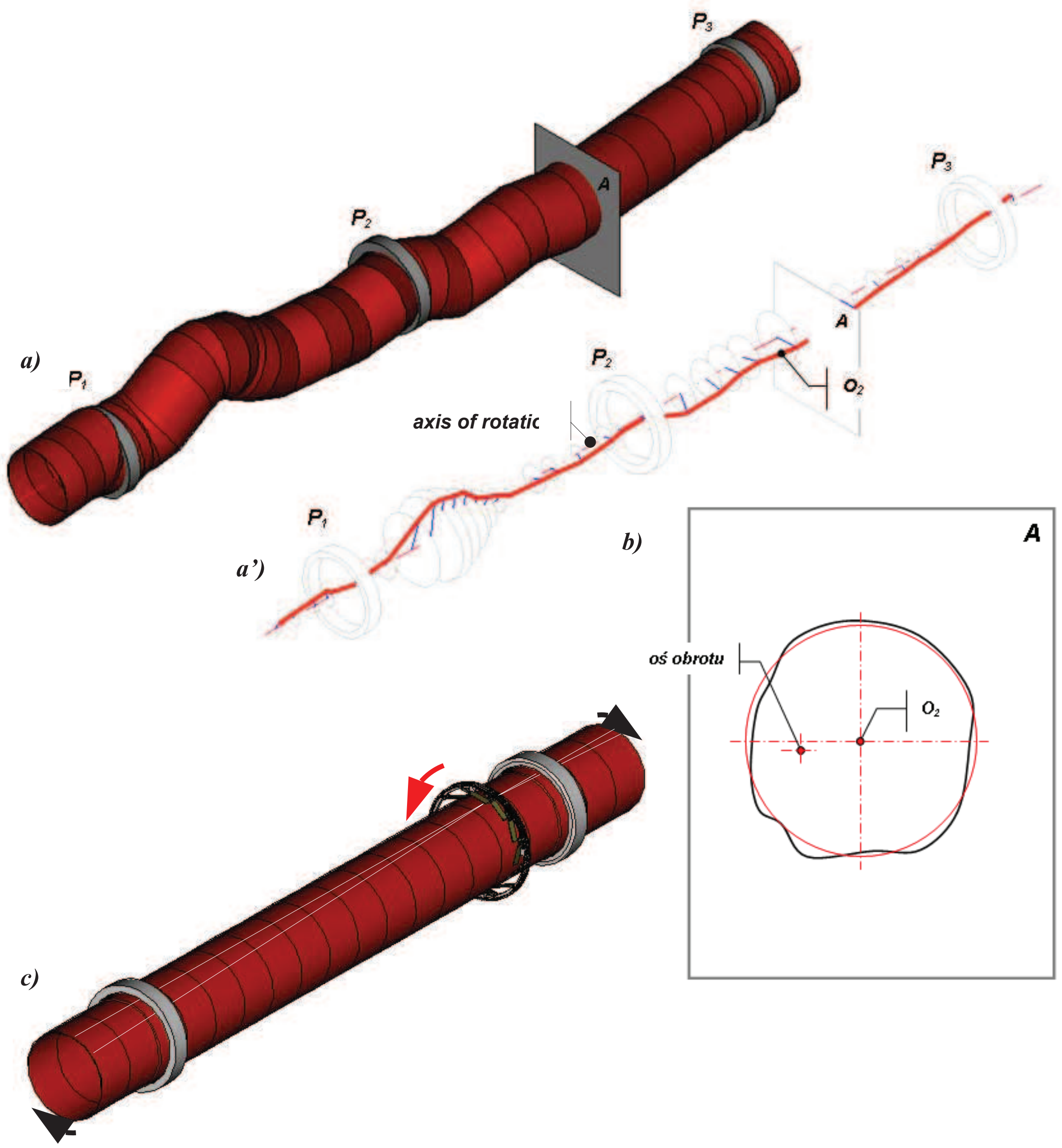

Fig. 2. Schemes of shell deformations' shapes: a) view of bended pipe, a') geometrical axis bending (scheme of O_2 pipe axis o bending of), b) deformation of selected cross-section A (sheet metal plate bending), c) torsion of pipe profile

The most probably, this fact should be connected with then technical level - limited in the relation to the present state. The current development of the technique, especially in the area of electronic devices, allows author to revive and by the way effectively enrich it by new useful possibilities.

The following contents of the article includes theoretical bases and proof of diagnostic effectiveness both the idea as well as the device. It is indispensable to understand the sense of the method
of measurement of rotary drum shell's elastic deformation during object's normal operation and to understand the idea of the instrument designed and implemented by the author to this end.

2. THE TYPES OF THE DEFORMATIONS OF THE ROTARY DRUM’S SHELL

We can classify the deformations of the typical rotary drum's shell according to the three main criterions of: form, reason and permanence of theirs appearance. According to the first of them, we can list (fig. 2):
- deformations of shell’s geometrical axis O_2 (pipe’s axis bending – figures: 2a and 2a’),
- deformations of cross-sections (shell’s sheet metal plate bending – figure 2b),
- torsion of pipe profile (figure 2c).

Next, according to the reason criterion, we can list:
- deformations caused by mechanical factors (incorrect manufacturing of component elements, incorrect assembly, external and self-weight loads),
- deformations caused by thermal factors (e.g. by unequal distribution of temperature – no-uniform on shell‘s circumference).

All of these deformations, mentioned above, we can additionally classify according to permanence of theirs appearance. From this point of view we can list:
- permanent (plastic) deformations,
- temporary (elastic) deformations,

moreover elastic strains can have a cyclic (if they are synchronized with the object’s rotation) or non cyclic character (if theirs values are independent on shell‘s turns).

3. THE ELASTIC OVALITY OF SHELL‘S CROSS-SECTION AND ITS CONSEQUENCES

Deformations of shell's cross-section - elastic and periodically variable, are one of the least desirable and simultaneously the most difficult to the quantitative determination. These deformations are caused by mechanical factors the most often, less by thermal. The under-ring shell’s sections are the places, where it occurs in the most intensive intensity. In these places the elastic shell, mounted with the play inside the ring, changes (self-adjust) its shape to quasi-circular inside diameter of ring. It happens under the influence of shell's self weight and the weight of the internal lining [5]. This adjustment takes place at the bottom and at the side parts of pipe profile. The shell undergoes clear flattening in its upper area and the value of its curvature radius violently grows up there. Schematically, this situation was shown on figure 3.

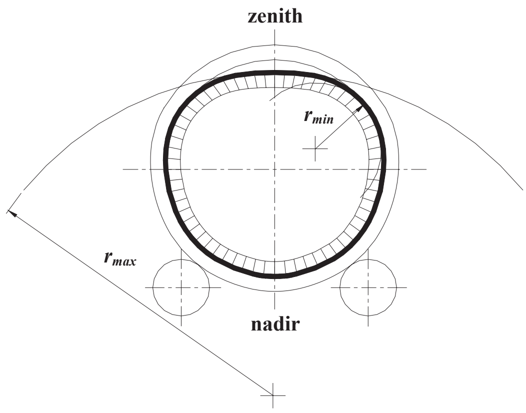

Fig. 3. Scheme of drum’s shell cross-section, where shell’s radius changes from minimal value r_{min} to maximal r_{max}

Thus, during the turn of the object, every point connected with the surface of the shell migrates not on the circle, but over the distorted outline, whose radius of the curvature has different value for every next circumference position of this point. The relative changes of the radius in the function of the angle of the object's rotation can be shown in the form of the graph, how this is presented on drawing 4. These changes of radius mean that the sheet metal plate of the shell undergoes cyclic bending, and this means also that shell's durability should be considered in the aspect of fatigue strength of the applied material.

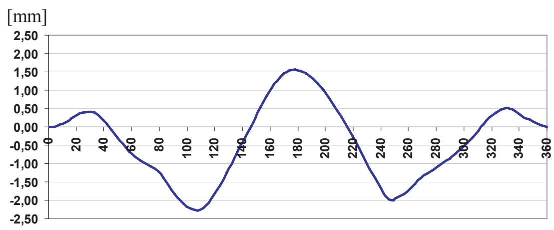

Fig. 4. The example graph of relative changes of curvature’s radius as function of drum’s rotation angle

The cyclic changes of the radius of the shell‘s sheet metal plate also have the influence on durability of the object's internal lining (if the object is equipped with such one). The best, it can be illustrated for furnace lining in the form of wedge-shaped bricks with tapers adapted to nominal - shell's inside diameter. Mainly, such brick lining is applied in rotary kilns.

In the situation when drum turns, his shell undergoes deformation and forces - tensioning and compressing - act on the lining alternately (look at figure 5).

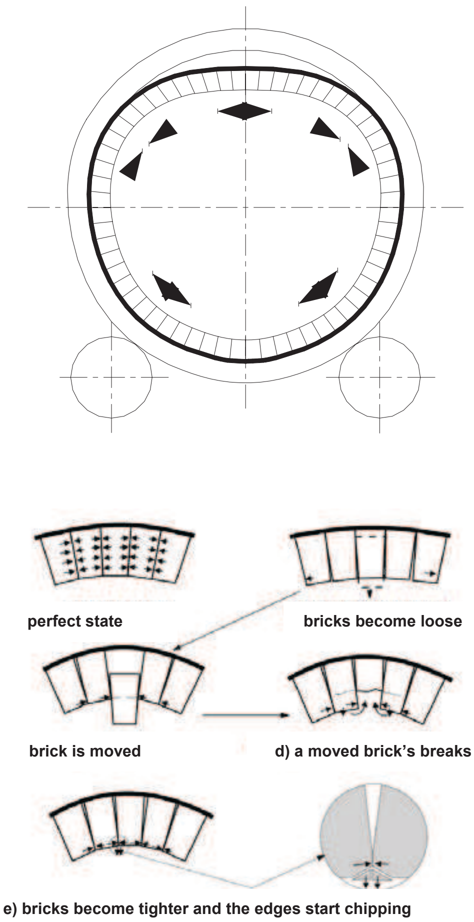

Fig. 5. Scheme of mechanical interaction on rotary kiln's brick lining - example mechanisms of lining's degradation [2]

In connection with intensity of this phenomenon, such alternating forces can lead to the brick falling out or chipping out. Typical mechanisms of lining degradation are shown in figure 5. Figure 3a represents a perfect situation, that is when the shell is not deformed and bricks correctly adjoin each other. The distribution of forces in the contact areas between the bricks is then correct. Figure 3b shows a situation when the radius of curvature increases excessively, the load on the surface of the bricks decreases, and even the gaps between them become wider. When the shell radius becomes large enough, the bricks may move /3c/ or even fall out totally. When a brick falls out, the adjacent bricks become loose, so in consequence it might lead to an extensive reduction of the lining, thus exposing the steel drum shell to high temperatures. If a loosened brick does not fall out but stays in place (fig. 3c), when the circumferential position of the facility changes then as a result of the reducing radius of curvature it will undergo compression (still look at fig. 5c). Such a situation might cause the braking of the moved brick in the cross-section compressed by the edges of adjacent bricks and the chipping out of a large portion of this one. The remaining part will resume its original position, but the lining in this area is already significantly thinner (fig. 5d). In case of smaller radius changes or better fit of the bricks (smaller initial play at installation), the movement of the bricks is limited, but chipping can also be observed. In this latter case, the chipping is caused by micro-losses in the areas of local accumulation of loads – on the edges. This situation is shown in figure 5e.

Degradation mechanisms, presented above, are chosen examples only.

To summarize, the phenomenon of cyclic change of the radius of curvature in the shell cross-section has a detrimental impact on both the life of the shell plate and on the life of drum's internal lining. The said strain is unfortunately inevitable, especially because of the frequent and necessary from the design point of view loose fit between the shell's outside diameter and the support ring's inside diameter. A periodical monitoring and keeping the strain as small as possible is consequently the only method to extend the life of trouble-free drum operation in this area.

Very useful estimator uses to evaluate the elastic strain of the shell cross-section is the parameter called in the scientific literature the elastic shell ovality ratio [3]. The definition of this parameter is based on assumption, that a deformed cross-section of the shell can be sufficiently approximated by an ellipse, i.e. a particular case of geometric figure from general collection of ovals. Then the degree of flattening (ovality) of an ellipse can be described by the following formula:

$$\omega = 2(a - b) \tag{1}$$

where:
a and *b* – length of ellipse semi-axes, suitably major and minor (look at fig. 6).

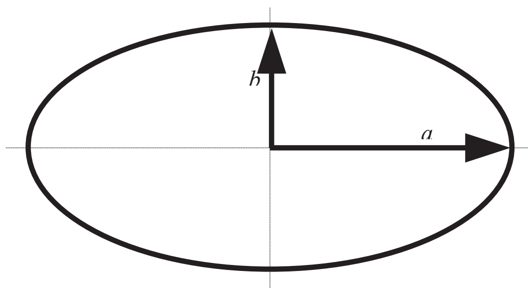

Fig. 6. Ellipse and its semi-axes *a* and *b*

In the reality, the form of the shell cross-section's deformation is more complicated, i.e. ideal symmetry between the individual half of the ellipse is not kept and the angle between the maximum and minimum position of radius doesn't equal 90^0 (go back and look at fig. 3). That is why in reference to the section of drum's shell, generalized ovality has been assumed to present by the formula:

$$\omega = 2(r_{\max} - r_{\min}) \quad (2)$$

where:
r_{max}, r_{min} – cross-sections' radiuses, suitably maximal and minimal (look at fig. 3).

However, the diagnostic parameter, defined in a such way, is still uncomfortable for use. It doesn't give the possibilities of comparison of objects with considerably different dimensions i.e. different shell's diameters. In order to eliminate this shortcoming, parameter called ovality ratio was used [3]. This parameter presents quotient of ovality (mentioned above) and internal – nominal diameter of shell's cross-section. It is expressed by following formula:

$$\omega_0 = \frac{(r_{\max} - r_{\min})}{r} \cdot 100\% = \frac{2(r_{\max} - r_{\min})}{d} \cdot 100\% \quad (3)$$

where:
r, d – suitably, nominal radius and nominal diameter of shell's cross-section.

The measurement of elastic ovality or elastic ovality ratio is reduced to the determination of the volumes r_{max} and r_{min}, and to determination of relative difference between these radiuses - in principle. The nominal diameter of the shell is the well known value.

There are two methods of determination of difference between the maximum and the minimum radius: direct and indirect one. The direct method consists in determination of the small and large axis of the ellipse using geodesy manners. However this method is very labour-consuming, technically burdensome and sufficiently exact only for the large deformations of the cross-section. The indirect method consists in measurement of the maximum change of the deflection of the curvature - on the one meter long circumference's part - during drum's rotation. It is made using special device and calculating ovality ratio is based on simplified formula:

$$\omega_0 = \frac{4}{3} d\sigma \cdot 100\% \quad (4)$$

where:
d – inside, nominal diameter of shell's cross-section [m], σ – maximal difference of deflection of curvature [m], determined on chord 1-meter long ($L = 1m$), according to figure 7.

It is possible to find the derivation of above formula in the study [3]. The device is characterized in the next chapter, and it is the implementation of presented idea of measurement of shell's cross-section's elastic ovality.

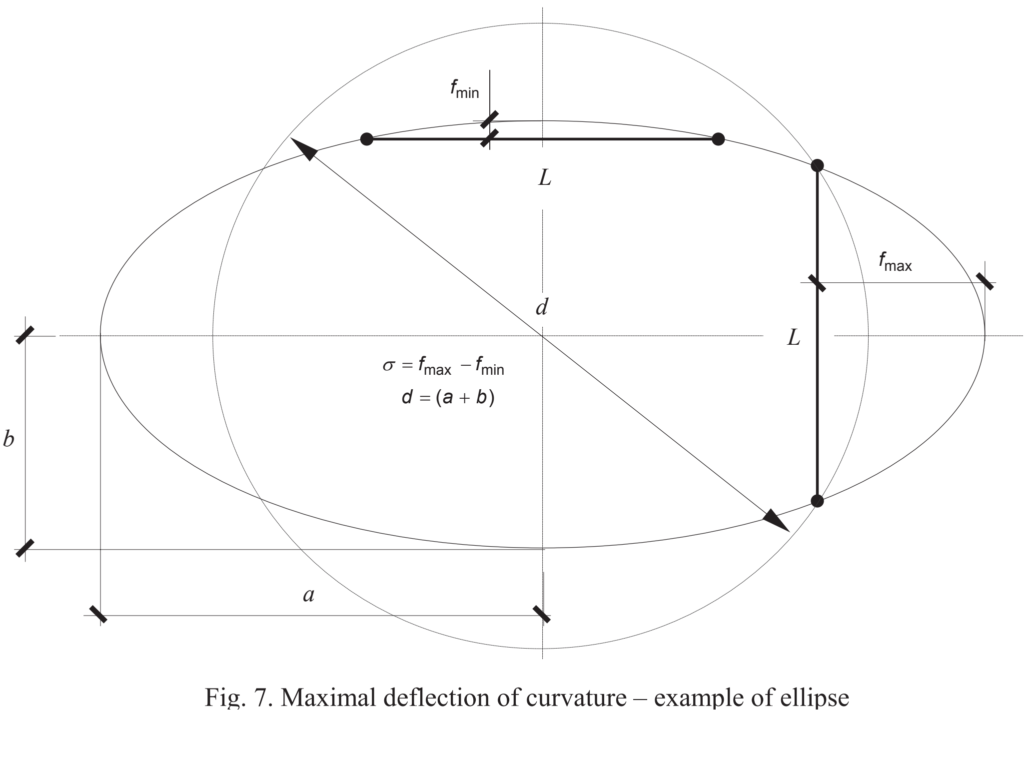

Fig. 7. Maximal deflection of curvature – example of ellipse

4. SHELLTESTER – CONSTRUCTION AND PRINCIPLE OF OPERATION

General structure of the device, called Shelltester, is presented in figure 8.

The device in the form of one-meter beam, according to measurement idea showed in figure 7, is installed by magnetic feet to the shell's external surface and it - turning with the object - measures continuously indications of electronic pin gauge, which is installed in the middle of distance between feet. These indications show relative changes of deflection *f* and are sent – with the help of radio-modem (built-in inside device's body) to radio receiver, connected to computer PC class. There, with the help of computing program – written by author – data is recorded and next is suitable processed and analyzed. Each measurement, thanks to inclination sensor - built-in device - is released and stopped in automatic mode – in the moment while device moves by so called nadir point.
Picture of device „in action" is showed in figure 9.

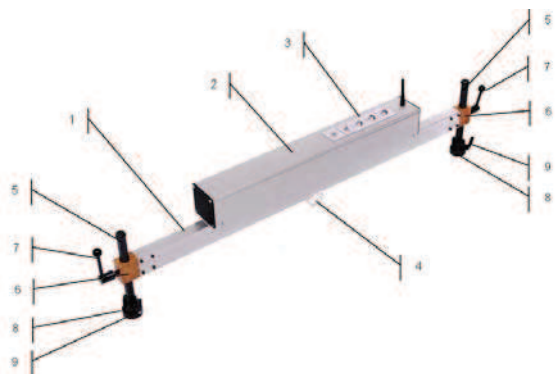

Fig. 8. Scheme of Shelltester's construction:
1 – carrying beam, 2 – body, 3 – control panel,
4 – terminal of electronic pin gauge, 5 – feet,
6 – guides of feet, 7 – clamps of feet,
8 – magnetic basis of feet,
9 – clamps of magnetic basis of feet

Fig. 9. Shelltester mounted on the rotary kiln's shell

5. SHELLTESTER – ROUTINE TESTS SCOPE, DIAGNOSTIC POSSIBILITIES

The routine test programme, assumed by author on the basis of his knowledge and experience - have been gained till now, includes installing device (measurements) on each drum's support - in two shell's cross-sections - inlet and outlet, i.e. close by front of and just behind the ring (fig. 10). In each measurement planes, the device is located in three places on the circumference (A, B and C), arranged every 120^0. Together, on every support (near every ring) it is made six measurements. This causes, that for the most typical - triple-support drum, the number of instrument's installations amount 18.

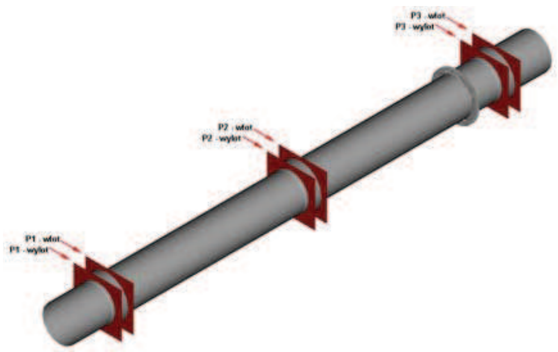

Fig. 10. Measurement planes for routine test scope for triple-support kiln

For such chose diagnostic programme, there are opportunities:

1. to determine the value of maximum degree of shell's elastic ovality ratio in every one from measured cross-sections and to compare the results to the allowable value - defined for given diameter and thickness of the sheet metal plate of the shell.
   The analysis, made by the author, shows that the ovality ratio of under-ring shell's sections should be placed below curves given on graph presented in figure 11. There, upper line is determined for minimal, and lower line for maximal values of shell's steel plate thickness – for given pipes' inside diameters, which presents domain of graph.
   The author foresaw to publish the calculation of these allowable limits, within separate article in the next future,
2. to execute the qualitative estimation (individual and comparative) of all gathered curves of deflection's changes in the function of rotation angle of the drum (for each cross-section and for each circumference position). Utilitarian example of such possibility is presented in the next chapter. There is selected results from measurements performed for: rotary lime kiln, which has been operated in Mondi Świecie S.A and rotary kiln number 4 for clinker baking, located in Rudniki Cement Plant.

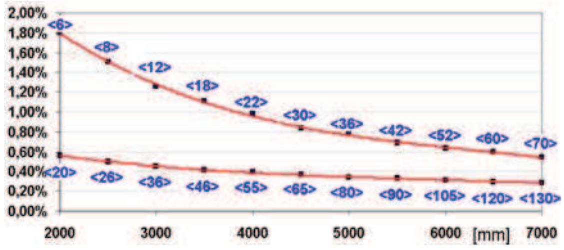

Fig. 11. The allowable limits of elastic ovality ratio of shell's cross-section in the function of inside diameter for suitable: minimal (upper curve) and maximal plate's thickness (lower curve). Plate thickness of shell are given in the brackets

6. EXAMPLE ANALYSIS OF VALUES AND OF OVALITY CHARTS

6.1. The rotary kiln (Mondi Świecie S.A.)

Measurements were executed 21st July 2009. The basic parameters of the object's shell and the conditions of the measurement are presented in table 1. The statement of got results of measurement in the form of the graph of cross-section's ovality ratio - on individual supports - is showed in figure 12. Example ovality curves, gathered on one of the kiln supports, are presented in figure 14. The shell unit with the largest elastic deformations of its cross-sections was chosen to the analysis (i.e. the support P2).

On the basis of such selectively presented results, it can be stated (diagnosed), as it follows:

- the average ratio of the shell elastic ovality on the support P2 is close to the allowable value, and for the case of the circumference position A of device - in the inlet cross-section – it is observed even overflow of accepted limit, what threatens with appearing the fatigue cracks of the shell,
- ovality curves for measurements realized for various circumference positions don't overlap, but this situation is almost the same both for the cross-section - located on the inlet and on the outlet side. This suggests stable (plastic) deformation of under-ring shell section and/or occurrence of the geometrical eccentricity of the shell's axis in reference to the axis of revolution. Because of the fact, that this un-overlapping on circumference positions corresponding with positions of rollers (30^0 and 330^0) is only slight, it is more probable that stable - significant value - shell's deformation is the main cause of this situation,
- curves which present average graphs for measurement made on A, B and C position - for the inlet and outlet cross-sections - are almost the same, what, connected with information about clear symmetry reference to vertical plane (determined by angle 180^0), shows that rollers' position are correct (the symmetrical load distribution, the uniform thrust on both rollers, correct slope of the rollers' shafts).

6.2. The rotary kiln (Cemex Polska Sp. z o.o. – Rudniki Cement Plant)

Measurements were executed 12th August 2009. The basic parameters of the object's shell and the conditions of the measurement are presented in table 1. The statement of got results of measurement in the form of the graph of cross-section's ovality ratio - on individual supports - is showed in figure 13. Example ovality curves, gathered on one of the kiln supports, are presented in figure 15. The shell unit with very high elastic deformations and simultaneously regards by the author as the most interesting from the diagnostic point of view was chosen to the analysis (i.e. the support P5).

On the basis of such selectively presented results, it can be stated (diagnosed), as it follows:

- the average ratio of shell elastic ovality on the supports P4 and P5 significantly exceeds values accepted as allowable limits. This fact should be connected with considerable eccentricity of shell geometrical axis in reference to object's axis of rotation, and also, especially in the case of P5 support, with increased value of under-ring gap (19,7mm – look at tab. 1). Measured values give the basis to the fears, that fatigue cracks of shell plate can appear. It simultaneously arise a doubts in the range of the life time of the internal kiln lining,
- the fact, that ovality curves from A, B and C device's position don't overlap mutually (it is visible also on angular co-ordinate 30^0 and 330^0), supports opinion about existing eccentricity,
- curves which present average graphs for measurement made on A, B and C position - for the inlet and outlet cross-sections - don't overlap. It suggest wrong rollers' positions (theirs wrong slopes) or occurrence of gaps in the contact between them and ring's raceway - on the outlet side of ring. I can be effect of e.g. taper shape of ring and/or taper shapes of rollers' raceways. Curves on the outlet side show distinct change of shell's radius, as an effect of rollers' load reactions. The same symptom doesn't exist on the inlet side.

Table 1. The basic parameters and measurement conditions for:
- lime kiln (Mondi Świecie S.A.),
- clinker kiln no.4 (Cemex Polska Sp. z o.o. – Rudniki Cement Plant)

kiln - Świecie	**Support #1**	**Support #2**	**Support #3**	**Support #4**	**---**	
shell's inside diameter	3750	3750	3750	3750	---	mm
thickness of shell's plate	45	45	45	45	---	mm
* under-ring gap	4,0	4,5	6,9	3,7	---	mm
** allowable ovality ratio	0,309	0,309	0,309	0,309	---	%
kiln no.4 - Rudniki	**Support #1**	**Support #2**	**Support #3**	**Support #4**	**Support #5**	
shell's inside diameter	3750	3750	3450	3750	3750	mm
thickness of shell's plate	60	60	60	60	60	mm
* under-ring gap	lack of data	lack of data	2,5	8,9	19,7	mm
** allowable ovality ratio	0,335	0,335	0,310	0,335	0,335	%

* determined during measurement using Shelltester, as difference of mean values of ring's inside diameter and shell's outside diameter,

** given on the basis of chart from figure 11, as approximation of suitable values.

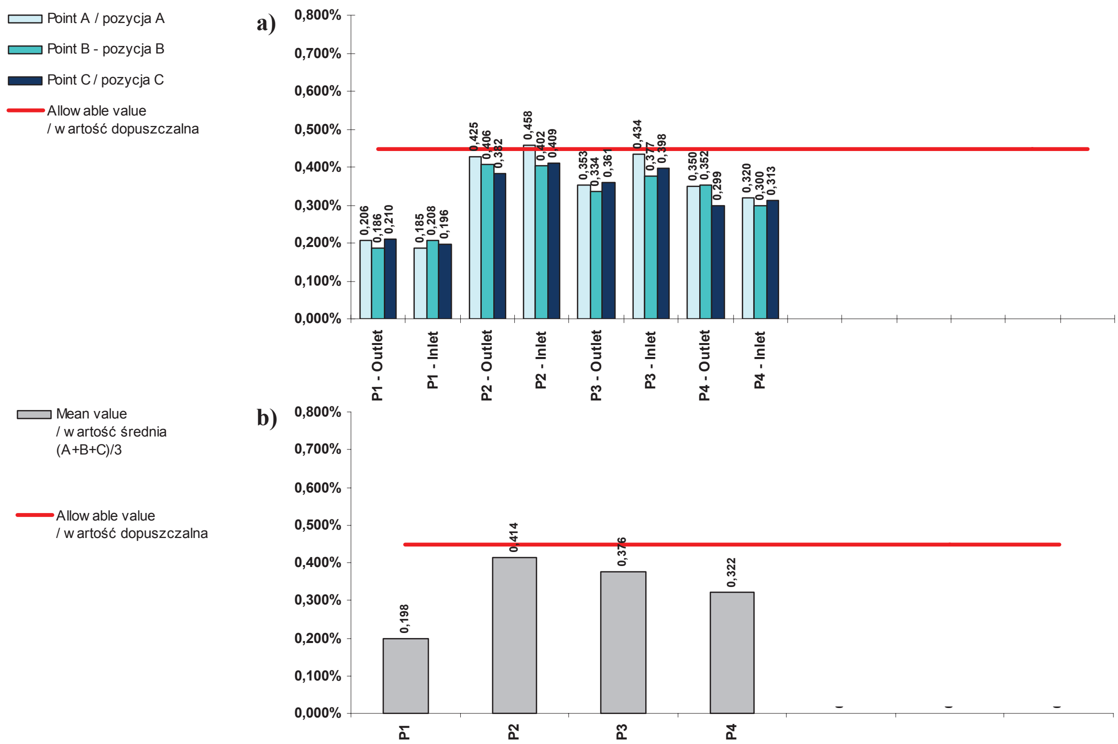

Fig. 12. Values of elastic ovality ratio of shell's cross-sections (kiln from Mondi Świecie):
a) detailed values, given for each plane and each circumference position of device,
b) mean values from particular supports

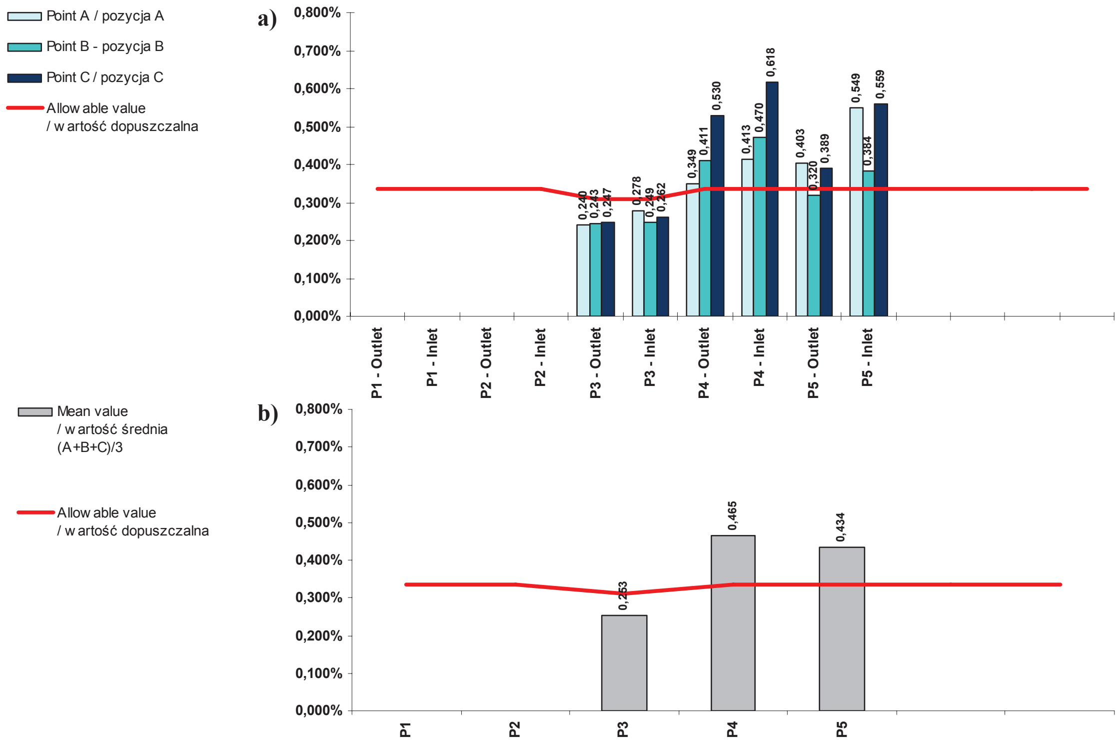

Fig. 13. Values of elastic ovality ratio of shell's cross-sections (kiln no.4 from Rudniki Cement Plant): a) detailed values, given for each plane and each circumference position of device, b) mean values from particular supports.
According to too high temperature of shell, measurements for P1 and P2 supports wasn't executed

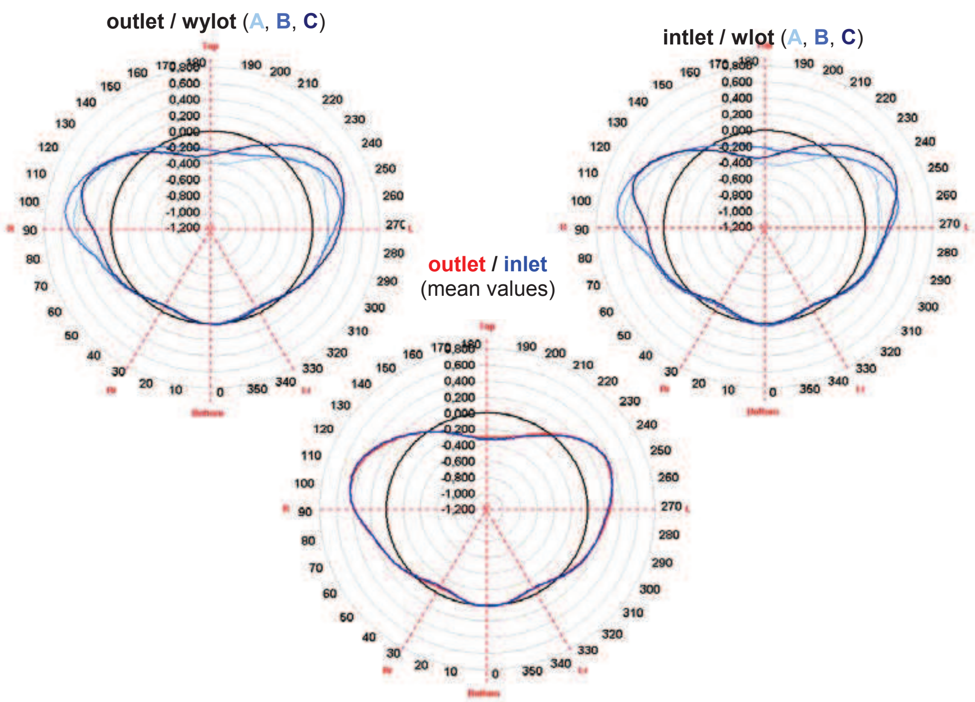

Fig. 14. Ovality curves i.e. changes of shell deflections *f* (kiln from Mondi Świecie – support P2)

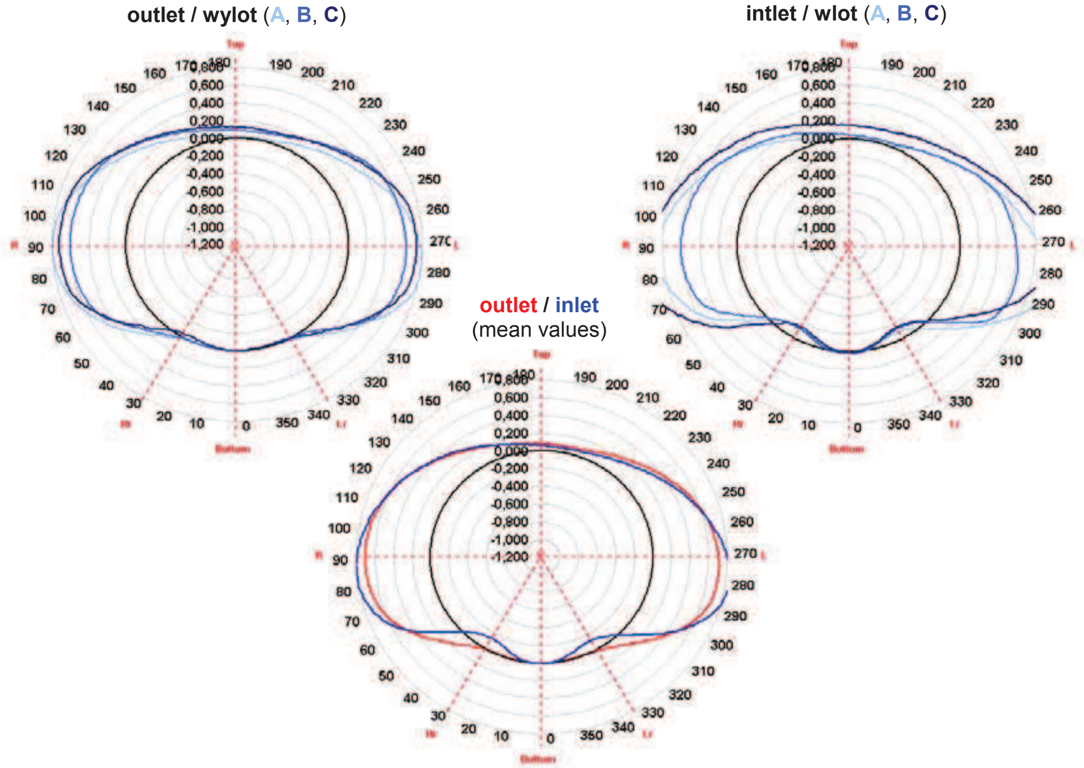

Fig. 15. Ovality curves i.e. changes of shell deflections *f* (kiln no.4 from Rudniki Cement Plant – support P5)

6.3. The comparative analysis of kiln's state

After detailed comparison of values and graphs got for both kilns, it can be established that:

- kiln located in Rudniki cement Plant is an object with clearly worse technical state. In spite, that the diameter of his shell has the same value as in the case of kiln from Świecie (except of the P3 support), elastic deformations of his shell's cross-sections are significant higher (even about 50%),
- this is particularly dangerous in the aspect of the fact that thicknesses of the shell's under-ring segments in Rudniki are indeed larger than in Świecie (60mm versus 45mm),
- un-overlapping curves got on circumference positions A, B and C is particularly visible on kiln located in Rudniki, where this situation appears on the whole kiln's circumference. In the case of kiln located in Świecie, un-overlapping exists for angles from 70^0 to 320^0, what is the natural range of circumference - if there is under-ring gap. This situation shows, that in Mondi problem of ovality comes from under-ring gaps and for kiln located in cement plant higher values of elastic shell's ovality are derivative of additional irregularities in the form of errors in shell's geometry and in the form of shortcomings in the positions of support system's components (wrong rollers' setting).

7. SUMMARY, CONCLUSIONS

Contents, given in the present publication, can be sum up, as follows:

1. method and device to the rotary drum's technical state's evaluation by measurement and analysis elastic ovality of the shell's cross-sections give very rich diagnostic information,
2. this information - first of all it is the quantitative determined value of the elastic ovality and secondly the graphs of the changeability of the shell's deflection in the function of the angle of the drum's rotation,
3. first of mentioned diagnostic parameters - after comparing to the appointed allowable limit - gives clear-cut view on the risk of appearing fatigue cracks in the drum's steel shell. Moreover this shows the danger of the lowering durability of the internal object's lining, if object is equipped in such one,
4. the graphs of the changeability of the shell's deflection are the derivative of changeability of the curvature radius during drum's rotation. The mutual comparison of these graphs - collected curves (in the range of section, support, the object, and even in the reference to different drums) gives possibilities for evaluation of their shapes and for the qualitative determination

of reasons - causing the departures from expected form,

5. these departures make up the qualitative symptoms of deviation from drum's normal mechanical conditions, and they include both basic mistakes in the geometry of the support system (including rollers positions) and more subtle irregularities, which can take place in the area
of shell,
6. thanks to such set of diagnostic information, described method and device become very valuable tool, which help to estimate the technical state of the object - rotary drum type,
7. next enrichment of the analysis may constitute described way and device in the rank of one of the most effective diagnostic performances. The author plans to do it within the next future. He intends to enrich method about the quantitative estimation of detected irregularities, which distort shapes of ovality curves.

8. LITERATURA

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