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AN INVESTIGATIONS OF DISPLACEMENTS AND DEFORMATION DURING COLD ROLLING OF TUBES IN PILGERING PROCESS

BADANIA PRZEMIESZCZEŃ I ODKSZTAŁCEŃ W PROCESIE WALCOWANIA NA ZIMNO RUR W WALCARCE PIELGRZYMOWEJ

The method of the calculation of strain distribution is based on the measurements of the displacements along the length and transverse cross-section of the conical working zone. Two measuring methods have been used. In the "classical" method the typical measuring microscope equipped with goniometric table has been used. The second method based on the photogrammetric analysis of the pictures has been elaborated and proved by authors. The special computer program has been elaborated for the photogrammetric image analysis and the later final results receiving. This method can be recommended as the best for using in the practice of researches carried out at the real object. The experiments carried out during the rolling of condenser tubes using pilgering process show that the each transverse section of input tube is twisted during successive working cycles.

Keywords: pilgering process, field of deformation, image analysis, physical modelling

W pracy zastosowano metodę określania rozkładu odkształceń w kotlinie odkształceń stożka roboczego w oparciu o pomiar przemieszczeń punktów na wzdłużnym i poprzecznym przekroju walcowanego metalu. W metodzie "klasycznej" zastosowano mikroskop pomiarowy, wyposażony w stolik goniometryczny. Druga metoda zastosowana przez autorów była oparta na analizie fotogrametrycznej. Oryginalny program komputerowy został opracowany w celu przeprowadzenie fotogrametrycznej analizy obrazu oraz uzyskania końcowych rezultatów. Sposób ten jest rekomendowany przez autorów dla realizacji badań wykonywanych na obiektach przemysłowych. Eksperymenty pomiarowe wykonane podczas walcowania pielgrzymowego rur kondensatorowych na zimno w warunkach przemysłowych, wykazały, że każdy poprzeczny przekrój walcowanej rury doznaje skręcenia w kolejnych cyklach procesu odkształcania.

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1. Introduction

Experimental determination of metal deformations in the tube cold rolling process in pilger mills possess a lot of technical problems. High speed of the rolling stand in the reciprocating motion makes immediate switching off in a precisely selected point of the rolling zone impossible. Compact and closed structure of the rolling mill, in particular of its working space, makes impossible to place sensors for measuring deformations, connecting measuring signals to the amplifying and recording equipment and protecting them against impact of high-pressure rolling emulsion mist. Therefore, the physical modelling method is often applied in investigations of deformation area in the cold tube pilgering process.

This paper presents a solution of the method for measuring the field of deformations in the working cone under real conditions of the pilgering process. The field of deformation in the working cycle has been determined on the basis of measurements of the distribution of displacements along the length and on the cross-section of the working cone. The investigation was conducted under real conditions of the condenser tube cold rolling process by using the KPW75YM pilger mill. For measurements of displacements the photogrammetric method designed by the authors was applied, with the use of digital photography and computer image analysis and processing. Displacement values determined for multiple cross-sections (with pins) of the working cone were the basis for calculating components of the state of strain with formulae indicated in this paper. High precision of this measurement method has been confirmed, and very fast development of results is its advantage.

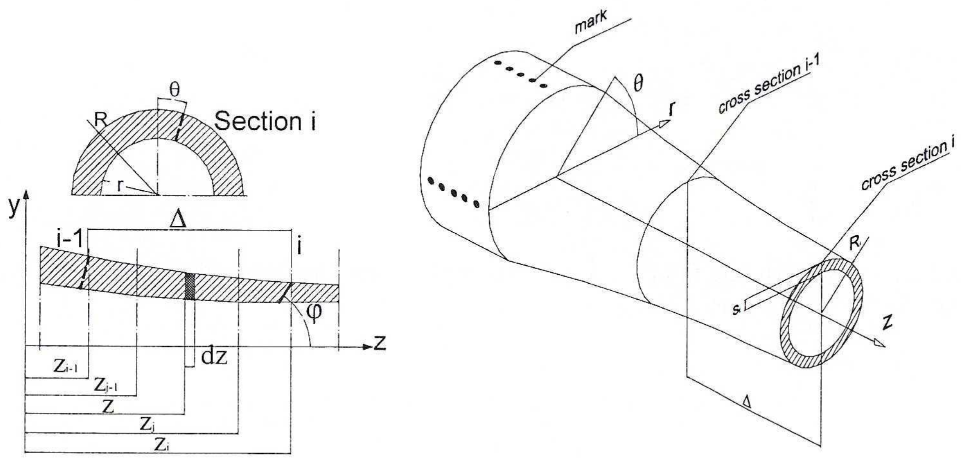
2. Analysis of metal deformations during tube cold pilgering process

The technological process takes place in modern, high-speed rolling mills with compact and closed structure. Due to this reason, the research of the state of strain on real objects is very complex, expensive and possible in limited range only [1]. Therefore, physical [2] and mathematical modelling techniques are often used; the latter in connection with computer simulation [3–5].

The complex and very in-depth theoretical analysis of the cold pilgering process was presented by Munekatsu and Chichiro [5]. When, according to the theory of plasticity, we assume the description of the state of stress in the temporary working zone with the Hencky's equations, the von Mises plastic flow and the conditions of equilibrium of internal forces, we obtain a complex set of equations, whose numerical solution defines distribution of radial stresses σ_r and circumferential stresses σ_θ on the selected cross-section of the working cone.

The subject matter of investigation includes displacements in the working cone and their changes in subsequent cycles. Experimental determination of these values allow to determine the field of deformations in the whole working cone with the method described below. When the cylindrical co-ordinate system r, θ, z is assumed, in which the z axis overlaps the rolling direction, the components of deformations in any cross-section are defined with the tensor in the form of:

$$\begin{vmatrix} \varepsilon_{rr} = \dfrac{\partial \mathbf{u}_r}{\partial \mathbf{r}} & \varepsilon_{r\theta} = \dfrac{\partial \mathbf{u}_r}{\mathbf{r}\partial\theta} + \dfrac{\partial \mathbf{u}_\theta}{\partial \mathbf{r}} - \dfrac{\mathbf{u}_\theta}{\mathbf{r}} & \varepsilon_{rz} = \dfrac{\partial \mathbf{u}_r}{\partial \mathbf{z}} + \dfrac{\partial \mathbf{u}_z}{\partial \mathbf{r}} \\ & \varepsilon_{\theta\theta} = \dfrac{\mathbf{u}_r}{\mathbf{r}} + \dfrac{\partial \mathbf{u}_\theta}{\mathbf{r}\partial\theta} & \varepsilon_{\theta z} = \dfrac{\partial \mathbf{u}_\theta}{\partial \mathbf{z}} + \dfrac{\partial \mathbf{u}_z}{\mathbf{r}\partial\theta} \\ & & \varepsilon_{zz} = \dfrac{\partial \mathbf{u}_z}{\partial \mathbf{z}} \end{vmatrix} . \quad (1)$$



a *b*

Fig. 1. a) Pins deformations in cross-sections *i* (actual) and *i*-1 (conventional) including stroke volume (in general, the *i*-1 and *i* cross-sections are located between the *j*-1 and *j*+1 control cross-sections), b) The working cone with the pins marked

Strains in the pilgering process are dependent on the stroke. According to **Figure 1**, when we assume that between the *i*-1 and i cross-sections, distant by $\Delta = z_i - z_i - 1$, the stroke volume is $V_m = mF_w$. When the pass spacing is neglected, no major error will follow then, assuming the functions of variation in the external radius $R_z = f_1(z)$ and in the internal radius $r_z = f_2(z)$ as given in the calibration table (in the discreet way), one may calculate the volume between any two cross-sections distant by 1:

$$V_{str} = \int_l F_z dz = \pi \int_l \left(R_z^2 - r_z^2 \right) dz . \quad (2)$$

With the relationship (2) one can determine the distance Δ on the way of numerical integration (e.g. with the trapezoid method), until the following condition is met:

$$V_{str} = \pi \sum_{k=1}^{n} \Delta V = \pi \Delta z \sum_{k=1}^{n} \left(\mathbf{R}_k^2 - \mathbf{r}_k^2 \right) \geq V_m . \tag{3}$$

It is possible to assume that the linear displacements along the rolling direction define an increment of the distance between pins $u_z = l_k - l_{k-1}$ and the angle of pin inclination φ (**Figure 1 a**). An angular displacement (twist) of the cross-section is described by the increment $\Delta\theta$ angle e.i. $\Delta\theta = \theta_k - \theta_{k-1}$ working cycles. With this assumption, the following may be obtained:

$$\varphi_i = \operatorname{arctg} \frac{z_A - z_B}{y_A - y_B}$$

$$z_{i'-1} = (R_{i-1} - r_{i-1}) \operatorname{tg} \varphi_{i-1} \qquad z_{i'} = (R_i - r_i) \operatorname{tg} \varphi_i$$

$$\frac{u_\theta}{r} = \frac{\Delta\theta}{R_i}; \qquad \frac{u_r}{r} = \frac{R_i - R_{i-1}}{R_i}$$

which, after substituting in (1) and not so complex transformations leads finally to (as an example for the external layer):

$$\left| \begin{array}{lll} \varepsilon_{rr} = \dfrac{R_{i'-1} - R_{i'} - R_{i-1} + R_i}{R_{i-1} - R_i} & \varepsilon_{r\theta} = -\dfrac{\Delta\theta}{R_i} & \varepsilon_{rz} = \dfrac{R_i - R_{i-1}}{l} + \varphi \\ & \varepsilon_{\theta\theta} = \dfrac{R_i - R_{i-1}}{R_i} & \varepsilon_{\theta}^{z} = \dfrac{\Delta\theta_i}{\Delta_i} \dfrac{u_{zi}}{R_i} \\ & & \varepsilon_{zz} = \dfrac{u_{zi}}{\Delta_i} \end{array} \right| . \tag{4}$$

and for any layer after substituting appropriate radii.

3. The method of strains measuring in the working cone

In order to determine the distribution of deformations along the length and on the cross-section of the working cone, a tube was rolled with drilled holes, in which pins were placed. The holes were located along four generating lines at the distance of every 20 mm, at least 30 in each of them, spaced every 90° over the circumference of the input tube. These should be made of material in different colour from that of the matrix (the tube material). The investigations performed during the cold pilgering rolling of brass tubes the holes were fulfilled with copper rivets. During the experiments, rolling speed should not exceed 40 strokes per minute as the rolling mill must be stopped in a very precise moment, when the first rolled pins make up the complete tube. After rolling, a working cone should be cut out with visible pins, their location should be determined in the global Cartesian co-ordinate system (**Figure 1b**), and then the section should be divided into rings and surfaces should be uncovered with pins in the longitudinal direction and across the rolling direction (**Figures 2a** and **b**).

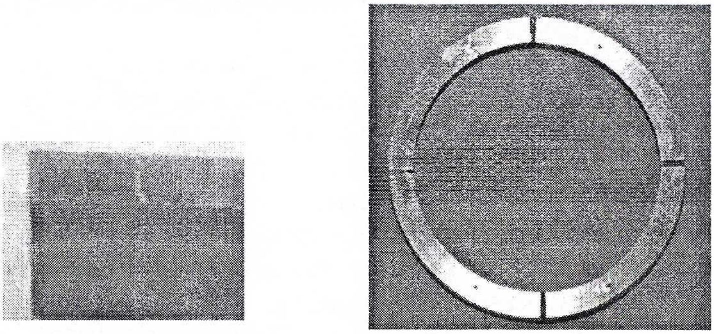


Fig. 2. The cross section of the uncovered sticks: a – longitudinal, b – lateral

In order to determine the field of deformations in the longitudinal and lateral cross-sections of the working cone, pins displacements should be measured (**Figure 1**).

Measurements of deformations may be performed with two methods: on the way of a direct measurement over the surface of he prepared samples or by taking photos of the examined surface and measurements with photogrammetric method. The latter method, combined with the performance parameters of modern digital cameras and computer technology enables very fast and high-precision processing of measurement results.

These are the reasons why the authors recommend it here. Before taking photos, a special working stand should be set up to enable taking photos with the microsection surface parallel to the photopgraph surface inside digital camera. To eliminate the possible parallelism errors of these surfaces, the "four point" method is applied, used in photogrammetry for processing aerial photographs or for measuring deformations in poles and buildings. One may assume that modern photographic techniques (especially under laboratory conditions) ensure very precise photo-taking. Then, calculating the real coordinates of the $P(X,Y)$ point of the object is possible on the basis of the photo co-ordinates (x, y graphic) using the m scale coefficient:

$$X = mx; \qquad Y = my, \tag{5}$$

where: $m = \frac{Y}{y} = \frac{X}{x}$.

4. Results of the state of strain investigations in the cold pilgering of capacitor tubes

Investigations of the field of deformations in the working cone during pilgering of tubes was conducted under following conditions:

- The KPW75YMR rolling mill.
- The rolling program: 76×6 –> 40×2 brass, MA77 grade.
- A single stroke of the mill stand TMP: 16 [mm].
- Rolling speed: 50 [strokes per minute].

Tool shape: according to the licensed calibration by Mannesmann – Meer.

Measurements of deformations in the working cone were performed according to the method described in chapter 3 of this paper. The input tube section with copper pins placed along four generating lines (every 90°) have been rolled. After measuring pin location, uncovering their surfaces and taking photographs with a digital camera, displacement measurements were performed with the photogrammetric method. Introductory results of strain analysis in the pins laying along the rolling direction but located in the same cross-section and originally placed in four different generating lines showed that there is no significant difference in their strain values. Each of the generating lines is then twisted in subsequent working cycles by the θ angle. No cross-section non-dilatational strain in of any of the four pins were found. It means that the uniform deformations in each of the cross-sections exists, and that the pin longitudinal displacements do not depend on its original location in the cross-section.

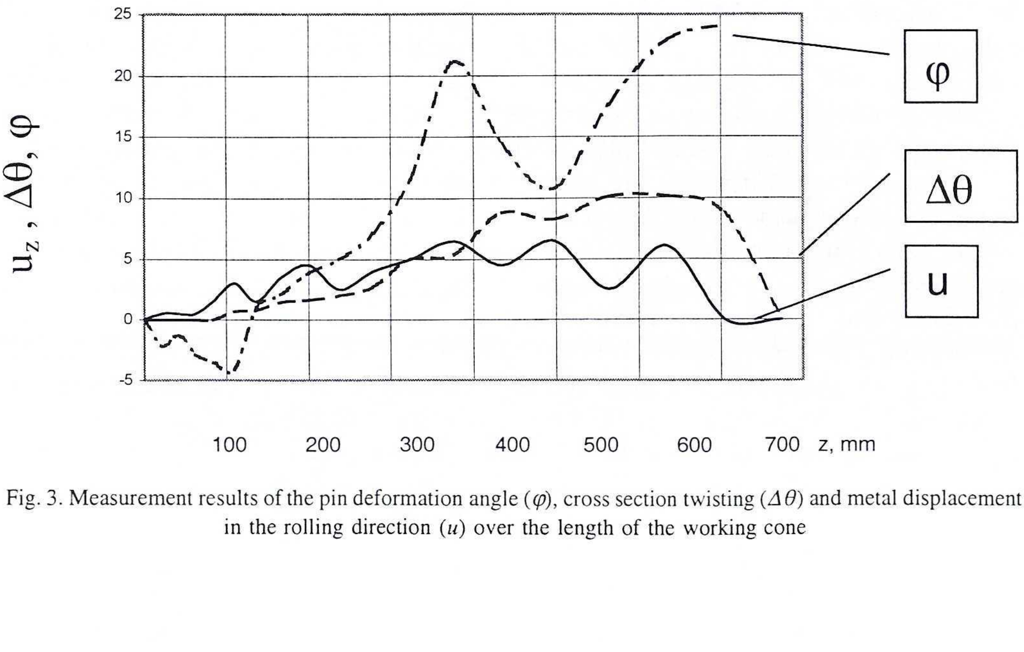


Fig. 3. Measurement results of the pin deformation angle (φ), cross section twisting ($\Delta\theta$) and metal displacement in the rolling direction (u) over the length of the working cone

Results of measurements of the pin longitudinal displacements and the cross-section twisting was processed statistically and the relationships were set: the angle of the longitudinal deformation of the pin $\varphi = f(z)$, the angle of the cross-section twisting $\Delta\theta = f(z)$ and the metal displacement $u_z = g(z)$ which is presented in **Figure 3**.

Prepared measurement results after using the described method and taking into account the relationships (2), (3), (4) and (5) allow to determine the equivalent strain distribution along the working cone, as given in **Figure 4**.

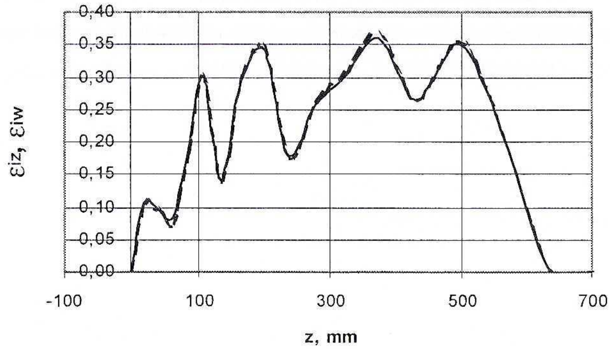


Fig. 4. Changes in equivalent strain over the length of the working cone brass tube cold pilgering

5. Conclusions

1. The conducted investigation of the field of deformation in the working cycle in the working cone for the real conditions of the cold pilgering tube process confirms that the adopted theoretical assumptions allow the significant simplification of the procedure of the field of deformation determining.
2. The described method of the field of deformation investigations in the working cycle of the cold pilgering of tubes allows to verify the experimental results obtained up to now on the way of physical or mathematical modelling. The proposed method is relatively simple and cheaper in comparison to actually used. This method may be recommended for performing research and investigations of the process under industrial conditions without the necessity of long production stoppages.

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