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DEVELOPMENT OF A METHOD TO DETERMINE DEFORMATIONS IN THE MANUFACTURE OF A VEHICLE WHEEL RIM

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Прагнення передбачити і прогнозувати якість виготовленої продукції, її відповідність технічним вимогам замовника на стадії проектування технології призводить до розробки різних методів теоретичного аналізу процесів пластичного деформування. Їх метою є встановлення явних закономірностей процесів, що реалізуються за допомогою інтуїтивно зрозумілих математичних функцій.

Сформульовано метод визначення відносних деформацій при локальному формозміненні замкнутої оболонки обертання способом радіально-ротаційного профілювання. Показано, що на підставі отриманих аналітичних залежностей можливе прогнозування розмірів напівфабрикату на стадії проектування технологічного процесу. На даний час аналітичних виразів, які б оцінювали однозначну залежність деформацій від співвідношення радіусів роликів, заготовки та величини подачі, не існувало. Встановлено, що величина відносних деформацій в трьох взаємноперпендикулярних напрямках залежить від співвідношення діаметральних розмірів деформуючих роликів і початкового діаметра заготовки. Порівняння результатів розрахунку, отриманих в даній роботі, з експериментальними даними та існуючими виразами дає підставу вважати, що даний метод розрахунку володіє прийнятною для виробництва точністю. Це дає можливість керувати полем напружень і деформацій з метою виготовлення однаковоміцного обіду колеса на стадії підготовки виробництва і проектування технологічного процесу. Застосування на практиці даного методу розрахунку дозволить технологам і конструкторам враховувати деформаційне зміцнення після кожного переходу профілювання, визначати операційні розміри напівфабрикатів і прогнозувати товщину готового виробу в радіусних переходах профілю, тобто інтенсифікувати розглянутий процес

Ключові слова: центральний струмок, посадкова полиця, радіально-ротаційне профілювання, обід колеса, деформаційне зміцнення, локальне стоншення

1. Introduction

Methods of local plastic deformation of billets in a cold state are considered sufficiently productive and promising metal forming processes [1, 2]. They are characterized by a decrease in efforts through the limitation of the site of plastic deformation and, accordingly, they allow the use of low-power equipment, provide for the possibility to change a shape of difficult-to-deform metals, as well as permit manufacturing the products with a predefined set of mechanical characteristics [3, 4].

Radial-rotational profiling is one of the methods for local plastic deformation of closed shells, which is used to fabricate bodies of rotation with a preset profile in the axial section. A given process is mostly common at industrial production of steel wheel rims for transportation vehicles and agricultural machinery [5]. As far as this process is concerned, there is an unresolved task to analytically calculate deformations and dimensions a of semi-finished product. This is due to a combination, in a single run, of the processes of expansion and crimping, to which different parts of a billet are exposed and, hence, their mutual influence on the resulting dimensions of a semi-finished product. The presence of dependences that establish the relationship between the geometry of a tool, of a billet, of a finished product, will make it possible to determine the required deformation at each profiling run. Hence the shortening of terms for technical preparation of production, savings of energy and material resources, additional time for readjusting the equipment, as well as the scientifically-substantiated techniques to improve a given process.

2. Literature review and problem statement

Determining the deformations and operating dimensions of a billet at radial-rotational production mode of wheel rims is sufficiently complex in character and is radically different from similar calculations employed in the traditional methods of sheet metal stamping. Thus, papers [6, 7] show that the coefficients of crimping and expansion, and deformation respectively, unambiguously depend on the diameter of the billet and the resulting product and are governed by conicity of the punch and its diameter. Determining the coefficients of crimping-expansion analytically poses no difficulties. In the sheet metal profiling processes, being the most similar to the radial-rotational profiling, deformation tensor components depend on the geometrical dimensions of the resulting stream, which directly correlates with the geometry of a molding tool. This circumstance makes it possible to calculate the longitudinal and transverse deformations based directly on the depths of tool penetration at each intermediate operation, up to the finished product [8, 9]. Thus, paper [10] defined action zones of the largest radial deformations using the method of finite-numerical modeling for a limited range of profile standard dimensions. The difficulties that occur when determining the stressed-strained state beyond the site of plastic deformation, in the zone of smooth transition, can also be eliminated by numerical solutions [11].

The difficulty of determining the stressed-strained state related to the examined manufacturing process of wheel rims was noted earlier in paper [12]. It is predetermined by the local loading of the billet [13]. Thus, papers [14, 15] analyzed the techniques and a procedure of approaches by various authors to determining the deformations at radial-rotational profiling; they also reported results of experimental research based on the models of wheel rims to study the field of deformations. It is shown that the grid method produces reliable results; it, however, requires conducting a large number of experiments and considerable time to process the results. The industrial production would accept results of the research undertaken but recommending this particular method is not possible because of its labor intensity and complexity. Engineers and designers would be interested in formal dependences and a definite method for determining the basic parameters of the profiling process, for calculating the billets, which are relevant when passing over to manufacturing the wheel rims with new standard dimensions. At present, Ukrainian wheel plants utilize the gained manufacturing experience, which implies the application of empirical dependences and conducting the test runs. This leads to the increased consumption of metal and long duration of the technical cycle for the preparation of production. Therefore, strict mathematical statements that would take into consideration patterns in the deformation of shells of rotation could eliminate the above-specified shortcomings as they are universal and applicable to the calculation of any standard size of a wheel.

3. The aim and objectives of the study

The aim of this work is to develop a method for determining the basic operational dimensions of a semi-finished product after first transition, as well as the components of deformation tensor, by constructing the analytical dependences that show key regularities in the process of radial-rotational profiling. These dependences must be directed towards the establishment of explicit relationship between the initial billet dimensions, the displacement of a deforming tool, and design dimensions of the finished product. That, in turn, would make it possible to intensify technical preparation of production.

To accomplish the aim, the following tasks have been set:

– to identify the patterns and kinematics of the mutual displacement of shape-forming rollers, the relationship between a deformation of the billet and a change in the interaxial distances of power shafts based on the schematization of the process of radial-rotational profiling;

– to define the components of deformation tensor in the meridional, tangential and radial direction, as well as the operational dimensions of a semi-finished product, based on the hypotheses on material incompressibility and deformation inseparability;

– to compare the expressions to be derived with experimental data on the measurement of deformations at profiling and known analytical solutions that employ the linkage between stresses and deformations in line with the deformation theory of plasticity.

4. Material and method of research into determining a field of deformations at radial-rotational profiling

4. 1. Determining the mutual displacement of shape-forming rollers in the vertical direction

Based on the study into mutual displacement of deforming rollers when switching on the feed of a power shaft, we determined basic geometrical and technological factors that affect the final dimensions of a semi-finished product.

At the first run of radial-rotational profiling, depending on the geometry of rollers, the end sections and the adjoining zone of cylindrical billet are exposed to the tangential extension with the zone of the central rim well to tangential compression. In this case, $R_p > R_o$; $R_r < R_o$ (Fig. 1) where R_o is the radius of the shell [16].

The resulting depth of the rim well is formed at a continuous power feed of the profiling machine shaft $h_k = A - A_k$. The resulting depth of the rim well can also be expressed in the following way:

$$h_k = h_p + h_r, \tag{1}$$

where h_p and h_r is the depth of a shelf zone and a rim well zone, respectively.

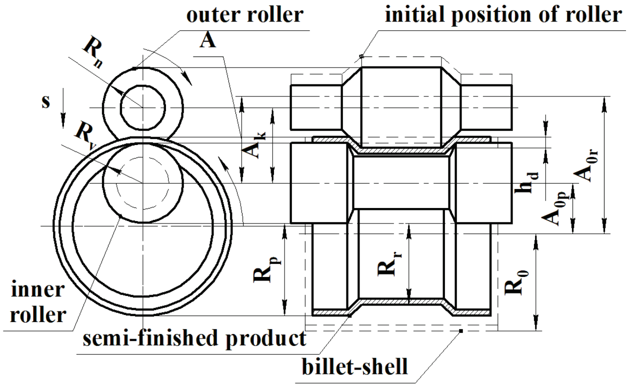


Fig. 1. Deformation of a semi-finished product by molding rollers (h_d – rim well depth; A_{0r} – initial distance between centers of the billet and the outer roller; A_{0p} – initial distance between centers of the billet and the inner roller)

Thus, the resulting depth of the rim well forms from two terms, each of which depends on the geometrical parameters of a deforming tool and a billet.

4. 2. Procedure for determining the components of a deformation tensor

To determine the deformation tensor components in the manufacture of a wheel rim, we adopted the following assumptions:

– elastic deformations do not affect the magnitude and distribution of deformations in the plastic zone;

– a billet metal is homogeneous, non-compressible, possesses the same mechanical properties for thickness and perimeter;

– the deformations are uniform at the surfaces of the principal radii of curvature;

– kinematic displacements of material points of the billet are not compensated for by shifts resulting from deformation.

The mean value of relative deformation in the tangential direction at the i-th rotation of the shell can be derived from the following dependence (Fig. 1):

– crimping zone:

$$\varepsilon_{it} = \frac{A_{0r} - (A_{ir})}{A_{0r}} = \frac{(R_n - R_0) - (R_n - R_0 - s_{ir})}{R_n - R_0} = \frac{s_{ir}}{R_n - R_0}; \tag{2}$$

– expansion zone:

$$\varepsilon_{it} = \frac{A_{ip} - A_{0p}}{A_{0p}} = \frac{(R_0 + R_v) - (R_0 + R_v + s_{ip})}{R_0 + R_v} = \frac{s_{ip}}{R_0 + R_v}, \tag{3}$$

where A_{0r}, A_{0p} are the initial distances between axes of the roller and a billet in the rim well and shelf zones, respectively; R_0, R_n, R_v are the radii of the billet, outer and inner rollers, respectively.

Because the feed of a power shaft is a technological characteristic of the process and the process of profiling itself is characterized by a dimensional uncertainty, one has to represent relative deformation in dependences (2), (3) through the resulting size h_k. This size is set by the design drawing, according to (1).

Total relative deformation of the billet, which depends on the convergence of axes of the deforming rollers, can be represented in the following way (Fig. 1).

$$\varepsilon_{tsum} = \varepsilon_{iobg} + \varepsilon_{irazd} = \frac{h_k}{R_n + R_v} = \frac{h_p}{R_0 + R_v} + \frac{h_r}{R_n - R_0}. \tag{4}$$

Substituting in this equality the value for a rim well depth from condition (1), and upon simple transforms, we shall obtain an expression for the depth of the shelf zone:

$$h_p = h_k \frac{(R_0 + R_v)^2}{(R_n + R_v)^2} \tag{5}$$

and for the rim well shelf:

$$h_r = h_k \left(1 - \frac{(R_0 + R_v)^2}{(R_n + R_v)^2}\right). \tag{6}$$

Finally, the expressions for relative tangential deformations will take the form:

– crimping zone:

$$\varepsilon_{it} = \frac{h_k}{R_0 + R_v} \left(\frac{(R_0 + R_v)^2}{(R_n + R_v)^2}\right); \tag{7}$$

– expansion zone:

$$\varepsilon_{it} = \frac{h_k}{R_n - R_0} \left(1 - \frac{(R_0 + R_v)^2}{(R_n + R_v)^2}\right). \tag{8}$$

Derived expressions for the tangential deformations account for an additivity property.

However, this property is inherent to the true (logarithmic) deformations only.

At radial-rotational profiling a tangential deformation is small compared to conventional sheet stamping processes and, therefore, one can accept with a small error that $\delta \approx \varepsilon$, where δ is the logarithmic deformation [17]. Next, we shall employ the additivity property in order to find deformations in the remaining two directions without taking into consideration the error of 1–5 % [18].

By integrating an expression for the continuity of deformations at an axisymmetric stressed state, as well as by determining the constant of integration from the boundary condition $r = R_0$ at $\varepsilon_\theta = 0$, we obtain:

$$\varepsilon_r = \varepsilon_\theta \left(1 - \frac{r}{R_0}\right), \tag{9}$$

where ε_θ, ε_r are the relative tangential and radial deformations, respectively; r is the independent variable in the direction of the product radius.

Meridional relative deformations will be found from the equation of volume constancy.

Then, finally, for the deformation tensor components, with respect to signs and the resulting dimensions of a semi-finished product, we shall obtain:

– crimping zone:

$$\varepsilon_{it} = \frac{h_k}{R_0 + R_v} \left(\frac{(R_0 + R_v)^2}{(R_n + R_v)^2}\right),$$

$$\varepsilon_r = \frac{h_k}{R_0+R_v}\left(\frac{(R_0+R_v)^2}{(R_n+R_v)^2}\right)\left(1-\frac{R_r}{R_0}\right),$$

$$\varepsilon_m = \frac{h_k}{R_0+R_v}\left(\frac{(R_0+R_v)^2}{(R_n+R_v)^2}\right)\left(\frac{R_r}{R_0}\right); \qquad (10)$$

– expansion zone:

$$\varepsilon_{it} = \frac{h_k}{R_n-R_0}\left(1-\frac{(R_0+R_v)^2}{(R_n+R_v)^2}\right),$$

$$\varepsilon_r = \frac{h_k}{R_n-R_0}\left(1-\frac{(R_0+R_v)^2}{(R_n+R_v)^2}\right)\left(1-\frac{R_p}{R_0}\right),$$

$$\varepsilon_m = \frac{h_k}{R_n-R_0}\left(1-\frac{(R_0+R_v)^2}{(R_n+R_v)^2}\right)\left(2-\frac{R_p}{R_0}\right). \qquad (11)$$

These formal dependences include two new technological parameters, R_p and R_r, the resulting radii of the shelf zone and the central rim well zone. Determining these dimensions is of interest not only from the standpoint of finding a deformation field, but also to predict the dimensions of a semi-finished product by calculation rather than conducting test runs.

We shall express relative deformation through crimping and expansion coefficients:

$$\varepsilon_{itrazd} = \frac{R_n}{R_0}-1, \quad \varepsilon_{itobg} = \frac{R_0}{R_p}-1. \qquad (12)$$

By equating these formulae to expressions for the tangential deformation (7) and (8), as well as considering dependences for depth (5), (6), we determine dimensions of the rim well and the shelf:

$$R_r = \frac{R_0}{\left(\frac{(R_0+R_v)}{(R_n+R_v)^2}h_k+1\right)}, \qquad (13)$$

$$R_p = \left(\frac{h_k}{R_n-R_0}\left(1-\frac{(R_0+R_v)^2}{(R_n+R_v)^2}\right)+1\right)R_0. \qquad (14)$$

It should be noted that the radial and meridional deformations can be determined only at the straight sections of the profile of a semi-finished product as these formulae do not account for the bend of a billet at the profile radii of curvature.

5. Results of research into determining the deformed state of a semi-finished product in the process of profiling the wheel rims

It is of interest to compare the obtained results, formulae (10), (11), to similar studies in this field. Thus, paper [19] reports dependences for calculating a stress field at the first run of radial-rotational profiling. Based on the relation between stresses and strains in line with the deformation theory of plasticity, the authors also derived expressions to calculate relative deformations for the first run of a wheel rim profiling.

For comparison, we shall calculate deformations for a rim of the wheel $6^{1/2}$Jx15H2, which is a typical representative of narrow wheel rims and is used for automobiles of «UAZ» brand. Design drawing set the following dimensions: $R_0 = 182$ mm; $R_v = 145$ mm; $R_n = 202.5$ mm; $h_k = 22$ mm. Results of calculation based on two procedures are shown in Fig. 2. Results of experimental modeling of the process for manufacturing the wheel rims, conducted earlier, are reported in study [15]. For the first run of profiling a narrow wheel, they are distributed in the following way (Fig. 3).

An analysis of theoretical and experimental curves revealed that the proposed method of calculation correlates quite well with data from experiment [15] and, at some zones of the profile, with the results derived by method [19]. For example, the meridional relative deformation increases from zero to its maximum value (zone 3 in Fig. 3). Then it gradually decreases, accepting the value that is slightly lower for zone 4 compared to zone 2. Fig. 2, *a* demonstrates as well that the meridional deformation also increases from zero to its maximum at $h_k = 22$ mm, but then, in Fig. 2, *b*, it continues its growth, that is, an extremum point is missing. However, the magnitude of deformations at the same depth of the rim well would always be larger for the expansion zone compared to the crimping zone. This pattern has been identified in the course of our study and was confirmed by the earlier conducted experimental modelling of the process [15]. Another important difference is the simplicity of the expressions presented and their conciseness as compared to solutions in [19]. The absence of a maximum point at the theoretical curves is explained by neglecting the bending moments at the profile radii of curvature, where there are the greatest longitudinal and radial deformations.

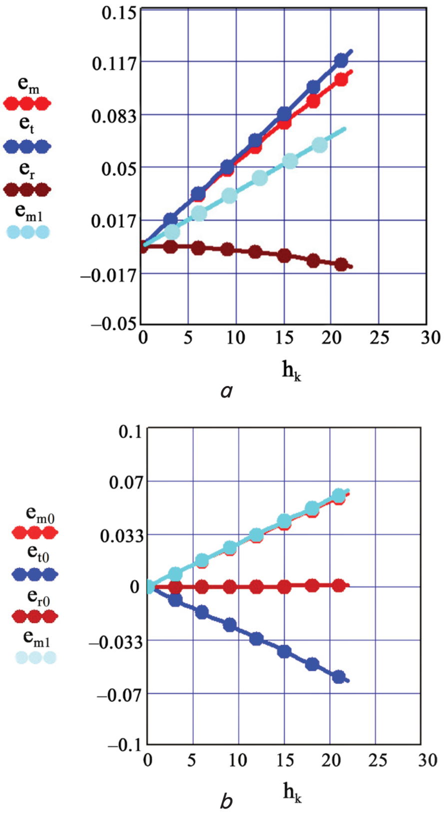
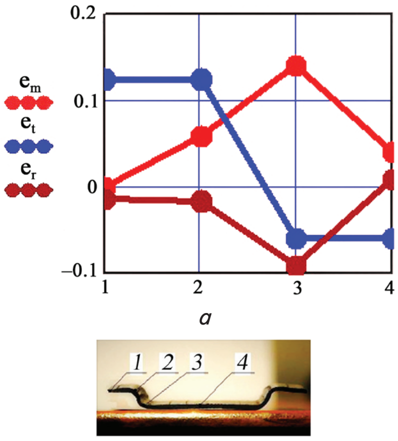


Fig. 2. Distribution of the deformation tensor components at the first run of profiling a rim of the wheel $6^{1/2}$Jx15H2: *a* – expansion zone; *b* – crimping zone (e_m, e_{m0} – meridional deformations; e_t, e_{t0} – tangential deformations; e_r, e_{r0} – radial deformations; e_{m1} – meridional deformations for dependences [19]; h_k – depth of the stream)



a

b

Fig. 3. Distribution of deformations at the first run of profiling a narrow wheel (experimental study): *a* — approximated distribution charts of the deformation tensor components; *b* — zones at a semi-finished product profile (1—4 — regions at the template; e_m — meridional deformations; e_t — tangential deformations; e_r — radial deformations)

It should be noted that all components of deformations depend on the location of zones along the length of the profile (Fig. 3), which is why formulae derived in this work can express only the mean deformation along the length of the characteristic sites of a semi-finished product.

6. Discussion of results of research into determining the deformed state when profiling the rims of wheels

Charts (Fig. 2, 3) indicate the following. The law of volume constancy does not hold for the expansion zone (this is explained by the assumption on the additivity of relative deformations, which is strictly obeyed for logarithmic deformations). We determined by calculation the following results at $h_k=22$ mm – $\varepsilon_m=0.11$, $\varepsilon_{m1}=0.061$ $\varepsilon_t=0.123$, $\varepsilon_r=-0.013$ (expansion zone); $\varepsilon_m=0.059$, $\varepsilon_{m1}=0.059$, $\varepsilon_t=-0.06$, $\varepsilon_r=0.008$ (crimping zone). The estimated values for meridional deformation based on dependences (10) and [19] do not match for the zone of expansion that confirms those patterns in the deformation of a billet at the first run of profiling, which have been identified here and were earlier described in [15]. The expansion zone receives the larger modulo tangential and meridional deformations compared with the crimping zone at the established ratios of diameters of the outer and inner rollers.

Greater convergence between the calculation and experiment is observed in the crimping zone. The greatest difference, to 10 %, is typical for a radial deformation $\varepsilon_r=0.008$ (calculation), $\varepsilon_r=0.009$ (experiment), which confirms the adequacy of the proposed method for the calculation of deformation tensor components and is partially consistent with the research findings from [20, 21]. An inconsistency between results of the experimental [15] and theoretical, presented in this paper, developments can be attributed to the accepted assumption on the equality of logarithmic and relative deformations, as well as the interpretation of results from experimental studies.

It is therefore of a particular interest to further investigate theoretical developments with stricter assumptions, which eliminate inconsistency between different kinds of deformations or a transition from the relative to the true deformations. This would make it possible to derive more accurate formal dependences and proceed to the calculation of the resulting thickness of a product, which is a limiting factor in the profiling process. However, expressions (10), (11) clearly demonstrate patterns in the change of deformation components due to radii of the tool and dimensions of the billet that is actually needed for rational design of the technological process of radial-rotational profiling. The obtained analytical dependences make it possible to estimate the degree of influence of each technological and design factor of the process on the field of deformations. The procedure was adopted for practical application at the enterprise SP «Obod» (Kremenchug, Ukraine), which specializes in the production of steel wheels for different transportation vehicles. The main disadvantage of a given method is the uncertainty for radial and meridional deformations in the junction zones of different sections of the profile, which to a certain degree limits its application in order to calculate the initial thickness of a billet.

7. Conclusions

1. Based on an analysis of mutual displacements of power shafts at a profiling machine in the vertical direction, we determined the initial, intermediate, and final positions of axes of the deforming tool. This enabled to link the inter-axial distances of shafts to radii of the forming rollers and feed, and to formally represent displacements through a relative tangential deformation of the billet. Such an approach is relatively simple and concise in the language to find the fields of deformations and makes it possible to explicitly define patterns in their distribution.

2. We have proposed a method for calculating the relative meridional, tangential and radial deformations, based on the condition for the continuity of deformations for the axisymmetric stressed state and the condition of volume constancy. Applying it allows the calculation of not only the magnitude of a deformation tensor components, but also determining the operational dimensions of a semi-finished product. This circumstance provides for the employment of a given method as a basic one when designing the transitions at radial-rotational profiling at the stage of technical preparation of production.

3. Comparison of calculation results, obtained in this work, with experimental data [15] and existing expressions [19] suggests that a given method of calculation has the accuracy acceptable for industrial production. An error of the estimated data does not exceed 10 % in comparison with the experiment and 3–6 % compared with expressions derived based on the relation between stresses and strains in line with the deformation theory of plasticity. Although the method from [19] is considered to be more accurate, it, however, is not sensitive to the mutual effect of simultaneous expansion and crimping at the field of deformations. This is manifested by the greater deformation of a seating shelf zone compared to the zone of a rim well. Our method eliminates this problem. Moreover, the simplicity, conciseness and visibility of the developed statements makes them a useful tool for practicing engineers in terms of production preparation. A distinctive feature of the proposed approach is the possibility to define basic geometrical factors of the process that exert a decisive influence on the resulting dimensions of a semi-finished product and on the distribution of a deformation tensor components.

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