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ANALYTICAL DESCRIPTION OF ADJUSTMENT OF ROLLS FOR MANUFACTURING PARTS FROM ELASTIC SHEET MATERIAL

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The object of research is the process of bending sheet material, taking into account its springiness. When manufacturing sheet parts by bending from a completely elastic sheet, its shape is completely restored after the deformation stops, unlike an elastic sheet. Thus, when producing cylindrical parts by drawing between three rolls, the resulting radius of the cylindrical part will be larger than the calculated one. This phenomenon is evaluated by the coefficient of springing – the ratio of the calculated radius to the one obtained after partial expansion.

When manufacturing conical parts, this approach cannot be applied, because the value of the radius is variable. The article applies the theory of surface bending from differential geometry. The curvature of the line on the surface has two components – normal and geodesic. When the surface is bent, the normal component changes, while the geodesic component remains unchanged. The magnitude of the normal component depends on the angle between the origin of the cone and its axis. So, for a cone with a base of radius R and an angle of 20°, the normal curvature is 0.94/R, and the geodesic curvature is 0.34/R. For cylindrical parts, the geodesic curvature of the cross-section (circle) is zero, so it is not necessary to take it into account.

Usually, adjustment of rolls for the production of conical parts is carried out experimentally. The difference of the proposed approach lies in the elimination of this problem thanks to the decomposition of the curvature of the base of the cone into two components. This allows to calculate the settings of the rolls and thereby reduce their adjustment time. The parameters of the rolls and their mutual placement are calculated for the production of conical parts of the required size, taking into account their springiness. The field of application of the obtained results is the production of parts by bending flat metal sheet blanks

Keywords: normal curvature, geodesic curvature, sheet part, billet calculation, conical rolls

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1. Introduction

The technology of manufacturing parts by cold or hot stamping is widespread. One of the types of stamping is hooding. By means of drawing, it is possible to produce three-dimensional parts, including conical and cylindrical ones, from flat blanks. This technology requires expensive equipment and is justified for the manufacture of parts whose surface is not developed (for example, a spherical segment). A popular method of manufacturing cylindrical parts is metal rolling on a sheet bending machine. The sheet acquires the required shape by passing it through the rolls of rolling machines. At the same time, the property of the material and the thickness of the sheet are taken into account: the denser and thicker the metal, the less plastic it is, therefore, when rolling thick sheets of metal, partial expansion, that is, springing, must be taken into account. When manufacturing conical parts, this approach cannot be used for the reason that the value of the radius changes along the axis of the cone. Therefore, there is a need to develop an analytical model of the formation of a flat sheet blank into a conical part.

2. Literature review and problem statement

The process of rotational bending of a high-strength thin-walled, rectangular welded pipe is considered in [1]. It is shown in the work that in this case, material wrinkles are formed quite easily due to the presence of a non-uniform welding zone and an angle formed by the effect of cold bending. In order to avoid such material defects, a model of the pipe was developed in the work and the effect of changing its geometric shape on the wrinkling of the inner flange and the side wall of the pipe itself was investigated. However, this model cannot be used to obtain parts of other geometric shapes, in particular, cylindrical and conical. In addition, this work outlines the possibilities of increasing the durability of tools by applying coatings obtained by laser methods and chemical vapor deposition. Much attention is paid to self-lubricating and functional materials and coatings. Modern trends in lubricants and lubrication methods for forming sheet parts, including tool texturing, are also presented.

In [2] it is indicated that there is no cost-effective production process of original bent parts from sheet material of serial quality at small volumes of production. The authors investigated the possibility of using additional manufactured functional elements for tools for extracting parts and described the proposed design of such a tool. In contrast to [1], the geometric shape of the obtained parts is no longer so limited, however, with the help of the proposed design, it is impossible to produce parts of a cylindrical or conical shape.

The work [3] proposed the process of forming a conical blank for the manufacture of a metal spiral blade of a turbine. However, in this case, only the manufacture of spirally curved forms is considered, excluding the possibility of manufacturing conical surfaces in the general sense.

The process of bending sheet material is described in detail in [4]. This study proposes modeling of sheet material using CAD software (ANSYS) to understand its bending process. However, the authors do not take into account the phenomenon of springing of the material, and the blank for bending is taken as the initial data.

The concept of hardness has a direct influence on the phenomenon of material springiness. In [5], the theoretical basis for the digital characteristics of hardness units, obtained by various measurement techniques, is established. In order to provide the physical content of the determination of hardness, the dependence of the volume of the displaced material on the applied load was determined in the work. The comparison of these values made it possible to realistically determine the ratio between units of different methods, not based on practical comparisons, but by drawing up a theoretical basis. However, this study does not show feedback with the possibility of applying its results to the study of the spring phenomenon.

During bending of a completely elastic sheet, its original shape is completely restored. On the other hand, when an elastic sheet is bent, the shape is partially restored [6]. It is important to take this into account during preliminary calculations in order to obtain a cylindrical part with the required radius after partial expansion of the sheet [7]. When manufacturing conical parts, this approach cannot be used due to the fact that the value of the radius changes along the axis of the cone. However, there is no unified analytical model of such a process in scientific research. Its presence can significantly simplify the process of forming a flat blank from sheet material.

In [8], the process of forming blanks from sheet material by the method of drawing between rolls is considered in detail. The areas of application of this method, its advantages and disadvantages are given, but without any analytical calculations suitable for practice.

Forming of sheet material is one of the most popular technologies for obtaining finished products in almost all branches of industrial production [9]. In parallel with the development of new forming methods, numerical and empirical approaches are proposed for improving existing and developing new methods of forming sheet material. These methods are mainly focused on improving the formability of materials, producing complex-shaped parts with good surface quality, speeding up the production cycle, reducing the number of operations and making the production environmentally friendly. However, there is still a lack of unified analytical models for the formation of sheet material blanks.

To unify this approach, the theory of surface bending from differential geometry can be used, which is the object of this study. According to it, the curvature of the line on the surface should be divided into two components – normal and geodesic. This approach was proposed in [10]. It contains calculations of a fictitious cone, on which a flat blank needs to be bent in order to obtain the desired part after partial expansion. But in the work [10], the parametric equations of the conical surface, which includes a dimensionless quantity – the so-called bending parameter, which takes into account the property of an elastic sheet to partially restore its original shape, were not compiled. Thanks to this, the analytical dependences of setting the conical rolls for the production of conical parts, taking into account the springiness, can be found.

In addition, the development of a unified analytical model for the manufacture of cylindrical and conical parts, taking into account the phenomenon of material springiness, will help to identify common approaches and fundamental differences. From a practical point of view, it is necessary to perform all the necessary calculations for setting up conical rolls for their manufacture.

3. The aim and objectives of the study

The purpose of the study is to develop an analytical model of the formation of a flat sheet blank into cylindrical and conical parts by rolling between rolls, taking into account the springiness of the metal.

To achieve the aim, the following objectives must be solved:

– set the springiness when rolling a metal sheet into a cylindrical shape and develop a scheme for adjusting the rolls;

– compile the parametric equations of the cone, which include the springiness;

– develop an algorithm for adjusting rolls for the production of conical parts, taking into account the blank springiness.

4. Materials and methods of the study

The object of the study is the process of bending sheet material, taking into account its springiness. The main hypothesis is the assumption that when manufacturing conical parts by bending sheet material, only the normal curvature of the base should be taken into account, since the geodesic curvature does not change during the bending process.

Research materials are based on the theory of differential geometry of surfaces. The bending of the surface is related to the deformation of the line on it. If the sheet is bent into a cylindrical shape, then it is possible to move from a spatial problem to a flat one – consider the deformation of not the entire surface, but the curve of its cross section. An important differential characteristic of a curve is its curvature. The curvature is the inverse of the radius, so it is constant for a cylinder with a cross section in the form of a circle. When bending a flat blank into a conical shape, the curvature of the line on the surface of the cone must be divided into two components - geodesic and normal. According to the theory of differential geometry, when surfaces are bent, only the normal curvature of the line on its surface changes, and the geodesic curve remains unchanged. This provision is central to the method of calculating the process of bending a flat blank into a conical part, taking into account springing, that is, its partial expansion.

In the study, a simplification was adopted, according to which the thickness of the sheet material is equal to zero. The adequacy of the model is based on the fact that when transitioning from conical to cylindrical parts, the integrity of the mathematical model is not violated and bending occurs without decomposition of the curvature into components.

The study was carried out in the environment of the software product "MatLab", with the help of which the surfaces of the cones were constructed. Graphic illustrations were made in the AutoCad environment.

5. Results of research on the bending of sheet material, taking into account its springiness

5. 1. Setting the springiness when rolling sheet material into a cylindrical shape and adjusting the rolls

The scheme of rolling a sheet, or its rolling, into a cylindrical surface is well known: a metal sheet is forced to pass between three cylindrical rolls and acquires a cylindrical shape (Fig. 1, *a*). The cross-sectional radius of the cylindrical surface is determined by the contact of the sheet with the rolls at three points A, B, and C (Fig. 1, *b*). However, it is necessary to bend a flat sheet blank not to a specified shape, but to a fictitious one, taking into account that the sheet will take the desired shape after partial unfolding. Therefore, cylindrical rolls need to be adjusted not to the actual radius, but to a smaller one. The ratio of these radii will give a certain coefficient p, which is used to estimate the springiness of the sheet material. Since the spring depends on the mechanical properties of the material and its thickness, the spring coefficient p is determined experimentally for each batch of sheet material. It is the ratio of the radii of the part before and after stretching. Let's assume that the rolls in Fig. 1, *b* are not set to a real radius, but to a fictitious one. Then, after point C, the part will partially expand and acquire the desired shape (shown by a dashed line).

By measuring the radius R_p of the cross-section of the real cylinder (after its partial expansion) and knowing the radius R_f of the cross-section of the fictitious cylinder, for the production of which the rolls are adjusted, it is possible to find the spring coefficient p:

$$p = \frac{R_v}{R_f} = \frac{k_f}{k_v}, \tag{1}$$

where k_v and k_f are the curvature of both the real and fictitious cylinders – values inverted to the corresponding radii. Thus, in order to find the cross-sectional curvature of the fictitious cylinder, to which the rolls are adjusted, it is necessary to multiply the cross-sectional curvature of the real cylinder by a coefficient *p*, i.e., to increase the cross-sectional curvature of the real cylinder by p times:

$$k_f = pk_v. \tag{2}$$

To manufacture a cylindrical part of a given radius, the rolls must be set to a fictitious radius. Fig. 2 shows the location of three identical rolls of radius r with the designation of the contact points A, B, C with the sheet and their centers C_A, C_B, C_C. Based on the given values of the radii *r*, R_f and the distance between the lower rolls 2*L*, it is necessary to find the location of the upper roll, i.e., the distance EC_B to its center C_B. Using symmetry about the *Ey* axis, consider the right triangle EC_AC_f. Leg $EC_A=L$, hypotenuse $C_fC_A=r+R_f$, from where let's find:

$$C_fE = \sqrt{\left(R_f + r\right)^2 - L^2}. \tag{3}$$

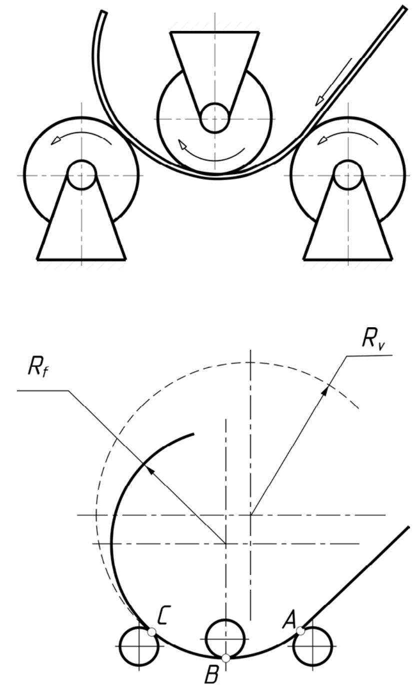

Fig. 1. Scheme of rolling a flat sheet into a cylindrical shape with the help of rollers: *a* – the movement direction of the blank between the rollers; *b* – real and fictitious radii

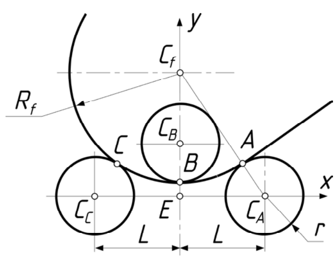

Fig. 2. Scheme of adjusting the rolls in such a way that a circle of radius R_f passes through points A, B, C

The EC_B distance is:

$$EC_B = EC_f - R_f + r = \sqrt{\left(R_f + r\right)^2 - L^2} - R_f + r. \tag{4}$$

The upper roller is installed in the desired position according to the found distance EC_B.

5. 2. Compilation of the parametric equations of the cone, which includes the springiness

A cone with an angle β of the inclination of its rectilinear generators to the axis is shown in Fig. 3. The size of the radius of its cross section depends on the length of the generator *u*, which starts from the top of the cone. For example, the radius *R* of the lower base will be written: $R=u\cdot\sin\beta$. The curve, which is the inverse value, will be written accordingly: $k=1/(u\cdot\sin\beta)$. It can be decomposed into two components: geodesic $k_g=k\cdot\sin\beta$ and normal $k_n=k\cdot\cos\beta$ (Fig. 3). According to the theory of differential geometry of surfaces, when they are bent, only the normal curvature of the line changes, and the geodesic curvature remains unchanged.

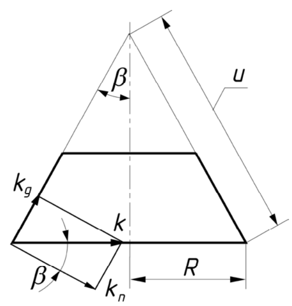

Fig. 3. Decomposition of the circle curvature – cone base – into normal and geodesic components

For cylindrical surfaces, β=0, so there is no geodesic component. In order to obtain a cone with valid values of the curvature k of the base and the angle β, it is necessary to carry out a biased bending, that is, to multiply the normal curvature by the index p of the spring. After that, the fictitious normal curvature of the base can be obtained:

$$k_{nf}=p\cdot k_n=p\cdot k\cdot\cos\beta.$$

The angle β will also change, that is, it will acquire a fictitious value β_f. It is possible to write the normal curvature for a fictitious cone, taking into account the new value of its normal curvature k_{nf}:

$$k_{nf}=k_f\cos\beta_f.$$

Two expressions of the normal curvature of a fictitious cone can be equated:

$$p\cdot k\cdot\cos\beta=k_f\cdot\cos\beta_f. \quad (5)$$

Expression (5) includes two unknown quantities: k_f and β_f. To find them, the equality of the geodesic curvature before and after bending can be used:

$$k\sin\beta=k_f\sin\beta_f. \quad (6)$$

Two equations (5) and (6) form a system of two equations with two unknowns k_f and β_f. The solution of this system is the following expressions:

$$k_f=k\sqrt{\sin^2\beta+p^2\cos^2\beta}, \quad (7)$$

$$\beta_f=\arccos\frac{p\cos\beta}{\sqrt{\sin^2\beta+p^2\cos^2\beta}}. \quad (8)$$

The equation of a cone, the vertex of which is located at the origin of the coordinates and all of whose components are inclined at an angle β to its axis, have the form:

$$X=u\sin\beta\cos v;$$

$$Y=u\sin\beta\sin v;$$

$$Z=u\cos\beta, \quad (9)$$

where u and v are independent variables, and u is the length of the rectilinear generator, the count of which starts from the top, that is, from the origin of the coordinates, v is the angle of rotation of the cone generator around its axis.

Taking (8) into account, the parametric equations (9) for the fictitious cone are as follows:

$$X_f=u\frac{\sin\beta}{\sqrt{\sin^2\beta+p^2\cos^2\beta}}\cos v;$$

$$Y_f=u\frac{\sin\beta}{\sqrt{\sin^2\beta+p^2\cos^2\beta}}\sin v;$$

$$Z_f=u\frac{p\cos\beta}{\sqrt{\sin^2\beta+p^2\cos^2\beta}}. \quad (10)$$

For p=1, equations (9) and (10) become identical, that is, in the absence of springing, the real and fictitious cones coincide.

5. 3. Adjustment of rolls for the production of conical parts, taking into account the blank springiness

Unlike rolls for the production of cylindrical parts, when setting up conical rolls, it is convenient to operate not with linear, but with angular dimensions. The surfaces of the cones of the forming rolls, as well as the surface of the fictitious cone with combined vertices, are placed in the center of the sphere (Fig. 4, *a*). Circles – the bases of all cones – will be located on the surface of the sphere. The radius of the base of each cone is determined from the product of the length of its element, that is, the radius of the sphere, by the sine of the angle β at the apex. If the sphere has a unit radius, then the radius of the base will be equal to the sine of the angle, that is, there is a transition from linear to angular dimensions. An analogue of the distance L for cylindrical rollers will be the angle γ for conical rollers (Fig. 4, *b*). The arcs C_AE and C_CE correspond to the angular γ. The size of the conical rollers is given by the angle β_r at their top, which corresponds to the arcs CC_C, BC_B and AC_A. The angle at the top of the fictitious cone β_f, which corresponds to the arc BC_f, is calculated by formula (8). It is necessary to find the position of the upper forming roll, i.e. the angle to which the arc BC_f corresponds.

By analogy with Fig. 2 right triangle EC_AC_f for the case under consideration is spherical. Leg EC_A=γ, hypotenuse $C_fC_A=\beta_r+\beta_f$, leg EC_f, to which the angle ε corresponds, is unknown (Fig. 4, *c*). Using spherical trigonometry formulas:

$$\varepsilon=\arccos\frac{\cos(\beta_r+\beta_f)}{\cos\gamma}. \quad (11)$$

The EC_B arc is part of the spherical leg EC_f. According to Fig. 4, *b* can be written as:

$$EC_B=EC_f-BC_f+BC_B.\ \ \varepsilon_r=\varepsilon-\beta_f+\beta_r. \quad (12)$$

The angle corresponding to the arc EC_B was denoted by ε_r. In equation (12), it is necessary to move from arcs to the designation of the corresponding angles:

$$\varepsilon_r=\varepsilon-\beta_f+\beta_r. \quad (13)$$

After finding the angle ε_r, the position of the middle roller becomes known: its axis must be turned by the angle ε_r around the axis OY upwards, starting from point *E*.

It is possible to bend a flat blank into the same conical part with a different location of the rolls, that is, the rolls can have an unchanged angle β_r at the top, but a different angle γ.

A possible option is when both angles change: γ and β_r. To confirm what has been said, let's give examples.

Example 1. It is necessary to adjust the rolls for the production of a conical part with an angle β=12° at the top. The spring coefficient is known – p=1.2. Forming rolls have an angle at the top of β_r=5°. Angle γ=±10°. Find the angle ε_r.

By formula (8), the angle β_f at the top of the fictitious cone can be found: β_f=10°. Using formula (11), let's find the angle ε: ε=11.24°. The rotation angle ε_r of the axis of the middle roller is found by formula (13): ε_r=6.24°. According to the angles found in Fig. 5, and the compartments of forming and fictitious cones were built.

For the manufacture of the same part, it is possible to take rolls with other angles β_r and γ. In Fig. 5, *b* according to equations (9) the surfaces of the forming rolls are constructed and according to equations (10) – the surfaces of the fictitious cone. The adjustment angles are given in the caption to the figure.

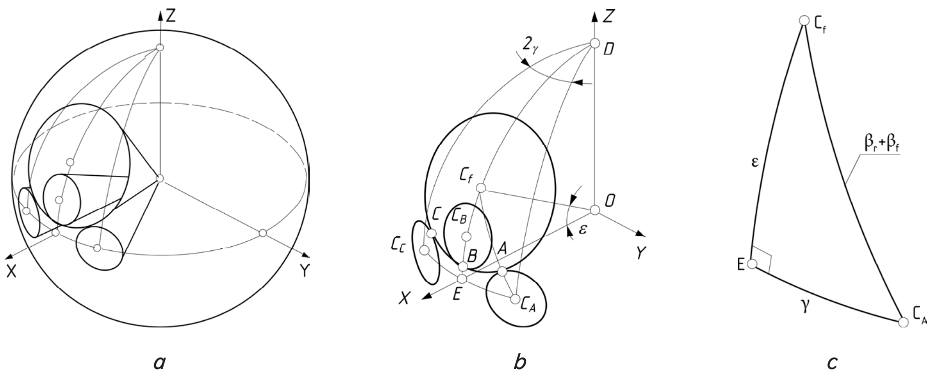

Fig. 4. Application of a sphere of unit radius to calculate parameters of adjustment of conical rolls: *a* – diagram of the arrangement of the surfaces of forming and fictitious cones in relation to the sphere; *b* – the relationship between the angular dimensions of circles (bases of the cone) and their centers on the surface of the sphere; *c* – spherical right triangle for determining the angle ε of the location of the center C_f of the fictitious cone

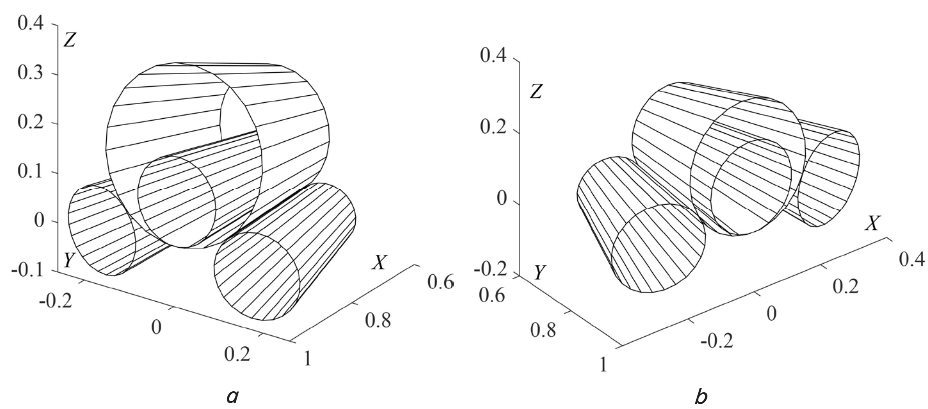

Fig. 5. The surfaces of the forming rolls and the fictitious cone with the known spring coefficient p=1.2 and the given effective angle β=12°: *a* – β_r=5°, γ=±10°, β_f=10°, ε_r=6,24°; *b* – β_r=7°, γ=±15°, β_f=10°, ε_r=5,09°

6. Discussion of the developed method of manufacturing conical parts from elastic sheet material

In contrast to [6], according to the developed method, it is possible to adjust conical rolls for the production of conical parts from sheet material with a known spring coefficient. However, the question arises how to make a conical part for which the radii of both bases are given. For a cylindrical part, such a question does not arise, since the rolls are set to a given radius. In addition, it does not matter in which place to pass a straight line between the rolls. The production of a conical part has its own characteristics. First, the flat blank is not a straight strip, but part of a flat ring. The concentric circles bounding this ring are transformed on the conical part into upper and lower bases. Second, the blank in the form of a flat ring cannot be passed between the conical rollers anywhere. The place of passage and the dimensions of the ring must be agreed with each other. Such matching is carried out due to the distance u from the common apex of the cones. This distance is common to both the conical surfaces of the forming rolls and the blank. Using this distance, it is possible to find the radii of the arcs that limit the blank in the form of a flat ring.

When the surface is bent, the geodesic curvature of the line on it does not change [12]. It is determined by the product of the curvature of the base of the conical part (lower or upper) by the sine of the angle at the top. The curvature of the arc of the circle (external or internal) that limits the flat ring will be the same. The radii of these circles are inverse values of geodesic curves. Hence, there are no difficulties in determining the distance u at given radii of the lower and upper bases of the conical part. Another dimension for a flat ring is the central angle, which limits its size. It is determined from the condition that the length of the arc of the ring and the corresponding circle of the base of the conical part must be equal. Thus, the given dependencies are sufficient to determine the dimensions of the flat blank and the place of its passage between the rolls.

The obtained results of adjusting the rolls for the production of conical parts from sheet metal are explained by the fact that the curvature was decomposed into geodesic and normal components. For cylindrical parts, the geodesic curvature of the cross-section is zero, so their bending can be replaced by a flat problem, that is, the bending of the curve of the cross-section. Then it seems quite clear to introduce the spring coefficient as the ratio of the radii of the circles of the real and fictitious cylinders (Fig. 1, *b*). This spring coefficient should also be used in the production of conical parts. If for cylindrical parts the geodesic curvature is zero, then for conical parts it is present and depends on the angle β (Fig. 3). According to the theory of differential geometry, the geodesic curvature does not change during bending. Therefore, the spring coefficient should be applied in relation to the normal curvature. Based on this, the parametric equations of the cone (10) were compiled, which include the spring coefficient. This makes it possible to adjust the conical rolls, taking into account that the curvature of the base of the conical rolls is decomposed into components. This is the peculiarity of the method and provides an advantage in the production of conical shaped parts with the help of rolls over the traditional method, which consists in the experimental adjustment of rolls with the production of trial parts [7]. This closes the problematic part of the production of conical-shaped parts by drawing a flat blank between conical rolls, in contrast to existing approaches [5].

The disadvantage of the presented method of forming conical parts is that the thickness of the metal sheet is not taken into account. This method is designed for forming parts from sheet material of only constant curvature. However, there is a need for the production of cylindrical parts of variable curvature, for example, various protective casings. This is the limitation of the proposed method. Further development of the research may be aimed at eliminating the indicated shortcoming, i.e. at improving the method for manufacturing parts taking into account the thickness of the flat blank.

7. Conclusions

1. When the sheet material is elastically bent, its shape is partially restored. The amount of recovery depends on the properties of the material, the thickness of the sheet and is estimated by the spring coefficient, which is set for a separate batch of sheet material. According to the coefficient found experimentally, the rolls are adjusted according to the calculations made for biased bending of cylindrical parts with a fictitious radius of the cross section. After partial expansion, the part takes the desired shape.

2. When manufacturing conical parts, the curvature of the circle – the cone base – is divided into two components: normal and geodesic curvature. This approach is known in the theory of differential geometry and is used in solving practical problems. To determine the shape of the fictitious cone, a position from the differential geometry of surfaces was used, according to which only the normal component of the curvature of the line changes during bending, and the geodesic component remains unchanged. Based on this, the parametric equations of the fictitious cone, which include the spring coefficient, were compiled.

3. Calculations were made for adjusting the conical rolls to a fictitious cone, for which parametric equations were compiled. For calculations, a sphere of unit radius is used, in the center of which are the tops of the forming conical rolls and the fictitious cone. With the help of formulas of spherical trigonometry, dependencies were found for adjusting the rolls for the production of a conical part of a given shape, which can be used in practice. These dependencies made it possible to obtain a unified model of the formation of the blank from the sheet material for its further bending into a cylindrical or conical shape, taking into account the springiness of the material. The confirmation of the reliability of the obtained results for setting up the rolls is the construction of spatial images according to the given initial data.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

References

1. Liu, H., Liu, Y., Zhang, P., Du, X. (2020). Effect of weld zone and corner with cold bending effect on wrinkling of rectangular welded tube in rotary draw bending. Thin-Walled Structures, 157, 107115. https://doi.org/10.1016/j.tws.2020.107115
2. Schuh, G., Bergweiler, G., Bickendorf, P., Fiedler, F., Colag, C. (2020). Sheet Metal Forming Using Additively Manufactured Polymer Tools. Procedia CIRP, 93, 20–25. https://doi.org/10.1016/j.procir.2020.04.013
3. Yang, S., Shim, D., Ji, H., Baek, J., Kim, B., Ahn, S., Park, S. (2016). Process Design of Conical Roll-Shaping for Fabrication of Variable Curvature Spiral Blade. Journal of the Korean Society for Precision Engineering, 33 (11), 911–918. https://doi.org/10.7736/kspe.2016.33.11.911
4. John Panicker, G. (2022). Study on Sheet Metal Bending. ScienceOpen. https://doi.org/10.14293/s2199-1006.1.sor-.pp0xuzu.v1
5. Semenovskyi, O., Titova, L., Mykhnian, O. (2021). Hardness – volumetric characteristic of material. Naukovij Žurnal «Tehnika Ta Energetika», 12 (4). https://doi.org/10.31548/machenergy2021.04.139
6. Kutsenko, A., Kutsenko, O., Yaremenko, V. (2021). On some aspects of implementation of boundary elements method in plate theory. Naukovij Žurnal «Tehnika Ta Energetika», 12 (3). https://doi.org/10.31548/machenergy2021.03.107
7. Pylypaka, S., Kresan, T., Hropost, V., Babka, V., Hryshchenko, I. (2022). Calculation of the bending parameters of a flat workpiece into a twist of a helicoid torso. Naukovij Žurnal «Tehnika Ta Energetika», 13 (4). https://doi.org/10.31548/machenergy.13(4).2022.81-88
8. Ikumapayi, O. M., Afolalu, S. A., Kayode, J. F., Kazeem, R. A., Akande, S. (2022). A concise overview of deep drawing in the metal forming operation. Materials Today: Proceedings, 62, 3233–3238. https://doi.org/10.1016/j.matpr.2022.04.221
9. Trzepieciński, T. (2020). Recent Developments and Trends in Sheet Metal Forming. Metals, 10 (6), 779. https://doi.org/10.3390/met10060779
10. Nesvidomin, V. M., Pylypaka, T. S., Babka, V. M. (2010). Pat. No. 53688. Sposib vyhotovlennia konichnykh detalei uperedzhenym zghynanniam za dopomohoiu konichnykh valkiv. No. u201005553; declareted: 07.05.2010; published: 11.10.2010, Bul. No. 19. Available at: https://iprop-ua.com/inv/pdf/ns283etl-pub-description.pdf