

# Development of 3D modeling technology for manufacturing finned ribbons from heat-resistant steels

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**Abstract.** The process of shaping a workpiece by a tool using the rolling method is, from the geometric point of view, a process of interaction of two conjugate surfaces. The technology of rolling finned stainless steel ribbons is close to the technology of shaping details by cutting. However, the problems of its practical implementation in the well-known papers analyzing this issue are practically not considered. As a result of the analysis of conjugate surfaces profiling methods in relation to the problem, it was concluded that it seems urgent to develop a methodology for the formation of corrugated ribbon based on 3D modeling use. The implementation of this methodology includes the creation of solid models of the product and the tool, as well as computer simulation of their shaping processes using rolling method. So, at the first stage, a 3D model of finned ribbon was developed, which was then used to produce a profile of a rolling tool. The modeling of this profile was carried out on the basis of the proposed software package in the CAD environment. The created theoretical model of the tool profile was replaced from the technological point of view by a rectilinear profile. To carry out the analysis of the obtained results, the inverse shaping problem was solved - according to the corrected profile of the tool, real profile of the corrugated ribbon is obtained. Computer modeling of extruded volumes in the process of shaping was performed. The analysis of qualitative and quantitative parameters of the extruded volumes made it possible to give recommendations on setting the increment of the tool motion parameter. Based on the results of the studies, profile parameters of the roller are assigned for its practical implementation. The proposed methodology, based on 3D-modeling, allowed to develop a technology for manufacturing finned ribbons from heat-resistant steels by rolling with high productivity, accuracy and stability of the sizes obtained.

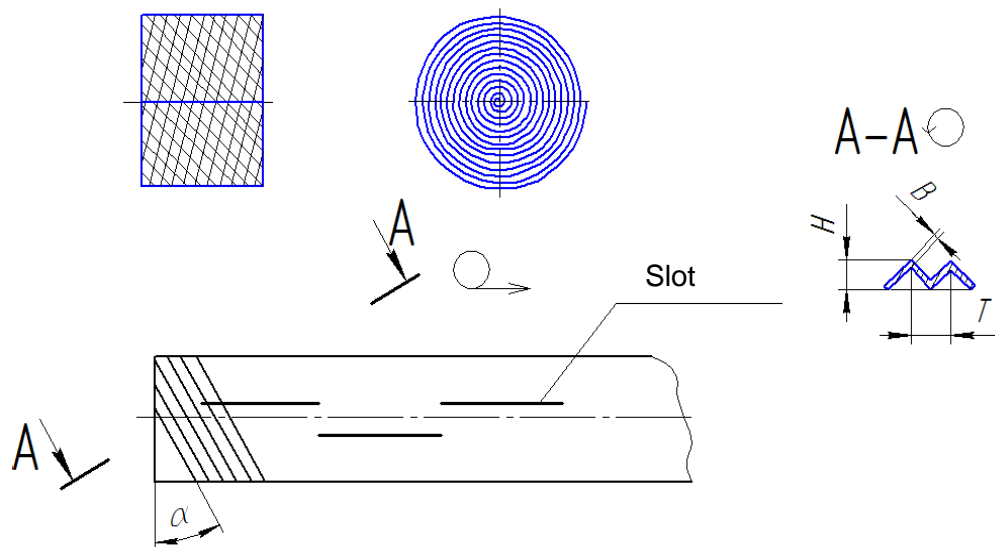
## 1.Introduction

There is a group of industrial heat exchangers where the heating of the medium is carried out by cylindrical elements equipped with corrugated stainless ribbon and forced feeding of the heated gas mixture is provided. Figure 1 shows a sketch of a corrugated ribbon made of heat-resistant steel of thickness  $B$ , height  $H$  and pitch  $T$ . The finned corrugations are inclined at angle  $\alpha$ . To reduce hogging of finned ribbons, cuts are made along them. Making corrugated ribbons tens of meters long is a technologically complicated process which requires the profile precision and ribbon straightness.

The technology of rolling finned stainless steel ribbons is close to the technology of shaping parts by cutting using the rolling method. If a lot of theoretical approaches are known in the field of the cutting tool profiling, though the problems of practical implementation of this method with regard to shaping corrugated ribbons are practically not considered in the existing studies. The problems are caused by operations of corrugations shaping. In this regard, the task is urgent. As a result of the analysis of



conjugate surfaces profiling methods, it was concluded that it would be advisable to develop a methodology based on the use of 3D modeling with respect to corrugated ribbon shaping.



**Figure 1.** Corrugated ribbon.

## 2. Statement of the problem

The purpose of this work is to develop a technology for processing corrugated ribbons with high efficiency, accuracy and stability of the resulting sizes based on the creation of geometric and solid models of a finned ribbon and a tool for rolling it using 3D modeling.

The research tasks are the following: creation of 3D-model of corrugated ribbon; creation of a software package providing, in an automated mode, modeling the shaping of a tool for processing a ribbon; replacement, from technological considerations, the obtained profile by the rectilinear one; solution of the inverse problem of shaping - modeling the ribbon profile by a tool obtained in the previous stage; analysis of the obtained data and developing a resulting technology for corrugated ribbons processing.

## 3. Computer modeling of ribbon shaping by rolling method

### 3.1. Statement of the shaping problem

The process of item shaping with respect to surface treatment by rolling and rolling is the interaction of two conjugate surfaces - the workpiece and the tool. These processes are quite similar by their kinematic schemes. In both cases, the shaping is carried out under certain relative movements of a tool and a workpiece. In these schemes, the combinations of rectilinear-forward and rotational motion are used. The rolling method is based on the principle of gearing, for which the kinematics is studied and the developed apparatus can be used to determine the parameters of the tool [1, 2].

Let us consider the rolling process from the point of view of the centroid envelope method. This method is characterized by the fact that during the process of shaping the workpiece, the centroids of the tool and the processed wheel roll over each other without sliding. The profile of the workpiece is

obtained as the envelope curve of different positions of the tool profiles. The centroids in these cases are the initial line and the initial circle.

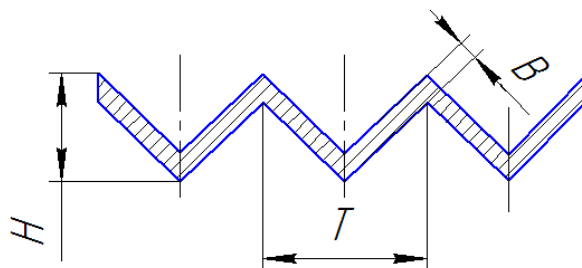
A lot of papers have tried to solve the problems of manufacturing workpieces with a cutting tool. During their solving by analytical methods for calculation the computational dependences with reference to various initial data are required. Such dependencies have often a form of transcendental equations. Their solution involves the use of numerical methods, which complicates the process of profiling.

Modern CAD-systems make it possible to perform the modeling of shaping and to study the influence of various tool parameters on the workpiece profile shape and vice versa [3 - 8].

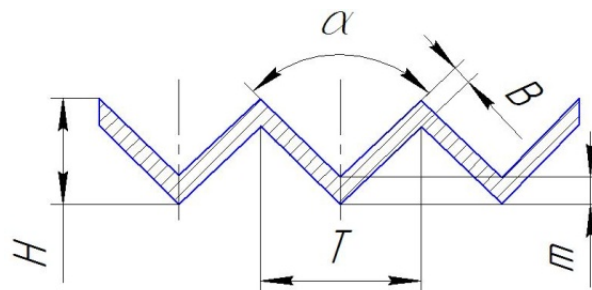
To solve this problem, algorithms and programs are proposed that perform in the automated mode solid modeling of the shaping of a rolling tool for manufacturing ribbon-like items which have the geometry of a rack-type tool. The inverse problem is also solved that is modeling the shaping of products of the ribbon type according to the obtained tool - the roller. In addition, in the process of shaping, solid modeling of the extruded layers is provided, which makes it possible to obtain some of their quantitative and qualitative characteristics. These characteristics are used for the optimal shape sizing. The proposed solutions are mainly based on the results of [8, 9]. A generalized algorithm for solving the problems based on the modeling of shaping workpieces by the method of centroid enveloping by means of computer graphics, proposed in [9], was also used to solve the described problem.

### 3.2. Creating a solid-state ribbon model

The initial data for modeling is the ribbon profile in its normal section, shown in Figure 5. However, for computer modeling of the ribbon profile, additional parameters  $\alpha$  or  $m$  are required (Figure 3).



**Figure 2.** Initial ribbon profile and its parameters.



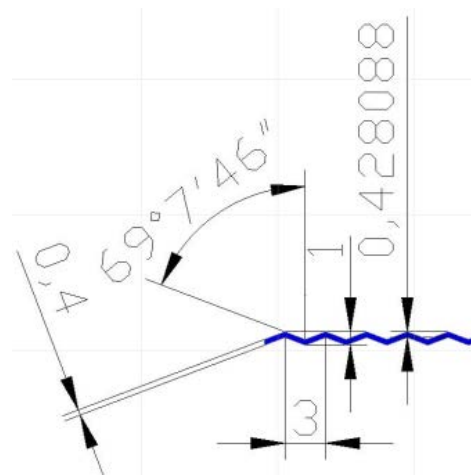
**Figure 3.** Ribbon profile and its parameters for modeling.

It follows from Figure 3 that

$$m = B / \sin(\alpha / 2),$$

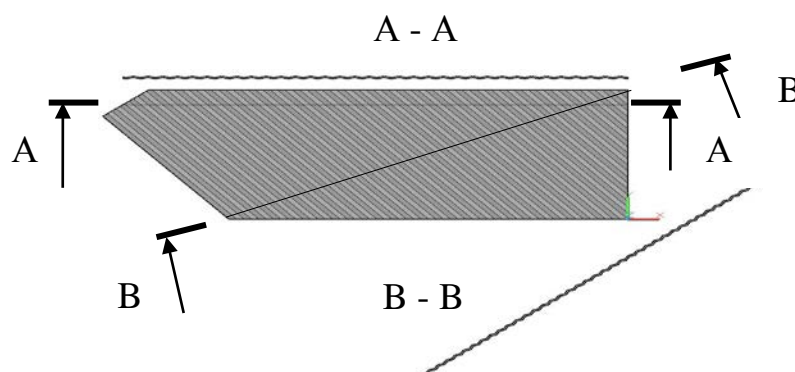
$$\sin(\alpha/2) = \left\{ B * H \pm \sqrt{B^2 * H^2 - [H^2 + (T/2)^2] * [B^2 - (T/2)^2]} \right\} / (H^2 + T^2)$$

Let us take the following values of the initial data for further modeling:  $B = 0.4$  mm;  $H = 0.1$  mm and  $T = 3$  mm. Then we get:  $m = 0.428088$  mm;  $\alpha = 69.1294^\circ$  or  $\alpha = 69^\circ 7' 46''$  (Figure 4).



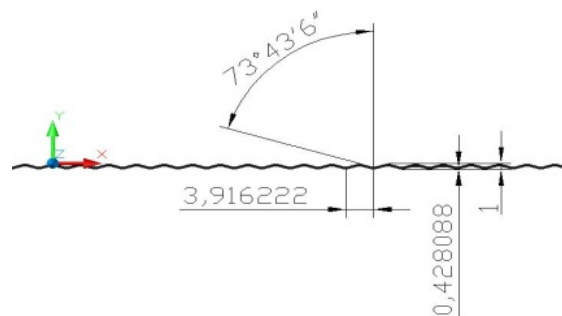
**Figure 4.** Ribbon profile parameters in the normal section.

The resulting profile is the initial one for the production of a solid-state ribbon model. At the first stage, a solid model of a workpiece is created for the ribbon, on the basis of which the ribbon model part is formed. The result of modeling the ribbon compartment is shown in Figure 5. It presents the projection of the model and its section: oblique – A-A and normal - B-B. Section A-A is the starting point for modeling the shaping of the tool - the roller. This section and its parameters is shown in Figure 6. Before modeling, let us determine the diameter of the initial cylinder  $D_{in}$  of the roller, knowing its outer diameter  $D$  and pitch  $H_k$  of the ribbon profile in its oblique section. The value of  $H_k$  is determined by the model of the ribbon profile ribbon (Figure 6) and is 3.916222 mm.  $D_{in}$ ,  $H_k$ , and the number of teeth  $Z$  are related by the dependence  $\pi * D_{in} = Z * H_k$ , so we get:  $Z = 64$  and  $D_{in} = 79.7806$  mm.



**Figure 5.** Projection of the cutoff model of the ribbon and its section: A-A is the oblique section; B-B is the normal section.

The resulting cross section model and its installation parameters are used later for modeling a tool for manufacturing the ribbon.



**Figure 6.** Computer model of the ribbon oblique section and its parameters.

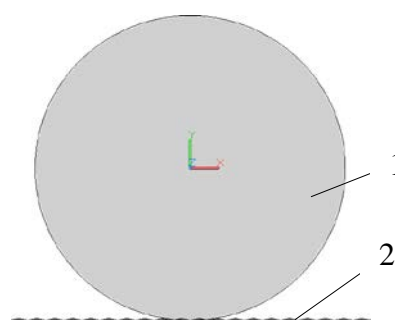
### 3.3. Computer and solid modeling of direct and inverse problem shaping

#### 3.3.1. Solid modeling of the tool for shaping the ribbon

In the developed software package, it is proposed to carry out the tool surface shaping on the basis of solid modeling to solve the described problem. Then, in accordance with the algorithm of shaping modeling [9], at first, solid models of the tool and the detail workpiece are created, each in its coordinate system. The location of these coordinate systems is determined by the installation parameters of the workpiece relatively to the tool.

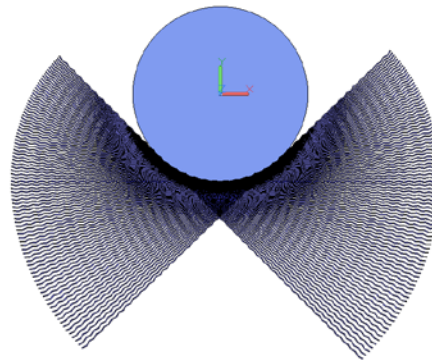
The relative movement of the ribbon model, which determines the kinematic pattern of the shaping, is similar to the kinematic scheme of shaping the workpiece with a tool rack.

The sequence of solving the task on the basis of the developed algorithms and programs is presented below. At the first stage of shaping, the models of the initial data are set: the model of the ribbon and the workpiece for the roller that is its end section (Figure. 7).



**Figure 7.** Models of a ribbon profile - 1 and a workpiece - 2 for a roller.

At the second stage, to obtain preliminary modeling results, a family of ribbon models is built by rolling its initial straight line along the initial circumference of the roller (Figure 8). The scaled-up fragment of the obtained family is shown in Figure 9. As it is known, the profile of the ribbon is outlined by the involute curve, which is confirmed by Figure 9. No transitional curves are observed. This means that the profile of the roller does not have sections outlined by special curves, which allows us to proceed to the next stage - solid modeling.

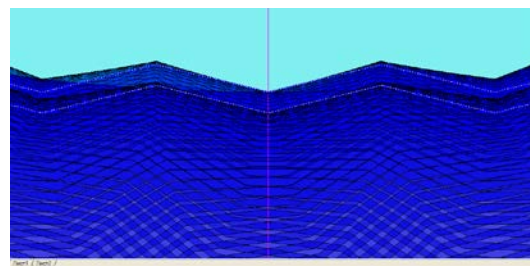


**Figure 8.** A family of ribbon profiles in its relative motion.

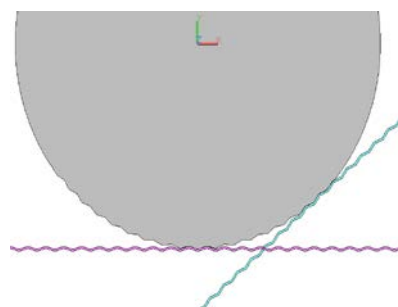
Figure 10 shows the shaping of roller profiles by a ribbon model. At this stage, the designer can vary the value of the family parameter to obtain the required accuracy of the tool profile.

The final result of the modeling is shown in Figure 11a. A scaled-up fragment of the ribbon and the roller profiles is shown in Figure 11b. According to the figure, practically these profiles contact not in a point touch (theoretically), but along the part of their profiles.

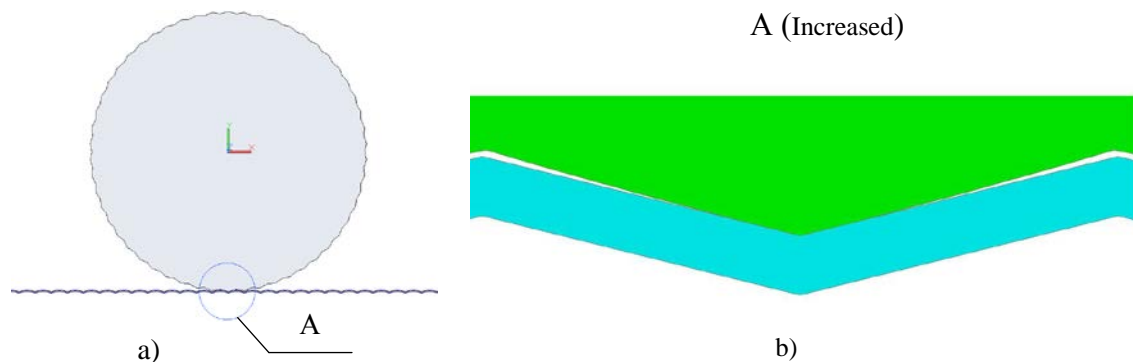
Due to the fact that it is technologically easier to produce a roller tooth having a rectilinear profile than the involute outlined (theoretically), the corresponding approximation is performed, as shown in Figure 12. In this figure, the profile side is replaced by a segment passing through the points of the vertex and the tooth hollows.



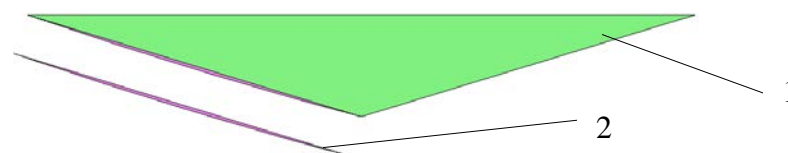
**Figure 9.** Scaled-up fragment of ribbon profiles family on an enlarged scale.



**Figure 10.** Shaping a roller by a ribbon model.

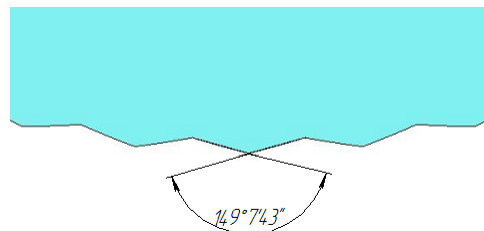


**Figure 11.** Result of roller profiles modeling: a) general view; b) scaled-up fragment of models.



**Figure 12.** Profile of the roller tooth and the part to be removed: 1 - tooth profile; 2 - extruded part.

In this case, the area of the removed part is  $0.0097 \text{ mm}^2$ , which is 0.6% of the total area of the tooth. As a result of the replacement, the real profile of the roller has the parameters shown in Figure 13. The obtained profile is further used to solve the inverse problem of shaping - obtaining the ribbon profile to the designed and corrected roller model.



**Figure 13.** Profile of the roller tooth after revision.

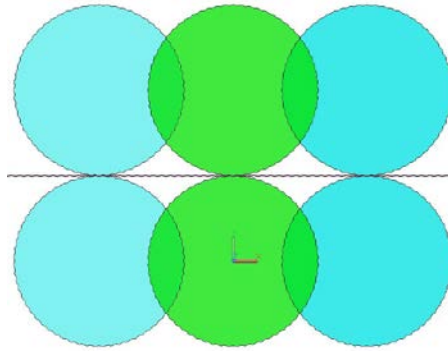
### 3.3.2. Solid-state ribbon modeling with the obtained tool

After correcting the tooth profile and obtaining the end section of the roller, a number of stages of ribbon profile modeling are performed being the solution of the inverse problem of shaping. At the first stage, like in the previous problem, a family of end sections of the roller is built. The initial data is the roller model and the workpiece model for the ribbon having rectangular profile. After analyzing the resulting family, solid-state modeling of the ribbon by the obtained tool is carried out (Figure 14). Scaled-up fragment of this modeling is shown in Figure 15. The resulting ribbon profile is used for its comparison with the original one. If the resulting profile meets the necessary requirements, the modeling is completed.

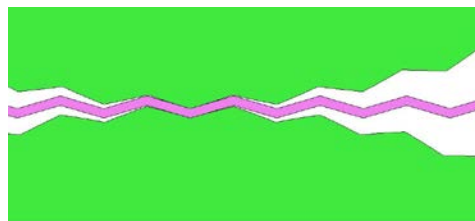
In some cases, there is a need to model the extruded volumes, which is provided for by the developed programs. The results of this modeling allow us to correct the technology of ribbons manufacturing. Figure 16 shows the fragments of roller and ribbon models, as well as models of deleted layers. The increment of the family parameter for the case under consideration is  $3^\circ$ . The analysis of the obtained



models allows us to make a series of qualitative and quantitative conclusions. So, it follows from Figure 16 that at a given family parameter at each instant of time, the shaping is performed mainly for three cavities of the ribbon profile. Moreover, the extruded volumes in shaping the various hollows are significantly different. In this regard, accordion folding of the ribbon is possible, which requires experimental verification.



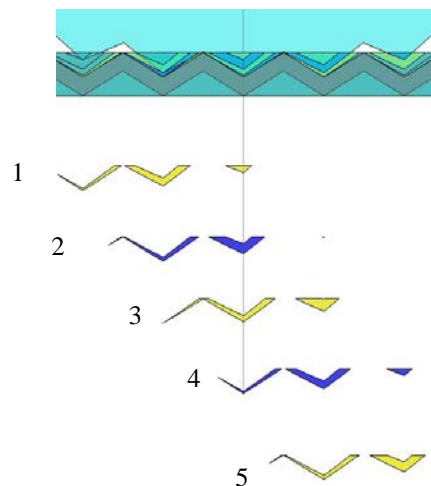
**Figure 14.** Modeling of ribbon shaping by two rollers.



**Figure 15.** Scaled-up fragment of ribbon shaping modeling by two rollers.

Thus, the implementation of 3D modeling of direct and inverse shaping problems, the analysis of the results obtained at different stages of the shaping, as well as possible experimental verification, let us define optimal parameters of the roller profile and its installation relatively to the ribbon workpiece.



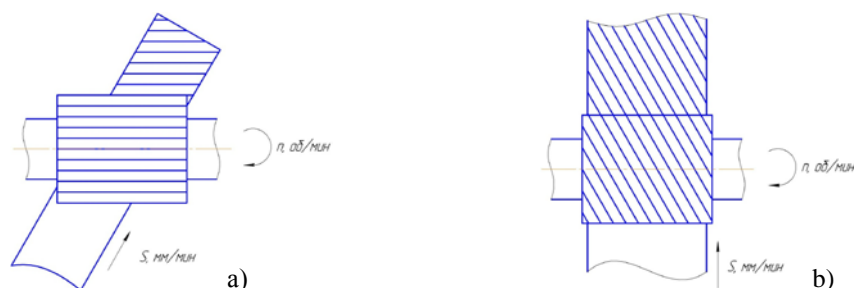


**Figure 16.** Modeling of extruded volumes under the family parameter change  $\varphi = 3^\circ$ .

#### 4. Experimental results

The most laborious operation of manufacturing finned elements of the gas heater is rolling the periodic corrugated profile.

The rolling pattern has dominant influence on manufacturing efficiency and quality. Two rolling patterns are possible for rolling the finned surface of the ribbon with the angle of the profiles inclination: by straight-toothed rollers with feeding of the workpiece at the angle the profile inclination to the rotation axis of the rolling rollers (Figure 17a) or by helical rollers with feeding of the workpiece at an angle of  $90^\circ$  to the axis of the shaping rollers (Figure 17b).



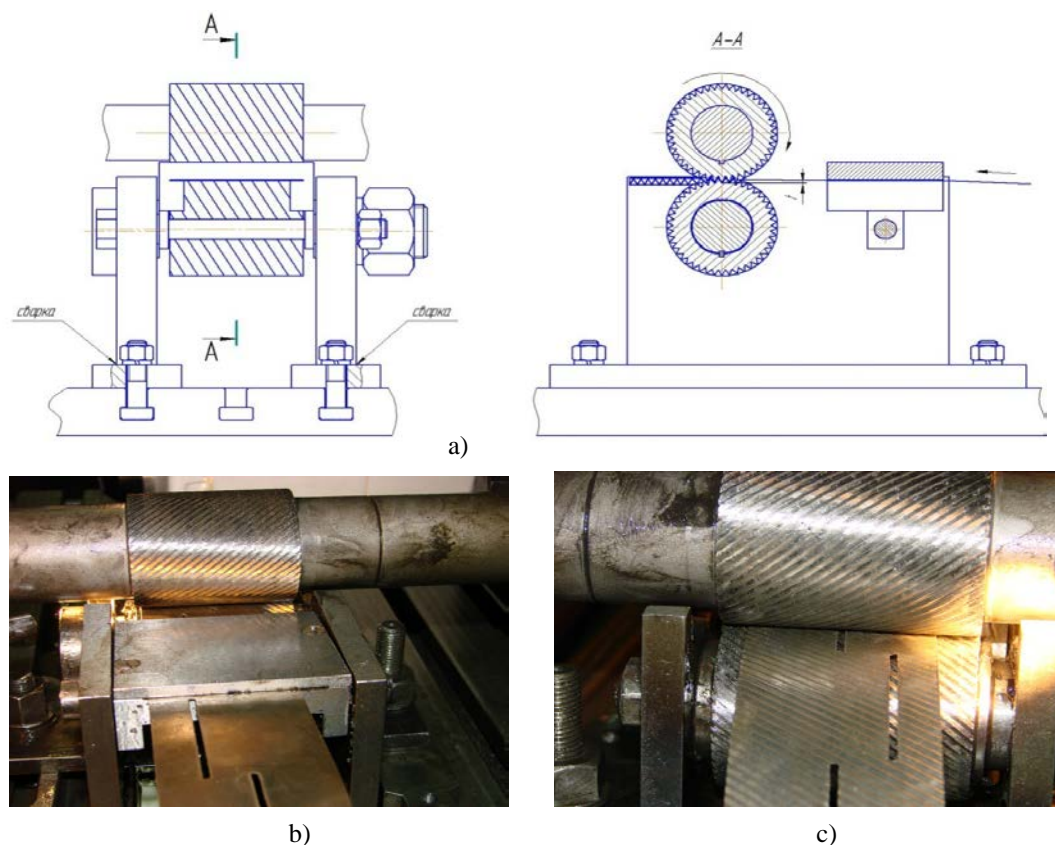
**Figure 17.** Schemes of rolling the finned elements of the nozzle with rollers: a) with straight teeth; b) with inclined teeth.

For rolling the finned elements of the nozzle between the rollers, a gap is set that corresponds to the thickness of the rolled ribbon, and the ribbon itself moves along the reference diameter. In the scheme shown in Figure 17a, the reference diameter has the shape of an ellipse, which leads to uneven rolling of the profile and "bending" of the ribbon (Figure 18). In this regard, the most optimal from the point of view of manufacturing efficiency and accuracy could be the scheme shown in Figure 17b.



**Figure 18.** Distortion of the rolled ribbon configuration.

In accordance with the obtained scheme of ribbon manufacturing, adjustment for rolling the finned profile with helical rollers was developed - Figure 19. In this scheme, one shaping roller is fixed in the tool and has free rotation, while the second is attached onto the spindle of the machine and is fixed from axial rotation. The ribbon is fixed into in the catching-guiding device and is fed to the working surface of the rolling rollers. The spindle of the machine starts to tighten the ribbon between the rollers. Then the process continues in an automatic mode. Between the teeth of the rolling rollers, a guaranteed clearance  $f$  is provided equal to the thickness  $B$  of the rolled ribbon. With a decrease in the clearance size, plastic deformation of the ribbon surface occurs, which leads to unacceptable hogging (Figure 20).



**Figure 19.** Adjustment for the rolling of the finned profile with helical rollers: a) general view of adjustment; b) feeding the ribbon into the catching-guiding device; c) ribbon after rolling.

The optimum range of roller speed, which determines the increment of the motion parameter, is from 10 to 20 rpm. Figure 21 shows the ribbon after rolling on the machine.



**Figure 20.** Ribbon surface hogging.



**Figure 21.** Ribbon after rolling operation.

## 5. Discussion

In the article, when solving the direct and inverse problem of shaping, modeling of the profile of the tool and then the profile of the ribbon according to the corrected profile of the tool was performed. During 3D modeling, models of extruded volumes were also obtained for different values of the tool motion parameter increment. The preconditions for the effect of this parameter on the possible ribbon hogging are revealed. The information obtained from 3D modeling concerning geometric parameters of the ribbon and tool profiles, as well as the extruded volumes, is necessary for further research, such as determining the shaping forces, tool stresses and ribbon performs at their contact points, as well as the development of tool wear.

## 6. Conclusion

Making corrugated ribbons of considerable length is technologically complicated process which requires the accuracy of the profile and straightness of the ribbon. It is proposed to solve this problem by the rolling method, similar to the rolling method used in the shaping of workpieces by cutting. To implement this method, a technique was developed that provides 3D modeling of the process of shaping the surface of a workpiece with a tool.

On its basis, geometric and computer modeling of the profile of the rolling tool was carried out. Based on the modeling results, the theoretical profile of the ribbon was replaced by a straight line (taking into account technological requirements). After replacing the roller profile, the inverse shaping problem was solved - a real ribbon profile was obtained. Then, a comparative analysis of the ribbon initial profile and the profile, designed theoretically and corrected (a real one) based on technological requirements was carried out. According to the results of the analysis, it was concluded that the obtained profile was consistent with the required result. A software package was developed that perform computer modeling of extruded volumes in the process of shaping. The analysis of the qualitative and quantitative parameters of the extruded volumes made it possible to give recommendations on setting the increments in the tool motion parameter. Based on the results of 3D modeling, a technology was developed for manufacturing finned ribbons from heat-resistant steels. It

allows to carry out the rolling process characterized by high efficiency, accuracy and stability of the obtained dimensions.

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