Improving the Quality of Elements of Flat Heat Exchangers and Roof Coatings Received by the Elastic Working Tool

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Abstract. The article discusses the issues of improving the quality of elements of flat heat exchangers and roof coverings. This is achieved by increasing the strength of the sheet metal, heat exchanger elements and by increasing the thickness of the roof covering. It is advisable to make such elements using an elastic working tool. The use of elastic media as a working tool makes it possible to significantly reduce the cost of die tooling, but it has drawbacks. The main one is small pressures in an elastic medium that is not enclosed in a closed volume; therefore, the forces that arise are not enough to deform alloys with a thickness of more than 0.5 mm. It is possible to increase the pressure and, accordingly, expand the technological capabilities by reinforcing polyurethane with high-strength aramid fabrics. The paper considers the behavior of a cylindrical polyurethane specimen during its settlement. The theoretical model coincides with the experiments. Two types of specimens were upset, cylindrical with reinforcement with different types of aramid fabric. The experiments carried out show that the reinforcement leads to a significant increase in the rigidity of the working elastic working tool and, as a result, to the expansion of technological capabilities and the range of products obtained by local processing with an elastic medium. This leads to an increase in the performance of flat heat exchangers, as well as an increase in the quality and strength of the roofs.

1. Introduction
Nowadays, the problem of insufficient strength of roof coatings often arises; due to insufficient strength, hail can deform the roofs of cars and buildings, which entails extremely expensive repairs. The problem of increasing productivity also arises in the manufacture of flat heat exchangers in the event that an increase in fluid pressure is required to increase productivity. To solve these problems, the use of an elastic tool of increased rigidity is required.

Molding with elastic media is widely used in metal forming. The advantages of this method include a decrease in the metal consumption of the resulting stamps and their significant reduction in cost. In addition, products obtained by localizing the center of plastic deformation have a lower mass while maintaining strength properties [3-7]. Of particular interest are the processes of manufacturing sheet blanks with a convex-concave relief surface on new devices for local molding. The formation of the relief on the surface of the workpieces is carried out by passing the latter between the relief surface of the matrix installed on a table with a horizontal movement drive and a rotating shaft with an elastic polyurethane shell. Since molding according to this scheme is carried out in an open volume, it is impossible to obtain high pressures in an elastic medium, which affects the technological capabilities of this process. However, when molding thin sheet blanks, due to the locality of the impact of loads, it becomes possible, at relatively low pressures, to produce molding over very large areas (up to several square meters) with minimal energy consumption.

In the past few years in construction, sheet coverings in the form of a corrugated sheet with a relief pattern on the surface that imitate tiles have been widely used. Over the past three years, the Russian
market has been filled with such products manufactured in the west (Sweden, Finland). Products of this kind are made from sheet metal (thickness $S = 0.8$ mm) such as aluminum alloys, aluminum-zinc alloys or galvanized steels. The relief on the surface of the sheet is obtained by rolling on a roll-forming mill, and then the relief is applied to the surface of the sheet by means of stamping on presses in dies of complex design. Which has a significant impact on the price of coverage. Such high prices do not allow widespread use of this modern, durable, lightweight and elastic material by our builders.

Today, the design of plate heat exchangers is the most advanced in the field of solving heat transfer problems.

The device and the principle of operation of the plate heat exchanger are quite simple. When the plate pack is pulled together, a number of channels are formed through which the fluids involved in the heat exchange process flow. All plates of the plate heat exchanger in the package are the same, only rotated 180 degrees relative to each other. This arrangement of plates in a plate heat exchanger provides an alternation of hot and cold channels. In the process of heat exchange, liquids move, most often, towards each other (in countercurrent flow), and the hot liquid transfers heat through the plate wall. In places of their possible overflow there is a double rubber seal, which excludes mixing of liquids. This principle of construction of a plate heat exchanger allows it to be quickly modified, both in the direction of increasing the number of plates, and thereby increasing the capacity of the plate heat exchanger, and easily repaired in the event of a failure of the rubber seal or heat exchange plate.

The widest use of plate heat exchangers in almost all areas of industry, where a heat exchange process is required, is due to their unique qualities: the highest heat exchange efficiency; reliability and resistance to external and internal influences; ease of installation and operation; ease of cleaning due to the collapsible design; small weight and size indicators; flexibility, i.e. the ability to change the characteristics of an already in use heat exchanger.

The main disadvantage is that when using an elastic medium as a working tool, on the one hand, we are limited by the maximum degree of deformation of the elastic medium (no more than 30%), since when this value is exceeded, the number of possible cycles to failure sharply decreases. In addition, the pressure of the working medium made of polyurethane of the hardest grades of the SKU-PFL type (when operating in an open volume) is not enough to deform sheet steels with a thickness of more than 0.5 mm.

The purpose of this work was: to increase the efficiency of heat exchange and the life cycle of heat exchangers, as well as to increase the rigidity of roofs by increasing the rigidity of an elastic working tool.

2. Experimental research

At the first stage of experimental studies, draft of reinforced samples was carried out. We investigated a sample of reinforced polyurethane mark SKU 6L. Then he Mooney- Rivlin coefficients were determined [1, 2, 10, 11].

At the first stage of the experiment, an unreinforced sample was sedimented on an INSTRON SATEC series TYPE UTM-HYD, model 600 DX-F1-G1 testing machine. A photograph with the sample mounted on the table of the testing machine is shown in Fig. 1.
Figure 1. Draft of a cylindrical sample.

At the stage of experimental studies, a cylindrical sample was loaded according to the uniaxial compression scheme. The loading results of a cylindrical specimen were used to calculate the Mooney-Rivlin coefficients. At the first stage, a cylindrical sample was examined: height - 10 mm, diameter - 65 mm.

The dependence of the draft force $F$ of the cylindrical sample on the stroke $x$ is plotted in Fig. 2.

Figure 2. Graph of the force of precipitation on the course.

From the graph presented in fig.3, the numerical values of the degrees of deformation at the corresponding points ( $\lambda_i$ ) and stress were determined as the ratio of the precipitation forces to the actual contact surface area of the working tool and the sample, which was also measured during the experiment. Then, using the obtained experimental data, the Mooney-Rivlin coefficients were determined for the case of precipitation (according to the method described in [1, 2, 4]).

Mooney-Rivlin expression for a deformed state:

$$W = C_1 \left( \lambda^2 + \frac{1}{\lambda^2} - 2 \right) + C_2 \left( \frac{1}{\lambda^2} + \lambda^2 - 2 \right)$$

(1)

The two-parameter equation of the relationship between stress and strain for an isotropic incompressible material with medium and small degrees of deformation of $1.5 \ldots 2 < \varepsilon < 3.5 \ldots 4$ is defined as [1,2,5]:
\[ p = 2\left(\lambda - \frac{1}{\lambda^3}\right)(C_1 + C_2) \]  

(2)

where \( p \) - "Terms Noah" equilibrium voltage.

The true voltage value is determined from the incompressibility conditions:

\[ \sigma = 2 \times \left(\lambda^2 - \frac{1}{\lambda^2}\right) \times (C_1 - C_2) \]  

(3)

\[ C_1 = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{\sigma_i}{\lambda_i^2} - \frac{C_2}{\lambda_i}\right) \]  

(4)

\[ C_2 = \frac{\frac{1}{n} \sum_{i=1}^{n} \frac{1}{\lambda_i^2} \times \sigma_i - \frac{1}{n} \sum_{j=1}^{m} \frac{\sigma_j}{\lambda_j^2}}{\frac{1}{n} \sum_{i=1}^{n} \lambda_i^2} \times \frac{1}{\lambda_i} \]  

(5)

Expressions (4), (5) allow us to determine the desired values of the parameters \( C_1 \) and \( C_2 \), however, with a large number of measurement points, it is advisable to create a computer program that will perform all mathematical transformations according to a given algorithm [3-7].

Calculations were made to determine the Muni-Rivlin coefficients in the MathCad software package. According to the results of the experiment, the Muni-Rivlin constants were determined. From formulas (4), (5), the following results were obtained for SKU-6L:

\[ C_1 = 1.45 \text{ MPa} \]
\[ C_2 = 0.62 \text{ MPa} \]

In order to evaluate the accuracy of the results obtained and their suitability for further theoretical calculations, the inverse problem was solved: simulated set by experiments, using the identified during the pilot study Mooney-Rivlin constants as input. In case, if the results of the theoretical solutions coincide with sufficient accuracy with the experimental results, the data rates Mooney-Rivlin can be used for modeling of deformation processes polyurethane SKU-6L. For this purpose, we have developed a mathematical model of these experiments using a specialized software package «Ansys» [3, 4, 5, 6].

During the simulation, the following material characteristics and the geometric dimensions of the samples (identical to those used in the experiment) were adopted.

Billet No. 1 - a cylinder with a height of 10 mm and a diameter of 65 mm made of SKU-7L polyurethane 3000 kg / m3, Poisson's ratio 0.49, constants of the two-parameter Muni-Rivlin model \( C_1 = 1.45 \), \( C_2 = 0.62 \).

In Fig. 3 shows the field of distribution of equivalent stresses (according to Mises) in a cylindrical workpiece during its deformation. The results of the solution show that the maximum equivalent stresses are of the order of 5.7 MPa in the central part of the workpiece and closer to the side region up to 3.5 MPa.

Figure 3. Field of equivalent stresses.
Let’s compare the results of the theoretical solution with the experimental results. The comparison will be carried out by force parameters, i.e. according to the dependences of forces on the draft of a cylindrical billet – the results are presented in Fig.4 and Fig.5 and the deformed state, i.e. in the shape of the side surface.

![Graph showing comparison of forces](image)

**Figure 4.** Comparison of the dependence of forces on the amount of draft for a theoretical solution and experiment.

For a cylindrical workpiece, a comparison of forces gives an error of 6 to 10%.

In Fig. 5 presents finite element models of a deformed and undeformed cylindrical sample.

![Finite element models](image)

**Figure 5.** Finite-element models of a deformed and undeformed cylindrical sample.

Let’s compare the shapes of the lateral surfaces of a deformed cylindrical specimen obtained during the experiment and the theoretical solution by superimposing the corresponding images obtained theoretically and experimentally (Fig. 6).

![Comparison of shapes](image)

**Figure 6.** Comparison of the shape of the side surfaces.
From Fig. 6 it is seen that the side surface forms, obtained in theory in the simulation and experimentally coincides give a high degree of accuracy.

In process of developing a composite material, fabrics of several manufacturers were used. A sample of aramid fabric 8601-90 (Kevlar) from the Advanced Textile Factory is shown in Fig. 7a. The surface density of the fabric is 190 g / m², breaking load: base - 3430 N, weft - 2940 N, elongation at break: base - 10%, ducks - 5%.

![Fabric for reinforcement](image)

**Figure 7.** Fabric for reinforcement.

A – fabric 8601-90 factory "Advanced Textile"; b - DuPont Twaron 2200 fabric sample; c - Teijin Aramid Fabric Sample 3360. In Fig. 7b is a sample of Twaron 2200, DuPont fabric. The surface density of the fabric is 220 g / m², elongation at break of 2.7%, tensile strength at break of 3014 MPa, elastic modulus of 105 GPa, weaving type twill (twill) plain. In Fig. 7, in a sample of 3360 of Teijin Aramid fabric. The surface density of the fabric is 468 g / m², the elongation at break is 3.7%, the tensile strength is 2863 MPa, the elastic modulus is 67 GPa, the type of weaving is plain (plein). Experimental samples (diameter 50mm, height 10mm.) Obtained by the method of layer-by-layer pouring are presented in Fig. 8.

![Reinforced polyurethane samples](image)

**Figure 8.** Reinforced polyurethane samples.

Initially, a cylindrical specimen was loaded, made of a target made of SKU-7L polyurethane. Further, loading of their cylindrical samples made of the developed composite material was carried out sequentially. Samples reinforced with aramid fabric New 8601-90(Kevlar) of the Advanced Textile Factory demanded maximum upsetting force.

Fig. 9 shows the results of loading a sample of unreinforced polyurethane and a reinforced sample.
Figure 9. Graph of the forces (N) versus the draft (mm) in the case of uniaxial compression of a sample of composite material and a sample of polyurethane without reinforcement.

From the graphs obtained as a result of experimental studies, we determine the numerical values of the degrees of deformation at the corresponding points (λi) and stress, as the ratio of the precipitation forces to the actual contact surface area of the working tool and the sample. Fig. 10 shows a graph of the dependence of stress on the degree of deformation for specimen No. 1 without reinforcement and No. 4 — reinforced with aramid fabric 8601-90(Kevlar) of the Advanced Textile Factory.

Figure 10. Graph of stresses (MPa) versus strain (%) in the case of uniaxial compression of a sample of composite material and a sample of polyurethane without reinforcement.

The graph shows that the stresses on the contact surface necessary for compressing a composite sample to a degree of deformation of 30% exceed the stresses for a polyurethane sample by 2 times.

To calculate the values of the Muni-Rivlin coefficients according to the obtained experimental data in accordance with the recommendation [10], as well as to automate the process and the ability to quickly obtain results from a large number of points, a program was written in the Python programming language. As a result of calculations in the program, the following Muni-Rivlin coefficients were obtained: For SKU-7L polyurethane: C10= 2.42, C01= 0.81; For a composite material reinforced with fabric 8601-90(Kevlar) of the Advanced Textile Factory: C1= 11.48, C2= 3.86.

3. Theoretical research
The modeling process of bending – forming of a sheet of steel St 10 was carried out using a working tool made of SKU-7L polyurethane, Kevlar reinforced, according to the scheme shown in Fig. 11. The working tool is a cylindrical shaft, outer diameter 110 mm, inner diameter 60 mm from reinforced polyurethane SKU–7L. The deformable sheet is St 10 0.5 mm thick, with a yield strength of 260 MPa and a tensile strength of 460 MPa.
The working tool was deposited on an absolutely rigid plane of the matrix to a degree of deformation of the polyurethane shell of 30%. This model was adopted by us, because from literature [10] it is known that when bending – forming of a sheet (roofing sheet for building roofs) in a hollow, even when manufacturing a sheet from aluminum alloys of the AMg type, it is impossible to obtain a qualitative study of the relief along section A-A (Fig. 11), and when deformation of steel sheets, the depth of the relief cavity reaches only 0.5 mm instead of 5 mm.

Figure 11. The scheme of modeling for bending-forming sheet.

Fig. 12 shows a diagram of a finite element model performed in the Ansys software and computer complex, taking into account all possible simplifications and assumptions.

Figure 12. The finite element model.

Having performed the calculations, we obtained the following results presented in Fig. 13, 14.

Figure 13. Fields of normal (vertical axis) stresses.
Figure 14. Contact stresses on the sheet surface.

According to the results of the calculation, the obtained stress-strain state shows that the shape change along the matrix profile will occur, and it becomes possible to obtain a high-quality study of the relief along section A-A (Fig. 11), even when the steel sheets are deformed, the depth of the relief depression reaches the required technical specification 5 mm.

4. New equipment for forming a thin sheet steel

Fig. 15 show a diagram of the structure of the mill for obtaining roof coatings from sheet steel by the method of local bending forming [4]. In this scheme, the working force applied to the shaft is created by a roller that moves along the copying rail and is rigidly connected to the working shaft.

Figure 15. Local bending mill diagram.

Metal processing at the bending - forming mill, according to the scheme in Figure 15, is carried out as follows: in the initial position, the traverse 6 is in the extreme position (left or right). On the table 6, with the matrix 8 installed on it, place the workpiece and turn on the engine 3, which drives the shaft-screw 4 and the nut 5 through the belt drive 2. Moreover, the nut 5 is rigidly connected to the table 6. On the bed 1 there is a vertical movement drive 12 of the deforming shaft 13 with an elastic shell 14. The drive 12 is made in the form of a threaded rod of adjustable length, on which a support roller 16 is fixed, which moves along the copy 17, which allows creating the same pressure on the workpiece on any fragment of the matrix 8 relief. bending occurs - the blank is molded into the shape of the matrix 8, due to the action of the elastic shell of the shaft 14 and the drive 12. The operation ends with the table 6 stopping in the extreme position. The finished product is removed, a new blank is placed on the matrix. Further, the engine 3 is turned on, which, through the belt drive 2, produces a reverse movement, thus the deformation process is repeated.
The local bending mill for forming sheet metal is intended for use in small-scale production, saves production space by combining the above-described modules (bending and forming) into a complex, expands the technological capabilities of processing various materials, for example, aluminum and copper, through the use of a reinforced tool alloys (up to 1.5mm thick), steels (up to 1mm thick), which significantly expands the range of manufactured products. The time for the production of products is reduced due to the combination of the above modules and their versatility. Easy, time-saving tool changeovers and changes are a big advantage. The existing drives for vertical movement allow achieving the required deformation of the metal by an elastic medium in one pass, which allows you to maintain the excellent appearance of the product without loss of quality.

Figure 16 shows the design of the mill for obtaining such coatings from sheet blanks by the method of local bending forming. In this scheme, the working force applied to the shaft is created by a roller that moves along the copying rail and is rigidly connected to the working shaft.

![Figure 16. Design of bending and forming sheet mill.](image.png)

On the bed 1 there is a drive for the horizontal movement of the table 17, which consists of an electric motor 3, a gearbox 2, a lead screw 4 and rollers 7. The nut 5 is rigidly connected to the table 17. On the table there is a matrix 8, on which there is a sheet blank, two clamps 9 and rail 6 copying the profile of the matrix. Also, on the frame is rigidly fixed unit for vertical movement of the shaft 14 with an elastic shell 13.

The mill works as follows: in the initial state, the table is in the extreme right position, a sheet blank is installed on the die, which is fixed with a left clamp.

The table is driven by an electric drive through a screw-nut transmission and moves along the rollers 7. In this case, the copy roller 16 follows the profile of the rack 6 and sets the vertical movement of the shaft with the elastic shell. The process ends when the table reaches the leftmost position. In this position, the clamp 9 is weakened, and the finished part is removed from the die. Then the new workpiece is placed on the die, fixed with the right clamp, and the table begins to move in the opposite direction. Then the process is repeated. Figure 17 shows a sample of a sheet blank formed on a mill of this design.
After the sheet blank is given the required shape, the preparation for painting and painting in an electrostatic field with powder dyes follows. After that, the workpiece takes on a presentation. Figure 18 shows a roof element assembled from sheets processed at a local bending-forming mill.

The technological process of obtaining corrugated roofing cover consists of the following main operations:
1. Cutting the roll (sheet) into blanks on scissors.
2. Processing at the bending-forming mill with an elastic tool.
3. Degreasing the surface (preparation for painting).
4. Painting in an electrostatic field with powder dyes.
5. Drying in the oven.

5. Conclusions
Analysis of the results of experimental studies and modeling of the bending process - sheet forming with an elastic tool made of reinforced polyurethane shows: reinforcement leads to a significant increase in both forces and stresses on the contact surface, relative to isotropic polyurethane. Thus, the obtained data can be used for the manufacture of high-quality (more durable, not subject to deformation in the form of large hail) and competitive coatings for roofs of buildings, as these results increase our capabilities in the manufacture of flat heat exchangers with the same thickness, it is possible to increase productivity or reduce weight without losing productivity.

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