Increasing the rigidity of an elastic working tool for processing thin sheet metal by creating composite material based on polyurethane elastomers and synthetic aramid fabrics

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Abstract. The paper presents the results of both experimental and theoretical studies on the creation of a new composite working tool for pressure treatment of thin sheet metals. The composite working tool is made on the basis of SKU-7L polyurethane with reinforcement with one layer of kevlar-type aramid fabric.

Key words: polyurethane, kevlar, aramid fabrics, elastic working tool

1. Introduction

In the aerospace and energy fields, various sheet metal products are widely used, such as elements of aircraft parts and various types of flat heat exchangers and the like. The analytical review showed that the production of parts from sheet blanks by stamping with a working tool made of polyurethane elastomers has been mastered [1,3,4,5]. The method is particularly cost-effective for single and small-scale production, but in some cases it is also used for batch production, for example, in the production of plates for flat heat exchangers up to 50 thousand pieces. At the same time, the production does not always have powerful pressing equipment for the introduction of polyurethane stamping of parts. In these cases, the most profitable are rotary shaping methods, characterized by lower energy consumption and high productivity. The disadvantage of this method is the limited technological capabilities of the elastic working tool, associated primarily with the low values of the conditional modulus of elasticity of modern polyurethane elastomers. Maximum thickness of processed materials: for steel - 0.5 mm, for sufficiently soft non-ferrous metals and alloys - 0.8-1 mm. [6-10]. Currently, one of the promising ways to obtain the required properties of materials is the development and creation of composite structures. One of the existing methods of increasing the rigidity of elastomers is its reinforcement with high-strength fabrics.

One of the important tasks was the choice of a mathematical model of hyperelastic materials. Hyperelastic material is a model type of ideally elastic material for which the dependence of stresses on deformations is calculated based on a function of the strain energy. A hyperelastic material is a special case of an elastic Cauchy material. The behavior of a hyperelastic material can be described using one of the common mathematical models - Neoguk, Mooney-Rivlin, Ogden, Blatz-Ko, Arruda-Boyce. We have chosen the two-parameter Mooney-Rivlin model, which is widely used for deformations up to 50%. [1,2].

2. Determination of Mooney-Rivlin constants

The Mooney-Rivlin constants for the hyperelastic state were determined by minimizing the standard deviation between the stress-strain diagram obtained experimentally and determined by the equation [1-3]:

\[ \sigma_{11} = 2\left(\lambda_1^{-2} - \lambda_1^{-1}\right) \left[ \frac{\partial W}{\partial I_1} + \lambda_1^{-1} \frac{\partial W}{\partial I_2} \right], \]

(1)

Where \( \sigma_{11} \) – deformation stress (specific force on the surface), MPa;

\( \lambda_1 \) – degree of deformation;
– deformation energy density; 

\( I_1, I_2 \) – the first and second invariants of the deformation tensor.

The final expressions for determining the constants are shown on the slide, where \( \lambda_i \) is the main degree of deformation in the \( i \)-th direction.

From the graphs obtained as a result of experimental studies, the numerical values of the degrees of deformation at the corresponding points \( \lambda_i \) and stresses were determined as the ratio of the upsetting forces to the actual area of the contact surface of the working tool with the sample.

As a result of calculations, the following Mooney-Rivlin coefficients were obtained:

For SKU-7L polyurethane: \( C_1 = 2.42, \ C_2 = 0.81 \)

For a composite material made of polyurethane SKU-7L reinforced with 8601-90 fabric from the Peredovaya Tekstilshchitsa factory: \( C_1 = 11.48, \ C_2 = 3.86 \).

Accurate material test data is critical to the mathematical modeling of elastomer products. To describe the mechanical characteristics, experimental dependences of stresses on deformations of the developed new materials should be obtained.

To determine the dependences of stresses on deformations, the samples were studied under loading according to the schemes of pure shear (plane deformation) (Figure 3) and the volumetric deformation of a sample square in plan (Figure 1).

To create the samples, a composite material was developed, shown in Figure 1.

![Figure 1. The structure of the composite material](image)

A 10 mm thick sheet of SKU-7L polyurethane was used as the basis for the developed composite material. Reinforcement was carried out with aramid fabrics. During the development of the material, aramid fabric 8601-90 (Kevlar) of Russian production by the Peredovaya Tekstilshchitsa factory was used. Fabric areal density 190 g / m², breaking load: warp 3430 N, weft 2940 N, elongation at break: warp 10%, weft 5%.

3. Method and results of studying samples according to the biaxial compression scheme

At the stage of experimental studies to determine the Mooney-Rivlin coefficients, upsetting of prismatic samples was carried out according to the biaxial compression scheme.

The objects of the study were the following samples (Figure 2):

1) Prismatic specimens 20mm x 10mm x100mm, which are glued polyurethane blanks 10mm x 10mm x100mm, used polyurethane brand SKU-7L.
2) Prismatic specimens 20 mm x 10 mm x 100 mm, representing a composite structure: the matrix is SKU-7L polyurethane, the reinforcing elements are aramid fabric, the binder is cyanoacrylate.

**Figure 2.** Prismatic specimens with and without reinforcement

The loading of the samples was carried out on an INSTRON testing machine model 600DX-F1-G1. To ensure the possibility of loading the samples according to the scheme of pure shear (plane deformation), at the first stage of research, the tests were carried out in a special matrix - a non-separable container, shown in Figure 3 (a).

**Figure 3.** (a, b) - container with a sample and in the process of upsetting

The results for biaxial compression are shown in Figure 4:
Figure 4. Results of upsetting (sample 1 composite, sample 2 normal)

Mooney-Rivlin constants for a hyperelastic material were determined by the equation [1]. The two-parameter equation of the relationship between stress and strain for an isotropic incompressible material at medium and small degrees of deformation 1.5 ... 2 <ε <3.5 ... 4 is defined as [1,2,5]:

\[ p = 2\left(\lambda - 1/\lambda^3\right)(C_1 + C_2) \]

(2)

where \( p \) - "conditional" equilibrium stress.

The true stress value is determined from the incompressibility conditions:

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

(3)

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

(4)

\[ C_2 = \frac{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{\sigma_i}{2\left(\lambda_i^2 - 1/\lambda_i^2\right)} \times \frac{\lambda_i \times \sigma_i}{2\left(\lambda_i^2 - 1/\lambda_i^2\right)} \times \frac{1}{2\left(\lambda_i^2 - 1/\lambda_i^2\right)} \right)}{1+\left(\sum_{i=1}^{n} \frac{1}{\lambda_i}\right)^2 \times \sum_{i=1}^{m} \frac{1}{\lambda_i} \left(\sum_{j=1}^{m} \lambda_j\right)} \]

(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 [8-11].

Calculations were made to determine the Mooney-Rivlin coefficients in the MathCad software package. According to the results of the experiment, the Mooney-Rivlin constants were determined. From the graphs obtained as a result of experimental studies, the numerical values of the degrees of deformation at the corresponding points (\( \lambda_i \)) and stresses were determined as the ratio of the upsetting forces to the actual area of the contact surface of the working tool with the sample.

To determine the dependences of stresses on deformations, the samples were studied under loading according to the scheme of biaxial nonuniform compression.

4. Method and results of the study of samples according to the scheme of biaxial uneven compression

At the stage of experimental research according to the scheme of biaxial uneven compression (Figure 5).
Figure 5. Samples on the table of the INSTRON testing machine a-composite, b-conventional
The research objects were the following samples:
1) Samples 100x100 mm, 20 mm high. Used polyurethane brand SKU-7L.
2) Samples 100x100 mm, 10 mm high, representing a composite structure: the matrix is SKU-7L polyurethane, the reinforcing elements are aramid fabric, the binder is cyanoacrylate. Figure 6 shows the prepared elements for the manufacture of a composite sample and a control one-piece sample.

Figure 6. Prepared elements for the manufacture of a composite sample and one-piece sample
After upsetting, the following results for uneven compression are obtained, presented in Figure 7
Dependences of stresses on deformations, as seen from Fig. 5 and 7, the reinforcement increases the deformation force by almost 2.5 times.

5. Mathematical modeling of the deformation process of a sheet blank
At the first stage, the deformation of the sheet in the cavity of the matrix was simulated with a working tool made of SKU-7L polyurethane, at the second - from a composite tool reinforced with 8601-90 fabric. The calculation was carried out in the Ansys software package.

The process of deformation of the sheet in the cavity of the matrix (the degree of deformation of the shell is 30%) was carried out according to the scheme shown in Figure 8.

The working tool is a cylindrical shaft with a diameter of 100 mm: density 3000 kg/m\(^3\), Poisson's ratio 0.49, elastic shell - outer diameter 140 mm, Mooney-Rivlin ratios for polyurethane SKU-7L: \(C_{10} = 2.42\), \(C_{01} = 0.81\), for composite material reinforced with 8601-90 fabric: \(C_{10} = 12.88\), \(C_{01} = 4.86\). Rigid shaft - a cylinder, outer diameter 100 mm, adopted by an absolutely rigid body.

To speed up the calculation, we used symmetry conditions in three planes. The matrix and the shaft were defined by absolutely rigid bodies (Rigid). The behavior of a deformable material (AD0) was described by a bilinear model (yield stress 40 MPa, ultimate strength 80 MPa with a relative elongation of 0.35), and the behavior of a polyurethane shell using a two-parameter Mooney-Rivlin model. To describe the contact between the matrix and the sheet, a frictional contact with a friction coefficient of 0.2 was used, a rigid shaft and polyurethane - a bonded contact, between polyurethane and a sheet, a frictional contact with the same friction coefficient of 0.2.
Figure 8. Diagram of the process of sheet deformation in the depression

The sheet is divided into parallelepipeds using the edgesizing command with dimensions of 0.05×4.5×5 mm. The polyurethane shell is broken up into parallelepipeds using the edgesizing command with dimensions of 1×1.25×3.8. For a better picture of the SSS in the near-contact area, the contactizing command was used, which reduced the size of the elements in the near-contact area. Thus, the task has 40413 nodes and 8500 elements. As a result, the following results were obtained, presented in Figures 9-12:

Figure 9. (a,b) - Fields of equivalent stresses a-polyurethane, b-reinforced polyurethane.

Equivalent stresses of polyurethane tools: maximum equivalent stress $\sigma_{eq,max} = 7$ MPa, minimum equivalent stress $\sigma_{eq,min} = 0.007$ MPa.

Equivalent stresses of the composite tool: maximum equivalent stress $\sigma_{eq,max} = 33$ MPa, minimum equivalent stress $\sigma_{eq,min} = 0.004$ MPa.
Figure 10. (a,b) - Fields of equivalent deformations a-polyurethane, b-reinforced polyurethane.
Equivalent deformations of polyurethane tools: Maximum equivalent deformation $\varepsilon_{eq,\max} = 30.1\%$, Minimum equivalent deformation $\varepsilon_{eq,\min} = 0.04\%$.
Equivalent strains of the composite tool: Maximum equivalent strain $\varepsilon_{eq,\max} = 22.3\%$, Minimum equivalent strain $\varepsilon_{eq,\min} = 0.002\%$.

Figure 11. (a, b) - equivalent stresses of the sheet when processing with a polyurethane tool a-polyurethane, b-reinforced polyurethane
Equivalent sheet stresses during processing with polyurethane tools: Maximum equivalent stress $\sigma_{eq,\max} = 84.2$ MPa, Minimum equivalent stress $\sigma_{eq,\min} = 64$ MPa
Equivalent sheet stresses during processing with a composite tool: Maximum equivalent stress $\sigma_{eq,\max} = 85.6$ MPa, Minimum equivalent stress $\sigma_{eq,\min} = 65.8$ MPa.

Figure 12. (a,b) - equivalent deformation of the sheet when processing with a polyurethane tool a-polyurethane, b-reinforced polyurethane
Equivalent deformations of the sheet during processing with polyurethane tools: Maximum equivalent deformation $\varepsilon_{eq,\max} = 20.6\%$, Minimum equivalent deformation $\varepsilon_{eq,\min} = 15.6\%$.
Equivalent deformations of the sheet when processing with a composite tool: Maximum equivalent deformation $\varepsilon_{eq,\max} = 20.9\%$, Minimum equivalent deformation $\varepsilon_{eq,\min} = 16.1\%$.

6. Conclusions
Mathematical modeling of the process of deformation of a metal sheet by a tool made of a composite material showed a significant increase in the forces required to deform a composite tool, as well as a significant increase in stresses on the contact surface at the same degree of deformation. The maximum equivalent stress in the composite tool was 33MPa, which is about 4.7 times that of a conventional polyurethane tool. The maximum normal stress in the X-axis in the composite tool was 33.5 MPa, about 2.5 times that of a conventional polyurethane tool. Thus, the reinforcement leads to a significant increase in the rigidity of the working elastic working tool, contact stresses will make it possible to process not only sheet parts up to 1 mm from aluminum alloys, but also steel billets, which is not possible with the use of conventional polyurethane. The use of a new composite material will significantly expand the range of products obtained by processing with this composite tool.
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