Thin sheet metal forming with composite material

D A Ikonnikov and I E Semenov

Bauman Moscow State Technical University, 5/1 Baumanskaya 2-ya ul., Moscow, 105005, Russia

1E-mail: sieprof@mail.ru

Abstract. This article focuses on the results of analytical and experimental studies on the mechanical characteristics of polyurethane and composite materials developed on its basis and reinforced with aramid fabrics for their use as an elastic forming tool to manufacture various products for the aviation industry and plate heat exchanger panels made of thin sheet metal. The article presents experimental data obtained by loading polyurethane and composite materials under uniaxial compression, composes a mathematical model, and compares the results of the experiment with the theoretical dependencies obtained in solving the problem of loading the polyurethane sample via the finite element method.

1. Introduction

Today, various thin sheet metal products, such as elements of aircraft parts and various types of flat heat exchangers, are widely used in the aircraft industry and heat engineering. An analytical review has shown that the production of parts from sheet blanks by polyurethane press forming has been mastered, as this method is the most cost-effective in programs for producing parts of the same name from 10 pieces to several thousand pieces in comparison with the pressing of parts in a rigid stamp. The method of polyurethane press forming is especially valuable for pilot and small-scale production, characterized by frequent product changeability, as well as tight deadlines for production preparation [1-4].

The elastic response or the relationship between stress and strain of rubber-like materials can be obtained using different approaches. Let us consider the hyperelastic material model was proposed by Mooney and expressed in terms of invariants by Rivlin. The two parameter Mooney-Rivlin model gives adequate results for strains less than 100 %, so it is widely used for this range of strains.

In general, the Mooney-Rivlin model where the strain energy density function $W$ is a linear combination of two invariants of the left Cauchy-Green deformation tensor can be written down as follows [5]:

$$W = \sum_{l=0}^{\infty} \sum_{m=0}^{\infty} C_{lm} (I_1 - 3)^l \cdot (I_2 - 3)^m,$$

(1)

where $C_{lm}$ is the empirically determined material constants or the Mooney-Rivlin constants that characterize the behavior of a rubber-like material; $I_1$, $I_2$ are, respectively, the first and second invariants of the deformation tensor.

By Rivlin:
\[ I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2, \]  
\[ I_2 = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2. \]  
\[ (2) \]

\[ I_2 = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2, \]  
\[ (3) \]

Equations for determining the Mooney-Rivlin constants were previously obtained [5-6]:

\[ C_{10} = \frac{\sum_{i=1}^{n} \sigma_i (\lambda_i^2 - \lambda_i^{-1})}{2 \sum_{i=1}^{n} (\lambda_i^2 - \lambda_i^{-1})^2} \cdot C_{01} \cdot \frac{\sum_{i=1}^{n} \lambda_i^1 (\lambda_i^2 - \lambda_i^{-1})^2}{\sum_{i=1}^{n} (\lambda_i^2 - \lambda_i^{-1})^2}, \]  
\[ (4) \]

\[ C_{10} = \left[ \frac{\sum_{i=1}^{n} \sigma_i \lambda_i^{-1} (\lambda_i^2 - \lambda_i^{-1})}{2 \sum_{i=1}^{n} \lambda_i^2 (\lambda_i^2 - \lambda_i^{-1})^2} \cdot \frac{\sum_{i=1}^{n} \lambda_i^{-1} (\lambda_i^2 - \lambda_i^{-1})^2}{\sum_{i=1}^{n} (\lambda_i^2 - \lambda_i^{-1})^2} \right] \cdot \left[ 1 - \frac{\sum_{i=1}^{n} \lambda_i^{-1} (\lambda_i^2 - \lambda_i^{-1})^2}{\sum_{i=1}^{n} \lambda_i^2 (\lambda_i^2 - \lambda_i^{-1})^2} \right] \cdot \left[ \frac{\sum_{i=1}^{n} \sigma_i (\lambda_i^2 - \lambda_i^{-1})}{2 \sum_{i=1}^{n} (\lambda_i^2 - \lambda_i^{-1})^2} \right], \]  
\[ (5) \]

where \( \lambda_i \) is the main degree of strain in the \( i \)-th direction; \( \sigma \) is the corresponding stress, MPa; \( n \) is the number of calculation points.

All data required for calculation by equations (4), (5) can be obtained as a result of experiments.

2. Methods and results of studies

At the stage of experimental studies, a cylindrical sample was loaded according to the uniaxial compression diagram. The results of cylindrical sample loading were used to calculate the Mooney-Rivlin constants, the results of prismatic sample loading according to pure shear (biaxial compression) diagram were used to further verify their reliability. SKU-7L polyurethane samples were studied. The deformation of samples was carried out on INSTRON 600DX-FI-G1 testing machine. At the first stage, the cylindrical sample was tested: height - 10 mm, diameter - 65 mm [7-11].

Figure 1 shows the cylindrical sample located in the test machine before loading.

**Figure 1.** The process of uniaxial compression of cylindrical sample.

Dependence graph of the load under compression \( F, \) N, of the cylindrical sample on the deformation (absolute deformation) \( \Delta h, \) mm, is shown in Figure 2. From this graph, the numerical values of strains (relative deformation) and stresses in the corresponding points (\( \lambda_i \)) were determined. Stresses were calculated as the ratio of compressive loads to the actual contact surface area of the tool and the sample,
which was also measured during the experiment. The following results were obtained for SKU-7L for the number of calculation points \( n = 7 \) by equations (4), (5): \( C_{10} = 1.45 \), \( C_{01} = 0.62 \) [7-11].

In order to evaluate the accuracy of the obtained results and their suitability for theoretical calculations, the inverse problem was solved: the experiments were simulated using the Mooney-Rivlin constants, determined at the stage of the experimental study, as the initial ones. If the results of the theoretical solution coincide with sufficient accuracy with the experimental results, then these Mooney-Rivlin coefficients may be applied to simulate the processes of SKU-7L polyurethane deformation. With this purpose, a mathematical model of these experiments was developed using the dedicated Ansys software package. The following material characteristics and geometrical dimensions of the samples were adopted during the simulation. The object of the research is a SKU-7L polyurethane cylinder with a height of 10 mm and a diameter of 65 mm; density is 3000 kg/m\(^3\), Poisson's ratio is 0.49, constants of the two-parameter Mooney-Rivlin model are \( C_{10} = 1.45 \), \( C_{01} = 0.62 \) MPa. The simulation results are presented in figures 3-5. Figure 3 shows the field of distribution of equivalent stresses (von Mises) \( \sigma \), MPa, in a cylindrical sample at its compression. The results of the solution demonstrate that the maximum equivalent stresses are of the order of 5.7 MPa in the central part of the polyurethane cylinder.

Let us compare the theoretical solution results with the experimental results. The comparison will be carried out by force parameters, i.e. by the dependences of load on absolute deformation value (figure 2) and by the deformed state, i.e. by the shape of the lateral surface. For the cylindrical workpiece, a comparison of the maximum forces gives an error \( \delta = 6.0 \% \). Figure 4 shows the finite element models of deformed and undeformed cylindrical sample. Let us compare the shapes of the deformed cylindrical
sample lateral surfaces obtained during both the experiment and the theoretical solution by overlapping of the corresponding images obtained theoretically and experimentally (figure 5). Figure 5 shows that the lateral surface shapes obtained theoretically during simulation and experimentally coincide with a high degree of accuracy.

Figure 4. Finite-element models of deformed and undeformed cylindrical sample.

Figure 5. Comparison of lateral surfaces shape.

Figure 3 shows that the maximum equivalent stresses do not exceed 6 MPa, which significantly limits the possibility of sheet metal deformation both in thickness (maximum 0.5 mm) and in deformable materials (soft aluminum alloys).

Currently, polymer composite materials are widely used in mechanical engineering and other industries due to their unique mechanical properties [12-14]. To expand the technological capabilities of an elastic forming tool, studies were conducted aimed at increasing the stiffness of polyurethane by reinforcement of the same. To create the samples, a composite material was developed, shown in figure 6 [15].

Figure 6. The composite material structure. 1 - matrix, 2 - filler, 3 - binder (cyanoacrylate)

5 mm thick SKU-7L polyurethane sheet was used as a matrix of the developed composite material. Reinforcement was made with aramid fabrics. When developing the material, fabrics of several manufacturers were used:

- 8601-90 fabric manufactured by Peredovaya Tekstilschitsa (Russia);
- Twaron 2200 fabric manufactured by DuPont (USA);
- 3360 fabric manufactured by Teijin Aramid (Netherlands) [15].
To obtain the required adhesion with a binder and filler, the following operations were carried out to prepare the polyurethane sheet surface:

- reaching of sufficient roughness;
- degreasing and drying;
- heating of the workpiece using a heat gun to the temperature of 80°
- coating of the sheet surface with cyanoacrylate activator before bonding.

The workpieces were bonded with fabrics after their surface treatment. As a result, the following samples objects were prepared for experimental studies (figure 7):

- The cylindrical sample No. 1 with a diameter of 50 mm and a height of 10 mm, which are bonded polyurethane workpieces with a diameter of 50 mm and a height of 5 mm. SKU-7L polyurethane was used.
- The cylindrical samples No. 2 – No. 4 with a diameter of 50 mm and a height of 10 mm, representing a composite structure: SKU-7L polyurethane is the matrix, aramid fabric is the reinforcing element and cyanoacrylate is the binder. The sample No. 2 was reinforced with the fabric manufactured by Peredovaya Tekstilschitsa, the sample No. 3 - by DuPont fabric, the sample No. 4 - by Teijin Aramid fabric.

![Figure 7. Cylindrical samples for material properties study.](image)

The composite materials were considered as a hyperelastic and isotropic materials, all studies were carried out according to the methods were described earlier. As a result of No. 1 - No. 4 samples loading, a dependence graph of the load under compression, \( F, H \), on the absolute deformation \( \Delta h \), mm was obtained (Figure 8). Figure 8 shows that when the samples of composite materials are deformed, with a deformation of 3 mm or strain of 30%, the compressive load increases by 60-100% in comparison with the polyurethane sample. The highest load was obtained for sample with Teijin Aramid fabric. In case of reinforcement, there is a sharp increase in polyurethane stiffness and improvement of its mechanical characteristics.

![Figure 8. Dependence of the load under compression on the absolute deformation value of the cylindrical polyurethane and composite samples.](image)
3. Conclusions
Reinforcement with aramid fabrics results in a significant increase in the polyurethane stiffness. With uniaxial compression of composite materials samples with a strain of 30%, the load value is higher by 60-100% than at the compression of unreinforced samples. The use of the developed polymer composite material for pressure treatment with elastic medium will allow to achieve higher values of contact stresses at the sheet metal deformation, which means expanding the technological capabilities of the elastic tool and the product range obtained by local treatment with elastic medium. The described method for determining elastomers characteristics allows to obtain adequate results for theoretical calculations with a strain of up to 30%.

References
[1] Semenov I E and Povorov S V 2019 Simulation of thin-sheet metal blanking and punching by elastic mediums IOP Conference Series: Materials Science and Engineering 537 (3) 032027
[2] Povorov S and Semenov I 2018 Method for calculating of cross-sectional dimensions of sheet blank at intermediate stages of roller forming process 2018 International Russian Automation Conference, RusAutoCon No 8501838
[3] Semenov I E and Ivanov A V 2019 Russian solar collectors for hot water supply of agricultural complexes and small private farms IOP Conference Series: Earth and Environmental Science 315 052016
[4] Lavrinenko V, Polyakova A and Polyakov A 2018 Analysis of the applicability of die pressing method for ring-shaped parts fabrication MATEC Web of Conferences 224 02074
[5] Bukhina M F 1984 Technical physics of elastomers (Moscow: Chemistry) p 224
[6] Muyzemnek A Yu 2005 Description of behavior of materials in system of automation engineering analysis (Penza: PGU Publ.) p 152
[7] Semenov I E, Ryzhenco S N and Krutova M V 2007 Simulation of the process of strip deformation by elastic and rigid working tool Steel 5 83–87
[8] Semenov I E, Ryzhenco S N and Povorov S V 2010 Simulation of processes of sequential forming of longitudinal channels in a sheet on a mill with an elastic and rigid tool Blank production in mechanical engineering. Press-forging production 6 29–32
[9] Semenov I E, Ryzhenco S N and Povorov S V 2007 Dynamic modeling of the local bendingshaping process for the technologies of roof covering production, Blank production in mechanical engineering 10 40–43
[10] Semenov I E, Ryzhenco S N and Daeva N N 2016 Prediction of the calculated accuracy of the workpieces’ geometry in case of separation by elastic mediums Mechanical Engineering Bulletin (Vestnik mashinostroyeniya) 3 40–4
[11] Semenov I E, Ryzhenco S N and Povorov S V 2010 Simulation of Mould Processes at Profile-Bending Mill with Elastic and Rigid Tools Herald of the Bauman Moscow State Technical University Series Mechanical Engineering, Vestnik MGTU 4 (81) 86–97
[12] Ruslantsev A N, Portnova Ya M, Tairova L P and Dumansky A M 2016 Analysis of mechanical properties anisotropy of nanomodified carbon fibre-reinforced woven composites IOP Conference Series: Materials Science and Engineering 153(1) 012003
[13] Dimitrienko Y I, Gubareva E A and Pichugina A E 2018 Theory of the multilayer thin anisotropic shells, based on the asymptotic analysis of the general equations for the elasticity theory Journal of Physics: Conference Series 1141 (1) 012097
[14] Evseev K B, Kartashov A B, Dashtiev I Z and Pozdeev A V 2018 Analysis viscoelastic properties of fiber-reinforced composite spring for the all-terrain vehicle MATEC Web of Conferences 224 02039
[15] Ikonnikov D A 2018 The research of stresses and strains of uniaxial compression of samples of developed composite material for pressure treatment of sheet metal parts Colloquium-journal 10 (21) 69-72