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Original Research

Study on Mechanical Properties of Polyurethane Elastomers in Different Strength Tests

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Abstract

Elastomeric materials are used in the methods of plastic forming of sheets made of difficult-to-deform materials. This article presents the results of strength tests of selected elastomeric materials intended for sheet metal stamping. Polyurethane elastomers with a hardness of 50, 70 and 90 Sh A were used for the tests. The behaviour of the materials was determined in a simple compression test, a volumetric compression test and a uniaxial tensile test. In the case of the simple compression test, the values of the maximum force for a set punch travel of 3 mm were 1400 N, 2250 N and 4950 N for samples with hardnesses of 50, 70 and 90 Sh A, respectively. In a volumetric compression test, the maximum compressive force for a sample with a hardness of 90 Sh A was more than twice lower than the compressive force of samples with a hardness of 50 and 70 Sh A. In the tensile tests, the values of the obtained strains ranged from about 750% for the sample with a hardness of 50 Sh A to about 1350% for the sample with a hardness of 90 Sh A.

Keywords: compression test, elastomeric material, mechanical properties, polyurethane, tensile test

1. Introduction

Elastomeric stamping tools are simpler to design and construct than traditional metallic tools. The process of forming metal using elastomeric tools is characterized by the fact that the rubber fills the workspace and thus deforms the sheet metal. This means that any sharp edges in the workspace can negatively affect the wear of the elastomeric forming material.

Elastomers are materials that are characterized by large elastic deformations while maintaining the continuity of their structure, which are reversible at a room temperature. Elastomeric materials belong to the group of cross-linked amorphous polymers, which have the ability to deform with strain values reaching even 600%. They also exhibit good shape memory properties. This means that after deformation to a certain level, they return to dimensions similar to those before deformation, after the acting force has been removed (Alarifi, 2023). This is a very important feature, which makes these materials suitable for use in applications requiring large deformations and high dimensional stability (Flamm et al., 2011; Perduta & Putanowicz,2015; Ramezani et al., 2009). The basic materials included in the group of elastomers include natural rubber, synthetic rubbers, silicones and polyurethanes. Due to their important role in industry, a group of thermoplastic elastomers can be distinguished. They have properties very similar to rubber, but under the influence of temperature they soften and exhibit viscous-plastic properties. This makes them easy to form and enables the use of manufacturing methods used for thermoplastic materials, such as injection moulding (Spontak & Patel, 2000).

Due to the large variety of elastomeric materials, there is practically no clear division of elastomers in the literature that would cover all groups of these materials. This is due to differences between them in physicochemical properties, their structure and production methods. There are a number of divisions of elastomers based on one of the above-mentioned parameters. However, there is no clear division that would cover all groups of elastomers. An example of this is the division based on the production method, including cast, rolled or thermoplastic polyurethane elastomers (Swinarew, 2014).

Elastomeric materials have many advantages when used for plastic forming of sheet metal. These advantages include good wear resistance and resistance to chemicals. At the beginning of the 20th century, the potential of elastomeric materials in industry was noticed as a substitute for traditional, rigid tools used for metal forming. The development of elastomeric materials led to the beginning of research work in which polymer materials were successfully used as parts of tools for cutting (Aravind, 2017), bending (Zaragoza et al., 2019), deep drawing (Benisa et al., 2012) and tube forming (Sayar et al., 2025). Due to the very large variety of elastomeric materials and the limited number of studies that have been conducted so far, it can be stated that there are a large number of materials whose properties suggest the possibility of use in sheet metal forming processes, but their usefulness has not been experimentally verified (Afteni et al., 2018; Kumar et al., 2014).

The first elastomeric material used in plastic working processes was natural rubber. Another material used in the industry for sheet metal forming is butadiene-styrene rubber. This is a popular elastomer that also has many other applications in industry. It has a good price-quality ratio. Although these tools turned out to be more durable than those made of natural rubber, a problem arose in the form of tearing of the elastomeric material in the case of large deformations. This meant that butadiene-styrene rubber did not replace natural rubber in applications for sheet metal forming tools (Thiruvarudchelvan, 2002; Al-Qureshi, 1972). Currently, the elastomeric material most often chosen for sheet metal forming tools is polyurethane. Polyurethane is obtained by polyaddition of aliphatic and aromatic diisocyanates with compounds having at least two hydroxyl groups. The main chain of polyurethane contains a chain of the urethane group [-O-CO-NH-]. Polyurethene elastomers are manufactured with a hardness between 35 and 98 Sh A. This material is highly wear-resistant and thermally stable. It is resistant to contact with chemicals. In most studies aimed at analysing sheet metal forming processes using elastomeric materials, a significant advantage of polyurethane elastomer over other materials has been proven (Ramezani et al., 2010). The criterion for the applicability of polyurethane for forming sheet metal parts can be the products obtained with their use, presented in publications by Thiruvarudchelvan (1993, 2002) and Quadrini (2010). Due to vibration damping properties, polyurethane elastomers are used for compression members (Ju & Hu, 2021), soundproof isolation systems (Bednarz & Targosz, 2013) and vibration isolators (Gehling et al., 2023).

Proper design of sheet metal forming tools requires knowledge of the behaviour of polyurethane elastomers in specific applications. The response of elastomeric materials depends mainly on their hardness and the state of loading stresses. Usually, one strength test is not adequate to recognise the properties of this group of materials. Therefore, this article presents the results of strength tests of polyurethane elastomers with hardness in the range of 50 and 90 Sh A using three different tests: simple compression test, a volumetric compression test and a tensile test. The results of the tests presented in this article were the basis for the development of flexible tools for deep-drawing process of stainless steel and Ni-based alloy sheets in ERKO sp. z o.o. sp.k. (Czeluśnica, Poland).

2. Materials and methods

2.1. Test material

Elastomeric materials made of polyurethane with a hardness of 50, 70 and 90 Sh A were used for the tests. The test samples were made from one batch of material so that there were no significant differences in their properties. Hardness tests, uniaxial tension tests, simple compression tests and a volumetric compression tests were carried out. For each test requiring initial deformation of the tested samples in order to reduce the influence of the Mullins effect, the samples were initially deformed to the assumed level in 18 measurement cycles. In the case of the tensile test, where the samples were stretched to the point of failure, a threshold of 500% elongation was assumed.

2.2. Simple compression test

The simple compression test of samples made of polyurethane material was carried out in accordance with the ASTM D575-91 (American Society for Testing and Materials, 2018) standard. Cylindrical samples with dimension ϕ = 28.6 mm and height h = 13 mm were prepared. Three samples were prepared for for hardness 50, 70 and 90 Sh A (Table 1). The samples were compressed at a speed of 12 mm/min to a height of 10 mm. The compression tests were carried out without the use of lubricant.

In order to avoid the surface of the sample sliding on the compression plate, tools with undercuts (Fig. 1) were used. The compression tests were carried out using a Zwick/Roell Z100 testing machine. In order to verify the deformation of the sample on the lateral surface during the compression test, an optical 3D scanner was used.

Table 1. Samples of elastomeric materials for compression tests.

Hardness of polyurethane elastomer	Test samples
50 Sh A	
70 Sh A	
90 Sh A	

Fig. 1. View of tools for compression test.

2.3. A volumetric compression test

The volumetric compression test was performed on a Zwick/Roell Z100 testing machine to determine the force necessary to compress the elastomeric material. A specially prepared tool in the form of a punch and container shown in Fig. 2 was used for this purpose. Cylindrical samples with dimensions ϕ = 28.6 mm and h = 13 mm were used. The speed of the testing machine crosshead was 12 mm/min and the compression travel was 1.5 mm.

Fig. 2. Container and punch used in the volumetric compression tests.

2.4. Tensile test

The uniaxial tensile test was carried out in accordance with the ISO 37:2004 standard (International Organization for Standardization, 2024). Samples with dimensions shown in Fig. 3 were prepared. The samples were stretched until they rupture. The test speed was 500 mm/min. In order to eliminate the possibility of the tested sample moving in the grips of the testing machine, hydraulic adjustment of clamping force was used during the test. Fig. 4 shows a photograph of the sample during the test. The test samples are presented in Table 2.

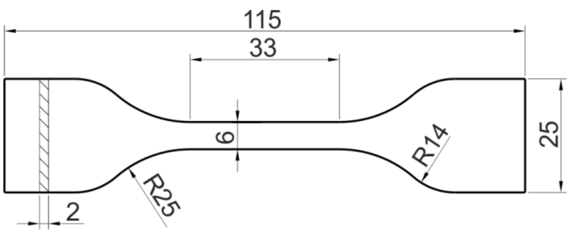

Fig. 3. Tensile test specimen dimensions.

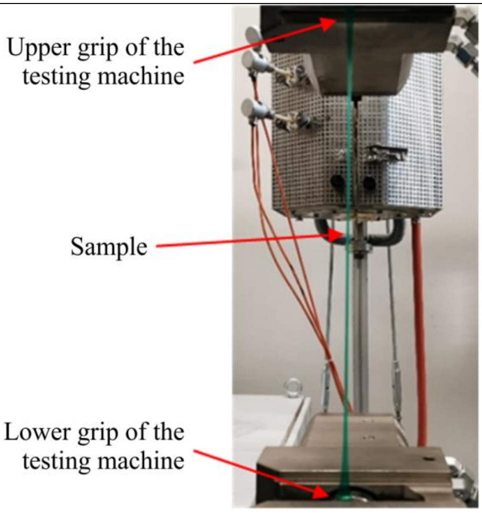

Fig. 4. Photograph of the sample during the tensile test

Table 2. Samples for tensile testing.

Hardness of polyurethane elastomer	Samples for tensile testing
50 Sh A	
70 Sh A	
90 Sh A	

3. Results and discussion

3.1. Simple compression test

Fig. 5 presents the results of the compression test of polyurethane elastomers with a hardness of 50 Sh A. Analysis of the results allows determining the maximum force necessary to compress the sample by 3 mm at a level of approximately 1400 N. The results for all three test samples are consistent, and the differences between them are small. During the measurements, a 3D optical scan of the sample was also performed. An example 3D model of the sample after deformation is shown in Fig. 6a. The radius of the rounding of the side surface of the sample under compression is in the range from 4.91 mm to 5.34 mm.

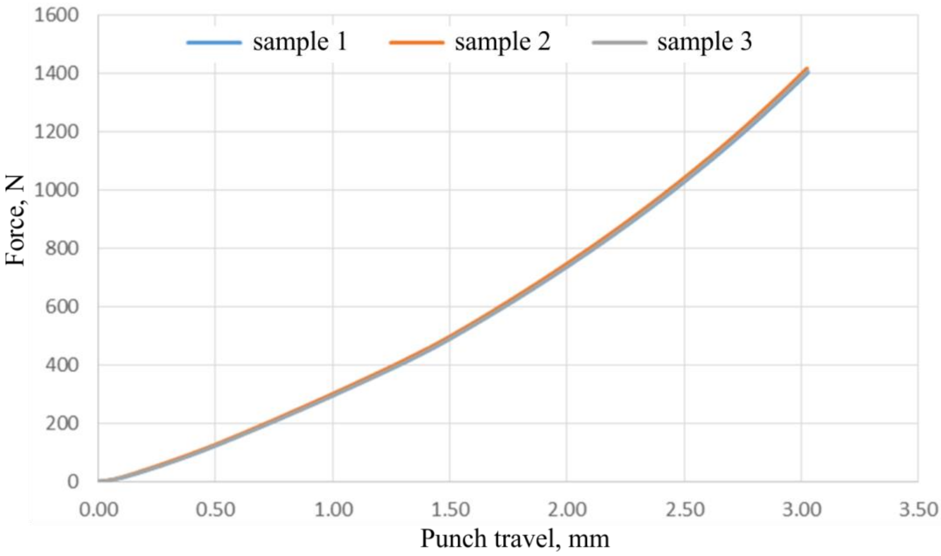

Fig. 5. Compression test results for an elastomeric material with a hardness of 50 Sh A.

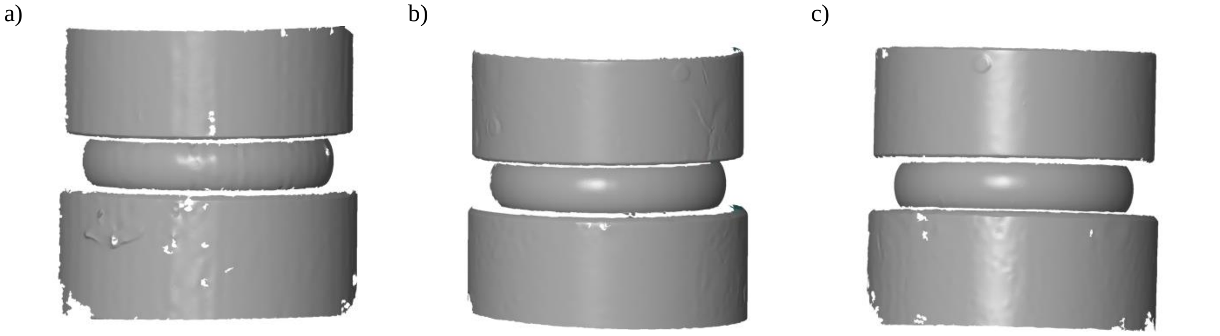

Fig. 6. 3D model of a compressed sample made of elastomeric material with hardness: a) 50 Sh A, b) 70 Sh A and c) 90 Sh A.

Fig. 7 presents the results of the compression test of elastomeric samples with a hardness of 70 Sh A. The maximum force necessary to compress the sample by 3 mm is approximately 2250 N. The results for the other two samples are the same. Sample no. 3 is characterised by a slightly higher force recorded during the measurements. The difference between the force values for the individual samples is 100 N. A 3D scan of the sample was also performed during the measurements (Fig. 6b). The radius of the rounding of the side surface of samples under compression is in the range from 5.51 mm to 5.60 mm.

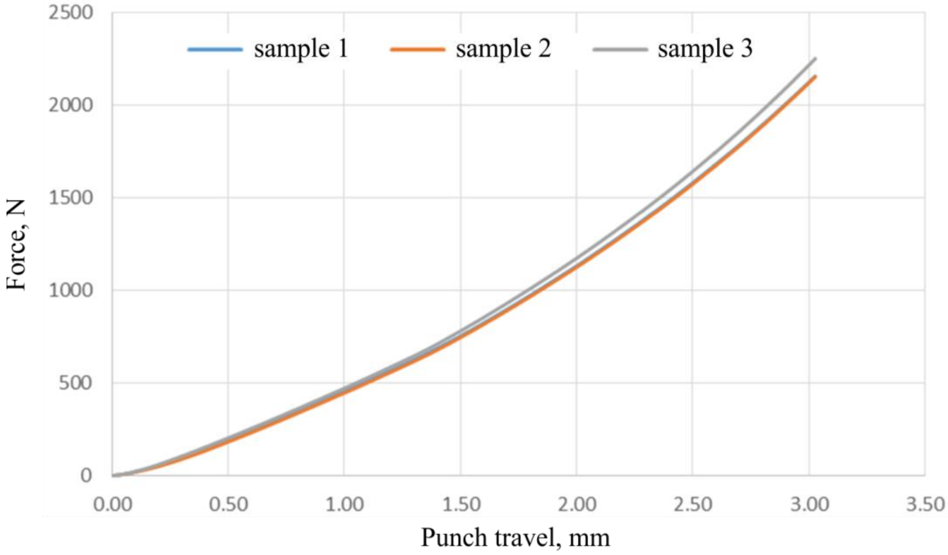

Fig. 7. Compression test results for an elastomeric material with a hardness of 70 Sh A.

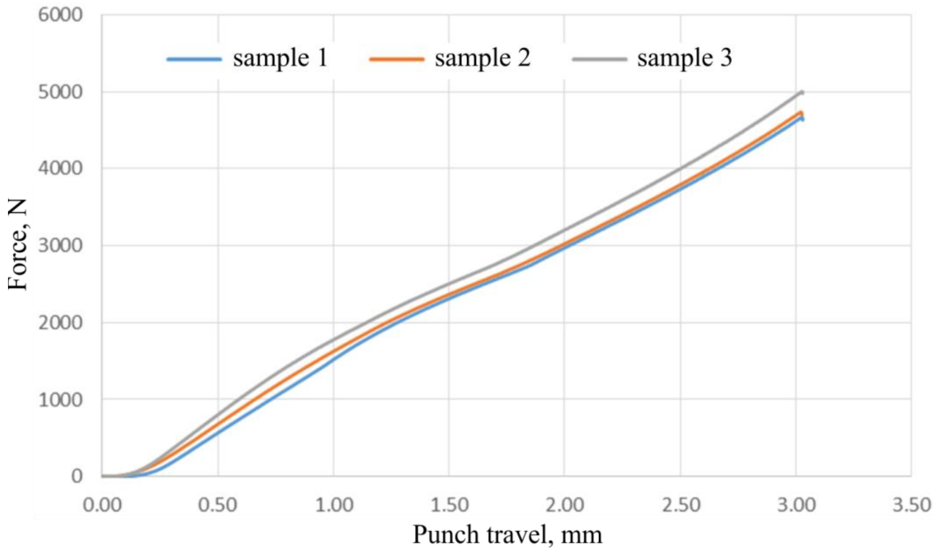

Fig. 8. Compression test results for an elastomeric material with a hardness of 90 Sh A

Fig. 8 presents the results of the compression test of polyurethane elastomers with a hardness of 90 Sh A. The maximum force necessary to compress the sample by 3 mm is approximately 4950 N. The results for 2 samples are the same, sample no 3 is characterized by a slightly higher force recorded during the measurements. The difference between the maximum force values for the individual samples is 300 N. An example 3D model of sample obtained from the non-contact measurements is shown in Fig. 6c. The rounding radius of the side surface of the sample under compression is in the range from 5.74 mm to 5.86 mm. In the case of polyurethane elastomers with a hardness of 50 and 70 Sh A, the compression curves are characterized by an asymptotic constant increase in the value of the compressive force (Fig. 5 and 7) as a result of increasing the working surface (diameter) of the samples. The sample with a hardness of 90 Sh A is characterized by a more linear increase in the force value in relation to the punch travel (Fig. 8).

3.2. The volumetric compression test

Fig. 9 shows the results of the volumetric compression test for an elastomeric material with a hardness of 50 Sh A. Analysis of the results presented in Fig. 9 allows determining the maximum force necessary to compress the sample by 1.5 mm at the value of 31,500 N. The difference between the force values for the individual samples is 2,000 N. Until the sample deforms by about 0.6 mm, the value of the compressive force changes in a small range. Only after exceeding this value, the increase in force become almost linear until the maximum value is reached.

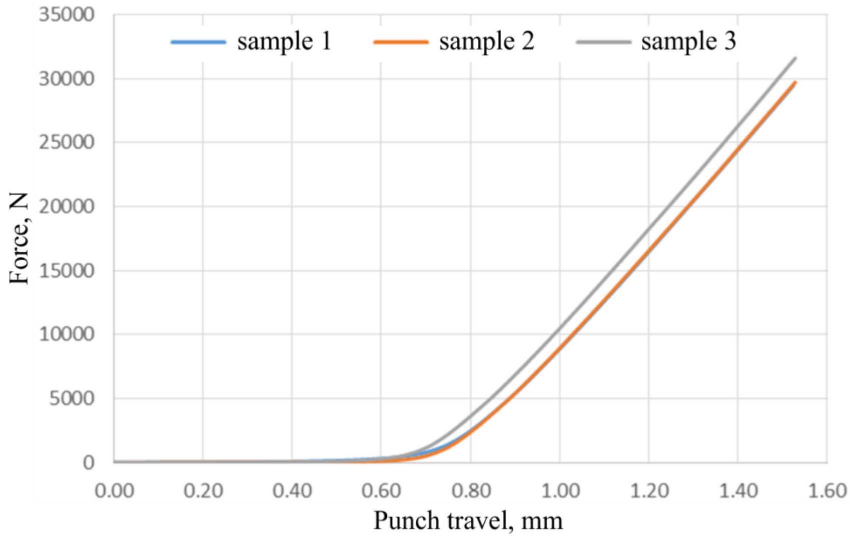

Fig. 9. Results of the volumetric compression test of the polyurethane elastomer with a hardness of 50 Sh A.

Fig. 10 shows the test results of the volumetric compression test for an elastomeric material with a hardness of 70 Sh A. The maximum force required to compress the sample by 1.5 mm was 31,100 N. The difference between the force values for sample no. 3 and sample no. 2 is 3,600 N. Despite the increased hardness, the value of the maximum force and the character of the compressive force changes during the volumetric compression test are similar to those for samples with a hardness of 50 Sh A (Fig. 9).

The maximum force necessary to compress a sample with a hardness of 90 Sh A in a volumetric compression test by 1.5 mm was 14100 N (Fig. 11). The results for samples no 1 and 2 are similar. The difference occurs in the case of sample no 3 and is 1800 N. Comparing the results obtained for different hardnesses of elastomeric materials, differences were observed in the initial phase of the tests. As the material hardness increases, the initial phase of the graph becomes longer, followed by a transition to the compression phase (rapid increase in compressive force). This means that with the increase in the hardness of the elastomeric material, the force exerted on the surface of the deformed material in the initial phase of the process increases. The differences in the maximum compressive force result from the use of an initial force of 10 N due to the friction resulting from the design of the measuring device. Despite the use of the minimum initial force, it significantly affected the obtained results. However, its use was necessary to make the measurement results comparable.

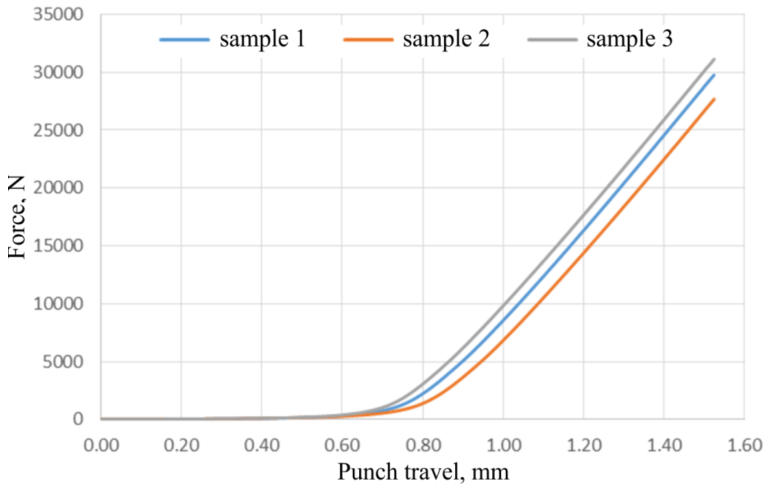

Fig. 10. Results of the volumetric compression test of the polyurethane elastomer with a hardness of 70 Sh A.

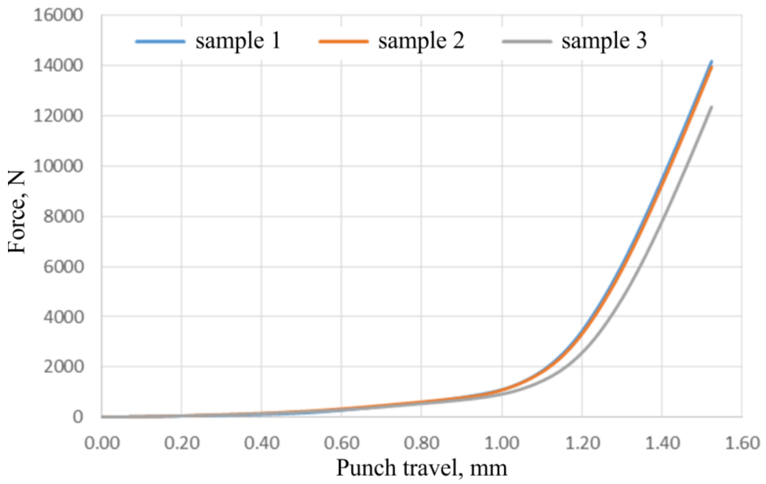

Fig. 11. Results of the volumetric compression test of the polyurethane elastomer with a hardness of 90 Sh A.

3.2. Simple tensile test

Three elastomeric materials with hardnesses of 50, 70 and 90 Sh A were selected for simple tension tests. Table 3 presents the view of the samples after the tensile test. Fig. 12a shows the results of the tensile test for the polyurethane elastomer with hardness of 50 Sh A. The analysis, based on the results presented in Fig. 12a, allows to determine significant differences for samples made of the same material. In the case of sample no 1, the Elongation ε_l was 860% at a stress of 11 MPa, for sample no 2 ε_l = 748.5% at a stress of 8.36 MPa, and for sample no 3 ε_l = 796.5% at a stress of 13.85 MPa. The stress-strain characteristics of the tested materials are in agreement with the results of tensile tests of typical hyperelastic materials (Ziobro, 2013). At the initial stage of the test, the material structure is amorphous, the elastomer strands are in a low-energy relaxation state and have little or no alignment with each other. Overcoming this initial low-energy state requires increasing the stress, but as the polyurethane strands begin to yield to the applied force, they stretch and large deformation of the material occurs with slightly increasing force. Once the inflection point in the curves is reached, the situation becomes reversed. A small increase in strain is associated with a large increase in stress.

Fig. 12b shows the results of the tensile test for an elastomeric material with a hardness of 70 Sh A. In the case of sample no 1, the elongation was ε_l = 680% at a stress of 11.2 MPa, for sample no 2 ε_l = 735% at a stress of 11.9 MPa and for sample no 3 ε_l = 693% at a stress of 18.0 MPa. So, with the increase in the hardness of polyurethane elastomer from 50 to 70 Sh A, the maximum elongation of the samples decreased. In addition, the large scatter of data confirms the assurance of statistical repeatability of the test results. Fig. 12c shows the results of the tensile test for the elastomeric material with a hardness of 90 Sh A. Small differences can be seen in the compression curves for the material. For sample no 1, the elongation was ε_l = 1346% at a stress of 47 MPa, for sample no 2 ε_l = 1342% at a stress of 47.7 MPa and for sample no 3 ε_l = 1306% at a stress of 47 MPa.

Table 3. Samples after tensile test.

Hardness of polyurethane elastomer	View of the samples after testing
50 Sh A	
70 Sh A	
90 Sh A	

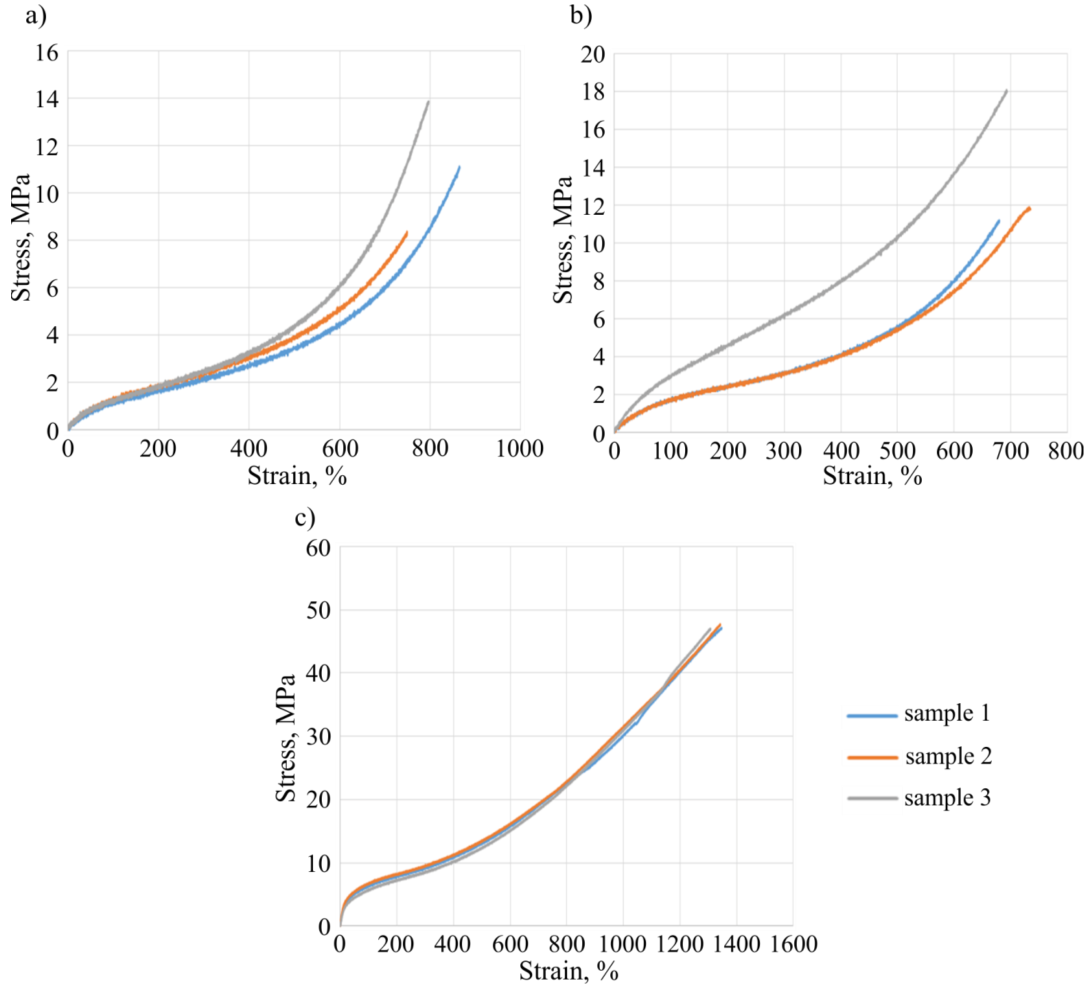

Fig. 12. Tensile test results for polyurethane elastomer with a hardness of a) 50 Sh A, b) 70 Sh A and c) 90 Sh A.

4. Conclusions

In the case of the simple compression test, the results of the force parameters were very repeatable for all analysed types of polyurethane elastomer samples with different hardness. The values of the maximum force for a set punch travel of 3 mm were 1400 N, 2250 N and 4950 N for samples with hardnesses of 50, 70 and 90 Sh A, respectively. In a volumetric compression test, the value of the average maximum compressive force decreased with increasing sample hardness. The maximum compressive force for a sample with a hardness of 90 Sh A was more than twice lower than the compressive force of samples with a hardness of 50 and 70 Sh A. At the same time, in the compression phase of the samples, the increase in force was more rapid for samples with higher hardness. In the tensile tests, the values of the obtained strains ranged from about 750% for the sample with a hardness of 50 Sh A to about 1350% for the sample with a hardness of 90 Sh A. The value of the sample breaking stress increased with the sample hardness from about 10 MPa for the sample with a hardness of 50 Sh A to about 47 MPa for the sample with a hardness of 90 Sh A. Due to the diverse mechanical properties of the studied polyurethane elastomers, resulting from their varying hardness, their selection in the sheet metal forming process should take into account both the geometry of the formed component and the material characteristics of the sheet itself. For hard-to-deform sheets, elastomers with higher hardness are recommended, as they provide better force transmission during forming. Conversely, for softer sheets and geometrically complex shapes, elastomers with lower hardness are preferable, as they facilitate easier mold filling with lower forming forces. However, the final selection of elastomer hardness should always be tailored to the specific requirements of a given forming process to optimize both the quality and efficiency of the technology.

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Badania Właściwości Mechanicznych Elastomerów Poliuretanowych w Różnych Testach Wytrzymałościowych

Streszczenie

Materiały elastomerowe znajdują zastosowanie w metodach plastycznego kształtowania blach wykonanych z materiałów trudno odkształcalnych. W tym artykule przedstawiono wyniki badań wytrzymałościowych wybranych materiałów elastomerowych z przeznaczeniem do tłoczenia blach. Do badań wykorzystano próbki elastomerowe wykonane z poliuretanu o twardości 50, 70 i 90 Sh A. Zachowanie się materiałów określono w teście ściskania swobodnego oraz objętościowego a także w próbie jednoosiowego rozciągania. W przypadku prostego testu ściskania wartości siły maksymalnej dla ustalonego przesuwu stempla wynoszącego 3 mm wynosiły odpowiednio 1400 N, 2250 N i 4950 N dla próbek o twardości 50, 70 i 90 Sh A. W teście ściskania objętościowego maksymalna siła ściskająca dla próbki o twardości 90 Sh A była ponad dwukrotnie mniejsza od siły ściskającej próbki o twardości 50 i 70 Sh A. W testach rozciągania wartości uzyskanych odkształceń wahały się od ok. 750% dla próbki o twardości 50 Sh A do ok. 1350% dla próbki o twardości 90 Sh A.

Słowa kluczowe: test ściskania, materiał elastomerowy, właściwości mechaniczne, poliuretan, test rozciągania