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Determination of Energy Expenditure in the Drawing Process in the Aspect of Environment Protection

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1. Introduction

In the present-day production and operations, efforts are undertaken to obtain the highest efficiency possible, to reduce manufacturing time and to minimize energy expenditure, and to minimize waste (Bohdal et al. 2014, Bohdal & Walczak 2013, Kaldunski 2016, Kukielka & Kukielka 2013, Kukielka et al. 2005). Efficiency is frequently connected with energy expenditure. In mass production and large series production, a reduction of energy expenditure related to a given process results in an increased durability of tools and machinery as well as savings of electricity. In the case of drawing of circular and symmetrical products, a reduction of energy expenditure is understood to be a decrease of the maximum drawing force. This can be in parallel with a reduction of the total work required to transform a flat disc into a cylindrical element with a bottom. For this purpose, it is necessary to use an optimal die block profile that ensures minimization of force and work. It is also necessary to guarantee adequate friction conditions. The friction coefficient of the contact between the metal sheet and the die block should tend to 0, while the friction coefficient between the drawing stamp should be as large as possible. This will prevent the product from an excessive elongation of its side walls and of the transition area of the bottom into the side wall. One of the options to determine the maximum drawing force and the total drawing work is to conduct a drawing test including the possibility to register force in the displacement function. Another option is to develop a numerical analysis and to carry out a computer simulation (Bohdal & Kukielka 2014) of the drawing process.

The present study contains the results from the numerical analyses conducted for five various die block profiles. For each of the die block profiles, three simulations were conducted with the use of materials models: bilinear, powerlaw and Barlat anisotropic models (Kaldunski & Kukielka 2010, Kaldunski & Kukielka 2014). A numerical measurement was made of the drawing force in the stamp path function. Based on this, the total work was computed required to form a good quality product. The numerical results were compared with the experimental results.

2. Model and conditions of the process

The numerical analyses were developed in the Ansys/Ls-Dyna software with an explicit method. The following were used: a bilinear type materials model with linear elasticity characteristics and linear plasticity, a model with powerlaw characteristics and a Barlat model that takes into account anisotropy on 3 main directions and 3 tangent directions (Chodor et al. 2011, Chodor & Zurawski 2015, Chodor & Kukielka 2012, Kukielka & Chodor 2007). The process was treated as isothermal and quasi-static, i.e. it was accepted that the strain speed has no influence on strain and stress forces.

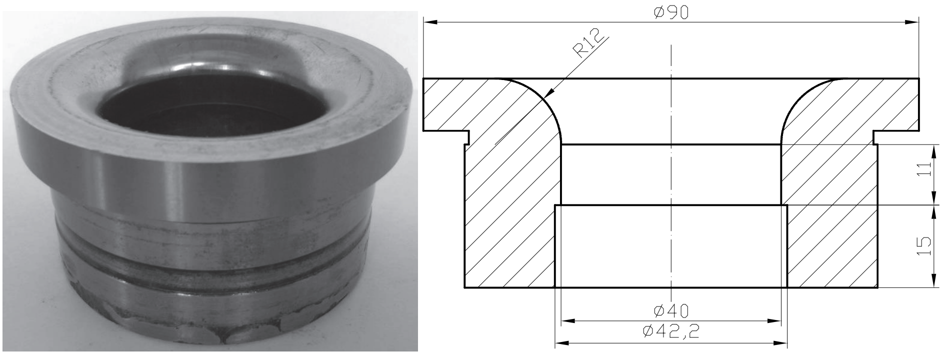


Fig. 1. Die block with 12 mm area rounding
Rys. 1. Matryca o promieniu powierzchni roboczej 12 mm

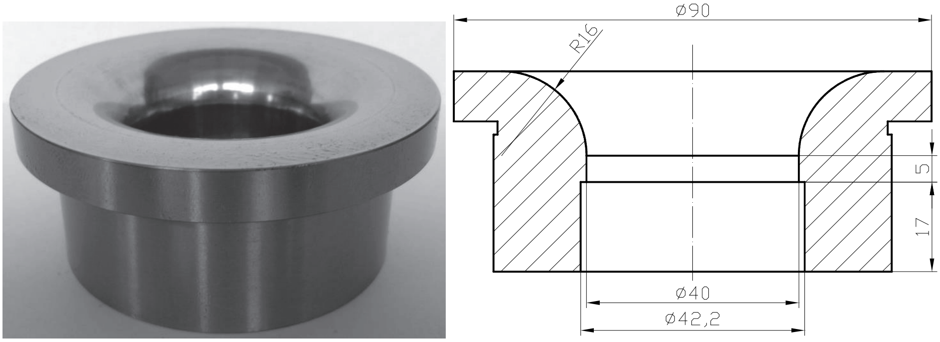


Fig. 2. Die block with 16 mm area rounding
Rys. 2. Matryca o promieniu powierzchni roboczej 16 mm

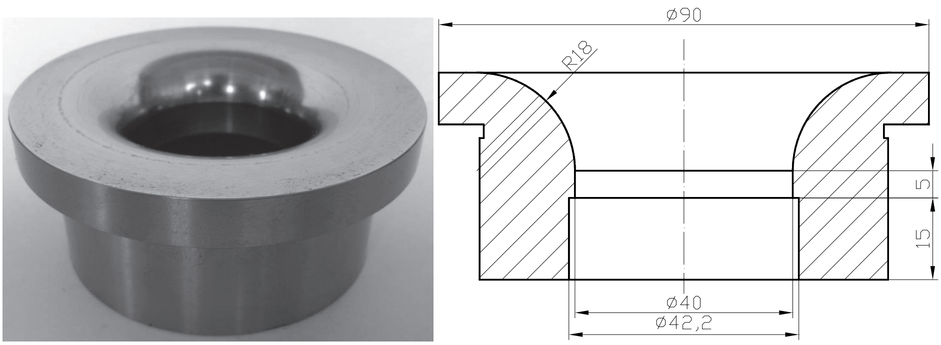


Fig. 3. Die block with 18 mm area rounding
Rys. 3. Matryca o promieniu powierzchni roboczej 18 mm

Figure 4 includes a curvilinear die block, while Figure 5 includes a cone die block.

DC01 metal sheet was accepted as the material for drawing. Its characteristics was determined based on stretching of a flat three-stage sample on a drawing press (Kukielka et al. 2009). The tools, i.e. the stamp and the die block, were modeled as non-deformable bodies. Furthermore, the tools were discretized with shell type finite elements, while the metal sheet for drawing was discretized with solid type elements. The simulation and experimental tests were conducted for the following conditions:

$D_0 = 70$ mm - disc diameter

$g_0 = 2$ mm - disc thickness

$d_m = 40$ mm - die block diameter

$d_{st} = 34{,}7$ mm - stamp diameter

$r_{st} = 4$ mm - stamp rounding

Three die blocks were used with area rounding as follows: 12 mm (Fig. 1), 16 mm (Fig. 2) and 18 mm (Fig. 3).

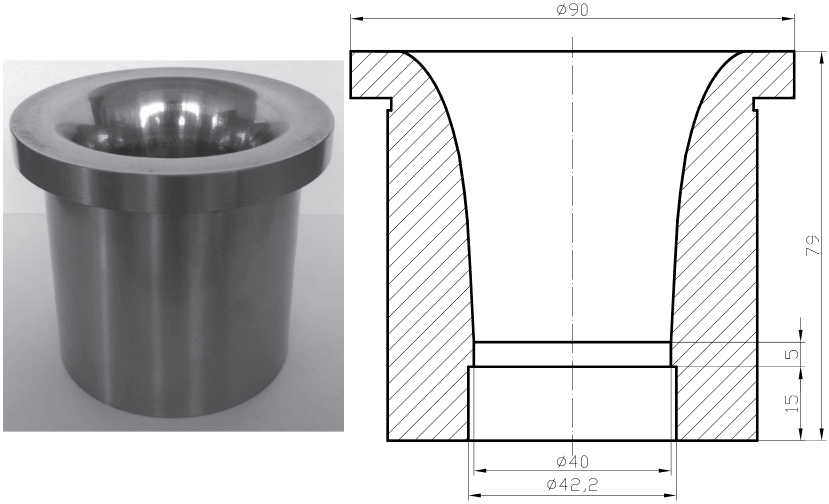


Fig. 4. Curvilinear die block
Rys. 4. Matryca krzywoliniowa

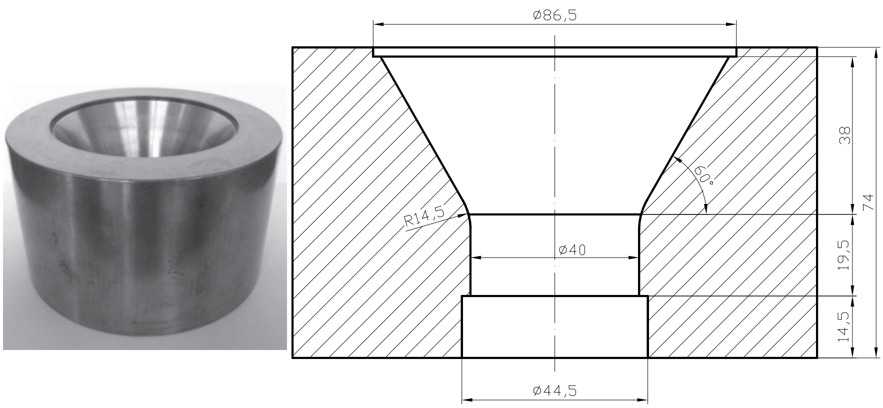
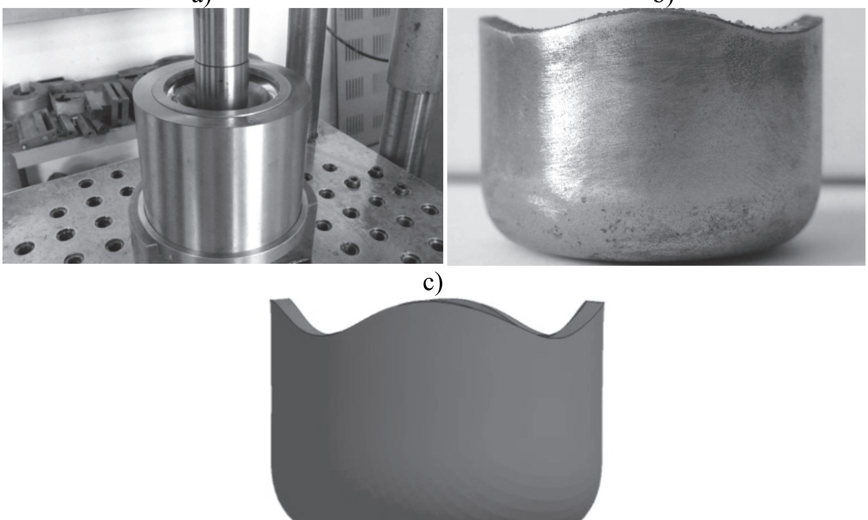


Fig. 5. Cone die block
Rys. 5. Matryca stożkowa

The experimental tests were conducted on a ZD 200 drawing press. The maximum pressure produced by the hydraulic press is 200 kN. The indication accuracy from the dial indicator and the registered record is 500 N. The drawing press can register the course of the dependence of force in the function of path. The friction conditions were the same in all of the cases of the experiment. The contact area between the die block and the metal sheet was lubricated with MARTOL EP 150 drawing oil. This is a product based on synthetic oils (alkylbenzenes). The flash point is > 160°C. The density in the temperature of 20°C was $\rho = 1079$ kg/m^3. This oil is insoluble in water. Viscosity in the temperature of 40°C was ca. 157 mm^2/s. It was only the die block surface that was lubricated. The stamp surface remained dry but it was not defatted. In numerical calculations, the friction coefficient of 0.1 was accepted as constant in the duration of the process. The equipment of the test stand is presented in Figure 7a. Figure 6b presents an example of a drawpiece obtained in the experiment. Figure 6c presents the product that was obtained with the use of the anisotropic model in a numerical method.

a) b)



c)

Fig. 6. Stand for tests of drawing process: a) course of process, b) finished product, c) product obtained with numerical method
Rys. 6. Stanowisko do badań procesu wytłaczania: a) przebieg procesu, b) gotowy wyrób, c) wyrób otrzymany drogą numeryczną

3. Results of numerical and experimental calculations

For each die block, three numerical analyses and an experimental test were conducted. The chief purpose was to register the course of the drawing force in the function of the path of the stamp. Fig. 7 presents data related to the course of the force for a die block with area rounding r = 12 mm. Small shifts of the diagrams in relation to one another are the result of the various strengthening models depending of the materials model. The maximum drawing force was 62 kN on average. The stamp penetration depth that was 0.04 m determined the total formation of the drawpiece wall.

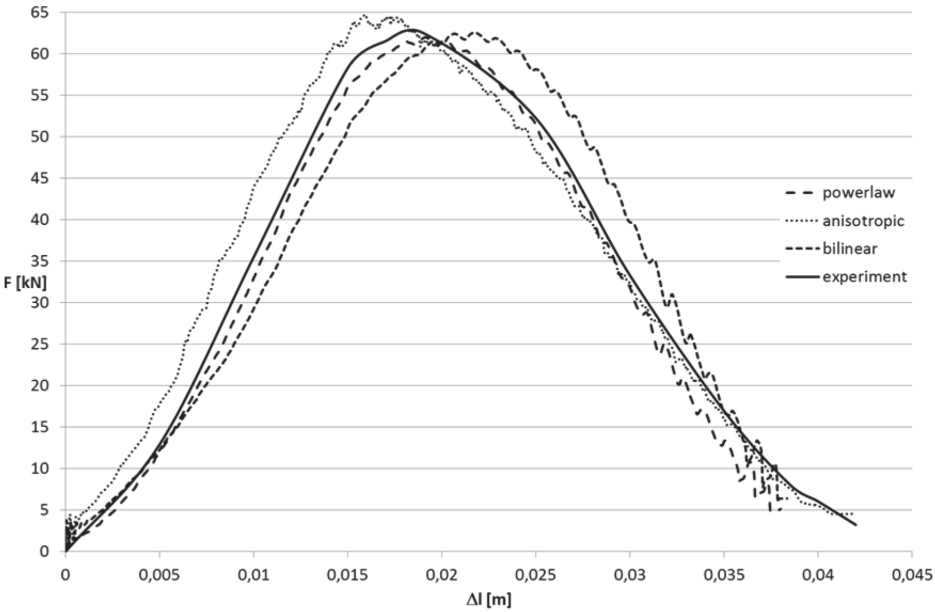


Fig. 7. Dependence of drawing force from stamp displacement for three models and experiment on die block with r_m = 12 mm
Rys. 7. Zależność siły tłoczenia od przemieszczenia stempla dla trzech modeli i eksperymentu na matrycy o r_m = 12 mm

In order to determine the total drawing work for each diagram, the sixth degree trend line was created to reflect as accurately as possible the shape of the diagram. The integral from 0 to 0.04 m from the function of the trend will permit obtaining the total work value in joules. An observation can be made that the total work values calculated do not exceed the significance level $\alpha = 0.05$ in relation to the experiment with the exception of the results obtained from the powerlaw model.

Work value calculated from the anisotropic model:

$$\int_0^{0,04} \begin{matrix} 1,58 \cdot 10^{14} \cdot x^6 - 3,24 \cdot 10^{13} \cdot x^5 + 2,52 \cdot 10^{12} \cdot x^4 - \\ 8,86 \cdot 10^{10} \cdot x^3 + 1,22 \cdot 10^9 \cdot x^2 - 1,62 \cdot 10^6 \cdot x + 4970 \end{matrix} = 1432\ \mathrm{J}$$

Work value calculated from the bilinear model:

$$\int_0^{0,04} \begin{matrix} -5,19 \cdot 10^{14} \cdot x^6 + 6,75 \cdot 10^{13} \cdot x^5 - 2,97 \cdot 10^{12} \cdot x^4 + \\ 4,66 \cdot 10^{10} \cdot x^3 - 1,49 \cdot 10^8 \cdot x^2 + 1,99 \cdot 10^6 \cdot x + 1660 \end{matrix} = 1357\ \mathrm{J}$$

Work value calculated from the powerlaw model:

$$\int_0^{0,04} \begin{matrix} -7,68 \cdot 10^{14} \cdot x^6 + 8,42 \cdot 10^{13} \cdot x^5 - 2,98 \cdot 10^{12} \cdot x^4 + \\ 2,82 \cdot 10^{10} \cdot x^3 + 1,92 \cdot 10^8 \cdot x^2 + 7,15 \cdot 10^5 \cdot x + 1340 \end{matrix} = 1291\ \mathrm{J}$$

Work value calculated from the characteristics from the experiment:

$$\int_0^{0,04} \begin{matrix} -3,31 \cdot 10^{14} \cdot x^6 + 3,25 \cdot 10^{13} \cdot x^5 - 6,78 \cdot 10^{11} \cdot x^4 - \\ 1,82 \cdot 10^{10} \cdot x^3 + 5,83 \cdot 10^8 \cdot x^2 + 5,26 \cdot 10^4 \cdot x + 101 \end{matrix} = 1392\ \mathrm{J}$$

The further graph (Fig. 8) presents the dependences of the course of the force in the path function for a die block with area rounding of 16 mm. The maximum drawing force was ca. 58 kN. The dependences were described with the functions of the sixth degree trend line. Then, the areas under the diagrams were integrated and the total work of the system was calculated.

Work value calculated from the anisotropic model:

$$\int_0^{0,045} \begin{matrix} -2,37 \cdot 10^{14} \cdot x^6 + 2,41 \cdot 10^{13} \cdot x^5 - 5,06 \cdot 10^{11} \cdot x^4 - \\ 1,59 \cdot 10^{10} \cdot x^3 + 5,32 \cdot 10^8 \cdot x^2 - 5,79 \cdot 10^5 \cdot x + 4000 \end{matrix} = 1405\ \mathrm{J}$$

Work value calculated from the bilinear model:

$$\int_{0}^{0{,}045} \begin{matrix} -2{,}58 \cdot 10^{14} \cdot \mathrm{x}^6 + 3{,}88 \cdot 10^{13} \cdot \mathrm{x}^5 - 1{,}94 \cdot 10^{12} \cdot \mathrm{x}^4 + \\ 3{,}44 \cdot 10^{10} \cdot \mathrm{x}^3 - 1{,}16 \cdot 10^{8} \cdot \mathrm{x}^2 + 1{,}56 \cdot 10^{6} \cdot \mathrm{x} + 904 \end{matrix} = 1423\ \mathrm{J}$$

Work value calculated from the powerlaw model:

$$\int_{0}^{0{,}045} \begin{matrix} -4{,}29 \cdot 10^{14} \cdot \mathrm{x}^6 + 5{,}47 \cdot 10^{13} \cdot \mathrm{x}^5 - 2{,}29 \cdot 10^{12} \cdot \mathrm{x}^4 + \\ 2{,}89 \cdot 10^{10} \cdot \mathrm{x}^3 + 9{,}76 \cdot 10^{7} \cdot \mathrm{x}^2 + 3{,}15 \cdot 10^{5} \cdot \mathrm{x} + 1100 \end{matrix} = 1355\ \mathrm{J}$$

Work value calculated from the characteristics from the experiment:

$$\int_{0}^{0{,}045} \begin{matrix} -1{,}39 \cdot 10^{14} \cdot \mathrm{x}^6 + 1{,}60 \cdot 10^{13} \cdot \mathrm{x}^5 - 3{,}96 \cdot 10^{11} \cdot \mathrm{x}^4 - \\ 1{,}19 \cdot 10^{10} \cdot \mathrm{x}^3 + 4{,}65 \cdot 10^{8} \cdot \mathrm{x}^2 + 7{,}08 \cdot 10^{5} \cdot \mathrm{x} + 278 \end{matrix} = 1380\ \mathrm{J}$$

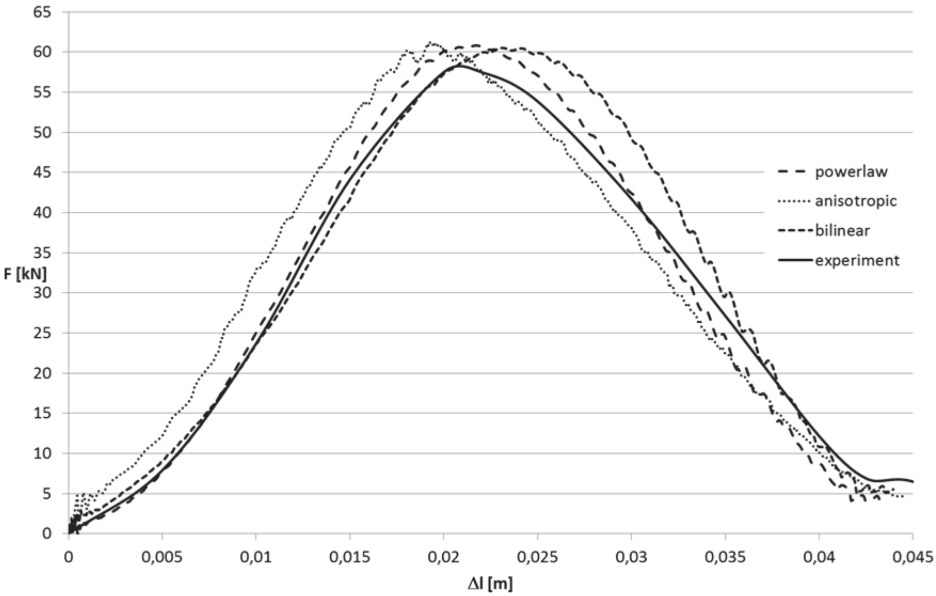


Fig. 8. Dependence of drawing force from stamp displacement for three models and experiment on die block with r_m = 16 mm

Rys. 8. Zależność siły tłoczenia od przemieszczenia stempla dla trzech modeli i eksperymentu na matrycy o r_m = 16 mm

The diagram in Figure 9 presents respectively the dependences of the force from displacement for a die block with area rounding of 18 mm. The average maximum press force value was ca. 56 kN. Below are included calculations of the work value for the further materials models and the experiment.

Work value calculated from the anisotropic model:

$$\int_{0}^{0,045} \begin{matrix} -1,93 \cdot 10^{14} \cdot x^6 + 2,15 \cdot 10^{13} \cdot x^5 - 5,75 \cdot 10^{11} \cdot x^4 - \\ 9,85 \cdot 10^9 \cdot x^3 + 4,52 \cdot 10^8 \cdot x^2 - 7,38 \cdot 10^5 \cdot x + 4550 \end{matrix} = 1402\ \mathrm{J}$$

Work value calculated from the bilinear model:

$$\int_{0}^{0,045} \begin{matrix} -3,02 \cdot 10^{14} \cdot x^6 + 4,66 \cdot 10^{13} \cdot x^5 - 2,50 \cdot 10^{12} \cdot x^4 + \\ 5,27 \cdot 10^{10} \cdot x^3 - 3,62 \cdot 10^8 \cdot x^2 + 2,17 \cdot 10^6 \cdot x + 663 \end{matrix} = 1322\ \mathrm{J}$$

Work value calculated from the powerlaw model:

$$\int_{0}^{0,045} \begin{matrix} -4,47 \cdot 10^{14} \cdot x^6 + 6,09 \cdot 10^{13} \cdot x^5 - 2,87 \cdot 10^{12} \cdot x^4 + \\ 5,10 \cdot 10^{10} \cdot x^3 - 2,25 \cdot 10^8 \cdot x^2 + 1,39 \cdot 10^6 \cdot x + 96 \end{matrix} = 1267\ \mathrm{J}$$

Work value calculated from the characteristics from the experiment:

$$\int_{0}^{0,045} \begin{matrix} -2,89 \cdot 10^{14} \cdot x^6 + 3,73 \cdot 10^{13} \cdot x^5 - 1,52 \cdot 10^{12} \cdot x^4 + \\ 1,51 \cdot 10^{10} \cdot x^3 + 1,68 \cdot 10^8 \cdot x^2 + 4,55 \cdot 10^5 \cdot x + 252 \end{matrix} = 1330\ \mathrm{J}$$

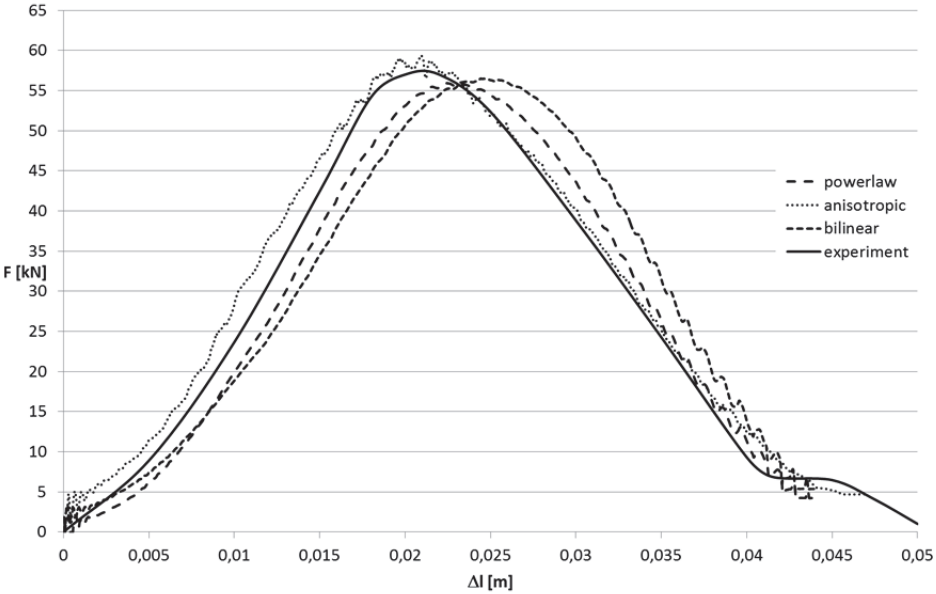


Fig. 9. Dependence of drawing force from stamp displacement for three models and experiment on die block with r_m = 18 mm
Rys. 9. Zależność siły tłoczenia od przemieszczenia stempla dla trzech modeli i eksperymentu na matrycy o r_m = 18 mm

The diagram in Figure 10 presents the dependences of the force from displacement for a matrix with a curvilinear outline. It does not possess any constant area rounding of the working edge. The average maximum press force value was ca. 28 kN. Below are included calculations of the work value for the further materials models and the experiment. It can be noted that the work values are by over 20 per cent greater in relation to a die block with a area rounding of 18 mm.

Work value calculated from the anisotropic model:

$$\int_0^{0,09} \begin{matrix} 5,64 \cdot 10^{12} \cdot x^6 - 1,69 \cdot 10^{12} \cdot x^5 + 1,87 \cdot 10^{11} \cdot x^4 - \\ 9,22 \cdot 10^9 \cdot x^3 + 1,75 \cdot 10^8 \cdot x^2 + 2,15 \cdot 10^5 \cdot x + 523 \end{matrix} = 1797\ \mathrm{J}$$

Work value calculated from the bilinear model:

$$\int_0^{0,09} \begin{matrix} 3,20 \cdot 10^{12} \cdot x^6 - 1,11 \cdot 10^{12} \cdot x^5 + 1,36 \cdot 10^{11} \cdot x^4 - \\ 7,31 \cdot 10^9 \cdot x^3 + 1,56 \cdot 10^8 \cdot x^2 - 1,51 \cdot 10^5 \cdot x + 3970 \end{matrix} = 1745\ \mathrm{J}$$

Work value calculated from the powerlaw model:

$$\int_{0}^{0,09} \begin{matrix} 3,79 \cdot 10^{12} \cdot x^6 - 1,27 \cdot 10^{12} \cdot x^5 + 1,51 \cdot 10^{11} \cdot x^4 - \\ 7,79 \cdot 10^9 \cdot x^3 + 1,51 \cdot 10^8 \cdot x^2 + 2,38 \cdot 10^5 \cdot x + 1720 \end{matrix} = 1669\ \mathrm{J}$$

Work value calculated from the characteristics from the experiment:

$$\int_{0}^{0,09} \begin{matrix} 6,67 \cdot 10^{12} \cdot x^6 - 1,90 \cdot 10^{12} \cdot x^5 + 2,04 \cdot 10^{11} \cdot x^4 - \\ 9,96 \cdot 10^9 \cdot x^3 + 1,96 \cdot 10^8 \cdot x^2 - 6,77 \cdot 10^4 \cdot x + 58 \end{matrix} = 1699\ \mathrm{J}$$

Work value calculated from the anisotropic model for friction = 0:

$$\int_{0}^{0,09} \begin{matrix} 4,39 \cdot 10^{12} \cdot x^6 - 1,31 \cdot 10^{12} \cdot x^5 + 1,45 \cdot 10^{11} \cdot x^4 - \\ 7,00 \cdot 10^9 \cdot x^3 + 1,15 \cdot 10^8 \cdot x^2 + 7,19 \cdot 10^5 \cdot x - 462 \end{matrix} = 1122\ \mathrm{J}$$

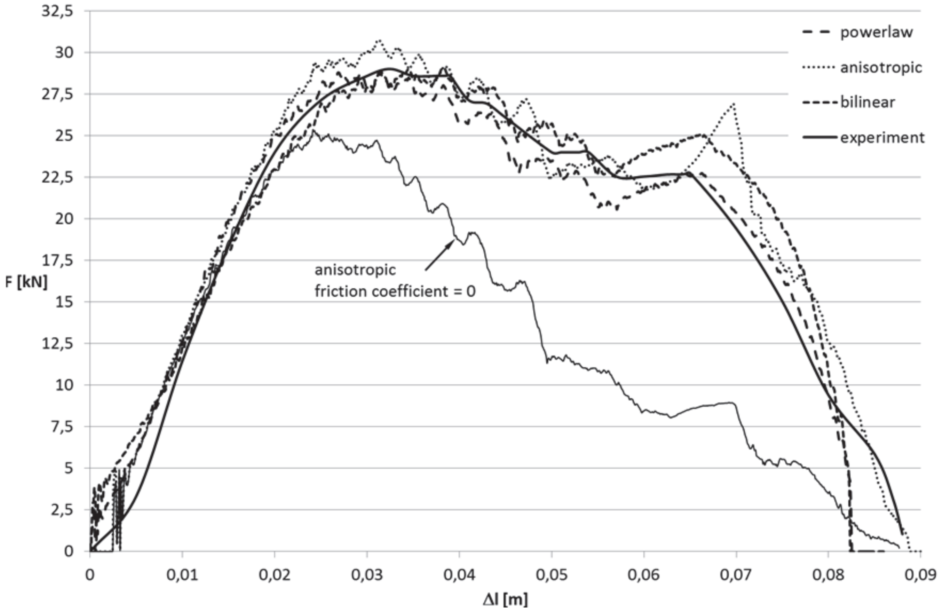


Fig. 10. Dependence of drawing force from stamp displacement for three models and experiment on curvilinear die block

Rys. 10. Zależność siły tłoczenia od przemieszczenia stempla dla trzech modeli i eksperymentu na matrycy krzywoliniowej

The last matrix used in the tests was a cone profile die block. The courses registered of the function of the force from the stamp displacement are presented in Figure 11. The average value of the maximum drawing force was ca. 54 kN. Below are found integrated sixth degree functions that serve the purpose of the calculation of the drawing work.

Work value calculated from the anisotropic model:

$$\int_{0}^{0,06} \begin{matrix} -7,11 \cdot 10^{13} \cdot \mathrm{x}^6 + 1,83 \cdot 10^{13} \cdot \mathrm{x}^5 - 1,62 \cdot 10^{12} \cdot \mathrm{x}^4 + \\ 6,15 \cdot 10^{10} \cdot \mathrm{x}^3 - 9,78 \cdot 10^8 \cdot \mathrm{x}^2 + 6,42 \cdot 10^6 \cdot \mathrm{x} - 3820 \end{matrix} = 1483\ \mathrm{J}$$

Work value calculated from the bilinear model:

$$\int_{0}^{0,06} \begin{matrix} 1,48 \cdot 10^{14} \cdot \mathrm{x}^6 - 1,79 \cdot 10^{13} \cdot \mathrm{x}^5 + 6,04 \cdot 10^{11} \cdot \mathrm{x}^4 - \\ 1,71 \cdot 10^9 \cdot \mathrm{x}^3 - 1,47 \cdot 10^8 \cdot \mathrm{x}^2 + 1,92 \cdot 10^6 \cdot \mathrm{x} + 681 \end{matrix} = 1465\ \mathrm{J}$$

Work value calculated from the powerlaw model:

$$\int_{0}^{0,06} \begin{matrix} 7,46 \cdot 10^{13} \cdot \mathrm{x}^6 - 5,31 \cdot 10^{12} \cdot \mathrm{x}^5 - 1,81 \cdot 10^{11} \cdot \mathrm{x}^4 + \\ 2,02 \cdot 10^{10} \cdot \mathrm{x}^3 - 4,19 \cdot 10^8 \cdot \mathrm{x}^2 + 3,35 \cdot 10^6 \cdot \mathrm{x} - 2090 \end{matrix} = 1396\ \mathrm{J}$$

Work value calculated from the characteristics from the experiment:

$$\int_{0}^{0,06} \begin{matrix} -7,23 \cdot 10^{13} \cdot \mathrm{x}^6 + 1,65 \cdot 10^{13} \cdot \mathrm{x}^5 - 1,37 \cdot 10^{12} \cdot \mathrm{x}^4 + \\ 4,99 \cdot 10^{10} \cdot \mathrm{x}^3 - 7,46 \cdot 10^8 \cdot \mathrm{x}^2 + 4,33 \cdot 10^6 \cdot \mathrm{x} - 780 \end{matrix} = 1469\ \mathrm{J}$$

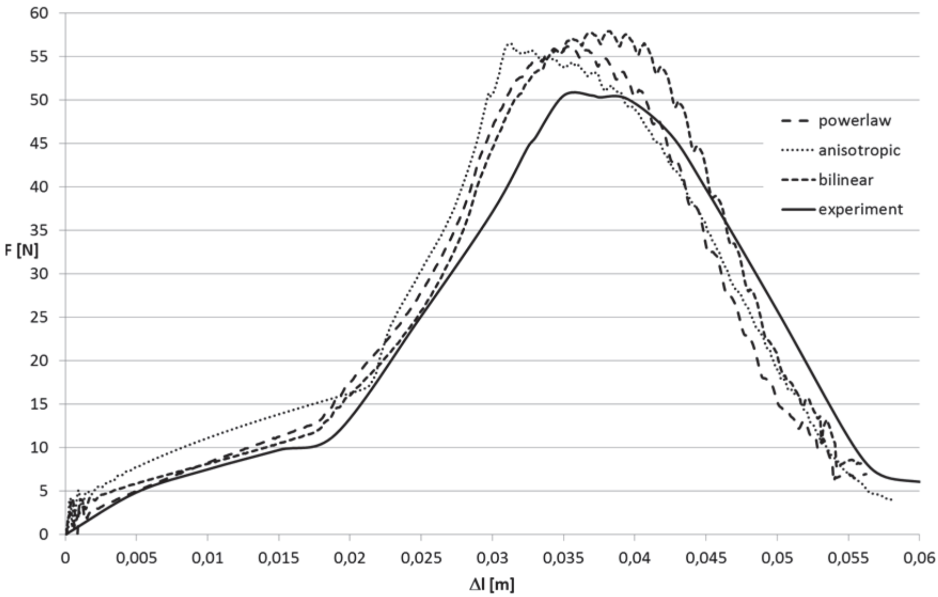


Fig. 11. Dependence of drawing force from stamp displacement for three models and experiment on cone die block
Rys. 11. Zależność siły tłoczenia od przemieszczenia stempla dla trzech modeli i eksperymentu na matrycy stożkowej

Collective diagrams of the drawing work value for each die block are found in Figure 12. The Barlat anisotropic model is the most favourable was as regards the projection of the shape of the drawpiece as it takes into account the formation of characteristic ears at the rim of the drawpiece. However, numerical calculations that employ this model are very time consuming for the computer. This is the result of the lack of circular symmetry, which occurs for the bilinear model and the powerlaw model, where material is isotropic. It is then possible to model a quarter of the objects. The bilinear model is the most favourable one for the determination of drawing work owing to the greatest accuracy achieved in these tests.

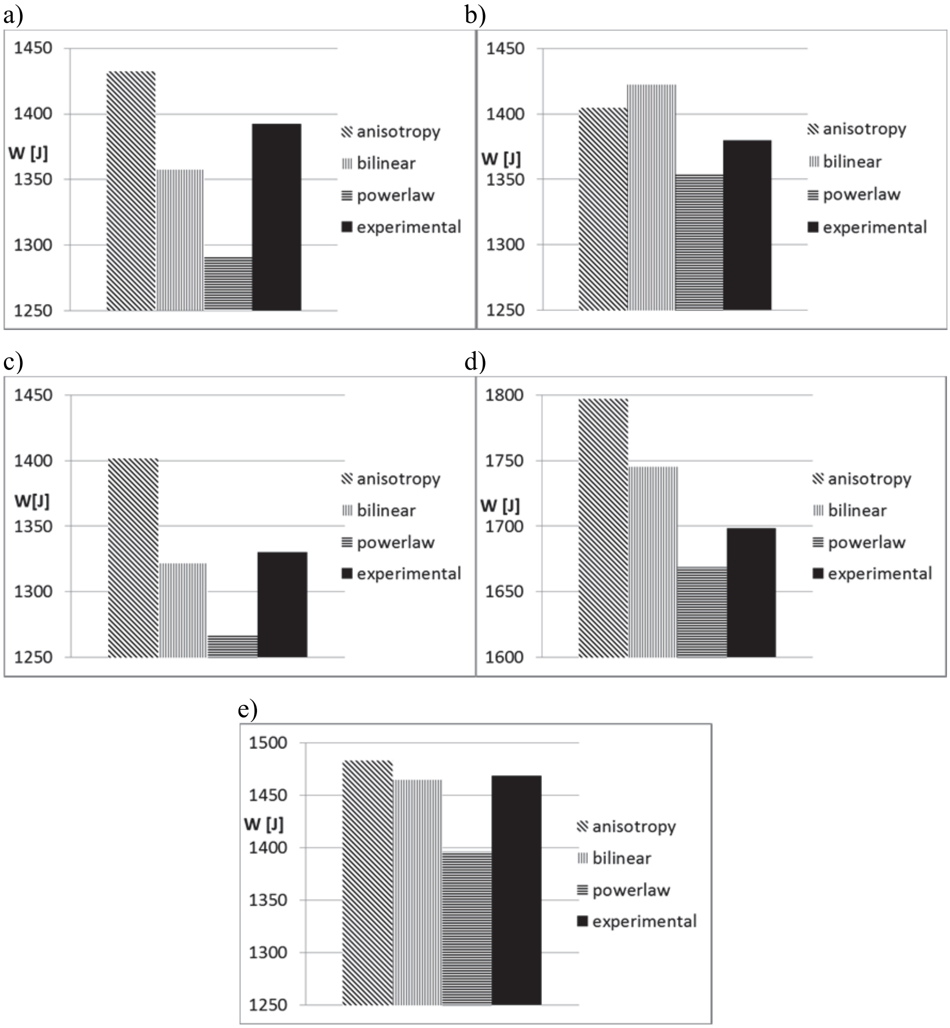


Fig. 12. Value of drawing work for various materials models and die block: a) r_m = 12 mm, b) r_m = 16 mm, c) r_m = 18 mm, d) curvilinear, e) cone

Rys. 12. Wartości pracy tłoczenia dla różnych modeli materiałowych i matrycy: a) r_m = 12 mm, b) r_m = 16 mm, c) r_m = 18 mm, d) krzywoliniowa, e) stożkowa

4. Conclusions

- Owing to the formulation of the computer model and numerical analysis, it is possible to make a measurement of the force in the function of the stamp path with the aid of the reading of contact pressures.
- By describing this function with the aid of the trend line with the known equation of any degree whose R^2 exceeds 0.95 and integrating this equation within the limits of the total displacement of the stamp, it is possible to determine the total drawing work.
- It was noted that owing to an increase of the area rounding of the die block from 12 mm to 18 mm, it was possible not only to reduce the maximum drawing force by ca. 10 kN but also to reduce to 5 per cent the total drawing work. With mass production, this constitutes substantial energy savings, whereas the result of a smaller force is a decreased use of the working surfaces of the stamp and of the die block.
- By using a die block with a curvilinear profile, where the surface of the drawpiece adheres all the time to the working surface of the die block, it was possible to decrease twice the maximum drawing force. The energy demand rose by over 20 per cent. This follows from a prolonged contact of the surface of the drawpiece with the die block. In order to minimize the work of the system, efforts are to be undertaken to obtain zero friction between the die block and the surface of the product's metal sheet. As demonstrated with the numerical analysis, work can be reduced in such a case by almost 40 per cent in relation to standard friction conditions in the drawing process.

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Określanie nakładu energetycznego w procesie wytłaczania w aspekcie ochrony środowiska

Streszczenie

Głównym celem tej publikacji jest przedstawienie możliwości zastosowania obliczeń numerycznych do wyznaczania siły i całkowitej pracy tłoczenia. Minimalizacja nakładu energetycznego jest ważnym elementem w nowoczesnej produkcji masowej, dlatego szybkie wyznaczenie całkowitej pracy pozwala optymalizować proces produkcyjny i zmniejszyć jego szkodliwy wpływ na środowisko.

W pracy zestawiono wyniki numeryczne z eksperymentalnymi w celu ich weryfikacji. Potwierdzono, że na poziomie istotności $\alpha = 0{,}05$ wyniki symulacyjne są zgodne z eksperymentalnymi. Określono, że na całkowitą pracę tłoczenia ma wpływ profil matrycy i warunki tarcia w obszarze kontaktu narzędzi.

Abstract

The main objective of this publication is to present the possibilities of using the numerical calculations to determine the force and the total drawing work. Minimizing the effort of energy is an important element in modern mass production, because the rapid determination of the total work allows optimizing the production process and reduce its harmful effects on the environment.

In this paper summarizes the numerical results with experimental data for the purpose of verification. It was confirmed that at significance level $\alpha = 0{,}05$ results of simulation are consistent with experimental. It has been determined that on the overall drawing work has an influence the profile of the die and the friction conditions in the contact zone.

Słowa kluczowe:
wytłaczanie, nakład energetyczny, Ansys/Ls-Dyna

Keywords:
deep drawing, energy expenditure, Ansys/Ls-Dyna