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I. NOWOTYŃSKA*[#], S. KUT**

THE INFLUENCE OF DIE SHAPE AND BACK TENSION FORCE ON ITS WEAR IN THE PROCESS OF WIRE DRAWING

In the paper an analysis of the influence of two parameters on the die wear, i.e. the shape of the die and the backpull with the specified force values has been presented. The conical and curve-profile tools have been selected to determine an influence of the die geometry on its wear, and the backpull force has been tested with the use of conical dies. The research was conducted for the drawing of copper wire by sintered carbide die with a mesh diameter of 3 mm. A fixed draw value of 30% relative gap loss was assumed. The axisymmetric numerical model of the drawing process was built and modeled in the MARC/Mentat commercial program for nonlinear and contact issues. As a result of the tests, wear of the dies according to their shape was determined. In addition, for the conical die the drawing force and the force of the metal pressure on the die using different values of the force of the contraction were calculated, as well as wear of the conical die according to the value of the applied backpull force. It has been shown that in the case of the arc die, the distribution of pressure and stress is more uniform over the entire length of the contact zone compared to the conical die. The highest stress gradients occurred in the area of the transition of the crushing part into the drawing part of the die, which caused that the use of the conical die in this area was more than twice as large as the arc die. In addition, on the example of a conical die, it was shown to what extent the depth of its wear decreases with an increase of the test pull force in the range (0-400) of Newtons.

Keywords: drawing; die shape; wear; copper wire

1. Introduction

The process of drawing is an operation in which the cross-sectional area of the rod is reduced by dragging it through a shaped die [1]. Drawing is a production process often used in industry because of its versatility and good mechanical properties of products (good final surface and dimensional accuracy) [2]. The effective implementation of drawing requires careful selection of process parameters in the appropriate selection of the geometry of the die, the degree of reduction in cross-sectional area or reducing the friction between the die and the material drawn [3-8].

The main limitation in wire drawing is the wear of tools, causing not only direct costs, but also time-consuming associated with their replacement and regeneration. In addition, tool wear has a direct impact on the process, and thus the quality of the drawn products [9]. The geometry of a drawing die is one of the parameters which has a significant impact on the drawing process. Therefore, the use of the die must be controlled to detect a significant loss or damage before, e.g.: the rod, wire or other device is manufactured in [10]. To ensure the best conditions to produce the final product, different types of dies, due to the shape of forming working area, are introduced e.g.: conventional dies of conical inclination of crushing zone and the arc dies - convex or concave (Fig. 1) [2].

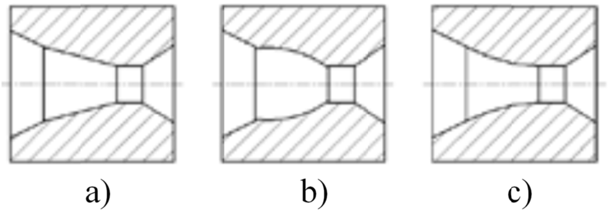

Fig. 1. Types of dies due to the shape of forming working area: (a) conical; (b) arc concave; (c) arc convex

In the case of a conical shape of the die crushing part, the inclination angle of the generator to the axis of the drawing is constant along the entire crushing zone, whereas for the accurate part of the crushing dies it is variable. With the arc-shaped part of the crushing die the intensity of decreasing of the outer diameter at the beginning of the deformation zone is the largest and decreases gradually as it approaches the sizing part. The arc die has a very smooth transition of crushing part into calibrating one, which ensures precise dimensions and high surface quality of drawn products.

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* RZESZOW UNIVERSITY OF TECHNOLOGY, DEPARTMENT OF COMPUTER ENGINEERING IN MANAGEMENT, 12 POWSTAŃCÓW WARSZAWY AV, 35-959 RZESZÓW; POLAND
** RZESZOW UNIVERSITY OF TECHNOLOGY, DEPARTMENT OF MATERIALS FORMING AND PROCESSING, 12 POWSTAŃCÓW WARSZAWY AV, 35-959 RZESZÓW; POLAND

[#] Corresponding author: i_nowot@prz.edu.pl

As the result very significant pressures in a drawing process, as well as friction of the shaped metal on the die surface, it is gradually worn out. The individual elements of the hole of the die wear out unevenly. Generally inside the die three zones of wear can be distinguished. The first zone of wear, manifested by the formation of the so-called crusher ring, is on the surface of the crushing cone in an area where the earliest wire is in contact with the tool. The second zone of wear is in the further part of the working cone in contact with the shaped material, and the third in the part which sizes dies.

According to Wistreich [11] the wear is highest in the first zone. He assumes that the so-called crusher ring of wear, which is in the first zone, occurs due to fatigue failure in the first point of contact between the wire and the die. According to Shatynski this assumption is not correct as the fracture surface is generally perpendicular to the direction of the main tensile stress [12]. Kim et al. [13] decided that the wear was not constant within the matrix due to changes in pressure forces. Numerical simulations with the use of the finite element method performed by Kim et al. and independently by Overstama [14] show changes, that the greatest stresses are exerted on the cone of the working die in the material input, and the lower value on the output of the die cone.

These “peaks” of loads may explain some of the non-uniform wear of the die in the form of so-called crusher ring of wear. If the wear ring occurred due to wire vibrations, it will not be uniform, but the biggest in the direction of oscillation. Pirso et al. [15] showed that the wear of cemented carbide during the dry friction conditions, is mainly caused by the removal of cobalt binder followed by cracking and breaking of the intergranular boundaries and reduction of carbide grain. In addition to the geometry of the die, its wear is also affected by the value of the used back tension. The back tension changes significantly the conditions of deformation and affects the conditions of power and technological drawing process. Numerous studies have shown that with an increase in the back tension the pressure of metal on the die decreases, e.g. [10,16]. Reducing the force has a significant influence on the intensity of use of the tool (the die). Proper construction of machine elements requires the ability to predict (forecast) of their behavior during operation. To predict the behavior of these elements, analytical models describing the processes which they will be subjected to, are necessary. The problem of forecasting of machine parts wear, including tools in the drawing process, is still not completely resolved.

The results presented in this paper relate to the study on the effect of two very important parameters on the die wear. The first parameter is the geometry of the shape of the die generator. Therefore, the arc die and the arc convex die were subjected to the comparative analysis of wear. The second parameter having a significant impact on the consumption of the die is to use the so-called back tension of a certain strength. For this reason, in the work an analysis of the impact of back tension on the value of the conical die was also conducted. The aim of the research presented in this work was to determine the effect of tool geometry and the use of back tension of different force values on the course and the amount of wear of the die using a numerical simulation based on experimental data taken from literature.

2. Numerical models of drawing process and FEM simulation

Drawing is a technological process, whose numerical modeling requires the consideration of nonlinear and contact phenomena. Typical numerical model of drawing process consists of three bodies that are in contact with each other. The first body is the drawn material, the second is the die, while the third is the die mount. While the drawn material is always modeled as a deformable body, then the die is often modeled as a perfectly rigid body. Such a simplified model does not consider the phenomena associated with the elastic deformation of the tool and its wear during operation. The inclusion of these phenomena requires that the die should also be modeled as a deformable body. The analyzed drawing process (Fig. 2) consists of drawn wire 1, the die 2 and the deformable rigid abutment surface 3. The drawing process is carried out by the action of drawing force F_c.

The first part of the paper concerns the influence of the die geometry on the value of its wear and it was implemented without the use of back tension. Thus , the back tension force F_0 in this case was zero. Numerical models were built, and calculations were made for two different types of dies, i.e. conical and arc whose shape and dimensions are shown in Figure 3.

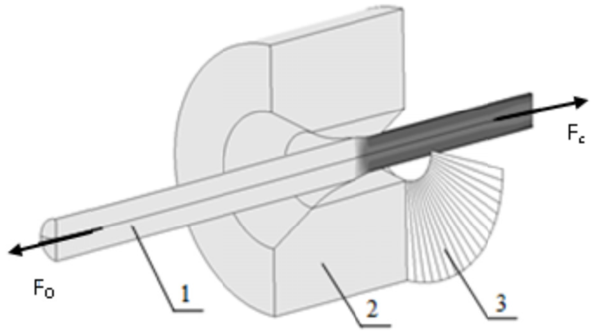

Fig. 2. Scheme of the modeled drawing process: 1 – drawn wire, 2 – die, 3 – abutment surface, F_c – pull force, F_0 – back tension force

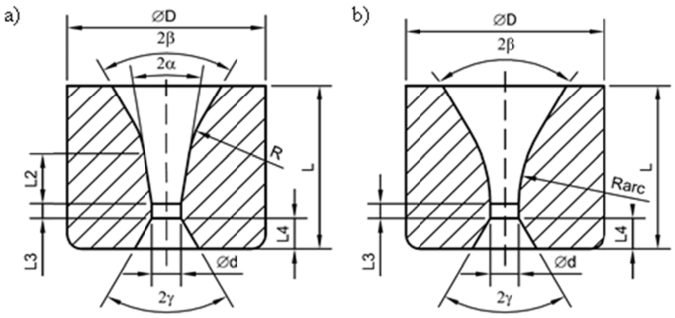

Fig. 3. Shape and dimensions of research tools: (a) conical die; (b) arc die; ϕd = 3 mm, ϕD = 20.45 mm, R = 10 mm, R_{arc} =14.5 mm $2\beta = 2\gamma$ = 60 deg, 2α = 18 deg, L = 17 mm, L_2 = 5.2 mm, L_3 = 1.5 mm, L_4 = 3.2 mm

In the second part of the completed research, the influence of back tension on the wear value of the conical die of geometry and dimensions as shown in Figure 3a was determined. The calculations were performed using the following values of back tension force F_0 = [0, 10, 20, 30, 40, 50, 60, 100 , 150, 200, 250, 300, 350, 400] N. The carried out calculations for both parts of the research described above required the development of two numerical models which differed only in the nature of the die. The first model had a conical die (Fig. 4a), while the second one the arc die (Fig. 4b).

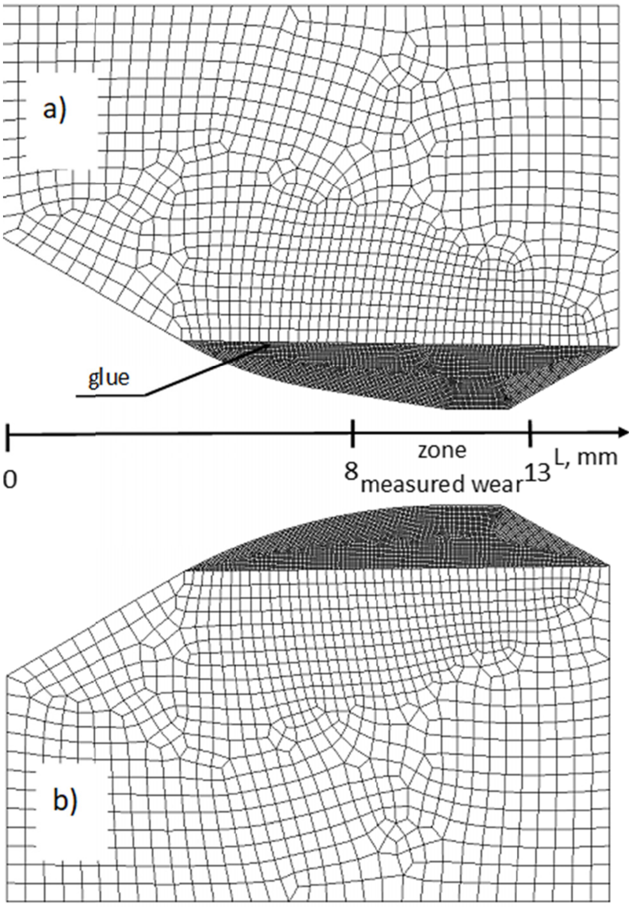

Fig. 4. MES models of dies and the measurement area of their wear: (a) conical die; (b) arc die

Axisymmetric numerical models of drawing process were built and modeled in the commercial program for non-linear and contact problems MARC / Mentat. Copper wire with a diameter of 3.6 mm was drawn by a 3 mm-die. The use of these parameters allowed gaining a draft of approximately 30%. For the construction of the finite element mesh of tools and wire, the quad 4 type 10 elements – arbitrary quadrilateral axisymmetric ring [17] were used. The dies models had two meshes of elements connected by means of glue contact condition (Fig. 4). The average mesh size in the concentrated area was 0.05 mm and in not concentrated area it was approximate 0.35 mm. The initial size of the mesh of the drawn wire in both models was 0.05 mm. In total, each numerical model consisted of approximate 24 000 finite elements. Material properties of dies made of tungsten carbide were described assuming perfectly elastic body model of E = 620 000 MPa and n = 0.22 [18]. To describe the material properties of the deformed copper wire one assumed elastic-plastic material model of nonlinear strengthening. The stress-strain in the elastic deformation was described by the Hooke's law, and in terms of plastic deformation by the Hollomon's power series equation. Strength properties of the wire material (Cu-ETP) and parameters of the hardening curve designated in an attempt of uniaxial tensile and used in the modeling, are shown in Table 1. The tests were carried out with the assumption of the same conditions in all cases, i.e. equal drawing speed at constant temperature. The cold drawing process was modeled. The influence of thermal phenomena generated in the process was not taken into account.

TABLE 1

Mechanical properties of drawn material

Drawn material	**Young's modul *E* [MPa]**	**Poisson's number *n***	**Yield stress *Re* [MPa]**	**Tensile strength *Rm* [MPa]**	**Strain hardening curve parameters**	
					***K* [MPa]**	***n***
Cu-ETP	127 000	0.35	57	227	368	0.3

To describe the friction between bodies in the model the Coulomb's model was used. The coefficient of friction between the drawn bar and the die equal μ = 0.07 [18]. The modeling process was carried out assuming a constant drawing velocity v = 0.7 m / s.

To determine the wear of the die the Archard's model was applied [19]:

$$dV = k\frac{dFdL}{H} \tag{1}$$

where:

k – dimensionless wear ratio,
dV – wear volume, mm^3,
dF – normal force, N,
dL – friction road, mm,
H – hardness of the tool surface, MPa.

The Archard's model was implemented in MARC software as:

$$\overset{o}{w} = \frac{k}{H}\sigma v_{rel} \tag{2}$$

where:

$\overset{o}{w}$ – wear velocity, mm/s,
s – normal stress in contact, MPa,
v_{rel} – relative lost motion, mm/s.

The wear size specified by wear indicator is calculated from the relation:

$$w_{n+1} = w_n + \overset{o}{w}\Delta t \tag{3}$$

where:

w_{n+1} – current value of the depth wear, mm,
w_n – wear value in the previous calculation step, mm,

$\overset{o}{w}$ – wear velocity, mm/s,

Δt – time in calculation step, s.

However, such calculated wear size allows to specify the wear in a qualitative way. In order to estimate the quantitative wear for the modeled cases, the relationship (2) was modified to the form:

$$\overset{o}{w} = \frac{k}{H}\frac{m}{m_{FEM}}\sigma v_{rel} \tag{4}$$

where:

m – real wire mass drawn through the die, Mg,

m_{FEM} – wire mass drawn through the die during the FEM modeling, Mg.

In this study the wear coefficient of the die k was adopted on the basis of research results in [10] $k = 3\times10^{-7}$ (mm^3/(m mm^2)), which after the units conversion is $k = 3\times10^{-10}$. In this work, the consumption rate was determined based on the results of experimental studies of the drawing process of wires with diameters from 2.6 mm to 5.6 mm. The values were calculated based on the volume of the die cavity after dragging a specific weight wire. The constant hardness of the tool surface during the process of its wear was also assumed and it HV30 = 1700 kp/mm^2 [10]. After units conversion it was adopted that $H = 17\,000$ MPa. The depth of die wear was calculated after dragging m = 6.35 Mg wire. The weight of the drawn wire, for which the modeling was completed, was $m_{FEM} = 4.45\times10^{-6}$ Mg.

Tintelecan et. al. in [20] measured the value of the drawing force for six drawing angles on the basis of 90 experiments and compiled them in tables with the values of forces calculated on the basis of a mathematical formula [21]:

$$F_c = A_1\cdot\sigma_c\cdot\left[\ln\frac{A_0}{A_1}+\frac{\mu}{\alpha}\cdot\ln\frac{A_0}{A_1}+\frac{2\cdot\alpha}{3}\right]+ \\ +\pi\cdot d_1\cdot l_1\cdot R_e\cdot\mu \tag{5}$$

where: A_0 – the cross section of the wire before its drawing process [mm^2], A_1 – the cross section of the wire after its drawing process [mm^2], σ_c – the mean of the yield tensions before and after its drawing process [MPa], $2\cdot\alpha$ – the approaching angle [Radians], μ – the friction coefficient [-], d_1 – the diameter of the wire after its drawing [mm], l_1 – the length of the cylindrical (calibration) area for the die [mm], R_e – the yield stress after drawing process. From the analysis of the numerical values set, it appears that, for example, using the angle α = 9 deg. and $l_1 = (0.4\cdot d_1)$ the value of the force calculated from the dependence (5) in the first pass is 2.6% greater than the experimental strength, while in the second and last pass 6.2% and 4.2%, respectively. On the other hand, in the third pass the calculated value was 3.3% lower than the experimental strength. Thus, the average value of the difference between the force calculated from the dependence (5) and the experimental force was about 2.5%. Due to the high convergence of the drawing force calculated from the dependence (5) with the experiment, this relationship was used to validate numerical models. Validations were performed by comparing the average value of the drawing force occurring in numerical simulation with the value of force calculated from formula (5). The course of the drawing force calculated in the FEM simulation is shown in the graph (Fig. 5). For this case, the average value of the drawing force calculated with the MES was 1085 N, while the drawing force calculated from the equation (5) was 1064 N. Thus, the force calculated in the FEM simulation is only 2% higher than the force calculated from equation (5) which proves the correctness of the applied FEM model for the analysis of the drawing process.

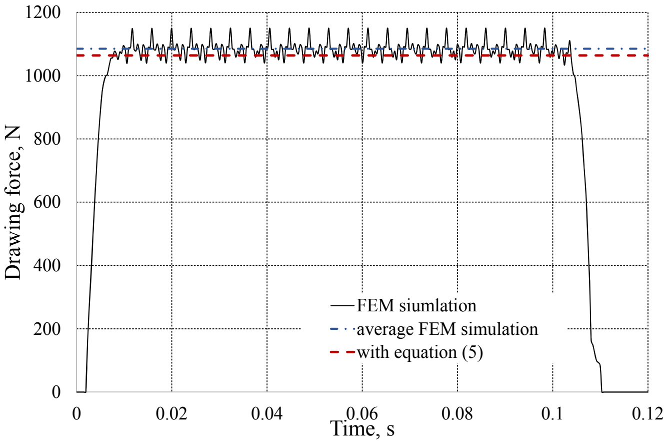

Fig. 5. Drawing force diagram without backpul

3. Calculations results and their analysis

3.1. Influence of the die geometry on the wear

Based on the results of numerical modeling the wear size of the conical and arc die in the drawing process with the use of the Archard's model was determined. The wear measurement on the numerical model was analyzed in the area of the length of the matrix from 8 mm to 13 mm, as shown in Figure 4. The numerical values of the calculated depth of wear were read in the subsequent nodes spaced at 0.05 mm.

Distribution of stress intensity depends largely on the shape of the crushing area of the tool (Fig. 6). In case of the use of the conical die (Fig. 6a) the most loaded area is near the part of the calibration tool. Its heavy burden on a small area can contribute to rapid wear of the die. In this area one can notice a considerable variation of stresses intensity. Their greatest gradient occurs in the region of the transition of squeezing cone into the sizing portion. The presence of such large stress gradients, in addition to the normal wear, can cause other mechanisms of wear or damage, e.g. the formation of micro-cracks. Stress distribution is different during the wire drawing die through the arc die (Fig. 6b). Stress can be distributed over a larger area of the working part of the tool without causing dangerous concentrations, which preferably may influence the quality of the products obtained by this method. For this reason, in industrial practice this type of tools are often used to draw profiles with small diameters, in which the conditions for the possibility of obtaining good quality small products are of great importance. In addition, a favorable distribution of stresses greatly extends tool life, and thus reduces the cost of production of drawn products.

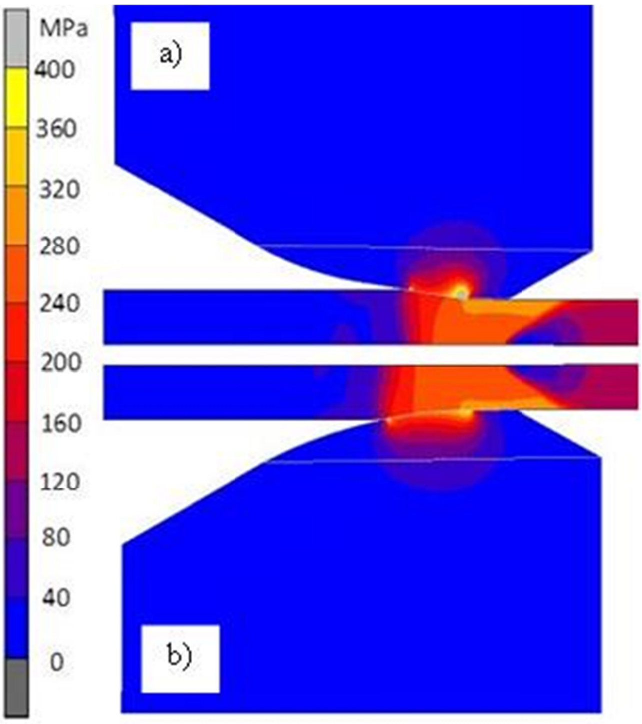

Fig. 6. Distribution of stresses intensity in the drawing process by the die: (a) conical; (b) arc

The calculated depth of wear *w* on the length of measuring area for the analyzed dies is shown in Figure 7.

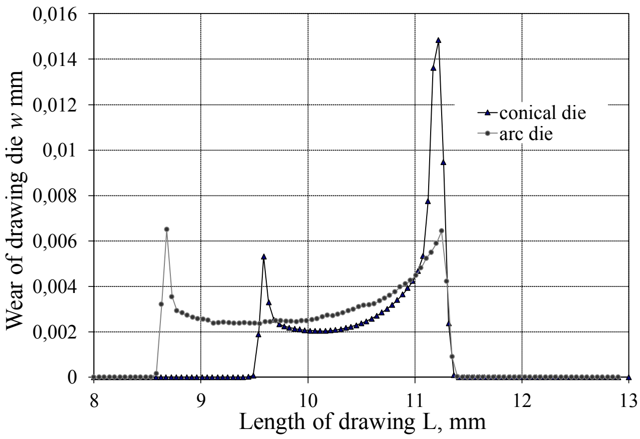

Fig. 7. The wear on the length of the conical and arc die

During wire drawing through the conical and arc die, there are two areas of higher values of wear. When using the die arc, the first area of intensive wear (i.e. the draft ring) starts earlier than when the conical die is used. The second area of increased wear in both considered tools occurs in the transition area of the crushing part into the calibration part. In this area, the recorded wear depth of the conical die was about 2.3 times greater than the arc die and was 15 μm. For the die arc both areas have similar value slightly exceeding 6 μm. Furthermore, the distance between the origin of these two areas of significant wear is different for the two dies. For the arc die it is approx. 3 mm and is larger than in case of the conical die where the distance is 2 mm. The study results (Fig. 7) show that, in comparison with the conical die, the arc die not only has lower wear, but it also wears much more evenly throughout the contact area with the working material.

3.2. Impact of back tension on the wear

The conducted studies showed a clear impact of back tension on the course and size of tool wear in the drawing process. Measurement of the wear on the numerical model was analyzed in the area of the length of the conical die from 9 mm to 13 mm (Fig. 4a). The numerical values of the calculated depth of wear were read in the subsequent nodes spaced at 0.05 mm. The calculated wear depth of the conical die w along the length of the measurement zone for each variants of back tension forces were shown on the graph (Fig. 8). Based on the results one can see that during the wire drawing on the surface of the die there are two areas of higher values of wear. The analysis of the results leads to the conclusion that the individual areas of the die wear out unevenly. This is true both in the case of the back tension application as in case of lack of it. The beginnings of the use are observed in the crushing cone, in the place of the abutment surface of the die to the metal (the first area of high wear). In this place the use of the die is large and is manifested in the form of a groove called the draft ring. The course of the curves on the graph (Fig. 8) shows that not only the groove depth but also its location along the length of the matrix depend on the amount of back tension force. For example, during drawing, without the back tension, the groove lies along the length $L = 9.643$ mm. The introduction and subsequent increase of the back tensions force shifts its position toward the opening of the calibration. In the case of the highest value of the back tension force $F_0 = 400$ N the position of the groove corresponds to the position of the groove $L = 9.792$ mm. With increasing amount of back tension force the groove depth decreases.

The second region of higher wear is in the place of the transition of the crushing cone into the sizing hole. In this area, the projected wear-depth is the largest and also decreases with the increase of the back tension force. The obtained values of wear in the event of back tension failure at the contact point of wire with the working surface reach the value $w = 0.0051$ mm, whereas in the region of the transition of the working cone part into the sizing wear value, it is $w = 0.015$ mm. In turn, among all back tension forces taken into account in the study, the most preferred from the standpoint of wear of the die is the use of the back tension force of 400 N. In the case of the use of such the force in the process of drawing, the most intense increase in the diameter of the die occurs in the area at the end portion of the crushing point of the die and it is 0.0128 mm. While the less intense increase in the diameter of the die is at the initial contact of the wire with the die and it is 0.0049 mm. The least favorable impact of back tension forces was recorded for the value of 10 N.

Here, also an intense increase in the diameter of the die occurs in the area at the end of crushing die crushing part, but it is 0.0302 mm, while the less intense increase in the diameter of the die is at the initial contact with the die and wire, and it is 0.0106 mm. The increases of back tension force by 40 times caused a decrease in the wear of the die in place of the first peak on the chart by 0.0004 mm. In the place of the second peak, i.e. in the crushing part by 0.0023 mm. The lowest wear occurred on the surface of the die sizing hole. In the case of drawing without back tension, the wear depth was 4.65×10^{-5} mm on average and decreased with the increasing back tension force to $F_0 = 100$ N. What is interesting that for the cases $F_0 = (150; 200; 250; 300; 350$ and $400)$ N the wear of the surface of the sizing hole did not occur. This is due to the fact that at sufficiently large values of back tension force, the rod by stretching may slightly reduce their diameter in the sizing aperture, which makes that the pressure of the material against the wall of the hole is very small, and the wear in comparison with other contact areas of deformable material with does not exist.

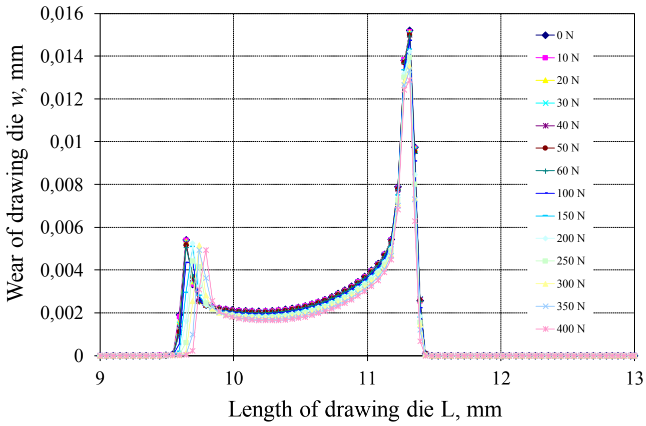

Fig. 8. The depth of wear of the conical die along its length depending on the value of the applied back tension force

The influence of the pull force on the drawing force and the force of the metal pressure on the dies was tested only for a conical die. The diagram (Fig. 9) shows the relationship of drawing load as a function of back tension for the conical die. The values of these forces were calculated on the basis of numerical simulations using the finite element method (FEM). One can observe an increase in drawing load with an increase of the back tension force (Fig. 9). Simultaneously, with an increase of the back tension force there is a reduction in load of the metal on the die, which in turn leads to a change in the deformation conditions in the crushing cone of the die, thus contributing to the increase of its durability.

It should be noted that the reduction of the metal load on the die F_m for all modeled cases of back tension force was greater than the increase in in drawing force F_c. For example, the increment value of drawing force in the case of back tension force of 400 N, with reference to the drawing without back tension, increased by 175 N, and the value of the metal load on the die F_m for the same back tension force decreased by 225 N.

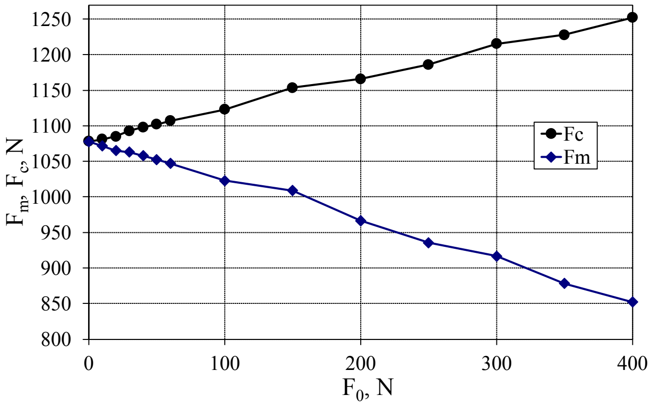

Fig. 9. The calculated relationship between the back tension force F_0 and the drawing force F_c, and the pressure load of metal on the die F_m for the conical die

5. Conclusions

Based on the conducted research and an analysis of the obtained results, the following conclusions can be drawn:

1. The influence of the shape of the dies has a significant impact on its wear. In the case of a conical die, the contact area of the material shaped with the tool in the crushing zone is approx. 30% lower than in the case of an arched drawing die. This results in the fact that, despite the same value of pressure, the material pressure of the conical dies in the contact area is greater. In addition, in the case of an arched drawing die, the distribution of pressure and stress are more uniform over the entire length of the contact zone. In the case of a conical die, there are much higher stress gradients in the crushing zone, which is a disadvantageous phenomenon due to fatigue strength and draught wear.

2. In the case of both drawing dies, the highest wear occurred in the place where the wire is at the earliest contact with the tool and at the transition point of the crushing zone into the calibrating one. However, in the case of arched drawing die, the depth of wear in both places is similar and amounts to approx. 6 micrometers. The depth of wear of the conical die in the place where the wire is the first in contact with the tool was similar and amounted to approx. 5 micrometers, while at the point of transition of the crushing zone in the calibrator it was three times larger and was about 15 micrometers.

3. The use of a back pull reduces the use of the drawing tool. The wear depth decreases as the back tension force increases. In addition, it has been observed that as the back tension force increases, the place where the wire is first in contact moves towards the calibration zone, which causes a slight reduction in the contact surface of the shaped material with the tool (see Fig. 7).

4. As the value of the back pull force increases, the pressure of the shaped material decreases, which is advantageous due to wear, but at the same time the drawing force increases (see Fig. 8).

5. It should be noted that the quantitative consumption of the dies may in fact be larger, in comparison to the calculated values due to their gradual degradation during the drawing process, which is not included in the computer simulation. This may particularly apply to the wear of the die in the areas at the transition of the working cone into the calibrating part of the die, and consequently the calibration zone itself, which can be subject to significant wear.

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