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**APPLICATION OF THE TORSION TEST IN CALCULATING THE EXTRUSION FORCE**

**ZASTOSOWANIE TESTU SKRĘCANIA W OBLICZENIACH SIŁY WYCISKANIA**

The paper deals with the calculation of the extrusion force using the results of the torsion test of aluminium alloy EN AW–2014. The mathematical model for the calculation of the extrusion force requires the knowledge of the functional relationship between the yield stress and the temperature, the deformation and the deformation rate. Based on the proposed mathematical model for the calculation of the yield stress, the functional relationship was derived to determine the extrusion force in the hot extrusion of semi-products of aluminium alloy EN AW–2014.

*Keywords*: extrusion force, torsion test, aluminium alloy

## 1. Introduction

Extrusion is one of basic metal forming technologies to prepare initial semi-products for the manufacturing industry and is used for a wide scale of materials [1-3]. Extrusion is popular for its low exigency in terms of finance, as well as time and execution. Hot extrusion is the most used technology.

Analytical methods for calculation of the hot extrusion force based on the utilization of the yield stress obtained from the tensile test in the area of extrusion temperatures did not bring satisfactory results. Therefore for simulation of hot metal forming processes (including extrusion), calculation methods based on FEM (finite element method) are currently intensively utilized [4-6].

Each method for calculation of the extrusion force, either analytical or FEM, requires the deformation resistance values in the dependence on the temperature and the deformation rate. The yield stress values obtained from torsion tests offer such a possibility [6, 7].

The general functional relationship for the extrusion force in extrusion can be described using the following equation [8]:

$$F = f(D_R, \eta_F, \lambda, v_r, T, f, L, \text{die shape, material constants}) \tag{1}$$

$$\lambda = S_R/S_V \tag{2}$$

*where: F – extrusion force [N]*

*$D_R$– chamber diameter [mm]*

*$\eta_F$– deformation efficiency degree [-]*

*$\lambda$ – extrusion ratio [-]*

*$S_R$– chamber cross-section [mm$^2$]*

*$S_v$– extruded piece cross-section [mm$^2$]*

*$v_r$– plunger rate [m·s$^{-1}$]*

*T – billet temperature [°C]*

*f – friction coefficient between the chamber and the billet, friction between the extruded piece and the die [-]*

*L – billet length [mm]*

Mathematical relationships that take into account the extruded piece shape are shown in [8] and [9]. The issues of calculation of the extrusion force are solved in a number of papers; KOPP and WIEGELS [10] made the analysis of published papers. In most cases, in practice the extrusion force is determined according to SIEBEL and FINK [11] using the following equation:

$$F = S_R \cdot \frac{\sigma_p}{\eta_F} \cdot \left(\varphi + 4 \cdot f \cdot \frac{L}{D_R}\right) \tag{3}$$

*where: $\sigma_P$– yield stress [MPa]*

*$\varphi$ – logarithmic deformation [-], $\varphi = \ln \frac{S_R}{S_V}$*

Hot extrusion is made at the temperature, the deformation and different deformation rates. Therefore the

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yield stress is the function of the deformation, the deformation rate and the temperature:

$$\sigma_P = f(\varepsilon, \dot{\varepsilon}, \mathrm{T}) \tag{4}$$

*where: $\varepsilon$ – deformation [-]*

*$\dot{\varepsilon}$ – deformation rate [$s^{-1}$]*

For the functional relationship required by the equation (4), BEISS and BROICHHAUSEN [12] used the following relationship:

$$\left[\sinh\left(\frac{\sigma_P}{D_1}\right)\right]^{D_2} = \frac{\dot{\varepsilon}}{D_4}\exp\left(\frac{D_3}{T'}\right) \tag{5}$$

*where: $D_1$[MPa], $D_2[-]$, $D_3[K]$, $D_4[s^{-1}]$– material constants*

*$T'$– temperature [K]*

In [13, 14] the yield stress was calculated from the equation (5) and then the extrusion force was calculated from the equation (3) for extruded copper and brass semi-products.

## 2. Experimental conditions

The calculation of the extrusion force requires the knowledge of the functional relationship between the yield stress and the temperature and the deformation rate. For this purpose, the torsion test was used. The torsion test, registering values of the torque along with the number of revolutions, and consequently leading to the stress-strain curve, enables to obtain information on the ductility of the investigated material. The torsion test was performed on a torsion machine at the temperature T= 300, 350, 400, 450, 500°C measured by a K-type thermocouple. After an induction heating in air with a heating rate of 1°C/sec and a time holding of 3 min, the samples fixed in an axial direction were deformed to the fracture at equivalent strain rates of $10^{-3}$, $10^{-2}$, $10^{-1}$, 1, 5 $s^{-1}$, and water-quenched immediately after the deformation. Other information about torsion test is described in [6, 7]. The results of the torsion test made on aluminium alloy EN AW–2014, as well as all necessary data calculating the extrusion force, were taken from [15].

## 3. Results and discussion

To mathematically describe hot torsion tests, the following equation is used:

$$\dot{\varepsilon}\cdot\exp\left(\frac{\mathrm{Q}}{\mathrm{RT'}}\right) = \mathrm{A}\cdot\left[\sinh\left(\alpha\cdot\sigma_{\mathrm{p}}\right)\right]^{\mathrm{n}} \tag{6}$$

*where: Q – activation energy [J·$mol^{-1}$]*

*R – universal gas constant [J·$mol^{-1}$·$K^{-1}$], R=8,314 J·$mol^{-1}$·$K^{-1}$*

*A – material constant [$s^{-1}$]*

*$\alpha$ – material constant [$MPa^{-1}$]*

*n – stress coefficient [-]*

In the equation (6) and following cases, the yield stress $\sigma_P$ is representing by the peak torsion stress and it is the stress that corresponds to the stress according to the functional relationship (4). If we compare the equations (5) and (6), we can see that they are, in principle, similar. In the equation (6), the material constants are transformed:

$$T_0 = \frac{Q}{R}, \sigma_0 = \frac{1}{\alpha}, \dot{\varepsilon}_0 = A, m = \frac{1}{n} \tag{7}$$

The set of equations (7) is introduced into the equation (6):

$$\dot{\varepsilon}\cdot\exp\left(\frac{\mathrm{T_0}}{\mathrm{T}}\right) = \dot{\varepsilon}_0\cdot\left[\sinh\left(\frac{\sigma_{\mathrm{P}}}{\sigma_0}\right)\right]^{\mathrm{n}} \tag{8}$$

From the equation (8), the $\sigma_P$ is expressed:

$$\sigma_P = \sigma_0\cdot\arg\sinh\left\{\left[\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\exp\left(\frac{T_0}{T}\right)\right]^m\right\} \tag{9}$$

The relationship (9) requires the determination of the deformation rate $\dot{\varepsilon}$ in extrusion. The mean deformation rate $\dot{\varepsilon}_{st}$ in the extrusion process is determined from the following relationship:

$$\dot{\varepsilon}_{st} = 6\varphi\cdot\frac{v_r}{D_R} \tag{10}$$

From the data presented in [15], the material constants were calculated using the set of equations (7):

$$\begin{aligned} T_0 &= \frac{Q}{R} = \frac{186200}{8{,}314} = 22396\mathrm{K} \\ \sigma_0 &= \frac{1}{\alpha} = \frac{1}{0,052} = 19,23\mathrm{MPa} \\ \dot{\varepsilon}_0 &= A = 1,5266.10^{10}\mathrm{s}^{-1} \\ m &= \frac{1}{n} = \frac{1}{3,37} = 0,2967 \end{aligned} \tag{11}$$

The equation (9) for the yield stress of aluminium alloy EN AW–2014 gets the following particular form:

$$\sigma_P = 19,23\cdot\arg\sinh\left\{\left[\frac{\dot{\varepsilon}_{st}}{1,5266\cdot10^{10}}\exp\left(\frac{22396}{273,15+T}\right)\right]^{0,2967}\right\} \tag{12}$$

The equation (12) represents a suitable mathematical model to simulate the conditions for extrusion of semi-products of aluminium alloy EN AW–2014.

The extrusion force can be determined from the equation (3), while the yield stress can be calculated from the equation (12):

$$F = \frac{\pi}{4} D_R^2 \cdot \frac{19,23}{\eta_F} \cdot \text{arg sinh} \left\{ \left[ \frac{6 \ln \lambda}{1,5266 \cdot 10^{10}} \cdot \frac{v_r}{D_R} \cdot \exp\left( \frac{22396}{273,15 + T} \right) \right]^{0,2967} \right\} \cdot \left( \ln \lambda + 4f \frac{L}{D_R} \right) \tag{13}$$

After rearranging the constants, the resulting equation of the extrusion force for aluminium alloy EN AW–2014 has the following form:

$$F = 15,103 \frac{D_R^2}{\eta_F} \cdot \left( \ln \lambda + 4f \frac{L}{D_R} \right) \cdot \text{arg sinh} \left\{ \left[ 3,9303 \cdot 10^{-10} \cdot \ln \lambda \cdot \frac{v_r}{D_R} \cdot \exp\left( \frac{22396}{273,15 + T} \right) \right]^{0,2967} \right\} \tag{14}$$

Based on the proposed mathematical model for calculation of the extrusion force in extraction of semi-products made of aluminium alloy EN AW–2014, the calculations of the following technological constants were made:

– friction coefficient f = 0,20
– extrusion efficiency $\eta_F$ = 0,40
– chamber diameter $D_R$ = 160, 200, and 250 mm

**Fig. 1** shows the comparison of the influence of the extrusion temperature on the extrusion force in the dependence on the extrusion ratio, while the chamber diameter is the parameter. The temperature significantly influences the maximum required installed force of the extrusion press.

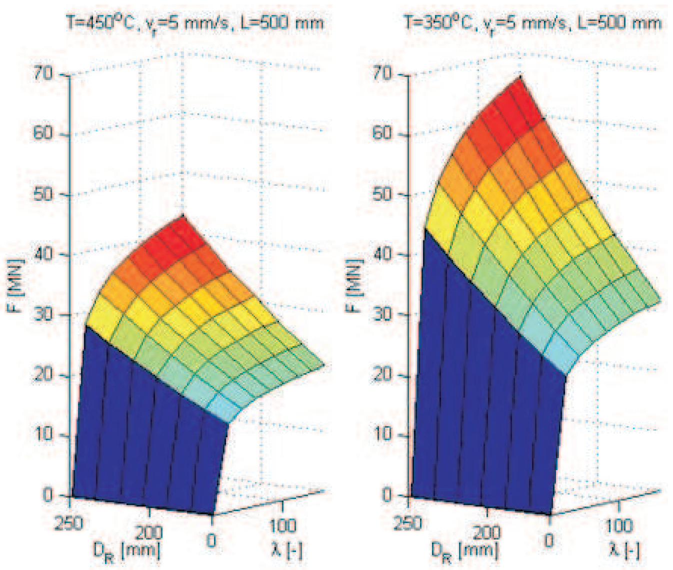


Fig. 1. The influence of the extrusion temperature on the extrusion force

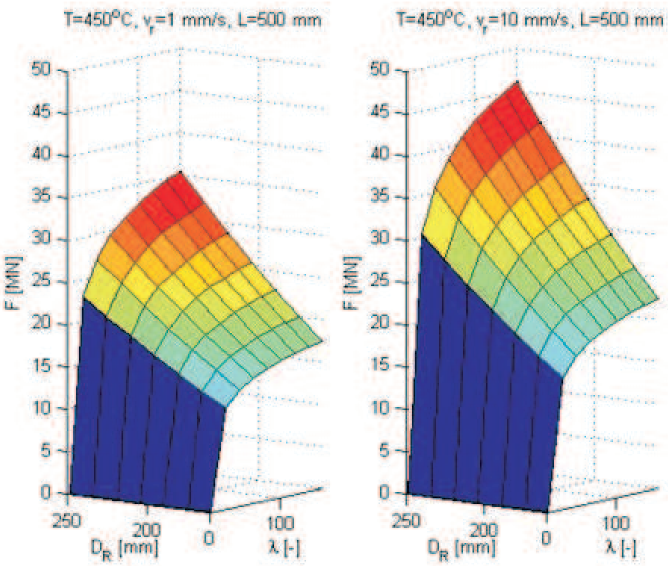


Fig. 2. The influence of the plunger rate on the required extrusion force

The influence of the extrusion rate (plunger rate) on the required extrusion force is shown in **Fig. 2**. Particular technological parameters for which the visualization of the extrusion force was made are always shown in the respective graph. The output rate of the extruded piece from the die is described by the following equation:

$$v_v = \lambda \cdot v_r \tag{15}$$

*where:* $v_v$ *– output rate of the extruded piece from the die* $[m \cdot s^{-1}]$

$\lambda$ *– extrusion ratio [-]*

$v_r$ *– plunger rate* $[m \cdot s^{-1}]$

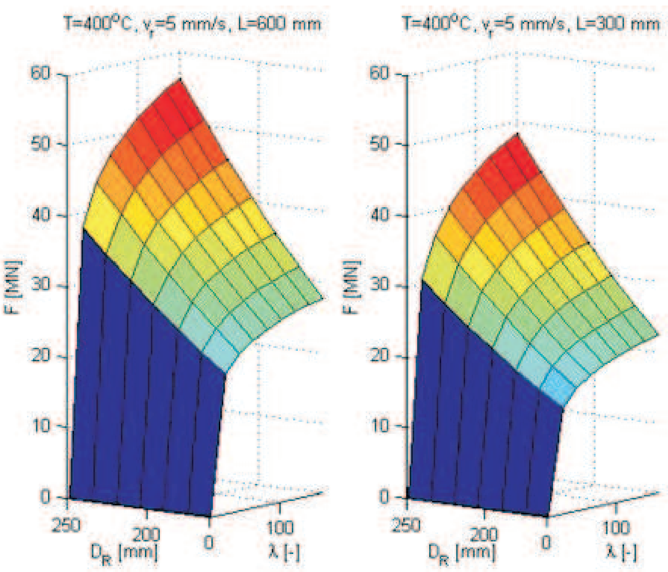


Fig. 3. The influence of the billet length on the extrusion force

The extrusion force is also significantly influenced by the billet length, see **Fig. 3**. Here it should be noted that the billet diameter must be less than the chamber diameter. In the technological practice billet diameter is determined from chamber diameter after the following equation:

$$D_B = D_R - 5[\mathrm{mm}] \tag{16}$$

*where:* $D_B$*– billet diameter [mm]*

$D_R$*– chamber diameter [mm]*

The above-mentioned difference between the chamber diameter and the billet diameter, 5 mm, will ensure that even after heating the billet to the extrusion temperature it can be smoothly inserted into the chamber.

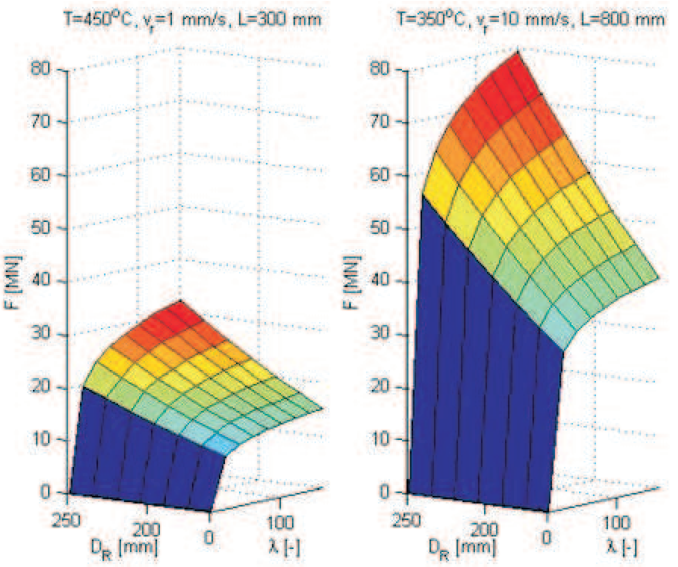


Fig. 4. The limit conditions for the extrusion force

The last pair of graphs, **Fig. 4**, indicates the limit conditions that can occur during extrusion. The minimum extrusion force $F_{min}$ is achieved at the higher extrusion temperature T=450°C, the plunger rate $v_r$=1 mm/s, and the billet length L=300 mm. The upper limit of the extrusion force $F_{max}$ is determined under the following conditions: extrusion temperature T=350°C, plunger rate $v_r$=10 mm/s, and billet length L=800 mm. It results from the two model cases that the ratio of $F_{max}/F_{min}$ ratio is >2.5.

## 4. Conclusion

The aim of the paper was to create a mathematical model to describe the yield stress and then to calculate the extrusion force for hot extrusion of aluminium alloy EN AW–2014. For the determination of the yield stress, an experiment was made, which was based on the mechanoplastic torsion test. For the results of the mechanoplastic torsion test, material constants of aluminium alloy EN AW-2014 were calculated and introduced into the equation (9), while the resulting equation describing the calculation of the yield stress got the following form:

$$\sigma_P = 19,23 \cdot \arg\sinh \left\{ \left[ \frac{\dot{\varepsilon}_{st}}{1,5266 \cdot 10^{10}} \exp\left( \frac{22396}{273,15 + T} \right) \right]^{0,2967} \right\} \tag{17}$$

The equation describing the calculation of the extrusion force based on $\sigma_p$ is expressed in the following form:

$$F = 15,103 \frac{D_R^2}{\eta_F} \cdot \left( \ln \lambda + 4f \frac{L}{D_R} \right) \cdot \arg\sinh \left\{ \left[ 3,9303 \cdot 10^{-10} \cdot \ln \lambda \cdot \frac{v_r}{D_R} \cdot \exp\left( \frac{22396}{273,15 + T} \right) \right]^{0,2967} \right\} \tag{18}$$

The calculation of the extrusion force was made for particular operating conditions (T=350-450°C, $v_r$= 1-10 mm/s, L = 300-800 mm), which resulted in graphs representing F = f ($D_R$, $\lambda$, T, $v_r$, L).

The above-described mathematical equations (12, 14) make it possible, based on experimental results from the precise mechanoplastic torsion test, to calculate the extrusion force for changing operating conditions, or to assess the possibilities of using the press from the viewpoint of achieving the nominal force, as well as in designing new extrusion equipment.

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