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RESEARCH INTO THE TECHNOLOGICAL PROCESS OF EXTRUSION-TYPE FORGING OF AUTOMOTIVE WHEEL MADE OF MAGNESIUM ALLOY PRODUCED WITH THE HELP OF LOADED-DIE

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Abstract

The presented paper deals with the manufacturing of the automotive wheels. It focuses on the effect of the forging die geometry on the loading conditions during the hot forging of the preform of the wheel. The investigation within the scope the paper has been done on the basis of the finite-element (FE) modelling. It was carried out by means of the FE commercial codes QFORM-2D/3D.

The FE modelling of the hot forging of the preform of the wheel showed the potentiality of the chosen scheme of the combined extrusion-type forging with the help of a loaded-die. The relationships between the geometrical parameters of the die and the technological parameters of the forging were established on the basis of numerical simulation.

Key words: Mg alloy, automotive wheel, safety factor, extrusion-type forging, FEM, hot forging

1. INTRODUCTION

Modern sport- and racing cars are equipped by the light-weighted wheels. As the material of a wheel one of known non-ferrous materials can be used for the wheel production, i.e. Al-alloys, Mg-alloys or composite materials. Application of the Mg-alloy as a wheel's material allows to reduce its weight significantly. From the technological aspect, there are at least five technologies of the automotive wheels production. These are casting under low pressure, thixoforming or semi-solid forming, hot extrusion type forging, hot forging with split dies, combined process of sheet forming and welding. For sport- and racing cars the preferable technological process for the manufacturing of the wheels is hot forging.

To choose the proper technological scheme of wheel forging, it should be emphasized the quality of a forged part of the wheel, its mechanical and maintenance properties as well as the economical benefits of the technology. The great impact on the mechanical and maintenance properties has the geometry of the wheel in its longitudinal section as it was shown in (Basyuk et al., 2010). Changing in the geometry of the longitudinal section of the wheel tends to the increase in the safety factor of the wheel up to 17 %.

The objective of the present paper is to investigate the effect of the geometry of loaded-dies for forging of a preform of the magnesium wheel on the

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loading conditions during forging at elevated temperature. It is considered that the material of the wheel is magnesium alloy MA2-1 of chemical composition given in table 1; the physical properties of the alloy are presented in table 2. The alloy is produced in accordance with the Russian standard and it is similar to *AZ31* alloy. The research within the scope of the paper has been done on the basis of the computer simulation by commercial code QFORM-2D/3D (Biba et al., 1994; Levanov et al., 1976).

Table 1. *Chemical composition of the alloy.*

Mg-alloy	Percentage, %										
	Mg	Al	Si	Mn	Ti	Zn	Fe	Ni	Cu	Be	Ca
MA2-1 (appr. AZ31)	base	3.5	0.15	0.22	0.1	0.88	0.05	0.005	0.05	0.02	0.1

Table 2. *Physical properties of the alloy.*

Density, kg/m^3	Linear expansion coefficient at 20-100°C, $\alpha\times10^6$, 1/°C	Thermal conductivity, W/(m·K)	Specific heat capacity, kJ/(kg·K)	Specific resistance, $r\times10^9$, Ω·m
1790	26	83.8	1.05	120

Elastic modulus, 10^4 MPa	Yield strength $\sigma_{0,2}$, MPa	Ultimate strength σ_B, MPa	Elongation, δ, %
4.2	160	265	12

2. NUMERICAL SIMULATION

QFORM-2D code is based on the flow formulation where the independent variables are velocity vector and mean stress. In rigid-visco-plastic model the material is considered as incompressible, isotropic continuum and elastic deformations are neglected. The effective stress is a function of the effective strain, effective strain-rate and temperature. Friction model describing contact friction on the die surface proposed by Levanov (Levanov et al., 1976) is used in the QFORM-2D.

Numerical simulation by means of QFORM-2D was carried out considering that:

1) the flow stress-strain curves of the MA2-1 alloy is defined by isothermal flow curves determined on the basis of the results of the uniaxial compression tests performed under constant deformation conditions for different values of a strain rate as well as a temperature;
2) the isothermal flow stress-strain curves (figure 1) were derived from the load-displacement data as described in (Petrov, 2010);
3) the load-displacement data were obtained after the compression of the cylindrical specimens of the MA2-1 alloy at temperature of 390°C as well as 430°C and under constant strain rate of 0.001 s^{-1}, 0.01 s^{-1} and 0.4 s^{-1};
4) initial temperature of the workpiece is constant and equal to 400°C;

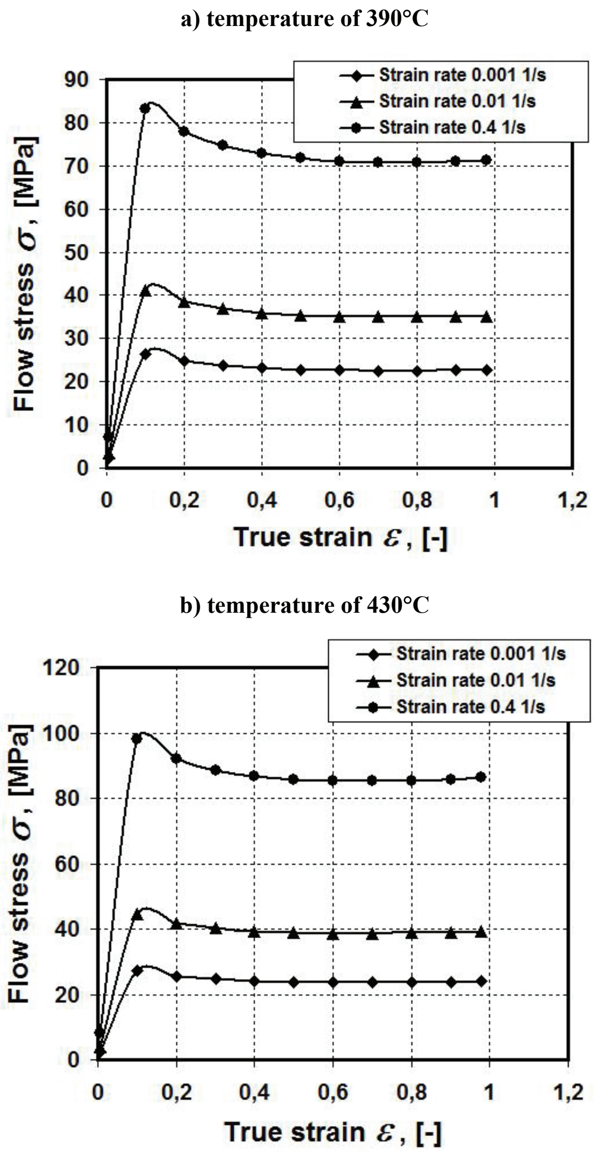
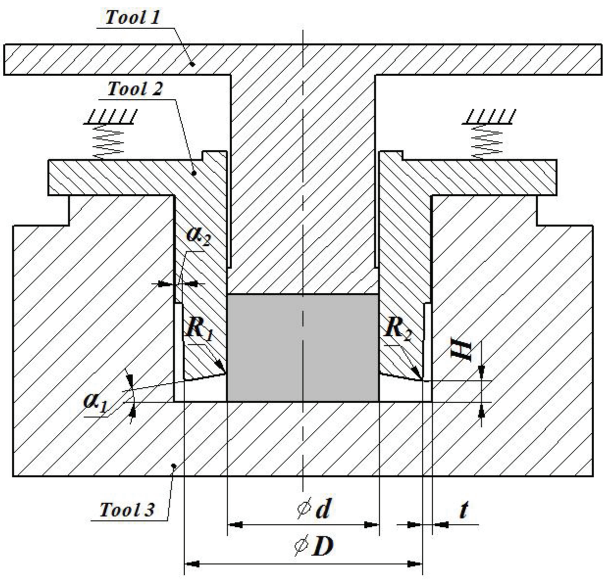
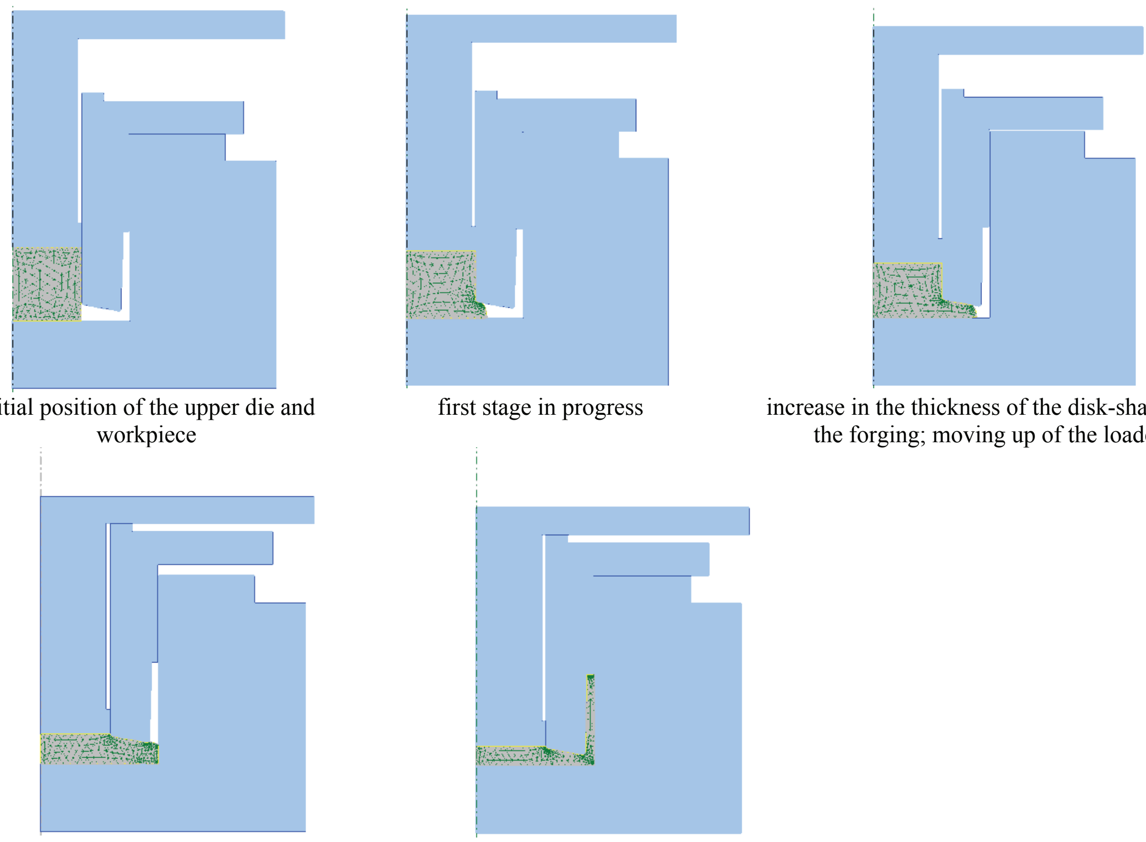


Fig. 1. *Isothermal flow stress-strain curves of MA2-1 alloy.*



a) drawing of the die set (Basyuk, 2009)



initial position of the upper die and workpiece

first stage in progress

increase in the thickness of the disk-shaped part of the forging; moving up of the loaded-die

beginning of the second stage

end of the second stage

b) FE model of the process

Fig. 2. *Scheme of the hot forging of a preform of the magnesium wheel.*

5) temperature of dies is constant and equal to 400°C during the deformation;
6) effective heat transfer coefficient of the lubricant is 1750 W/(m^2·K);
7) since the forging of the investigated shell is an axisymmetric process, the forming process is simulated for a half of workpiece (figure 2);
8) a hydraulic press with die velocity of 2.0 mm/s is used for forging.

The peculiarity of the investigated forging process is connected to the kinematic of one of the upper tools. The central upper tool (punch) is a rigid tool moving in the longitudinal direction from top to bottom. The second tool presented on the scheme (see figure 2) is the loaded-die. The position of this tool depends on the contact pressure on the interface between the deformed material and die. If the back pressure is less than contact pressure, the loaded-die moves up. Otherwise, the position of the loaded-die does not change or it moves down.

The die filling occurs due to the material extrusion in three directions, i.e. the radial, the backward and the forward directions. Considering that, the material flow is divided into the following two stages:

1) First stage – *extrusion in the radial direction* (see figure 2b) – starts from the first contact between the upper die (punch) and the workpiece and lasts till the complete filling of the bottom cavity, which is formed between the clamping tool and the lower die. At the end of the first stage the extruded material contacts the wall of the container (see figure 2b). It should be noted that the thickness of the disk-shaped part of the forging increases during the material extrusion in the radial direction. It occurs due to that the back pressure is applied to the loaded-die (Tool 2, see figure 2a). When the contact pressure on the interface becomes greater than the back pressure applied to the loaded-die, the loaded-die starts to move up till the contact with the rigid part of the punch. The presence of the contact between the loaded-die and the punch (Tool 1, see figure 2a) gives rise the initiation of the second stage of the process under study.
2) Second stage – *extrusion in the backward direction* (see figure 2b) – starts after the contact of the deformed material with the container as well as the contact of the loaded-die moving up with the rigid punch and lasts until the complete filling of the cavity, which is formed between the die and the container.

3. RESULTS AND DISCUSSION

The effect of the die geometry as well as the effect of friction on material flow were investigated numerically only. The variational parameters were the following (see figure 2a): 1) draft angle α_1 of the end surface of Tool 2; 2) height H defining the lowest point of the end surface of Tool 2; 3) back force applied to Tool 2; 4) friction factor of the lubricant covered the surface 1 on the Tool 2 (figure 3). The value of the effective heat transfer coefficient of the lubricant is assumed as constant. The numerical values of these parameters are given in table 3.

Table 3. *Variational parameters value.*

Angle α_1,	Back force F applied to Tool 2, MN
7°; 10°	0.1; 0.2; 0.3
Height H, mm	Friction factor k_n on surface 1 (see figure 3)
2; 3.5; 5; 7	0; 0.22; 1

One of the peculiarities of the forging process under study is the kinematic of the Tool 2. The other feature of the process deals with the abrupt change in the strain rate when the deformed material flows through the radius R_2 (see figure 2a) and the vertical wall of the part starts to form (see figure 2b). This flow corresponds to the beginning of the second stage of the investigated process.

The kinematic of the Tool 2 depends on the die geometry, the value of friction factor on the surface 1 (see figure 3) and the value of the back force F. On the other hand, it has a great impact on the material flow during the first stage of the investigated process. This effect can be defined by the ratio of areas S_0/S_1 (figure 4).

The parameter $S_0 = 0.25\pi d_0^2$ defines the cross-section area of the cylinder of diameter d_0 related to the height h_0 (see figure 4). The area $S_1 = \pi d_1 h_1$ is defined by the area of the surface of the cylinder related to the diameter d_1 and the height of h_1 (see figure 4). The area d_1 depends on the height h_1 which changes due to the displacement of the Tool 2. Hence, the value of S_1 changes with the change in h_1. The material flow depends on the value of the H_i to H_0 ratio, where H_0 = initial height of the workpiece defines the initial position of the Tool 1 (see figure 7a); H_i = current height of the deformed material defines the position of the Tool 1 in regard to the bottom of the Tool 3.

Figure 5 illustrates the typical plots which characterize the effect of the H_i to H_0 ratio on the value of the ratio of S_0/S_1 for different values of friction factor k_n as well as the back force F. The plots presented in the figure 5 correspond to the fixed die geometry of $H = 5$ mm and $\alpha_1 = 7°$ (see figure 2a).

The change in the ratio of S_0/S_1 is analysed till the appearance of the contact between the extruded material and the wall of the container (see figure 6). The plots in the figure 5 illustrate the investigated effect till the moving up the Tool 2.

Figure 8 illustrates the effect of back force on the thickness (height) of the disk-shaped part of the forging at the beginning of the displacement of the

Tool 2 up. The initial stage of the moving up of the Tool 2 is estimated by the H_n/H_0 ratio where H_n = the height of the part at the beginning of the moving up the Tool 2 (see figure 7).

Figure 9 shows the dependence between the ratio of S_{1K}/S_{1H} and position of the Tool 2 defined by the ratio of S_0/S_{1H}. The ratio of S_{1K}/S_{1H} defines the change in the value of S_1. The value of S_{1K} is the cross-section area which corresponds to the contact between the extruded material and the vertical wall of the container (see figure 6).

Squared dark points correspond to the FE modelling of the process. Each of these points refers to one numerical computation by means of QFORM-2D code. The solid lines correspond to the regression of the obtained results by polynomial functions. Each of the FE simulations was carried out for fixed set of the variational parameters (α_I, H, F, k_n) (table 3). The parameters α_I, H define the ratio of areas S_0/S_{1H}.

Figure 10 illustrates the typical force-time relationship, which characterizes the forging process. Peculiarity of the investigated process is linked to the abrupt increase in the forming load (Petrov et al., 2010). This increase happens between the 8th and 9th seconds of the deformation (see figure 10). The increase in the forming load happens due to the abrupt increase in the strain rate, which occurs when the deformed material flows through the section A-A (see figure 11) being extruded to the vertical cavity of the die due to backward extrusion. The value of strain rate $\dot{\varepsilon}$ increases over 10 times after the section A-A.

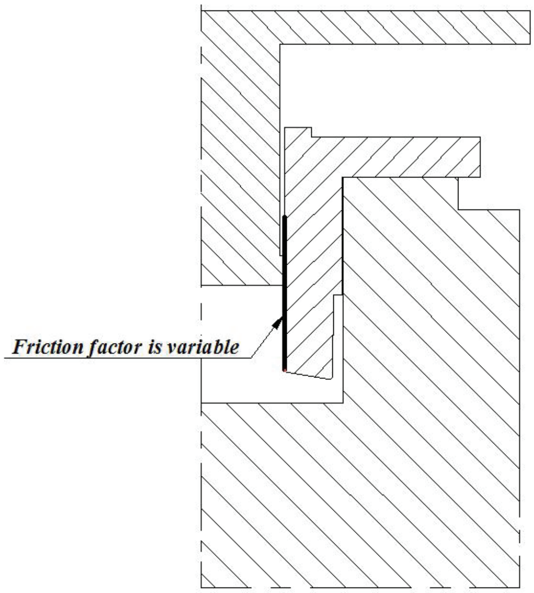


Fig. 3. Scheme for FE simulation of the forging process.

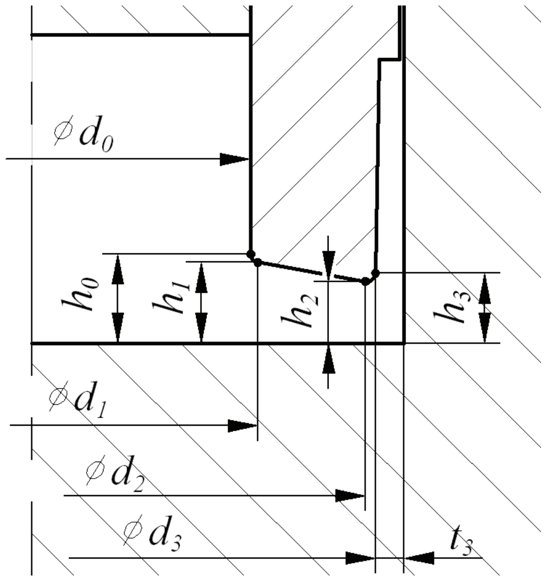


Fig. 4. Scheme for the definition of the cross-section areas.

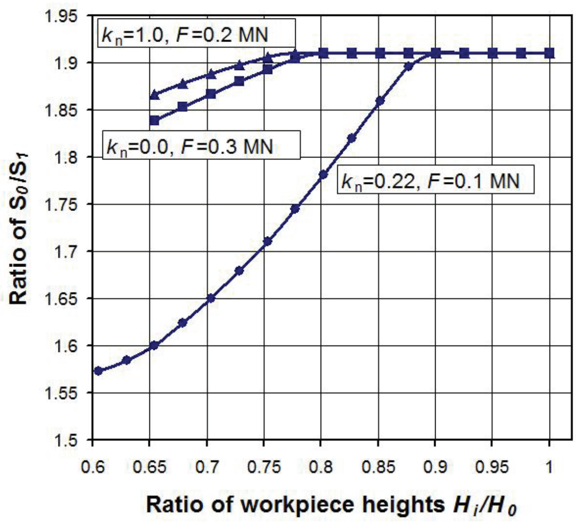


Fig. 5. Plot of the ratio of cross-section area versus ratio of workpiece height (for die set with H=5 mm and α_I=7°).

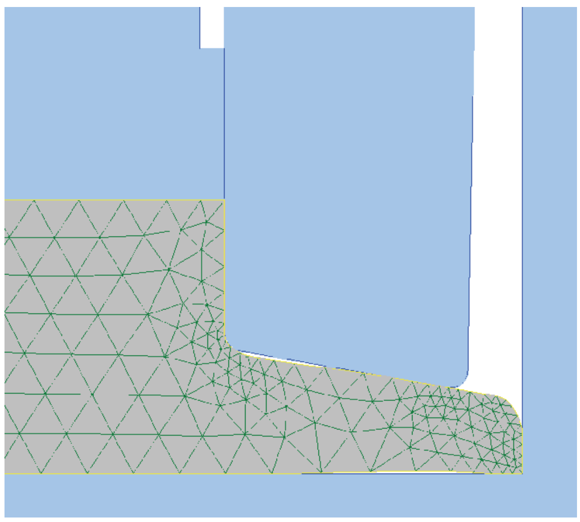


Fig. 6. Scheme of contact between the material and Tool 3.

The ratio of S_3/S_2 has an influence on the value of the strain rate of a material point flowing through the section A-A as well as the change in strain rate $\Delta\dot{\varepsilon}$. The $\Delta\dot{\varepsilon}$ is calculated from the formula:

$$\Delta\dot{\varepsilon} = \dot{\varepsilon}_{csr} / \dot{\varepsilon}_{before}, \qquad (1)$$

where $\dot{\varepsilon}_{crs}$ = strain rate of a material point, which flows through the section *A-A*; $\dot{\varepsilon}_{before}$ = strain rate of the material point before its flow through the section *A-A*.

The parameter $S_2 = \pi d_2 h_2$ defines the area of the surface of the cylinder related to the diameter d_2 and the height h_2 (see figure 4). The area $S_3 = \pi(0.5d_3+t_3)^2 - 0.25\pi(d_3)^2$ is related to a conditional ring, which is formed due to the dissection of the vertical cavity by the horizontal plane at the height h_3 (see figure 4). The ratio of S_3/S_2 changes when the Tool 1 and Tool 2 move down. It causes the decrease in the $\Delta\dot{\varepsilon}$. The plot shown in the figure 12 illustrates this effect.

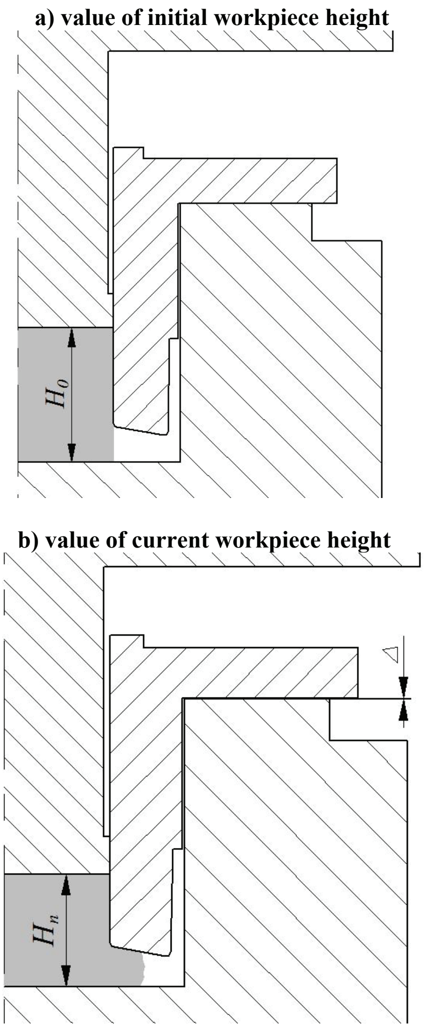


Fig. 7. *Scheme of definition of the height.*

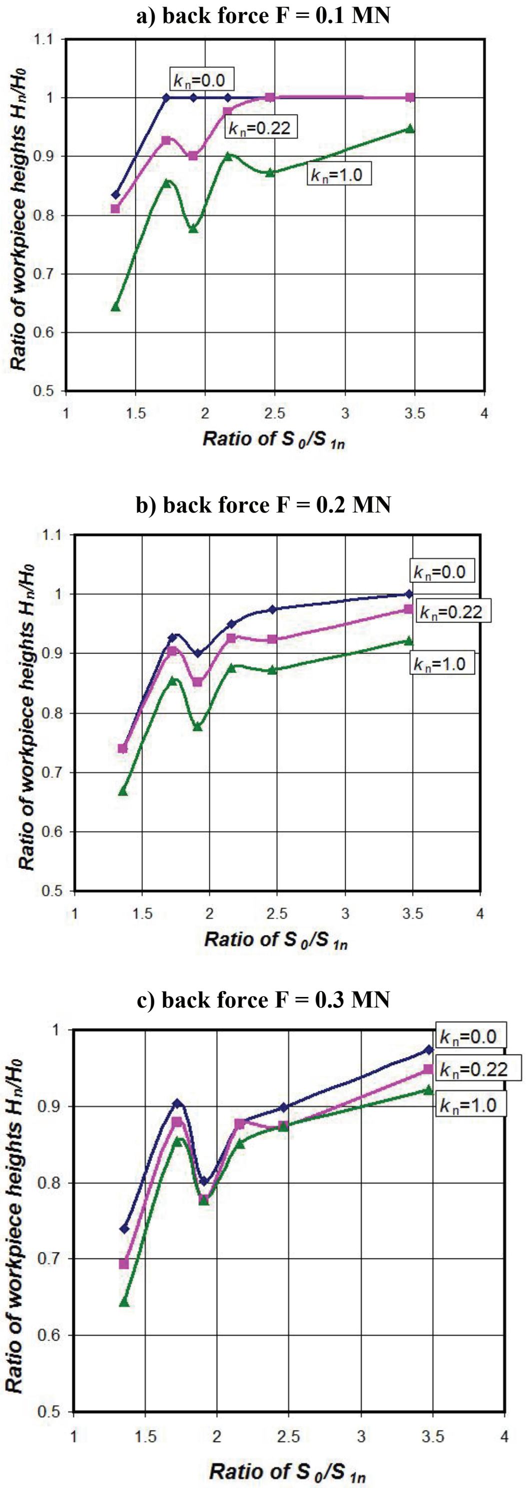


Fig. 8. *Effect of back pressure on the thickness (height) of the disk-shaped part of the forging.*

4. CONCLUSIONS

This paper presents the results of the investigation of the possible technological scheme of forging of a preform of the magnesium wheel. It is shown that the ratios S_0/S_1 as well as k_n and F are the major parameters, which allow to control the material flow during the extrusion type forging with the help of the loaded-die according to the scheme «radial extrusion» – «backward extrusion».

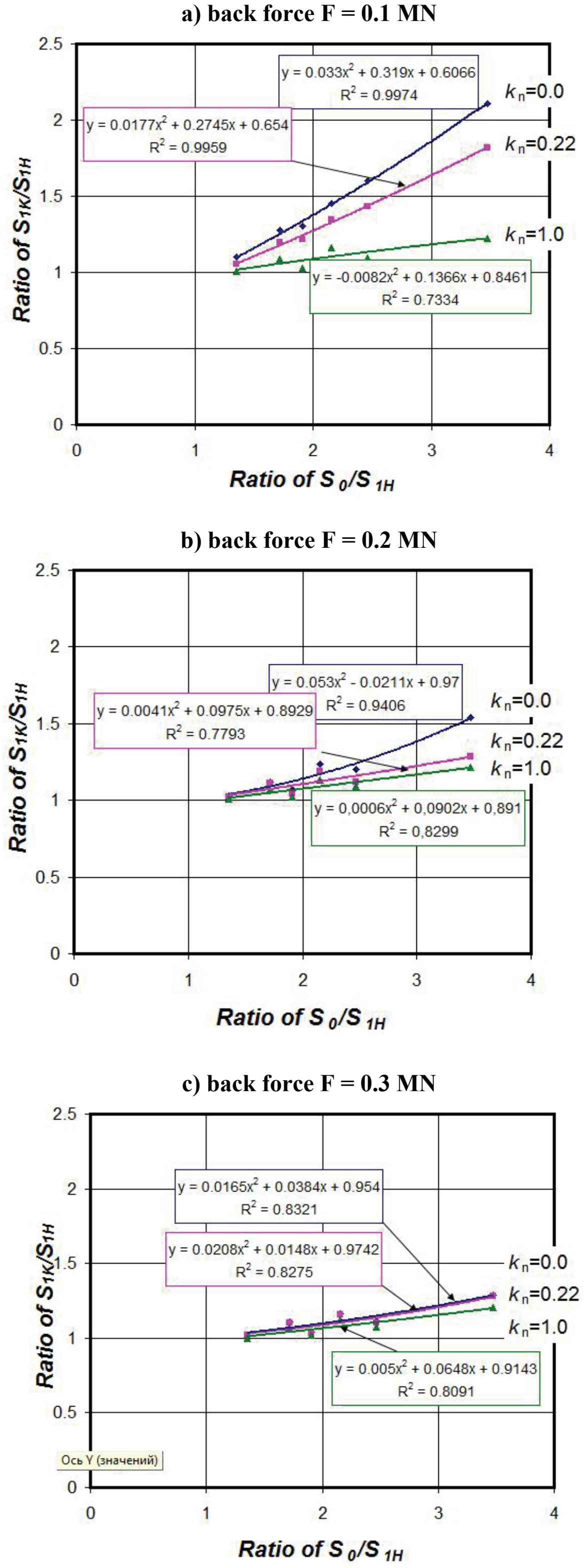


Fig. 9. Effect of back pressure on value of S_1.

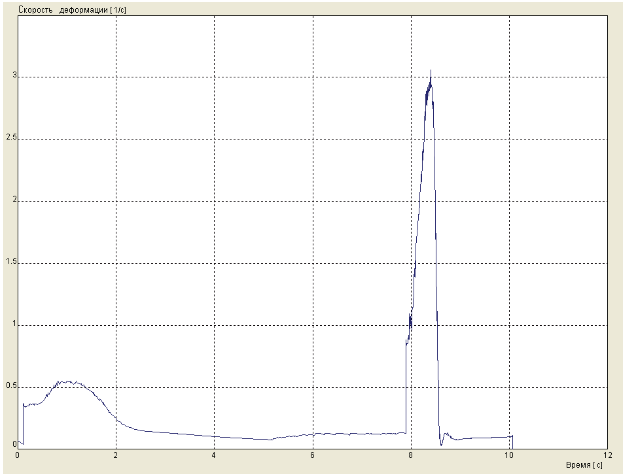


Fig. 10. *Typical plot of the force versus time of the forming process (α_1=7°, α_2=1°, H=5 mm).*

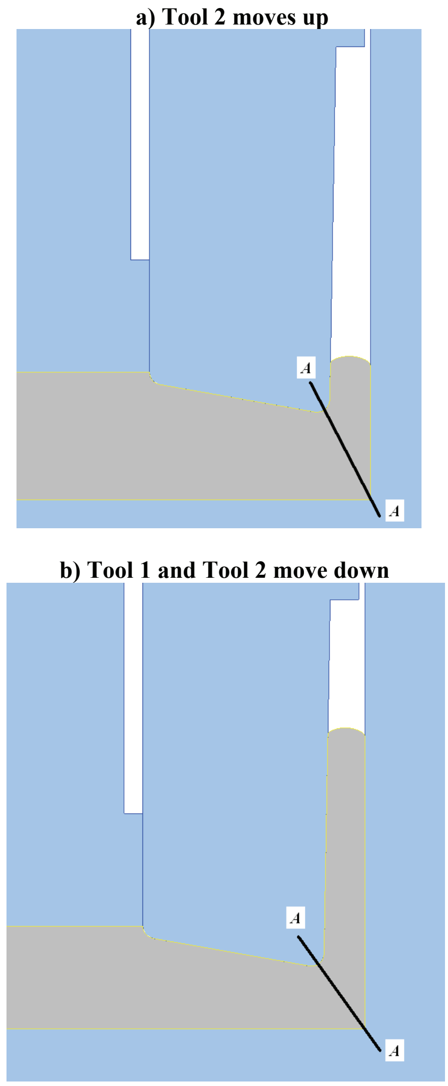


Fig. 11. *Kinematic of material flow through the section of A-A.*

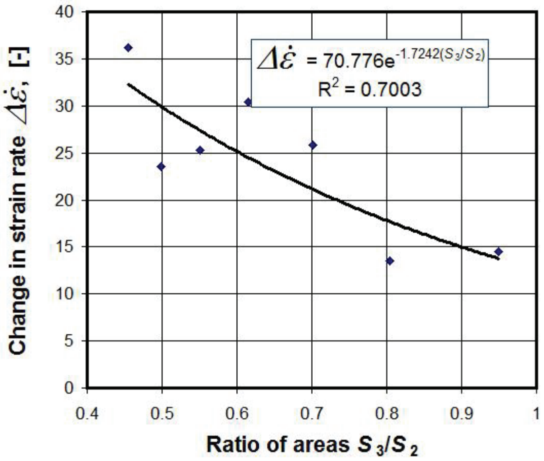


***Fig. 12.** Plot of change in strain rate $\Delta\dot{\varepsilon}$ versus S_3/S_2.*

The analysis presented here can be extended to include more complex material flow during the hot forging of shell-shaped parts. This can be relevant for the numerical simulation of the combined extrusion-type forging with the help of the loaded-die in accordance with the scheme «radial extrusion»-«simultaneous backward and forward extrusion». This scheme has more potentialities in comparison with the investigated scheme of forging.

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BADANIA PROCESU TECHNOLOGICZNEGO WYCISKANIA-KUCIA FELGI SAMOCHODOWEJ ZE STOPU MAGNEZU WYTWARZANEJ WE WSTĘPNIE OBCIĄŻONEJ MATRYCY

Streszczenie

Artykuł dotyczy wytwarzania felg samochodowych. Badany jest wpływ kształtu matrycy na siły w procesie kucia na gorąco. Do badań wykorzystano komercyjny program MES QFORM-2D/3D. Symulacje kucia felgi samochodowej pokazały potencjalne możliwości kombinowanego procesu wyciskania-kucia we wstępnie obciążonych matrycach. Wyznaczone zostały zależności pomiędzy kształtem matrycy i parametrami technologicznymi kucia.

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