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Development and research on near net shape forging technology of round part with flange made of aluminium alloy A95456

This paper describes the development of isothermal enclosed die forging technology of an aluminium part with flange. The optimum conditions of forging were obtained by means of FEM simulation. That allowed the production of parts without defects and with defined mechanical properties. Moreover, the new technology ensures the reduction of forging force and the improvement of die filling. The dies for experimental forging were designed according to the results of FEM simulation. The presented results of experimental forging indicate that isothermal enclosed die forging allows the formation of round parts with flange.

The development of any technological process of bulk forging requires the solution of the following tasks: 1) choose the forging method or forming process; 2) design a forging part in according to machined part; 3) determine the necessary amount of forging operations; 4) determine the size and shape of workpiece; 5) design forging dies; 6) choose the suitable press-forging equipment and lubrication; 7) try out experimentally the developed technology and if necessary make some modifications. Thus the main disadvantages of any forging process design are its complexity and labouriousness.

Recently in the forging industry there is a strong tendency to decrease the time of preproduction, the cost of the forged part and, at the same time, to improve the quality of the parts [1]. Without the knowledge of the influence of variables such as friction conditions, material properties, workpiece and forging part geometry on the metal flow, it would not be possible to design the dies adequately or to predict and prevent the occurrence of forging defects such as laps, folds etc [2]. The application of CAD/CAM/CAE systems for design and investigation of metal forming processes allows the achievement of these goals [3, 4, 5 etc.].

Generally the numerical simulation of metal forming processes is carried out by means of the finite-element method (FEM) [6, 7, 8]. In the application of FEM to metal forming, there are two formulations, namely, flow formulation and solid (elastic-plastic) formulation. The flow formulation neglects the elastic response of the deformed material, while the solid formulation includes elasticity [2]. As shown in [2] both formulations agree with each other very well with only minor differences. The comparison was carried out for metal forming processes such as ring compression [2, 9], forging and rolling [9].

The selection of formulation for the simulation of the forming process depends on the objective of the simulation, its computational efficiency, solution accuracy and reliability. The solution reliability is a major concern. It can only be determined by comparing predictions with experimental studies. The determination of reliability depends on how closely the boundary conditions and material behavior are defined for the concerned physical problem.

At present there are a number of FEM systems to numerically investigate the forging process. QFORM-2D/3D is one such system [10, 11 etc.]. QFORM-2D/3D (QuantorForm Ltd., Russia) uses the flow formulation for material behavior. The estimation of the QFORM simulation results was carried out in several works [12, 13]. The analysis of these papers shows the good compatibility between the results of numerical simulation and experimental data.

The present paper applies QFORM-2D for the development and investigation of new forging technology of the round part with flange. The axisymmetric part with flange made of aluminium alloy A95456 is shown in Figure 1.

Conventionally such parts are formed in dies so that the flow of metal from the die cavity is restricted. As a result flash appears around the forging part at the die parting line. The closed-die forging with flash has several disadvantages: 1) large material loss in flash and in cutting; 2) large values of deformation load; 3) too many technological operations; 4) complicated and expensive machining. As a result it is necessary to choose powerful press-forging equipment.

In case of forging the round part with flange the technological process includes two forging operations such as finishing forging and clipping of flash. The weight of the

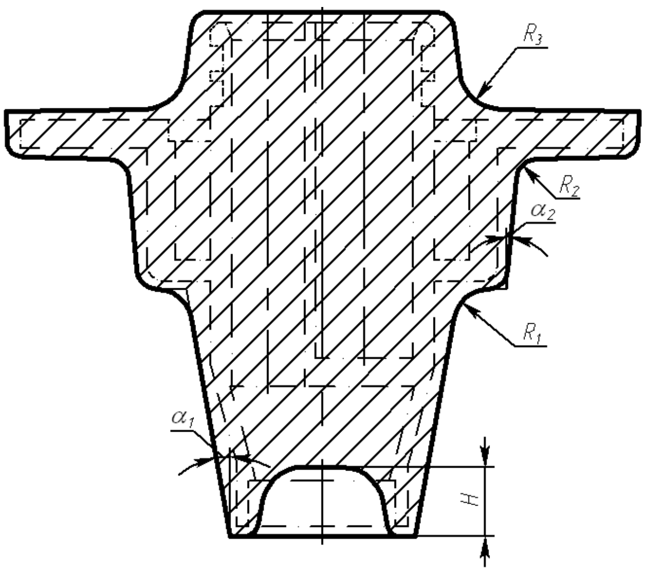

Fig. 1: Drawing of forged part (chain line corresponds to machined part)

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workpiece is about 0.85 kg while the weight of the machined part is equal to 0.2 kg. Because of that the closed-die forging of the above mentioned part leads to large material losses and time-consuming machinery.

The disadvantages of this process can be overcome by the application of near net shape (fully-enclosed die) forging. Moreover the forging must be carried out in isothermal conditions.

Practical implementation of isothermal near net shape forging has become available with the development of heat resistant tool materials. Isothermal forging has several advantages over hot bulk forging. Here they are: 1) uniform temperature distribution; 2) lower deformation load due to lower strain-rate; 3) high material plasticity due to full relaxation and diffusion healing of micro pores. In turn it allows to reduce allowances, fillet radii and draft angles when a forged part is designed and consequently to reduce the cost of machining and material losses.

On the other hand, in case of fully-enclosed forging the material flow is more complicated and difficult to predict. The forging defects such as laps, folds, non-filling of dies and dead regions tend to appear, which results in the production of defective forging parts. On account of this disadvantage the numerical simulation of appropriate forging technology is necessary. The choice of optimum forging conditions can be done on the basis of the results of numerical simulation.

In this paper the development of isothermal near net shape forging technology of the round part with flange is presented. The main objective of the forging process design is to ensure adequate metal flow in the dies so that the desired finished part geometry can be obtained without defects and with advanced mechanical properties. The investigation of the isothermal forging is carried out by means of QFORM-2D simulation. Then the experimental forging is conducted for the optimum conditions selected.

Numerical simulation

Finite-element formulation. QFORM code is based on flow formulation where independent variables are velocity vector and mean stress. In rigid-visco-plastic model the material is considered as incompressible, isotropic continua and elastic deformations are neglected. The constitutive equation is used to describe the material flow:

$$\sigma_{i'j} = \frac{2}{3}\frac{\overline{\sigma}}{\dot{\overline{\varepsilon}}} \bullet \dot{\varepsilon}_{ij} \quad (1)$$

where σ_{ij} = the stress tensor components, $\overline{\sigma}$ = the effective stress (flow stress), $\dot{\overline{\varepsilon}}$ = the effective strain-rate, $\dot{\varepsilon}_{ij}$ = the strain-rate tensor components.

The effective stress depends on effective strain ε, effective strain-rate $\dot{\overline{\varepsilon}}$ and temperature T and can be expressed by

$$\overline{\sigma} = \overline{\sigma}(\overline{\varepsilon},\ \dot{\overline{\varepsilon}},\ T) \quad (2)$$

The effective strain-rate and effective strain are defined as follows

$$\dot{\overline{\varepsilon}} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij} \cdot \dot{\varepsilon}_{ij}}\ ,\quad \overline{\varepsilon} = \int_0^t \dot{\overline{\varepsilon}}dt \quad (3)$$

where $\dot{\overline{\varepsilon}}$ = the strain-rate tensor components.

The friction model describing contact friction on the die surface proposed by Levanov [14] is used in QFORM and can be written as

$$\tau = m\left(1 - exp\left(-1{,}25\left(\sigma_n/\sigma_{T.K.}\right)\right)\right)\frac{\sigma_{T.K.}}{\sqrt{3}} \quad (4)$$

where m = friction factor, σ_n - contact pressure in given point of contact surface, $\sigma_{T.K.}$ - yield stress of layer in sample near contact surface with die.

The virtual work-rate principle and finite element technique are used to obtain the non-linear system of algebraic equations describing the material forming process. The system includes such equations as equilibrium equation, compatibility equation, constitutive equation as (1) and incompressibility. The energy balance equation is treated by means of weighted residual method (Galerkin's method) resulting in a system of ordinary differential equations that is integrated numerically. The indices i and j, for two-dimensional problems, vary from 1 to 2. Velocity and mean stress fields are approximated by quadratic and linear shape functions respectively within the 6-node triangular elements with curved sides. Finite-element mesh is generated and regenerated automatically. The details of the algorithm can be found in [15].

Since the forging of round part with flange is an axisymmetric process, therefore the forming process is simulated for a half of workpiece in QFORM-2D.

Material. The material of the forging part as mentioned above is aluminium alloy A95456. The chemical composition is given in **Table 1**.

Table 1: Chemical composition of alloy A95456

Element	Percentage
Cu	0.04
Si	0.16
Mn	0.63
Mg	6.80
Ti	0.1
Zn	0.2
Fe	0.22

Lubricant. Colloidal graphite mixed with industrial oil can be used as a lubricant for isothermal forging of aluminium alloy, in particular, alloy A95456. The friction factor of this lubricant can be determined by means of ring compression. This technique is the simplest, most reliable and widely used. The friction factor was defined within the temperature interval of isothermal forging of aluminium alloy A95456. The investigated temperatures were 430°C, 450°C and 470°C. The sizes of samples were: inner diameter - 20 mm, outer diameter - 40 mm, height - 14 mm. The investigation was carried out in the following sequence.

The ring samples were heated to the required temperatures in the electric furnace. The deformation of the heated samples was carried out with flat dies warmed with an induction installation to the same temperature as the samples. Before compression the samples had been covered with the above mentioned lubricant. They were compressed to about 50% from the initial height. Die velocity was constant and equal to 2.0 mm/s (hydraulic press, 2.5 MN), that corresponds to the following initial strain rate – 0.14 s^{-1}.
The values of height h_k and inner diameter d_{in} were determined after the compression of rings. The inner diameter was measured in three locations along their height. Finally, the value of inner diameter was determined as $d=(d_{top}+d_{mid}+d_{bot})/3$, where d_{top}, d_{mid}, d_{bot} = inner diameter at the top, in the middle and bottom along the height of the ring accordingly.

The values of friction factor for appropriate temperatures were determined numerically by means of QFORM-2D/3D simulation. The obtained friction factors are given in **Table 2**.

Table 2: Friction factor values for alloy A95456

Temperature, °C	Friction factor
430	0.155
450	0.116
470	0.14

Investigated scheme of forging. The analysis of the part drawing (see Fig.1) shows that the die filling occurs due to material extrusion along the part axes, namely, forward and backward directions, and in the radial direction. The radial material flow provides flange filling. So, the metal flow during extrusion is very complicated and will depend on the following parameters: 1) die geometry; 2) workpiece dimensions; 3) temperature conditions of deformation and so on.

In general these parameters influence the distribution of the effective strain and flow stress in the deformation area and especially the forming load. In turn it will affect the mechanical properties of forging part. To choose the optimum forging conditions several simulation trials were conducted.

On the first stage the effect of die geometry was investigated. The variational parameters were the following (see Fig. 1): 1) draft angle α_1; 2) draft angle α_2; 3) radius R_1; 4) radius R_2; 5) radius R_3; 6) rough draft height H. The numerical values of these parameters are given in **Table 3**.

Table 3: Variational parameters value

Parameter	Value
Angle α_1	7°30′; 10°
α_2	1°; 3°; 5°; 7°
Radius R_1	1; 3; 5
R_2	1; 3; 5
Radius R_3	2.5; 4; 6; 8; 10
Depth H	2; 5; 7; 10; 15; 20

On the second stage the effect of forging temperature was examined. The FE simulation was conducted for some possible forging temperatures of alloy A95456 - 430°C, 450°C and 470°C. The die temperature was chosen to correspond to the workpiece temperature. So that three possible cases of the isothermal forging of round part were examined to investigate the effect of temperature on the material flow.

On both stages the hydraulic press was used for simulation of round part with flange forging. The ram speed was constant and equal to 2.0 mm/s. The flow curves for alloy A95456 were taken from handbook [16].

Evaluation of the simulation results

Effect of die geometry. The analysis of FEM results shows that the parameters α_1, α_2 and R_1, R_2 only weakly influence the material flow as well as the strain-stress state parameters and the forming load while the radius R_3 and height H have a strong effect on them.

The minimum value of α_1 is equal to 7°30′ (see Table 3). It provides the forging part with a minimum machining allowance. However its value is not reduced further, because it causes cutting of some part of the component in machining. At the same time the value of the angle α_2 can be taken as minimum, i.e. 1° (see Table 3).

On the other hand the parameter R_3 affects the material flow during forging significantly. It may cause the appearance of a lap in the flange area. The shape and size of the

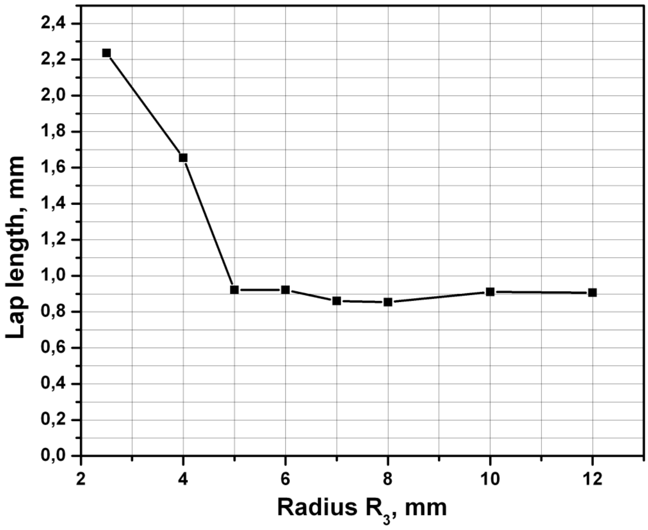


Fig. 2: Plot of the lap length versus radius

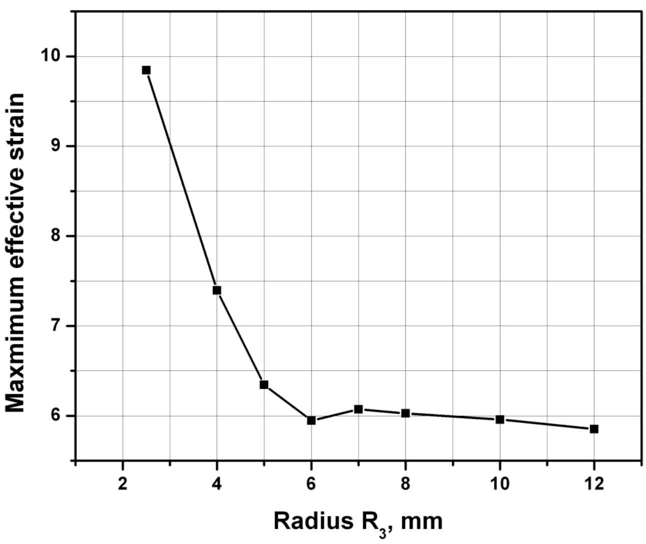


Fig. 3: Plot of the maximum effective strain versus radius

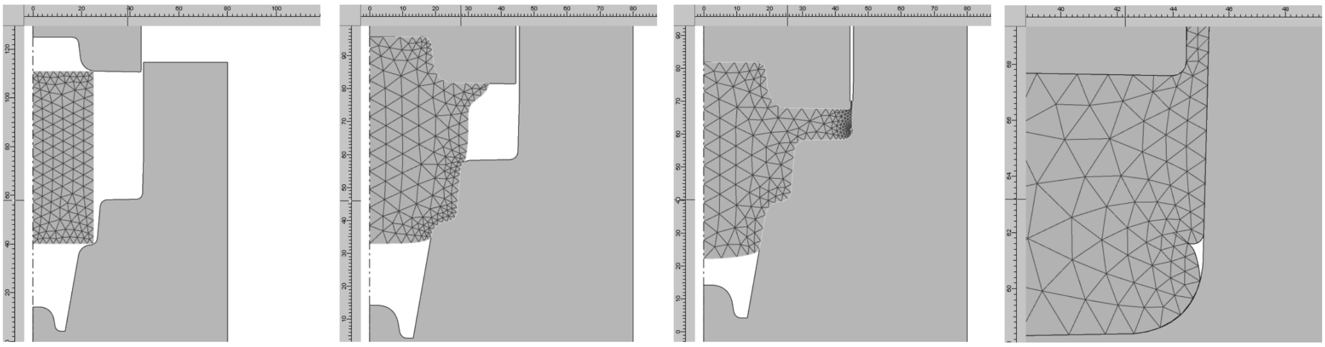


Fig. 4: Stages of metal forming process: a – initial position; b – intermediate stage; c – intermediate stage with lap; d – lap (magnified view)

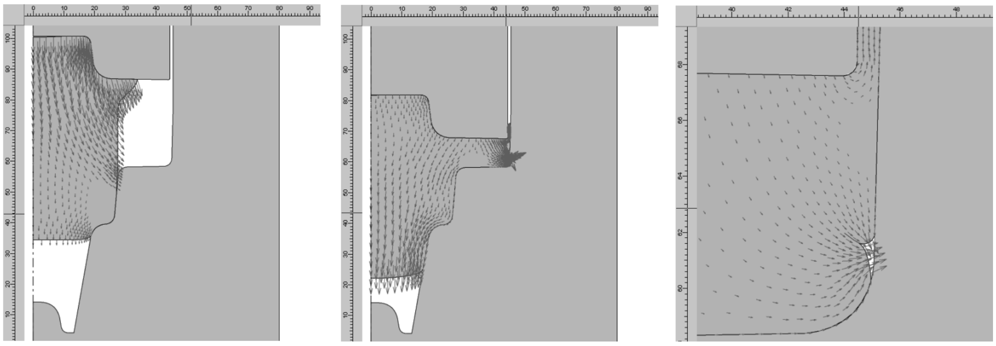


Fig. 5: Velocity distributions in isothermal near-net shape forging: a – initial position; b – intermediate stage with lap; c – lap (magnified view)

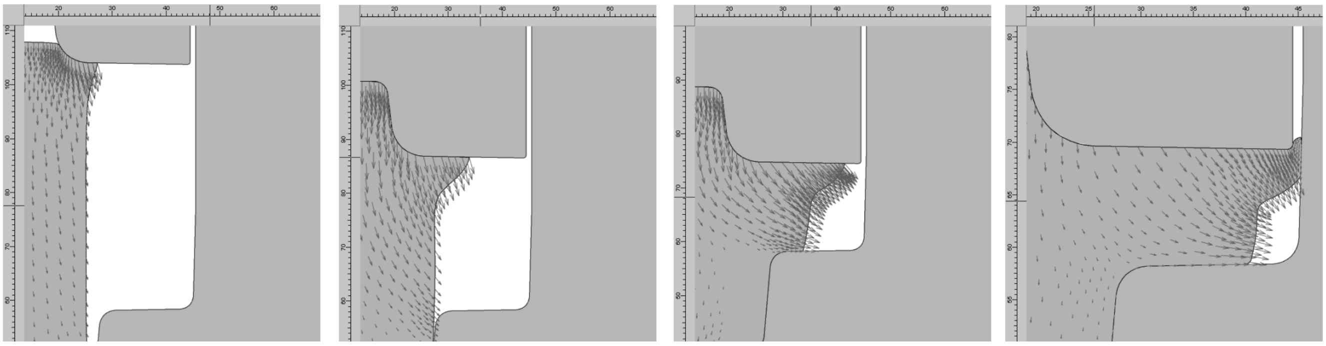
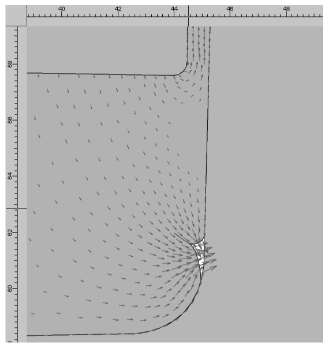


Fig. 6: Lap formation in forging process: a, b, c, d – stages of lap formation;



e – lap (magnified view)

defect depends on the value of parameter R_3. The proper choice of its value allows a reduction of the lap size (**figure 2**).

It should be noted that the size of lap decreases considerably when the radius R_3 changes from 2.5 mm to 5 mm. After that the curve for lap length vs. radius is sensibly constant. The lap size in the part cross-section was calculated on the basis of the FE simulation results.

At the same time increase in the value of radius R_3 causes displacement of lap to the front flash region (see **Fig. 4**) and decrease in the value of effective strain in the area of radius R_3 (**Fig. 3**). These results were obtained numerically.

Figure 4 shows the metal-flow patterns at various upper die displacements. Numerically calculated velocity distributions are given in Fig. 5. As seen from the figure when the cavities of dies are substantially filled, the material starts to flow through the gap between the upper and lower dies, and a flange is formed. The velocity distributions in the flange area are different for upper and lower dies (see Fig. 5). It results in lap formation. The stages of lap formation process are shown in Fig. 6.

The front flash is the excess material which is extruded through a gap between upper and lower die. This gap provides the sliding of dies with respect to each other. The value of gap was over 0.715 mm (see **Fig. 7**).

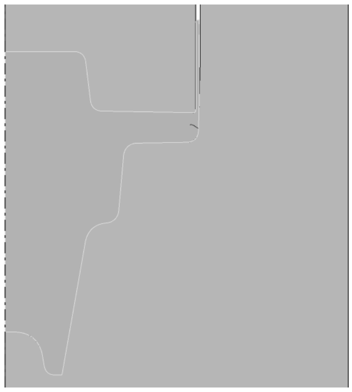
Another interesting feature in the forming process under study is the effect of the rough draft height on the value of deformation load. **Figure 8** shows the curve load vs. rough draft height that was plotted on the basis of the finite-element simulation results. From this figure it can be seen that the significant change in load occurs when the height H exceeds 12 mm.

Such a change in load can be explained on the basis of power balance equation [17] which can be written as

$$W_P = W_\varepsilon + W_\tau + W_\Delta \quad (5)$$

where W_P = external power, W_ε = internal power in the deforming volume, W_τ = power of friction forces, W_Δ = power on the surfaces of velocity discontinuity.

The larger rough draft height H increases the volume of metal undergoing shear deformation and the length of the lower die. It results in an increase in the friction power W_τ. On the other hand the values W_ε and W_Δ remain unchanged. According to eq.(5) the value of the external power will increase as well as the forming load.



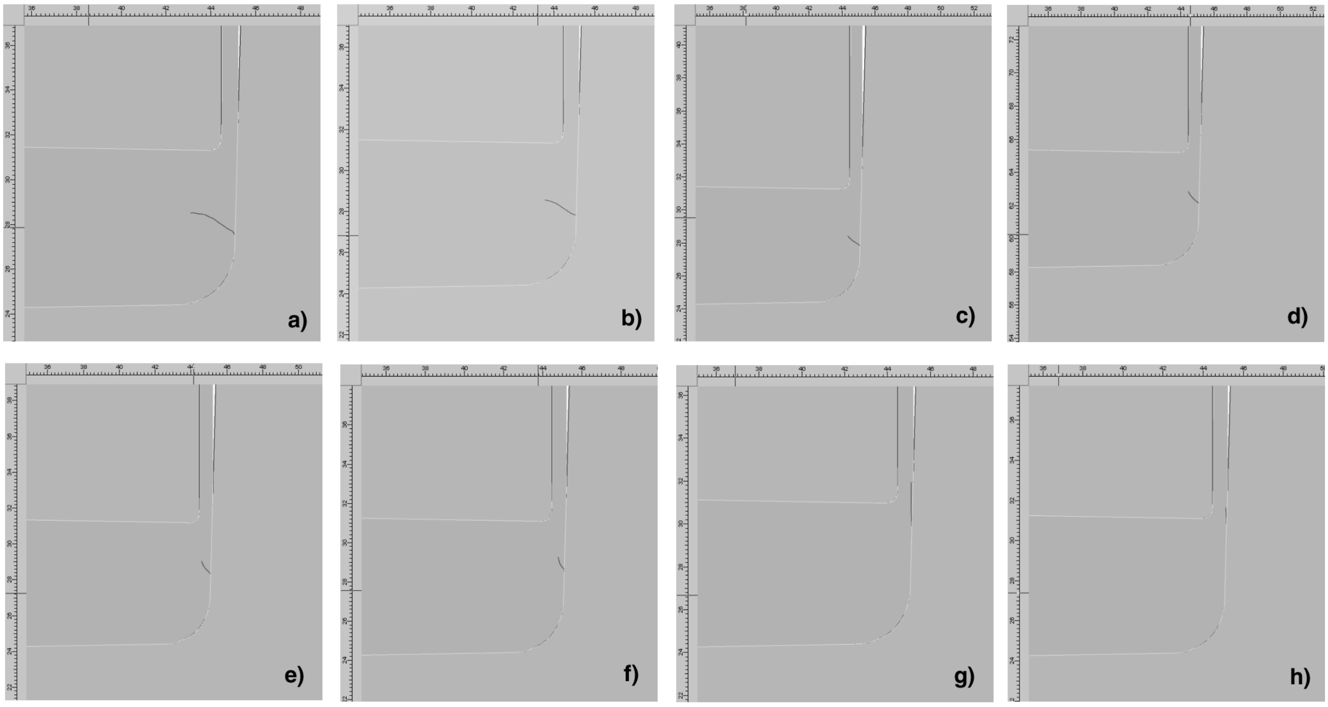


Fig. 7: Shape of lap for different radii:
a – R_3 = 2.5 mm;
b – R_3 = 4 mm;
c – R_3 = 5 mm;
d – R_3 = 6 mm;
e – R_3 = 7 mm;
f – R_3 = 8 mm;
g – R_3 = 10 mm;
h – R_3 = 12 mm

Effect of temperature. The results of the temperature effect on the simulation are shown in **Fig. 9**. It is seen that the temperature of the workpiece and correspondingly the dies temperature influence the forming load. The die velocity was constant and equal to 2 mm/s in all trials.

Generally the forming load depends on part geometry, friction and flow stress. In turn the flow stress of a metal is influenced by temperature, degree of deformation and rate of deformation. The increase in temperature gives rise to decrease in friction (see Table 2) and decrease in flow stress. Therefore, the external power W_P and the friction power W_τ

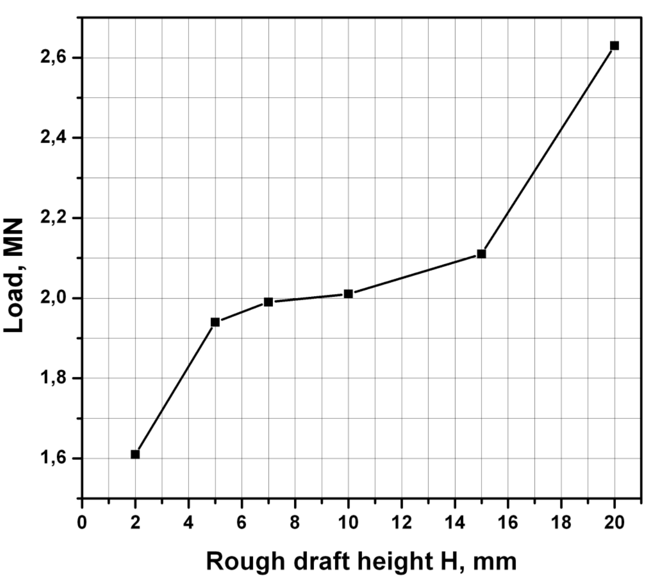


Fig. 8: Load versus rough draft height

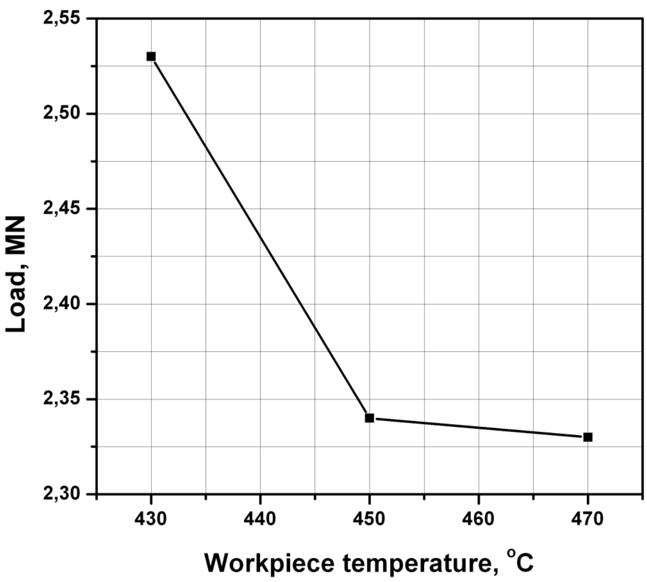


Fig. 9: Load versus workpiece temperature

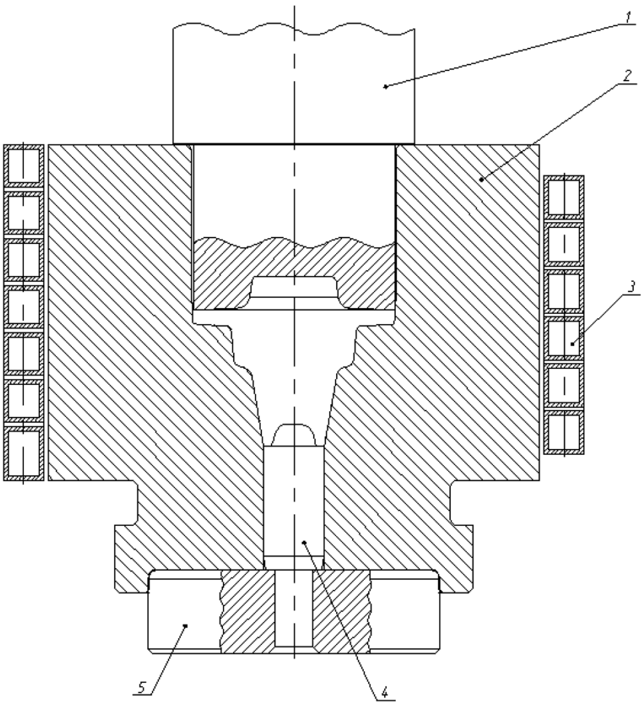


Fig. 10: Schematic view of isothermal enclosed die forging dies.

decrease their values as well as the external power and the forming load in according to eq.(5).

The temperature variation within the forging part is no more then 30.8°C due to heat generation of plastic deformation independently of the initial temperature of the workpiece and the dies. The maximum increase in temperature up to 70°C occurs in the region of the front flash which will be cut during machining.

Experimental study

The FE simulation allowed a determination of the optimum forging condition of forging of round part with flange. On the basis of simulation results the experimental dies were developed. **Figure 10** shows the schematic view of dies for experimental study of isothermal near net shape die forging.

In order to provide the strength and life of parts 1, 2, 4, 5 (see Fig. 10) at the high temperature, die steel 5CrNiMo was selected as their material. An induction heater 3 and temperature control system, installed at the die case, were developed to heat the dies and control the temperature of die. It ensured isothermal conditions of the forging.

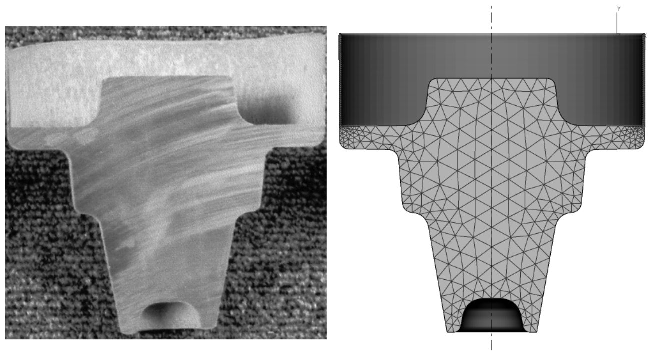


Fig. 11: Forging part with flange: a – experiment; b – FEM.

The hydraulic 2.5 MN press was used for the experimental study. The ram speed was the same as in the simulation trials and equal to over 2 mm/s. The conditions of forging were: 1) temperature of workpiece and dies – 430°C and 470°C; 2) lubricant – graphite mixed with oil provided the friction factor 0.155 at the forging temperature; 3) geometry of lower die 4 – R_1 = 5 mm, R_2 = 3 mm, R_3 = 6 mm, α_1 = 10°, α_2 = 5°, H = 10 mm.

Discussion of results

Figure 11 shows the experimental forging parts. The figure demonstrates that the agreement between finite-element simulation results and experimental observations is good. Moreover the lap has been found experimentally when the temperature of workpiece and dies was equal to 430°C. The experimental forging part with lap and its corresponding FE model are shown in **Fig. 12**. The lap location in the experiment coincides with that predicted theoretically. It should be noted that the microstructural analysis showed that the size of the lap in the cross-section of the part is less than the machining allowance. Consequently, the quality of the product can be produced by means of machining from the forging part with lap obtained at a temperature of 430°C.

The investigation of macrostructure and mechanical properties of forging part material was carried out**. Figure 13** demonstrates the results of macrostructure analysis for the experimental part and its FE model. The comparison between metal flow lines in both cases indicates the correctness of the FEM simulation. **Table 4** includes the mechanical properties of alloy A96456 before and after isothermal forging.

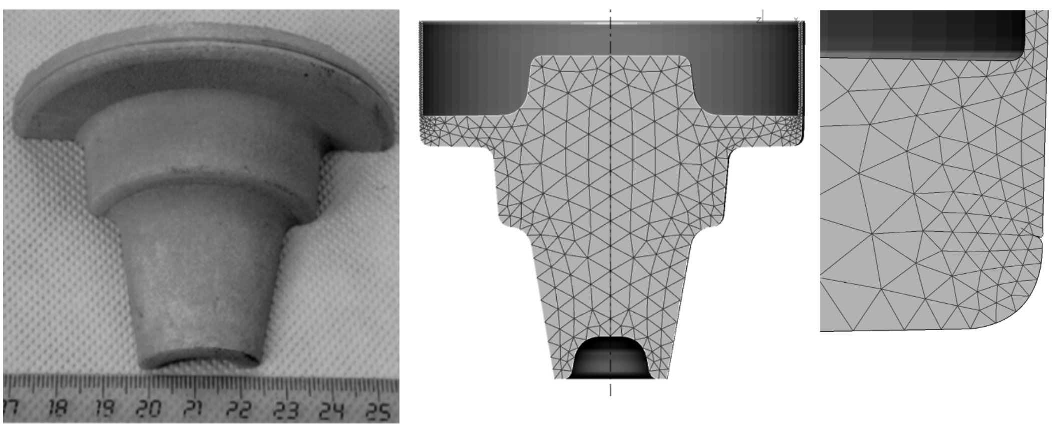


Fig. 12: Lap identification: a – experiment; b – FEM; c – lap (magnified view).

Table 4: Mechanical properties before and after isothermal forging

Parameter	Before	After
Yield strength, MPa	170	184
Ultimate strength, MPa	340	370
Elongation, %	20	17.1

Conclusions

- Experimental investigation and FEM of the isothermal near net shape die forging of part with flange were carried out. The simulation results are in excellent agreement with experiments.
- The developed technology of isothermal near net shape forging allows a reduction in the material loss, machining and manufacturing cost.

Acknowledgements

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References

[1] H. Nägele, H. Wörner, M. Hirschvogel: Journal of Materials Processing Technology, Vol. 98 (2000), p. 171/175.

[2] S. Kobayashi, Soo-Ik Oh, T. Altan: Metal forming and the finite-element method, Oxford University Press, New York, Oxford, 1989.

[3] Z.M. Hu, J.W. Brooks, T.A. Dean: Journal of Manufacturing Science and Engineering, Vol. 121 (1999), p. 366/371.

[4] S. Debin, L. Yan, L. Fang: Research on Isothermal Fully-Enclosed Die Forging of a Rotor with Blade, Proc. 7th Intern. Conf. on Technology of Plasticity, Yokohama, 2002, Vol. 1, p.109/114.

[5] N.V. Biba, S.A. Stebounov, P.A. Petrov, V.I. Perfilov: Development of Near Net Shape Forging Technology Using Three-Dimensional Finite Element Program QFORM 2D/3D, Proc. 5th Esaform Conference on Material Forming, eds, M. Pietrzyk, Z. Mitura, J. Kaczmar, Krakow, p. 395/398.

[6] V. Pidvysotskyy, R. Szyndler, J. Kusiak, M. Pietrzyk: Modelling of Forging of Gear-Wheel Using Reversibly Rotating Die, Proc. 6th Esaform Conference on Material Forming, ed., V. Brucato, 2003, Salerno, p. 943/946.

[7] S. Argentero, C. Testani: Superplastic Forging of AA2618 Aluminium Alloy, Proc. 6th Esaform Conference on Material Forming, ed., V. Brucato, Salerno, 2003, p. 955/958.

[8] A.E. Salienko, A.N. Soldatkin, A.M. Rudis: Forging and Stamping Production, Vol. 4 (2004), p.36/39 (in Russian).

[9] I. Pillinger, P. Hartley, C.E.N. Sturgess, G..W. Rowe: Finite Element Modelling of Metal Flow in Three-Dimensional and Temperature-Dependent Forming, NUMIFORM 86, eds, K. Mattiasson, A. Samuelsson, R.D. Wood, O.C. Zienkiewicz, Gothenburg, publ. A. Balkema, Rotterdam,1986, p. 151/155.

[10] N.V. Biba, A.I. Lishny, O.B. Sadykhov, S.A. Stebunov: Forging and Stamping Production, Vol. 7 (1994), p.12/14 (in Russian).

[11] N.V. Biba, S.A.Stebunov, A.I. Lishny, A.V. Vlasov: New approach to 3D finite-element simulation of material flow and its application to bulk metal forming, 7th Int. Conf. on Technology of Plasticity, Yokohama, 2002, p. 829/834.

[12] S.V. Smirnov, N.V.Biba, S.A. Stebunov: Damage modeling in cold bulk metal forming using adaptive theory, Proc. Esaform Conference on Material Forming, eds, M. Pietrzyk, Z. Mitura, J. Kaczmar, Krakow, 2002, p.139/142..

[13] P.A. Petrov, J. Sinczak, A. Lukaszek-Solek: Hot forging of joint – process modification using three dimensional finite element analyses, Proc. 7th Esaform Conference on Material Forming, ed., S. Storen, 2004, Trondheim.

[14] A.N. Levanov, V.L. Kolmogorov, S.P. Burkin, B.R. Kartak, U.V. Ashpur, U.I. Spasskiy: Contact Friction in Metal Forging, Metallurgia, Moscow, 1976 (in Russian).

[15] N. Biba, A. Lishnij, O. Sadykhov, S. Stebounov: Design and Analysis of Superplastic Forming Technology with FORM-2D System. In: Superplasticity of Advanced Materials ICSAM'94, Material Science Forum, Vol.170-172 (1994), p.667/692.

[16] P.G. Mikliev, Mechanical properties of Light Alloys in Temperatures and Strain Rates of its Forging, Metallurgia, Moscow, 1976 (in Russian).

[17] V.I. Tarnovskij: Variational methods in the mechanics of metal forming by pressure, Proc. 6th Int. Conf. Metal Forming 96, eds, 1996, eds, M. Pietrzyk, J. Kusiak, P. Hartley, I. Pillinger, Krakow, 435/439.

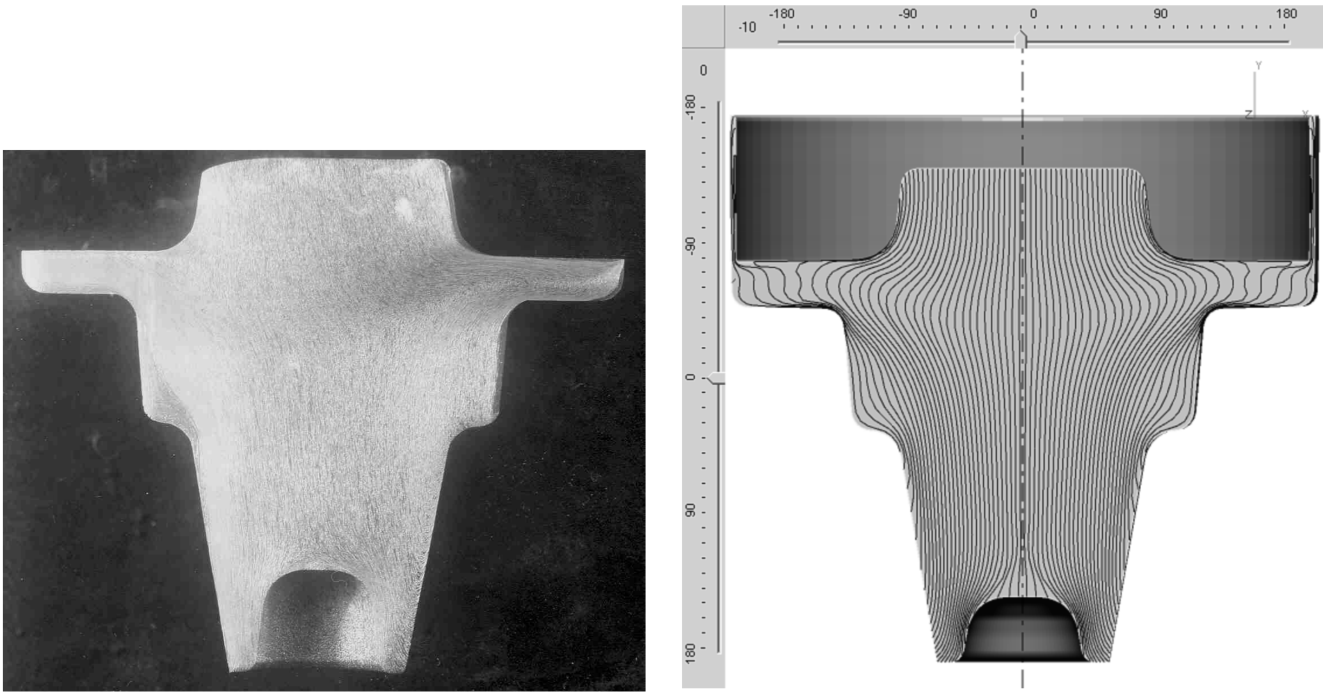

Fig. 13: Forging part macrostructure: a – experiment; b – FEM.