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APPLICATION OF NUMERICAL SIMULATIONS FOR A MULTI-VARIANT ANALYSIS OF THE CONSTRUCTION OF TOOLS ASSIGNED FOR HOT PRECISION FORGING OF SMALL SIZE FORGINGS IN MULTIPLE SYSTEMS

The article presents the results of a complex analysis referring to the possibilities of applying different types of construction of forging dies used on a hydraulic hammer Lasco HO-U 160 in order to select the optimal solution in the aspect of obtaining the required dimension-shape accuracy. The analysis involved the use of the numerical simulation software FORGE 3.0 NxT. 12 different variants were analyzed, of both different tool constructions and detail arrangements on the die (in a quadruple and sixfold system). The effect of the forces as well as the way of material flow and degree of the forging tool seat's filling were verified. The most ergonomic and technologically justified detail arrangement on the die was described. The results of the numerical simulation analyses were presented with the indication of the pros and cons of the particular solutions. The selected solution of the forging tool construction, implemented in a mass production, was especially discussed to verify of obtained FEM results and improvement actual technology.

Keywords: Narrowed tolerance forging; hammer precision forging; forging FEM modelling; forging defects; multiple systems in forging

1. Introduction

Precision die forging is a broadly applied, popular method of producing responsible components of machines and devices for the automotive, agricultural, aircraft and machine-building industry. It makes obtaining products with very good mechanical properties possible, making it competitive with other production technologies [1]. Moreover, the development of the precision die forging technology ensures more and more accurate products, which are then, to a small degree, further mechanically processed and, in extreme cases, not subjected to further subtractive manufacturing [2]. This provides the possibility to deliver forgings directly onto the assembly line, which makes precision die forging more and more desired and developed. It should be noted that hot die forging processes are one of the most challenging production technologies, due to the complicated working conditions, including vibration, dustiness, high temperature, as well as cyclic thermal and mechanical loads [3]. One should also consider the forging aggregate, on which the forging process is realized, as, for a crank, hydraulic or screw press, as well as for steam, drop or hydraulic hammers, the working conditions will be slightly different, which are mainly connected with the deformation rate, vibration, blow energy transfer and load distribution [4]. The state-of-the-art analysis and the literature review suggest that such theoretical differences resulting from the application of different forging aggregates can be important, as, sometimes, even for similar forgings, produced on the same aggregate, we can observe different destruction mechanisms and intensities of their occurrence in time [5].

Additionally, it should be emphasized that forging tools, especially those used in hot precision forging, characterize in unstable and relatively low durability, which, in turn, significantly affects the quality and cost of the forging production [6]. The low durability of the forging tools is caused by the extreme operation conditions existing in the industrial hot forging processes, resulting from a simultaneous occurrence of many complex phenomena and destruction mechanisms. It constitutes a complicated and unsolved problem, both in the scientific and economical aspects. The durability of a tool is expressed by the number of operations which can be carried out by throug this tool obtaining products with the required quality, or the resistance to the operation of destruction mechanisms [7-9]. The classic division of factors affecting the tool's durability considers those connected with the tool itself and those related to the realization of the forging

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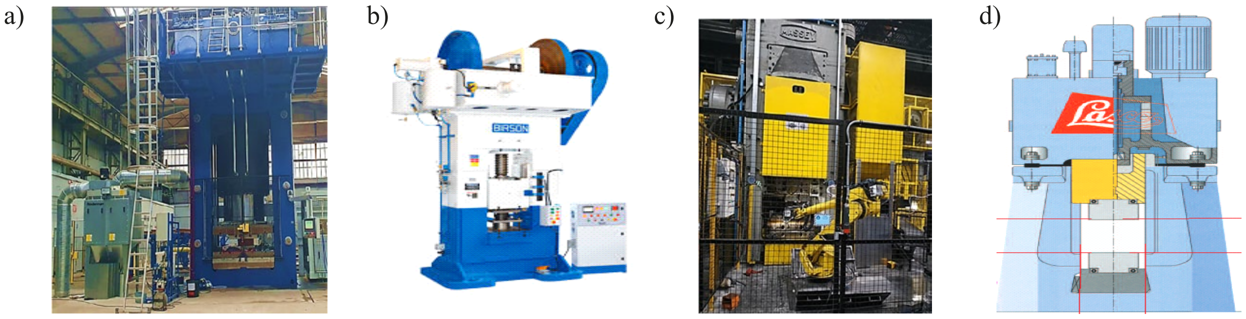
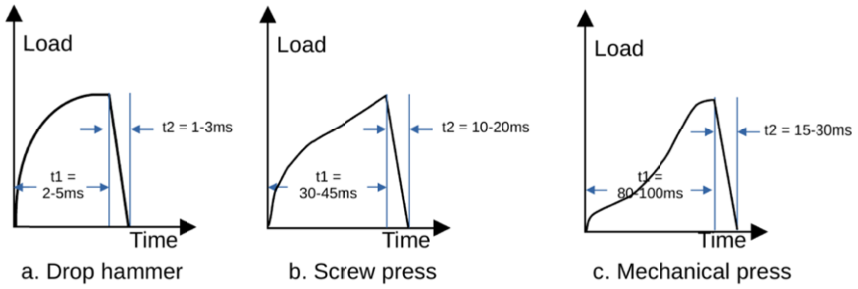


e) t1 - pressure build-up time in milliseconds, t2 - pressure release time in milliseconds



a. Drop hammer b. Screw press c. Mechanical press

Fig. 1. View of: a) exemplary, most often applied forging aggregates: a) hydraulic press, b) screw press, c) crank press, a) hydraulic hammer, e) a comparison of the loading time curves for forging

technology. The former includes: design-construction factors (geometric notches), material factors (anisotropy of the mechanical properties of tool steel, non-uniformity of distribution and size of carbides, microcracks in carbide bands, non-metallic inclusions, pores or the tool's thermal treatment itself). In turn, the factors connected with the technology include temperature of the preform material, tool heating and working temperature, heating rate, atmosphere, type of lubricant, frictional resistances; type and technical state of the device on which the tool works – changes in the way of load application, e.g. on a low rigidity press, clearances in the guiding of the press slide. What is more, designing forging tools for a hot die forging process is well-known and commonly applied, similar to other guidelines for designing such processes [10]. Nevertheless, the source literature provides the general rules of forging tool design for presses and hammers. In the case of precision die forging of geometrically complicated forgings, the use of standard rules of forging tool design can find no application. In many cases, the geometry of a given forging should be approached individually, and this requires a significant commitment on the side of the forge constructors [11]. At present, there are no clear criteria for the assessment or the selection of methods of improving tool durability. We only know the general directions, and each forging process should be analysed separately, as the process parameters resulting from the technology, tribological conditions, and many other factors are strictly related to the given industrial process and so [12,13]. What is also important is the human factor, as, sometimes, despite the high experience and the will to improve the process, the changes introduced by the human can improve one aspect but significantly worsen the others. Thus, if possible, a specific solution is automatization and robotization of the forging process to minimize the human effect [14]. Only an in-depth and complex analysis of the process enables an optimized approach to this issue and points to the main problem in the given process as well as to the key factors deciding about low durability. Currently, the most popular and commonly applied durability improving methods include a proper selection of the tool material for a given process or operation, its thermal and thermo-chemical treatment, surface engineering techniques and optimization of the tool shape and construction [15,16]. Another solution is a choice of conditions and technological parameters, e.g. those related to the determination of the optimal temperatures, the cooling and lubricating agent and the manner of its feed, or the construction-technological solutions, as well as the control and measurement systems, which can constitute unique tool operation supervision systems [17,18]. Also, CAD/CAM/CAE methods are still applied, which aid the production processes, as well as IT tools using artificial intelligence, which often cooperate with the numerical modelling of production processes [19-21]. Because of the above, to avoid time-consuming and costly trials under industrial conditions, specialized programs and calculation packages (based, among others, on FEM, FVM, and others) are used more often for numerical simulations before the manufacturing process [22-25]. They enable verification of the elaborated technology and the tools' design before their production in order to verify the filling of the tool impression, the flow manner and the forging defects, as well as determine the forces and pressures in the tools, the temperature distribution or even the microstructure with a detailed parameters like a grain size [26-30].

The aim of the study is to apply numerical modelling for a complex analysis of the presently realized forging technology in order to improve, through testing, the selected variants of the chosen solutions, including different arrangements of details on the die, different configurations of folding, the use of different charge material diameters and different approaches to the forming of the flash, e.g. into a U-shape, in order to ensure a stable and repeatable course of the technological process.

2. Test subject, scientific problem and research methodology

The subject of the studies is a complex analysis of different types of forging tool constructions for forgings constituting components of window and door fittings (with elevated dimension-shape accuracy) produced in the process of hot precision forging on a hammer in a multiple system. The tests included multi-variant numerical simulations for different arrangements of details on the die, different quadruple and six-fold systems, as well as with the application of different charge material diameters, in order to determine the effect of the charge material size on the forces, the filling of the forging tools' work impressions and an effective use of the charge material. The main aim of the scientific research was the selection of the best solutions, mostly in the aspect of obtaining the required dimension-shape precision and forging quality, and, at the same time, increasing the process efficiency and the durability of forging tools. The 12 different variants of forging tool construction were selected and analyzed for different configurations, which, in the authors' opinion, are the most interesting and have the highest chance of success. TABLE 1 shows the selected solution variants, for which numerical simulations were performed, whereas the colour green is used to mark the variants chosen for a detailed analysis. These 4 out of 12 variants were selected, which, in the authors' opinion, were the best of the solutions, which were additionally verified in industrial conditions.

Out of all the variants, the study presents the results for 4 selected variants, verified under industrial conditions, which differed in the following most important elements:

- numbers of details produced from one bar;
- arrangements of the work impressions on the die;
- application of different diameters of the charge material;
- application of different folding constructions to obtain a high shape-dimension precision of the forgings, including, mostly, the joggle parameter;
- procedures aiming at ensuring stability and repeatability of the forging process;
- number of hammer blows.

2.1. Description of chosen variants

All the tools were designed in the SolidWorks 2022 software according to the rules of forging tool design. Fig. 2 shows a design of forging tools for a quadruple system, in which the elements in the form of forgings are arranged one behind the other. This is variant 1, which is a simple construction solution, making it possible to apply the minimal diameter of the charge material, Ø12. The process should be realized in two blows, one blow on the roughing seat, the other bow on the finishing seat.

Fig. 3 presents variant 4 of a design of forging tools for a quadruple system, in which one element is rotated by 180° in respect of the other, and this solution is duplicated. For this solution, the charge material diameter is also Ø12 mm. The symmetrical position constitutes an advantage, whereas the pins are significantly distanced from the charge material axis. The process should be realized in two blows, one blow in the roughing seat, the other in the finishing seat.

Fig. 4 shows variant 10 of a design of forging tools for a six-

TABLE 1

Variants of forging tools for a bolt forging

No.	Number of elements	Charge material	Charge material temp.	Energy of blow 1 (roughing seat)	Energy of blow 2 (roughing seat)	Energy of blow 3 (finishing seat)
1	4 (arrangement: one behind the other)	Ø12×200 mm	1250°C	50%/8 kJ	NA	45%/7.2 kJ
2	4 (arrangement: one behind the other)	Ø12×200 mm	1250°C	50%/8 kJ	NA	45%/7.2 kJ
3	4 (arrangement: rotated by 180° in pairs of 2)	Ø12×190 mm	1200°C	60%/9.6 kJ	NA	45%/7.2 kJ
4	4 (arrangement: rotated by 180° in pairs of 2)	Ø12×200 mm	1200°C	60%/9.6 kJ	NA	45%/7.2 kJ
5	6 (arrangement: two pairs each, pin axis in shaft axis)	Ø14×250 mm	1200°C	60%9.6 kJ	NA	30%/4.8 kJ
6	6 (two pairs each, pin axis in shaft axis)	Ø16×235 mm	1200°C	80%/12.8 kJ	NA	70%/11.2 kJ
7	6 (two pairs each, pin axis in shaft axis) Additional guiding pins on lower die	Ø16×235 mm	1200°C	80%/12.8 kJ	NA	70%/11.2 kJ
8	6 (two pairs each, pin axis in shaft axis)	Ø15×240 mm	1200°C	77%/12.3 kJ	NA	48%/7.7 kJ
10	6 (two pairs each, pin axis in shaft axis) U-shaped flash	Ø16×235 mm	1200°C	80%/12.8 kJ	70%	45%/7.2 kJ
11	6 (two pairs each, pin axis in shaft axis) U-shaped flash	Ø15×240 mm	1200°C	55%/8.8 kJ	45%	50%/8 kJ
12	6 (two pairs each, pin axis in shaft axis) Inclinations for the detail on prelim-finishing seat for lower die smaller than for upper die	Ø16×235 mm	1200°C	55%/8.8 kJ	NA	25%/4 kJ

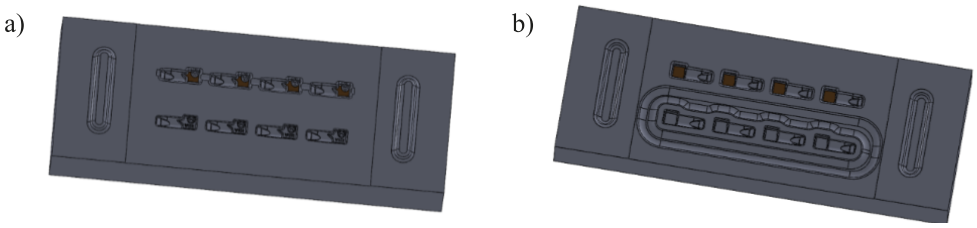


Fig. 2. Construction of the forging tools in the arrangement: element behind element, with folding 10×80 mm: a) lower die, b) upper die

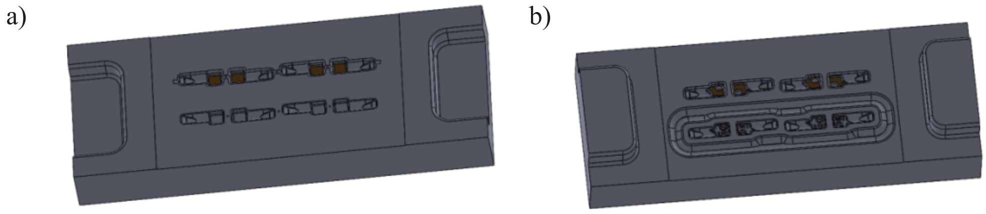


Fig. 3. Forging tool construction in the arrangement: element-element rotated by 180°, with folding 40×90 mm: a) lower die, b) upper die

fold system, which involved three pairs of double elements. This arrangement makes sure that the pin is located in the axis of the charge material. Also, this solution ensures rigidity of the flash, which, during the process, is formed into the U-shape. For this solution, the charge material diameter is Ø16 mm. The process should be realized in three lows: two blows in the roughing seat and one in the finishing seat.

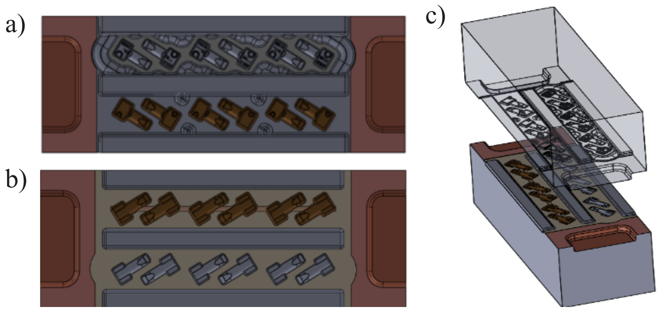


Fig. 4. Forging tool construction in the arrangement: 6 elements rotated by 35° with folding 40×90 mm and bending of the flash into a channel shape: a) lower die, b) upper die, c) 3D view

Fig. 5 shows variant 12 of a design of forging tools for a six-fold system, in which three pairs of double elements are used.

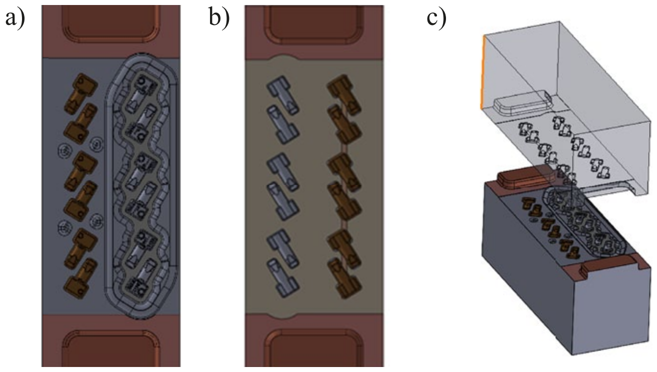


Fig. 5. Forging tool construction in the arrangement: 6 elements rotated by 35° with folding 40×90 mm: a) lower die, b) upper die, c) 3D view

This arrangement ensures that the pin is located in the axis of the charge material. For this solution, the charge material diameter is Ø16 mm. The process should be realized in three blows: two on the roughing seat and one on the finishing seat.

2.2. Process of hot die forging description

The forging production (Fig. 6) is realized in the process of hot precision forging on a hydraulic hammer with the nominal blow energy of 16kJ in open dies, in two seats: the roughing pass and the finishing impression, from a cylinder-shaped bar with the diameter in the scope of 12 to 16 mm, from steel 1.7139, from which 4 or 6 forgings are made at the same time, and whose protruding spigot-type elements perpendicular to the main axis are located in one axis. Forgings of this type are difficult to make due to their complicated shape (the material flows in perpendicular directions) as well as dimension-shape accuracy (low tolerances -0.1mm, radii 0.5mm), and also the forging process realized for multiple systems (a slim, long and thin forged element).

The tools for the forging process are made of steel WNLV with the hardness of about 49-51 HRC, heated to the working temperature of about 150-200°C. The charge material is heated to about 1250°C and next, it is placed in the lower die, in the roughing pass, and reforged in two blows of the upper die with the use of: 50-80% of total energy. Next, it is replaced in the finishing impression (equipped with a repository for the flash) in the lower die, where it is reforged with the blow energy of about 50% (depending on the variant). The forging process is followed by a blow-through of the tools in order to remove the scale and next the tools are lubricated by means of a graphite and water mixture. The most common defects include: twisting of both the whole forged element (so-called leaf) and the spigot type elements (resembling a truncated cone perpendicular to the forging's main axis) in single forgings, made in a multiple system, as well as insufficient filling of these areas in the upper

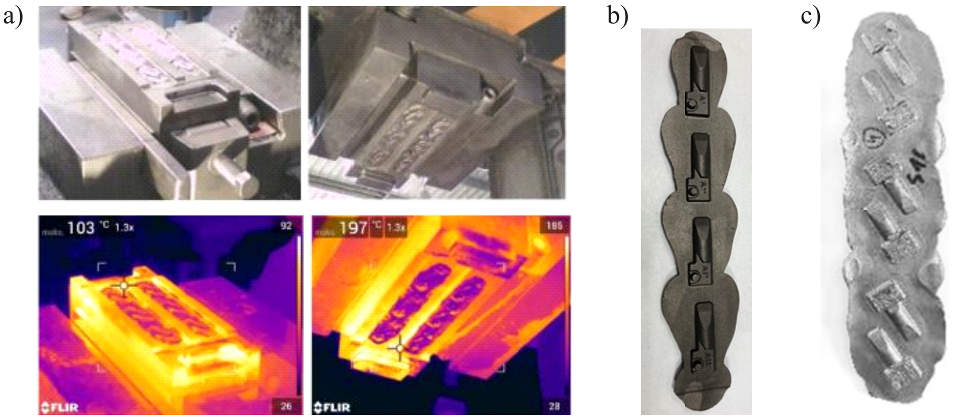


Fig. 6. View of: a) an image of the forging tools with the process thermograms, b) the material arrangement and the consecutive forging phases, c) images of the forgings in a 4-fold system

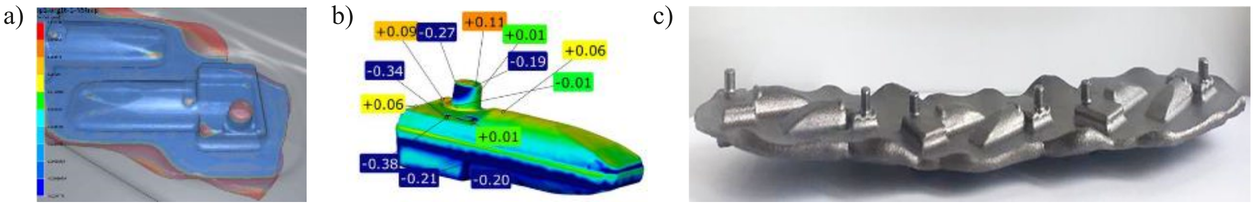


Fig. 7. Image of the main forging defects: a) underfill of the area in the vicinity of the pins b) twisting of the pin, twisting of the whole forged element

part of the spigot (Fig. 7), which also results in lack of a proper radius (0.15 mm) of the rounding at the top of the pin.

The mentioned defects are periodical-random in character, as it happens that, in the whole production series equalling about 500-600 forged elements, the so-called "leaves", there is a total of about 25 single defected forgings, which constitutes about 5% of rejects. The present technology of hot die forging in multiple systems for the analysed assumes forging inclinations for the whole forging equalling 3°, which agrees with the literature data referring to the designing of dies for hammers [16]. The produced forgings are subject to control, both during the initiation of the process and cyclically, about every 100 forged elements, i.e. the so-called "leaves". **For this reason, the conducted multi-variant simulations also aim at solving the above problems.**

2.3. Numerical simulations of different variants of forging tool construction – initial-boundary conditions

The numerical modelling of the forging process was carried out by means of the FORGE NxT 3.0 software. The calculations were realized according to the assumptions mentioned in the section above. The modelling was performed on simplified thermo-mechanical models with rigid tools, and next, the calculation model was gradually expanded. The tool geometries in the particular forging processes were assumed for the calculations based on the CAD models from the section above.

The technical parameters, Young's modulus and the yield stress curves in the function of deformation rate for the charge material, i.e. carburizing steel 16MnCrS5, were preliminarily assumed from the library of the FORGE NxT program. The forming conditions connected with the kinematics of the tool movement were assumed according to the characteristics of the LASCO HO-U 160 hammer with the maximal blow energy of 16 kJ. The initial conditions referring to the initial temperature of the charge material, the tool temperature and the times in the particular processes were assumed according to TABLE 1. The assumed ambient temperature was 50°C.

Presented below are selected results of numerical simulations performed for some of the tool variants illustrated above.

Assumption for variant **1** (Fig. 2):

- forging: 2 operations,
- charge: a round bar, diameter 12 mm, cutting length 200 mm,
- number of details: 4
- charge temperature: 1250°C,
- tool temperature: 250°C,
- lubricant: water with graphite,
- number of hammer blows: 1 on the roughing seat, 1 on the finishing seat.

Assumption for variant **4** (Fig. 3):

- forging: 2 operations,
- charge: a round bar, diameter 12 mm, cutting length 200 mm,
- number of details: 4
- charge temperature: 1250°C,
- tool temperature: 250°C,
- lubricant: water with graphite,
- number of hammer blows: 1 on the roughing seat, 1 on the finishing seat.

Assumption for variant **10** (Fig. 4):

- forging: 2 operations,
- charge: a round bar, diameter 16mm, cutting length 235 mm,
- number of details: 6
- charge temperaturę: 1250°C,
- tool temperature: 250°C,
- lubricant: water with graphite,
- number of hammer blows: 2 on the roughing seat, 1 on the finishing seat.

Assumption for variant **12** (Fig. 5):

- forging: 2 operations,
- charge: a round bar, diameter 16 mm, cutting length 235 mm,
- charge temperature: 1250°C,
- tool temperature: 250°C,
- lubricant: water with graphite,
- number of hammer blows: 1 on the roughing seat, 1 on the finishing seat.

In the FE modelling, four-wall elements type TET4 (tetrahedrons) were used, where the material consisted of 22,244 and 36,148 (pre- and post-process element quantity) on initial operation and 244,206 and 311,965 elements in finishing operation. Such density of the mesh has a positive effect on the mapping of near-surface temperature changes where the temperature gradient is the highest. During the calculations, the finite element mesh was rebuilt 18 times on the stock, the standard criterion was used with the deformation option turned on. It was assumed the dies as deformable, where the lower die was fixed in relation to the stationary base, and the upper die was set to parameters in accordance with the hydraulic hammer specification in the vertical direction. The numerical model of the forging process, its geometry was divided into finite elements of various sizes. In the case of tools, the volumes for which elements of larger and smaller dimensions were imposed were distinguished. In the area of the cut, smaller elements were used, the edge of which, if possible, was about 0.3 mm, which, assuming that at least 3 elements should represent the rounding radius on the tools, gives a radius of about 1 mm. The tools were discretized with TET4 elements in the amount of 9,458 and 11,328 (top and bottom). The selection of the size and number of elements was made based on the authors' experience, in such a way as to reflect the industrial process to the greatest extent possible, and on the other hand, so that the calculation time for the computer hardware was acceptable and did not exceed 50-60 hours. The tribological conditions were assumed based on the bilinear Coulomb friction model for the coefficient of depend on condition (μ about 0.25), for all the working surfaces of the tools (in the industrial process, graphite with water is used). The assumed heat exchange coefficients in the contact and with the environment were 30 and 0.25 N/s/mm/°C, respectively.

3. Discussion of results

The tests with the application of numerical modelling included multi-variant simulations of different variants, which were considered and analyzed chronologically (every consecutive variant was created based on a thorough analysis and the drawn conclusions from the previous one) in order to obtain an optimal solution ensuring the best filling of the impression and material flow, lack of defects, the lowest forging forces and the possibility of obtaining simple joggles (pins) perpendicular to the main forging axis. Such assumptions were made so that, based on the available knowledge and own experience in forging process realization, the most advantageous parameters and process indexes would be achieved, enabling the introduction of possible to apply improvements into the currently realized technology.

3.1. Variant 1

The results for the first two analyzed variants included four single forgings in one leaf, which were used in the preliminary analysis of the possibilities of modelling the forging process. At the same time, in the production aspect, they are inefficient.

Variant 1 refers to a process of forging from a round bar Ø12, 200 mm long. The results for this process have been presented in Figs. 8 and 9 for the roughing operation and the finishing operation.

In the roughing operation from the Ø12 mm bar, we can achieve the desired thickness of the flash as a result of one blow on the roughing seat. The forging force has been shown in Fig. 8b. Nevertheless, it is not possible to obtain a full filling of the pin on the roughing seat (marked in red in Fig. 8). On the finishing seat, one blow is sufficient. The filling of the pin was achieved

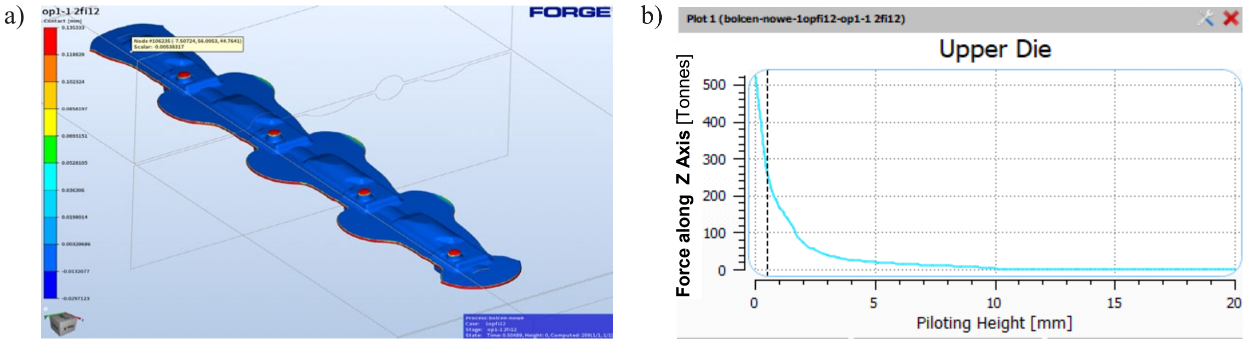


Fig. 8. Results for variant 1: a) the roughing operation for charge Ø12 mm – contact – end of the forging process, b) the course of forging force

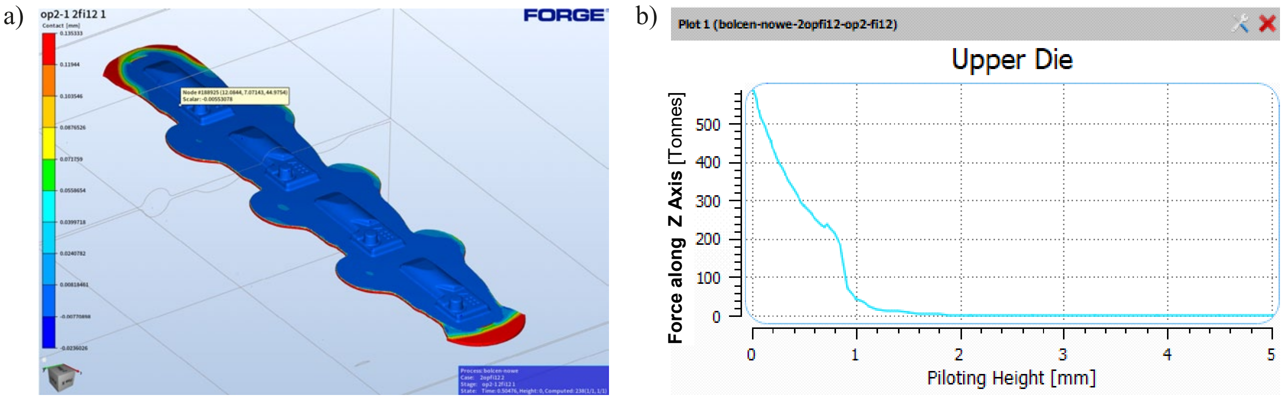


Fig. 9. Results for variant 1: a) the finishing operation for charge Ø12 mm – contact – end of the forging process, b) the course of forging force

according to Fig. 9a. The maximal forging force necessary to achieve a proper filling of the impression and obtain a ready forging is at the level of only 600 t.

3.2 Variant 4

The following analyzed variant with a slightly different arrangement of the forgings in the whole leaf (in respect of the previous one) was variant no. 4, which involved forging from a round bar, Ø12 in diameter and 200 mm long, from forgings arranged symmetrically in pairs (contact between the heads of forgings 1 and 2, and 3 and 4). The obtained modelling results have been presented in Figs. 9 and 10.

In the roughing operation, by forging from a Ø12 mm bar, we can obtain the desired thickness of the flash as a result of one blow on the roughing seat. The forging force has been shown in Fig. 10. Nevertheless, it is not possible to achieve filling of the pin on the roughing seat (Fig. 10). On the finishing seat, one blow is sufficient. The filling of the pin was achieved according to Fig. 11.

3.3. Variant 10

Variant 10 refers to a process of forging 6 forgings simultaneously in one "leaf" from a Ø16 bar, where, additionally, in order to increase the rigidity of the whole forged element, the

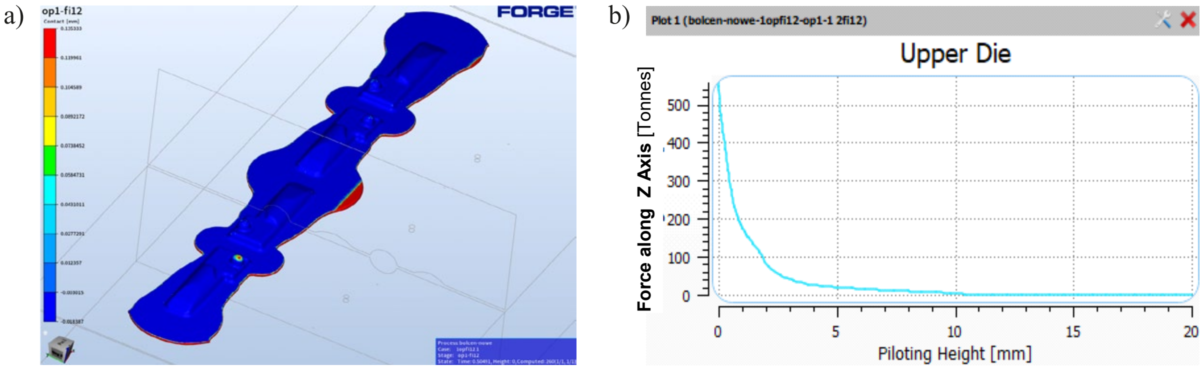


Fig. 10. Results for variant 4: a) the roughing operation for charge Ø12 mm – contact – end of the forging process, b) the course of forging force

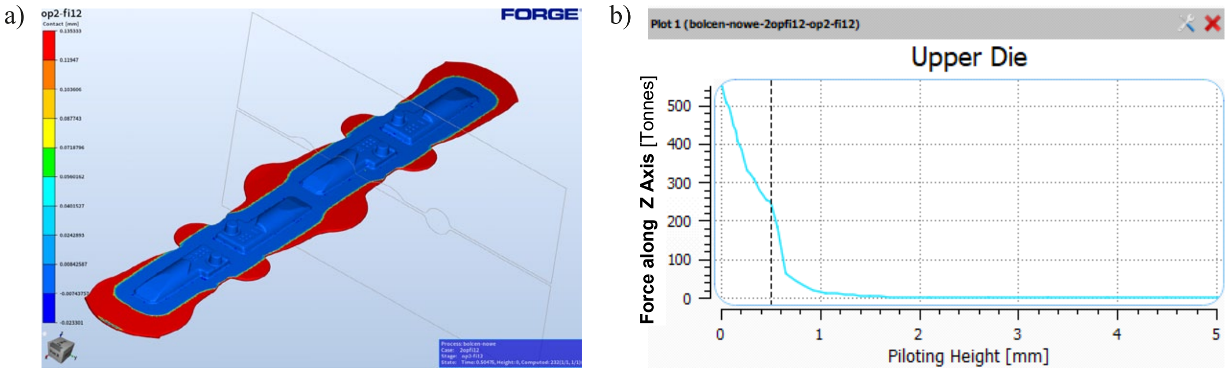


Fig. 11. Results for variant 4: a) the finishing operation for charge Ø12 mm – contact – end of the forging process, b) the course of forging force

flash was twisted in the perpendicular direction to the neutral plane. The obtained simulation results have been presented in Figs. 12-13.

Unfortunately, in the roughing operation of forging from a Ø16 mm bar, there is no possibility to obtain the desired flash thickness. It is necessary to perform another blow, which causes the occurrence of very high forging forces in the tools, according to Fig. 13.

Especially the second blow generates a force reaching 200 tons, as the material flows with very high deformation rates and is already significantly reinforced, and the change in the forging height is small, which, in the case of forging on a hammer, is caused by the change of the kinetic energy into plastic deformation work. Additionally, we should point to the problem of elastic deformations of the dies, which can cause the forgings to stick onto the upper die, in which the pins are placed. The deflections along the movement of the ram affect the thickness of the forging and its flash, as well as change the tribological conditions (Fig. 14).

For this reason, on this basis, we should perform a partial redesign of the impressions, especially for the extreme forgings, that is no. 1 and 6, in order to obtain a product with the desired geometry. Fig. 15 presents the plastic deformation and temperature field distributions for variant 10 (twisted flash) for the finishing operation, whereas Fig. 16 shows the contact for the final deformation in II operation.

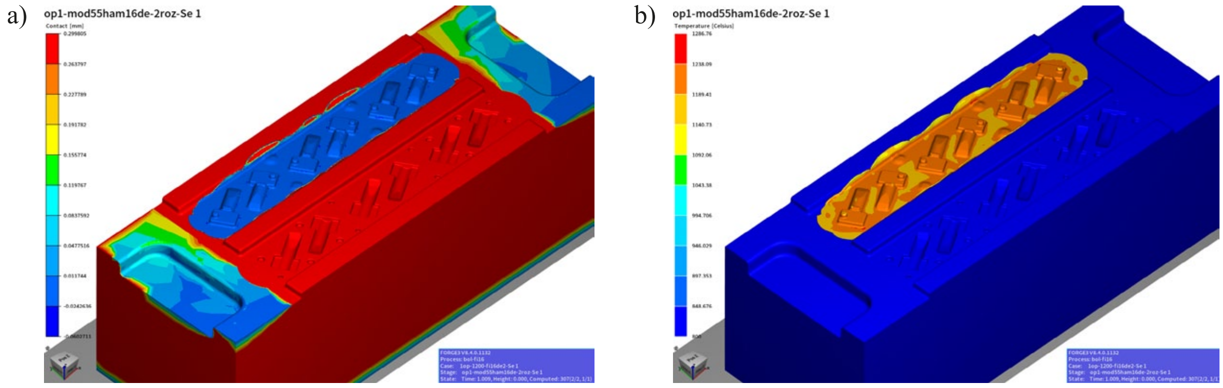


Fig. 12. Results for variant 4, roughing operation for a Ø16 mm charge – contact – end of the forging process: a) contact, b) temperature field distributions

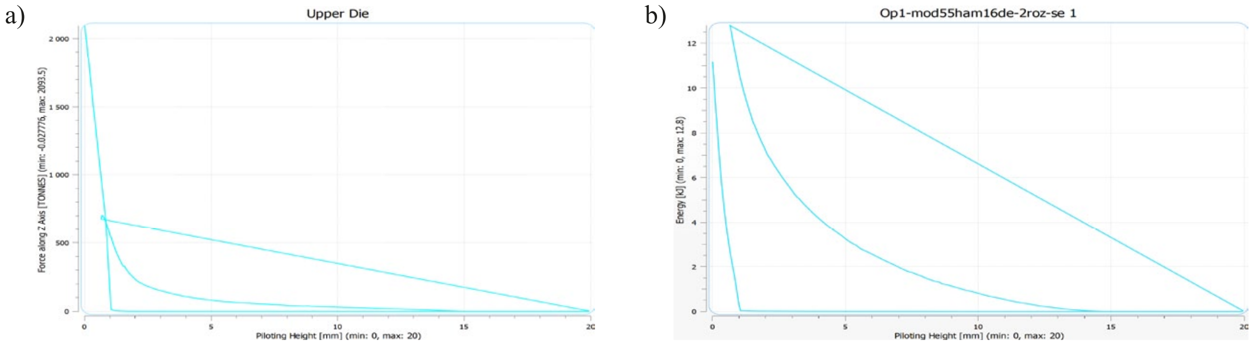


Fig. 13. Simulation results for variant 10 – roughing operation for a Ø16 mm charge: a) forging forces, b) energy

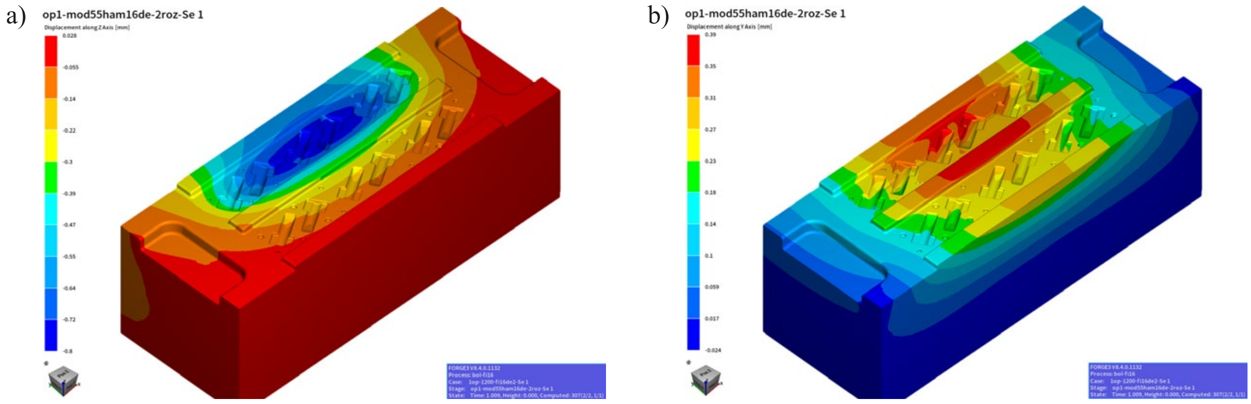


Fig. 14. Results for variant 4, roughing operation of a Ø16 mm charge: a) dislocations in the direction of axis z, b) displacements in the direction of axis y – end of the forging process

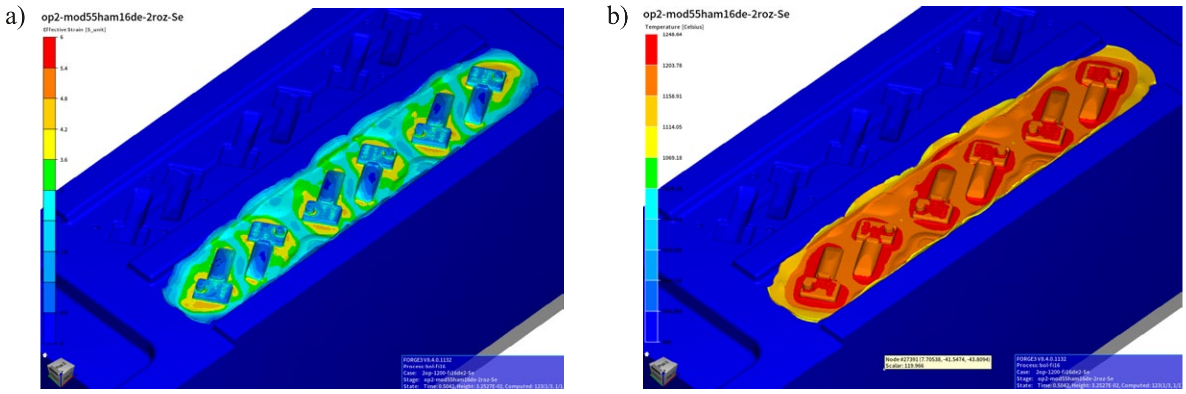


Fig. 15. Simulation results for variant 10 – finishing operation for a Ø16 mm charge: a) plastic deformation distributions, b) temperature field distributions

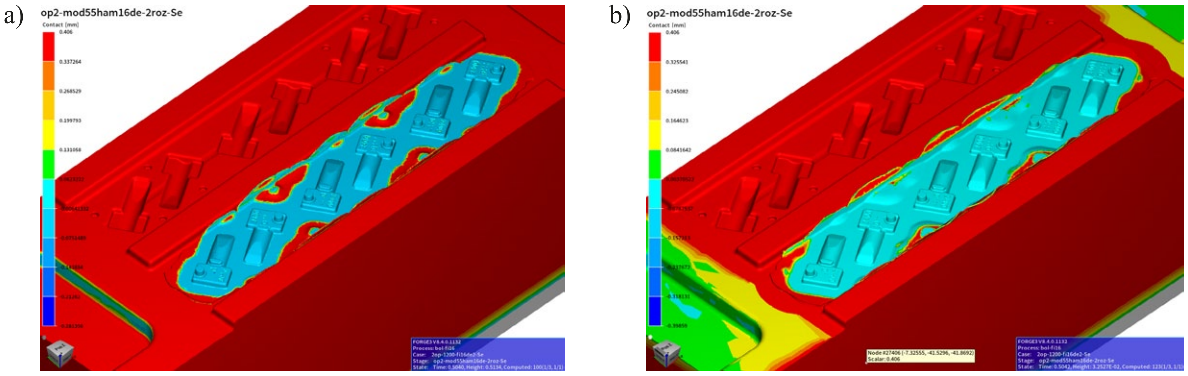


Fig. 16. Variant 10 – finishing operation for a Ø16 mm charge: a) 0.5 mm contact before the end of the forging process, b) contact at the end of the forging process

The plastic deformation distributions suggest that the highest values can be observed in the endings of the pins and on the surface of the big longitudinal mandrel. In turn, in the case of the temperature distributions, we can state that the highest temperature is in the areas were the material flows with the most intensity, which, in the final phase, takes place in the flash closest to the forging.

Fig. 17 shows the results referring to the dislocations in the die in directions Y and Z for the lower die.

Also, in the case of the finishing operation can we notice twisting of the dies, where, for example, the twisting in direction Z is almost 4 times smaller than the one observed for the roughing operation, which also manifests itself in the force and the energy (Fig. 18).

Analysing the obtained force and energy results in the roughing and finishing operation, we can state that, in the roughing operation, much more energy is needed, as the bar material is strongly reformed into almost the shape of the ready product.

3.4. Variant no. 12

Variant 12 refers to forging from a round Ø16 diameter bar, where, contrary to the previous analyzed variant, no twisting of

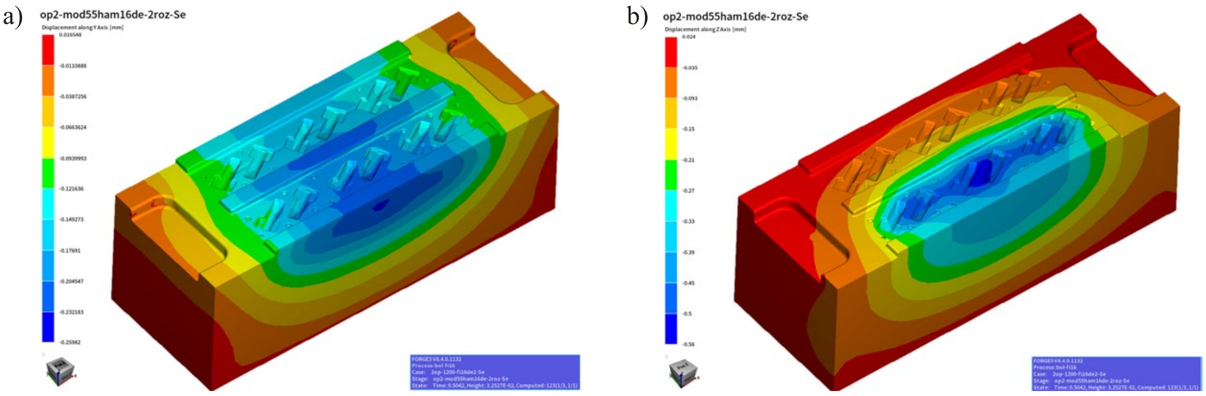


Fig. 17. Variant 10 – finishing operation for a Ø16 mm charge – dislocations in the direction of axis y – end of the process

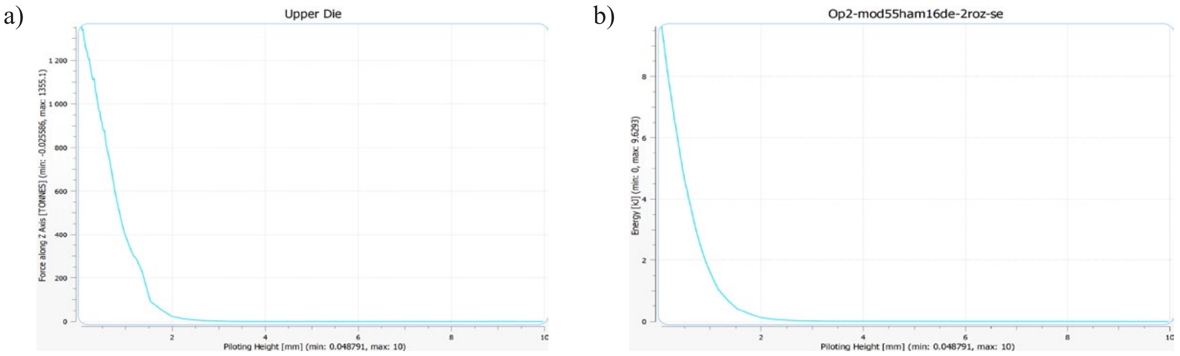


Fig. 18. Variant 10 – finishing operation for a Ø 16 mm charge: a) forging force, b) energy

the flash in the perpendicular direction was performed, but additional repositories were introduced, making it possible to accept the material excess as well as stiffen the leaf with the forgings. The results have been presented in Figs. 19-21.

In the roughing operation, during forging from a Ø16 mm bar, the desired thickness of the flash and filling of the pin were obtained (Fig. 19a). However, it was necessary to apply a force over 400 tons (Fig. 19), while only one blow was needed for the forming.

For the finishing operation, filling of the seats and the pin was obtained according to Fig. 20, which enabled forging with only one blow with the maximal force of about 1100 t and the energy necessary for the deformation at the level of over 4 kJ (Fig. 21).

The simulation results obtained for this variant point to the best conditions both in the technological aspect (after one blow in the roughing and finishing operation ensuring proper filling, relatively low maximal forces ensuring high tool durability) and in terms of production (6 forgings in one leaf).

TABLE 2 shows the analysis results as well as a comparison of the four forging variants in regard of the hourly production

TABLE 2

Compilation of the process parameters

Parameter	Variant 1	Variant 4	Variant 10	Variant 12
Number of items produced in one cycle	4	4	6	6
Hourly efficiency (item/h)	600	600	840	900
Cycle time (s)	15	15	17	15
Fraction of forging mass in charge mass (%)	70	72	57	57
Discard (g)	13	12	27	27

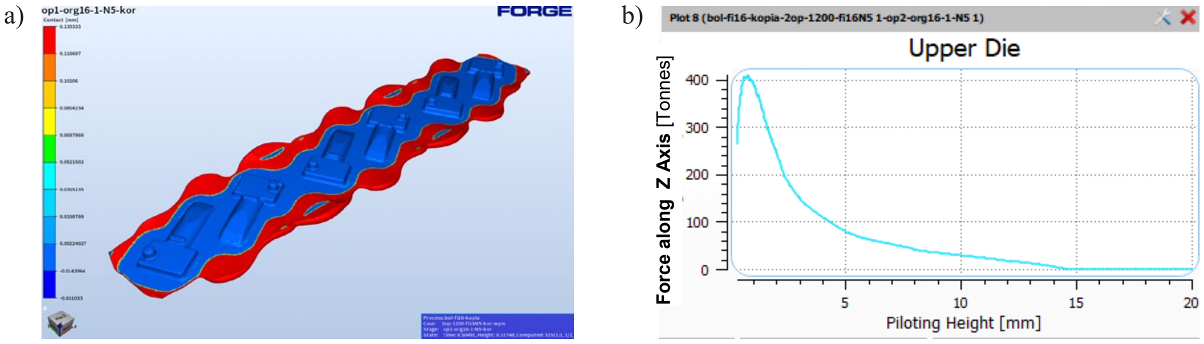


Fig. 19. Variant 12 – finishing operation for a Ø16 mm charge – contact with the tools – end of the forging process, top view

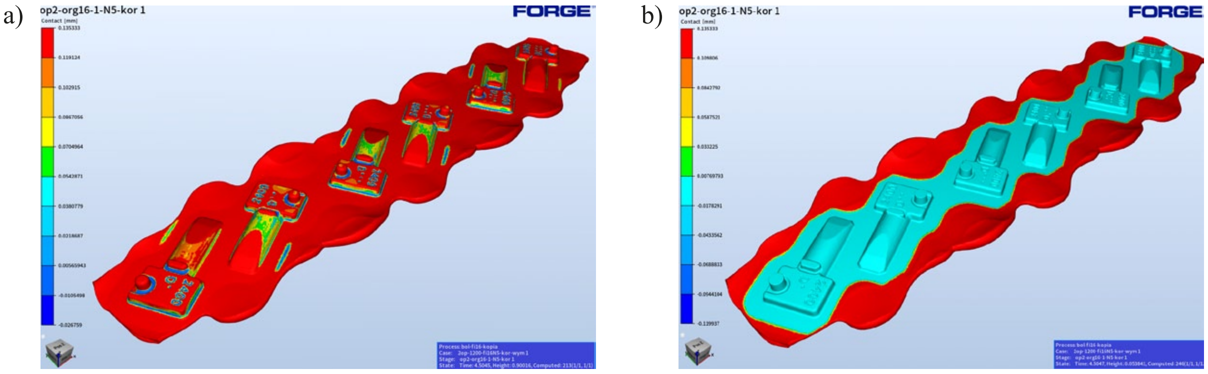


Fig. 20. Variant 12, finishing operation, contact with the tools: a) 0.5 mm to full contact, b) end of the forging process

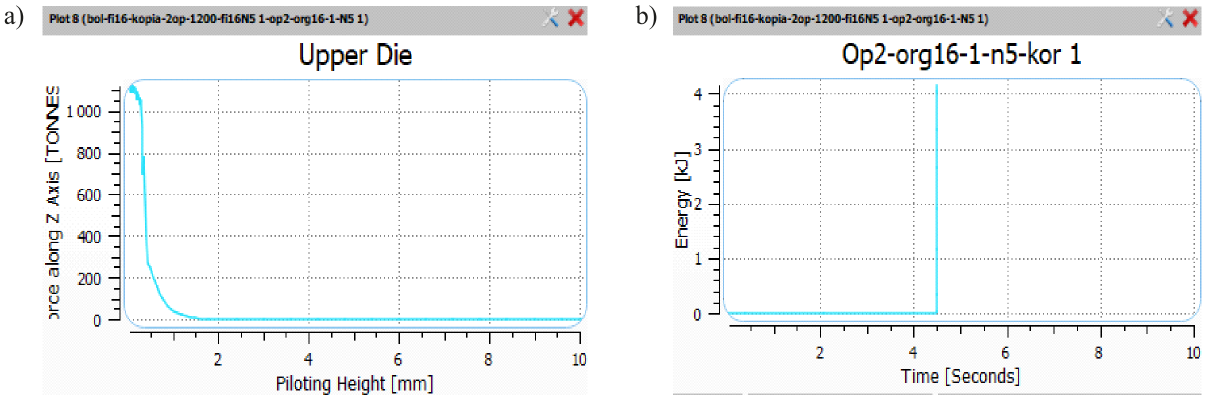


Fig. 21. Variant 12, finishing operation: a) force in the process, b) blow energy

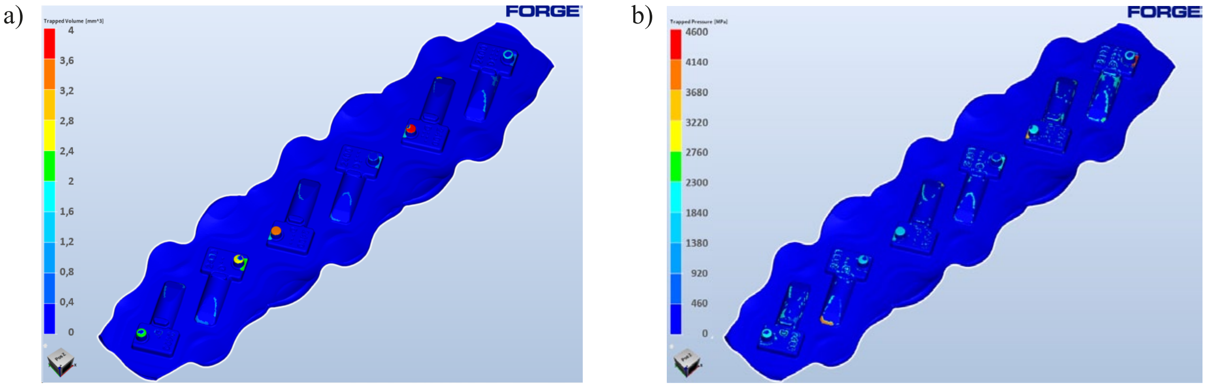


Fig. 22. Results obtained from numerical modelling with the use of special functions in the FEM: a) underfilled volumes, b) pressure distributions towards the end of the forging process

efficiency, the cycle time, the fraction of the forging mass in the charge mass and the amount of the generated discard during the production of one forging.

And so, on this basis, it was decided to conduct technological trials for variant 12 in order to confirm the obtained numerical simulation results.

4. Verification of the numerical modelling results

In order to verify the performed numerical simulations under industrial conditions, one variant, no. 12, was selected. The hot die forging process on a hydraulic hammer with the nominal blow energy of 16 kJ to produce a bolt forging was carried out in a sixfold system. This is the solution which was selected as the most optimal one for the series production among the many variants subjected to analysis. Before the forging process, the tools are heated to the preset temperature, i.e. 150-200°C, which lasts about 1 h. After the heating of the charge material in the form of 16MnCrS5 bars to the proper forging temperature, i.e. 1250°C, the bar sections are manually carried into the processing area of the forging hammer by the forge operator. The operator places the heated bar first onto the roughing pass, where 1 blow of the hammer's ram takes place, and then replaces it onto the finishing impression, where 1 hammer blow takes place. After the last blow, the forge operator takes the forging with the flash and places it onto the feeder. After the cooling, the elements are shot-peened and transported to the subsequent operation of cutting off of the flash, where the forging is separated from the details. This process is realized on a press. The consecutively cut forgings are shot-peened and transported to the last operation of the technological process, i.e. calibration. This process is also realized on a press in order to obtain the proper shape-dimension precision of the final product.

All the forging tools were made from the ORVAR 2M material produced by the Swiss steel plant Bohler Uddeholm and thermally improved into the hardness of 49-51 HRC. The working impressions were made through ablation according to the above-mentioned CAD model for variant 12. During the forging process, lubricant in the form of a graphite-water mixture was applied. For the control of the tool and charge temperature, a thermovision camera FLIR T840 with the image capture speed of 40 fps was used (Fig. 23).

Based on the presented thermograms, we can observe that the difference between the temperature of the lower and upper tool decreases with the consecutive trails. From the middle of the cycle on, the temperature of both tools stabilizes, and the temperature distribution becomes more uniform. The introduced geometrical changes of the tools do not have a negative effect on the process temperature, stabilizing it minimally. Fig. 24 shows camera images for the finishing seat from the beginning of the process 15-16 s as well as from the end of the process

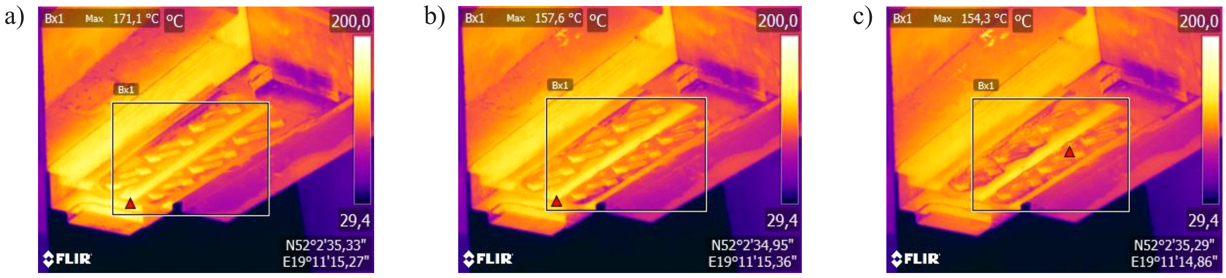


Fig. 23. Upper die temperature distribution: a) beginning of the production cycle, b) middle of the cycle, c) end of the cycle


a) b) c) d)

Fig. 24. Camera images for the finishing seat from the beginning of the process15-16 s and from the end of the production series 56:58-56:59 s (right before the blow)

26:58-26:59 s (right before the blow), which confirm that no lifting of the forged elements was observed either in the roughing seat or the finishing seat.

The performed complex analysis for a series of about 100 leaves (6 forgings in one leaf) demonstrated only one observed lifting of the forging from the lower roughing seat. It was probably caused by the cooling of the upper tool and blocking of the tools themselves in the lower tool.

4.2. Analysis of the quality and geometry of the forged parts

In order to analyze the quality of the forgings and measure the geometry of the forgings, measurements of single randomly selected forgings were carried out using 3D scanning and a coordinate measuring machine. Fig. 25 shows the results of scanning for 3 randomly selected forgings after trimming in relation to the CAD model.

The presented results of scanning the forgings make it possible to confirm the reproducibility of the process based on the obtained similar shape deviations on the upper part of the forgings.The obtained results are consistent in the remaining range of dimensions and confirm that the main problem of this type of forgings will be maintaining the specifications related to the shape and diameter of the pin, additionally for such small and accurate forgings it is important to minimize exaggeration. This may make it necessary to calibrate the forgings after trimming.

The qualitative analysis of the forgings was performed for elements made during the forging process (6 forgings) with the use of a coordinate measuring machine Mitutoyo. The measurements were made at the temperature of 20 ±1°C. The measurement expanded uncertainty was U = ±(1.7 + 4.0 L/1000) [µm], where L is the measured length expressed in millimeters. The

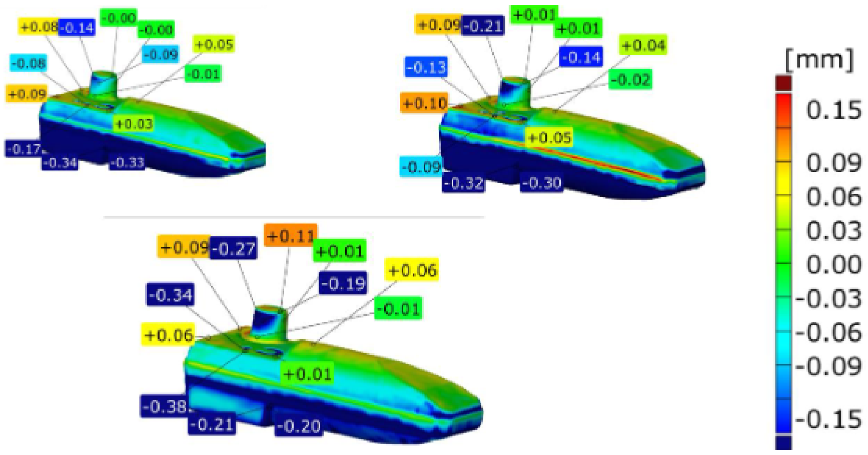


Fig. 25. Scanning results for random forgings obtained from the process after trimming referred to the nominal CAD model

provided uncertainty values constitute expanded uncertainties at the confidence level of about 95% and with the coverage factor k = 2.

TABLE 3 shows the measurement results for 4 leaves (6 forgings each) after the forging process with the results of the pin's inclination, as this geometrical feature is key for the forging's dimension-shape precision. The requirements for this forging assume that the inclination angle of the pin should be within the scope of 88.8 to max. 91.5 degree.

TABLE 3

Measurement results for 4 leaves, 6 forgings on each, in 4 directions, for the consecutive forgings, for the finishing operation within the pin's inclination scope

	Sample no.	**Angle zy (90)**	**Angle –zy (90)**	**Angle zx (90)**	**Angle –zx (90)**
Leaf 1	**1**	91.64	89.97	90.71	90.42
	2	90.49	91.37	90.45	90.82
	3	91.43	90.69	90.53	90.91
	4	89.91	91.88	90.84	91.17
	5	91.48	90.11	90.75	90.7
	6	90.03	91.73	90.45	90.73
Leaf 2	**1**	90.79	90.18	89.87	90.46
	2	90.31	91.2	90.84	90.24
	3	91.52	90.41	90.57	90.81
	4	90.70	90.61	90.46	90.4
	5	91.22	90.36	90.24	90.72
	6	89.95	91.27	90.14	90.56
Leaf 3	**1**	89.53	90.70	90.97	90.10
	2	90.54	91.5	90.50	91.04
	3	91.78	90.49	90.58	90.53
	4	89.95	91.65	90.64	90.89
	5	91.95	90.33	90.46	90.93
	6	89.85	91.13	90.73	90.73
Leaf 4	**1**	90.77	90.72	91.04	90.27
	2	89.93	90.75	90.20	90.61
	3	91.21	90.74	91.38	90.11
	4	90.24	91.11	90.06	90.84
	5	91.29	90.16	90.49	90.45
	6	89.88	91.06	89.81	90.34

The obtained measurement results suggest that, for each of the 24 forgings, in four directions, from the selected 4 leaves, the pin's inclination dimensions are within the assumed dimension scope, as the maximal deviation from the nominal value equalling 90.5° is 91.95° and 91°, and thus, 1.45° and 0.97°, respectively, in the opposite direction.

Another crucial geometrical feature is longitudinal and transverse elongation, which point to the differences in the position of the upper part of the forging in respect of the lower part (in relation to the neutral plane). The obtained measurement results have been presented in TABLE 4.

In the case of joggle, the highest obtained displacement values were below 0.1 mm, which confirms the effectiveness of the designed lock system in the dies.

TABLE 4

Measurement results for 4 leaves, 6 forgings, in terms of joggle

	Sample no.	**Longitudinal joggle (mm)**	**Transverse joggle (mm)**
Leaf 1	**1**	0.03	0.06
	2	0.06	0.03
	3	0.02	0.05
	4	0.05	0.05
	5	0.04	0.04
	6	0.02	0.05
Leaf 2	**1**	0.05	0.02
	2	0.03	0.03
	3	0.05	0.05
	4	0.04	0.02
	5	0.06	0.05
	6	0.08	0.03
Leaf 3	**1**	0.05	0.02
	2	0.02	0.04
	3	0.06	0.02
	4	0.08	0.03
	5	0.05	0.05
	6	0.07	0.04
Leaf 4	**1**	0.03	0.06
	2	0.05	0.05
	3	0.02	0.06
	4	0.05	0.03
	5	0.04	0.04
	6	0.03	0.06

The obtained results of the verification measurements for the two key features demonstrated that they are within the assumed tolerances, which proves the correctness of the developed technology based on numerical modelling.

This also confirms that the application of numerical modelling for the optimization of the production process, in this case the process of precision forging on a hammer in multiple systems, is fully justified and makes it possible to significantly shorten the designing process as well as eliminate the expensive and time-consuming tests/technological trials in order to verify the elaborated solution.

5. Summary

The conducted complex studies and analyses with the use of numerical modelling and the performed multi-variant simulations confirmed by the results of measurements on measuring devices have demonstrated that, through realization of a whole series of scientific research verified in technological trials under industrial conditions, it is possible to improve the currently realized technology, as well as achieve high-quality forgings (without defects, with elevated surface quality and dimension-shape accuracy).

The analysis of the present technology has shown that it is correct, however, certain details may be crucial, which, in the case of forgings of this type, are much more important than for other similar forging processes on hammers which also involve high deformation rates.

The investigations conducted in the last few years, for different constructions of forging tools with the use of a spectrum of methods and measuring devices, have made it possible to determine the most optimal construction of the tool and course of the technological process. In consequence, the solution in the form of variant 12 enables an effective use of machines and devices as well as production of forgings without defects, with a high dimension-shape precision. This solution can certainly be applied in a series production of die precision forgings without flaws. The proposed approach to the issue related, among others, to the twisting of the pins in the forgings made in multiple systems in a hot process on a hammer can constitute the basis for solutions for other similar forgings and processes. In the authors' opinion, this article presents the most interesting results of the project realized for the last two years, which have been the turning points in the realization of the target solution, in the form of variant 12. It should be emphasized that the die forging process was performed, in the analyzed case, on a hammer. Hot forging on a hammer is one of the most difficult production processes, due to the high plastic deformation rates, vibration as well as the effect of temperature on the realized processes.

The measurements of the forgings through scanning of their geometry have shown that the forgings were made properly, while their slight joggle may occur. The results of measurements on the CMM machine have demonstrated twisting of whole forged elements (leaves) as a result of the process dynamics, as well as elastic deformations and a small temperature shrinkage. In turn, the results of the measurements of the pin twisting have demonstrated that the biggest errors are observed for the extreme forgings; the middle forgings, before the introduced changes, did not show big errors of shape. The results of numerical simulations have shown that, in the case of forging of this type of elements, in which forgings are placed alternately, as a result of the dynamic deformation process on a hammer (0.08s), we can observe significant elastic deformations and twisting of the extreme parts in upper. Additionally, numerical modelling has also shown high pressure values in the pins' impressions as well as the formation of air pockets, which made the inflow of the forging material and proper filling of this area impossible, and this has also been confirmed by the measurements (scanning of the pins' profiles).

The realized complex tests and analyses prove that, in the case of thin and slim elements (forgings in multiple systems with small masses and complex shapes), the application of numerical modelling enables a fast and relatively accurate analysis of the proposed solutions without the necessity of performing expensive and time-consuming technological trials, which makes it possible to produce high quality items without defects. The conducted investigations have demonstrated that, with the preservation of the proper technological process parameters and tool construction, we can multiply the number of manufactured forgings from 4 to 6, with the same forging cycle. This unequivocally translates to an increased production process efficiency. It should be emphasized that an important aspect of the multiplication of the forged elements is the preservation of a stable and repeatable process in order to obtain a high shape-dimension precision of the manufactured details. This solution is undoubtedly innovative and enables a stable and repeatable.

We should clearly state that producing this type of precision forgings in multiple systems on hammers constitutes a big challenge, both for technologists and constructors, which requires an individual approach for each item, despite similar geometries. The reason for it is that, as it has been demonstrated by the complex studies and analyses, in the case of producing this type of forgings, even small changes in the tribological conditions or tool construction, as well as the subjective human factor, are of big importance, and each of them can introduce mutual interactions. And so, it seems that the subject matter has not been exhausted and further research in this field is still justified.

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