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Analysis and Improvement of an Industrial Process of Hot Die Forging of an Elongated Forging Tipped with a Joggle with the Use of Numerical Simulation Results

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ABSTRACT

The article performs an analysis of a hot die forging process of producing an elongated forging ended with a joggle in a double system realized on a crank press Masey 1300 t, in open dies, in 3 operations. The thermomechanical model of the forging process considering the changes in the grain size and the forging material recrystallization was elaborated with the use of the calculation packet Qform 7. In the first place, an in-depth analysis of the currently realized forging technology was made, with a special consideration of the temperature changes in the tools as well as in the formed forging. Next, numerical modelling of the process was carried out, as a result of which the following were obtained: correct filling of the tool impressions by the deformed material, the temperature distributions for the forging and the tools, the plastic deformation distributions (considering the thermally activated phenomena), the changes in the grain size and the forging force courses. The results obtained from FEM enable a thorough analysis of the forging process, including: the effect of the deformation time and temperature on the grain size in the forging material, which was confirmed by the microstructure examination results.

Keywords: closed die forging; numerical modelling; yoke type forging; quality and microstructure of forgings

INTRODUCTION

Adapters are elements which connect the steering wheel of a motorcar with the steering gear and which constitute an important safety element. In large lot production of adapter-type forgings, hot forging in open dies is applied, after which the obtained forgings undergo trimming of the flash as well as additional procedures (cooling, cleaning, thermo-chemical treatment, shot peening, finishing trimming treatment, defectoscopic tests and final check-up). The process of manufacturing adapter forgings for steering columns constitutes a not entirely solved problem, as, in die forging processes, a huge role is played by the selection of the proper process parameters. This is of significant importance in the case when the forgings are additionally required to exhibit a specific structure and hardness, which are obtained as a result of the forging process itself as well as a proper thermal treatment [1]. The most crucial factors strongly affecting the quality and precision of the produced forgings as well as the tool wear are: the technological parameters, the shape and quality of the tools, their proper thermal treatment, the geometry of the preform and the slug forging, as well as the thermal parameters connected with the preform and tool temperatture, and also the tribological conditions []. We should also note that hot die forging processes belong to the most difficult production process to realize, due to the hard working conditions: cyclic mechanical (over 2000 MPa) and thermal (from 80 °C to over 1000 °C in contact) loads, vibration and elastic deflections of the tool sets, as well as relatively high working temperatures of the operators or the manipulators with grippers, dustiness, etc.

[2]. Although the die forging technology is relatively well-known, producing proper forgings, especially those of complicated shapes, which will fulfill the precision and quality requirements posed by the recipients, demands from constructors and technologists, as well as the operators, to possess extensive knowledge and experience. At each stage of the technological line, there is a potential risk of error causing a lowered quality of the produced forgings [3], or unfulfilled geometrical and quqlity requirements [4]. Often, the cause of the flaws and defects identified at a given stage are errors or poorly implemented technology at earlier stages [5].

For this reason, at present, for the design, analysis and optimization of the whole forging process, a series of CAD [6] and CAM/CAE tools are used [7], as well as methods usually based on numerical modelling, as a simultaneous application of many methods and techniques aiding the design, simulation and production [8] enables a holistic approach to the given problem [9]. A proper elaboration of a plastic treatment process requires many experiments and tests, which is connected with huge costs, as well as a large time input, and still, the most important stage of design and optimization is the verification of the developed process under industrial conditions [10]. The design of preforms and slug forgings in forging processes, with the use of numerical modelling and other measurement methods (e.g. 3D scanning), is an important aspect for the improvement of the product quality and lowering of the production costs related to material losses for the flash, or losses connected with improperly produced elements [11]

The available literature offers a lot of studies and articles referring to the selection, design or optimization of the charge material geometry [12], while there are few papers discussing the application of numerical modelling based on FEM for the analysis of the causes of forging defects and tool wear [13]. The possibilities of applying FEM numerical simulations were presented in [14-16]. Numerical modelling FEM is mostly used for the determination of the optimal shape and dimensions of the slug forging, as well as of the material flow and impression filling, and also of the deformation and temperature field distributions, both in the forging and the tools [14]. For example, the authors of the study [15], by means of the finite volume method (FVM) and parametric design, elaborated a procedure of designing the optimal slug forging for complicated shapes. While paper [16] presents an innovative methodology for preform design in metal forging processes based on the convolution neural network (CNN) algorithm. This is especially justified in the case when the forging has a complex shape such as that of a turbine blade, a toothed gear, a yoke, etc. [17-26]. In turn, the authors of [17] developed an experimental-numerical methodology of identifying coefficients for constitutive equations in the case of die forging on presses. The article [18] uses FE modelling for the simulation of a process of quenching with water of a forged block made of high durability steel, in order to determine the deformation and residual stresses. In paper [19] authors propose a novel analytical solution for open-die forging for the billet of elliptical cross-section for AA6063-T7 and AA6061 alloys. In a similar manner, the FEA simulation for a closed-die forging process has been carried out and validated against experimental result. The study [20] uses FEM for the analysis of the process of trimming the flash. In turn, in the studies, FEM was applied for a complex analysis of the forging process in order to optimize or improve the currently realized technology of forked forging used in the excavator drive system [21]. The article [22] presents numerical calculations of the whole process of producing a forging of a toothed gear assigned for motorcar gear boxes. In article [23] authors report the results of theoretical and experimental studies of the process of die forging a bimetallic door handle intended for the production of a helicopter. In turn, the study [24] presents the results of a numerical analysis (by means of FEM) of a new process of forging a hollow sphere. The article [25] demonstrates the results of a numerical simulation by means of Deform 2D/3D of a flange forging in a multi-operation forging process, in which 42CrMo4 steel pipes were used as the ingot material. In turn, the authors of the article [26] apply numerical simulations of the process of forging railroad axles from steel with the use of the Forge program, with the consideration of the grain size evolution in a multi-operation forging process with high deformation rates.

The use of numerical modelling applying both FVM and FEM for the analysis of the issue of improper geometry and/or arrangement of the preform is currently the most common solution reached for by forges. The presently applied calculation packets, like: Forge [27], QForm

[28], Simufact [29] and Deform [30], which are equipped by the software producers with more and more functions enabling a better and fuller analysis of plastic forming processes, through e.g. detection of forging defects or analysis of the tool durability. Taking advantage of such functions by the user makes it possible to significantly shorten the time of implementing a new project and limit the errors in tool design. Of course, the classic designing methods of designing the charge without the use of specialized computer programs continue to be used, as is the case in older forges, although, they too, more and more often, reach for IT tools [31]. Despite the unquestionable justification of the implementation of numerical modelling and tools based on artificial intelligence in the field of plastic forming processes, we should also take into consideration certain limitations of these methods. The main limitation of the use of techniques based on a mathematical apparatus (FEM, IT) in the designing process is the correctness of the obtained results. This uncertainty can be caused by wrong assumptions, an improper model or errors in calculations, which cause the obtained results to be burdened with error of up to 10%. Although numerical modelling and IT tools significantly change the role and scope of the experiment into a virtual one, the real experiment still remains the most expensive and time-consuming stage of design and optimization [32]. Nevertheless, numerical modelling has been and still is a very convenient, fast and most commonly used tool for the analysis, design and optimization of production processes, including also those of hot die forging. What is more, its continuous development through the introduction of new functions and possibilities makes it possible to even more closely approach the real experiment. The additional aid for the FEM results in the form of other measurement techniques and microstructural tests enable a complex analysis of the whole technology, as well as its improvement and development. This makes the application of numerical modelling for the above-mentioned activities fully justified.

The aim of the study is the construction of a proper numerical model of a hot forging process of producing an adapter forging, which will be used for a better process analysis, especially that of the changes in the forging's microstructure, in the particular forging operations. This can turn out useful in the case of applying heat for the forging process and thus also the necessity of repeated heating of the forgings in order to perform the thermal treatment.

TEST SUBJECT AND METHODOLOGY

The study analyzes an elongated forging – an adapter, presented in Figure 1 and a CAD model (Fig. 1d). The process of producing the adapter forging realized at the Jawor Forge SA runs in 3 forging operations in a double system.

The charge material, 50 mm in diameter and 62 mm long, is made of steel for thermal improvement with high hardenability 42CrMo4 (1.7225). This steel is used for machine elements with very high strength and ductility and is not suitable for welding. After the cutting of the charge material, its heating takes place in an induction furnace, followed by forging on a crank press Massey 1300 (pressure of 13 MN). The forging process is realized in 3 operations in a double system (Fig.2a). The first forging operation consists in flattening a cylindrical preform placed on its diameter. The operation is roughing (with a rotation after the first operation). In this operation, the highest pressures and material deformations take place. In the third operation – finishing die forging – the forging obtains a shape which is close

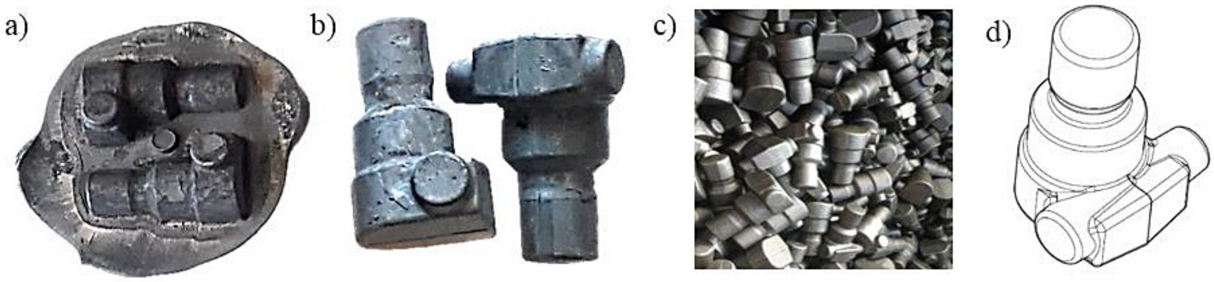

Fig. 1. Images of: a) forgings with the flash after forging in a double system, b) ready forgings after trimming, c) after shot peening, d) a CAD model

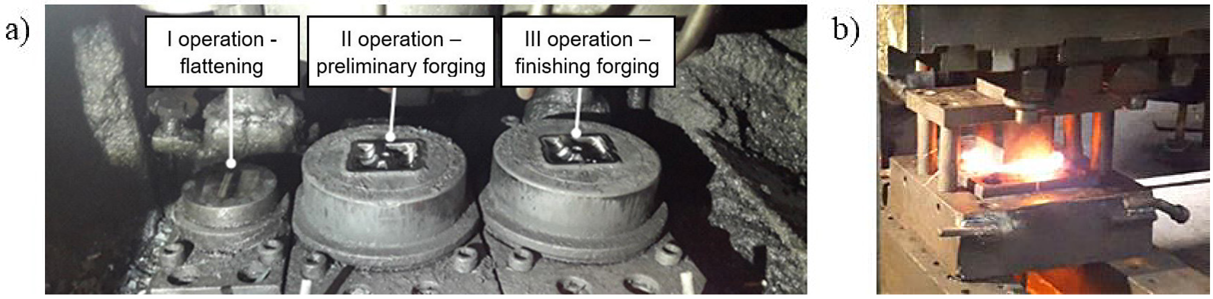

Fig. 2. Images of: a) the die inserts, b) the process of trimming the flash on a blanking die

to that of a ready product. The final shape of the item is achieved as a result of hot trimming of the flash on a special blanking die (Fig. 2b).

In order to perform a complex analysis of the process of producing a yoke type element, the following procedures were conducted: an in-depth analysis of the forging process with the use of a thermovision camera Flir 840 and a fast camera (Casio Exilim Pro Ex-F2), a macroscopic analysis of the tools and the forging defects by means of a camera Cannon EOS 65D, and 3D scanning (with the use of a measuring arm ROMER Absolute ARM 7520si integrated with an RS3 scanner) of the ready forging obtained in the current technology. On the basis of the technical documentation, CAD models of the ready forging and the tools were built with the use of the Catia V5R20 program by Dassault. Based on the above information, numerical models were elaborated and computer simulations of the hot forging process were conducted with the use of the calculation packet Qform 7 by QUNTORform in order to determine the key parameters and physical quantities as well as identify the most important problems. With the purpose to verify the introduced changes and improvements resulting mostly from the numerical modelling, a measurement of the forging's geometry was made in respect of the forging before the changes.

TESTS DISCUSSION OF RESULTS

Complex analysis of the current forging technology

Figure 3 shows a view of the production line of the adapter forging. In the analyzed process, the die inserts are made of steel WCLV, and, after thermal treatment, they are nitrided (except for the tools for I operation) into hardness of 1100-1200 HV0,1; the thickness of the nitrided layer equals about 0.2 mm. The initial temperature of the charge is 1200–1250 °C. On average, every 2 hours, a control of selected dimensions of the forging is performed and the level of the lubrication liquid is checked. Figure 3 presents a general view of the whole technological line including the forging and the hot trimming process. Figure 4 shows images of a partially worn set of forging tools, consisting of upper and lower die inserts for III operation.

The performed analysis of the tool wear showed that, in I operation, the dominating mechanisms are thermal fatigue and plastic deformations, whereas II and III operations are dominated by thermo-mechanical fatigue, abrasion wear and plastic deformations. The lowest mean tool durability is in the case of II operation and equals about 12 thousand forgings (6 thousand forging

Fig. 3. View of the technological line: left – the die forging process on a press Masey, pressure 13MN, right – the process of hot trimming of the flash on a trimming press

Fig. 4. Image of the particular die inserts used in the process of producing an adapter forging

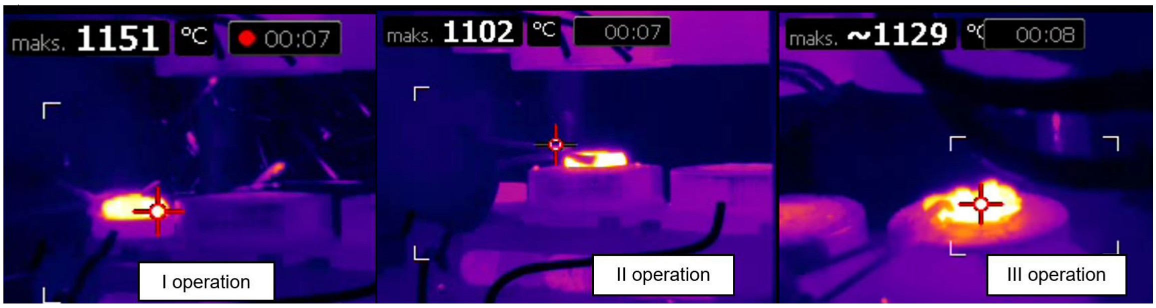

Fig. 5. Temperature measurements made after the consecutive operations of flattening, preliminary and finishing forging

actions in a double system). As II operation including roughing is crucial for the quality and dimension-shape precision, usually, after reaching the approximate mean durability for these tool, the operator carefully examines and analyzes the forgings' quality. In the case of detected defects or when the dimensional tolerances of the forgings are exceeded, a decision is made to remove the tools from further production.

Thermovision measurements

For the purpose of an analysis of the temperature field distributions in the industrial process, temperature measurements were made with the use of a thermovision camera. Figure 5 presents the thermograms with the temperature distributions for the forgings after the consecutive forging operations. In turn, Figure 6 shows the thermograms with the temperature of the lower and upper tools used for forging as well as trimming of the flash.

The tool temperature (for the second and third operation) equals about 180–200 °C (Fig. 6a), whereas the upper insert in the first operation has a temperature of over 400 °C (the lower one – 100 °C less), due to the fact that the tools are not cooled during the process. The tools are heated to this temperature by means of a heated charge material with the temperature of about 1100 °C; the heating time is about 1–1.5 hrs. Additionally, for a more thorough analysis, measurements of the temperature of the charge and the forgings in each operation were conducted. The temperature course in the function

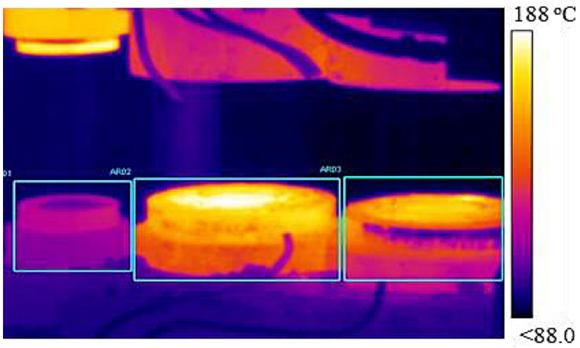

Fig. 6. Thermograms with the temperature field distributions for: a) lower die inserts, b) before the flash hot trimming process, c) after hot trimming

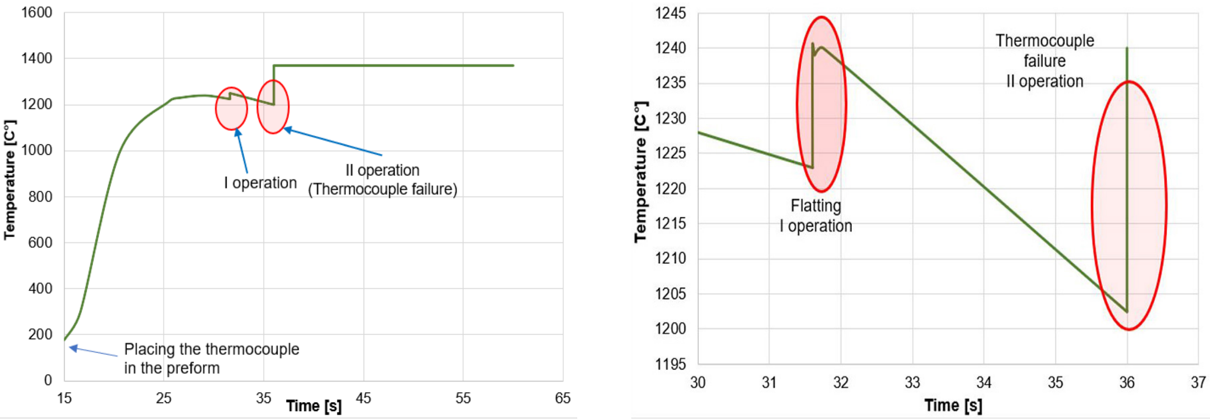

Fig. 7. Temperature course in the function of time during forging in the particular operations. Recording by means of a measurement system

of time was determined by means of a measuring system UniTest, presented in Figure 7.

Such investigations were carried out in order to precisely determine the temperature in the preform material as well as in the particular slug forgings and forgings, so that it can be taken into consideration in the analysis of the grain size and the conditions for the occurrence of recrystallization in the material.

Forging quality and defects

The forgings are made with the precisions according to EN-10243-1:1999. Apart from the typical technological problems taking place in die forging processes, one of the biggest risks during the forging of such elements as an adapter are forging defects, of which the most important ones are laps and wraps, as well as lack of dimension-shape accuracy in respect of the assumed product. During the flow, a part of the material remains between the dies, forming a wrap, which, in the following operation, is partially pressed and forms a lap – marked in red in Figure 8a (observed sometimes in industrial process).

Figure 8b shows the results of the analysis of the geometry changes in the 5000th forging obtained in the current technology in respect of the CAD model – the nominal forging – by means of a measuring arm ROMER Absolute ARM 7520si integrated with an RS3 scanner. Slightly better results (lower dimensional deviations) were obtained for the following forgings collected every 500th item, up to the 6000th one (the mean tool durability for this forging), with a small tendency to expand the dimensions. On the basis of the analysis of the presented results (Fig. 8b), we can notice that the dimensions in selected points on the forging demonstrate significant discrepancies. In the case of forgings of this type (considering the forging surfaces subjected to mechanical treatment after forging), the dimensional deviations should be within the following scopes: lower: -0.3 mm, upper: +0.7 mm. The observed deviations on the upper and lower surface of a vertical roller divided by a parting plane equalling from +0.4 to + 0.9 mm (upper part) and from -0.06 to -0.43 mm, are too big. On this basis, we can conclude about the occurrence of a joggle and thus the necessity to improve the geometry of

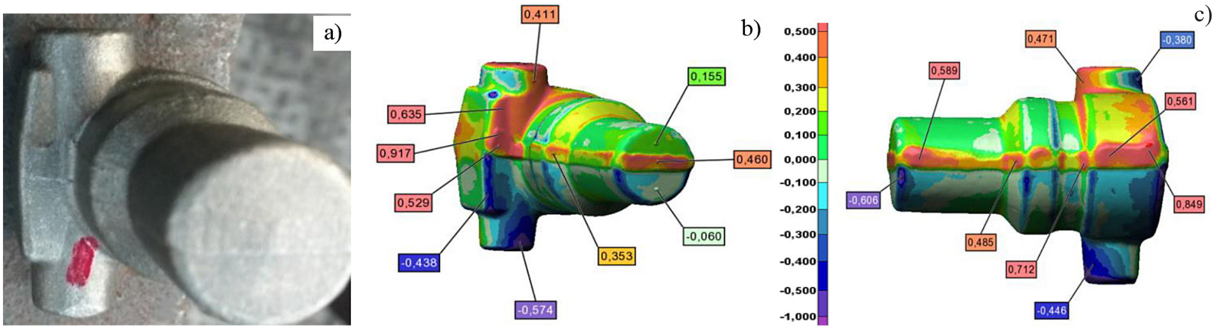

Fig. 8. Images of the forgings: a) defects in the form of laps observed after shot peening, b) 3D scanning measurement results

the working impressions. While the deviations in plus are theoretically acceptable (after forging and thermal treatment, mechanical treatment is also performed), in the case of deviations in minus, it is unacceptable. The least acceptable are the deviations on the shorter vertical pin (cylinder) of the forging, as too small a diameter can cause an insufficient amount of material during the mechanical treatment and also the so-called "non-hard spots". In this area, an opening is made as well as external treatment is performed.

NUMERICAL MODELLING

Numerical simulations of a multi-operation process of hot forging on a press were conducted with the use of the Qform 7 software. The preliminary calculations aiming at determining the modelling parameters were made on simplified mechanical models with rigid tools, and next the calculation models were gradually expanded. All the simulations were made on numerical models FEM 3D with the consideration of the most complex thermomechanical model.

Selection of materials and parameters

For proper numerical simulations, it is crucial to correctly define all the initial-boundary conditions of the process. The geometry of the tools, the preform and the other technological process parameters were implemented into the program based on the original 2D model and the operation sheets. The material used for the charge (42CrMo4) was selected from the program's material database with a specific heat of 625 J / (kgK) and rest of most important parameters, and the die insert material was tool steel for hot operations according to the standard DIN 1.2344 (WCLV) with the Young modulus of 210 GPa. The crank press from the program was chosen. The speed of the punch movement was dependent on the angular position of the press. Previously, data on the forging press was prepared (press force 13MN, 90 strokes per minute, stroke 254mm, 0.17 crank radius to conrod length ratio). The punch movement speed depended on the angular orientation of the press. The CAD models of the die inserts and the input material were digitized. In the modelling, four-wall elements type TET4 (tetrahedrons) have beeb used, with the assumed maximal ratio of the largest to the smallest element equalling 4 and where the material consisted of 14,644 and 26,924 (pre- and post-process element quantity) on flatting operation, 28,344 and 211,427 preliminary forging elements, and 242,108 and 307,465 finishing forging elements. It was assumed that the die inserts are deformable, where the lower tool was immobilized (driving) in relation to the stationary base, and the upper tool was set to parameters in accordance with the press specification in the vertical direction. The tools were discretized with TET4 elements in the amount of 9,379 and 32,928 (top and bottom upset), 198,721 and 799,759 (top and bottom rough), 710,756 and 802,409 (top and bottom finishing). The slug forging after the first operation was heated to 1175°C. The mean forging cycle of one forging recorded by means of a fast frame camera (3 operations) equalled 12.5 seconds. The tribological conditions were assumed based on the Levanov friction model for the coefficient of 0.4, 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 25 and 0,35 N/s/mm/ºC, respectively.

Impression filling

Figure 9 shows the consecutive stages of producing an adapter forging in the lower die inserts (the upper figures show the slug forgings before deformation, the lower ones – after the forging process). The input material in the form of a cylinder in the flattening operation is replaced outside in order to achieve a better distribution of masses and prepare the material for the roughing step.

After the flattening, the slug forging is placed into the roughing pass with the rotation of 180 degrees (Fig. 9b). The roughing operation is followed by finishing forging, which makes it possible to obtain the final shape. Figure 9c presents the results of a proper filling of the impression after III forging operation.

Temperature field distributions

Figure 10 shows the temperature distributions for the formed material towards the end of the second operation for a double system as well as for one forging in two longitudinal sections. The highest temperatures occur inside the formed forging (Fig. 10b and 10c) and in the flash, as a result of intensive material flow

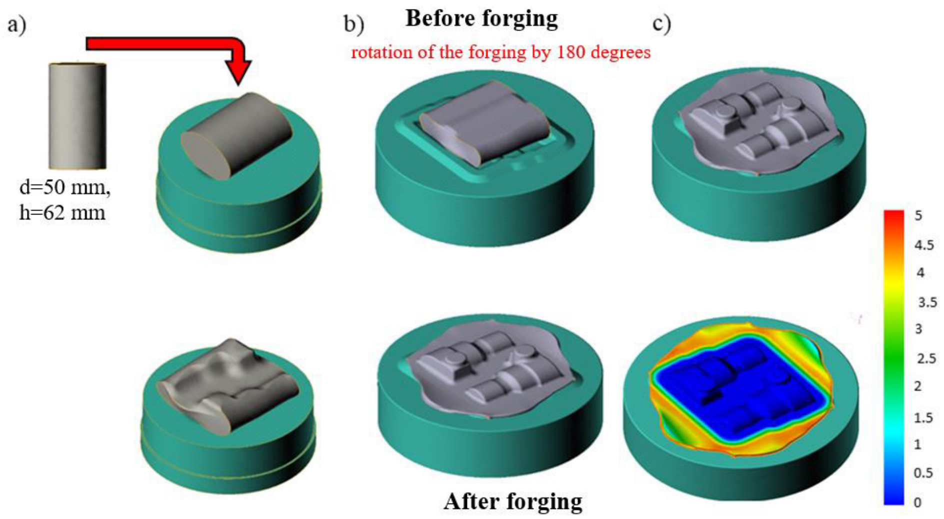

Fig. 9. Consecutive stages of producing an adapter forging in the lower die inserts: a) before and after upsetting , b) before and after roughing, c) before and after finishing forging, with plastic stran distribution

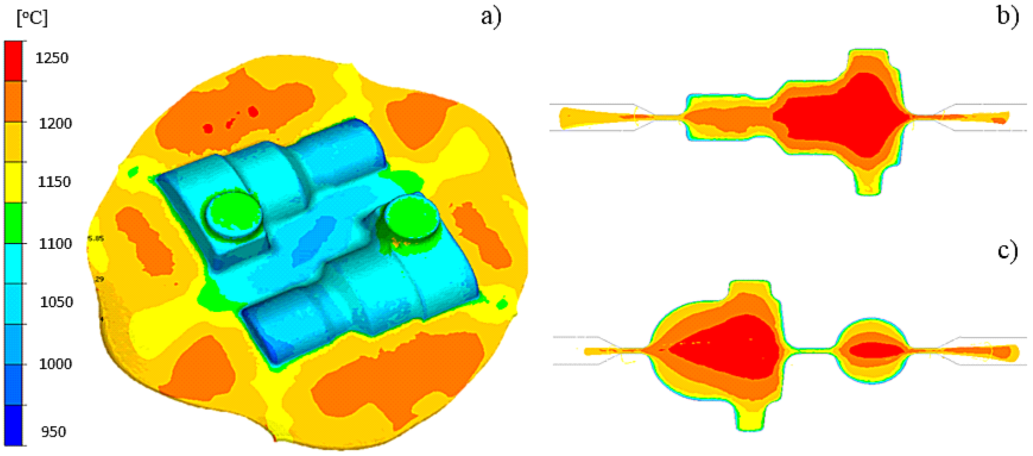

Fig. 10. Temperature distributions of the deformed material in II forging operation: a) for a double system, b) for a longitudinal section in the parting planes, c) for a longitudinal section in the perpendicular plane

in this area as well as the effect of friction. In turn, on the surface of the forgings (Fig. 5a), the temperature is slightly lower as a result of contact with the cooler tools.The defects observed in the industrial process in the form of laps were also indentified with the use of the numerical modelling results; by means of the "laps" function, it is possible to detect the potential areas in the forging where defects in the form of laps may occur (Fig. 11).

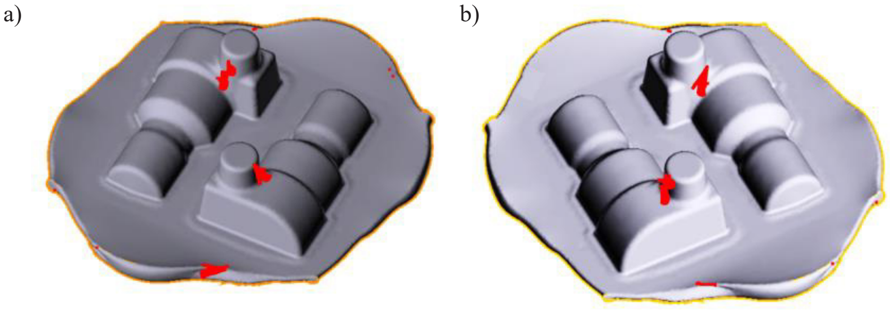

Fig. 11. Numerical simulation results – detection of defects in the form of laps: a) the upper part of the forging, b) the lower part of the forging

Similar defects were observed in the industrial process, especially in the case when the technology was not properly followed, e.g. an improper arrangement of the slug forging or forging from in improperly prepared slug forging. A defect of this type is visible sometimes after trimming and shot peening, or already during the defectoscopic tests (Fig. 8a).

Plastic deformation distributions and grain size in the forging

The QForm software enables an analysis of the plastic deformations both with and without the consideration of recrystallization. Figure 12 shows the deformation distributions for the formed forging material after the consecutive forging operations, without the consideration of the thermally activated dynamic processes of microstructure reconstruction (recovery and recrystallization). In the first operation, the plastic deformations for the double system of the forging are localized mainly inside, in the area where the upper upsetting insert deformed the material, preparing the slug forging for the rotation and being placed in the roughing pass (Fig. 12a). In the second operation, the biggest plastic deformations are localized in the areas of the highest section reductions as well as in the flash right at the bases (Fig. 12b), as a result of the longest path of friction. In turn, in the central part of the forging, similarly to the first operation, the material is weakly deformed. The plastic deformation distribution after the third operation did not change significantly compared to the distribution after the second operation (Fig. 12d), which is caused by the filling of the finishing impression being is similar to the roughing pass. The biggest deformations were recorded near the flash.

The initial grain size was assumed at the level of 40 μm (Fig. 13) on the basis of the performed microscopic tests and analyses. In the QForm program, the mean grain size (its diameter, in μm) is defined as follows:

$$d_{\mu m} = 1000 \cdot \sqrt{10^{-\frac{ASTM+2.95}{3.32}}} \qquad (1)$$

where: ASTM can be read out from the Table 1 [28].

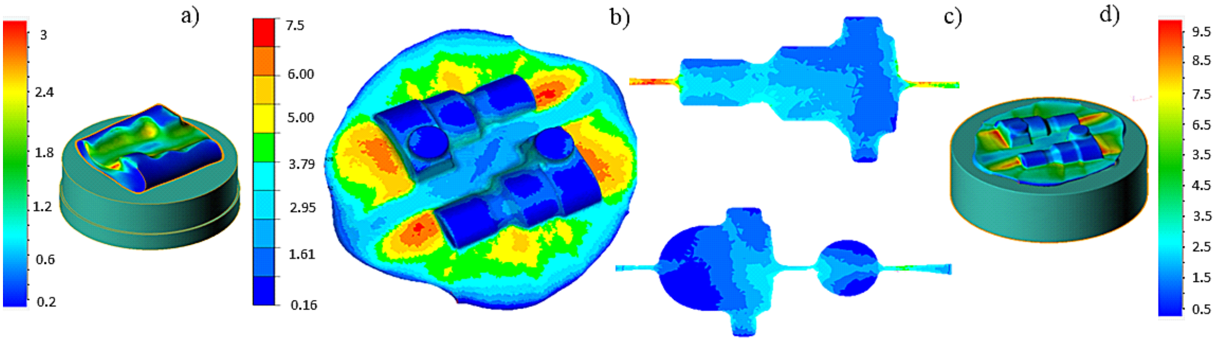

Fig. 12. Deformation distributions for the formed forging material after the consecutive operations, without the consideration of recrystallization: a) after I operation, b) after II operation, c) in the sections after II operation, d) after III operation – finishing forging

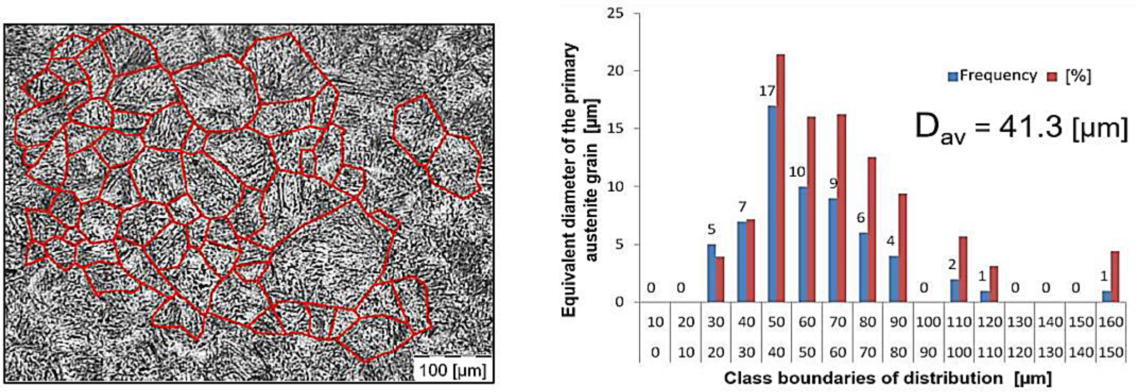

Fig. 13. Microstructure images of the charge material with different magnifications

Table 1. Grain size referred to ASTM

ASTM	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Grain size [μm]	2	3	4	6	8	11	16	22	32	45	63	90	127	180	254	360

In turn, Figure 14 shows the grain size distributions in the final phase of II operation, with full immersion. Based on the presented grain size distributions in the final phase of the process, we can observe that the biggest mean grain diameters equalling about 35 μm are localized in the forging areas with the highest volume, i.e. where the material was least deformed.

In turn, Fig. 15a and 15b presents the deformation and grain size distributions after about 1s from the moment of full forming of the forging in II operation. We can notice that, as a result of dynamic processes, the recrystallization did not occur in the analyzed time scope in the whole forging volume (Fig. 15a), and the degree of plastic deformation was reduced (Fig. 15b) in respect of

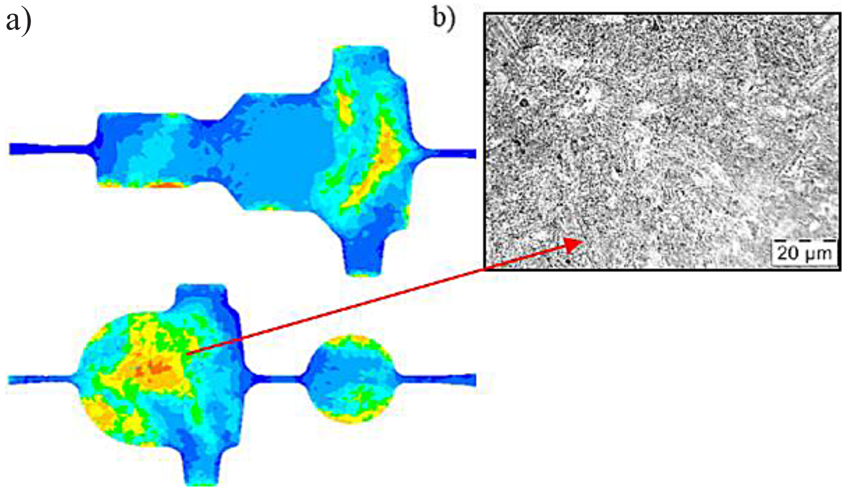

Fig. 14. Grain size distributions of the forging material in the final phase of II operation: a) a view of the full forgings in a double system, b) a view of selected sections of a single forging with microstructure image in a selected area

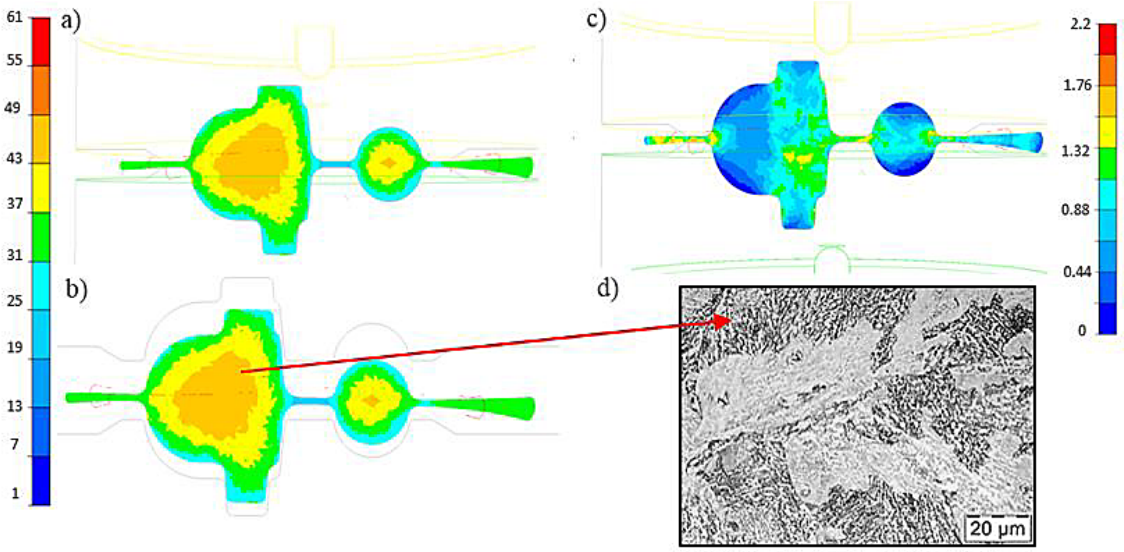

Fig. 15. Results of the simulations for a selected forging section in II operation: a) the grain size distributions of the forging material after 1s from the end of the forging, b) after 1.5s, c) the plastic field distribution after 1s, d) a microstructure image in a selected area

the deformation distribution for the forging in the final forging phase. In turn, we can see that, in the case of a longer time (Fig. 15b), it has no significant effect on the grain growth (in the modelling, the assumed time between operations was 2s, just like in the industrial process). The microstructure obtained for the selected forging section (Fig. 15d) is in ¾ a bainitic structure after tempering with pearlite and ferrite precipitates, with elongated misshapen grains of the mean surface area of 1200 μm (an oval with the longer axis length of 50 μm and the shorter of 25 μm).

In turn, Figure 16 shows the simulation results with the distributions of the changes in the grain sizes and plastic deformations for 3 forging operations in the final phase and after the time of 2s. The presented results with the grain size and plastic deformation distributions demonstrate that, in reference to the results for II operation, the changes in the grain size and plastic deformation are not that big, which results from the fact that III operation is one of calibration. For this reason, the forging does not undergo large deformations, which makes the effect of time prolongation on the changes in the grain size and plastic deformations not big.

The determined mean grain surface is about 1300 micrometers (an oval with the longer axis length of 60μm and the shorter of 35μm).

Forging force courses

Figure 17 presents the course of forging forces in the function of displacement (closing of the upper die inserts with the lower ones for a specific thickness of the flash).

In the diagram of forging forces for the particular operations (Fig. 17), we can see that, in the first operation, the maximal force value is relatively low and reaches about 300 kN, compared to the forces in the second and third operation, where it equals over 4000 kN. In the case of II operation – roughing – the maximal force is nearly 4400 kN and it does not increase rapidly, which

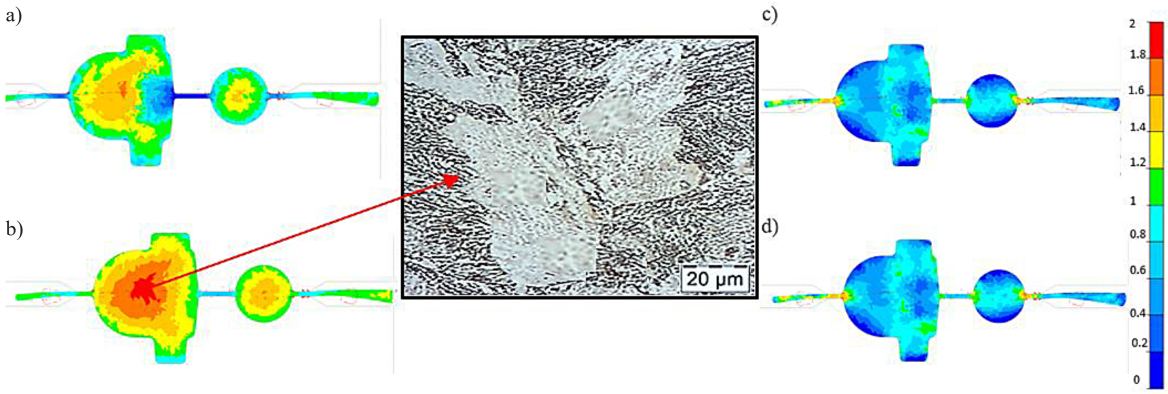

Fig. 16. Simulation results for forging section in III operation: a) the grain size distributions of the forging material in the final forging phase, b) after 2s (with microstrucure), c) the plastic deformation field distribution in the final forging phase, d) plastic strain after 2s

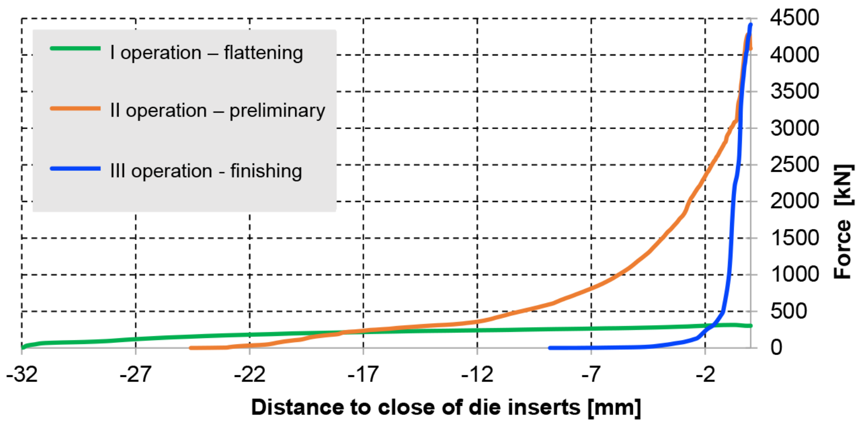

Fig. 17. Forging force courses for the particular operations in the function of dislacement

proves that the impression is properly filled by the formed material. The highest force occurs in the III forging operation and equals over 4417 kN, that is, it does not exceed the acceptable force of the industrial press (a Massey 1300 t press, with the nominal pressure of 13000 kN). The increase of the force in this operation is caused by the fact that, the last operation is basically about calibration, whose purpose is to obtain the final geometry of the forging.

The performed analysis demonstrated that the technology applied so far was designed properly, yet it requires certain improvements in respect of the technological parameters: lubrication and heating of the dies. The identified defects, confirmed by the numerical modelling results, as well as the problems occurring in the process caused the necessity to introduce changes in the technology. A decision was made to slightly change the lubrication conditions through a small dilution of the lubricant and reduction of the doses to be fed during lubrication, which should result in a slight reduction of friction and easier flow of the material, as well as a reduction in forging forces. Numerical simulations conducted for a lower value of the friction coefficient for the Levanov model (from 0.4 to 0.3) showed a slight decrease in forging forces (about 8%) in individual operations determined in FEM. What is more, an automated lubrication-cooling device was used in place of the manual lubrication, which will additionally affect the repeatability and stability of the tribological conditions. Also, small changes in the lower die were made – the parting plane was lowered, as the track after the trimmed flash has to be symmetrical in respect of the division. The radius of the exit from the bridge onto the impression was made as small as possible, so that it could constitute a good base for the trimming operation on the piercing die and play the function of a brake counteracting the material's outflow beyond the impression.

Verification of results

In order to verify the results after considering the information obtained from FEM referring to reconstruction of the tool geometry and ensuring more optimal tribological conditions, the forging process was carried out again. Just like in the previously realized process, for the geometry change examinations, the 500th and then every 500th forging were collected and then scanned. By means of the PolyWorks program, the dimensional deviations of the ready 6000th forging were illustrated in respect of the nominal dimensions (Fig. 18).

Based on the presented comparison of the scans before the changes (Fig. 8) and after the introduced changes (Fig. 18), we can conclude that, as a result of the implemented improvements, in the industrial process, more precise products were obtained – forgings with a narrowed dimensional tolerance field, which justifies the application of FEM for the optimization of forging processes.

CONCLUSIONS

The performed numerical modelling of the forging process of producing an adapter forging have provided a lot of important information and results referring to: the forging forces, the plastic deformation distributions, the temperature fields in the tools and the forging, which affect the grain size (considering the thermally activated phenomena). Such parameters would be very

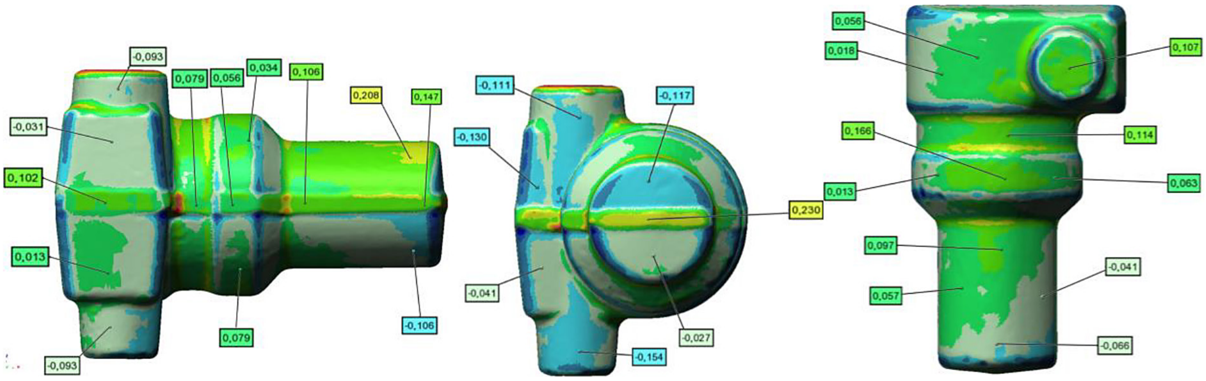

Fig. 18. Comparison of the manufactured 6000th forging with the CAD model after improvements

difficult to determine under experimental conditions or during a typical process analysis. The obtained results can also be useful during the design of the forgings' thermal treatment, in the context of the obtained forging grain size after the forging process and the inter-operation times affecting the changes in the grain size. Owing to this, it becomes possible to design the forging process in such a way so that it is possible to reduce the necessity of heating the forgings to high temperatures and take advantage of the forging heat for the planned thermal treatment, as well as obtain a specific grain size and structures. The obtained FEM results referring to the grain size changes as a result of deformation and temperature changes demonstrated a good agreement with the results of the microstructural tests, especially those referring to the grain size. Moreover, we should emphasize that the big temperature gradients observed in numerical modelling as well as high pressures occurring during the forging process can cause damage of the tools and worsen the quality of the forgings.

On the basis of the process observations (e.g. thermovision studies) and owing to the consideration of the FEM results and introduction of process corrections, a good dimensional accuracy of the ready forging was obtained, which confirmed the validity of the assumptions for numerical modelling.

The obtained results can be used for the optimization of the main technological process parameters as well as the geometry of the tool working impressions, in order to increase the quality of the forging (minimize the defects), as well as prolong the operation time of forging tools and instrumentation.

The presented investigation results and the complex analysis have proved the validity of the use of numerical simulations for the analysis of the production processes, aided and/or verified by other tests, such as thermovision measurements, 3D scanning as well as other advanced engineering methods. It seems that it is a good direction of the development of science, especially in the aspect of the search of new solutions for problems on the border of manufacturing technology, production process design and materials engineering. In many cases, such an approach enables an in-depth analysis of the problem and selected issues as well as verification of the proposed solutions under industrial conditions.

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