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ANALYSIS OF THE INDUSTRIAL PROCESS OF PRODUCING A LEVER-TYPE FORGING USED IN MOTORCYCLES

The article presents an analysis of the multi-operation hot die forging process, performed on a press, of producing a lever forging used in the motorcycles of a renowned producer by means of numerical simulations. The investigations were carried out in order to improve (perfect) the currently applied production technology, mainly due to the presence of forging defects during the industrial production process. The defects result mainly from the complicated shape of the forging (bent main axis, deep and thin protrusions, high surface diversity in the cross section along the length of the detail), which, during the filling of the die by the deformed material, causes the presence of laps, wraps and underfills on the forging. Through the determination of the key parameters/quantities during the forging process, which are difficult to establish directly during the industrial process or experimentally, a detailed and complex analysis was performed with the use of FEM as well as through microstructure examinations. The results of the performed numerical modelling made it possible to determine: the manner of the material flow and the correctness of the impression filling, as well as the distributions of temperature fields and plastic deformations in the forging, and also to detect the forging defects often observed in the industrial process. On this basis, changes into the process were introduced, making it possible to improve the currently realized technology and obtain forgings of the proper quality as well as shape and dimensions.

Keywords: hot die forging; numerical modelling; microstructure analyze; forging defect; improving of technology

1. Introduction

The competitiveness observed in the motor industry in the recent years stimulates the search of new energy saving and eco-friendly technologies of producing car subassemblies, such as connecting rods, gear wheels, worm gears, including also lever-type elements used in motorcycles. This is especially important in the case of the customers of the motor and aircraft industry, where the requirements connected with the accuracy and quality of the forging are at the highest level. Hot die forging is one of the most difficult to realize production processes, both for technological reasons and in respect of the quality of the obtained products as well as the durability of the forging instrumentation. It is so because the shape of the forgings is calculated with the consideration of the costs of the forging tools needed to produce them in the assumed amount and shape-dimension quality, with the pre-established number of such forgings obtained from the given tool. Despite the fact that the die forging technology is relatively well-mastered, the proper manufacture of forgings with complicated shapes fulfilling the high quality demands of the consumer requires high experience of the constructors, technologists and machine operators [1]. Introducing new forging designs, the continuous optimization of the existing technologies and the big number of factors affecting the correctness of the whole production process as well as their interaction make the die forging processes very difficult to analyze. This also results from the fact that a lot of crucial technological parameters of the process are difficult or impossible to determine, and additionally, the forging processes are still often realized by a human, which makes the human factor play an important role in the process [2-4]. That is why, at each stage of the whole technological chain of the die forging process, it is necessary to control and measure (sometimes on-line) the key parameters/quantities [5,6], as there is a potential risk of error, resulting in the formation of defects and a lowered quality of the end product, i.e. the forging (Fig. 1).

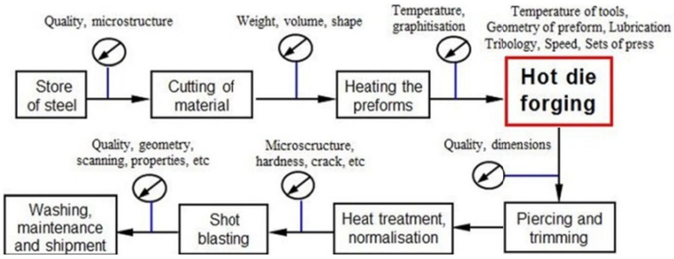

Fig. 1. Block diagram of the technological chain of the die-forging technology [4]

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The situation is much more serious in the case of developing new technologies, where, beside the standard control procedures, additional analyses and measurements are required. At present, in such a case, the knowledge and experience of the technologists and constructors is usually applied. However, more and more often, the analysis and optimization of the whole forging process take advantage of a range of IT engineering tools as well as numerical methods based on FEM, and also thermovision measurements and dimensional analyses with the use of laser scanners [7-9]. Here, it seems that the highest amount of information can be obtained from numerical modelling based on FEM/FVM, as calculational packages of this type make it possible to determine many physical quantities as well as other technological parameters which are difficult or impossible to determine experimentally.

2. Subject matter

The wear of forging tools as well as other instrumentation causes a change in the geometry of the manufactured product, and any tool surface defects are reflected on the forged item, affecting the quality and functionality of the final product made from the forging. The main and most frequent wear mechanisms include: abrasive wear, mechanical cracking, plastic strain as well as thermal and thermo-mechanical fatigue [1]. Damaged, defective and often wrong designed tools are the cause of numerous product defects obtained in the forging processes, i.e. forgings. One can distinguish between two groups of forging defects. The first group is constituted by defects caused by the realization of the forging process. The other group includes forging defects created for reasons independent of the forge, for example caused by the subcontractors cooperating in the scope of the delivered material and the production of tools used in the forging process, as well as their thermal and mechanical treatment [10]. The most frequent forging defects are:

- Incorrect shapes and dimensions of the forgings, joggles, twists, underfills, underforgings, deformations, bends, etc.,
- Defects of the outer and inner surfaces, cracks, hot tears, laps, shells, etc.,
- Hidden inner defects, decarburizations, internal cracks, incorrect fibre arrangement, incorrect grain size.
- Inappropriate mechanical, chemical, physical and technological properties [10].

Fig. 2 shows exemplary forging defects.

At present, because of the costs of forging tools, one can notice an increased interest of the industry in research related to forging tool durability. It seems that the proper designing of preforms and slug forgings in the forging processes is an important aspect of improving the quality of the product and lowering the production costs connected with material losses for the flash, or losses related to improperly manufactured elements. Additionally, it shortens the process of designing, activating and supplying the compatible forging patterns, fulfilling the time frames of the customers in the motor industry branch. Most researchers and experienced forge engineers state that the most frequently observed forging defects (underfills, laps) are the result of incorrect geometry and/or improper placing of the preform or slug forging on the roughing tool. These errors result sometimes from the unavailability of given bar profile at the steel plant, as well as the geometry of the designed detail making it impossible to prepare the material to be arranged or the lack of proper machinery for the preparation of the slug forging. In the die forging processes, the appropriate distribution of cross section fields on the length of the straight axis of the preform (or slug forging) and its preparation through shaping is very important for the material to fill the die impression [11-13]. Other causes of the presence of forging defects can be: too high temperature of the charge material, the use of too strong drafts, badly made tools, imprecise removal of the scale or an imperfect technology. Most of the causes of the formation of defects is dependent on the activities of the forge, but there are also incompatibilities independent of its actions and yet possible to be controlled and supervised in order to prevent product quality reduction [14-16].

In the available literature, there are a lot of research studies and articles referring to the selection, designing or optimization of the geometry of the charge material, while there are few works concerning the application of numerical modelling based on FEM for the analysis of the formation of forging defects. The

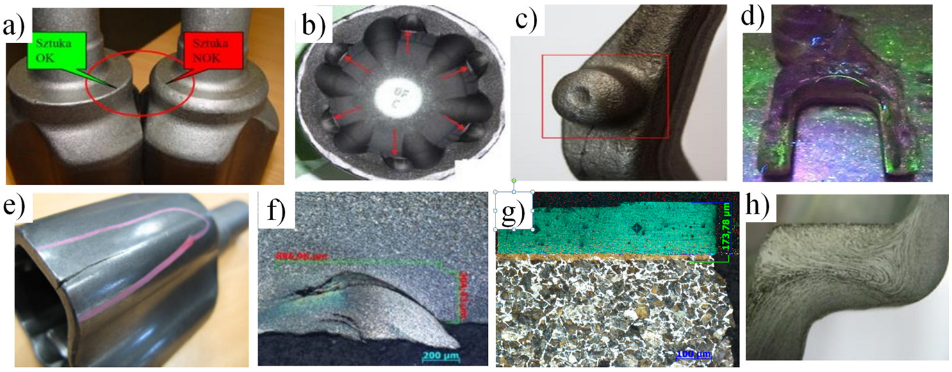

Fig. 2. Examples of the most frequent forging defects: a) an underfill – no edges, b) joggles, c) an underfill as a result of the so-called Rebinder effect, d) a lap – revealed after flaw detection, e) a lap, f) a crack beneath the surface, g) decarburization, h) incorrect distribution of the fibres – Jacewicz test

possibilities of the use of FEM have been discussed in [17-21]. FEM numerical modelling applied in these studies is used mostly in order to determine the optimal shape and dimensions of the preform and the slug. This is especially justified in the case when the forging has a complex shape, such as a turbine blade, toothed gear, a yoked forging, etc. [22-27].

The use of numerical software taking advantage of both FVM and FEM for the analysis of the issue connected with improper geometry and/or arrangement of the preform, or incorrect geometry of the tool impression, is at present the most frequently applied solution at forges. The calculational packages currently used are equipped by the software producers with more and more functions making it possible to perform an even better and more thorough analysis of the plastic treatment processes, thus enabling e.g. a detection of defects in the forgings or an analysis of the tool durability (Forge, QFORM, Simufact) [28,29]. The application of such functions by the user makes it possible to significantly shorten the time of new project implementation and limit the errors in the instrumentation design. One of such functions available in the program Forge 2011 is lap detection ('folds' function) [28]. During the simulation of the forging process, it can happen that some of the areas of the deformed element get in contact with each other. Initially, these are lines on the surface of the forging, which during the simulation, expand and penetrate the inside, thus precisely representing the size and depth of the defect. The software localizes the areas where the laps are formed, as well as their growth and final shape. The defects of the deformed forging in the form of laps are visible in the post-processor as a cloud of red dots (spots). Fig. 3a shows the stages of the formation and growth of laps in the examined element, revealed with the use of the mentioned folds function.

Fig. 3b, in turn, shows the results of a metallographic analysis confirming the obtained FEM results in the selected area of the forging. The development of laps is estimated in each calculational step. Additionally, the consideration of the line of material flow in the forging enables a more precise analysis of the causes of the appearance of this type of defects. Of course, the classic methods of designing the charge and the shape of forging tools without the use of specialized computer programs are still used at older forges, although even such places more and more often reach for IT tools. However, a combination of the numerical modelling results with microstructural tests is a good direction of science development, especially in the aspect of the search of solutions for problems being on the border of production technology and material engineering. In many cases, such an approach enables an in-depth and fast analysis of the problem as well as a verification of the proposed solutions.

The aim of the study is an analysis and perfection of the currently realized technology of the multi-operation process of producing a lever-type forging (with complicated geometry) with the use of numerical modelling and microstructural tests.

3. Test subject and methodology

The study performs an analysis of the industrial hot die forging process of producing a lever-type forging, made from a specially prepared slug through longitudinal rolling on groove rolls. A forging of this type is used as an important element in the motorcycles of a popular producer (Fig. 4), and so it is required to exhibit high operational properties, which is connected mainly with ensuring the appropriate flow of the forging material during the forming, as well as lack of surface and internal defects, and also a high quality and shape and dimensional accuracy. It should be pointed out that, due to its quite complicated geometry (bent main axis of the forging, deep and thin protrusions), developing the proper technology of its production is made additionally more difficult. In serial production, the method of multi-operation hot forging on a press is applied through the operations of preparing the slug on a rolling mill and then roughing as well as finishing die forging, followed by trimming combined with partial hot piercing. Next, forgings of this type undergo the standard thermal treatment, i.e. normalization.

Due to many factors affecting the properness of the industrial forging process, especially the multi-stage, complex and very often very dynamic production technologies (the deformation during one forging operation lasts about 0.2s), as well as their mutual interaction, processes of this type are difficult to analyze [23-25].

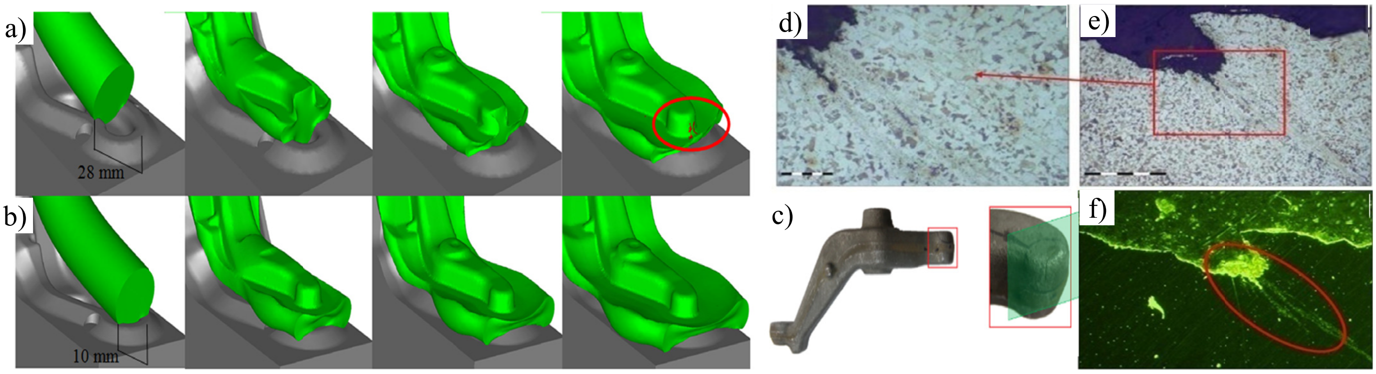

Fig. 3. Shapes of the forgings for different values of the opening between the tools: a) a forging moved 28 mm from the die's end – the end of the process reveals laps owing to the use of the folds function, b) a forging moved 10 mm – no laps, c) the lever forging with cross-section marked, d), e), f) microstructure analyses [10]

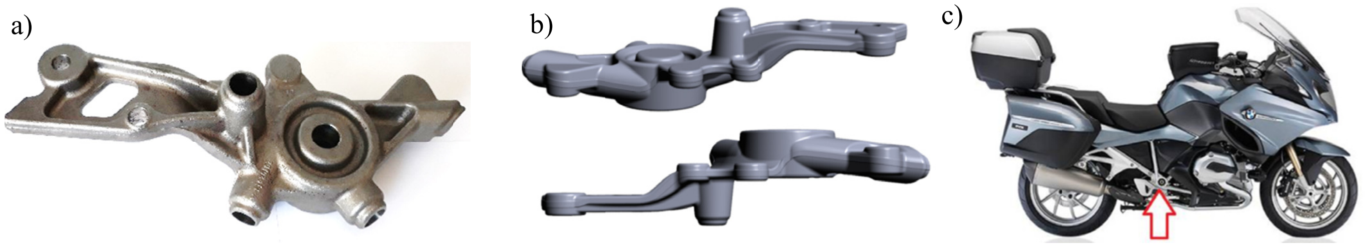

Fig. 4. Images of: a) a ready product of a lever-type with preliminary mechanical treatment, b) a CAD model, c) a motorcycle with marked lever elements

The process of producing the selected element, realized at the Forge of Jawor SA, runs in over a dozen forging procedures and operations. The input material is an alloy steel bar of elevated strength (weldable, from the S355J2 steel group) with the profile ϕ 50 and the length 210 mm. After the cutting of the charge material, the latter is heated in an induction furnace to the temperature of 1050°C, followed by the removal of the scale on a descaler, rolling to obtain a slug and then die forging on a crank press with the pressure of 13MN in two impressions. The die inserts are pre-heated with a waste material up to 200-250°C. Fig. 5 shows an image of the forging work centre used to produce a lever forging.

As important elements used in the motor industry, the lever-type forgings are required to exhibit good strength properties, dimensional accuracies, non-carburization and the proper arrangement of the fibres, and so, after the operation of separating the flash, normalization, two-stage shot peening, cold calibration, defectoscopy as well as 100% final control are applied.

4. Result analysis and discussion

In successive subchapters there are presented results relating to numerical simulations, as well as tests under industrial conditions, micro- and macro-structural analysis.

4.1. Numerical modelling

For a more thorough analysis of the industrial forging process based on the current technology, numerical modelling was performed. On the basis of 3D scanning of a ready lever-type element as well as the available technical documentation, CAD models of the ready element and the tools were built with the use of the Catia V5R20 program, by Dassault. The numerical simulations of the multi-procedure process were performed with the use of the calculational package Qform VX, by Quantorform. All the simulations were made on 3D numerical models with the consideration of the most complex thermo-mechanical model with deformable tools. In order to perform a proper simulation, it is necessary to select the parameters corresponding to the actual process. The material used as the charge (S355J2) was chosen from the material database of the program, and for the die inserts, hot operation steel WCLV, standard DIN 1.12343, Young's modulus about 200000 MPa, was applied. The tool temperature was assumed at the level of 250°C. The charge material in the form of a cylinder was heated to 1050°C, and after being rolled into a slug, it was cooled in air for about 3s, and between the operations, for 2s. The Levanov friction model was assumed, with the coefficient of friction 0.4 (in the industrial process, graphite with water is used). As the forging aggregate, a crank press was selected from the program's database, with the characteristics and parameters being in accordance with an industrial press. In the first place, the filling of the impressions was analyzed in the particular procedures (Fig. 6).

The preliminary results referring to the filling of the working patterns of the tool showed that the technology is designed properly, although its certain elements related to process repeatability should be perfected, as they can be the cause of the appearance of flaws and defects in the forgings. Fig. 7 shows the results together with the temperature field distributions for the slug after rolling, roughing and finishing forging.

During the rolling, no temperature drop was observed in respect of the initial temperattue of 1050^{o}C (before the rolling, the bar is descaled). Additionally, the deformed part had a slightly higher temperature. Similarly, during the roughing, the temperature dropped about 100^{o}C in the impression, whereas in the flash, in the areas of intensive flow, the temperature even in-

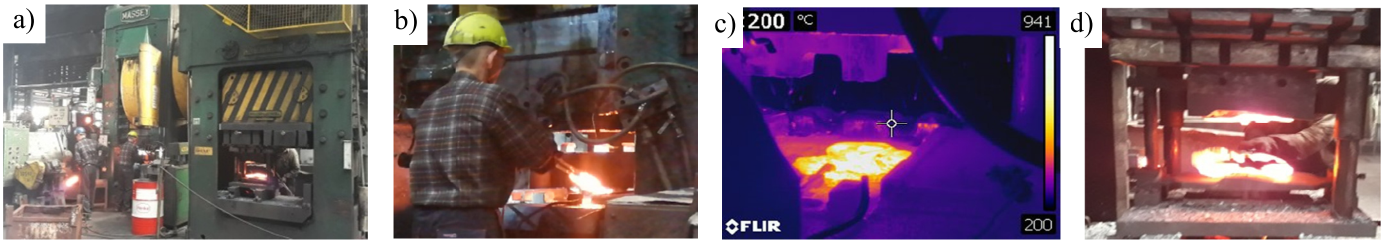

Fig. 5. Production line to produce a lever type element: a) view of the forging work centre, b) the process of die forging, c) a thermogram of die forging, d) trimming of a hot forging

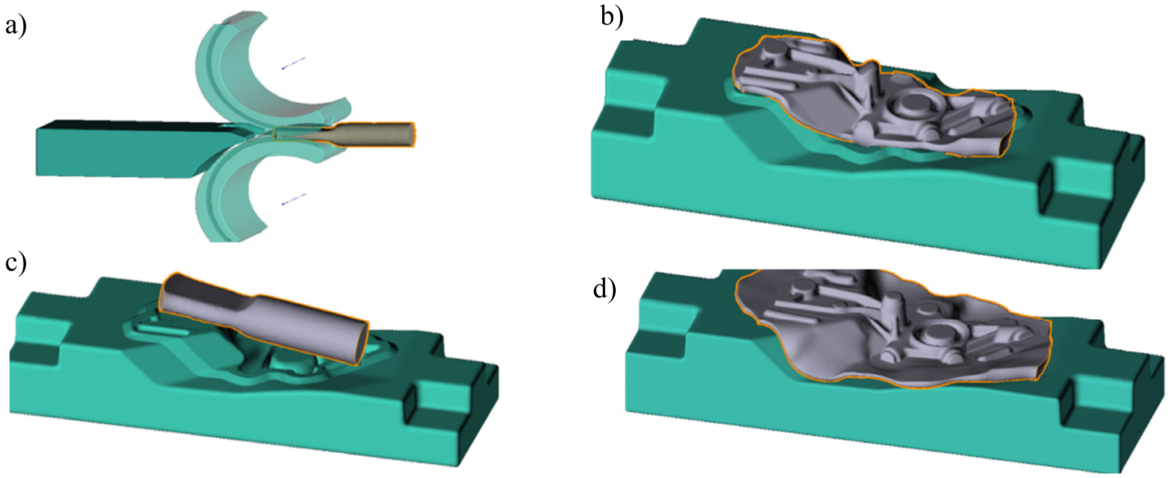

Fig. 6. Material forming – filling of the impressions in particular operations: a) during rolling, b) arrangement of the slug in the roughing pass, c) preliminary forging, d) finishing forging

Fig. 7. Temperature field distributions for particular operations: a) rolling, b) roughing, c) finishing forging

creased by 50°C. The most heated section of the shaped material is the thin flash, on which the temperature rises very fast. This is caused by the low thickness compared to the whole forging (Fig. 7b). During the finishing forging, the temperature drop in the forging is higher, and the mean temperature of the deformed part equals about 1000°C (Fig.7c). The distributions of plastic deformations for the slug after rolling as well as roughing and finishing forging have been shown in Fig. 8. In the case of the slug (Fig. 5a), in the rolled deformed section, the plastic deformations equal about 1.

In turn, for the forging after roughing (Fig. 8b) and finishing forging (Fig. 8c), the deformations are within the scope of 2,5 to as much as 4, depending on the area and the deformation size. It can be seen that, in both cases, the least deformed area is the central round part, which, at further production stages, is pierced and mechanically treated.

4.2. Tests under industrial conditions, micro- and macro-structural analysis

One of the highest risks occurring during the forging of such elements as a lever (a forging of a relatively complicated shape and a bent axis), especially in the case of the newly activated technology, are forging defects, of which the most dangerous ones are mostly laps and material wraps. The first trial series of producing 100 test forgings under industrial conditions showed numerous wraps and laps, a part of which was revealed only in defectoscopic tests (Fig. 9).

The defects observed and then detected during the tests are mainly localized in three areas shown in Fig. 9. The highest amount of defected forgings had clear laps in area no. 2 – a thin, deep plug. In turn, in the vicinity of area no. 1, a defect in the form of a visible lap was observed on the so-called “small fin”

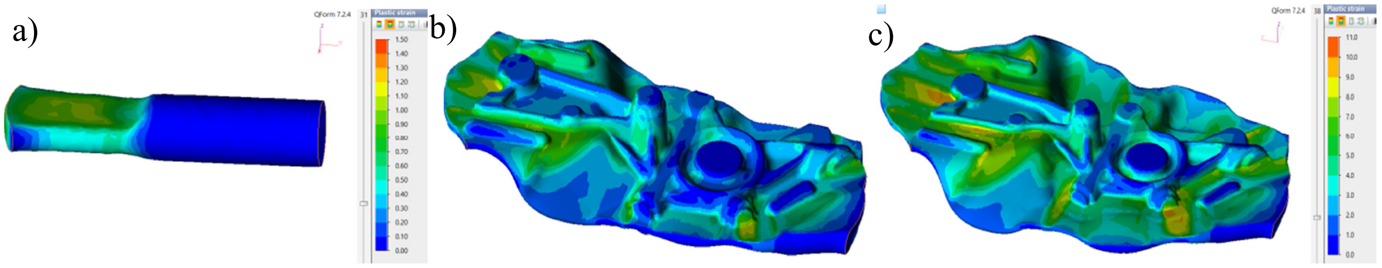

Fig. 8. Distributions of plastic deformations after: a) rolling, b) roughing, c) finishing forging

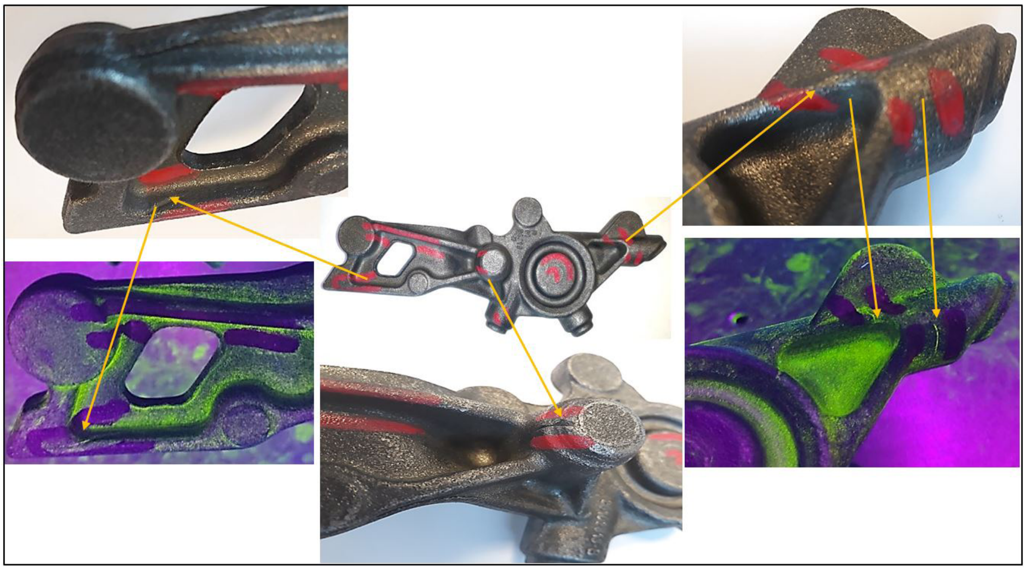

Fig. 9. Defects observed during the test series of forgings

as well as a lap detected only during the defectoscopy, marked with an ellipsis. In area no. 3, shallow material wraps were much more often observed than laps.

The performed defectoscopic tests were supplemented by microscopic metallographic examinations. Microscopic optical tests as well as tests on a scanning electron microscope with the use of an SE and BSE detector were performed (in order to determine the presence of inclusions and oxygens in the material's structure). Fig. 9 shows the product/forging subjected to the analysis. One can see the areas where the material was collected for the tests (Fig. 9). Fig. 10 shows the area from Fig. 9, on which material folding was revealed during the defectoscopic tests.

This defect, in this shape, can be qualified as underfilling of the impression. No presence of laps in this area was detected. The lines of material flow run properly, without disturbances. There are no inclusions in the material's structure. The structure of the material is correct, i.e. ferritic-pearlitic. Fig. 11 shows a visible lap of the material in area 2 (Fig. 9). The figures present inclusions of iron oxides lapped in the material's surface layer.

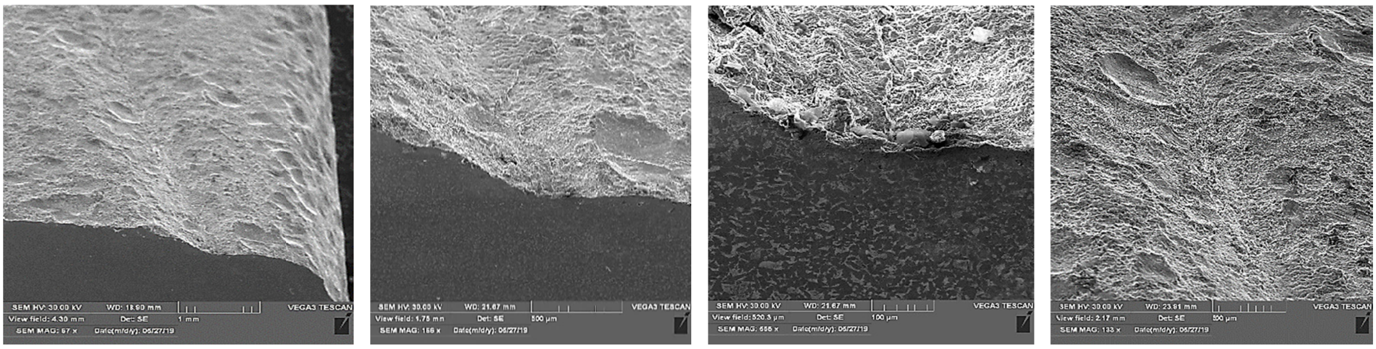

Fig. 10. Surface fold – no lap – area 1

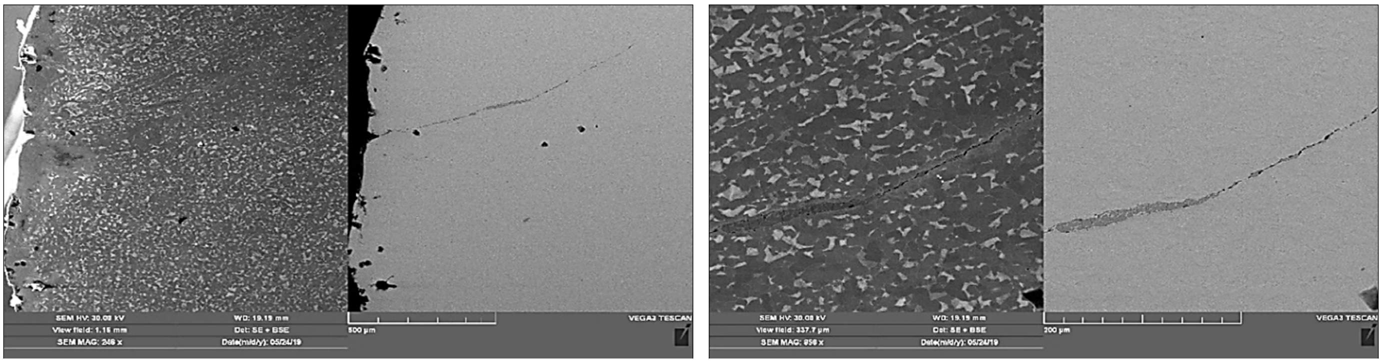

Fig. 11. A lap in area 2. A composition image – SE + BSE detector

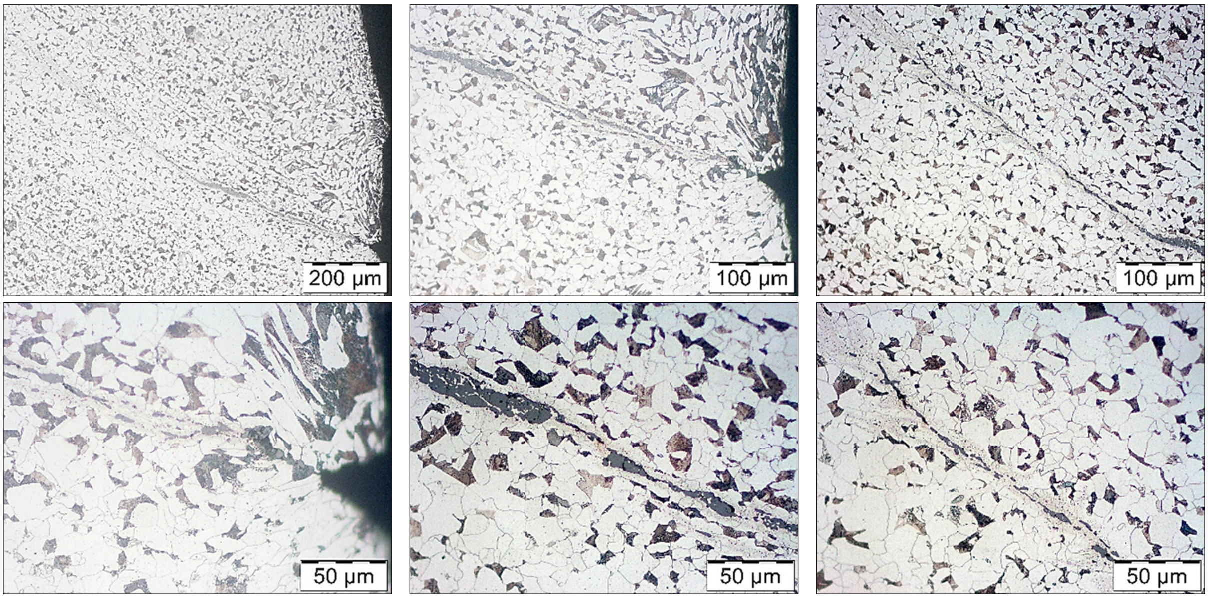

Fig. 12. Laps in area 2. Nital etched

The analyses were performed with the use of an SE and BSE detector (descriptions on the images). The measured length of the lap is about 2,5 mm. Visible material's discontinuity in the area of the lap and microstructure deformation at the material's surface. Fig. 12 shows the results of the optical microscopic analysis.

Similarly to Fig. 11, one can see a lap of the forging material. The laminarity of the structure is in accordance with the direction of the lap – incorrect flows of the die impression material.

The examinations of area 3 were carried out on a scanning electron microscope with the use of an SE and BSE detector. Fig. 13 shows a visible material lap in area 3 (Fig. 9).

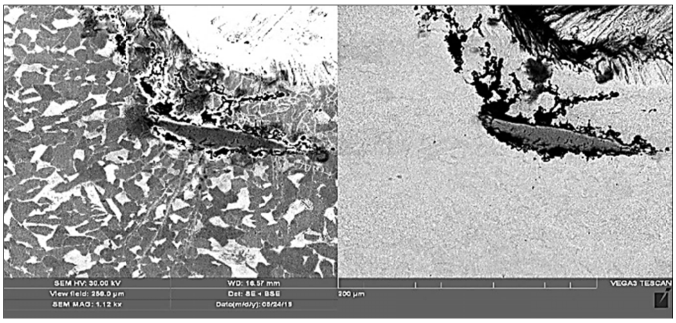

Fig. 13. A lap in area 3. A composition image – SE + BSE detector

Fig. 13 and 14 shows iron oxide inclusions lapped in the material's surface layer. There are visible disturbances of the material flow line. This proves an incorrect filling of the die impression during the forging process. Both in the electron and optical microscope images, one can observe the presence of lapped scale originating from the surface of the treated material.

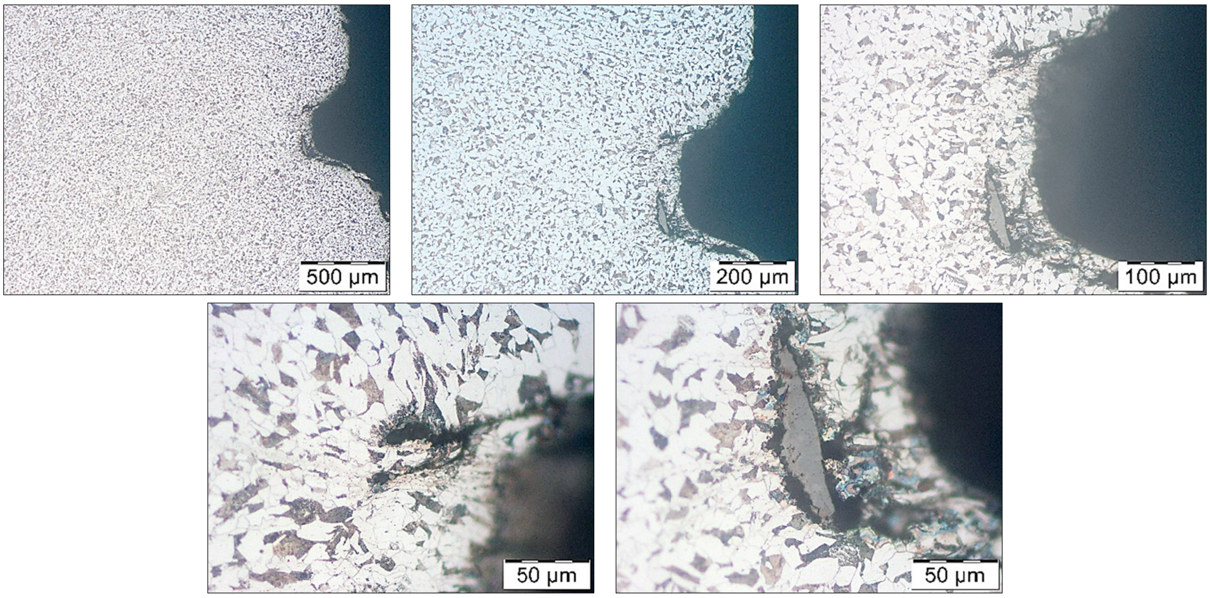

Fig. 14. A lap in area 3. Nital etched

During the microscopic analysis in areas 2 and 3, the presence of laps from the industrial process was observed. In area 3, based on the FEM examinations, the presence of a fold on the surface was established. No laps were observed in this area. The material in area 3 is coherent and does not have inclusions in its microstructure.

4.3. Additional numerical analysis

In order to perform an additional analysis by means of numerical modelling, analyses with the use of the flow lines introduced into the charge material in the form of layers in the longitudinal (Fig. 15a) and transverse (Fig. 15b) direction were carried out.

The presented results of numerical modelling referring to the distributions of the fibres in the forging in two directions confirm the fact that the defects in the form of laps can appear in the areas determined in the forged test series of forgings. This can be especially noticed in area no. 2, i.e. a deep pin, where one can see that the fibres in both the longitudinal and transverse direction have a tendency for folding and intersecting.

Also, in order to determine the causes of the detected defects, after the analysis and interviews with the operators participating in the technological trials, it was established that their cause could be an improper length of the rolled part of the slug as well as a problem with the correct positioning of the slug in the roughing pass. Next, by means of special functions (e.g. laps, folds, etc.) in the QForm program, a decision was made to simulate different variant arrangement and detect the most defect-risky areas of the formed material. Owing to the use of modelling, it is possible to easily and quickly localize the areas in which defects may possibly appear. Fig. 16 shows the results of the simulation for the three variants which are most frequently observed in the industrial process.

The test results obtained on the basis of the performed numerical modelling demonstrated that, in the analyzed case, the appropriate length of the part rolled in the wire rod (Fig. 15a) as well as its arrangement in the roughing pass (Fig. 15b and 15c) are of utmost importance. Also, the presented results show how much, in the industrial process, depends on the operators-blacksmiths, or in fact on their knowledge and manual skills. This fact makes an improper preparation or arrangement of the slug result in a defected final product.

5. Proposed changes and verification of introduced solutions

On the basis of the presented results of tests performed with the use of numerical modelling as well as micro- and macroscopic tests, a decision was made to introduce changes into the existing technology. The changes concerned mainly a reconstruction of the working impressions of the dies used during roughing. Additionally, the charge material temperature was raised by 100°C and an automatized cooling and lubricating

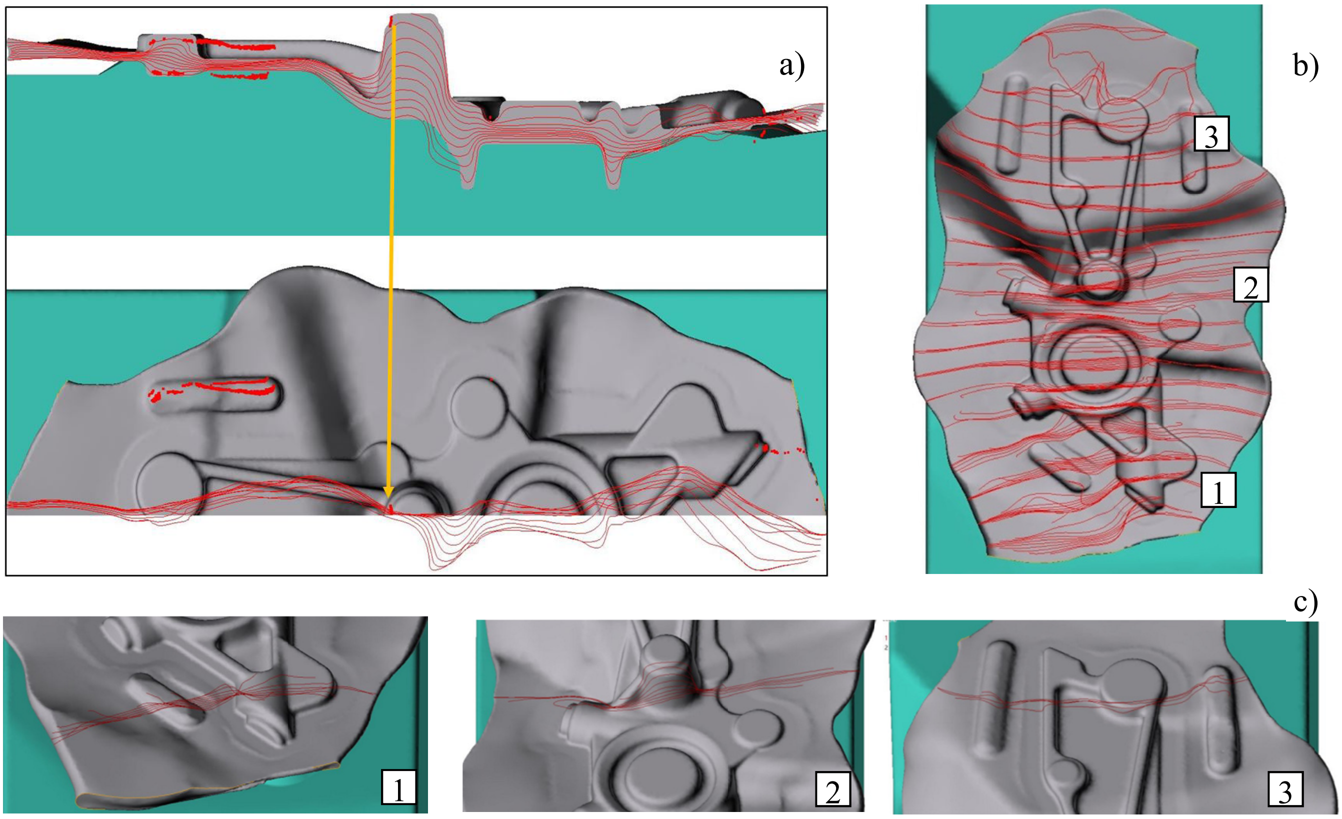

Fig. 15. Analysis of the flow and distribution of the fibres in FEM: a) image of the lines arranged in the charge material in the longitudinal direction, b) transverse direction, c) a detailed analysis for layers 1, 2 and 3

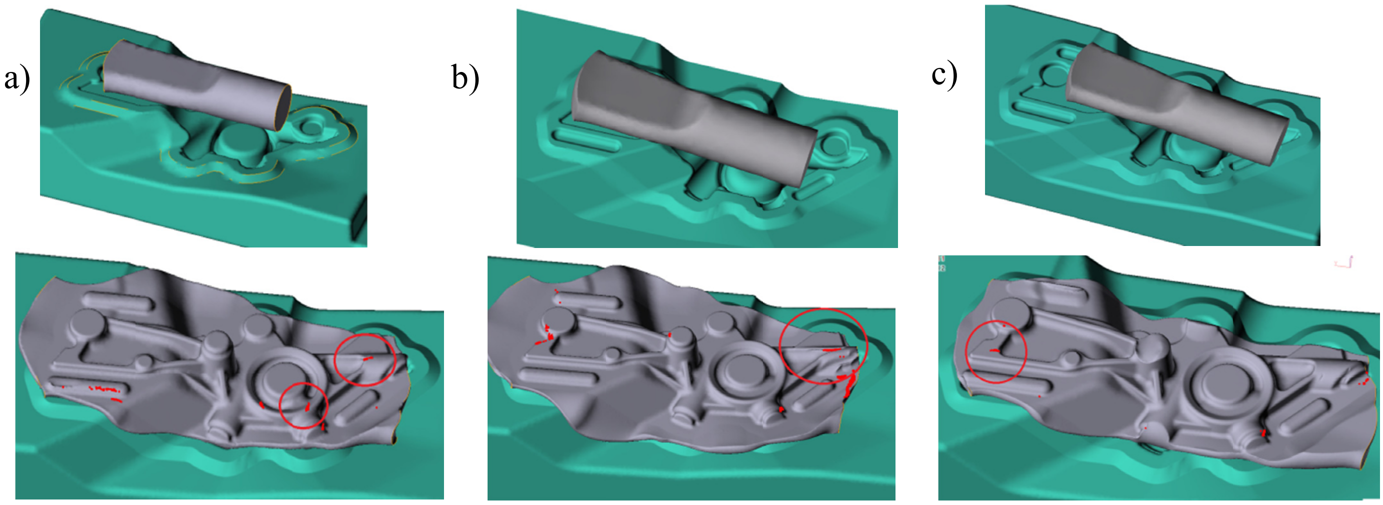

Fig. 16. Forging defects (at the bottom, the slug at the top): a) too long rolled part of the slug, b) too big shift of the slug towards the left side of the impression, c) too big shift of the slug towards the right side of the impression

device was used, which meant stabilized tribological conditions. Summing up, slightly increasing the charge material temperature and applying better lubrication may ensure a better material flow in the area of the pin. Detailed information on the elaborated lubricating device can be found in the studies [30,31]. Fig. 17 shows a compilation of the changes introduced into the die impressions used in the roughing operation.

The main changes (denoted with numbers 1 and 2) in the lower tools referred to:

1. Selection of the wire rod end for the positioning before forging.
2. Expanding the radius on the pin – a change in the material shift during forming and elimination of the lap near the pin.

In turn, in the upper tools (denoted with numbers 3,4 and 5) referred to:

3. Introduction of a phase, finishing with a radius – a change in the schematics of the shifts, avoidance of material closing (lap).
4. Shallowing the pin and increasing the radius on the high pin. Eliminating the lap/underfill.
5. Increasing the radii, eliminating the lap on the front of the forging.

Next, for the tools reconstructed this way, numerical simulations were performed again with the use of the folds function, and the obtained results are shown in Fig. 18.

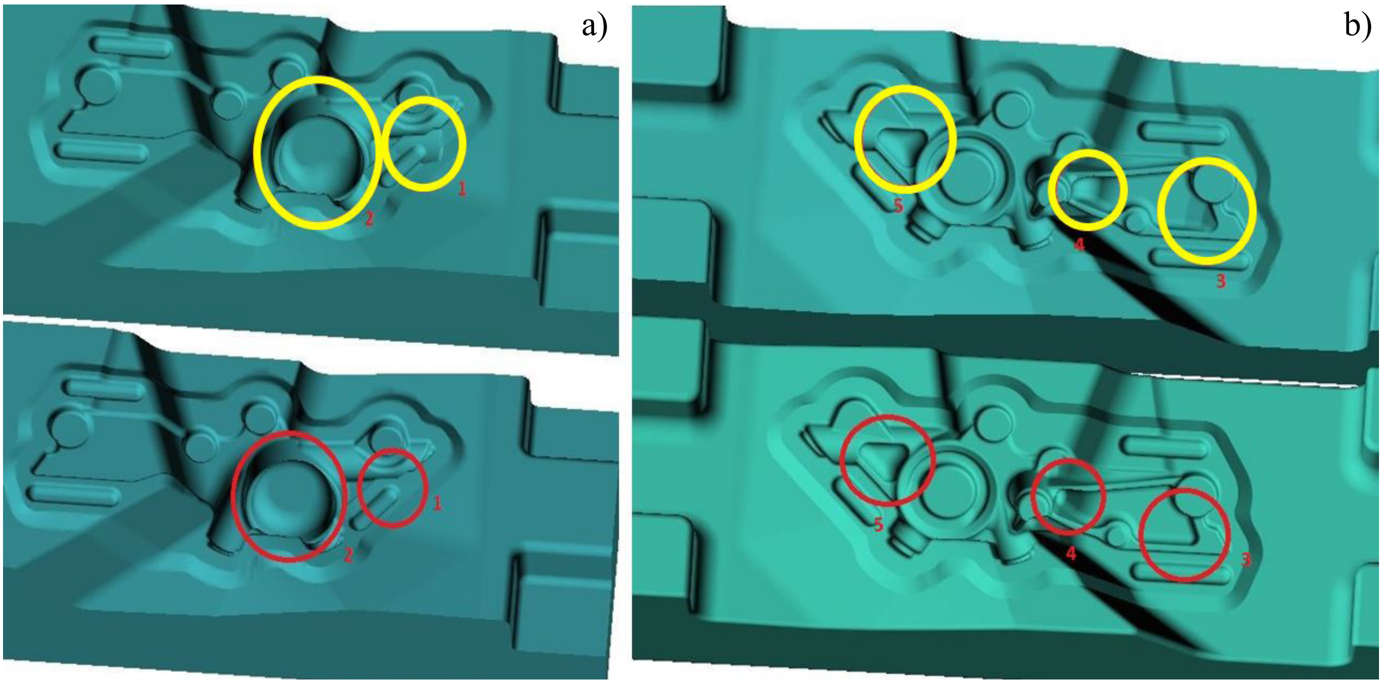

Fig. 17. Suggestion of a change in the geometry of the impression of tools used for the roughing operation – the upper images show the tool after the changes: a) lower dies, b) upper dies

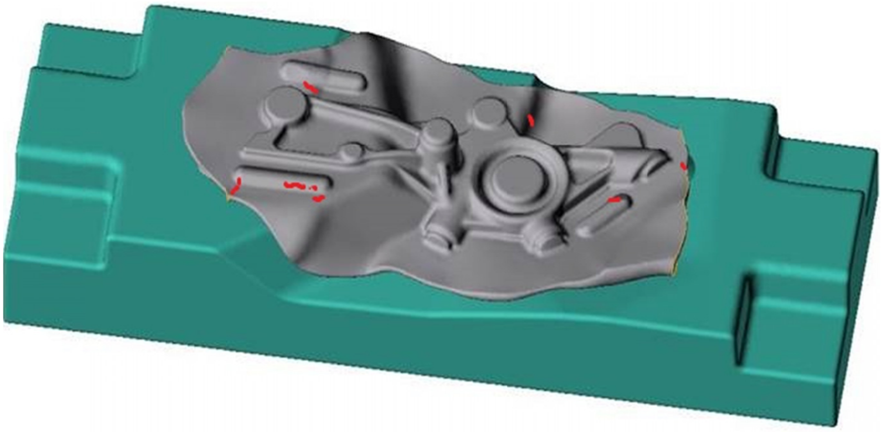

Fig. 18. Results of numerical modelling after the introduced changes into the roughing tools geometry – folds function (lap detection)

The presented modelling results referring to the detection of areas in which laps can possibly appear show that, in the area of the forging, such areas do not exist. One can only see "red spots" in the vicinity of the magazines as well as in the areas where the main forging axis is bent, while all of them are localized beyond the forging.

On this basis, a decision was made to produce a test series of forgings under industrial conditions on the reconstructed dies and, additionally, to increase the temperature of the charge material from 1050 to 1150^{o}C, as well as to apply an automatized cooling and lubricating device. After producing a test series of 50 forgings, the latter underwent a macroscopic analysis, which revealed sporadically appearing small material folds. For one of such forgings, microstructure tests were performed in the same areas for which the defects were previously detected. Fig. 19 shows an image of one of the forgings from the tests as well as microscopic images of the selected areas: 1, 2, 3.

The performed microscopic analysis and the macroscopic tests did not reveal laps in any of the analyzed areas of the forging. A fine-grained ferritic-pearlitic structure. No inclusions in the surface layer. A proper arrangement of the fibres. The new technology also prevents the appearance of material folds in the analyzed areas. In turn, it can be observed that increasing the temperature of the charge material in some areas with high deformation causes changes in the microstructure – a different shape of the ferrite precipitates (feathery), which can point to local overheating (Fig. 19b). Fig. 19a shows the microstructure obtained in the technology used so far. Its effects are removed in the standard thermal treatment applied for this product, i.e. normalization after forging.

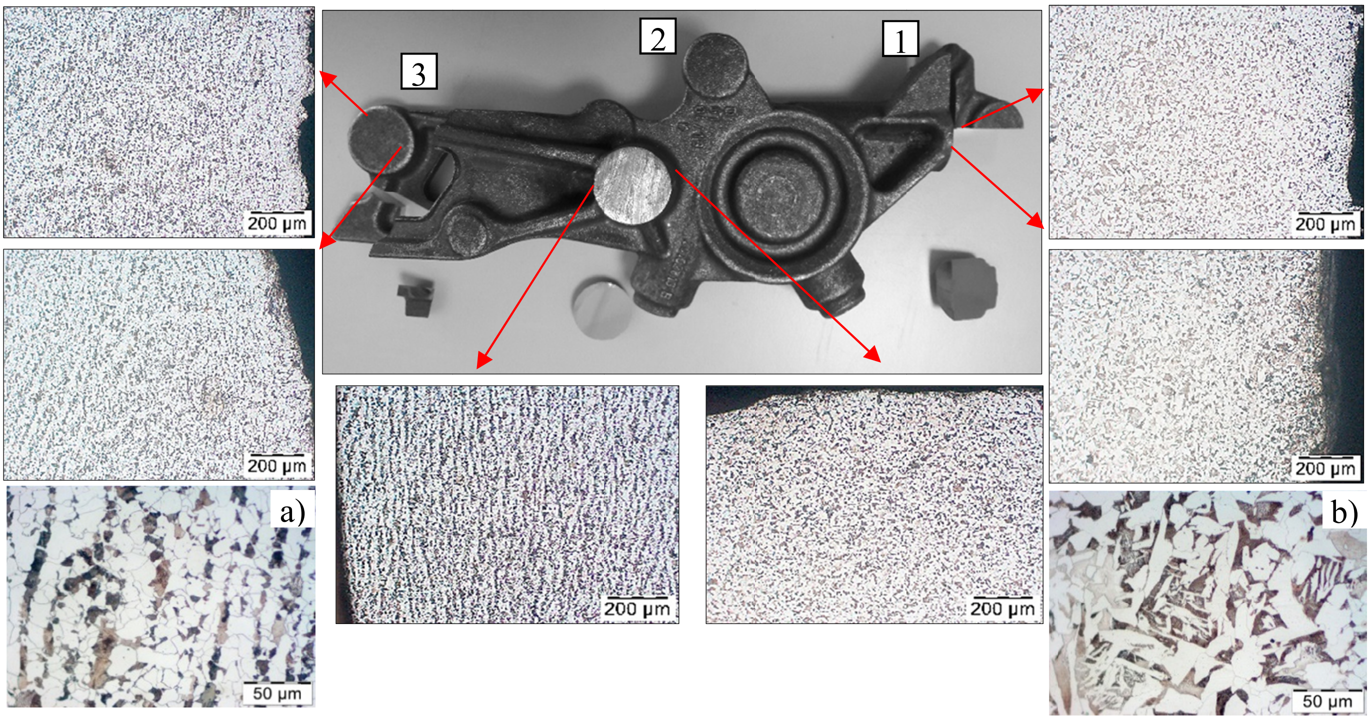

Fig. 19. Image of a forging from the tests and the microstructure of the selected areas: a) before the charge material temperature change, b) after the charge material temperature change

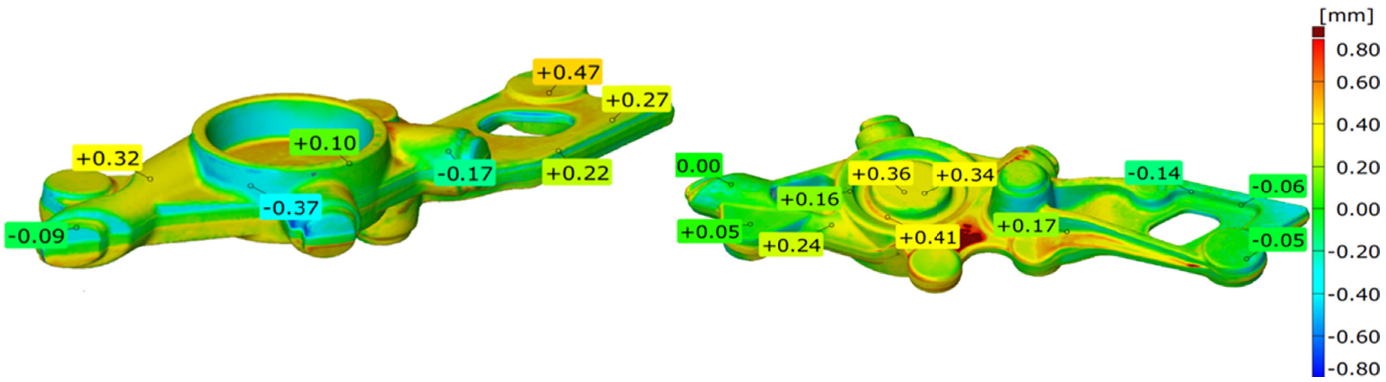

Fig. 20. Comparison of the produced forging with the CAD model after the introduced changes

Additionally, in order to verify the results, one of the forgings obtained from the test series was scanned by means of a measuring arm. With the use of the PolyWorks program, the dimensional deviations of the ready forging were illustrated in the nominal dimensions (Fig. 20).

Based on the presented results obtained from scanning, it can be inferred that the obtained forgings, after the introduced changes into the technology applied so far, are within the scope of the assumed tolerance field, which, in the case of the forging's thickness from the parting plane, equals from –0.8 to +1,2 mm, and on the length – from –0.2 to +0,5 mm. The presented results confirm the validity of the proposed procedures and the changes introduced into the technology applied so far, as well as point to the possibility of perfecting the technology of die forging with the use of the approach presented above.

6. Conclusions

The performed numerical modelling of the process of producing a lever-type forging for motorcycles has provided valuable information, difficult to obtain during an analysis of the industrial process, which concerned, among others: the distribution of plastic deformations, temperature fields as well as detection and localization of the potential defects of such forgings. With the use of the FEM results and by the introduction of possible corrections in the industrial process, it is possible, to some degree, to optimize the current technology and obtain a correct product in respect of the shape and dimensions as well as the quality. The performed analysis showed that the roughing pass as well as the bridge and the input radii were designed appropriately. There is a problem with the levelling on the roughing pass (no levelling points) and with the input/output radii for the selected shaping surfaces (causing of laps). The proposed, and then verified by means of numerical simulations, series of test forgings performed in the improved technology as well as the microstructural tests and the geometrical analysis of the forgings have made it possible to optimize the forging technology, even in the case of a complex geometry of the forging. Of course, it is necessary to perform further verification studies in order to perfect this technology for the case of large series forging production. On this basis, it can be stated that, by means of the current numerical method combined with microstructural tests, and with the support of other techniques, it is possible to design or verify and perfect the die forging production technology.

The presented results can also be used for the optimization of selected parameters of similar forging processes in respect of the quality of the forging and the durability of the tools.

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