











Capabilities of numerical simulation support for defect investigations in die forgings

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Abstract

The article concerns the use of the results of numerical simulations, primarily for the detection of defects in forged products identified at various stages, along with the analysis of the geometry of forgings and the way in which the material flows in tools. The work presents the results of measurements and analyses using numerical modelling based on computational packages dedicated to forging processes such as: QForm, Forge, etc., which are equipped with special functions that significantly facilitate analyses by both technicians and designers. These functions include: contact of the deformed material with the tool, flow line distribution, “trap” or “fold” functions for detecting forging defects, as well as other technological parameters and physical sizes, which are crucial in the case of a comprehensive analysis of the industrial die forging process. The novelty of the work is the presentation of the possibility of simultaneously combining many different non-destructive techniques and methods, e.g. results of FE simulations with 3D reverse scanning, minimizing interference in the industrial process. The research carried out allows for the thorough and rapid analysis of the correctness of the deformation of the forging material for selected forging processes, along with the presentation of methods for their prevention and solving various technological and engineering problems, which is particularly important in terms of reliability and production efficiency

Keywords: forging defects, FE modelling, hot forging process, special function in FEM packages

1. Introduction

The high competitiveness of producers of forged products observed recently means that the main factor determining the potential choice of a supplier of forgings (apart from the price, which is the main factor taken into account) is

primarily the quality and dimensional and shape accuracy of the offered products (Liu G. H., et al., 2012). The quality of forgings is especially important as described by Dyja et al. (2004) in the case of typical forged products, and for heavy forging (Liu Y. et al., 2018). This is particularly important in the case of the automotive (Park & Kwon, 2016), aviation, and military industries, where

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the requirements related to the accuracy and quality of forgings are at the highest level (Hawryluk et al., 2023). Hot die forging technologies are among the most difficult production techniques, especially in the case of precision forging processes (Douglas & Kuhlmann, 2000). It is a manufacturing method whose most crucial advantage from different types of die forging is a reduction in material waste (up to 70%) resulting from the minimization of flash (Gronostajski & Hawryluk, 2008) and the production of a finished product with minimal allowances for mechanical processing (Zuo et al., 2014). In general, forgings obtained in the precision forging process have good mechanical as well as operational properties and are characterized by high manufacturing accuracy and a narrow tolerance range (Behrens et al., 2009). On the one hand, due to its advantages, this technology is most often used to produce parts for the automotive industry from different steel materials, for the production of gears, connecting rods, worm gears, tripods, turbines, alternators and constant velocity joints (Shan et al., 2004). On the other hand, although these technologies are relatively well mastered, the correct production of forgings with complex geometry, and additionally meeting high requirements of dimensional and shape accuracy and quality, requires extensive experience from technicians, designers and operators of forging units (Dieter et al., 2003). The improvement and implementation of new forging projects, continuous improvements and optimizations of implemented technologies, as well as a large number of important factors and phenomena affecting the correctness of the entire process, as well as the interaction of these factors, make die forging processes one of the most difficult manufacturing

processes to implement and analyze (Gronostajski et al., 2014). At each of the individual steps of forging technology, there is a risk of mistakes and defect development in the forging process. The literature states that the most common defects in forgings (lack of filling, curling and crimping) are the result of incorrect shapes (Politis et al., 2018) as well as improper positioning of the blank or forging (Vazquez & Altan, 2000). Other causes of defects in forgings may include: too low temperature of the input material, the use of too large deformations, poorly made tools, inaccurate removal of scale or underdeveloped technology (Banaszek & Stefanik, 2006). Therefore, the design of blanks and forgings is an important issue for improving product quality and reducing production costs related to material losses per flash as well as losses related to defected manufactured parts (Liu Y. et al., 2018). One of the greatest threats during the forging process are forging defects and imperfections (Rathi & Jakhade, 2014). The most common in terms of forging quality, but at the same time the easiest to diagnose (Hawryluk & Ziemba, 2018), are errors in the flow of the deformed material (Fig. 1a) and incorrect filling of the working blanks (Fig. 1b) as well as partial or complete lack of filling (Fig. 1c, d).

The consequences of defects in the form of incorrect flow or failure to fill the blank with the deformed material are often material curls (partially visible on the forging – Fig. 2a) and crimping, which can only be noticed during defectoscopic examination or under a microscope (Fig. 2b), and sometimes at a later stage of production, e.g. after heat treatment (Fig. 2c) or, in extreme cases, only after final mechanical treatment (Fig. 2d).

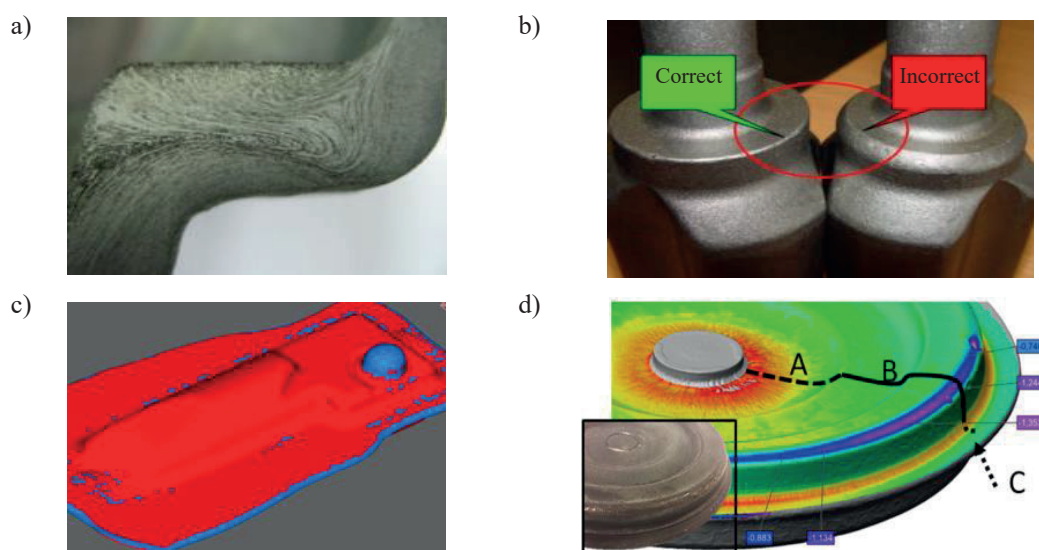


Fig. 1. Examples of forging flaws: a) improper material flow in the form of incorrect fiber distribution; b) failure to fill – no edge on the forging on the right side; c) FEM results – lack of filling in the area of the so-called “pin” in the forging of the window lock element; d) failure to fill part of the circumference in the forging of the front wheel disc

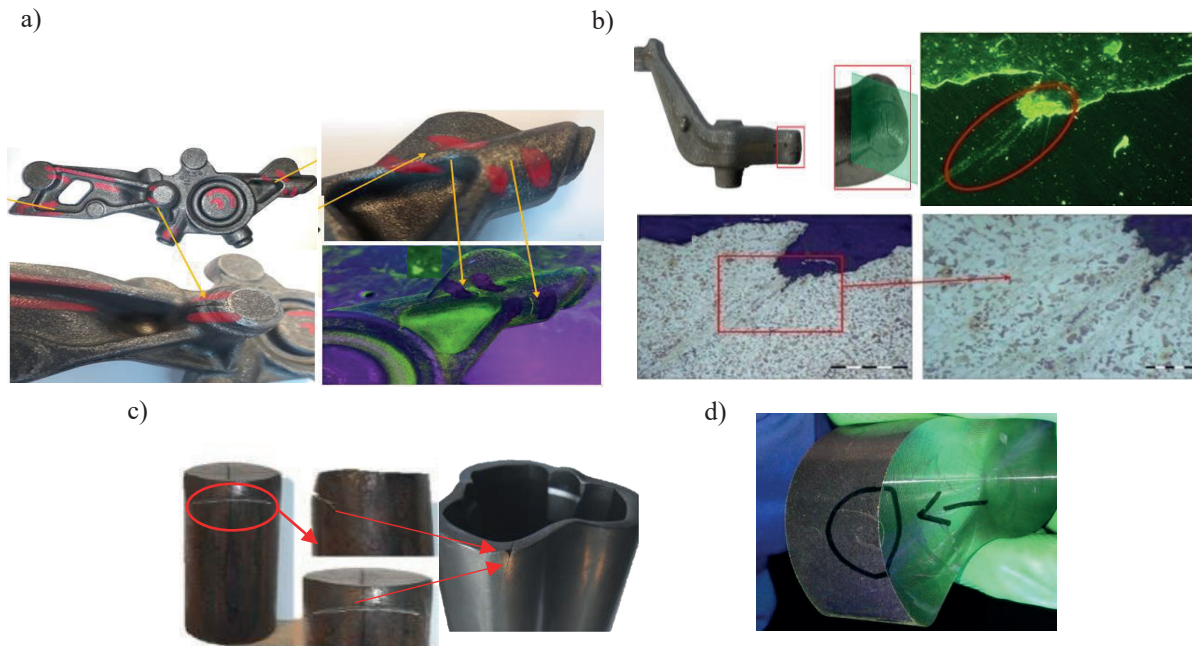


Fig. 2. Identification of exemplary defects in forgings: a) defect in the form of fold in the area of the pin and the tip of the elements in the forging of a drive lever for a sports motorcycle; b) forging photo in the head of the lever-type forging with marked defect (confirmed by defectoscope) – the microstructure with incorrect material flow; c) forging in the expander forging, revealed only after mechanical processing; d) a crack in the form of a fold revealed after mechanical treatment

The most difficult to detect and diagnose are folds/pressing areas, which are most often formed during poor material flow, when some of the deformed material still remains between the forging tools, creating bends which, in subsequent stages/operations, are pressed into the flash (Kumar et al., 2022). Also into the forging itself, which is unacceptable and causes disqualification of such elements from the process (Iwand & Wagner, 2010). Therefore, in order to design and improve the industrial forging process, a number of CAD/CAM/CAE tools are used, in particular numerical modeling and simulations, supported by IT techniques or measurement systems, like: coordinate-measuring machine, 3D scanners, advanced devices, others (Gronostajski et al., 2016). The use of numerical programs using both FEM and FVM to analyze issues related to incorrect geometry and/or positioning of the blank is currently the most common solution used by forges. The most popular and eagerly used programs are: Forge (Forge, n.d.), QForm (QForm UK, n.d.), SimufactForming (Simufact, 2015), etc. Currently, they are equipped by software producers with newer and newer functions enabling even more accurate analysis of bulk metal forming processes (Lu et al., 2018), enabling not only the basic technological parameters, although difficult to determine in any other way, or physical quantities: material flows, forces, strain distributions, temperature fields, etc. (Mohammadi & Sadeghi, 2009), but also more advanced ones, such as contact or the detection of flaws in forging elements,

or even analysis of tooling durability after a specified number of forging cycles (Hawryluk et al., 2021). The use of these functions by an experienced user allows to significantly shorten the time needed to complete a new project and eliminate errors in instrumentation design. An example of one such special feature is the ability to analyze distances of the deformed forging material from the surface of the tool blank (contact) or forgings based on the “folds” function. This function works on the principle of lines on the surface of the forging, which expand and penetrate deeper during simulation, which, if they overlap, treat the situation as folding or crimping and enable accurate tracking of this defect, determining its size and depth and locating places formation of forges, their growth and final geometry with high accuracy (depending on the adopted size of the initial mesh and remeshing). Numerical modeling programs also enable the detection of air pockets (“trap” function), i.e. empty areas between the forging and the tool in which air is retained in the form of surface or volume. If this type of “trap” defect is detected, the computational solver determines the pressure in this area is based on the volume enclosed in this place and thus takes it as the initial boundary condition during numerical simulations, thus affecting the flow of the deformed material and the correct filling of the forging tool cavity (Hawryluk & Jakubik, 2016). Air pockets may cause gaps in the die cut, as well as premature destruction of dies by increased pressures in these surfaces. Therefore, further

development and use of numerical modeling using new and very useful functions, such as contact, trap or folds, is fully justified both from the scientific and economic perspective due to the possibility of designing, comprehensive analysis and optimization of industrial forging processes, increasing thus, production efficiency and reliability (He, 2011).

2. Numerical detection of flaws and defects in the forged products

Currently, in order to analyze the correct flow of the deformed material and the appearance of possible flaws in forged parts, the aforementioned FE modelling is mainly applied. This concept is based on more or less advanced functions that allow for the detection or prediction of a defect in the process.

2.1. The use of contact functions in numerical simulations

Contact detection in FEM is often used to analyze the correct flow of the deformed material and the degree of filling of the press forging die's working impression. Figure 3 shows the results of numerical modeling for the three-operation process of forging a 60E1A needle rail into a 60E1 rail profile.

The presented results of numerical simulations indicate in which areas the material did not flow or flowed incorrectly. In the analyzed case, these are mainly areas in red/yellow color, where the distance of the forged material to the surface of the cutout ex-

ceeds 2 mm (Fig. 3a). In next, both upper drawings present are places where there was no deformation due to the lack of a tool, therefore they are marked in red color. Figure 3b shows an enlargement of the zones of the forged end, where it can be clearly seen that the material did not fill the die working cavity. But gaps visible at the end of the forging of the needle rail are not a problem because it is contained in the part cut off (in the industrial process after forging) with a length of 100–150 mm. A more significant problem in this case is the lower part of the rail (foot), because the lack of material in this area causes the disqualification of such an element. Similarly, the contact function was used in the simulation of forging a geometrically complicated hinge-type element. The simulation of manufacturing a forging consists of 4 stages: bending and flattening on an MPM6300 hammer, followed by roughing and finishing forging on an MPM16000 hammer. Figure 4 presents the results of the impression filling in the operations: roughing and finishing forging.

The results obtained show that although no proper filling within the pin area was obtained in the roughing operation (area marked with red), the filling was correct in the finishing forging operation as that area was the closest to the die parting and it was deformed first in the finishing forging operation.

Similarly, in the case of another forged element – forgings with a transverse axis in a 6-fold arrangement (a window lock forging), an analysis of the regularity of deformation and the amount of filling of the blank by the deformed forging material was carried out using the contact function. The contact detection function was applied, where Figure 5a shows the final phase of filling (0.3 mm before full contact). In turn, in Figure 5, a complete filling of the impression is shown.

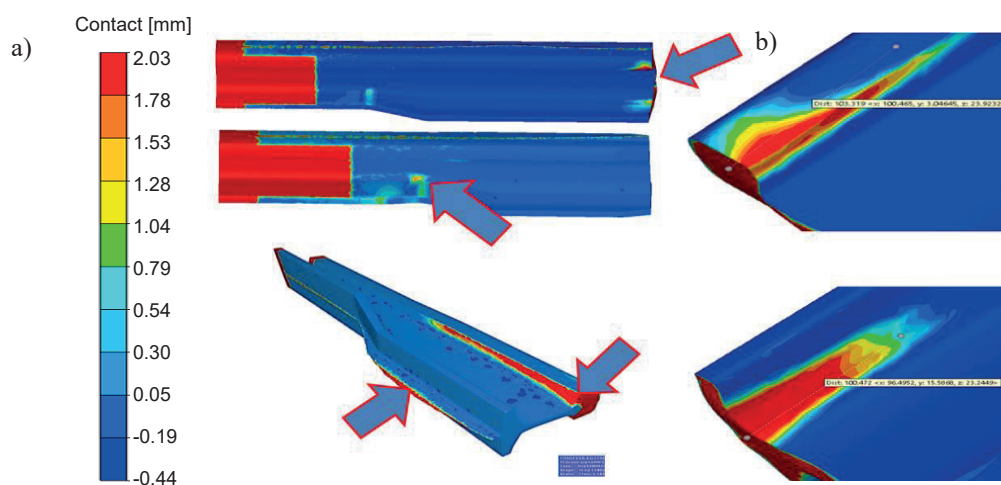


Fig. 3. The results of numerical simulation for the contact: a) at the end of deformation in final operation; b) image of enlarged areas with detected imperfections in the foot and head of the needle rail forging

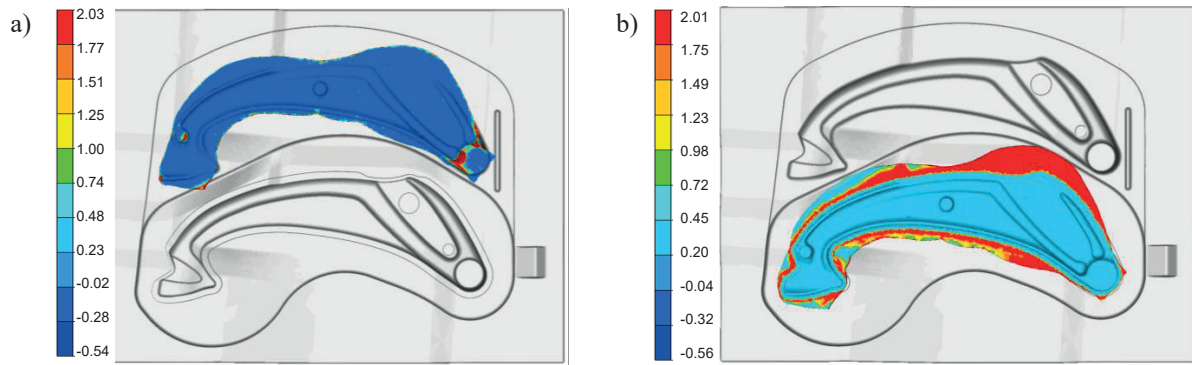


Fig. 4. The FEM results of material flows and filling cavity presented as the contact function: a) the roughing operation; b) the finishing forging operation

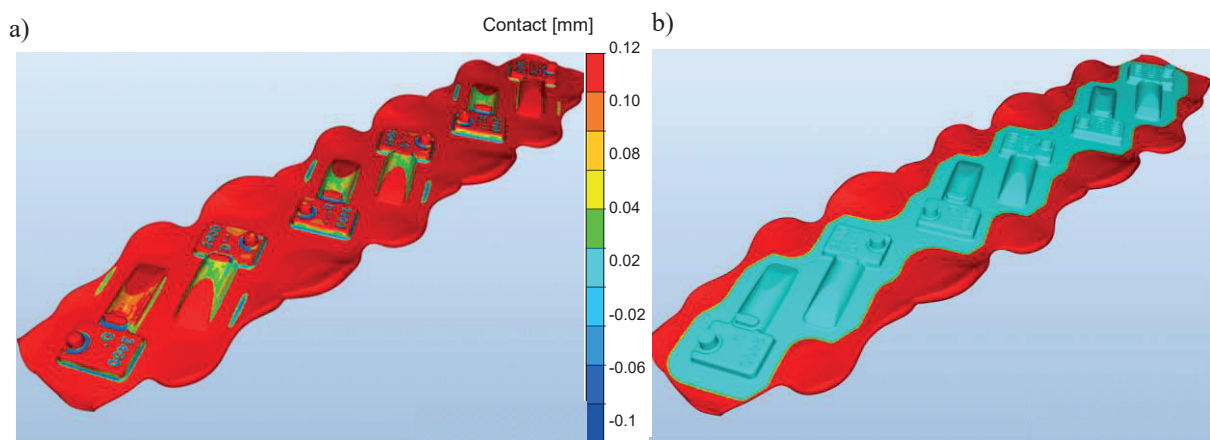


Fig. 5. FE results for finishing operation, with contact function deformed material with tools: a) 0.5 mm to full contact; b) end of the forging process

By means of this function, one can thoroughly analyse which areas in the forging are still deforming and flowing and which are no longer doing so. Such an analysis makes it possible to predict whether the deformed material is flowing according to the predictions or whether corrections are required.

2.2. The use of subsurface line functions to analyze the flow of the deformed forging material

A frequently used function in numerical simulations that facilitates the analysis of the flow of deformed material is the so-called subsurface lines or flow lines. Before the simulation, lines are introduced in the feed material in a rectangular arrangement in one or both directions. Then, during the simulation, the lines deform, showing the flow of the material. Figure 6 shows the results of modeling using flow lines for the deformed material of a tow hook forging intended for passenger cars towing trailers.

Surface lines were also used to analyze the way the material flowed during the forging process of a geometrically complex motorcycle lever type-forging (Fig. 7).

Figure 7 presents the results of deformed flow lines implemented into the feed material as a grid in both perpendicular directions. The FEM results regarding the distribution of fibers in the formed material confirm that defects (overlaps) may appear in the analysed zones. This is especially visible in area no. 2, i.e. in the recess, where one can see that the fibers from both directions have a high tendency to cross and bend. The results from the analysis of subsurface lines are similar for a fork-type forging in a double system. In Figure 8a one can see the line near the die dividing plane. There is continuity from the shoulder of the forging through the rear part, with no clear indications of cutting individual elements. Figure 8b, presents a similar correct way of arranging the flow lines in the protrusion of the forging. Additionally, when combining the obtained results with the Gartfield function, according to which the value is >0.8 , a defect may occur.

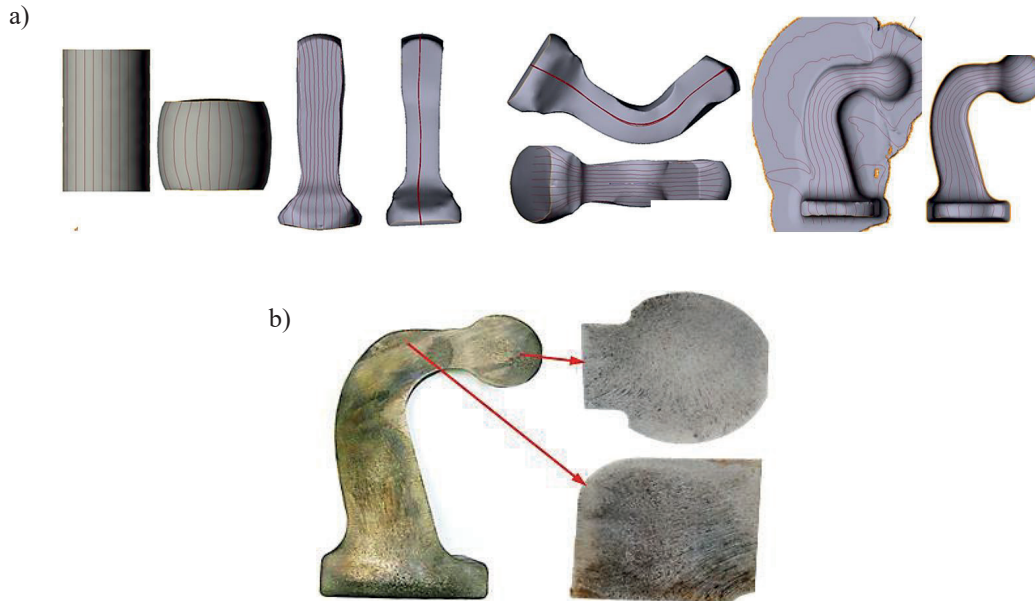


Fig. 6. FEM results of the correctness of deformation for the forging of a hook type forging:
 a) material flow lines for individual manufacturing operations;
 b) fiber distributions in the forging obtained as a result of the Jacewicz test

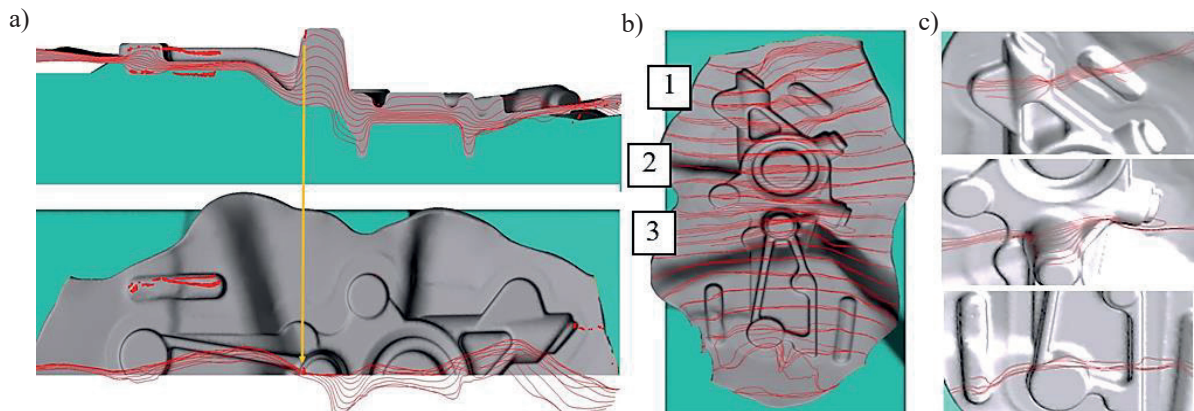


Fig. 7. The FE modelling results: a) the material flows with a distribution of flow lines in longitudinal;
 b) arrangement of fibers in the opposite direction; c) magnification for analysed zones 1–3

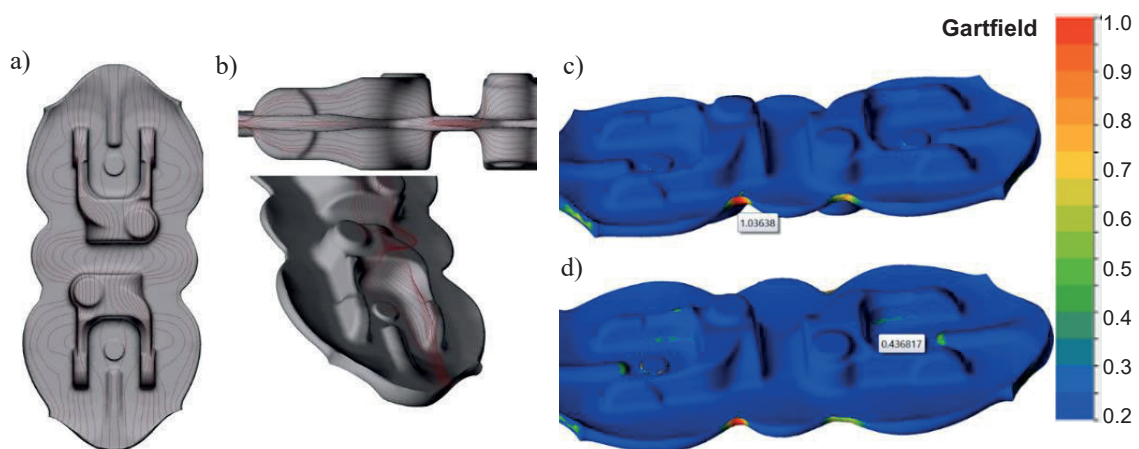


Fig. 8. Analysis of the subsurface (flow) lines of the forging during preliminary forging: a) lines around the dividing plane;
 b) flow lines in the plane of the arm zone; c) value of the Gartfield coefficient of the forging during preliminary forging
 in a double system; d) the results of Gartfield coefficient at the end of the process

Figures 8a and 8b show the flow line distribution for a fork forging produced in a double system. In turn, Figure 8c shows the place where the highest value of the Gartfield coefficient occurs in the place of material deficiency in the flash, which is permissible because there is still 1.8 mm left to completely fill (touch the dies). However, at the end of the forging process (Fig. 8d), there is no visible risk in the marked area, because the highest Gartfield values are 0.45 and occur on the arms, where they do not cause a risk of defect. It should be taken into account that when using the Gartfield criterion, the dimensional and shape tolerance values for a given forging should be taken into account, because it is on this basis that it is possible to determine what type of defect it is. Finally, one should also be aware that these are the results of numerical modeling and should be confirmed in reality.

2.3. FEM with a trap function to detect “air pockets”

A more advanced analysis function in calculation packages based on FE modeling is the so-called trap function, which enables the prediction of defects in the deformed material based on air pockets. Also, as result of an under-developed technology or its improper implementation (underheated tools or an excess of the lubricant, which has not managed to evaporate from

the surface of the impression), it is possible to notice the possibility of a defect in the form of under-filling the tool cutout (Fig. 9a) in the process of manufacturing a yoke forging or a crank forging (Fig. 9c). The use of FEM numeral modelling with an active “trap” function for the detection of air pockets by means of the Forge program showed that, during the roughing operation, between the forging and the tool, a series of empty spaces containing air and the lubricating agent is formed (Fig. 9b).

Similarly, in the case of a crank-type forging, one can notice that so-called “air pockets” may be formed in the lowest areas of the tool impression and which reveal themselves in the form of underfills. Moreover, in both analyzed cases, an increased pressure value caused by the presence of an air pocket in this area can not only lead to a forging defect, but it can also damage the tools, thus accelerating the occurrence of microcracks and causing the so-called Rehbinder effect.

The “contact” function, in combination with the “trap” function, was used to analyze the failure to fulfil the so-called pins, i.e. small, conical areas in forgings that constitute elements of a window lock. Figure 10 shows the results of numerical simulations for the forging process of such elements in a multiple system. Figure 10a shows the results using the contact function in the final phase of the process. In turn, Figure 10b shows the results using the trap function, illustrating unfilled volumes in the analyzed areas.

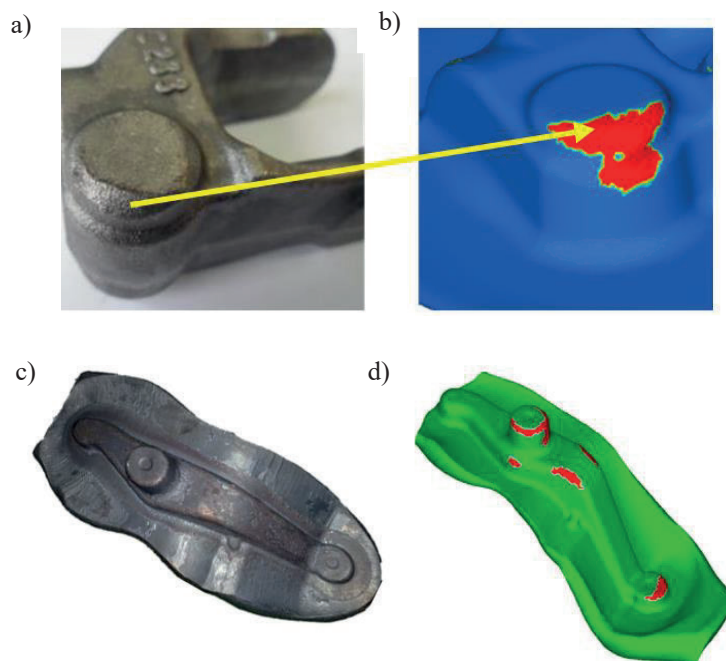


Fig. 9. The view of: a) failure of the forked type forging the real forging with defect of underfilling; b) results of FE modelling (the unfilled area marked with red) by use of the trap function; c) photo of a lever forging; d) visible laps in FEM

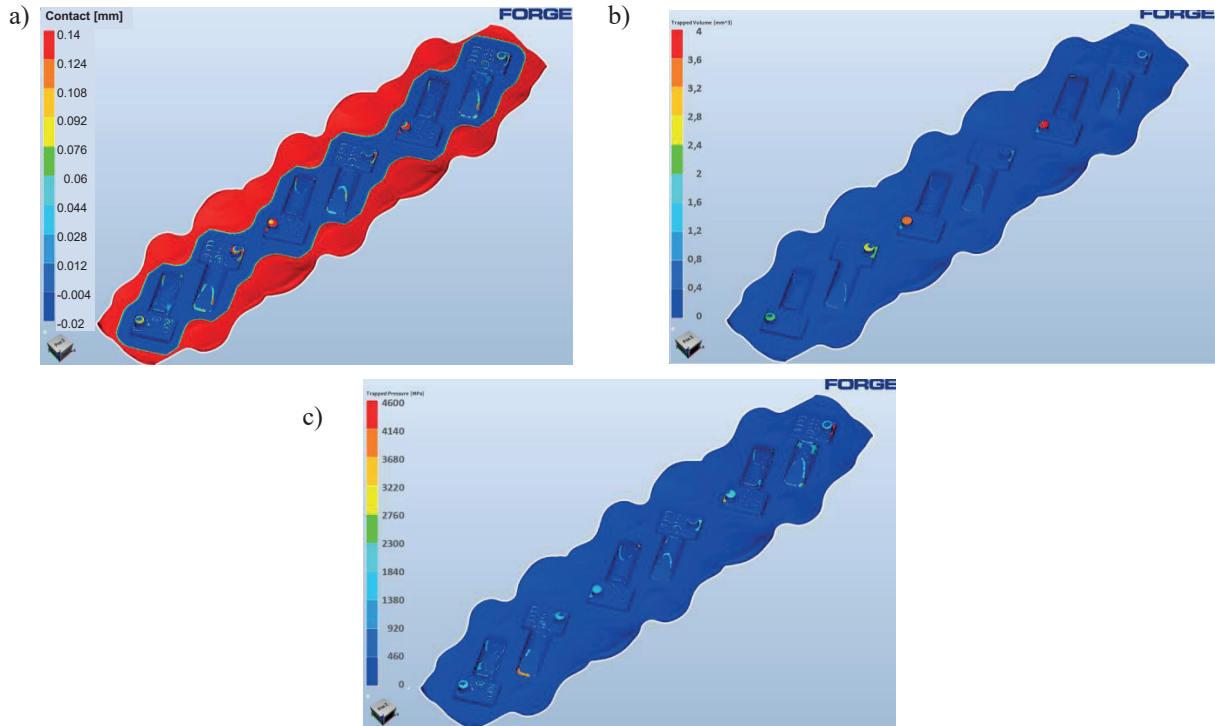


Fig. 10. FE results with the special functions – air pockets:

- a) filling of the pins's cavities – contact during the end of the process;
- b) trapped and underfilled volumes;
- c) distribution of the pressure field during the final phase of the forging process

In turn, Figure 10c shows how high the pressures are generated in these areas, which, on the one hand, may make it difficult to fill the blanks and, on the other hand, cause tools to break.

2.4. The use of the folds function – folds and laps of material

Defects of the deformed forging in the form of laps can be identified with the use of the folds function, where the laps are visible in the postprocessor as a cloud of red dots (spots). The use of the folds function is very helpful in analyzing this type of defects, because it allows to easily and quickly identify the area in the forging where a defect is likely to appear in the industrial

process. For example, in the analyzed process of the initial forging of an element, such as a fork for the drive system of excavators (Fig. 11), there is a tendency for some parts of the deformed material to flow out of the shape of the blank, so the defects do not affect the parameters of the product.

However, in the case of the inexperience of the blacksmith operator and inappropriate manipulation and arrangement of the forging in the initial and finishing blanks, this may contribute to the occurrence of defects also in the forging, which unfortunately causes significant problems (Fig. 11).

Figure 12 shows the subsequent stages of forming using the folds function, thanks to which it is possible to analyze the flow of the material and the formation of possible defects on an ongoing basis.

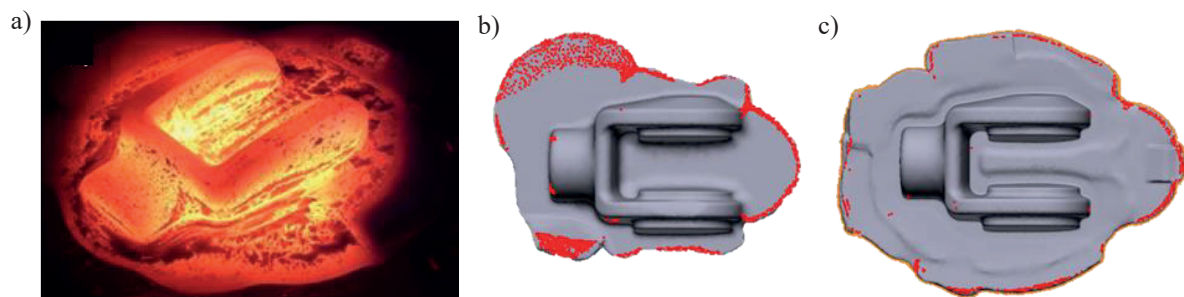


Fig. 11. Exemplary results of detection of forging defects:

- a) the photo of hot forging;
- b) wrong arrangement of the die (too high) – laps on the arms;
- c) too flat end (laps on the corners and the mandrel)

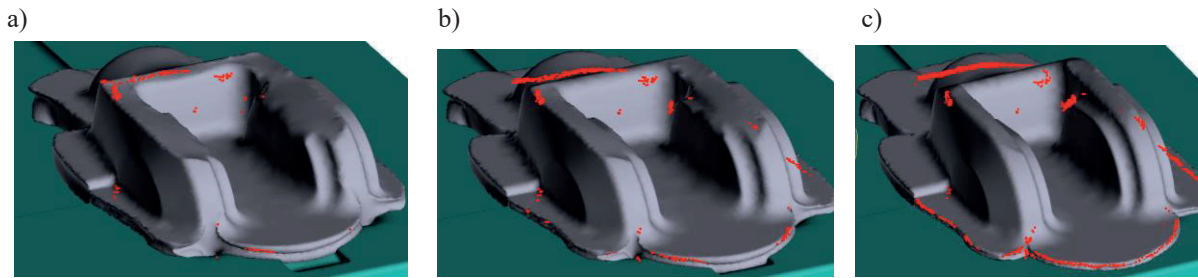


Fig. 12. Results of numerical modelling of fork type forging – the consecutive deformation phases: a) at the beginning; b) in the middle of deformation; c) at the end of forming

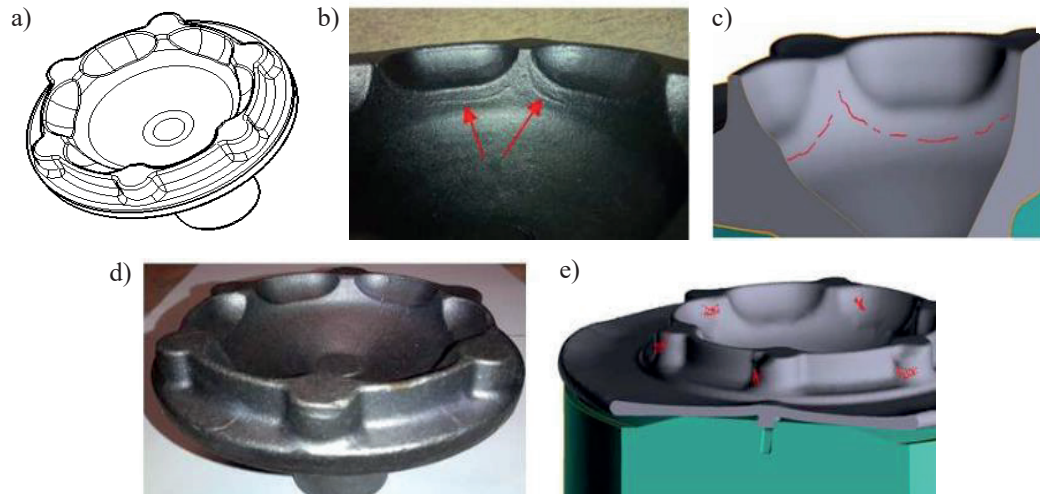


Fig. 13. Example results of detecting defects in forgings: a) model of a hub-type forging; b) forgings and reflections in the forging; c) results of defect modeling; d) forgings on the front surface; e) FEM – rotational displacement of tools in the axis

A similar situation with flaws in the form of folds was observed in the hot forging process of a very important element, such as the hub, which is intended for the drive systems of passenger cars (Fig. 13).

A defect in the form of a chisel/groove was observed (marked by arrows in Fig. 13b), which may also be caused by incorrect tool geometry (Fig. 13c). Another defect in the form of crimping was sometimes observed in the process and which was caused by the incorrect orientation of the upper tool relative to the lower one (Fig. 13d, e). Therefore, the use of special fold functions allows to simulate various arrangement variants and detect the areas of the formed material that are most vulnerable to defects.

2.5. Application of FE modelling to measurements of geometrical features of the forged parts

Combining numerical modeling with other IT tools or methods now gives even better results and allows for a more complete analysis. For example, using mea-

surement techniques, e.g. based on scanning combined with 3D analysis, it is possible to mutually verify the developed numerical model (simulation results) and the geometry of forgings as nominal CAD models or forgings obtained from an industrial process. Figure 14 shows a comparison of the geometry and dimensional deviations map for the 60E1A6 rail profile, calculated numerically, with the developed nominal CAD model, which in this case allows the determination of the correctness of the assumptions made in the numerical modeling of the accurate forging process of needle rails used in railway turnouts.

Another, similar example of the simultaneous use of the results of numerical modeling and 3D scanning techniques may be the analysis of the trimming process of a forked type forging. Figure 15a presents the results of numerical simulation tests for the production process with worn forging and trimming tools as a comparison of the FE results after the forging and trimming processes. In turn, Figure 15b shows the scanning results of forging without flash from an industrial forging process (and trimming) in comparison to the nominal CAD model.

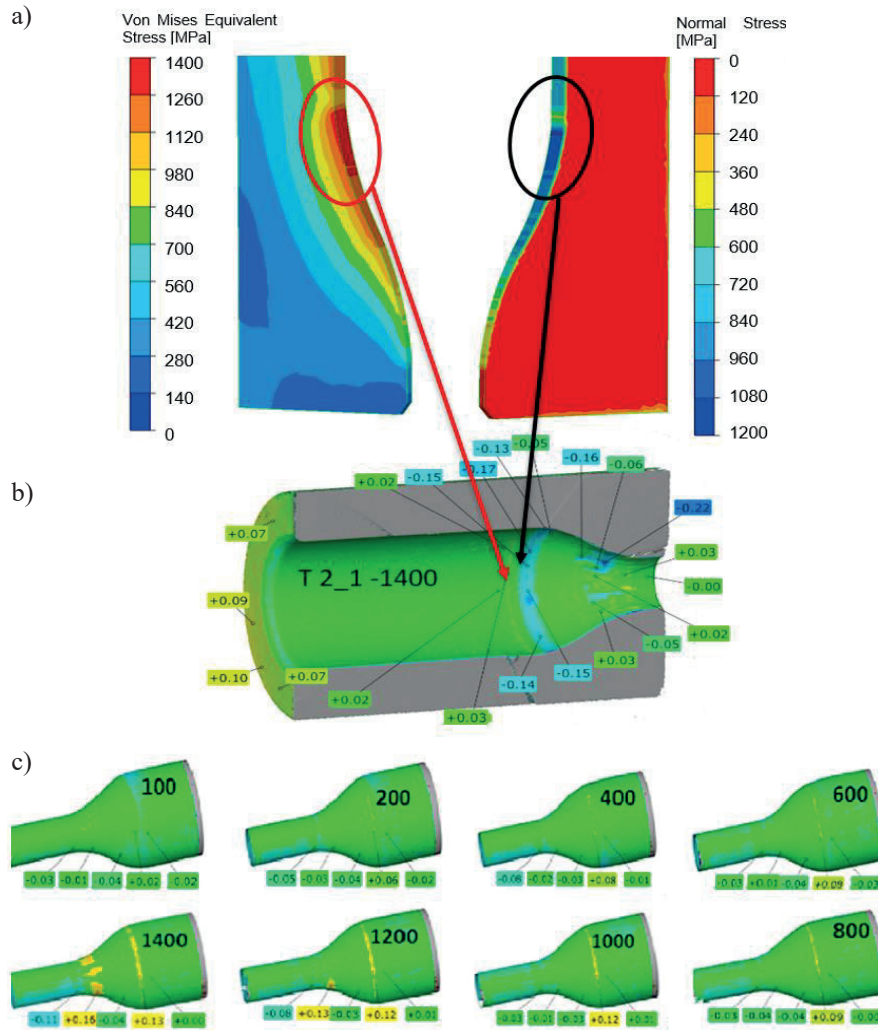


Fig. 16. Analysis of the operation of the forging tool and forgings: a) results of numerical simulations with the distribution of equivalent stresses and normal pressures in the tools; b) results of scanning the used die; c) scans of forgings periodically taken from the process (Hawryluk, 2021)

3. Summary

The article presents the results of a number of years of scientific research on the possibility of using mainly numerical simulations to analyze and detect defects in forgings and eliminate them. The use of computational packages not only made it possible to carry out relatively simple analyzes of forging processes, but also measurements and analysis of process correctness in order to determine key technological parameters, such as forging force patterns, temperature and strain field distributions, i.e. typical analyzes and process optimization. Additionally, the use of more advanced functions, such as: contact lines, flow lines, or the Gartfield criterion, as well as others, such as the appearance of air pockets and crimps, allow the detection and prediction of defects in forged products. It should be emphasized, as shown in the final part of the article, that the best re-

sults and most comprehensive analysis are obtained by combining and using many methods at the same time, such as: numerical modeling with 3D scanning. Combined FE modelling with scanning techniques can also be used to analyze the progressive wear of the forging dies, as well as allowing for the prediction of defects in the forgings.

Based on the presented results one can observe the vast potential of this type of numerical tools and IT techniques for applications in the forging industry, because they can significantly shorten analysis time and the measurement of key parameters. They also provide a lot of valuable information and physical quantities that are difficult to determine analytically or experimentally. This means that a virtual experiment using all these methods allows for a significant reduction in the costs associated with carrying out research and the development of a technology in an industrial processes.

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