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ANALYSIS OF THE IMPACT OF FORGING AND TRIMMING TOOLS WEAR ON THE DIMENSION-SHAPE PRECISION OF FORGINGS OBTAINED IN THE PROCESS OF MANUFACTURING COMPONENTS FOR THE AUTOMOTIVE INDUSTRY

ANALIZA WPŁYWU ZUŻYCIA NARZĘDZI DO KUCIA I OKRAWANIA NA DOKŁADNOŚĆ WYMIAROWO-KSZTAŁTOWĄ ODKUWEK UZYSKIWANYCH W PROCESIE WYTWARZANIA ELEMENTÓW DLA PRZEMYSŁU MOTORYZACYJNEGO*

The study presents the results of an analysis of the manufacturing process of a yoke-type forging for automotive industry with the use of numerical modelling and 3D scanning techniques, taking into account the gradual wear of both forging tools and trimming to determine the mutual impact of their operation on the dimensional accuracy of the forgings. The performed analysis included the 4 variants which are that have the most common place in the industrial process that is, for a combination of new and partly worn out die inserts (used during hot forging) and new and partly used cutting tools used for cold trimming. The first stage involved modelling of a hot die forging process. Next, the obtained results were implemented into second modelling stage, which involved a simulation of a cold trimming process of a flash, with the use of the normalized Cockcroft-Latham fracture criterion, with the consideration of eliminating the removed elements, for which the cracking value has been exceeded. The obtained results was verified by means of a case study under industrial conditions for the least favourable operating conditions of both types of tools and their impact on the dimension-shape precision of the forgings. These results allowed for a more complete analysis of the trimming process for a variety of operating conditions and the confirmation of the correctness of carried out numerical modelling, and thus the possibility of its use in combination with scanning technique to computer-aided manufacturing processes. The proposed solution allows the selection of optimum conditions for implementation of the processes of forging and trimming because of their use to provide the required net shape forgings.

Keywords: *trimming process; numerical simulation; geometric quality of forgings; wear of tools.*

W pracy przedstawiono wyniki analizy procesu wytwarzania odkuwki typu rozwidlonego dla przemysłu motoryzacyjnego z wykorzystaniem modelowania numerycznego oraz technik skanowania 3D przy uwzględnieniu sukcesywnego zużywania się zarówno narzędzi do kucia, jak i do okrawania w celu określenia wzajemnego wpływu ich eksploatacji na dokładność wymiarową odkuwek. Przeprowadzona analiza obejmowała 4 warianty najczęściej występujące w procesie przemysłowym, czyli dla kombinacji nowych i częściowo wyeksploatowanych wkładek matrycowych (stosowanych podczas kucia na gorąco) oraz nowych i częściowo zużytych narzędzi okrojczych wykorzystywanych do okrawania na zimno. W pierwszym etapie zamodelowano proces kucia matrycowego na gorąco. Następnie uzyskane wyniki zaimplementowano do drugiego etapu modelowania, w którym zasymulowano proces okrawania na zimno wypływki przy zastosowaniu znormalizowanego kryterium pękania Cockcrofta-Lathama z uwzględnieniem eliminacji elementów, dla których została przekroczona wartość pękania. Uzyskane wyniki zostały zweryfikowane za pomocą studium przypadku w warunkach przemysłowych dla najmniej korzystnych warunków eksploatacji obu rodzajów narzędzi oraz ich wpływu na dokładność wymiarowo-kształtową odkuwki. Uzyskane wyniki pozwoliły na pełniejszą analizę procesu okrawania dla różnych warunków eksploatacyjnych oraz potwierdzenie poprawności przeprowadzonego modelowania numerycznego, a tym samym możliwości jego wykorzystania do komputerowego wspomagania procesów wytwarzania. Zaproponowane rozwiązanie pozwala na wybór optymalnych warunków realizacji procesów kucia i okrawania ze względu na ich eksploatację w celu zapewnienia wymaganej dokładności wymiarowo-kształtowej odkuwek.

Słowa kluczowe: *process okrawania; symulacje numeryczne; jakość geometryczna odkuwek; zużycie narzędzi*

1. Introduction

Die forging is a competitive method of producing construction elements, such as pistons, crankshafts, gear wheels and gears used in the automotive and aircraft industries, in respect of other production technologies. The reason for this is that the items produced by this technology are characterized by good mechanical properties as well as dimensional and shape precision with a reduced amount of material waste and total cost of production. Additionally, the obtained material structure predisposes them to be used for responsible machine parts working under difficult operation conditions. However, the forging of such type of components is usually performed by means of a

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** multi-stage production process rather than a single operation. Steffens and Wilhelm [35] have conducted a review of the quality and accuracy of producing forged items at the particular stages of the whole forging process, especially with the application of computer simulations of these processes. Similarly, in their works, Gronostajski and Hawryluk [12,13] performed an analysis of the whole technological sequence for typical die forging processes and proposed methods for their improvement and optimization. At present, the most frequently used methods of analysis and optimization involve the application of computer simulations with the use of numerical modelling. In the current practice, the main forging process stages, including preforming, die forging, further transport and cooling, can be effectively simulated by means of calculation packages based on FEM/FVM [18]. These methods are usually used to evaluate the material flow, analyze the state of stresses/deformation and temperature distribution as well as to validate the process design. However, those simulation procedures still face difficulties in respect of the proper performance of the operation of trimming and possible piercing of forged elements realized directly after their removal from the forging tools [3,6,21].

Operation is indispensable phenomenon accompanying the production of products and is associated most often with a maximum utilization of the machine / system / tools within a specified period, after which ends with partial or total wear. Therefore, in the technical literature, the issue of exploitation is devoted to a lot of space and a number of studies are carried out to determine the relevant parameters affecting this phenomenon, as well as industrial research and development works that allow to increase the service life [20,25,29]. In the case of the forging industry, despite the large development in this area of technology, so that the production process is accurate, reliable and efficient [5], the durability of the tooling is still the key issue, ie the operation time is usually determined by the number of correct forgings produced. As is known, the time of the process of forming (forging) material in one stage / operation is about 0.08 to 0.2 s, which makes it very difficult to follow or observe and analyze the process in such a short period of time [34]. Furthermore operated forging tools are complex and difficult to analyze due to the interaction of many, often contradictory factors and mechanisms, in particular during the hot forging process [1]. The situation becomes even more complicated if the subsequent stages of the technological sequence are taken into account (such as: trimming after the forging process), at the end of which the correct product in geometric, qualitative and functional form is created - forging [2].

Also, the process of trimming (cutting) is geometrically and physically complex. Blanking consists in overcoming the material's cohesion due to stress concentration along the shearing line. A concentration of stresses can be obtained by exerting pressure on the material by means of tools (mounted in instruments called trimming dies) adjusted to the type of the trimmed products and to the required cutting precision. The cutting process consists of four phases proceeding together with the increase of the cutting force. In the first phase, elastic deformations and minor bending of the cut surface are observed. When the stresses become sufficiently high, they cause local softening of the material. This moment initializes the second phase of the cutting process, called the elastic-plastic stage. Together with the further increase of stresses, the boundary of the softened area shifts towards the inside of the material, and the metal flows plastically in the surroundings of the shear area (plastic flow phase). In the last stage, we observe a loss of cohesion and cracking of the material, when the stresses reach the critical value. The cracking begins in the areas of maximal stress concentration (edges of the punch and the cutting plate). If the clearance between the tools is optimal, the cracks coming from both shearing edges meet, forming a surface with the shape close to that of S. In order to ensure a gradual course of shearing, the edges on the cooperating tools should be positioned obliquely, and the bevel of the edges should not be unidirectional. In order to obtain a high accuracy, after the trimming process, the shearing edges should not be blunted and the clearance between the cooperating surfaces should be maintained within the specific boundaries. The bigger the clearance, the stronger the bending of the edges of the trimmed flash and the bigger the disadvantageous conic and matt zone (cracking phase). A big clearance also favours the presence of burr on the sheared surfaces. Too small clearances are also disadvantageous, as they can cause wedging of the material between the tools and excessive wear of the trimming tools. Therefore plays an important role in the operation of the tools used in cutting processes, which, with the additional pre-process for producing a forging makes the determination of whether the current state of tools and their corresponding selection throughout the manufacturing process is critical to the quality of products [2, 36].

At present, it is possible to simulate the process of 2D or 3D blanking of a simple part with the use of the commercial functions of the FEM software. Unfortunately, calculation-wise, it is not beneficial to simulate the process of cutting and trimming at a large scale for a complex component, due to very long calculation times, resulting from the number of elements of the digitized models [18,31,32]. Performing a detailed simulation of the trimming operation of an item with a complex shape is difficult due to the complexity of the shearing mechanisms or the ductile cracking mechanisms of the materials [3,9]. In the literature, a lot of research is devoted to mathematical crack models, which are then implemented in numerical modelling of the cutting and trimming processes [37]. For example, Hambli and Reszka [14] proposed a reverse approach to examine different damage models for the blanking processes. In work [8], Cockcroft and Latham proposed a model which emphasizes the importance of the basic tensile stress in the crack initiation. Oyane et al. [30] viewed the hydrostatic stress as the most important factor of void and coalescence growth in the cracking process. With the use of those models, the operations of cutting and blanking can be successfully simulated in the case of 2D Goijaerts et al. [11] examined the use of a localized model of plastic cracking during the precision blanking process of different materials. A big problem in the case of numerical modelling of trimming processes are algorithms referring to the separation and removal of the elements during the process [10]. It should be mentioned that during numerical simulations, the problem of remeshing, that is reconstruction of finite element mesh, is still difficult to solve [4,7,33]. In the literature on the subject, many studies can be found on the analysis of trimming using analytical methods [19,24] and experimental [15,17,23], as well as numerical simulations [3,16], which allowed for a more detailed evaluation of cutting and trimming processes for various materials and under various operational conditions [22]. In study, Lu et al. [26, 27] developed a simple method of trimming simulation for multi-stage-forged elements. It is worth noting the study of [28], whose authors presented a complex approach to the processes of trimming a flash after die forging for an airframe blade forging. Despite the fact that the available literature has discussed a few key issues connected with shearing modelling, it is difficult to find practical applications of numerical modelling applications, in particular for the analysis of industrial trimming processes that would be useful for engineers in solving production problems. Therefore, despite the significant contribution of the mentioned studies in this scope, it is highly justifiable and interesting to analyze the effect of the progressing trimming tool wear on the quality of the trimming of a flash and the dimensional and shape precision of the forgings after these operations, with the consideration of the wear of the forging tools which form the forging with the flash.

The aim of the study is an analysis of the process of trimming of a yoke type forging with the consideration of the progressing wear of the trimming tools and the effects of the forging process (proceeding wear of the forging tools) by means of numerical modelling as well as 3D scanning methods.

2. Research methodology

The research was divided into two stages: numerical modelling of the hot die forging and cold trimming processes and measuring of the geometry of the trimming tools and the forgings before and after trimming with the use of 3D scanning techniques for chosen variants and their comparison with an analysis of the numerical modelling.

2.1. Description of the analyzed industrial process of forging and trimming

The process of producing a yoke forging is realized on the Massey press, nominal pressure 13 MN (Fig. 1). All the tools are heated to approx. 250°C. The die inserts in the analyzed process are made of WCL steel. After quenching and tempering, the hardness range is 48-52 HRC. In order to ensure a possibly uniform deformation of the material in its whole volume, the preliminary and finishing die inserts are lubricated with a water solution of graphite. The yoke type forgings are an important safety element in a car (being part of the steering gear) and require a special supervision and attention during the production process as well as the development of advanced techniques of their production and ensuring of their repeatability.

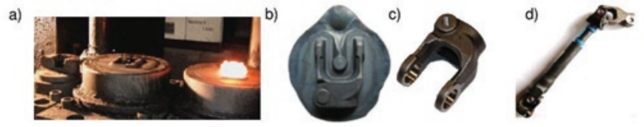

Fig. 1. The general view of: a) the process of producing a yoke type forging – photo of the lower die insert with the preform placed in the insert's impression before the finishing forging, b) a yoke type forging with the flash, c) a ready detail - after mechanical treatment, d) a fragment of the steering column with the yoke

The analyzed yoke type forgings are made of C45 steel. The net mass of a yoke is 0,32 kg. After the bar is cut into proper dimensions, the charge material is heated to 1120°-1150°C and next subjected to 3 hot forging operations.

In the case of the trimming process after earlier cooling of the forgings to the ambient temperature, the deburring process is carried out cold and consists in separating the flash from the usable part. Then the trimming process for such forgings is carried out as a separate element of the production process. This manner of trimming prevents bending of the yoke arms and ensures a good surface quality after trimming. The trimming of the forgings is realized on the two-point crank press Wilkins & Mitchell with a frame construction and the following parameters: nominal pressure 2MN.

The mean durability of the forging tools for this forging, depending on the used tool material and the applied thermo-chemical treatment (or surface engineering treatments), equals from 6000 to 16000 items.

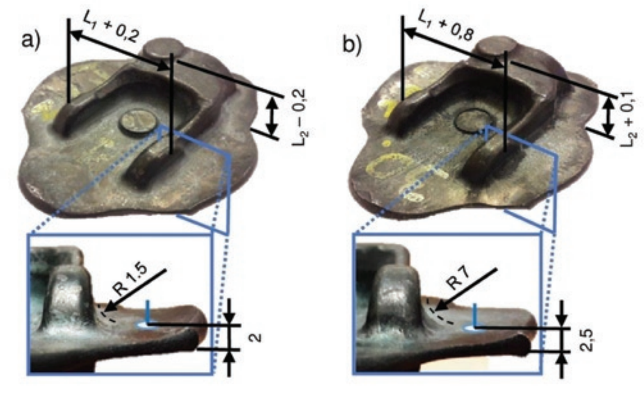

Fig. 2. The view of the forgings after the forging process: a) initial forging phase – unworn tools, b) final forging phase (worn die inserts) – enlarged dimensions of the tool and the forging

It should be noted that with the proceeding operation and wear of the forging tools, the working patterns are enlarged (loss of tool material and occurrence of other destruction mechanisms); also, the radii of the inserts are bigger, especially in the area where the material shifts to the flash, and the flash thickness increases (Fig. 2). However, the consequence of the wear of the trimming tools is the increase of the cutting plate pattern and the circumferential decrease of the punch cutting edge line.

This causes the worn-out trimming tools to have an increased gap between them (large clearance). This may result in the trimming of forgings coming from forging tools of varying degrees of use with the creation of the final product with dimensions beyond the dimensional tolerance. A consequence of forging tool wear is the fact that the forging itself (without the flash) becomes slightly bigger (the volume of the forging in the impression increases), and its flash is reduced in respect of the surface but becomes slightly thicker (with the same constant volume of the forging with the flash – the charge material). In the case of the trimming process, an important issue are the increased radii of the material's shift to the flash, as this results in an increased width of the shearing line (Fig. 2), which causes significant problems with the proper trimming of the flash and maintaining the dimensions in the assumed tolerances. An additional problem is the progressing wear of the trimming tools, which significantly complicates the obtaining of a proper forging after trimming which is within the assumed dimensional tolerance (Fig. 3).

In the case of blanking accepted for the analysis, the maximum deviation in the horizontal direction from the cutting line, when looking at the sample forging after cutting from the top, cannot exceed +0,3 mm outside. At the same time, the situation is not allowed when the deviation is in the negative dimensional tolerance (inward) in the dividing line - creating a local material loss in the matrix division plane (Fig. 3b). However, the width of the cutting line results from the size of the material's transition radius to the flash and its thickness and should not exceed 4 mm on the entire circumference of the cut.

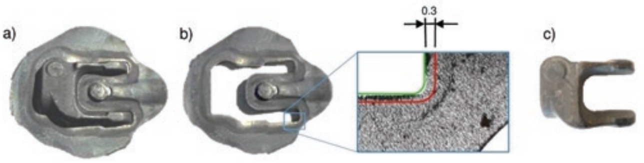

Fig. 3. View of a yoke forging: a) with the flash before trimming, b) the flash after trimming, c) the forging after trimming

In the sample (analyzed) production process, assuming an average durability of 6000 die inserts and an average durability of 16000 trimming tools, it is important to choose the durability of the cutting and cutting tools to obtain geometrically correct forgings without chips (in accordance with dimensional tolerance). If the manufacturing process "starts" from the beginning, assuming that the above values of tool life, it seems that the crucial moment will be the situation (marked as number IV in Fig. 4) when the exploited are two sets of forging tools, ie the production of forgings 12000 and the forging process will start on the third set of inserts, and the tooling process will continue to work in the trimming process, which has already cut off 12,000 forgings (Fig. 4).

It can therefore be assumed that in this particular case durability means an acceptable change of geometry for both types of tools, which when searching for maximum performance or inadequate selection of new or partly worn down tools for forging and trimming (as is the case in the production process) may be the reason production shortages. It can therefore be assumed that the schematic of the manufacturing process shown in Figure 4 is typical for industrial conditions, an operational issue that technologists and engineers must face and which must be resolved.

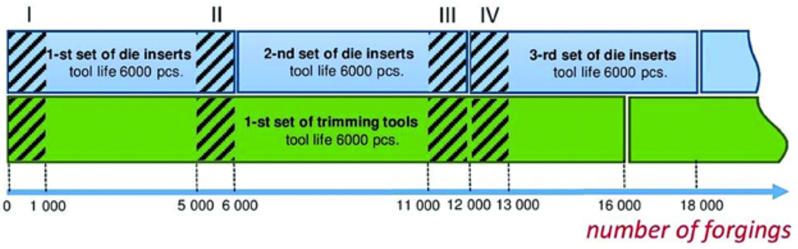

Fig. 4. Diagram of the manufacturing process in the aspect of operation of forging and trimming tools

Therefore, the following 4 (most frequently occurring in the industrial process) comprehensive analyzes were analyzed (variants):

- variant I (fig. 4) - unused trimming tools and unused - new die inserts for forging, forging with flash up to 2 mm thick (as a reference point);
- variant II (fig. 4) - unused trimming tools and die inserts (about 5000 forgings) in the final phase of operation, resulting in a forging with a larger flash with a thickness of more than 2.2 mm;
- variant III (Fig. 4) - partly used trimming tools (about 11-12 thousand forgings) and die inserts (about 5000 forgings) in the final phase of operation, allowing forging with a larger flash with a thickness of more than 2.2 mm;
- variant IV (Fig. 4) - worn trimming tools (about 12-13 thousand forgings) and unused - new die inserts, forging with flash up to 2 mm thick.

The obtained results should enable a more thorough analysis of the trimming process for different operation conditions of forging and trimming tools and the selection of the optimal conditions for the realization of the forging and trimming processes, which should, in turn, increase the durability of the trimming tools and ensure the required dimension and shape accuracy of the forgings.

2.2. Numerical modelling of forging and trimming

The first stage of the research was divided into two sub-stages: numerical modelling of the forging process and modelling of the trimming process for 4 different variants, together with an analysis of the obtained results. The numerical simulation for forging and trimming were performed with the use of the ForgeNxt 2.0 calculation package. In the case of the forging process, a thermo-mechanical 3D model with fixed tools (die inserts – elements with a heat exchange) was constructed. The geometry of the tools, the preforms, as well as the remaining technological parameters of the process were implemented into the program based on the original 3D models and the operation sheets. The stroke speed of the upper dies, assumed according to the kinematic parameters of the applied crank presses (for forging and trimming), was dependent on the angular position of the crank. A bilinear model of friction was used, which considered the applied lubricant in the form of a water graphite solution. The preform after the first operation was heated to 1150°C. The tool temperatures, which were measured by means of a pyrometer and a thermovision camera, equalled 250°C. The times of the consecutive operations were determined with the use of the CASIO camera with the option to record 300 frames per second. The recorded mean forging cycle for one forging (3 operations) equalled 19 seconds. The assumed tribological properties were determined by by the Treska friction model with a factor of 0.35 for all the working surfaces of the tools. The Forge program uses the following equation in the case of the extended friction model according to Treska:

$$\bar{\tau} = \bar{m}\frac{\sigma_0}{\sqrt{3}}\frac{\Delta\bar{v}}{\Delta\bar{v}} \qquad (2.1)$$

where:

$\bar{m}$ – is friction factor in range from 0 to 1;

σ_0 –von Misses stress;

$\Delta\bar{v}$ – relative velocity in contact.

The heat exchange coefficients in the contact between the charge material and the tool material and with the environment were assumed to be 25 and 0,35 kW/m2K, respectively.

The Forge software uses the viscoplastic right of the flow of Norton-Hoff as a constitutive equation. The general form of this law is as follows:

$$\sigma = 2K\left(\sqrt{3}\,\dot{\varepsilon}_i\right)^{m-1}\dot{\varepsilon} \qquad (2.2)$$

The coefficient m can have the following values:

- ***m* = 1** it corresponds to the Newtonian liquid with viscosity η = K;
- ***m* = 0** gives the right of plastic flow for material meeting the Huber-Mises-Hencky plasticity criterion;
- **0 < *m* < 1** corresponds to the conditions of hot metal deformation.

For most metals *m* is in the range of 0.1 - 0.2. The C45 steel material model was downloaded from the Forge database "FPD Base 1.3" as the Spittel equation, in the form (2.3):

$$\sigma_f = Ae^{m_1 T}T^{m_9}\varepsilon^{m_2}e^{\frac{m_4}{\varepsilon}}\left(1+\varepsilon\right)^{m_5 T}e^{m_7\varepsilon}\dot{\varepsilon}^{m_3}\dot{\varepsilon}^{m_8 T} \qquad (2.3)$$

where individual coefficients for hot and cold conditions are shown in Figure 5.

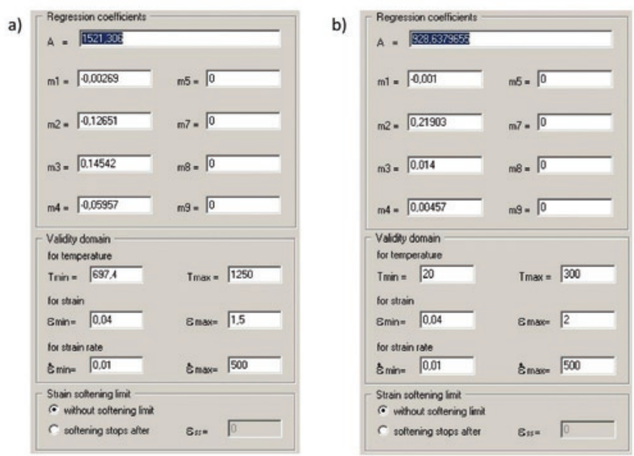

Fig. 5. Comparison of the values of the Spittel equation parameters: a) hot (forging), b) cold (trimming)

Modelling was carried out for new (nominal CAD model of tools) and partially worn forging tools (CAD model of worn tools obtained on the basis of their 3d scanning). In this way, two different geometries of forgings with flash were obtained, which were implemented into the deburring process. In addition, the obtained geometries of "virtual" forgings with flash were compared with scans of real forgings for the corresponding operating conditions of the tools. Obtained results of the comparison of geometries obtained from FEM for both new and used tools with real forging confirmed the high conformity of their shape (deviations in the scanner's accuracy range, at the level of ± 0.05 mm). From the results obtained from the modelling of the forging process, only the forgings' geometries (without the remaining deformation history) were exported to the subsequent trimming stages, due to the fact that in the current technology the trimming process is carried out cold. Currently, the first works on the robotic station are already being carried out, where the trimming process is carried out on a hot basis. The boundary initial conditions and the remaining trimming process parameters were determined based on the technology as well as the actual industrial conditions. The three-dimensional geometric model was created in its entirety (the forging is unsymmetrical). In simulations, the dies were created as non-deformable bodies in order to shorten the calculation time. The forging and tools in the trimming operation were at 20 ° C. The adopted calculation model took into account gravity. The coefficient of heat transfer in contact was 10,000 W / m². ° K.

The trimming simulation assumed a constant press speed of 220 mm / s (due to the lack of knowledge of the exact characteristics of the press). In order to accurately analyze the process, in the FEM simulations, each step was saved every 0.1 mm of the stroke. Remeshing took place every 20 calculation steps, that is every 2 mm. In the case of cold trimming, the Coulomb friction model with a coefficient equal to 0.4 (according to software recommendations) was adopted. The ForgeNxT program enables simulations of the process of material separation according to two cracking criteria: Oyane and Cockcroft–Latham. In the simulations of the flash trimming process, a normalized Cockcroft–Latham criterion was applied, which is expressed by the following formula [8]:

$$C = C_o + \int_0^{\bar{\varepsilon}} \pounds d\dot{\varepsilon} \qquad (2.4)$$

and:

$$\Sigma = \frac{\sup(\sigma 1, \sigma 2, \sigma 3)}{\sigma i} \qquad (2.5)$$

where:

σ_1 ,σ_2, σ_3- maximal principal stress principal in a superposition,
σ_i - equivalent stress,
ε - cracking limiting strain,
C_o - material constant.

The value of the normalized Cockcroft–Latham criterion determining the shape of the crack profile, the maximal force and the local deformation, can be set within the scope of 0 – 1 (where, for a cold trimming process, the value recommended by the Forge program is within the scope of 0.4 to 0.5). Based on the many performed simulations verified by observations under industrial conditions, it was assumed that, for the analyzed trimming process, the best results were obtained for the Cockroft-Latham criterion of 0.5. Due to the accuracy of the obtained results, in the simulation of the material separation process, it is important that the elements of the shearing line are as small as possible, which ensures a good representation of the shearing plane, while significantly prolonging the calculation time. And so, the finite element web was densified in the key areas for the calculation process, with the use of the so-called "meshboxes", which are used for a local densification of the web. Fig. 7c shows a fragment of the meshed up forging model with a densified web on the shearing line (size of the elements in the densification – 0.1 mm, the remaining elements – 0.5 mm). In the model, Tetrahedral type elements were used, whose mean number for the whole forging (considering the increased local densification) equalled about 62700 elements for each modelled variants. The mean calculation time for a 4 processor license on a standard calculation by unit PC was about 160 h.

The trimming computer simulations were performed for 4 different variants described above, i.e.: varying dimensions of the flash and the forging after the forging process as a result of the wear of the forging tools, as well as new and old trimming tools.

2.3. Forging geometry measurements

The second stage of the study included measurements of the forgings after the trimming process, which applied the measuring arm ROMER Absolute ARM 7520si integrated with the scanner RS3, together with the Polyworks software making it possible to perform scanning in the Real Time QualityMeshing technology (Fig. 6a). In order to make measurements for the needs of the developed measurement technology was built laboratory measuring stands were presented in Fig. 6.

Fig. 6. Measuring station with the measuring arm ROMER AbsoluteArm 7520si integrated with the linear scanner RS3 for the measurements of: a) photos of the measuring arm with scanner, b) scanning of the

trimming tools, c) scanning of the forging

The applied arm enables contact measurements with the use of a contact measuring probe as well as non-contact measurements with the use of the linear laser scanner integrated with the arm. The device makes it possible to perform measurements by means of the laser scanner RS3 integrated with the arm, which provides the possibility to collect up to 460 000 points/s for 4600 points on the line with the linear frequency of 100 Hz. The accuracy of the scanning system SI according to the standard B89.4.22 equals 0.053 mm

3. Results and discussion

The first stage involved modelling of a hot die forging process including 3 shaping operations. Next, the obtained results were implemented in the second modelling stage, in which the process of cold trimming of a flash was simulated by means of the Corcroft-Latham crack criterion (value 0.5), with the consideration of eliminating the elements (for which the cracking value has been exceeded) and adjusting the knot position near the shear line, as well as mapping the state variables from the original grid to the new grid. This study only discusses the results referring to the numerical modelling of the trimming process.

Fig 7a shows a diagram of the trimming process with a forging (marked in red), as well as the upper (mobile) and lower (immobile) set of tools. Fig. 7b presents a yoke forging with a plotted finite ele-

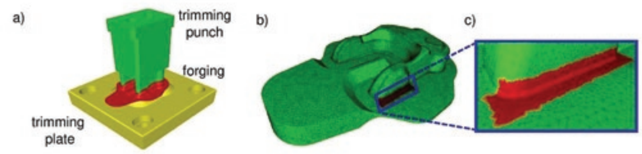

Fig. 7.View of: a) a diagram of the trimming process, b) a meshed up forging before trimming for the whole forging, c) densification of the web on the trimming line with the use of "meshboxes"

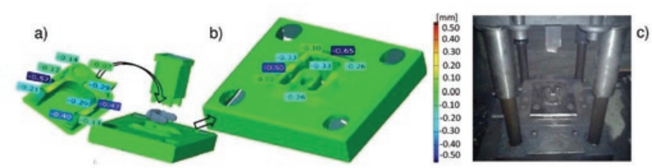

Fig. 8. Measurement-scanning results for trimming tools: a) a punch, b) a die (cutting plane), c) view of trimming device

ment grid. In the crucial areas (arms of the forging), the element grid was additionally densified, in order to obtain more accurate and more realistic results.

Fig. 8 shows the scanning results for a selected set of worn trimming tools towards the end of their operation (about 15000 forgings). As it can be seen in Fig. 8, in the case of the trimming punch, the edges cutting (trimming) the arms-eyes of the forging are the most worn, especially in their sharpest area, where the wear reaches even 0.57 mm. In turn, in the case of the trimming plate, the most worn area is the edge by the outside part of the forging arms, where the wear also reaches 0.65 mm.

Next, for each case described in subchapter 2.1, a numerical analysis was performed in order to determine the distribution of deformation and reduced stresses with the maximal trimming force. Additionally, for a more thorough analysis, the deformation and stress distributions were determined for both sides of the yoke, that is on the side of the punch and the trimming plate. The analysis for the strain distributions for all variants had a similar character as in the case of stress distributions in terms of location and variability of occurrence. Therefore, the detailed results are presented only for the distribution of von Misses stresses from the punch side - higher pressure values in relation to the cutting plate (Fig. 9).

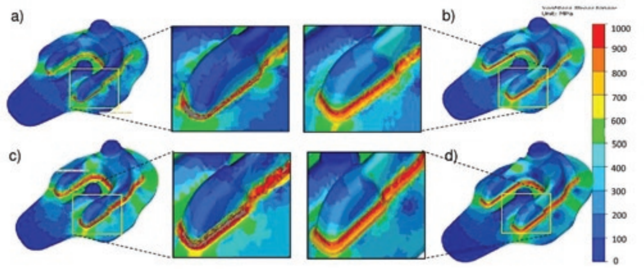

Fig. 9. Distribution of von Misses stresses for 4 analyzed variants of tool exploitation: a) variant I - for the forging forged in new tools for forging and trimmin, b) variant II - forging made in used forging tools and relatively new trimmin tools, c) variant III for the forging forged in used forging tools with flash at the level above 2.2 mm and worn-out trimmin tools, d) variant IV - for the forgings made of new tools for forging with flash2 mm and worn-out trimming tools

In the case of von Misses stresses for variant I (Fig. 9a), they locate along the trim line. The maximum values are above 800 MPa, while the width of the cutting line is the smallest among the variants. For variant II, i.e. for the forgings, with a larger thickness of flash (g = 2.2mm) forged in worn die inserts (about 5000 forgings), and then trimming in relatively new cutting tools (5000 forgings compared to their maximum average durability on the surface 16000 forgings) the equivalent stresses are very similar to those for a forging with a thinner flash (g = 2mm). The values of stresses have slightly higher values, and the maximum values are from the side of the trimming die and amount to about 850-900 MPa (Fig. 9b). On the other hand, the distributions of the von Misses stresses for the variant III (Fig. 9c) are the highest in all cases and amount to over 1000 MPa. The additive can be observed that they cover considerably larger areas of forging on the cutting line. However, for the last, IV variant, concerning new die inserts and much worn out trimming tools (about 1500 forgings), maximum stress values are about 900-950 MPa and are slightly lower, compared to variant III, while maintaining a similar cutting line (Fig. 9d). The changes in the stress values are mainly the result of different geometry of the forging after the forging and the state of the trimming tools (different geometry of the trimming tools). It would be worthwhile to carry out an additional analysis taking into account the effect of the change in the condition of forging tools during their use on the values of forces and the distribution of stresses during trimming. For the forging after the forging process in the aspect of tool exploitation changes its geometry, which consequently affects changes in the stress distribution field during cold trimming.

The greatest stress values can be observed for the variant III, or the case where the greatest difference in the dimensions of the trimming tools takes place (the clearance) and the forging has the largest geometric dimensions due to the operation of the forging inserts.

Analysing the graph of the trimming forces for individual variants (Fig. 10), it can be observed that the value of the maximum force takes place for the third variant and is slightly over 720 kN. Also its shape is different in comparison to the other variants, as it can be seen that it builds up the fastest, which can be caused by significant differences enlarged as a result of exploiting the dimensions of the forging and deburring tools. The most advantageous course of trimming forces was obtained for the first variant, i.e. new forging tools and new trimming tools, for which the maximum force is around 550 kN, and the beginning of force build begins at the latest with respect to the other variants. Also, based on the analysis of the force courses, we can state that the strongest effect on the maximal trimming force value is exhibited by the geometry of the forging, that is, in fact, the state of the trimming tools, rather than that of the forging tools. For relatively new trimming tools (about 5000 forgings) and forgings obtained from partially worn out forging tools, the maximum trimming force is 650 kN. Indeed, in the case of used trimming tools and forgings of the forging from the beginning of the forging process, the deburring force is 700 kN. In addition, the shape (slower decrease) in the trimming force for this variant, in the final stage is slightly different than in the previous cases, which may be the reason for the unfavourable insertion of the forging material between the deburring tools. Such situations were sometimes observed in the industrial process.

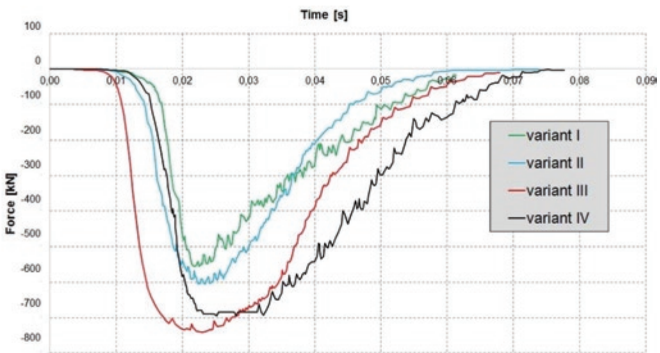

Fig. 10. Comparison of trimming forces for all variants

On the basis of presented results with distributions of equivalent stresses and forging forces for the forged type analyzed, it seems that the key and the most "unfavourable" conditions in the production process take place for both types of worn tools (variant III) and the variant of used trimming tools and new ones forging tools (variant IV). Therefore, the verification of numerical modelling results was carried out for both variants.

4. Verification of the numerical modelling results

Fig. 11a shows images of the measurement of the flash thickness with the indicated approximate measurement areas from the industrial trimming process for a case of significant operation of both types of tools (option III). In turn, Fig. 14b presents the measurement results

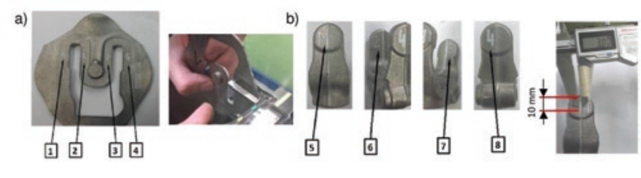

Fig. 11. Exemplary images from the performed measurements: a) flash thickness, b) shearing line width

Table 1. Measurement results of the flash thickness and the shearing line width in selected areas for a forging made in worn forging tools and trimming tools after 6000 items and trimming tools after 15000 pieces

	Place of measurement [mm]							
No pcs	1	2	3	4	5	6	7	8
A	2.17	2.12	2.24	2.04	3.94	3.97	3.89	3.84
B	2.11	2.22	2.30	2.17	3.95	3.96	3.87	3.89
C	2.18	2.3	2.42	2.17	3.98	3.98	3.75	3.88

of the shearing line width for a forgings after trimming. The obtained results are presented in Table 1.

The obtained measurement results show that, for 3 forgings collected from the process, the flash thickness in selected areas is within the scope of 2.11 to 2.42mm, whereas the shearing line width – in the scope of 3.75 to 3.98 mm.

Fig. 12a presents the results for the case when in the production process is the wear of both types of tools (variant III) in the form of comparison of results obtained from the FEM model after trimming, and in Fig. 12b the results of 3D scanning of the forgings from the industrial process in relation to nominal dimensions in the form of a CAD model.

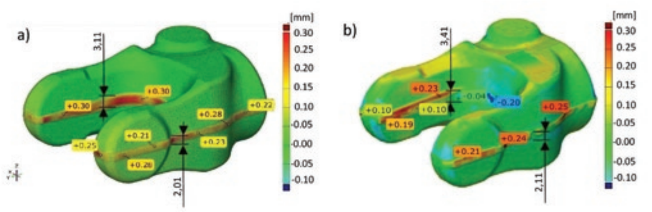

Fig. 12. Comparison of a forging model after flash trimming for III-rd variant: a) obtained from FEM with the nominal CAD model, b) obtained from the industrial process for similar conditions (a scan of a forging after trimming compared to the CAD model)

Based on the presented comparative results obtained from scanning, we can state a similarity between the geometries together with the deviations in the trimming zone (shearing line) for a forging obtained from FEM and a forging obtained in the industrial process under similar conditions. For the FEM model of forging, the shearing line width is within the scope of 2.00-3.11 mm, and the deviations in the normal direction equal from 0.11 to 0.3 mm. The case is similar of a forging from the industrial process, whereas both the width (2.1 do 3.41 mm) and the deviations in the normal direction are slightly higher and more diversified on the whole shearing line (0.10 to 0.25 mm). In the case of the numerical model, it should be emphasized that such a process is realized under "virtual", i.e. ideal, conditions. In turn, in the industrial process, we can observe other additional unpredictable factors affecting the final geometry of the forging. The presented results, especially in the case of the industrial process, where the deviations reach above 0.3 mm, show that the wear of the trimming tools (and perhaps also the forging tools) it is in the upper tolerance range (see Fig. 3).

The last stage of the analysis was the case (variant IV) for the used trimming tools (about 15000 pieces) and new forging tools (about 1000 pieces). Similar analyzes were performed as for the case above and the results are presented in Figure 13.

In the case of used trimming tools and a new forging set, the results obtained with FEM are confirmed by 3D scanning results of the forging after trimming for similar operating conditions. The cut line width value ranges from 3.68 mm to 4.13 mm for measurements taken from the forging process and from 3.57 mm to 4.20 mm for numerical simulation of the trimming process. Similarly, the circumference of the cutting line is in the range of 0.34 mm to 0.47 mm for measurements of the forged process taken and from 0.29 mm to 0.47 mm for the numerical simulation of the trimming process. You can see that both the cutting line is wider and not within the tolerance, as well as the perimeter of the cutting line is greater than the permissible value of +0,3 mm. This caused exceeding the permissible tolerance of the shape error of the determined surface in the circumference of the forging cutting line (see Fig. 3). This forging can be subjected to an additional procedure to remove excess material,

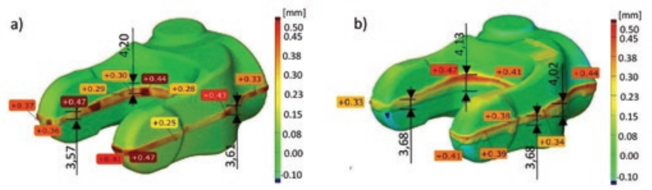

Fig. 13. Comparison of a forging model after flash trimming for IV-th variant: a) obtained from FEM with the nominal CAD model, b) obtained from the industrial process for similar conditions (a scan of a forging after trimming compared to the CAD model)

which will allow it to meet the set quality criteria. Obtaining a forging with such dimensions from the forging process indicates the necessity to analyze geometrically the condition of the tools and their possible replacement with another unused trimming set. In the analyzed case, despite the fact that the obtained value of the maximum force from numerical modelling was higher for the operation condition of both types of tools compared to new forging tools and worn-out trimming tools, this state of affairs makes it more unfavourable in terms of dimensional and shape accuracy forgings. Initial assumptions showed that used forging tools as well as used trimming tools would be the "worst" operating condition (option III) of both types of tools. However, based on a detailed analysis (based on FEM modelling and comparison with scans), it turns out that the 4th case, i.e. new forging and used trimming tools, is "the worst" because the forging does not fall within the tolerance range. Therefore, in a typical production process, one should pay attention and approach with caution to the situation of option III, but one should definitely avoid and not allow for the situation with option IV.

5. Conclusion

The presented comparative analysis made with the use of numerical modelling provided a lot of information referring to the effect of the different geometries of the forging and the trimming tools on the distributions of equivalent deformations and reduced stresses as well as the courses of the forces. Additionally, the conducted verification of the numerical modelling results for a selected variant based on a comparison of the geometry obtained from FEM and the scan of a forging collected from the industrial process shows the validity of the assumptions made in respect of numerical modelling. In the case of the most disadvantageous, extreme variant, which is quite often present in the industrial process, i.e. the case of worn forging and trimming tools, the differences in the selected key dimensions are small (a few percent), which allows you to say that through the right and thoughtful selection of tools for forging and trimming, you can avoid the most undesirable variants, and thus increase the efficiency of the process. Therefore the obtained results can be useful for the evaluation of the phenomena and mechanisms occurring during the trimming process in different situations connected with the production conditions and dependent on the current state of the forging tools and the trimming tools. Although the finite element methods are approximate methods, as shown in the study, with extensive experience in modelling this type of phenomena, supported by practical knowledge and engineering approach, the obtained results are convergent and do not differ much from real conditions.

And yet it seems that it is necessary to perform further research in this area for an even better representation of the industrial conditions by means of a virtual model of the process. Nevertheless, the obtained good agreement of results makes it possible to optimistically look at the use of numerical modelling for the still difficult as well as geometrically and physically complex trimming processes. In the analyzed case study, the results obtained under the industrial conditions are valuable, as they enable a complex analysis of the trimming process, which in consequence should cause the initiation of proper actions with the purpose of a better control as well as technical and technological perfection of these processes. Also, combining the results obtained from numerical modelling with those from microhardness tests and microstructure investigations should provide even more value information on e.g. the possible occurrence of defects (cracks) in the forging. It can also stimulate attempts to transfer from the cold trimming technology to the hot trimming one (directly after the forging process), which would significantly increase the efficiency of the whole process.

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