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PROPER ASSEMBLY AND GEOMETRICAL PARAMETERS AS A CRITERION FOR THE COMPUTER AIDED DESIGN OF MANUFACTURING CYCLE FOR SCREWS

MARIUSZ SKÓRA[1]*, MACIEJ PIETRZYK[2]

[1]GAWEL Zaklad Produkcji Srub S.A., 36-073 Strazow, Poland
[2]AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Kraków
**Corresponding author: mariusz.skora@zps.pl*

Abstract

Paper presents an application of numerical modelling to the design of the best manufacturing technology for fasteners. Imbus screw M6x20 was selected as an example. Since simulation of the one case of manufacturing requires very long computing times, application of classical mathematical optimization was not possible. Therefore, an approach known as variant optimization was applied. In this approach trial and error method is combined with the knowledge of the expert. The objective was to improve the shapes of the fibres in the forging and to improve the contact between the head of the screw and the material being joined. Finite element method was used to simulate the whole manufacturing chain. The model was validated and its good accuracy was confirmed. Various variants of the technology were simulated and new technological parameters were proposed, which gave noticeable improvement of the objective function.

Key words: forging, fasteners, numerical modelling, technology design

1. INTRODUCTION

There are numerous examples of computer aided design of technology for a single forming process. Some papers dealing with modelling and optimization of the multi-stage forging processes have been published during the last fifteen years (McCormack & Monagan, 2002; Park et al., 2007; Pietrzyk et al., 2008). In some works a particular focus was on the analysis of workability during multi stage forging. Behrens et al. (2000), Ghiotti et al. (2011) and Bariani et al. (2011) used numerical simulations to follow damage occurrence in few stages of forging. Chiesa et al. (2004) presented optimization of forging with properties of product included in the cost function. All these papers dealt with a sequence of forging operations.

The main objectives of the present work was considering not only one particular type of manufacturing process, i.e. forging, but modelling of the entire production chain. It is expected that this approach would provide possibility of accounting for relations between subsequent operations (Hon & Xu, 2007; Pereira & Paulre, 2001; Madej et al., 2007; Kuziak et al., 2011a; Skóra et al., 2012). The second objective was connected with a basic challenge for the design of metal forming processes, which is dimensional accuracy. The knowledge about the metal flow in subsequent operations is essential for the design of the best technology with respect to product dimensions. Therefore, the design of the best manufacturing technology assuming assembly and geometrical parameters as a criterion is considered in the paper.

Development and experimental validation of the model, which simulates production chains and predicts product properties, was one of the additional tasks in the present project. An attempt of connec-

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tion of simulation of production chains with variant optimization was made. The idea of this approach is presented in the paper and application to the production chain based on forging is proposed.

2. MANUFACTURING CHAIN

Developed strategy for the technology design can be applied to any manufacturing process based on metal forming. Production of the imbus screw M6x20 according to ISO 4762 standard was selected as an example. Main features of the manufacturing process for this product are given in this chapter.

2.1. Product and material

Technological process for the selected screw M6x20 is shown in figure 1. The material was wire with the diameter of 9.76-003 mm made of 30MnB4 steel. The flow stress equation proposed by Hansel and Spittel (1979), with coefficients determined using inverse analysis of plastometric tests (Skóra, 2013), was used for this steel:

$$\sigma_p = 8420397\varepsilon^{0.0679}\exp\left(-0.01546\varepsilon\right) \dot{\varepsilon}^{0.019}\exp\left(-0.00048T\right) \qquad (1)$$

where: ε - strain, $\dot{\varepsilon}$ - strain rate, T - temperature in ^{o}C.

The whole process is composed of three operations:

- upsetting with reduction of the bolt diameter,
- primary upsetting and shaping of the head,
- finishing operation, in which hexagonal nest is made and final shape of the head is formed.

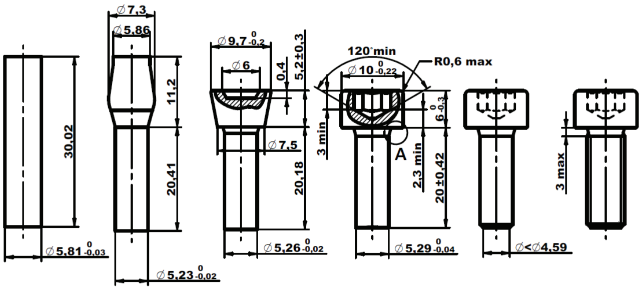

Fig. 1. *Current technology for forging of the investigated screw M6x20.*

Application of both upsetting and reduction of the bolt diameter in one operation is a characteristic feature of this process. To perform this process the material flow has to be constrained. Thus the bolt is supported by a die pusher. Tool setting used to reach this goal is presented in figure 2.

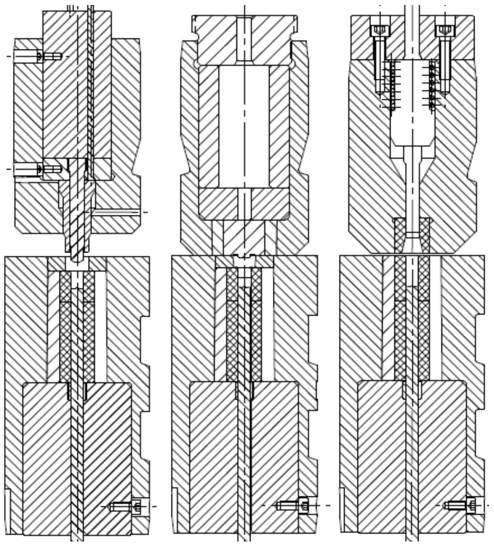

Fig. 2. *Setup of tools for forging of the screw M6x20 according to the standard ISO 4762.*

The most commonly observed now faults in the investigated process are presented in figures 3-5 and they are listed below:

- Discontinuity of the surface under the head in the area of the transition radius (figure 3).
- Misalignment between the fibres and the shape of the screw. This fault is shown in figure 4a, where curved shape of fibres is seen. Misalignment of fibres causes cracks during tensile test, as seen in figure 4b.
- Misfit between surfaces shown in figure 5, which cause problems during assembly, in particular increase of the screw torque.
- Misfit between axis of the hexagonal nest and axis of the bolt.

Fig. 3. *Faulty shape of the transition radius between the head and the bolt.*

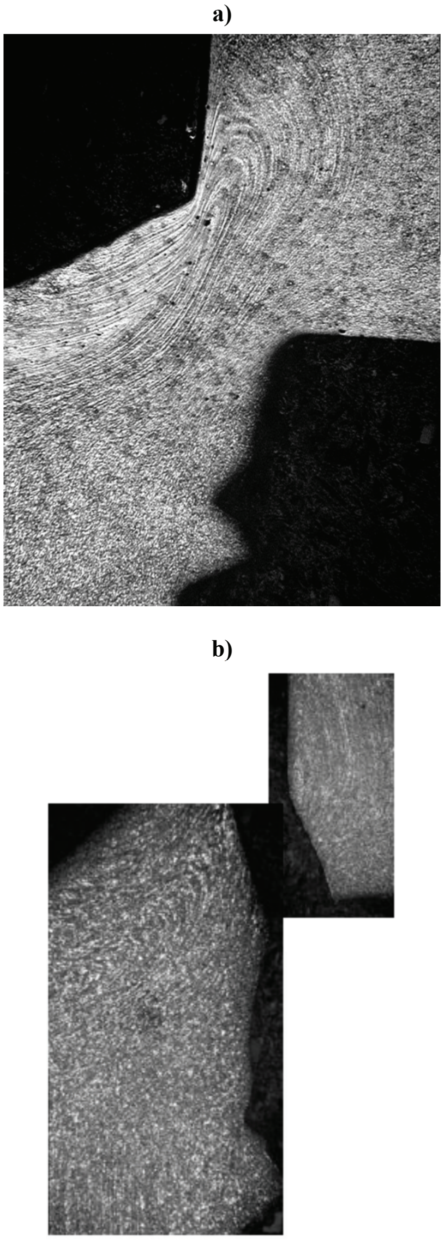

Fig. 4. *Misalignment between the fibres and the shape of the screw (a) and crack occurring during tensile test, caused by this misalignment (b).*

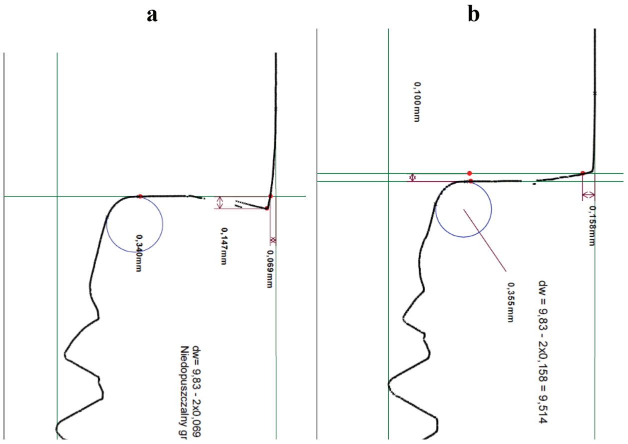

Fig. 5. *Measurements of the contact surface, a) concave surface, b) convex surface.*

Manufacturing of the investigated screw is a large capacity production. Therefore, to check the capability to maintain stable process conditions (stable geometrical parameters) the analysis of the process capability parameters was performed. Results of this analysis allowed to distinguish main reasons of faulty products. These reasons are discussed below

Diameter of the contact area under the head is the main parameter, which influences the screw torque needed to obtain certain level of tensile force in the screw joint. Beyond this, the torque depends on the friction conditions at this area and surface roughness. Knowing these parameters designers calculate the torque required for a selected joint. When geometrical parameters of the contact surface do not meet requirements, maximum allowed force in the joint can be exceeded during assembly.

Problems with the shape of the fibres in the head and with the alignment between axes of the nest and the bolt are due to combining processes of upsetting and bolt diameter reduction in one operation. Having the above remarks in mind, the objective of this work was to select process parameters, which influence contact surface and fibres alignment, and to design the technology giving the best product parameters. Numerical simulation of the manufacturing chain was used to design the new technology.

3. FE SIMULATIONS

3.1. FE model

The finite element (FE) code Forge based on the Norton-Hoff visco-plastic flow rule (Norton, 1929; Hoff, 1954) was used in simulations. The constitutive law in Forge is (Chenot & Bellet, 1992):

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

where: $K(T,\varepsilon_i,\dot{\varepsilon}_i)$ – consistency, which is a material parameter dependent on the flow stress σ_p calculated from equation (1), $\boldsymbol{\sigma}$ – Cauchy stress tensor, $\dot{\boldsymbol{\varepsilon}}$ – strain rate tensor, $\dot{\varepsilon}_i$ – effective strain rate, T – temperature, ε_i – effective strain.

The visco-plastic mechanical formulation was coupled with the finite element solution of the Fourier heat transfer equation:

$$\nabla \cdot k\nabla T + Q = c_p \rho \frac{\partial T}{\partial t} \tag{3}$$

where: k – conductivity, Q – heat generated due to plastic deformation, c_p – specific heat, ρ – density, t – time.

3.2. Simulation of the manufacturing chain

Primary operation of wire drawing was simulated first. The input diameter was 6.5 mm and the output diameter was 5.81 mm. The objective of the simulations was to determine distribution of the flow stress along the radius, which was the input parameter for further simulations of forging. Results of simulation are presented in figure 6. More information on the analysis of the drawing process can be found in earlier publications (Madej et al., 2009; Kuziak et al., 2011b; Skóra et al., 2013).

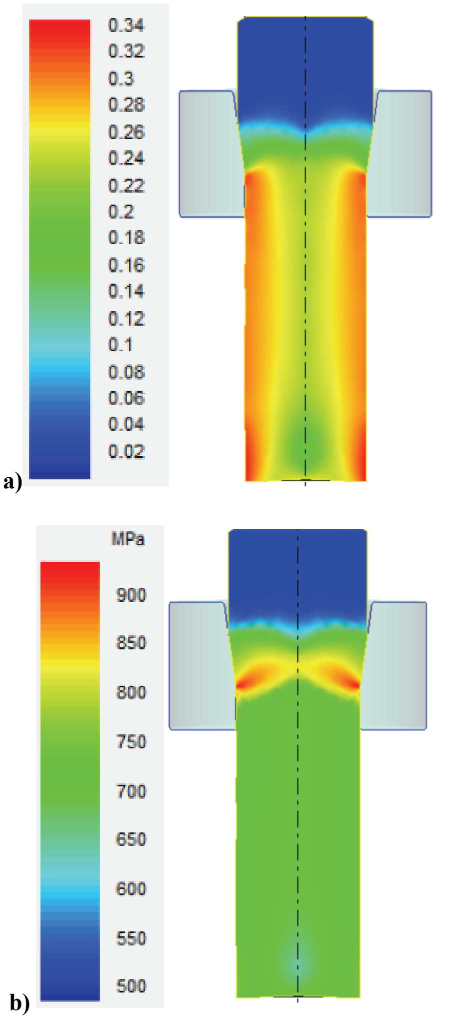

Fig. 6. *Results of simulations of wire drawing, distributions of the effective strain (a) and the effective stress (b).*

Three forging operations in the manufacturing chain were simulated next. These operations are listed in section 2.1 and are presented in figure 1. Central lubrication system was applied in all forging operations and friction coefficient for these conditions was evaluated as 0.07. Results of simulations of forging are presented in figures 7-11. Analysis of the results showed that the larger displacement of the material occurs in operations 2 and 3. The second operation forms the shape of the transition between the bolt and head. Primary shape of the contact surface is prepared in this operations, as well. The final shape is obtained in the last operation, which imposes the dimensions of the product. Performed simulations have shown that for certain critical depth of the penetration of the stamp, which forms the nest, the faulty contact surface is obtained, see area D in figure 10.

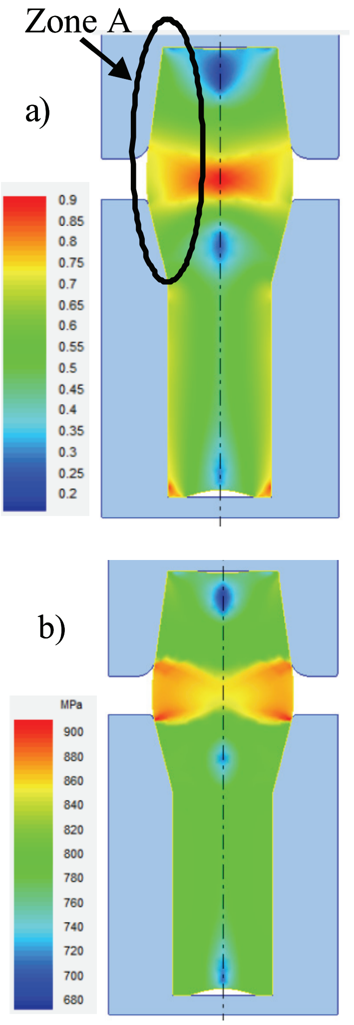

Fig. 7. *Results of simulations of the first forging operation, distributions of the effective strain (a) and the effective stress (b).*

At this stage of the analysis verification of the model was performed and the calculated shapes of the screw were compared with the measurements using profilograpgh. The results are presented in figure 11. Calculated and measured shapes of semi products and final product in zones A, B and D coincide what confirms good accuracy of the model.

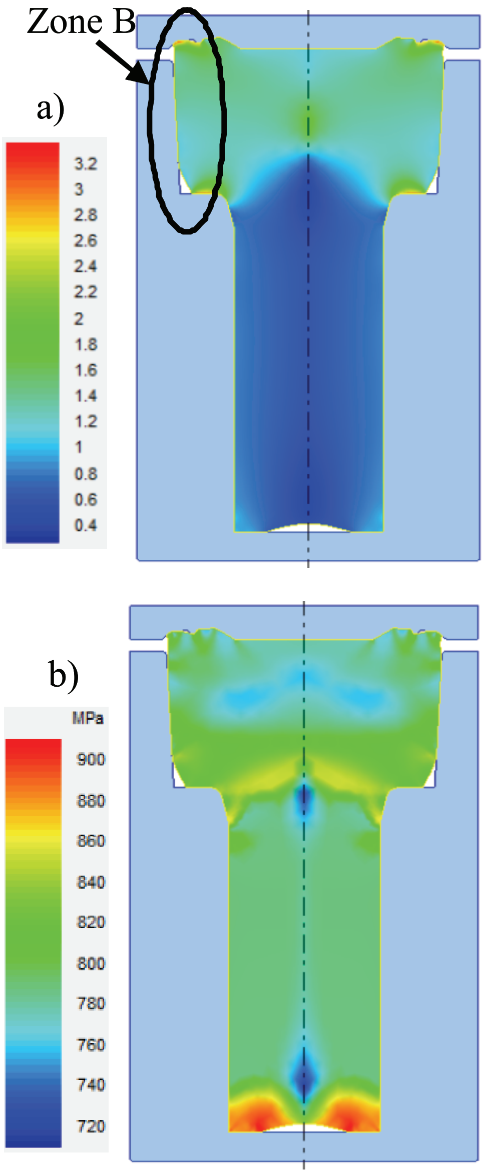

Fig. 8. Results of simulations of the second forging operation, distributions of the effective strain (a) and the effective stress (b).

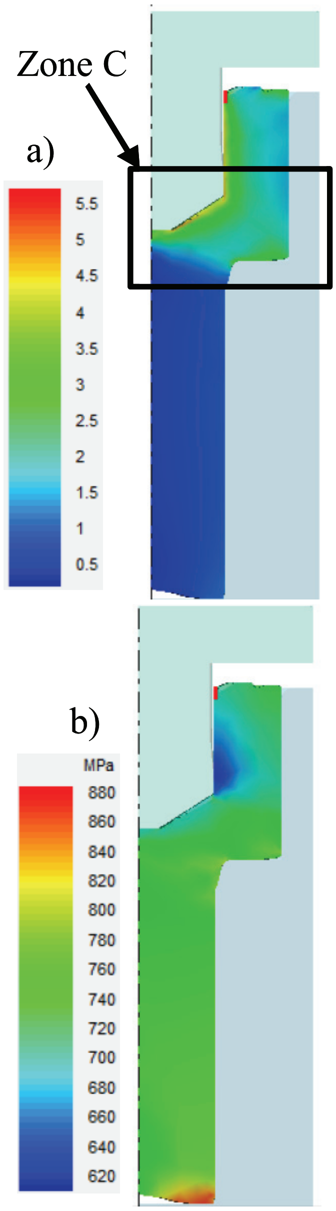

Fig. 9. Results of simulations of the third forging operation, distributions of the effective strain (a) and the effective stres (b).

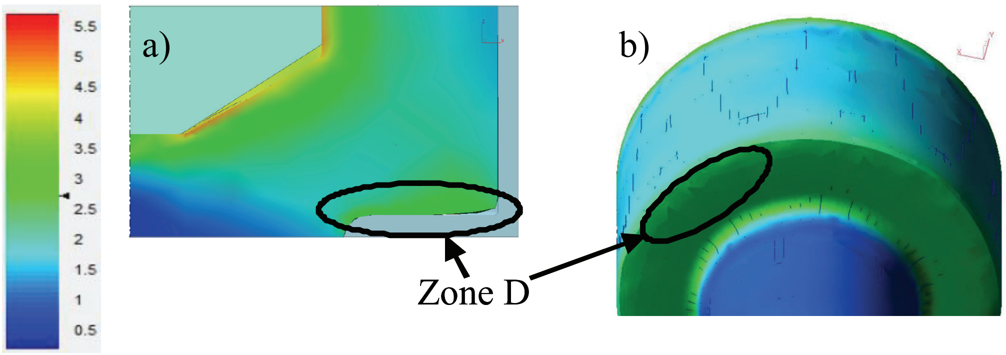

Fig. 10. Results of simulations of the third forging operation, distributions of the effective strain. The faulty contact surface in the area D: cross section (a) and view (b)

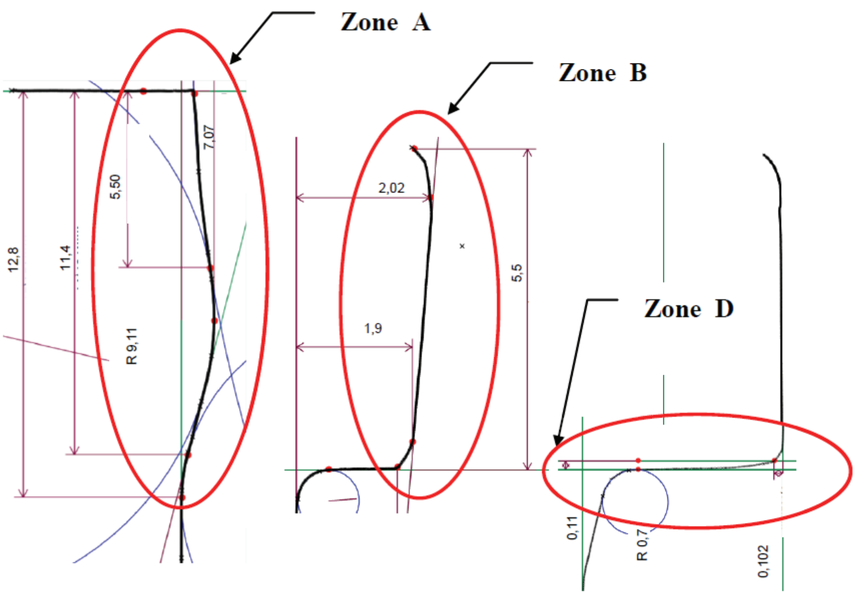

Fig. 11. *Comparison of calculated shapes of the screw with the measurements using profilograpgh.*

3.3. Design of the best manufacturing technology

Mathematical formulation of the optimization task for the investigated process is possible. The proper shape of the contact surface and good alignment between fibres and the shape of the screw should be the objective function and shapes of tools in subsequent operations should be the optimization variables. However, since one calculation of the objective function is extremely time consuming, solution of this optimization problem is practically impossible. Therefore, an approach known as variant optimization was applied in the present work. In this approach trial and error simulations are combined with the knowledge of an expert and the best solution is found.

Analysis of results of simulations shown in section 3.2 and additional simulations of other variants led to the following proposition:

- The first forging operation is substituted by the two independent operations: i) reduction of the bolt diameter and ii) primary upsetting, in which the final diameter of the head is reached. The remaining two operations were not changed.
- Critical values of the depth of the nest with respect to the contact surface are determined using simulations of the last operation. These values allow to obtain proper height of the head and proper contact surface.

Simulations of the last forging operation allowed to identify relation $A_w = \mathrm{f}(g)$, where A_w is the area of the contact and g is the distance between the edge of the nest and the contact surface (figure 12). On the basis of measurements of the diameter of the contact surface and the distance g the function $A_w = \mathrm{f}(g)$ was determined, see figure 13. It was concluded that the contact area for the investigated screw is between 50.24 mm^2 (result of forging in the third operation) and 78.5 mm^2 (maximum dimension of the M6 according to ISO 4762).

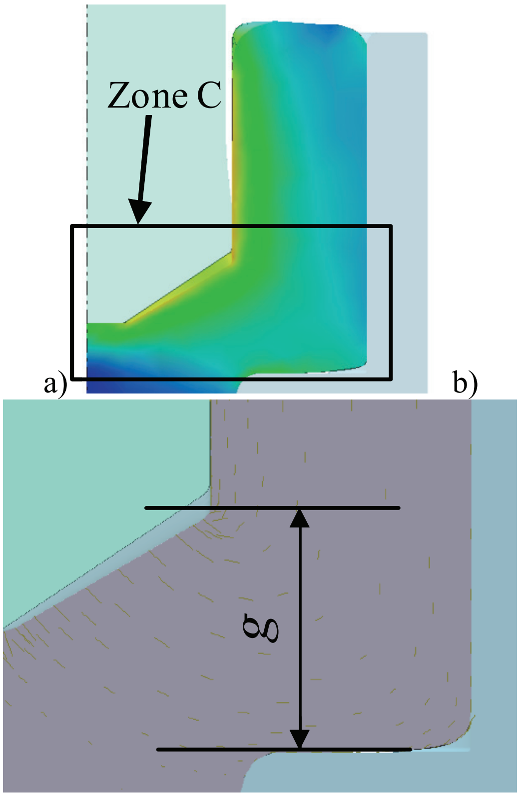

Fig. 12. *Strain distribution at the cross section of the head (a) and zone C with the marked distance g (b).*

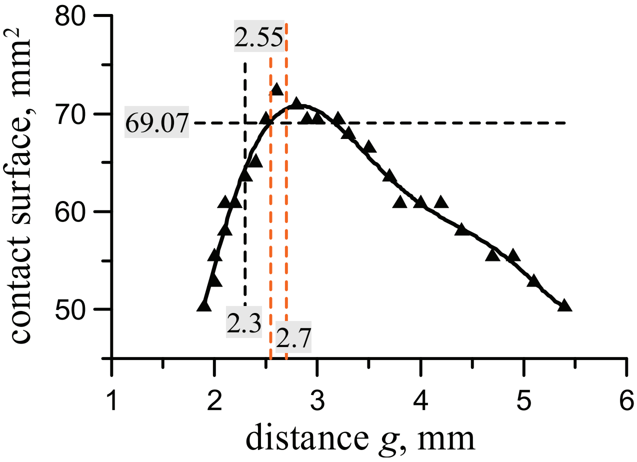

Fig. 13. *Relation between the distance g and the contact surface A_w.*

The standard ISO 4762 defines the minimum distance *g* as 2.3. mm. This dimension assures the minimum volume of the material in the area between the nest and the bolt, which is needed to obtain the required strength in tension. Relation in figure 13 shows that maximum contact surface was obtained for *g* = 2.7 mm. Accounting for the limitations due to the standard ISO 4762 the optimal range of the distance *g* was determined as 2.55 - 2.7 mm.

On the basis of this analysis the distance *g* was selected and simulations of the manufacturing chain were performed. Figure 14 shows the forging sequence according to the new technology. Drawing process was not changed in the new variant and strains shown in figure 6a were used to calculate flow stress of the rod in the first operation. Results of simulations of the modified forging sequence are shown in figures 15-18. Analysis of these results confirmed an improvement of the geometrical parameters of the forging. Introduction of the operation 1 (reduction of the bolt diameter, figure 15) caused clear distinction between the parts of the material, from which bolt and the head of the screw are made. In consequence, due to the established length of the bolt setting following operations was easier. It decreased possibility of errors and assured proper shape of fibres. This decreased diameter of the bolt allows to eliminate the guiding cone in the following operations (the radius is the same in subsequent dies).

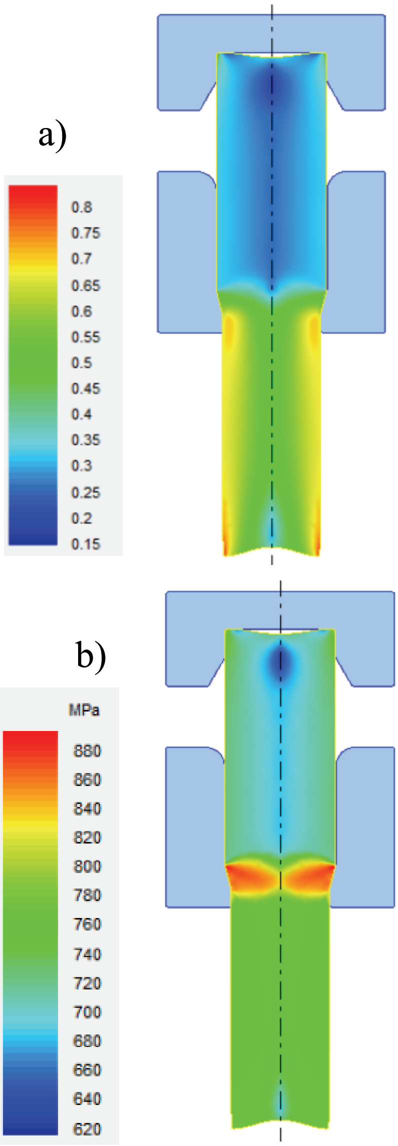

Fig. 15. *Results of simulations of the reduction of the bolt diameter, distributions of the effective strain (a) and the effective stress (b).*

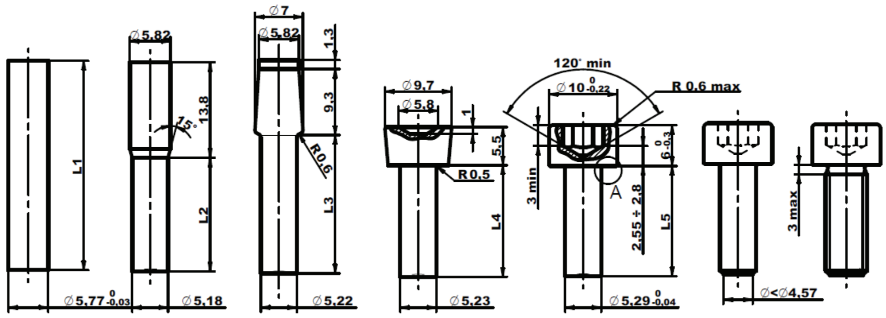

Fig. 14. *Modified technology for forging of the investigated screw M6x20.*

4. INDUSTRIAL TRIALS

Industrial trials were performed to validate the designed technology. The set of the tools which were used is shown in figure 19. Screws obtained from the old and modified processes were compared. The following tests were performed to enable this comparison:

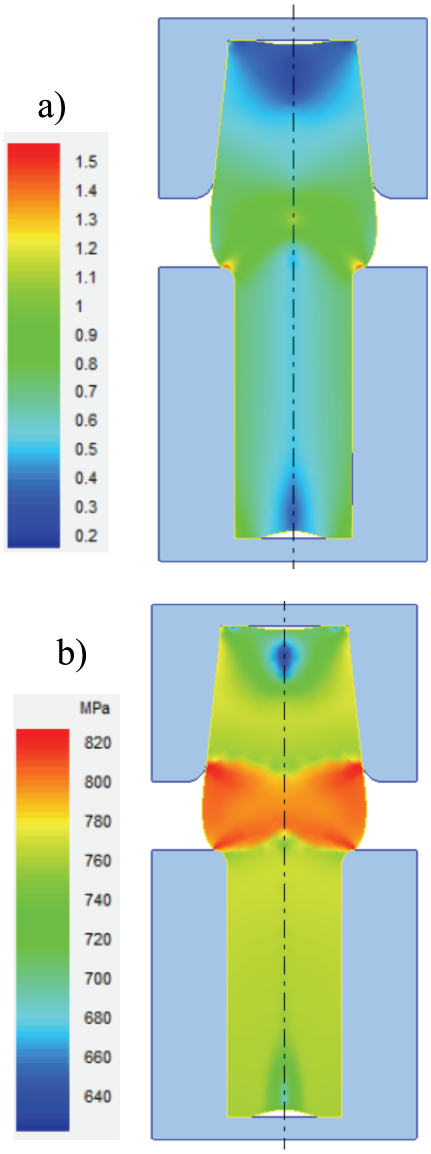

Fig. 16. Results of simulations of the primary upsetting operation, distributions of the effective strain (a) and the effective stress (b).

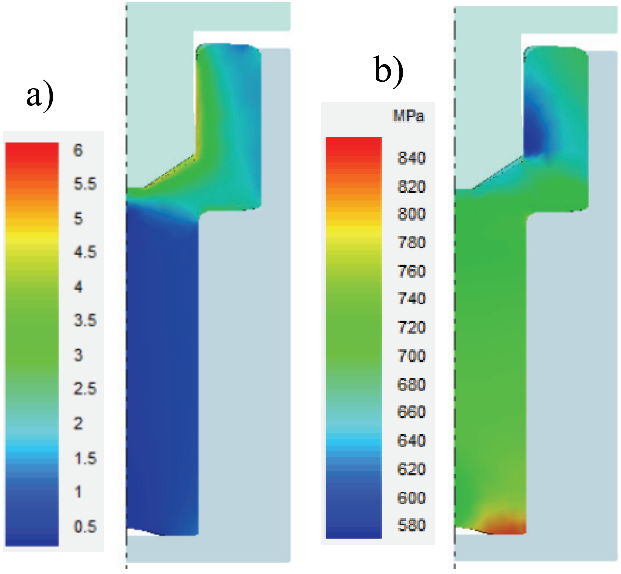

Fig. 18. Results of simulations of the final forming of the head, distributions of the effective strain (a) and the effective stress (b).

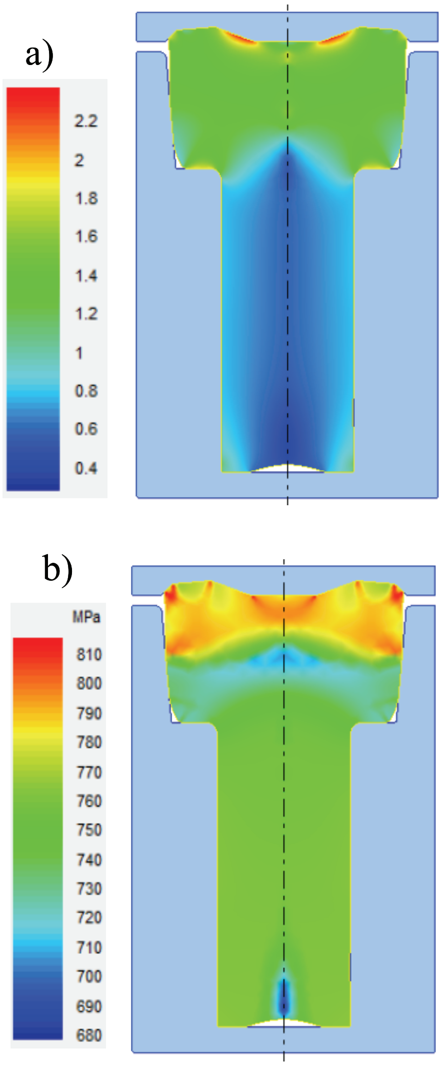

Fig. 17. Results of simulations of the primary forming of the head, distributions of the effective strain (a) and the effective stress (b).

- Measurements of the profile using profilograph (figure 20).
- Analysis of macrographs and evaluation of the shape of the fibres (figure 21).
- Investigation of the of the alignment between the axis of the bolt and the nest and evaluation of the contact surface (figure 22).
- Measurements of the screw torques for the selected 10 products with the diameter of the contact surface of 9.5 mm (5 pieces) and 9.7 mm (5 pieces). These diameters were obtained for the two setups for the last operation, according to the relation in figure 13.

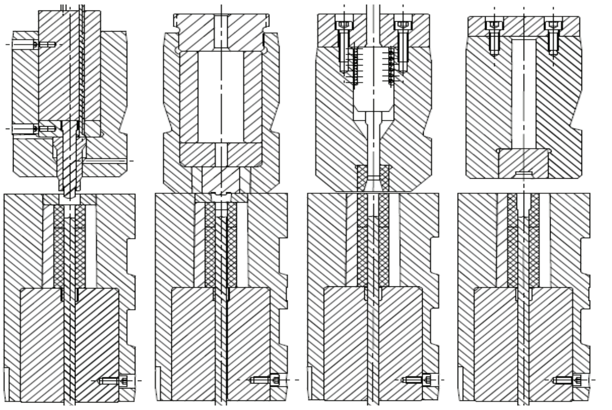

Fig. 19. Modified tools for forging of the investigated screw M6x20.

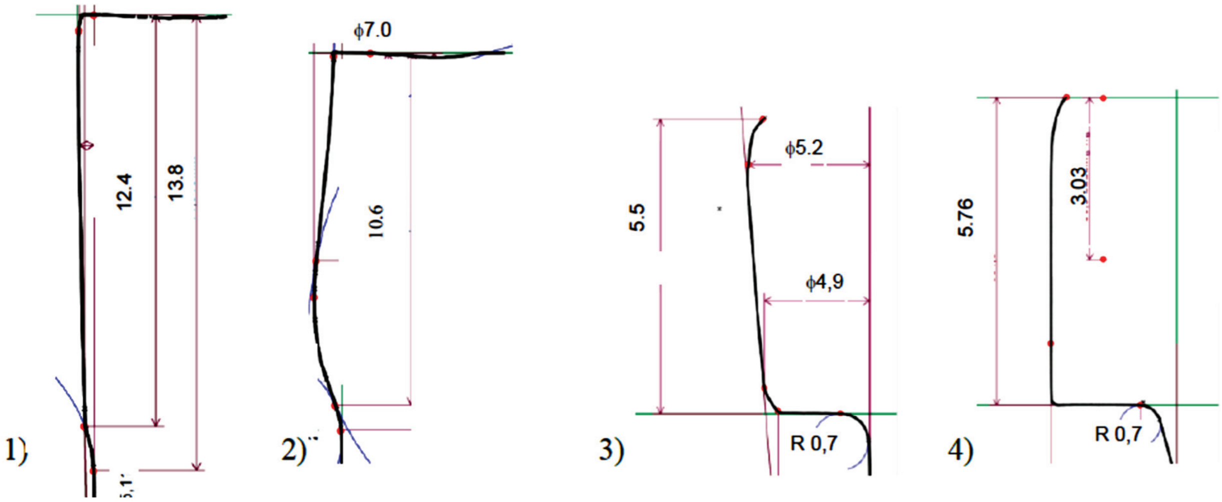

***Fig. 20.** Measurements of the shape of semi products and final product after operations 1, 2, 3 and 4 in the new technology.*

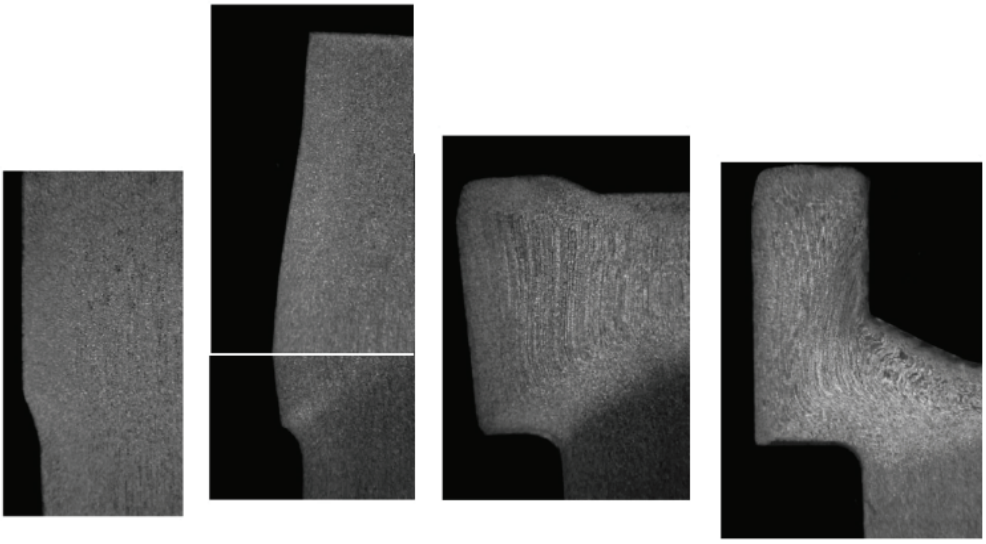

***Fig. 21.** Micrographs revealing the fibres in the semi products and in the final product after operations 1, 2, 3 and 4 in the new technology.*

Comparison of the symmetry of the nest and the contact area for the two technologies showed an average improvement of the alignment from 0.194 mm to 0.08 mm and an average increase of the contact surface diameter from 9.491 mm to 9.70 mm. Results of the measurements of the screw torque showed an average increase of the total torque from 10.8 to 13.98 Nm and an average increase of the torque on the screw from 5.9 to 8.31 Nm.

Measurements of the shape of the semi products and the final product (figure 20) are in agreement with simulations and show that modification of the new technology gave better dimensional accuracy of products. Investigation of the shape of the fibres justified splitting of the first operation into two. Observed shape of the lines (figure 22) coincide with the shape of the forging. The waviness in the area C in Figure 14 is much smaller for the new technology.

5. CONCLUSIONS

Methodology of an application of the variant optimization to design the forging technology for

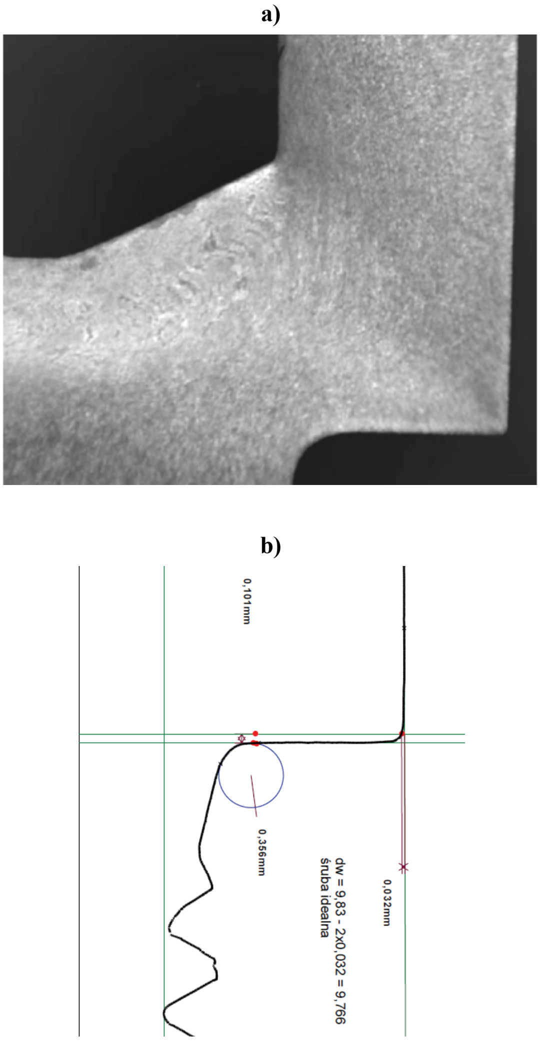

Fig. 22. *Micrograph of the area between the nest and the contact surface revealing the fibres (a) and selected example of the measurement of the contact diameter for the new technology.*

screws was presented. The optimization criterion composed improvement of the contact between the screw and the joined material and improvement of the shape of the fibres in the forging. Analysis of the process based on numerical simulations resulted in the following conclusions:

- Splitting the first operation into two (reduction of the bolt diameter and primary upsetting) improved the shape of the fibres in the forging.
- The optimal distance between the edge of the nest and the contact surface was determined as 2.55 - 2.7 mm.
- Developed methodology of the design of the best technology can be applied to other products of the same type.
- Relation between the distance g and the contact surface A_w has to be determined for each new type of the nest.

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PARAMETRY MONTAŻOWE I GEOMETRYCZNE JAKO KRYTERIUM DLA KOMPUTEROWEGO WSPOMAGANIA PROJEKTOWANIA TECHNOLOGII PRODUKCJI ŚRUB

Streszczenie

W artykule przedstawiono zastosowanie numerycznego modelowania do projektowania najlepszej technologii wytwarzania elementów złącznych. Jako przykład do analizy wybrano śrubę imbusową M6x20. Ponieważ symulacja jednego przypadku wytwarzania śruby wymaga bardzo długich czasów obliczeń, zastosowanie klasycznych metod optymalizacji nie było możliwe. Dlatego zastosowano podejście znane jako optymalizacja wariantowa, w której metoda prób i błędów jest połączona z wykorzystaniem wiedzy eksperta. Celem optymalizacji była poprawa kształtu włókien oraz poprawa styku śruby z łączonym materiałem. Do symulacji cyklu wytwarzania śruby zastosowano metodę elementów skończonych. Weryfikacja modelu wykazała jego dobrą dokładność. Przeprowadzono symulacje różnych wariantów technologicznych i zaproponowano wariant, który dał znaczną poprawę funkcji celu.

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