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NUMERICAL SIMULATION OF TOOL WEAR AS SUPPORT OF OPTIMIZATION OF MANUFACTURING CHAIN FOR FASTENERS

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Abstract

Computer aided design of the manufacturing technology for fasteners is presented in the paper. This work puts special emphasis on the tool wear analysis. The particular objectives of the work were twofold. The first objective wss selection of the tool wear model and identification of coefficients in this model on the basis of measurements of tool shapes in industrial processes. Measurements after various number of produced forgings were performed and coefficient in the tool wear model was identified using inverse approach. In the second part of the paper the idea of simulation of the manufacturing chain is adapted to the analysis of the tool wear. Simulations of various variants of manufacturing chains were performed and the alternative, which gives the longest tool life, was selected. Industrial trials were performed for the selected cycle and the efficiency of this cycle was evaluated.

Key words: Forging, tool wear, identification

1. INTRODUCTION

Numerical simulations help to predict behaviour of the material during plastic deformation. Forging process has several centuries tradition, while the theory of plasticity is relatively young scientific discipline. This theory, however, allows to understand better the forging process. Numerical simulations, which are based on the theory of plasticity and numerical methods, are an efficient tool, which helps design of the best forging technology. Not only one step forming operations are considered in these analyses, but also whole manufacturing chains are simulated. Application of the finite element (FE) simulation code to the design of multi step forging of fasteners is the subject of the present work. This approach allows to solve various complex problems in the design of the forging technology. Improvement of the forging of fasteners with the tool life selected as the main optimization criterion was the objective of the present work. Tool life is one of the main factors, which influence the manufacturing costs and material loses.

2. MODELS

2.1. Finite element program

Forge 3 FE software was used in all simulations. This software is based on the Norton-Hoff visco-plastic flow rule. The main equation of this law is (Chenot & Bellet, 1992):

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

where: $\boldsymbol{\sigma}$, $\dot{\boldsymbol{\varepsilon}}$ – stress and strain rate tensor, respectively, $\dot{\bar{\varepsilon}}$ – effective strain rate, K – material consistency, m – coefficient equal 1 for Newtonian flu-

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ids and 0 for rigid–plastic materials, which obey Huber-Mises yield criterion ($\sigma_f = \sqrt{3}K$) and Levy-Mises flow rule.

The mechanical model is coupled with the FE solution of Fourier heat transport equation:

$$\nabla \cdot k \nabla T + Q = \rho c_p \frac{\partial T}{\partial t} \tag{2}$$

where: k – heat conductivity, T – temperature, Q – rate of heat generation due to plastic work, ρ – density, c_p – specific heat, t – time.

Neumann boundary condition is assumed, with the heat transfer coefficient of 10000 W/m^{2}K at the contact surface between the tool and the forging. Cooling in air was simulated on the remaining part of the surface. Friction coefficient of 0.07 was used.

2.2. Flow stress model

Low carbon steel 19MnB4 containing 0.2%C, 1.05%Mn, 0.4%Si, 0.035%P 0.035%S and 0.02%B was investigated. Axisymmetric compression tests were performed to determine the flow stress model of this steel. The tests were performed on the Gleeble 3800 in the IMŻ Gliwice, Poland. The samples were compressed at temperatures 20-300^{o}C and at strain rates 0.01-500 s^{-1}. The Hansel and Spittel equation was used to describe flow stress dependence on temperature, strain and strain rate:

$$\sigma_f = 841.2 \exp\left(-0.00112T\right) \varepsilon^{-0.175} \dot{\varepsilon}^{0.0127} \exp\left(\frac{-0.00116}{\varepsilon}\right) \tag{3}$$

where: T – temperature in ^{o}C, ε – effective strain.

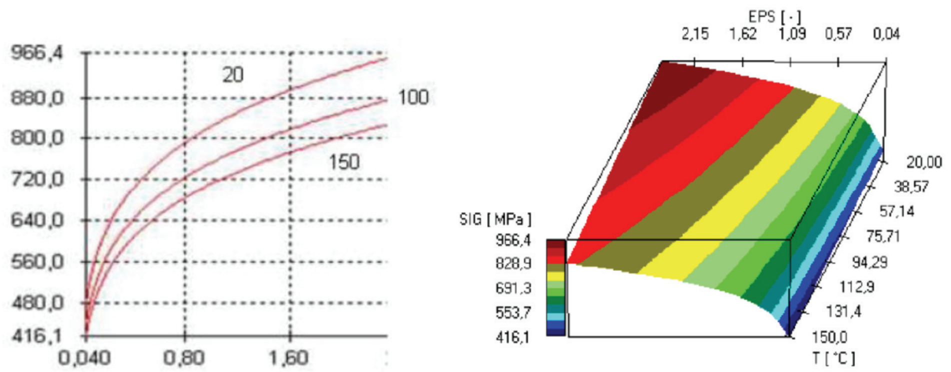

Fig. 1. The influence of temperature (left) and the strain rate (right) on the flow stress.

Flow stress σ_f is a material parameter in the Norton-Hoff viscoplastic law. Inverse algorithm described by Szeliga et al. (2006) was applied for identification of the coefficients in equation (3). Low values of some coefficients mean that temperature sensitivity and strain rate sensitivity are low and softening during deformation is negligible (figure 1).

2.2. Tool wear

An increased tool life is required for economical production with high process reliability. Therefore, estimation of the tool life was included in the process of the design of the manufacturing cycle. The tool wear model based on the fundamental work of Archard (1953) was considered. The volume of the worn off material is proportional to the sliding distance:

$$V = \frac{C_s}{H} \int_0^t \mu p \Delta v dt \tag{4}$$

where: C_s – coefficient, H – hardness of the tool material, p – normal pressure, μ – friction coefficient, Δv – slip velocity between the die and the deformed material.

Sliding wear is the dominant phenomenon that controls tool wear during drawing and forging in the manufacturing of fasteners. The primary results of the analysis of the tool wear in this process can be found in (Madej et al., 2009). In the present work the coefficients in the model were identified and various technological variants were analyzed and compared.

3. SIMULATIONS

Simulations were performed using Forge 3 code with the flow stress model given by equation (3). Forging of the screw M6x14 was investigated. Two technological variants distinguished by modification of the 3rd stage (figure 2) were considered.

Figure 3 shows distribution of the effective stress at the cross section of the forging for subsequent stages. Differences between stages 3, 4 and 5 are in the character of distribution and in the level of stresses. The largest difference is in the area A at the stage 3 and in the area B at the stage 4. The level of stresses at the last stage does not exceed 900 MPa. Distributions in the area crucial for the quality of the screw (area C) are qualitatively similar.

tool wear for the variants in figure 2 requires specification of the areas of the tool, which are crucial for obtaining dimensional accuracy and for smooth running of the process. The 1st stage (extrusion) is common for both variants. Tool wear and construction of the tool with the critical area are show in figure 4. The largest wear and the largest stresses are

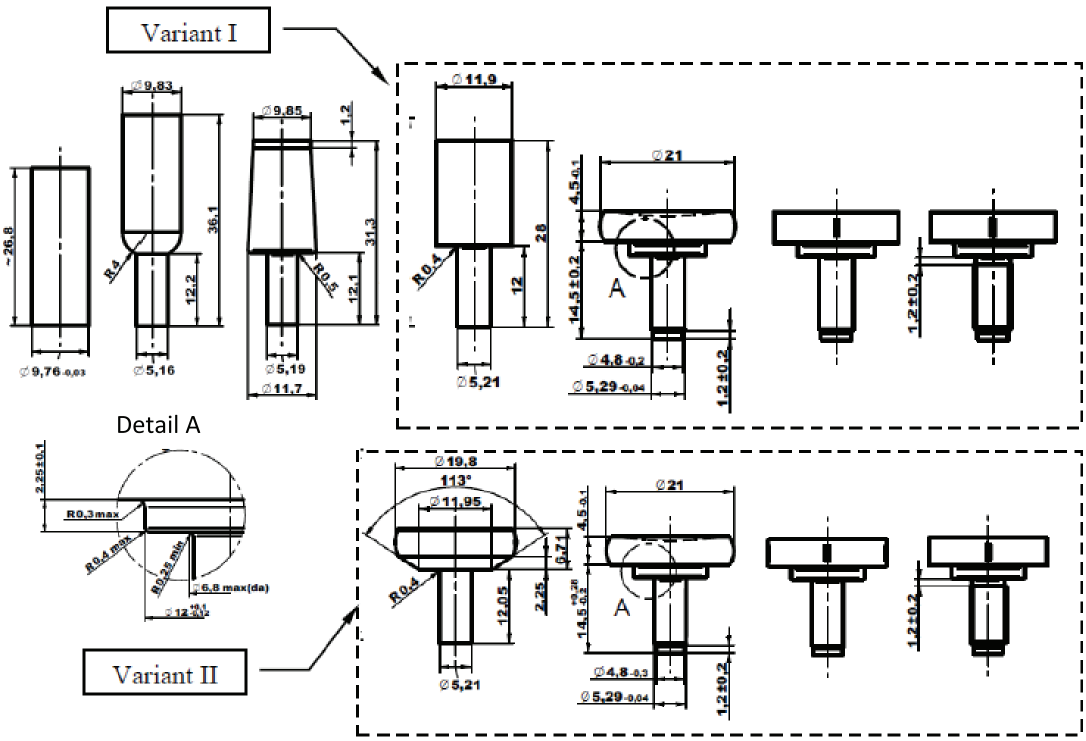

Fig. 2. Technology of manufacturing of the M6 screw – variant I and variant II.

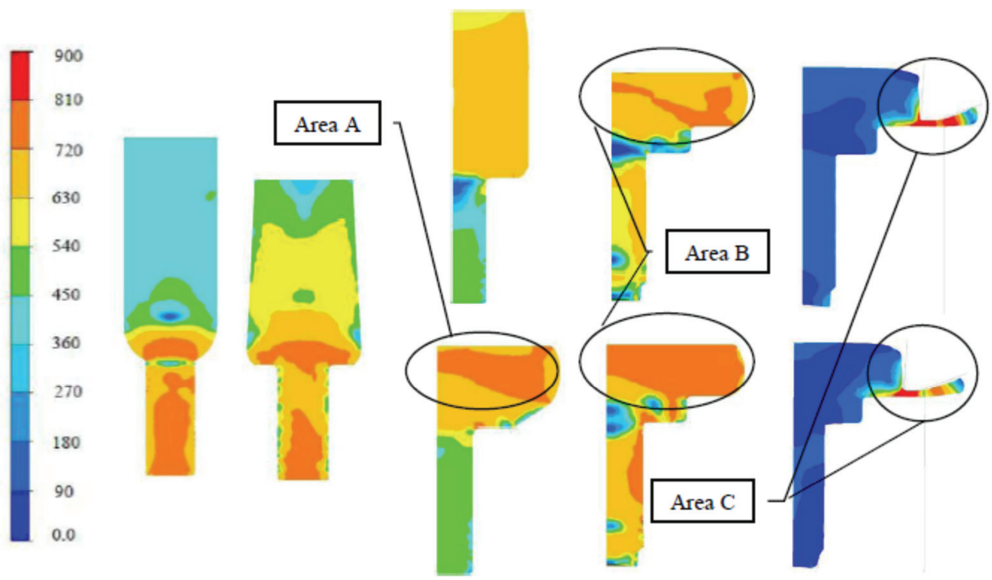

Fig. 3. Distribution of the effective stress at the cross section for subsequent operations.

At the primary stage of calculations coefficient $C_s = 1$ was assumed and the calculated tool wear factor presented below can be used only for comparison of wear for various variants. Analysis of the

in the area D at the radius between extrusion cone and cylindrical calibrating part. Critical surface 1 has the tool wear factor of 5.6. Figure 5 shows tool wear and stresses in tools for the 2nd stage. The largest wear is on the front part of the die (area E) and on the cone (area F). The largest stresses are in the area G. Critical surface 2 (figure 5) achieves the local tool wear factor of 1.66 but the value below 1.08 was observed for 98% of the surface. Tool wear for the remaining parts of the surface is negligible and does not affect the product dimensions.

and the maximum value is 1.26, which is comparable with the stage 3 (surface 3) and stage 2 (surface 2). The largest wear in the area J with the factor of 1.8 may cause problems at the contact surface in the next stage of manufacturing.

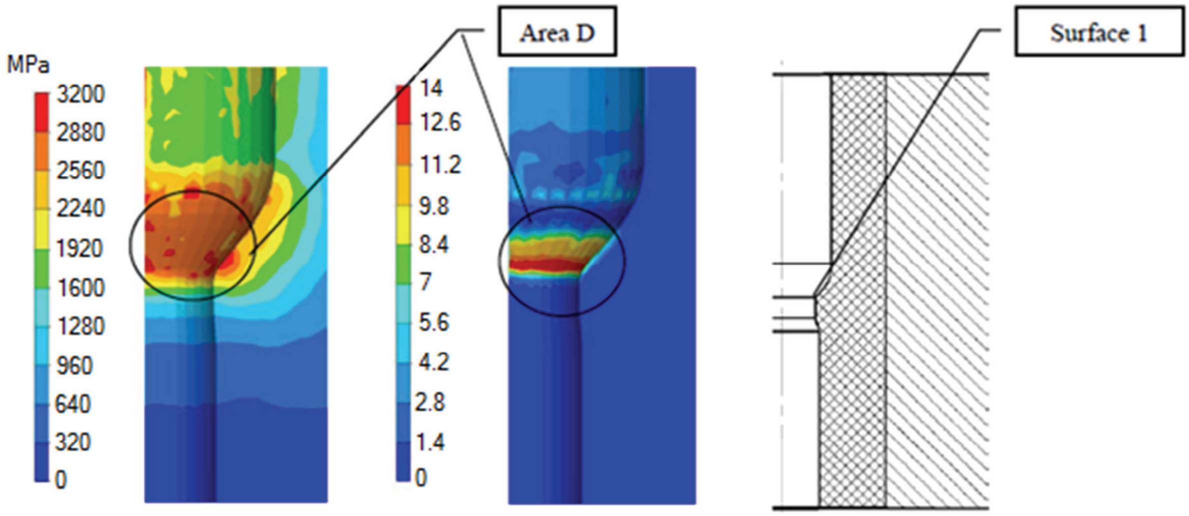

Fig. 4. *1st stage, a) distribution of stresses at the cross section of the extrusion die, b) wear coefficient in the extrusion die, c) design of the extrusion die.*

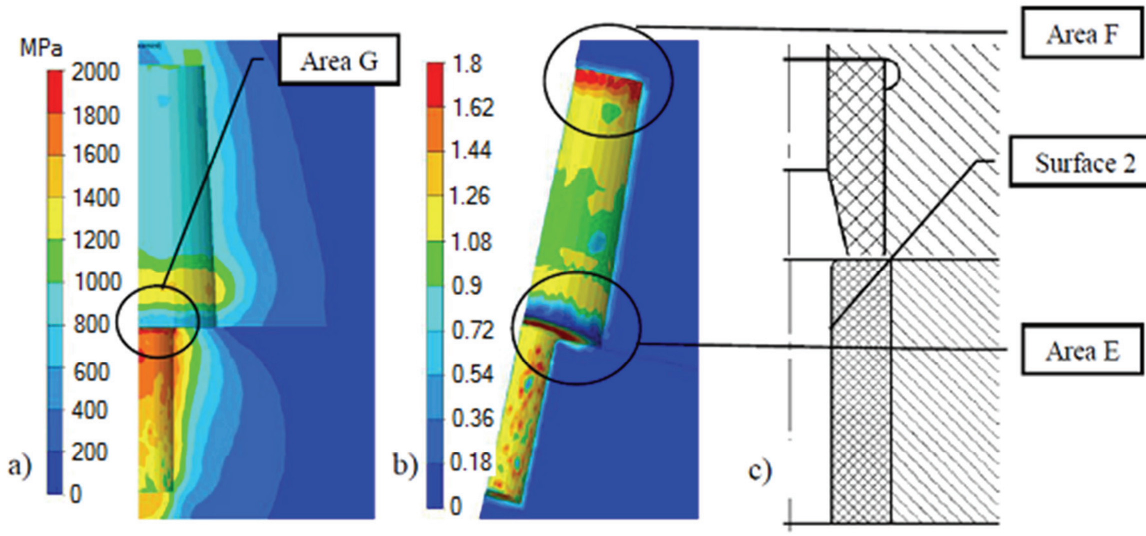

Fig. 5. *2nd stage, a) distribution of stresses at the cross section of the moduling die, b) wear coefficient in the moduling die, c) design of the moduling die.*

Compression in the die is the 3rd stage in the variant 1. Results for this operation are in figure 6. As in the stage 2, the largest wear is at the front of the die (area H). The largest stresses occur in the area I. The majority of the critical surface 3 achieves wear factor of 0.9. Figure 7 shows simulations of tool wear and stresses for the 3rd stage of the variant 2. As for the variant 1, the largest wear is at the area J and the largest stresses are in the area K. 80% of the of the critical surface 4 has wear factor of 0.9

The 4th stage,which is upsetting using die 4 and ram 4 (the same dimensions for both variants), is critical for obtaining accurate dimensions of the part for both variants. Beyond the head, all critical dimensions are controlled at this stage. Figures 8 and 9a show simulations of the tool wear and stresses for the variant 1. The largest tool wear is at the cylindrical part of the die, at the radius (area L) and on the forming cone (area M). On the remaining surfaces the wear factor is max 2.0 for the surface 5, max 1.8 for the surface 6, between 1.0 and 1.6 for the surface 7, between 0.4 and 1.6 for the surface 8. The maximum wear factor for the ram for variant 1 is in the area N. This factor achieves 4.0 at the half of the radius (surface 9).

Results for the stage 4 of the variant 2 are show in figures 9b and 10. The largest tool wear occurs at the contact under the head and at the radius (area O). At the critical surfaces the tool wear factor achieves between 1.2 and 2.0 at the surface 5, max 2.0 at the

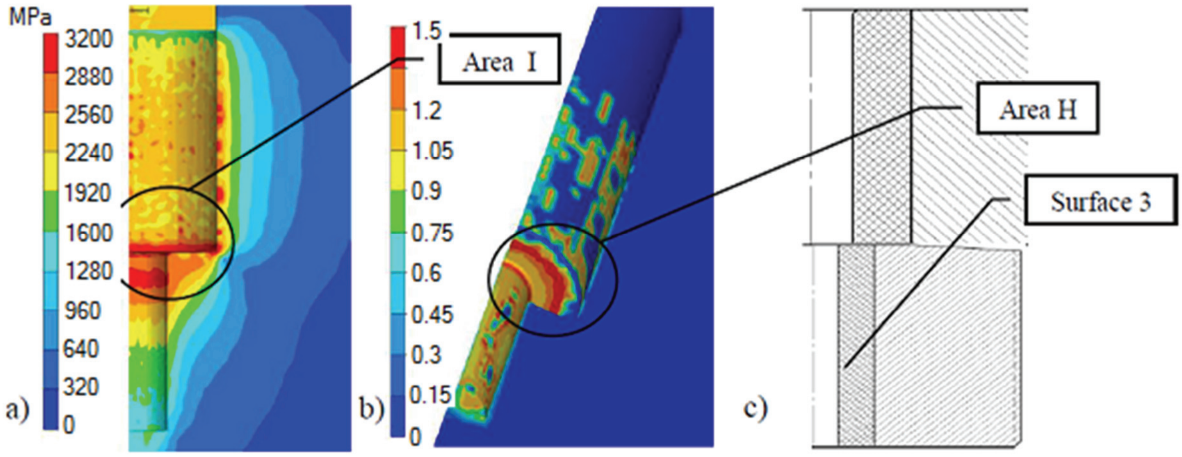

Fig. 6. *3rd stage for the variant 1, a) distribution of stresses at the cross section of the moduling die, b) wear coefficient in the moulding die, c) design of the moulding die.*

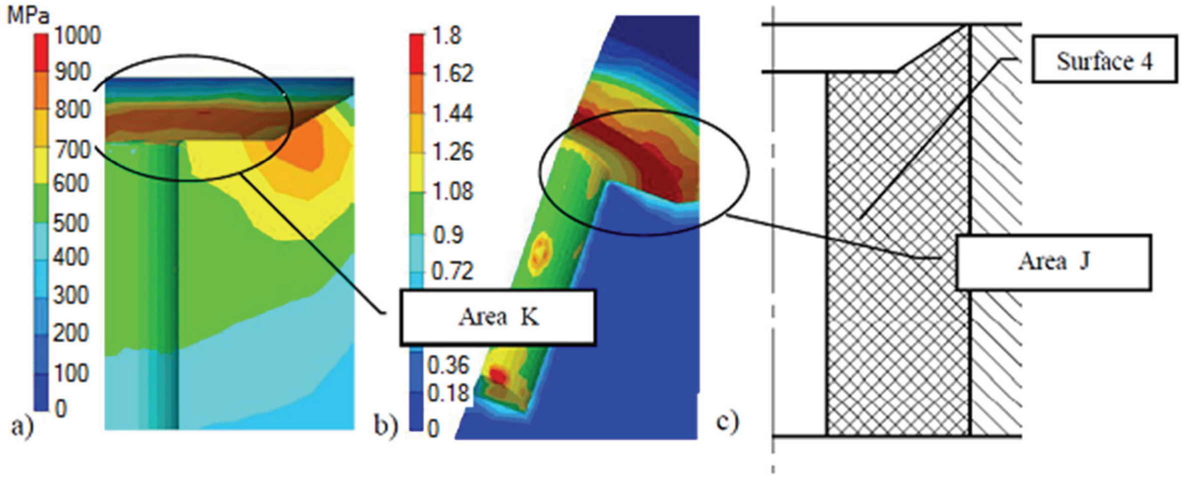

Fig. 7. *3rd stage for the variant 2, a) distribution of stresses at the cross section fo the moulding die, b) wear coefficient in the moulding die, c) design of the moulding die.*

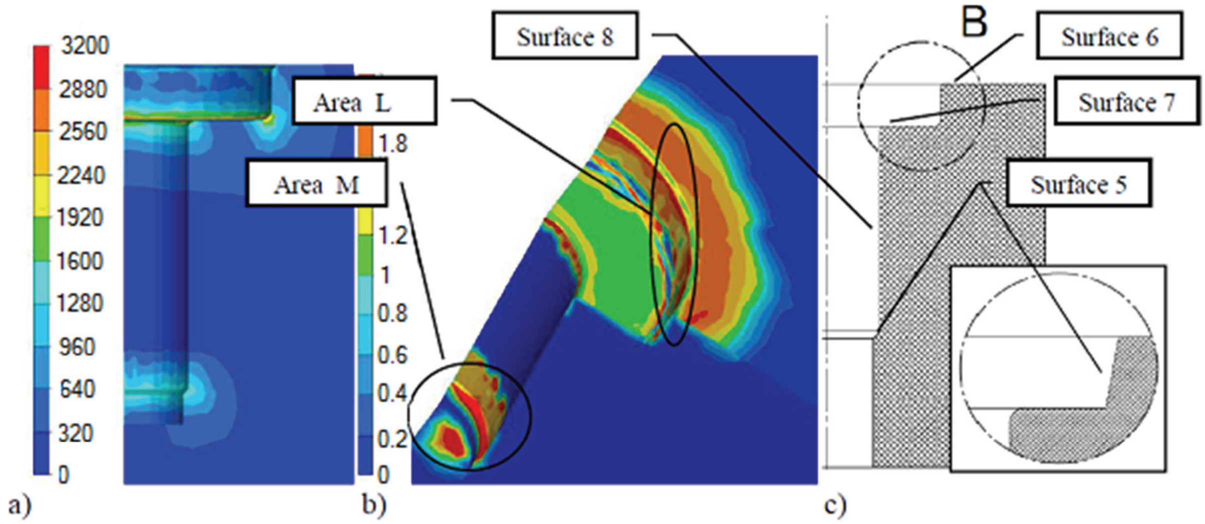

Fig. 8. *4th stage variant 1, a) distribution stress at the cross finish die, b) wear coefficient in finish die, c) design finish die.*

surface 6, max 0.2 at the surface 7 and between 0.2 and 1.2 at the surface 8. Area P is the area of the largest ram wear. The largest tool wear is 4.0 at the half radius (surface 9).

material surplus using cutting die (the same dimensions for both variants). Figure 11 shows results of simulations. Tool wear factor at the critical surface 10 achieves value about 3.6 for 90% of the length of the cutting edge for both variants. The area of the

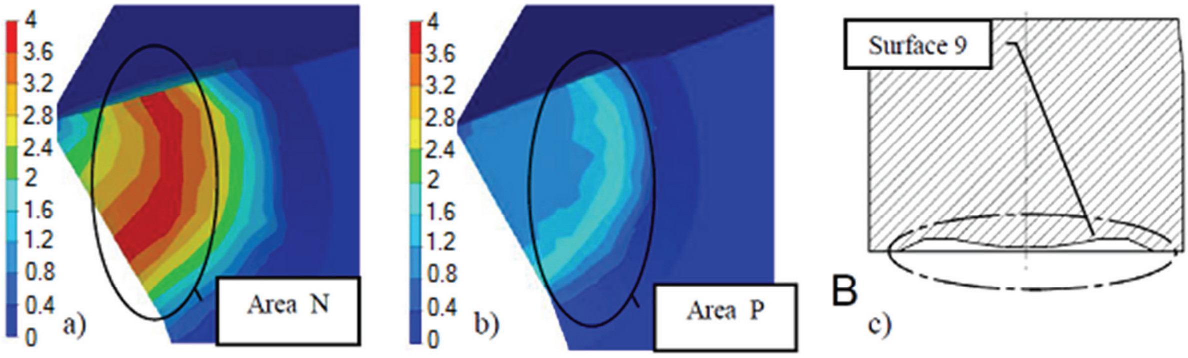

Fig. 9. 4th stage - punch die, a) wear coefficient for the variant 1, b) wear coefficient for the variant 2, c) design of the punch die.

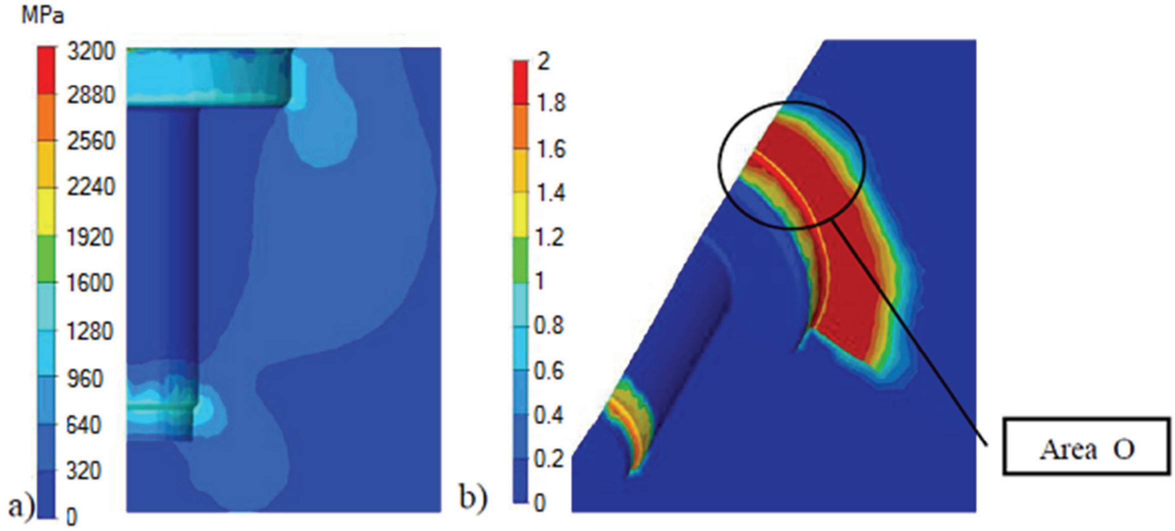

Fig. 10. 4th stage for the variant 2, a) distribution of stresses at the cross section of the finish die, b) wear coefficient in finish die, c) design finishing die.

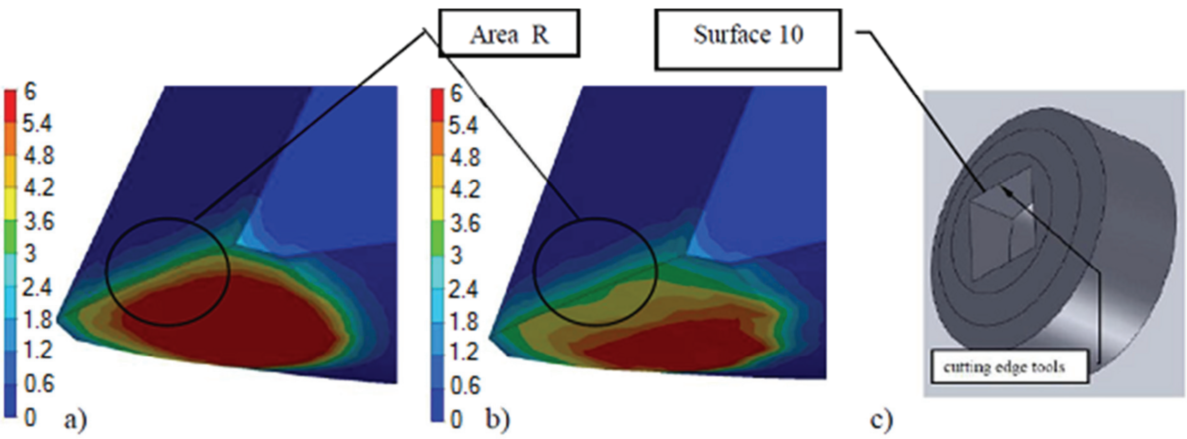

Fig. 11. Distribution of the wear factor: a) 5th stage variant 1 - cutting die, b) 5th stage variant 2 - cutting die, c) view of the cutting die.

largest tool wear differs slightly for the two variants. Tool wear is lower for the variant 2, due to higher contribution of the value 6.5 for the tool wear factor at the area R.

4. INDUSTRIAL TRIALS

The 5th stage determines final dimensions of the head in both variants. It is achieved by cutting of the

Steel 19MnB4 introduced in section 2.1 was used for industrial trials of forging of screws M6×14. Schedule of the preparing of the material for cold forming is described by Kuziak et al. (2011). The cold forging process was carried according to the variant I in figure 2 on the multi stage press NB-515. Figure 12 shows samples during industrial trials.

Fig. 12. *Photograph of samples made during industrial trials.*

New tools, as well as tools after forging of selected number of parts, were measured using profilograph. The following tools were investigated: extrusion die for the 1st stage, ram for the 4th stage, upsetting die for the 4th stage and cutting die for the 5th stage. Figures 13 and 14 show pictures of the cross sections of tools and profiles obtained from measurements for technological variant 1. Tool wear for forging of one part was calculated for critical surfaces.

Constant coefficient C_s in equation (4) for one material of the die and proportional wear for subsequent parts were assumed. Correction of the C_s coefficient accounting for specific shape of tools in subsequent stages was introduced. Results for both variants are in table 1. Assumed limiting wear for various surfaces are determined by dimensional toler-

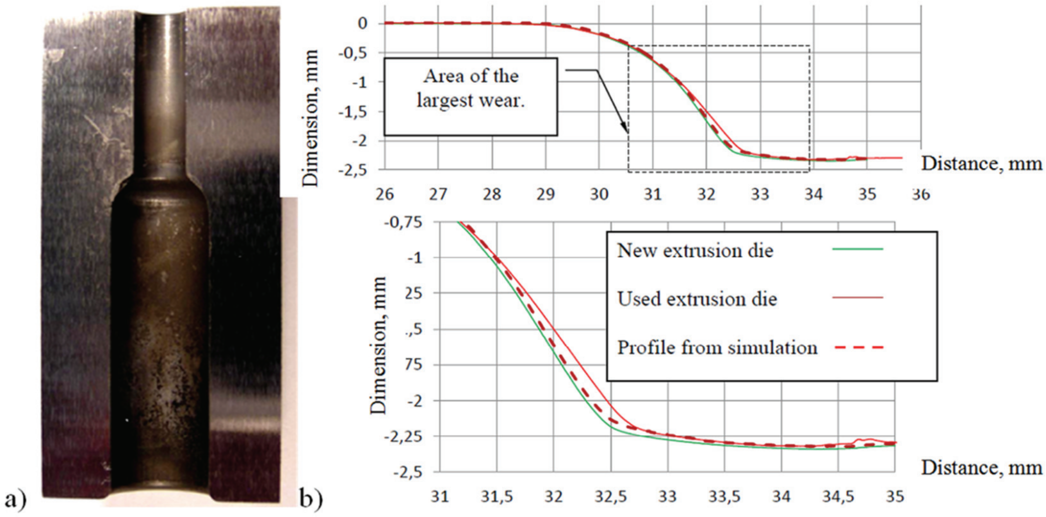

Fig. 13. *a) Photograph of the extrusion die, b) profiles of new and used after production of 650000 pieces extrusion die at the area of the largest wear.*

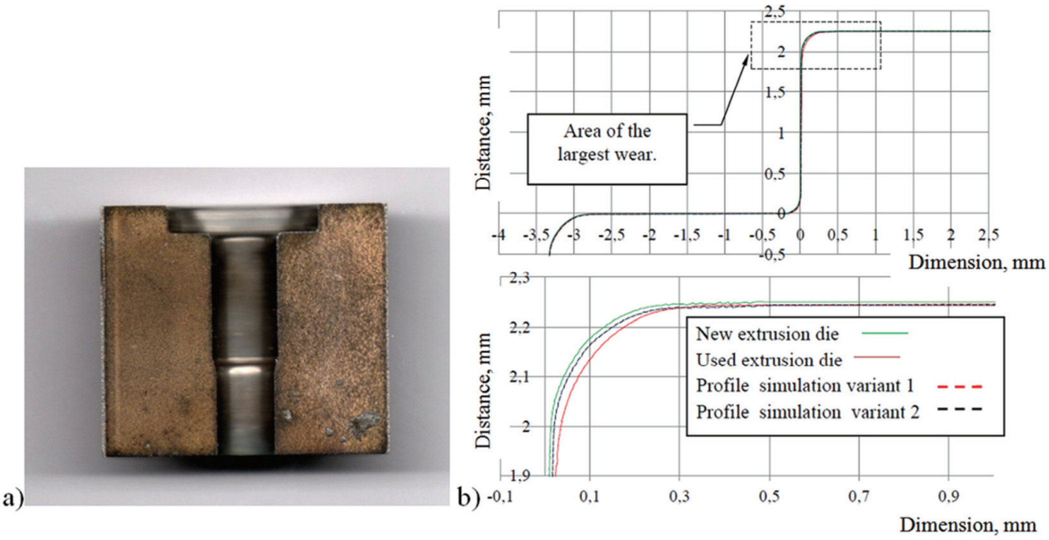

Fig. 14. *a) Photograph of the finish forming die, b) profiles of new and used after production of 650000 pieces finish forming die at the area of the largest wear.*

ances of products and by technological aspects of the process, eg. tool wear in one operation can cause too large clearance between forging and the die in the next operation. The total cost of tools for forging of 1 mln of pieces was calculated on the basis of the number of tools used in production.

Table 1. *Tool wear factors for subsequent stages and technological variants obtained from simulation (*- Tools in anvil, # - tools in sidle).*

Variant	Stage	Tool surface	C_s correction	Tool wear [mm/piece]	Limiting wear for the surface [mm]	Number of tools for 10 000 000 pieces piece	Tool production cost for 1 mln pieces
1	1*	1	280	0.03076 x10^{-8}	0.04	7.7	4.8
	2*	2	280	0.00593 x10^{-8}	0.04	1.5	2.1
	3*	3	280	0.00747 x10^{-8}	0.04	1.9	3.3
	4 *	5	280	0.00879 x10^{-8}	0.11	0.8	6.0
		6	280	0.00989 x10^{-8}	0.05	2.0	
		7	280	0.00549 x10^{-8}	0.1	0.5	
		8	280	0.00219 x10^{-8}	0.04	0.5	
	4#	9	200	0.33333 x10^{-8}	0.05	66.7	0.6
	5#	10	240	0.5 x10^{-8}	0.07	71.4	0.9
						Total costs	**162.66**
2	1*	1	280	0.03076 x10^{-8}	0.04	7.7	4.8
	2*	2	280	0.00593 x10^{-8}	0.04	1.5	2.1
	3*	4	280	0.00692 x10^{-8}	0.04	1.7	4.0
	4*	5	280	0.01098 x10^{-8}	0.11	1.0	6.0
		6	280	0.01098 x10^{-8}	0.05	2.2	
		7	280	0.00109 x10^{-8}	0.1	0.1	
		8	280	0.00109 x10^{-8}	0.04	0.3	
	4#	9	200	0.16667 x10^{-8}	0.05	33.3	0.6
	5#	10	240	0.5 x10^{-8}	0.07	71.4	0.9
						Total costs	**144.35**

Calculated tool wear for one piece is presented in table 1 and number of tools necessary to produce 10 million pieces is calculated. The maximum tool wear obtained from the technological assumptions was used in calculations.

5. CONCLUSIONS

Calculations of the tool wear and related tool costs for manufacturing of fasteners are presented in the paper. Two technological variants were considered and the costs of tools are lower for the 2nd variant in figure 2. It is shown in the paper that application of the tool shape measurements and inverse analysis allows to determine the coefficient in the tool wear model.

Following the idea proposed by Skóra et al. (2012), presented methodology can be applied to optimization of the manufacturing cycles for fasteners.

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NUMERYCZNA SYMULACJA ZUŻYCIA NARZĘDZI JAKO WSPOMAGANIE OPTYMALIZACJI CYKLU WYTWARZANIA ELEMENTÓW ZŁĄCZNYCH

Streszczenie

Przedmiotem artykułu jest wspomagane komputerowo projektowanie technologii wytwarzania elementów złącznych. Specjalny nacisk położono na analizę zużycia narzędzi. Cele pracy były dwojakie. Pierwszym celem był dobór modelu zużycia narzędzi i identyfikacja współczynników w tym modelu na podstawie pomiarów wykonanych w przemysłowym procesie kucia. Pomiary przeprowadzono dla różnej liczby wykonanych odkuwek i współczynniki w modelu zużycia narzędzi wyznaczono stosując analizę odwrotną. W drugiej części artykułu opracowany model zużycia narzędzi zaadaptowano do idei symulacji całego cyklu wytwarzania elementów złącznych. Wykonano symulacje różnych wariantów cykli wytwarzania i wybrano wariant dający najdłuższy czas życia narzędzi. Przeprowadzono próby w warunkach przemysłowych dla wybranego wariantu i oceniono jego wydajność.

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