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# COMPUTER AIDED DESIGN OF THE MANUFACTURING CHAIN FOR FASTENERS

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**Abstract**

Computer aided design of the forging technology for the fasteners made of bainitic steels is the objective of the paper. Three steels were tested and rheological models of these steels were developed. The models were implemented into the finite element code for thermal-mechanical simulations of metal forming processes. The particular objectives of the work were twofold. Simulations of various variants of manufacturing chain were performed first. Operations, which were considered, include: cold drawing to reduce diameter and harden the material, forging in three operations, heat treatment. The best manufacturing chains were selected on the basis of numerical simulations. Industrial trials were performed at the for the selected cycles and the efficiency of these cycles was evaluated.

**Key words**: Bainitic steels, fasteners, manufacturing cycle, FE simulation

## 1. INTRODUCTION

New bainitic steels are characterized by high strength properties and reasonably good ductility, what creates wide possibilities of applications of these steels for manufacturing of fasteners (Bhadeshia & Edmonds, 1980). The manufacturing chain for these products is composed of a number of operations, which influence material properties. The objective of the whole project is investigation of possibilities of manufacturing of fasteners made of bainitic steels. Next objective, which follows the idea proposed in (Madej et al., 2005; Pietrzyk et al., 2008; Rauch et al., 2008), is application of numerical techniques to selection of the best parameters of the manufacturing chain, having in mind properties of products. The particular objectives of the present work are twofold. The first is simulation of various variants of manufacturing chain and selection of the best variant. The second objective was performing of industrial trials for the selected cycle and evaluation of the efficiency of this cycle. Numerical method of designing of manufacturing chain for fasteners is the main output of the work.

## 2. MODEL

All simulations were performed using Forge 3 finite element software. Rheological model and finite element model are described briefly below.

### 2.1. Finite element model

Forge 3 software is based on the Norton-Hoff viscoplastic flow rule. His rule was originally introduced by Norton (1929) for one-dimensional creep.

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It was extended by Hoff (1954) to three dimensions. The main equation of his law is:

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

where: $\boldsymbol{\sigma}$, $\dot{\boldsymbol{\varepsilon}}$ - stress and strain rate tensor, respectively, $\dot{\varepsilon}_i$ - effective strain rate, $K$ – material consistency, $m$ – coefficient equal 1 for Newtonian fluids and 0 for rigid –plastic materials, which obey Huber-Mises yield criterion ($\sigma_p = \sqrt{3}K$) and Levy-Misesa flow rule. For typical metal forming processes the values of $m$ are in the range [0,1].

The mechanical model is coupled with the finite element solution of the nFourier heat transport equation:

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

where: $k$ – heat conductivity, $T$ – temperature, $Q$ – rate of heat generation due to plastic work, $\rho$ – 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 is simulated on the remaining part of the surface. Friction coefficient of 0.02 is used.

## 2.2. Rheological model

Flow stress $\sigma_p$ is a material parameter in the Norton-Hoff viscoplastic model. Plastometric tests were performed to identify the flow stress model. Two steels with chemical composition given in table 1 are investigated. The first is low-alloyed steel 30MnB4 with addition of boron, according to EN-10263 part 4. The second is binitic steel, which was rolled into wire rod having 12 mm in diameter. Two variants of rolling were conducted, namely, with finish rolling temperature around 800ºC (B1) and 950 ºC (B2). Axisymmetrical samples were compressed on the Gleeble 3800 simulator at the temperatures 20-300$^o$C with strain rates of 10-200 s$^{-1}$. Hansel & Spitel (1979) model was used to describe relation of the flow stress on the temperature and strain rate:

$$\sigma_p = A\varepsilon^B \exp\left(-C\varepsilon\right)\dot{\varepsilon}^D \exp(-ET) \tag{3}$$

The coefficients in equation (3) were determined using inverse algorithm (Szeliga et al., 2006) and they are given in table 2. Low values of coefficients $D$ and $E$ confirm low sensitivity with respect to temperature and strain rate, in particular for steels B1 and B2. Figure 1 shows selected examples of the flow stress vs. strain relationships for the three steels. The value of the objective function Φ, which is a measure of the accuracy of the solution, is given in the last column of this table. It is seen that a very good accuracy was obtained in all cases.

***Table 1.*** *Chemical compositions of the investigated steels, wght%.*

| | C | Mn | Si | Ni | B |
|---|---|---|---|---|---|
| 30MnB4 | 0.12 | 1.8 | 0.3 | 0.3 | 0.02 |
| BS | 0.07 | 1.8 | 0.30 | 0.25 | 0.002 |

***Table 2.*** *Coefficients in equation (3) determined by the inverse analysis for the investigated steels.*

| | *A* | *B* | *C* | *D* | *E* | *Φ* |
|---|---|---|---|---|---|---|
| 30MnB4 | 842.4 | 0.0679 | 0.0154 | 0.0191 | 0.484 | 0.04087 |
| B1 | 1089.7 | 0.072 | 0.107 | 0.00464 | 0.0826 | 0.0299 |
| B2 | 1033.6 | 0.0874 | 0.115 | 0.00509 | 0.0547 | 0.035 |

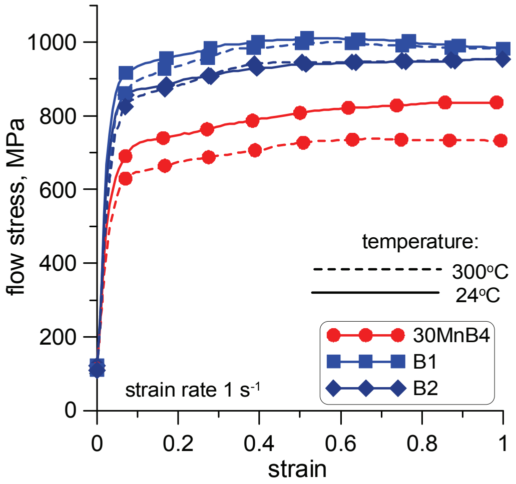

***Fig. 1.*** *Selected examples of the flow stress vs. strain relationships for the three steels.*

Rheological model in the form of equation (3) with the coefficients in table 2 were implemented into the Forge 3 finite element code and simulations of manufacturing of connecting parts were performed.

## 3. SIMULATIONS

Two products were selected for the analysis, standard screw M8×25 according to ISO 4017 grade 8.8 according to ISO 898 part 1 and imbus screw M8×25 according to ISO 4762 grade 8.8, as presented in figures 2 and 3. Calculated distributions of strains at the cross sections of these screws are shown in figure 4.

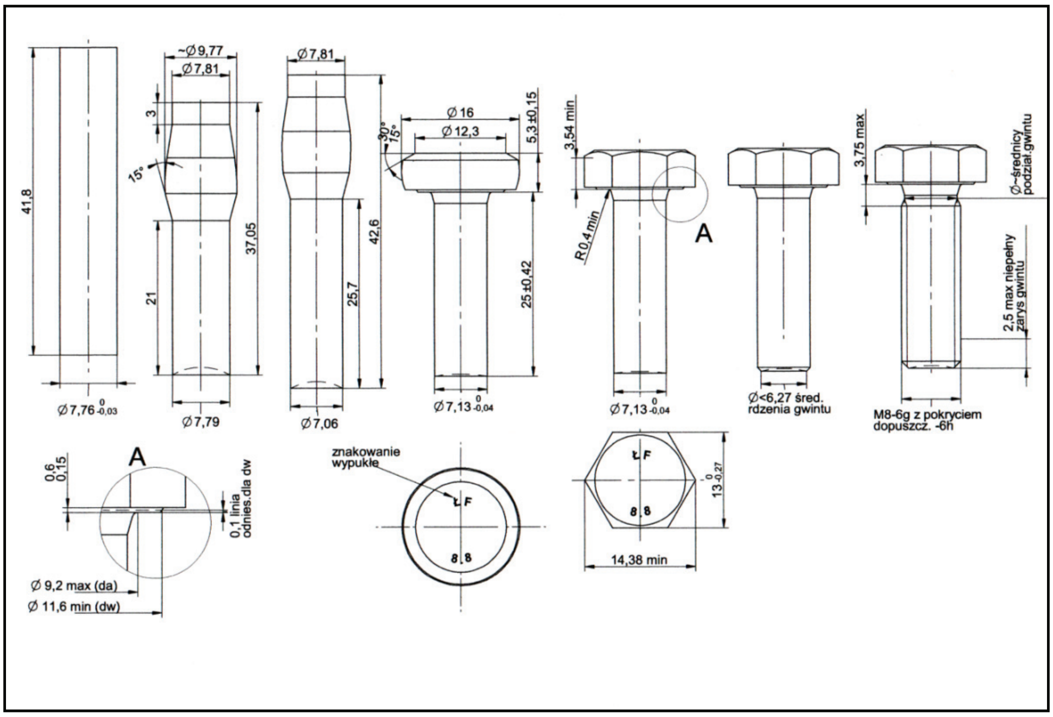

*Fig. 2. Production technology of the screw M8x25 according to ISO 4017.*

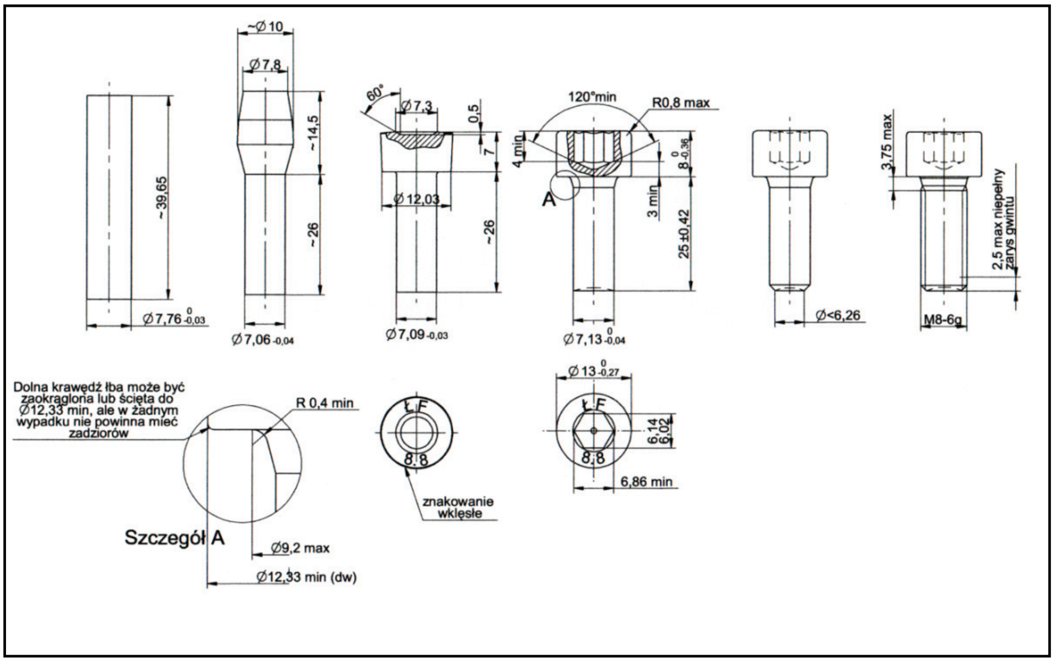

*Fig. 3. Production technology of the screw M8x25 according to ISO 4762.*

## 3.1. Comparison of bainitic steels with conventional steels used for fasteners

Comparison of forging parameters for bainitic steels and conventional steels used for manufacturing of fasteners was performed first. The objective was to evaluate to what extent bainitic steels involve increase of loads and may cause increase of the tool wear. Simulations of forging of the M8 screw were performed for DP steel and for bainitic steel. Simulations of the second step of forging of the imbus screw were performed for 30MnB4 steel and for the bainitic steel B1. Comparison of strain distribution is presented in figure 4 and differences between various steels are small. Slightly larger concentrations of strains are observed for bainitic steels in the case of the screw M8. Results of calculations of the effective stress distribution are shown in figures 5 and 6. It is concluded that stresses in the head of the screw for the bainitic steel are about 20% higher than for the 30MnB4 steel (figures 5c and 5d). DP steel, which is characterized by a steep hardening curve, gives stresses slightly larger than the bainitic steel. Finally, stresses are higher for the steel B1 than for B2 (figures 6 b and c).

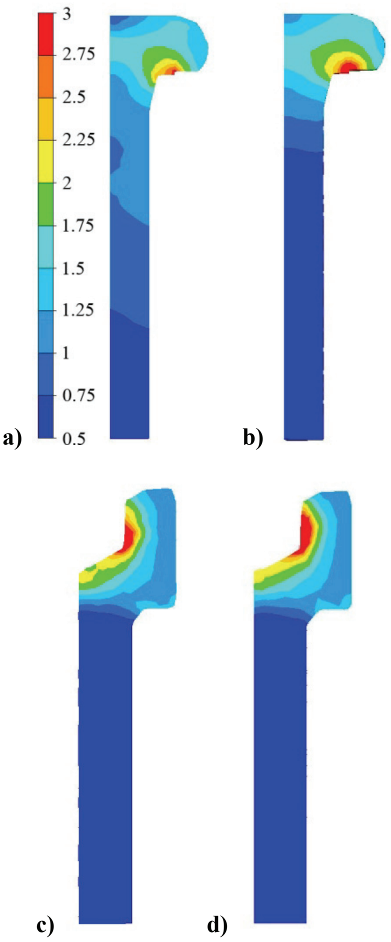

***Fig. 4.*** *Strain distribution at the cross section of the screw M8 made of DP steel (a) and bainitic steel (b) and the imbus screw made of 30MnB4 steel (c) and bainitic steel B1 (d).*

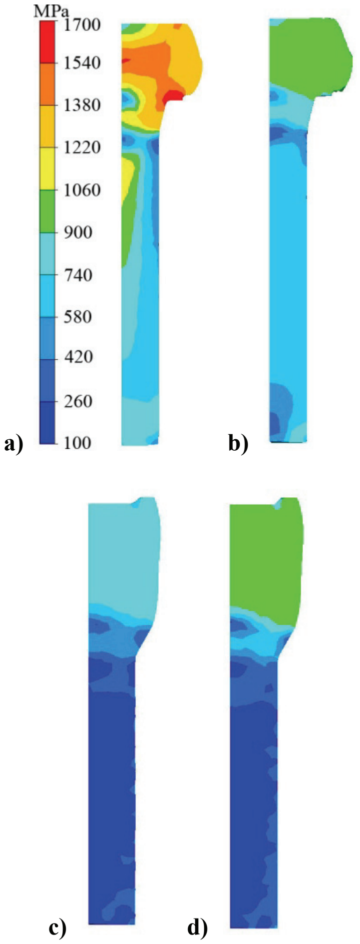

***Fig. 5.*** *Effective stress distribution at the cross section of the screw M8 made of DP steel (a) and bainitic steel (b) and the imbus screw (stage 2 of forging) made of 30MnB4 steel (c) and bainitic steel B1 (d).*

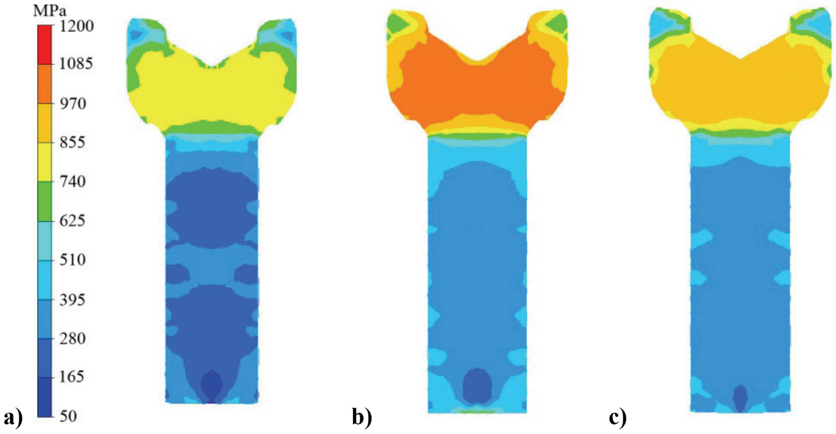

***Fig. 6.*** *Effective stress distribution at the cross section of the imbus screw (final forging) made of 30MnB4 steel (a) and bainitic steels B1 (b) and B2 (c).*

### 3.2. Simulation of manufacturing chain for fasteners

Selection of the best technology on the basis of simulation of manufacturing chain for fasteners made of bainitic steels is the main objective of the project. The whole manufacturing chain is composed of rolling of rods, drawing, three stages of forging and heat treatment. Rolling process is not considered in this work. The particular objective is to explore possibilities of modification of the technological parameters of cold forming to improve the hardness of the head and in the area of thread. Primary simulations and industrial trials have shown that changes of the forging parameters allow to improve properties of product. But these changes create problems with obtaining accurate dimensions of products and involve additional costs connected with manufacturing of new dies. Therefore, change of the rod diameter after rolling is proposed next. Two diameters before drawing are considered: ϕ8 mm and ϕ10 mm. Strain distribution during these two processes is shown in figure 7. More results of simulations of the drawing process as a part of the manufacturing chain for fasteners can be found in (Madej et al., 2009).

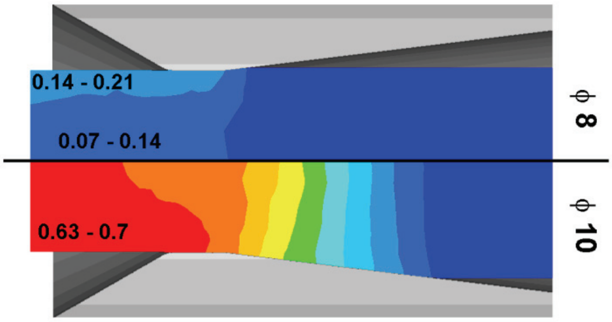

***Fig. 7.*** *Distribution of strains during drawing of ϕ8 mm (top) and ϕ10 mm (bottom) rods.*

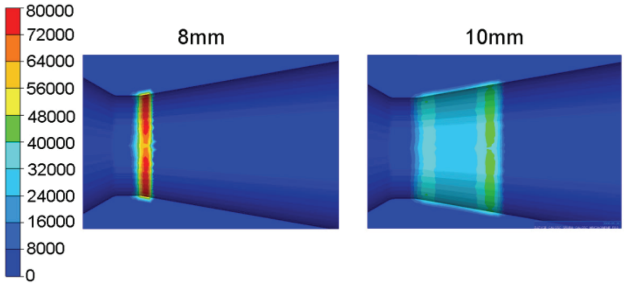

***Fig. 8.*** *Die wear during drawing of ϕ8 mm (left) and ϕ10 mm (right) rods.*

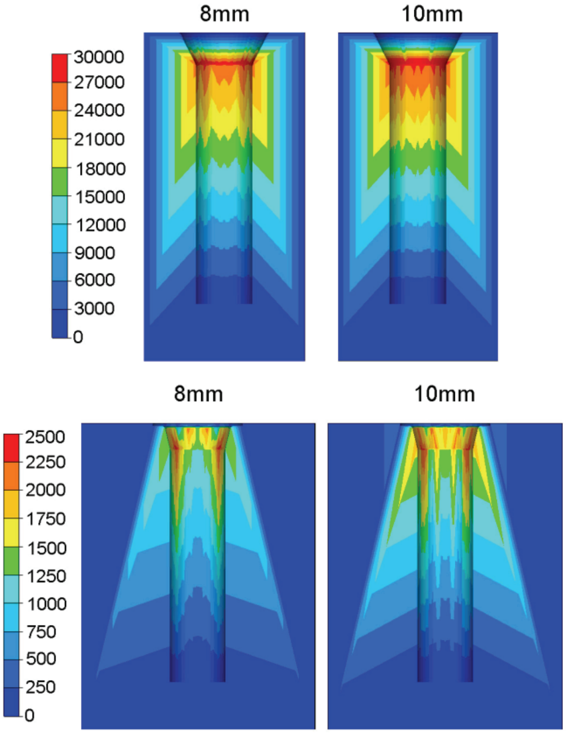

***Fig. 9.*** *Die wear during the second (left) and third (right) stage of forging after drawing of ϕ8 mm and ϕ10 mm rods.*

It is expected that larger strains will involve increase of the tool wear, what is show in figure 8. Volume of wear due to sliding calculated according to Archard (1953) model is shown in this figure. Tool wear during the two stages of forging is presented in figure 9.

Large wear of drawing die, due to localized strains, is observed in the 1st variant (ϕ8 mm). Value of the wear is large but it is very localized. As far as forging is concerned, due to larger hardening variant 2 (ϕ10 mm) involves increase of the die wear, in particular in the second stage of the process. This option will be further explored in future works, having in mind workability of the hardened material and tendency to cracks. Due to low die wear, results for the first stage of forging are not presented.

Simulation of manufacturing of imbus screw was performed next. The stock dimensions are ϕ8×20 mm. Three technological variants, which differed by the reduction of the material height in the first stage of forging (1.99 mm, 5.51 mm and 1.05 mm), are considered.

Results of simulation of the three stages of the forging process for the intermediate technology (5.51 mm reduction in the first stage) are presented in figure 11. Distributions of strains are presented in this figure. Comparison of parameters for the three variants is presented in figures 12-14, the largest reduction in the first stage of forging is on the left.

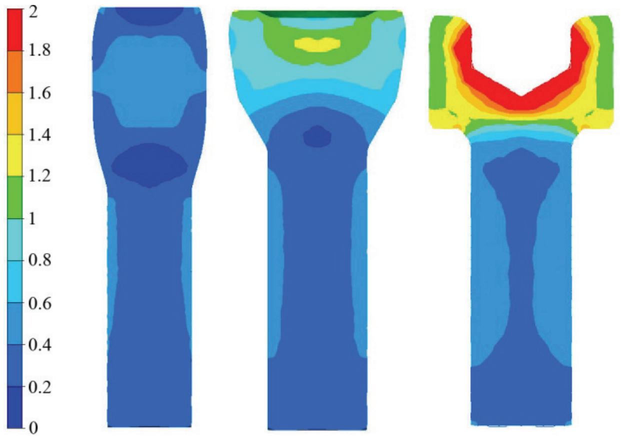

***Fig. 11.*** *Strain distribution at the three stages of forging of the imbus screw.*

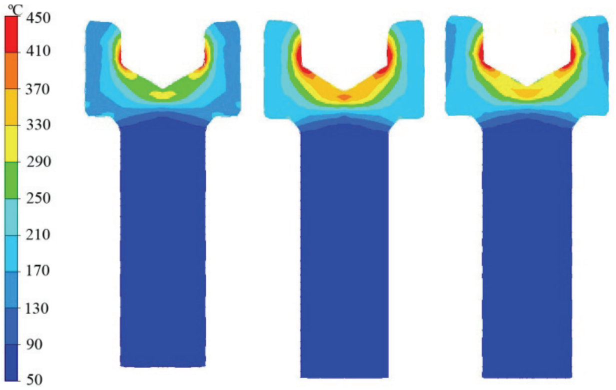

***Fig. 12.*** *Temperature distribution at the end of forging for the three considered variants.*

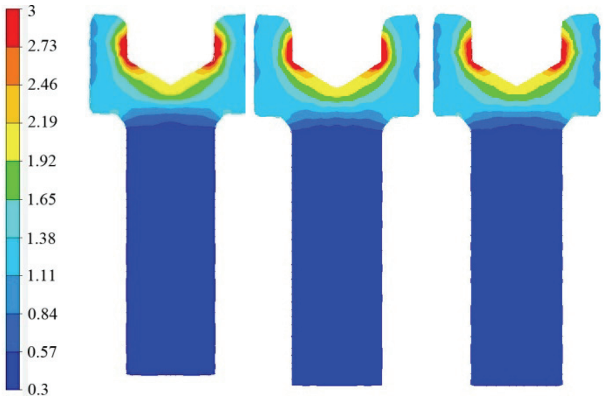

***Fig. 13.*** *Effective strain distribution at the end of forging for the three considered variants.*

## 4. INDUSTRIAL TRIALS

Three steels introduced in section 2.2 were used for industrial trials of forging screws M8×25 according to ISO 4017 grade 8.8 according to ISO 898 part 1. 30MnB4 and B1 steels were used for trials of forging M8×25 according to ISO 4762 grade 8.8. Schedule of the manufacturing processes is given in Table 3.

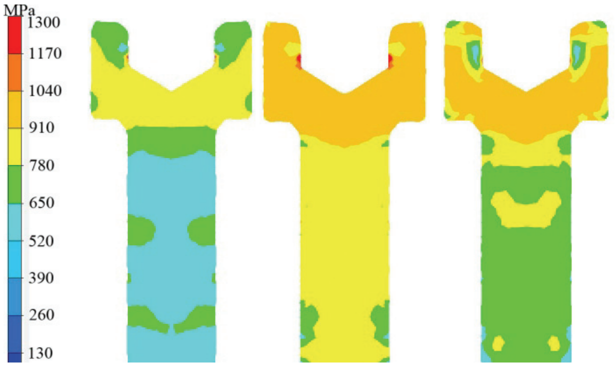

***Fig. 14.*** *Effective stress distribution at the end of forging for the three considered variants.*

***Table 3.*** *Schedule of the manufacturing processes.*

| Operations | M8x25 acc. to ISO 4762 | | M8x25 acc. to ISO 4017 | | |
|---|---|---|---|---|---|
| | 30MnB4 | B1 | 30MnB4 | B1 | B2 |
| Picling | X | | | | |
| Spheroidizing annealing | X | | | | |
| Picling | X | X | X | X | X |
| Phosphatizing | X | X | X | X | X |
| Cold forming | X | X | X | X | X |
| Heat treatment | X | | X | | |
| X – operation proceeded | | | | | |

**Pickling and preparing of the surface**. The following stages are included. Pickling HCl and fhosphatizing in order to cover the surface with zinc phosphate. For this process the products of HENKEL were used. The second stage is the surface preparation, which includes:

- Cascade pickling in HCl (concentration 70 g/l, 120 g/l, 180 g/l) + inhibitor at 28°C;
- Cascade water deep rinsing at 28°C;
- Activation (SALE TZ (concentration 10 g/l, pH = 10, temperature 30°C) time 0,5 min;
- Phosphatizing (Fe = 7 g/l) at 55°C for time 9 min;
- Cascade water deep rinsing at 28°C;
- Neutralzation (pH = 9) at 40°C;
- Hot air drying at 120°C.

After the process, the coating of crystals zinc phosphate on the wire rod surface was 9 g/cm$^2$.

**Drawing**. The drawing process was carried out on single-hole drawing machine with the speed of drawing 1 m/s with usage of drawing die made of sintered carbide from DIE system ParaLocc TM

Pressure system, angle of drawing cone $2\alpha = 16°$, lubricant TRXIT CV.

**Annealing.** The annealing process was carried out on bell annealing furnace EBNER and included following stages: heating 730°C, hydrogen/nitrogen protective atmosphere; holding 730°C, time 3h, hydrogen atmosphere; slowly cooling 10°C/h at 680°C, time 5h.

**Cold forging.** The cold forging process was carried out according to figures 2 and 3 on the multi stage press TDZR 8.

After the press set-up the batches were made of all grades of steel without adjustments of tools. The dimensional parameters were compatible with ISO 4017 and ISO 4762 in all cases.

After forging process the tensile strength were performed according to DIN 898, in order to compare mechanical properties. The tensile stress values are given in table 4.

***Table 4.*** *Strength of the investigated screws after forging.*

| Property | M8x25 - ISO 4762 | | | M8x25 - ISO 4017 | | |
|---|---|---|---|---|---|---|
| | 30MnB4 | B1 | B2 | 30MnB4 | B1 | B2 |
| $R_m$, MPa | 860 | 1105 | 993 | 880 | 1173 | 1006 |
| $R_{p0.2}$, MPa | 680 | 866 | 825 | 690 | 827 | 855 |

## 5. DISCUSSION

Numerical analysis has shown that technological variant with larger rod diameter after rolling ($\phi$10 mm) causes lower and less localized wear of the drawing die. This variant involves increase of the die wear in the second stage of forging. It is concluded that these changes, as well as investigated earlier changes of the forging technology, require further investigation before they are introduced in the industrial practice. Thus, forging trials were performed for the variant 1 (rod diameter 8 mm) only and the focus was on evaluation of possibilities of introduction of bainitic steels into production. Simulations and forging trials confirmed possibility of manufacturing of fasteners made of bainitic steels. Increase of die wear due to increased flow stress is acceptable, while increase of properties of products is noticeable.

The production technology of M8x25 (ISO 4017) and M8x25 (ISO 4762) made of new bainitic steels was verified in industrial trials. A proper screw geometry and mechanical properties according to 8.8 property category was achieved without heat treatment. The numerical simulations have shown that the hardness distribution in screws head can be effectively affected by changing the forging technology (pass design). As a result, bainitic steels can be applied to the production of screws with low cross section in the head area. This particularly concerns the screws produced according to ISO 4014, EN 1662 , ISO 10642, DIN 6921, ISO 8676, ISO 8765 etc. In this case, plastic deformation introduces substantial inhomogeneity and, as a result, an increased susceptibility for cracks initiation during quenching.

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## REFERENCES

Archard, J.F., 1953, Contact and rubbing of flat surfaces, *J. of Applied Physics*, 24, 981-988.

Bhadeshia, H.K.D.H., Edmonds, D.V., 1980, The mechanism of bainite formation in steels, *Acta Metall.*, 28, 1265-1273.

Hansel, A., Spittel, T., 1979, Kraft- und Arbeitsbedarf Bildsomer Formgeburgs Verfahren, VEB Deutscher Verlag fur Grundstoffindustrie, Lipsk.

Hoff, N.J., 1954, Approximate analysis of structures in the presence of moderately large steps deformation, *Quart., Appl. Mech.*, 2, 49.

Madej, Ł., Szeliga, D., Kuziak, R., Pietrzyk, M., 2007, Physical and numerical modelling of forging accounting for exploitation properties of products, *Computer Methods in Materials Science*, 7, 397-405.

Madej, Ł., Węglarczyk, S., Pietrzyk, M., 2009, Simulation of drawing as an important stage in the steel bolt manufacturing chain, *Hutnik-Wiadomości Hutnicze*, 76, 71-73.

Norton, F.H., 1929, *Creep of steel at high temperature*, McGraw Hill, New York.

Pietrzyk, M., Madej, Ł., Węglarczyk, S., 2008, Tool for optimal design of manufacturing chain based on metal forming, *Annals of the CIRP*, 57, 309-312.

Rauch, Ł., Madej, Ł., Węglarczyk, S., Pietrzyk, M., Kuziak, R., 2008, System for design of the manufacturing process of connecting parts for automotive industry, *Archives of Civil and Mechanical Engineering*, 8, 157-165.

Szeliga, D., Gawąd, J., Pietrzyk, M., 2006, Inverse analysis for identification of rheological and friction models in metal forming, *Comp. Meth. Appl. Mech. Engrg.*, 195, 6778-6798.

# WSPOMAGANE KOMPUTEROWO PROJEKTOWANIE CYKLU TECHNOLOGICZNEGO WYTWARZANIA ELEMENTÓW ZŁĄCZNYCH ZE STALI BAINITYCZNYCH

## Streszczenie

Celem pracy jest wspomagane komputerowo projektowanie technologii wytwarzania elementów złącznych ze stali bainitycznych. Badano dwie stale, w tym jedną dla dwóch różnych temperatur końca walcowania. Opracowano modele reologiczne dla tych stali. Te modele zaimplementowano w programie z metody elementów skończonych dla termomechanicznej symulacji procesów kształtowania metali. Szczegółowe cele pracy były dwojakie. Pierwszym celem było wykonanie symulacji różnych wariantów wytwarzania elementów złącznych. Badaniami objęto operacje ciągnienia na zimno w celu zmniejszenia średnicy wsadu i umocnienia materiału, kucia na zimno w trzech etapach oraz obróbki cieplnej. Na podstawie wyników symulacji oceniono efektywność różnych wariantów technologii i wybrano najlepszy wariant technologiczny, dla którego przeprowadzono próby w warunkach przemysłowych.

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