Journal of Metallic Materials 2019, 71 (3), p. 8–11

DOI: 10.32730/imz.2657-747.19.3.2

Roman KUZIAK
Valeriy PIDVYSOTS'KYY

Łukasiewicz Research Network – Institute for Ferrous Metallurgy

Stanisław WĘGLARCZYK
Maciej PIETRZYK

AGH University of Science and Technology

PRECIPITATION-HARDENED LOW-CARBON HIGH-STRENGTH BAINITIC STEELS FOR MANUFACTURING OF FASTENERS

NISKOWĘGLOWE STALE BAINITYCZNE UMACNIANE WYDZIELENIOWO DO PRODUKCJI ELEMENTÓW ZŁĄCZNYCH

Design of the manufacturing chain for fasteners made of precipitation-hardened low-carbon high-strength bainitic steels was the objective of the paper. The choice of the material was based on the good performance of these steels in various applications. Compression tests at different temperatures (20–300°C) and different strain rates (0.1–10 s^{-1}) were performed to provide data for identification of the flow stress model for the selected steels. Authors inverse algorithm was applied to determine coefficients in the flow stress model, which was implemented into the FE code Forge. Simulations of the whole manufacturing chain involving hot rolling of rods, controlled cooling, drawing and 4-step cold forging were performed. Physical simulations were performed on the Gleeble 3800 to validate material models, which were used in optimization of manufacturing chains for fasteners. Good predictive capability of the material models was confirmed.

Final part of the paper presents an application of numerical modelling for the design of the best manufacturing technology. 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 was combined with the knowledge of the expert. The objective was to improve the material flow in the forging and to improve the contact between the head of the fastener and the material being joined. Various variants of the technology were simulated and new technological parameters were proposed, which gave noticeable improvement of the objective function.

Keywords: fasteners, precipitation strengthened bainitic steels, cold forging, numerical simulation

W artykule scharakteryzowano proces projektowania technologii kucia elementów złącznych z niskowęglowych stali bainitycznych umacnianych wydzieleniowo. Technologię kucia zaprojektowano na podstawie symulacji numerycznych z wykorzystaniem programu Forge. Do symulacji użyto modelu reologicznego badanych stali opracowanego metodą analizy odwrotnej prób plastometrycznych zrealizowanych za pomocą symulatora Gleeble 3800. Badania plastometryczne przeprowadzono na próbkach cylindrycznych w przedziale temperaturowym 20÷300°C i prędkości odkształcenia 0,1÷10 s^{-1}. Celem przeprowadzonych badań było przeprowadzenie symulacji fizycznych i numerycznych całego łańcucha produkcyjnego elementów złącznych z uwzględnieniem walcowania i chłodzenia walcówki, przeciągania i kucia na zimno.

W końcowej części artykułu scharakteryzowano możliwości modelowania numerycznego w celu opracowania najkorzystniejszej technologii wytwarzania elementów złącznych. W tym przypadku zastosowanie klasycznych algorytmów optymalizacyjnych okazało się niemożliwe. Dlatego zastosowano podejście optymalizacji wariantów technologicznych metodą prób i błędów, połączoną z wiedzą ekspercką. W wyniku zastosowanej metody opracowano najkorzystniejszy wariant kucia zarówno z uwagi na płynięcie plastyczne materiału, jak również optymalny kontakt główki elementu złącznego z łączonym elementem.

Słowa kluczowe: elementy złączne, stale bainityczne umacniane wydzieleniowo, kucia na zimno, symulacja numeryczna

1. INTRODUCTION

It is expected that the tendency to increase strength-to-density ratio, as well as decreasing the production costs, will be the main objectives of research on materials processing for many years. Manufacturing of high strength fasteners without heat treatment is considered in the present work. Pursuit for new steels, with higher strength, is one of the objectives of the research. Advanced High Strength Steels (AHSS) are one of the possibilities to reach this goal. The necessity of precise control of cooling process after hot rolling of these steels is typically beyond the capabilities of the Stelmor lines

Corresponding Author: roman.kuziak@imz.pl

[1] and is the disadvantage of using this material for rods and wire rods. The objective of the present work is searching for an alternative for manufacturing of the high strength fasteners without heat treating operations. The preliminary research described in [2, 3] have shown that new generation bainitic steels can be considered for this purpose. These steels are characterized by high strength properties and reasonably good ductility [4], what creates wide possibilities of their applications. The main idea of designing the compositions of bainitic steels combining strength with ductility was to develop the granular bainite morphology in wire rod cooled in the Stelmor line and to strengthen the bainitic ferrite matrix with titanium carbide, TiC, particles. Several bainitic steels with various chemical compositions were tested in [6] and optimal compositions were selected. General aspects of modelling of closed die forging of bainitic steels are described in [7]. Present paper is focused on manufacturing of fasteners made of the modern bainitic steels.

2. MATERIAL MODELS

Although the present paper is focused on cold forging of fasteners, the whole manufacturing chain including hot rolling, controlled cooling, cold drawing and cold forging was considered. The models describing flow stress and microstructure evolution during hot rolling, as well as phase transformations during cooling, were developed and are described in earlier publications [1]. As far as cold drawing and forging are considered, two steels with chemical composition given in Tab. 1 were investigated. The first with addition of boron is used now for manufacturing of fasteners. The second, is a bainitic steel considered as potential material, which would allow to eliminate the heat treatment of products. Two variants of rolling were conducted for the bainitic steel, namely, with finish rolling temperature around 800°C (B1) and 950°C (B2).

Flow stress σ_p was determined for all steels on the basis of the plastometric tests and inverse analysis using algorithm described in [8]. Cylindrical samples (Φ10 × 12 mm) were compressed at the temperatures 20–300°C with strain rates of 10–200 s^{-1}. Recorded load-die displacement data for all steels are presented in [3]. Hansel & Spittel [9] model was used to describe the flow stress:

$$\sigma_p = A\varepsilon^B \exp(-C\varepsilon)\dot{\varepsilon}^D \exp(-ET) \tag{1}$$

where:
ε – strain,
$\dot{\varepsilon}_i$ – strain rate,
T – temperature in °C,
A–E – coefficients.

Coefficients in equation (1) determined for the steels with chemical compositions in Tab. 1 are given in Tab. 2. Selected results showing the comparison of the flow stress for the three steels are shown in Fig. 1.

It is seen that the flow stress of the bainitic steel is much higher than that of 30MnB4 steel. Finishing of rolling at 800°C gave slightly larger flow stress that after finishing of rolling at 900°C. Beyond this, the 30MnB4 steel shows larger temperature sensitivity and strain rate sensitivity than the bainitic steel. Rheological model in the form of equation with the coefficients in Tab. 2 were implemented into the Forge 3 finite element code and simulations of manufacturing of connecting parts were performed.

Table 1. Chemical composition (wt%) of the investigated steels
Tabela 1. Skład chemiczny (% cięż.) badanych stali

Steel	C	Si	Mn	Ni	P	Nb	Ti	S	B	N
30MnB4	0.12	0.3	1.8	0.3	0.01	0.002	0.001	0.01	0.02	0.004
BS	0.07	0.3	1.8	0.25	0.01	0.032	0.13	0.01	0.002	0.0036

Table 2. Coefficients in equation (1) determined for the investigated steels
Tabela 2. Współczynniki w równaniu (1) wyznaczone dla stali doświadczalnych

Steel	*A*	*B*	*C*	*D*	*E*
30MnB4	842.4	0.0679	0.0154	0.0191	0.484
B1	1089.7	0.072	0.107	0.00464	0.0826
B2	1033.6	0.0874	0.115	0.00509	0.0547

a) b)

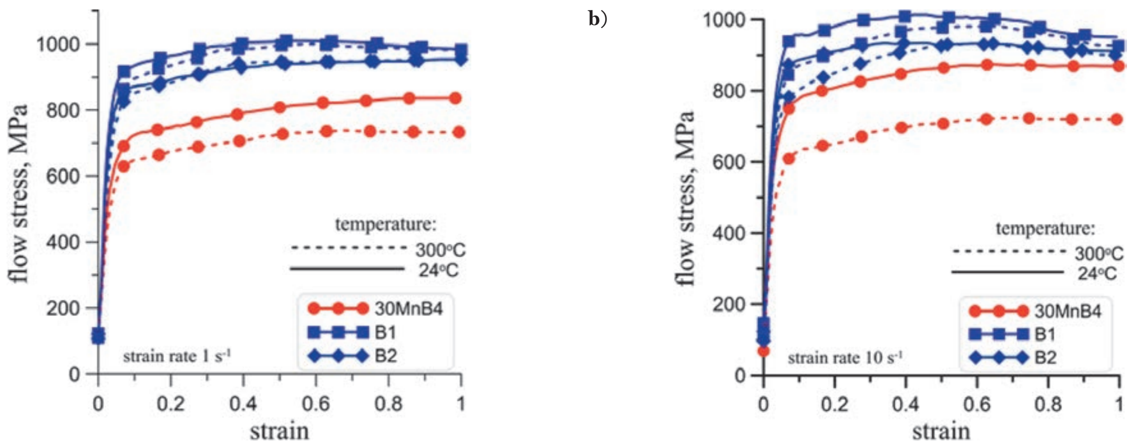

Fig. 1. Comparison of the flow stress for the three steels, strain rate 1 s^{-1} (a) and 10 s^{-1} (b)
Rys. 1. Porównanie wartości naprężenia uplastyczniającego dla stali doświadczalnych: prędkość odkształcenia 1 s^{-1} (a) i 10 s^{-1} (b)

3. RESULTS OF SIMULATIONS

3.1. FINITE ELEMENT MODELLING

Cold drawing followed by the three-step forging of the imbus screw M8×25 mm according to ISO 4762 was considered. Primary calculations were performed to determine strains at various stages of the manufacturing chain. Calculated distributions of strains during drawing of rods with entry diameter of ϕ8 mm and ϕ10 mm are shown in Fig. 2. Distributions of strains after all stages of cold forging are shown in Fig. 3.

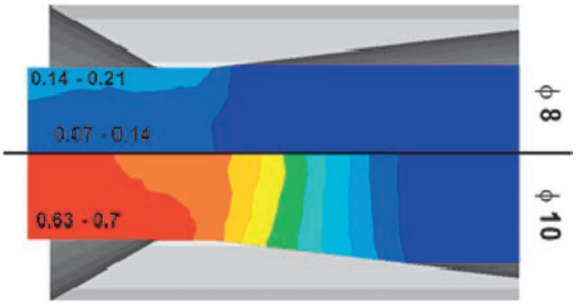

Fig. 2. Calculated distributions of strains during drawing of rods with different input diameter

Rys. 2. Obliczone rozkłady odkształcenia po procesie ciągnienia z różnymi średnicami wejściowymi

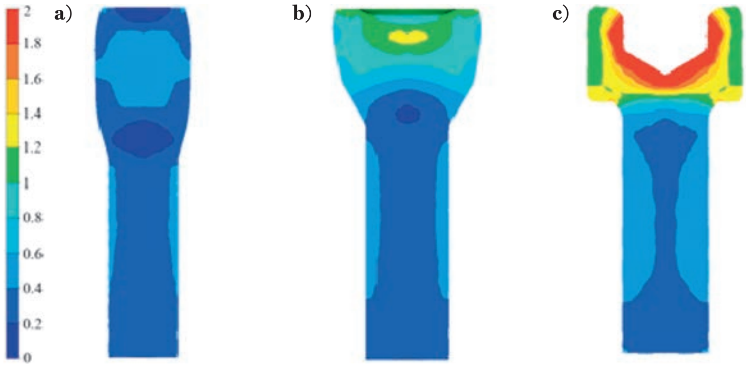

Fig. 3. Distributions of strains after stage 1 (a), stage 2 (b) and stage 3 (c) of forging

Rys. 3. Rozkład odkształcenie w etapie pierwszym (a), drugim (b), trzecim (c) kucia na zimno

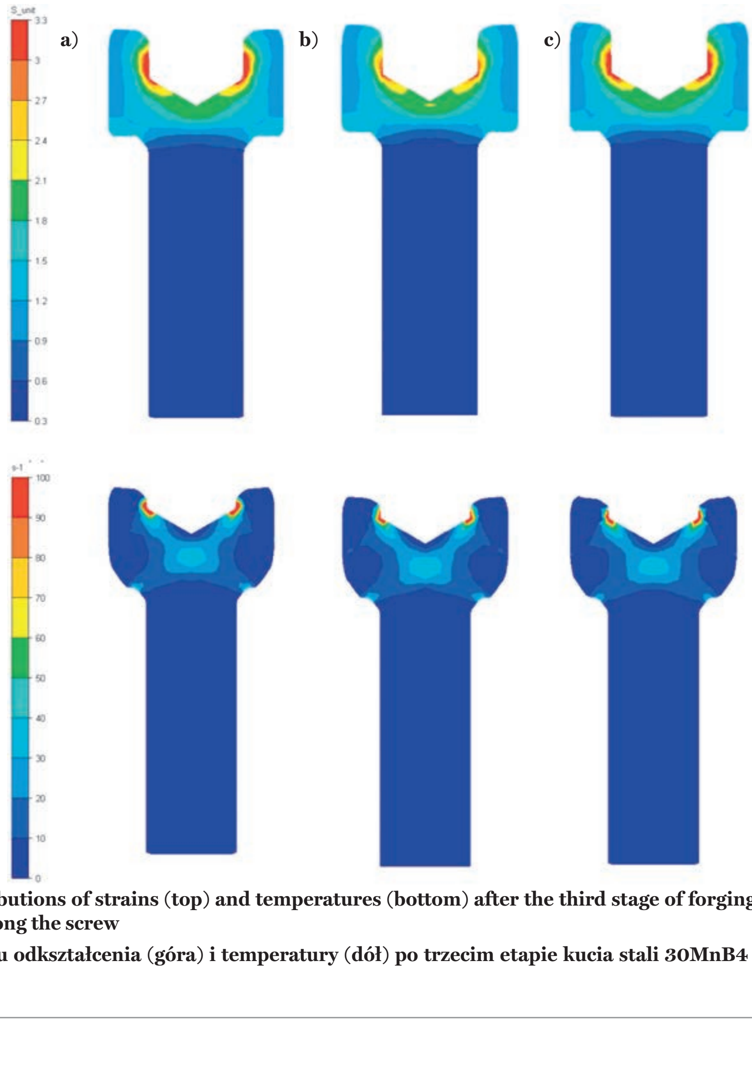

Fig. 4. Comparison of distributions of strains (top) and temperatures (bottom) after the third stage of forging of steels 30MnB4 (a), B1 (b) and B2 (c) – cross section along the screw

Rys. 4. Porównanie rozkładu odkształcenia (góra) i temperatury (dół) po trzecim etapie kucia stali 30MnB4 (a), B1 (b) i B2 (c) – przekrój wzdłużny śruby

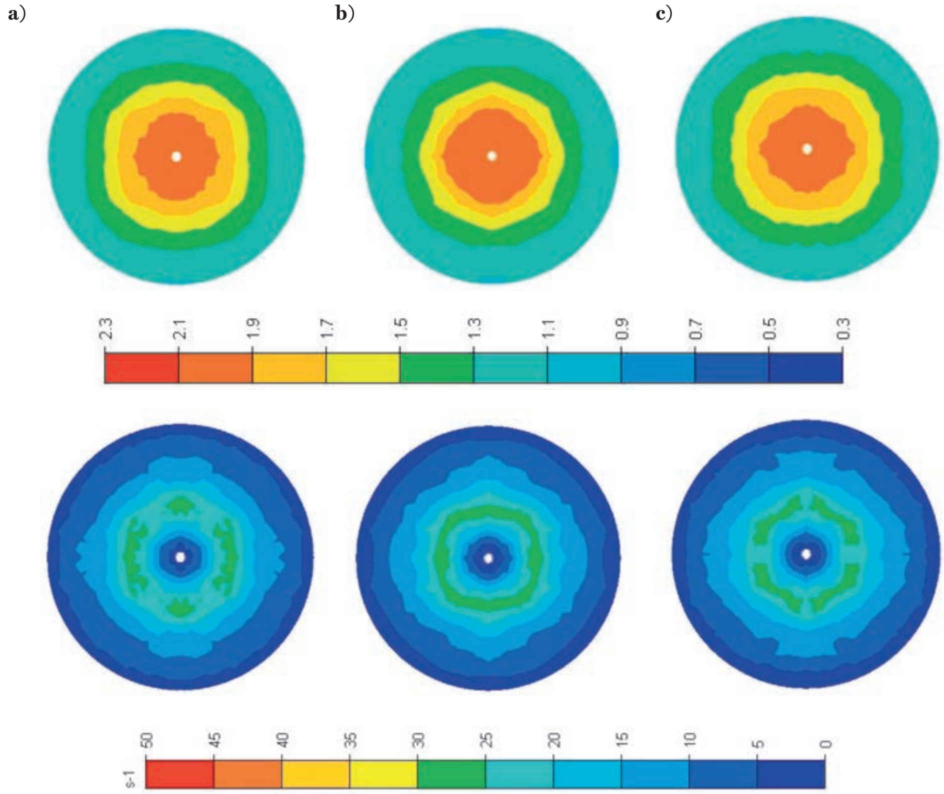

Fig. 5. Comparison of distributions of strains (top) and temperatures (bottom) after the 3rd stage of forging of steels 30MnB4 (a), B1 (b) and B2 (c) – cross section perpendicular to the screw axis just below the recess

Rys. 5. Porównanie rozkładów odkształcenia (góra) i temperatury (dół) po trzecim etapie kucia stali 30MnB4 (a), B1 (b) i B2 (c) – przekrój prostopadły do osi śruby u podstawy główki

3.2. SIMULATIONS FOR DIFFERENT STEEL GRADES

Simulations of the whole manufacturing process for the steels in Tab. 1 were performed next and calculated strains, stresses and temperatures were analysed and compared. Selected results of this analysis are presented below. Comparison of distributions of strains and temperatures after the third stage of forging of steels 30MnB4, B1 and B2 are shown in Fig. 4 for the cross section along the screw axis and in Fig. 5 for the cross section perpendicular to the screw axis just below the recess. The temperature raise is reasonable and it does not exceed 80°C. Strain concentrations are clearly seen in Fig. 3 and in Fig. 4 top and they can be further used for evaluation the fracture criterion in the optimization of the process.

4. CONCLUSIONS

Presented results show differences in the behaviour of various materials during deformation. At each step of forging, the largest stresses were observed for the bainitic steel in B1 state. In consequence the largest increase of the temperature was predicted for this steel. The accumulation of strains always occurs in the screw head. It was observed that decreasing the finishing rolling temperature to 800°C leads to decrease of the product properties. On the basis of the performed simulations and industrial trials the following manufacturing chain parameters for bainitic steel fasteners were proposed: hot rolling with the finishing temperature 900–880°C, accelerated cooling (3–3.5°C/s, finished at 400–450°C), pickling, phosphatizing, cold drawing (reduction 7–10%), annealing, 3-step cold forging, machining and rolling of the thread.

REFERENCES

[1] R. Kuziak, V. Pidvysots'kyy, S. Węglarczyk, M. Pietrzyk. Bainitic steels as alternative for conventional carbon-manganese steels in manufacturing of fasteners-simulation of production chain. *Computer Methods in Materials Science*, 2011, 11 (3), p. 443–462.

[2] S. Waengler, R. Kawalla, R. Kuziak. High strength-high toughness bainitic steels alloyed with niobium for long products. *Steel Research International*, 2008, 79 (2), p. 273–279.

[3] R. Kuziak, M. Skóra, S. Węglarczyk, M. Paćko, M. Pietrzyk. Computer aided design of the manufacturing chain for fasteners, *Computer Methods in Materials Science*, 2011, 11 (2), p. 243–250.

[4] H.K.D.H. Bhadeshia, D.V. Edmonds. The mechanism of bainite formation in steels. *Acta Metallurgica*, 1980, 28 (9), p. 1265–1273.

[5] S. Zajac, V. Schwinn, K.H. Tacke. Characterization and quantification of complex bainitic microstructures in high and ultra-high strength linepipe steels. *Materials Science Forum*, 2005, 500–501, p. 387–394.

[6] R. Kuziak, K. Radwański, K. Perzyński, Ł. Madej, M. Pietrzyk. Validation of material models for bainitic steels used in optimization of manufacturing chain for fasteners. *Computer Methods in Materials Science*, 2014, 14 (1), p. 37-52.

[7] R. Kuziak, V. Pidvysots'kyy, K. Drozdowski. Validation of the thermo-mechanical-microstructural model of hot forging process. *Computer Methods in Materials Science*, 2009, 9 (4), p. 424–434.

[8] D. Szeliga, J. Gawąd, M. Pietrzyk. Inverse analysis for identification of rheological and friction models in metal forming. *Computer Methods in Applied Mechanics and Engineering*, 2006, 195 (10), p. 6778–6798.

[9] A. Hensel, T. Spittel. *Kraft- und Arbeitsbedarf bildsamer Formgebungsverfahren*. Leipzig: VEB Deutscher Verlag für Grundstoffindustrie, 1978.