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PHYSICAL AND NUMERICAL MODELLING OF FORGING ACCOUNTING FOR EXPLOITATION PROPERTIES OF PRODUCTS

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Abstract

Idea of modelling of the life cycle of materials is presented and benefits of this approach are stated in the paper. Simulation of the entire life cycle of materials creates a possibility that properties of products can be controlled at the stage of technology design for materials processing and manufacturing. All steps of this methodology are discussed using production of connecting parts as an example. Investigation of the role of forging in the production chain is the particular objective of the project but other processes are considered, as well. Description of the experimental stages related to material structure development and investigation of material properties under loading conditions are supported by the numerical investigations. Results obtained from FE (Finite Element) simulations with the conventional rheological model and from the multi scale CAFE (Cellular Automata in Finite Element) model of the connecting parts forging processes are presented and discussed in the paper. Particular attention is put on strain localization development during cold forging and its influence on properties of products.

Key words: life cycle of material, multi scale modelling, forging

1. INTRODUCTION

Novel approach to design of manufacturing processes is based on considering the whole Life Cycle (LC) of material including processing and exploitation stages. Modelling of the Life Cycle provides possibility of the control of the final product properties at the stage of manufacturing. It means that required properties and specific behaviour of product under exploitation conditions can be obtained by optimization at the stage of material processing. Investigation in this approach is not focused only on a single manufacturing operation, i.e. forming or machining or heat treatment, but the whole chain of process operations is considered in prediction of the final product in use properties. The objective of this paper is presentation of the idea of Life Cycle modelling. Manufacturing of the connecting part is an example and particular emphasis is put on control some in use properties at the stage of one of the operations in the production chain, which is forging.

2. BASIC IDEA OF THE LIFE CYCLE METHODOLOGY

Physical and numerical simulations of phenomena and processes occurring in metallic materials during manufacturing allow to manufacture products with better in use properties, such as strength (in particular at elevated temperatures), crack resistance, fatigue resistance, shear resistance, wear resistance,

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creep resistance, corrosion resistance, hardness, ductility, porosity, adhesive properties, high temperature resistance, toughness, conductivity, low temperature resistance, etc. According to this analysis risk of material failure during exploitation can be minimized before final product is manufactured and ready to use. The Life Cycle modelling methodology provides possibility of taking into account the entire production chain and relationships between the subsequent operations.

Investigation of complete cycle of production of various connecting parts is an example of LC methodology (Figure 1). Materials used to manufacture these cold forged components should be characterized mainly by elevated mechanical properties and fatigue resistance. Low and medium carbon steels are commonly used for bolts manufacturing, however, several heat treatment operations have to be involved to obtain proper ductile properties and high static and dynamic load carrying capacity. Each additional thermomechanical operation leads to increase of production time and, what is even more important, to significant increase in the production costs. Therefore, researchers search for materials that are characterized by high ductile and strength properties obtained without the need of additional costly heat treatment operations. Bainitic steels (Pickering, 1996) may be one of the possible solutions.

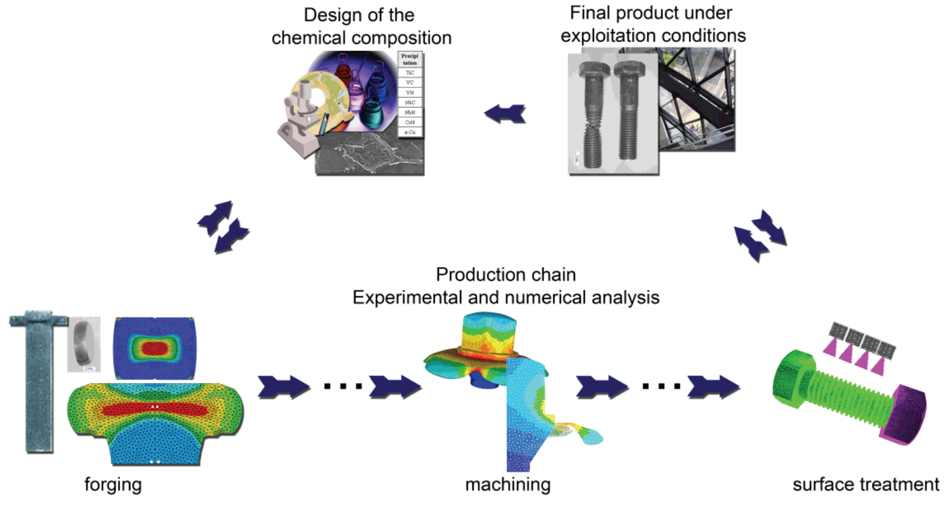

Fig. 1. Idea of the Life Cycle modelling using manufacturing of the connecting part as an example.

These steels meet mentioned above requirements but, on the other hand, they are characterized by a reasonably high tendency to micro crack initiation during forming. The latter phenomenon is caused mainly by micro shear and shear bands initiation and development. Elimination of micro cracks is important from the point of view of exploitation of final products, their durability and fatigue resistance. Thus, decreasing this effect is essential during the design of technology for future manufacturing processes.

All the stages of the design of production process, starting from design of chemical composition through experimental analysis of material properties, creation of the material rheological model (inverse analysis) and numerical simulations of manufacturing processes and product behaviour, are discussed in the following sections of the paper.

3. DESIGN OF CHEMICAL COMPOSITION

Cold workability of steels is affected by many factors including the chemical composition, surface condition and microstructure of the material. It was found that this property is particularly sensitive to differences between the mechanical properties of hard and soft microstructure constituents. In general, the hard phases, such as for example pearlite and coarse cementite, contributes to the material strength and hardness, whereas the soft phases, such as ferrite or spheroidized microstructure, contributes to ductility and toughness. To avoid the problems connected with low ductility of hard constituents in conventional steels used for cold forging low-carbon bainitic steels are recently under development to be formed without heat treatment operations (Park et. al 2005). There are two ways, in which a bainitic microstructure can be obtained in low-carbon low-alloyed steels. The first alternative is to modify the steel hardenability without substantially changing the processing conditions. The hardenability must be carefully controlled in order to secure that, in spite of the small grain size, the steel transforms to uniform and fine bainitic structure during further cooling. The second alternative involves an increase in cooling rate in order to allow the austenite to super-cool into the bainitic transformation range.

The principles for the novel bainitic steels lie in low and ultra-low carbon, low alloys steels, containing small amounts of boron and other bainite promoting elements, which are added to increase bainitic hardenability and suppress allotriomorphic ferrite formation, as well as microalloying elements to provide precipitation strengthening (Zajac et al., 2004). Precipitation strengthening allows a decrease in carbon content in steel, which gives the lowest transition temperature at a given strength and improves formability. By retarding the growth of brittle cementite, microalloying additions minimise low temperature embrittlement caused by the formation and growth of cementite. The formation of dispersed microalloy carbides in bainitic ferrite, instead of cementite, will give optimum impact properties and formability in high strength bainitic steels. The rejection of impurities from grain boundaries, which are associated with the classical site competition effects, is also influenced by microalloying additions.

To produce the high ductility and toughness properties at high strength, the microstructure of bainitic steels must be composed of ductile (tough) components with the ultra-fine domains (grains/laths). The most important feature of such microstructure is minimised lattice friction combined with minimised solid solution strengthening from interstitial elements of C and N. To achieve these properties without expensive alloying, it is necessary to produce a fine pancake austenite grain structure prior to transformation. Therefore, a proper control of austenite recrystallization and pancaking, as well as accelerated cooling/quenching during TMCP processing, is important in achieving the required microstructure.

4. LABORATORY EXPERIMENTS

To characterize the effect of bainite morphology on the cold workability, the die allowing for the physical simulation of cold heading has been constructed. The schematic picture of the die, which can be installed on the Gleeble 3800 simulator, is shown in figure 2. The samples were prepared from the 16 mm diameter wire rod made of steel with the following composition: 0.074%C, 2.0%Mn, 0.98%Cr, 0.13%Ti, 0.038%Nb and 0.002%B. The wire was subjected to the accelerated cooling in the Stelmor line to produce granular bainite morphology. The dimensions of the samples used in the cold heading simulations were ϕ5×25 mm. The final shape of the sample was reached with one deformation conducted at an average strain rate of 300 s^{-1}.

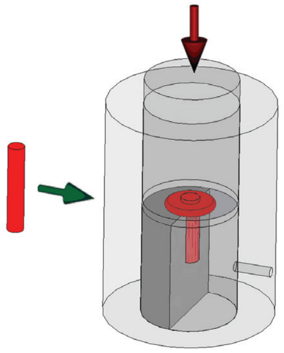

Fig. 2. Schematic picture of the die for the physical simulation of cold heading in the Gleeble 3800 simulator.

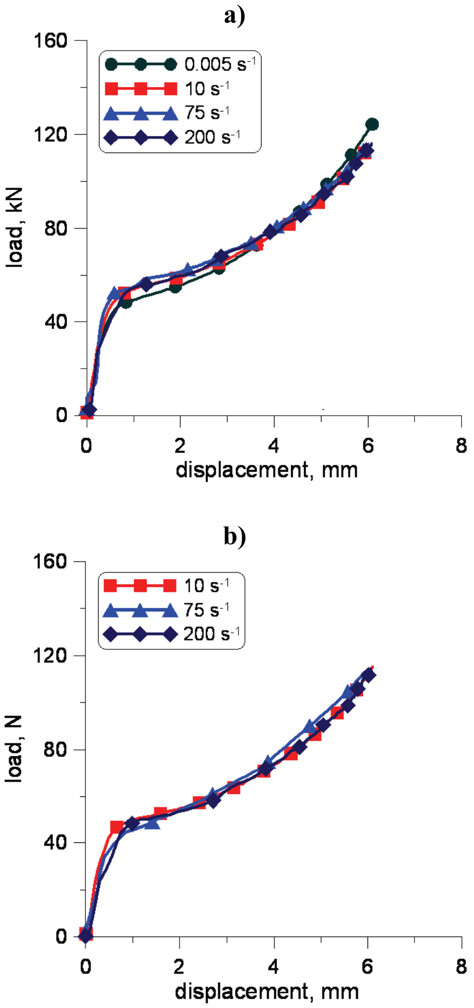

Fig. 3. Selected examples of the load vs. displacement curves for the bainitic steels under various deformation conditions, temperature 20°C (a) and 100°C (b).

The stress–strain curves were measured by deforming cylindrical samples (ϕ8×10 mm) in the Gleeble 3800 simulator. The samples were deformed at constant strain rates 0.005, 10, 75 and 200 s^{-1} and at temperatures 20, 100 and 300°C. Selected examples of the load-displacement curves recorded for the experimental material deformed at 20°C and at 100°C are shown in figure 3. It is seen in this

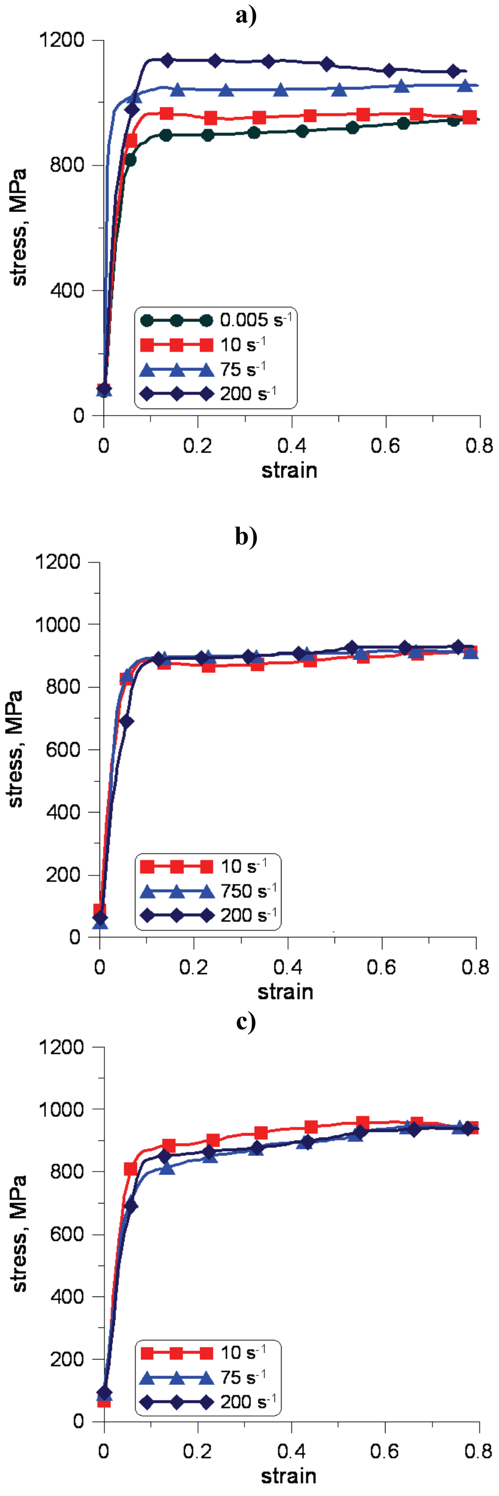

Fig. 4. *Examples of stress vs. strain relationships obtained using inverse analysis for the bainitic steels deformed at temperatures 20°C (a), 100°C (b) and 300°C (c).*

figure that strain rate sensitivity of loads is very low. Bainitic steels exhibit moderate sensitivity to strain rate, generally higher at the beginning of deformation to a strain of 0.15. For higher strains, this sensitivity is low which results in the shear bands initiation. So, the general idea of the current research activity is to design the forging process capable of reducing the plastic flow localisation caused by shear bands initiation. All the recorded load-displacement data are used as an input to the inverse analysis in the next chapter.

5. INVERSE ANALYSIS

Numerical simulations require a realistic information about the material behaviour during deformation. Thus, a proper rheological model for bainitic steels have to be created for use in numerical simulations. The model must be able to describe material behaviour during deformation, accounting for all discontinuities occurring as a physical material response to the loading conditions. On the other hand, model has to be insensitive to the disturbances resulting from the parameters not connected with thermo-mechanical aspects of deformation. An inverse analysis algorithm described in (Szeliga et al., 2006) is applied to meat all these requirements.

Plastometric UC (uniaxial compression) tests for bainitic steels were performed at various temperatures and various strain rates given in the previous section. Experimental data are combined with the optimization techniques and the coefficients in the model are determined by searching for the minimum of the cost function, which is defined as a square root error between measured and calculated load:

$$\Phi = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{F_{im}-F_{ic}}{F_{im}}\right)^2} \qquad (1)$$

where: F_{im}, F_{ic} – measured and calculated load, n – number of sampling points for measurements of loads.

Examples of the obtained results of the stress-strain curves are presented in Figure 4. These results are obtained in a form of stress-strain data given in a tabular form. It is again seen that the strain rate sensitivity is very low at elevated temperatures. Moreover, in some cases increase of the strain rate leads to small decrease of the flow stress (eg. Figure 4b). Further analysis focused on determination of the coefficients in the equation describing flow stress as a function of strain rate, strain and temperature. The following function proposed in (Gavrus et al., 1996) was selected for the identification purposes in the present work:

$$\sigma_p = \sqrt{3}\left\{K_0\varepsilon^n \exp\left(-R_0\varepsilon\right)\exp\left(\frac{\beta}{T}\right)+\right.$$

$$\left.\cdot\left[1-\exp\left(-R_0\varepsilon\right)\right]K_{sat}\exp\left(\frac{\beta_{sat}}{T}\right)\right\}\left(\sqrt{3}\dot{\varepsilon}\right)^m \qquad (2)$$

where: m, n, R_0, K_0, K_{sat}, β_{sat}, β – coefficients, which are determined using the inverse analysis, ε – strain, $\dot{\varepsilon}$ – strain rate, T – temperature in K.

Coefficients in equation (2) determined using inverse analysis are presented in Table 1. Identified flow curve was implemented in the FE code and used in the numerical simulations of the bolt forging performed with the FE and CAFE models. Description of the results is presented in the following section.

Table 1. *Coefficients in equation (2) determined using inverse analysis*

K_0	β	K_{sat}	β_{sat}	m	n	R_0
511.4	51.14	0.00243	0.001	0.03	0.00243	100

Among all operations in the production chain, cold deformation has the strongest influence on the resulting product fatigue resistance. It is due to microcrack initiation caused by micro shear and shear banding. Therefore, the cold forging is investigated in this section and particular emphasis is put on strain localization.

6. MULTI SCALE CAFE SIMULATION OF STRAIN LOCALIZATION

The problem of strain localization in metallic materials during deformation has been investigated for over thirty years. Experimental and theoretical analysis of the shear band phenomena during various kinds of deformation has been performed (Anand and Spitzig 1998; Cizek 2002; Harren, 1988; Korbel, 1998; Sematin and Laohoti, 1982). Despite series of theories regarding micro shear and shear band development, there is still a lack of an efficient numerical model that accounts for the influence of the formation of shear bands, and which can adequately describe the material behaviour in the FE simulation. This problem has been investigated by several researchers (Makarov, 2000; Olivier, 1995; Pecherski, 1998) but the major disadvantage of the proposed models is lack of flexibility and lack of the possibility for generalization, what leads to difficulties with accurate simulation of various industrial forming operations.

All of the mentioned above facts are the reason for the ongoing search for an alternative approach to describe strain localization phenomena. Authors of papers (Beynon et al., 2000; Makarov, 2002, Shterenlikht, 2003) have shown that the multi scale CAFE method should be an efficient method in this field. CAFE is the multi scale approach taking care of phenomena that occur at different scales in the material. Initiation and development of micro and macro shear bands during various forming processes is one example of such phenomena. Microshear bands initiate in the microscale, while shear bands develop at the mezoscale. According to those two scales, following the approach proposed in (Shterenlikht, 2003), two cellular automata spaces representing the material behaviour in the micro- and mezoscale are introduced and attached to the finite element code.

In the CAFE model both CA spaces, microshear band space (MSB space) and shear band space (SB space), are defined by several state variables that describe each particular cell, as well as by a set of transition rules defined respectively for those spaces. Transition rules, which control changes between states in the MSB and SB spaces, are defined based on the experimental knowledge (Cizek 2002; Korbel, 1998). Details describing the assumed cell state and relevant transition rules are presented in (Madej et al., 2006, Madej et al., 2007).

Flow of the information between the scales goes in both directions, from macroscale to mezoscale and microscale, as well as from microscale and mezoscale to macroscale. In each time increment, information about the stress tensor is sent from the finite element solver to the MSB space, where the development of microshear bands is calculated according to the transition rules. After exchange of information between CA spaces, transition rules for the SB space are introduced, and propagation of the shear bands is modelled. Based on the information supplied by the CA spaces, a new value of the flow stress, which is obtained by correction of equation (2) accounting for the influence of the microshear and shear bands, is calculated. This flow stress is sent to the FE program and is used in further FE calculations. The idea of the developed CAFE model is presented in Figure 5, where σ is the Cauchy stress tensor calculated in the FE program and σ_p is the corrected flow stress of the material.

Developed CAFE model proved its good capabilities in modelling of strain localization during simple plastometric tests (Madej et al., 2005), as well as real industrial processes (Madej et al. 2006). That is the reason why this model is used in the present work to simulate forging of connecting parts. Selected examples of results obtained from the FE program with the conventional rheological model (referred further to as FE model) and from the CAFE simulation, performed for laboratory experiments, are presented in Figure 6.

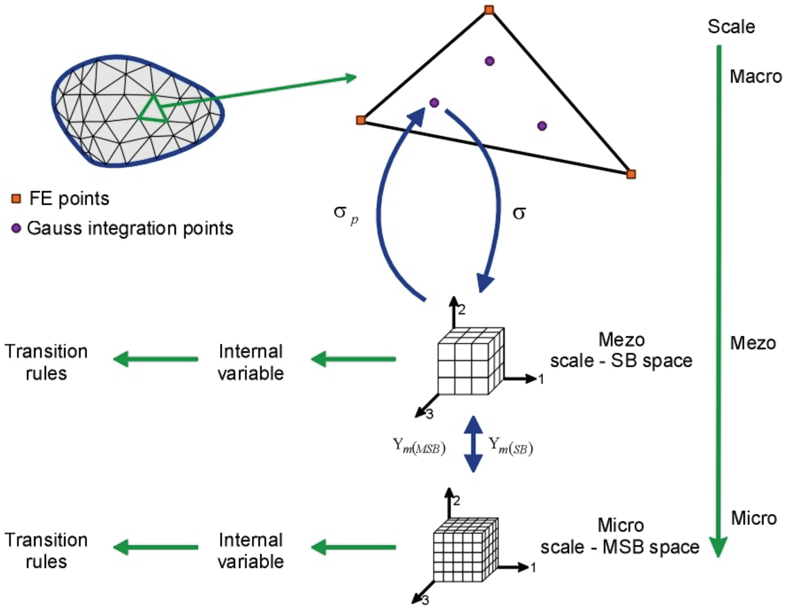

Fig. 5. *Illustration of the flow of information between scales in the developed CAFE model.*

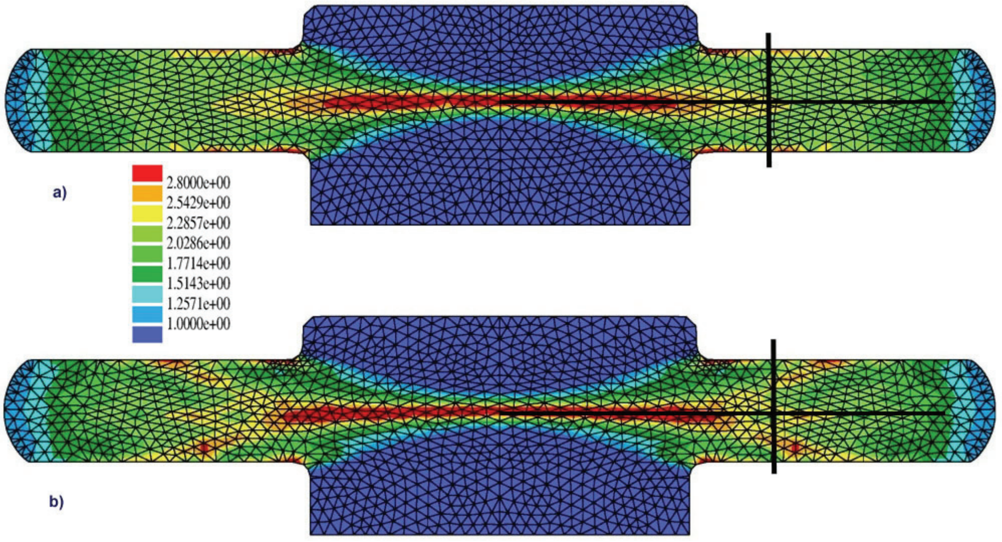

Fig. 6. *Comparison between strain distributions obtained from the (a) FE and (b) CAFE models of the laboratory bolt forging.*

Results obtained from the conventional FE and CAFE models presented in Figure 6 are similar in the middle part of the sample. However, when the outer part of the sample is under consideration, differences in material flow are observed, see Figure 7.

It is seen in Figure 6b and 7 that strain localizes in the bands in the outer part of the sample when CAFE model is applied. This behavior is different from the one seen in Figure 7a, where strain is high only in the central part of the sample, as well as close to the sample surface what is due to the friction, see Figure 7. No strain localization bands are observed in this region when FE with conventional flow rule is applied.

Optical and electron microscopy was performed to help in interpretation of the obtained results. The macrostructure of the element forged in the die described in Figure 2 is shown in Figure 8. The etching revealed plastic flow localisations in the head, which compares fairly well with the results of the CAFE simulations. Figure 9 shows the microstructure, which proves that the intense deformation did not cause the crack initiation in the rivet head. The more severely deformed region in Figure 9b than in Figure 9a consist of elongated bainitic ferrite grains and the second phase (grey objects) witch follows the deformation pattern of matrix. However, no decohesion between the matrix and second phase was observed. Transmission electron microscopy shows the dislocation substructure development in the moderately deformed area of the sample (Figure 10a). However, a clear indication of the incidental micro-shear bands development was also provided by the investigation of the flow localisation region (Figure 10b). The flow localisation resulted in hardness increase by factor of approximately 1.8 as compared to the initial hardness of the rod.

Numerical simulations are an important step during life cycle modelling, due to the fact that they significantly lower the production cost. At this stage of the project only one operation in the production chain is considered. Development of the effective system of the optimal technology design will be possible when all operations in the chain are included in the model. However, even this partial solution shows that modelling of the whole life cycle of material creates capability of controlling the final product properties at the stage of manufacturing. In consequence, a series of expensive experimental

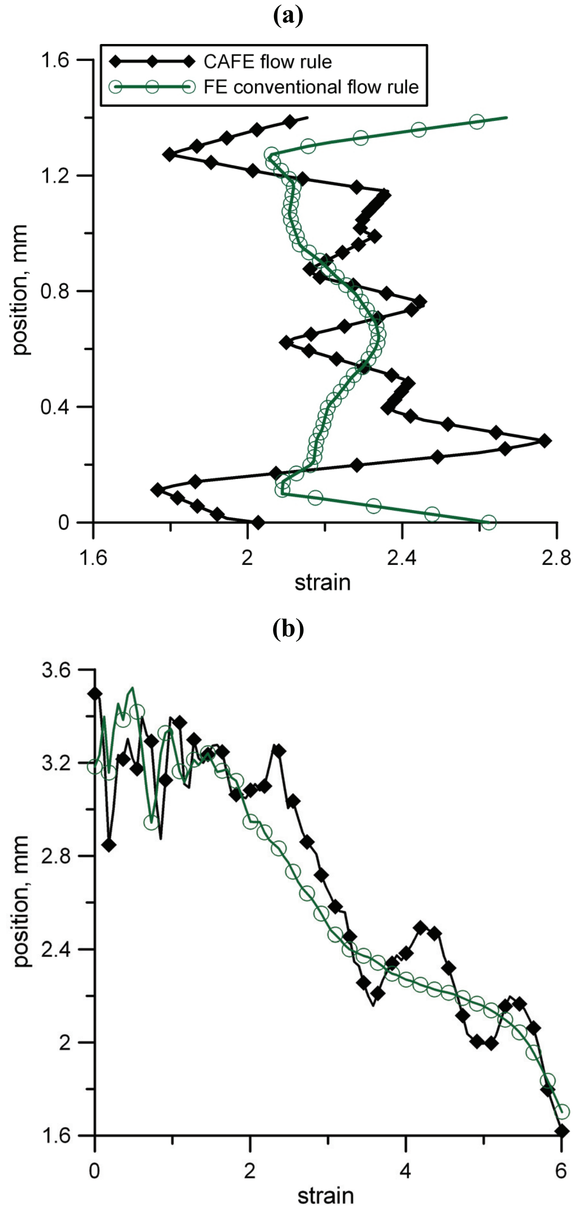

Fig. 7. Strain distributions obtained along the black vertical (a) and horizontal (b) lines presented in Figure 6a and b.

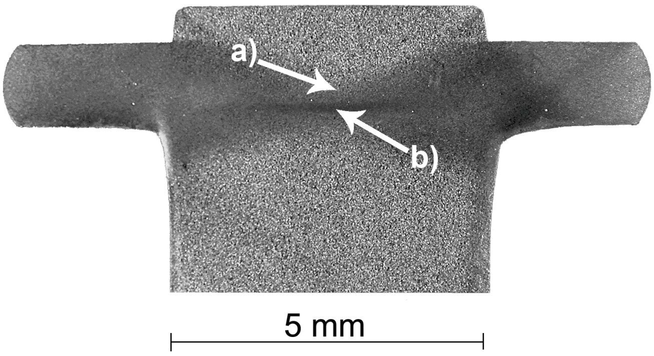

Fig. 8. Macrostructure of the rivet obtained by deforming the rod ϕ5×25 mm made of bainitic steel in the die shown in figure 2, installed in the Gleeble 3800 simulator. Arrows a) and b) indicates moderately deformed and highly deformed area respectively.

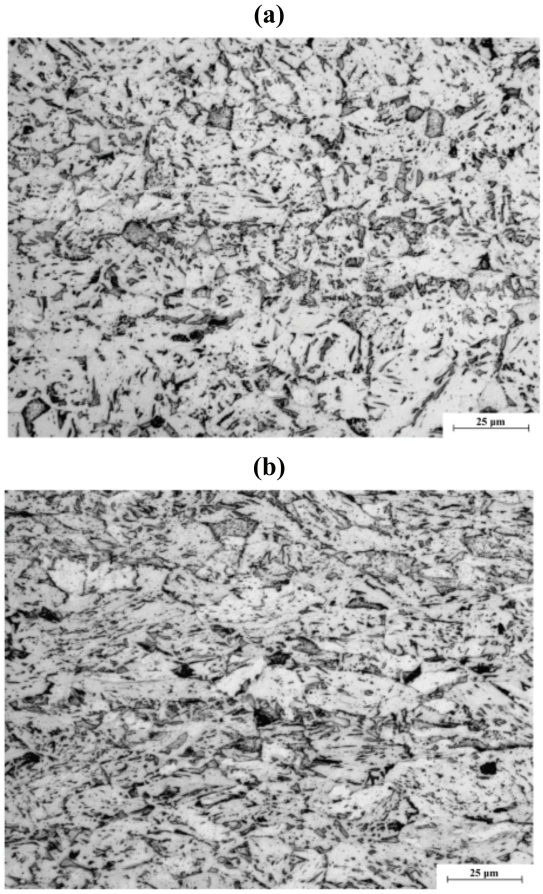

Fig. 9. Microstructure of the rivet shown in Figure 8 in the moderately deformed area – (a) and region where plastic flow localization occurred (b). Both regions are indicated with arrows in Fig.8).

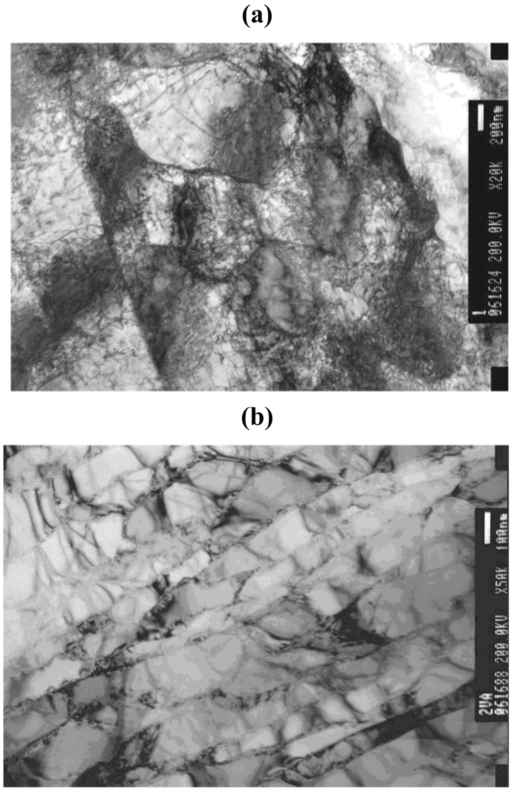

Fig. 10. Example of the microstructure in the selected areas of the thin foil prepared from the rivet in (a) the moderately deformed area (Figure 9a) and (b) region where plastic flow localization occurred (Figure 9b) (TEM).

trials can be avoided and all the possible problems can be solved virtually.

7. CONCLUSIONS

The idea of modelling of the whole production chain is presented in the paper using manufacturing of the connecting part as an example. Realization of such simulation system requires models, which can describe changes of microstructure during manufacturing and, in consequence, can predict the properties of product. The present work is focused on development and application of such model for the forming processes. It is shown that application of the CAFE model to simulation cold forming of steels allows to predict materials tendency to micro crack initiation. The areas in the product, which are the most probable locations of decreased fatigue resistance, can be identified. It is also shown in the paper that correlation between forming process parameters and strain localization in the form of bands can be predicted, therefore, the control of tendency to micro crack initiation is possible at the stage of cold forming.

Future works in this field should focus on development of models for the remaining operations in the production chain, such as machining, heat treatment and surface treatment. All the models will be connected in a single simulation system for modelling life cycle of materials.

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FIZYCZNE I NUMERYCZNE MODELOWANIE WPŁYWU WARUNKÓW PROCESU KUCIA NA WŁASNOŚCI UŻYTKOWE GOTOWEGO WYROBU

Streszczenie

W pracy zaprezentowano możliwości oraz zalety symulacji numerycznej pełnego cyklu życia materiałów, począwszy od fazy obróbki plastycznej a kończąc na testach gotowego wyrobu. Zastosowanie tej metodologii umożliwia określenie własności użytkowych wyrobu gotowego w funkcji parametrów technologicznych na kolejnych etapach produkcji, np. formowanie, obróbka skrawaniem, obróbka cieplna. Dla weryfikacji takiego modelowania wykonywane są próby laboratoryjne oraz próby zachowania się wyrobów w warunkach eksploatacji. Poszczególne elementy metodologii symulacji cyklu życia omówione są na przykładzie wytwarzania elementów łącznych. Szczególny nacisk położono na analizę wpływu procesu kucia na zimno na własności wyrobu gotowego. Symulacje numeryczne prowadzono z wykorzystaniem konwencjonalnych modeli reologicznych oraz alternatywnego wieloskalowego modelu CAFE (połączenie Metody Elementów Skończonych i Metody Automatów Komórkowych). Analizie poddano zjawisko lokalizacji odkształcenia występujące podczas procesu kucia na zimno. Uzyskane wyniki symulacji numerycznej porównywane są z wynikami badań laboratoryjnych.

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