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NUMERICAL MODELING OF BULK METAL FORMING PROCESSES WITH INDUCED STRAIN PATH CHANGE

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Abstract

A review of the developed numerical models for simulation of the bulk metal forming processes that take into account influence of the strain path change on material flow is presented in this paper. The strain patch change effect influences many crucial properties of the deformed material i.e. leads to increase in ductility. That provides a possibility of forming materials, which are difficult to form in a conventional manner. In recent years a lot of experimental and numerical research have been done on development of these new non-conventional bulk forming processes. The main advantages and limitations of the modified forging, extrusion and simple compression tests are summarized and presented in this work. Difficulties in development of the complex rheological model that takes in to account both thermal and structural changes in the deformed material are also discussed.

Key words: severe plastic deformation, strain path change, heat generation, micro shear bands

1. INTRODUCTION

Accuracy of numerical simulations of metal forming processes depends, to a large extent, on the correctness of description of material rheological properties as well as mechanical and thermal boundary conditions. It seems that this accuracy is particularly important in the case of forming processes with induced strain path change. There are two main mechanisms that significantly affect material behavior under those conditions. The first is effect of the heat generation on material flow under deformation. Increase in the temperature during material processing is well known in literature for many years. This effect is also taken into account by most of the Finite Element (FE) models used in industry.

Contrary, the second effect, which is a discontinuous microstructure evolution is little know. In literature there is a lack of detailed description of the basic mechanisms leading to i.e. micro shear bands development, when material is subjected to the change of the strain path. Some aspects of this phenomenon are discussed in [4], where author claims that a change in the deformation scheme and increase in temperature can cause instant initiation of micro shear bands in metallic materials. It seems that under these conditions shear bands become the major mode of plastic deformation. Interesting observations are presented in [3], where a simple change in the strain path and its influence on the flow curve were investigated. Two deformation modes were applied, torsion-tension-torsion, and torsion-torsion-torsion, as presented in figure 1. Flow stress obtained from the measurement for the 1st and 3rd steps is presented schematically in figure 2.

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Figure 2 shows drop in the flow curve when deformation path changes, what is a result of the development of micro shear and shear bands leading to strain localization. This observations confirm a positive effect of the strain path change on materials processing. However this effect is less pronounced when the second deformation scheme was applied.

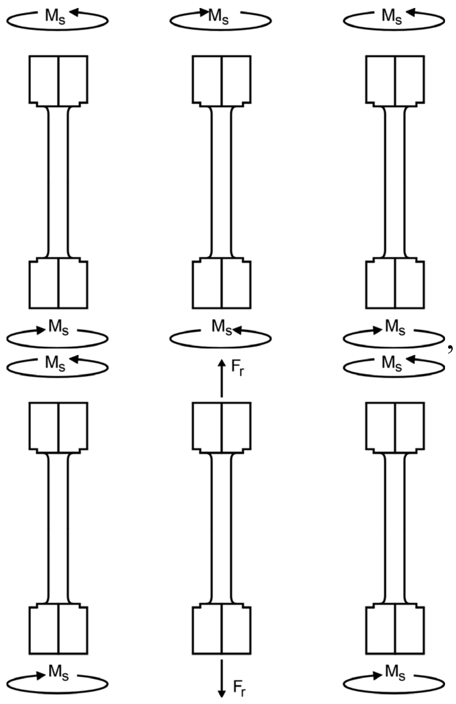

Fig. 1. *Schematic illustration of the performed tests with the change in the strain path [3].*

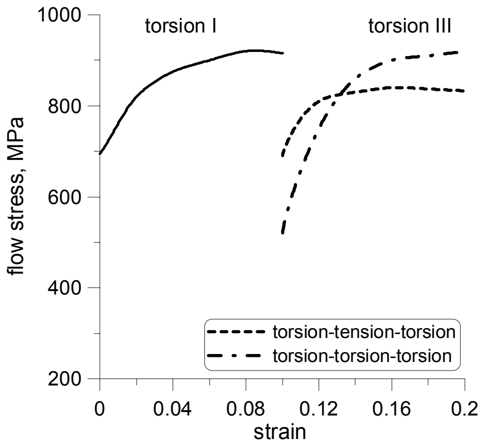

Fig. 2. *Flow stress achieved from torsion–tension–torsion and torsion–torsion–torsion tests [3].*

Other works consider cyclic deformation where change in the strain path occurs many times [2]. The main focus is on the effect of the strain path change on the macroscopic material properties and not on the physical aspects leading to initiation and development of the strain localization.

The main advantage provided by mentioned temperature changes and micro shear band development during the strain path change is an increase in the forming capabilities of many materials, that are difficult to form by conventional metal forming operations. This behavior is also closely related to better filling of the die during i.e. rotary forging. An increase in the tool life can be expected as well.

All these advantages are the reason why new non-conventional bulk forming processes are being designed and developed in laboratory and industrial conditions. To support these experimental investigations advanced numerical approaches are also required. Numerical simulation usually considers only one of the discussed phenomena, which is additional heat generation during strain path change. There have been attempts to take into account micro shear band development, however, due to the complexity of this phenomenon developed models usually describe material behavior in a quantitative manner, based only on continuum mechanics [9,10]. Multi scale modeling approaches based on discrete methods to model shear band development during monotonic deformation can also be found in literature [6]. Modifications of this approach to simulate simple 2D processes with the strain path change can be found in [7]. The major problem with these approaches is computational time that for the large industrial 3D cases is still inadequate for real time applications. That is the reason why most of the conventional FE numerical simulation neglect this effect and considers only influence of the heat generation.

The main aim of this work is to present selected examples the FE numerical simulations of non-conventional forming processes that take into account additional oscillatory movement of tools during deformation.

2. NUMERICAL MODEL

As previously mentioned the FE numerical models can not easily take into account the effect of the strain path change that is related to the shear band development. They usually, (i.e. the commercial Forge 3 code used in this work) consider influence of the strain path change on temperature and strain rate changes during deformation. The Forge code is based on the Norton-Hoff law in the form:

$$\sigma_{ij} = 2K\left(\sqrt{3}\dot{\varepsilon}_i\right)^{m-1}\dot{\varepsilon}_{ij}$$

where: σ_{ij} – deviatoric stress tensor, $\dot{\varepsilon}_{ij}$ – strain rate tensor, $\dot{\varepsilon}_i$ – effective strain rate, K – the material consistency, m – strain rate sensitivity coefficient. K is the material parameter used in Forge3, which represents the flow stress and is calculated from the following equation:

$$K = \frac{\sigma_p}{\sqrt{3}\left(\sqrt{3}\dot{\varepsilon}_i\right)^m}$$

These equations lead to the Levy-Misses flow rule, which describes the relationship between deviatoric stress and the strain rate tensors:

$$\sigma_{ij} = \frac{2}{3}\frac{\sigma_p}{\dot{\varepsilon}_i}\dot{\varepsilon}_{ij}$$

The temperature field evolution is calculated according to the equation:

$$\rho c\frac{\Delta T}{\delta t} = div\left(k\,\mathrm{grad}T\right) + \dot{W}$$

where: ρ – material density, c – specific heat capacity, T – temperature, t – time, k – thermal conductivity, $\dot{W}$ – internal energy dissipation.

The heat generated during deformation is calculated with the following equation:

$$\dot{W} = \eta\sigma_{ij}\dot{\varepsilon}_{ij} = \eta K\sqrt{3}\dot{\varepsilon}^{m+1}$$

where: η – strain efficiency (also can be named the heat conversion efficiency).

In this case the heat generation during additional cyclic movement plays an important role in material behavior. All the results obtained for the simple compression with additional cyclic oscillations, extrusion with cyclic die oscillation and closed die rotary forging are based on the mentioned assumptions.

3. BULK METAL FORMING PROCESSES WITH INDUCED STRAIN PATCH CHANGE

3.1. Compression with cyclic oscillations

Compression with cyclic oscillations is an example of a laboratory test that is used to investigate influence of the additional oscillations on material behavior under deformation. Laboratory equipment was developed at the Department of Process Modeling and Medical Engineering of the Politechnika Śląska in Katowice and is presented in figure 3 a,b. The developed FE model to simulate this process is presented in figure 3c.

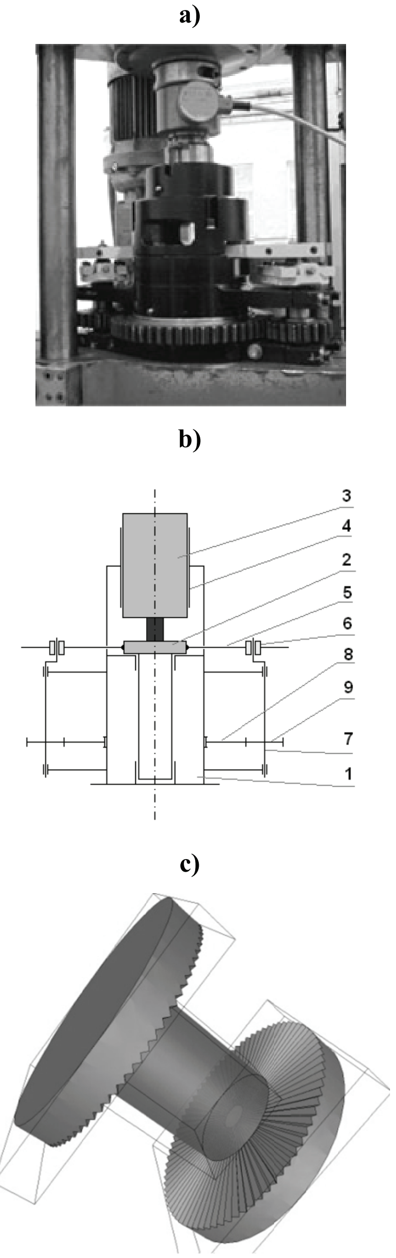

Fig. 3. Laboratory equipment (a), setup of the laboratory equipment (b) (1 – body, 2 – lower die, 3 – upper die, 4 – non-rotating movable bearing, 5 – shift fork – lower die arm, 6 – roller, 7 – crankshaft, 8 – toothed ring, 9 – gear wheel), finite element model (c).

One of the major problems occurring during numerical simulations of these kind of processes is excessive computational time, which is due to large number of FE elements. To transfer additional reversible oscillation into the deformed material, a series of narrow groves is introduced at the dies surfaces (figure 3c). Highly refined FE meshes have to be used in the numerical model to accurately transfer shape of these grooved dies into the deformed sample (figure 4). That eventually leads to long computational times. One of the solution to eliminate this problem is to apply anisotropic frictions conditions instead of using grooved dies. That can be done mainly using in-house codes because in commercial FE packages there is a limited access to the FE codes, and user subroutines usually do not give such possibility. The anisotropic friction was successfully used in [8].

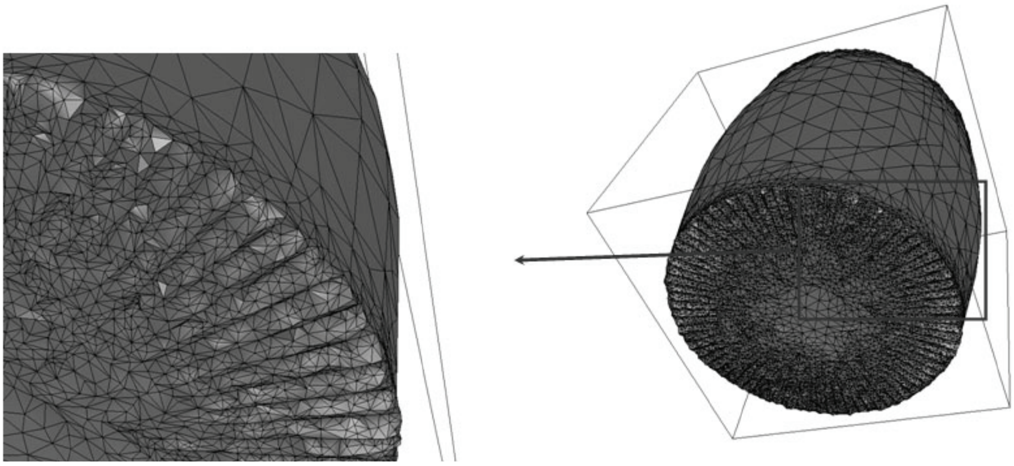

Fig. 4. Die shape transfer on the deformed sample.

As mentioned, the temperature increase is one of the major mechanisms in the FE model that influences material behavior under strain path change conditions. Temperature changes can be quite significant depending on the process conditions, mainly press velocity. The latter directly influences number of oscillations occurring during deformation what eventually leads to temperature increase, as seen in figure 5. Additional deformation heating results in reduction in stresses and finally in applied loads. Detailed analysis of this process is presented in [12].

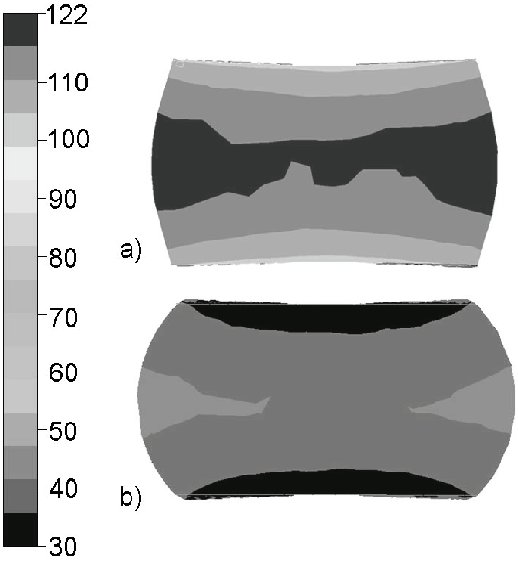

Fig. 5. *Difference in temperature (℃) distribution obtained for cyclic compression with f = 0.4Hz and press velocity a) v = 0.3m/s and b) 0.6 m/s.*

This laboratory process is mainly used to analyze differences in material flow while reversible oscillations are applied and obtained results can be transferred to set up real industrial processes like KOBO type extrusion [1] or forging of the gear wheel [11].

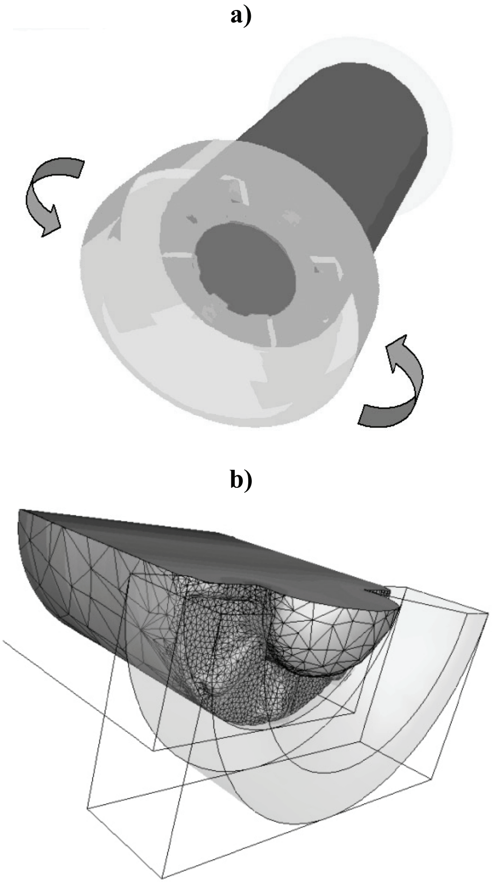

Fig. 6. *a) FE model of the KOBO extrusion process, b) fine mesh reflecting shape of grooved die.*

3.2. KOBO type extrusion

The KOBO extrusion was extensively studied experimentally [1,5] and numerically [13] and proved its advantages in extruding hardly formable materials. Due to additional reversible die oscillations large degree of deformation can be obtained without danger of material failure. Developed numerical model to simulate KOBO extrusion is presented in figure 6. Comparison of temperature distribution obtained from monotonic and reversible extrusion is presented in figure 7.

Temperature increase in the KOBO extrusion in comparison to monotonic extrusion is observed in figure 7. As seen additional heat generation in the deformation area results in temperature increase in the entire billet.

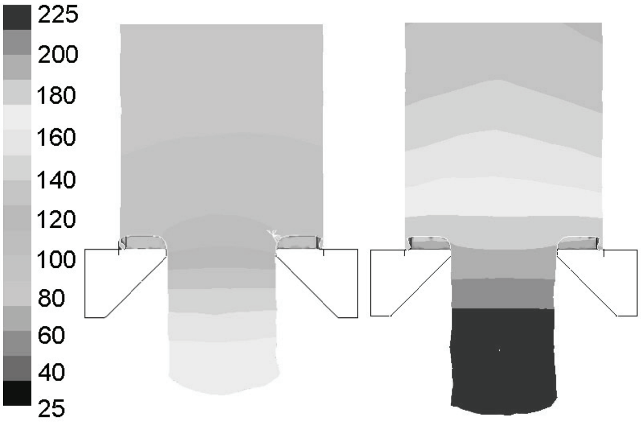

Fig. 7. Comparison between temperature (°C) distributions in conventional extrusion process and extrusion with additional cyclic oscillations (KOBO type extrusion).

3.3. Rotary gear wheel forging

The same methodology was also applied to the gear wheal forging process. Examples of numerical simulation obtained from monotonic and reversible forging process are presented below.

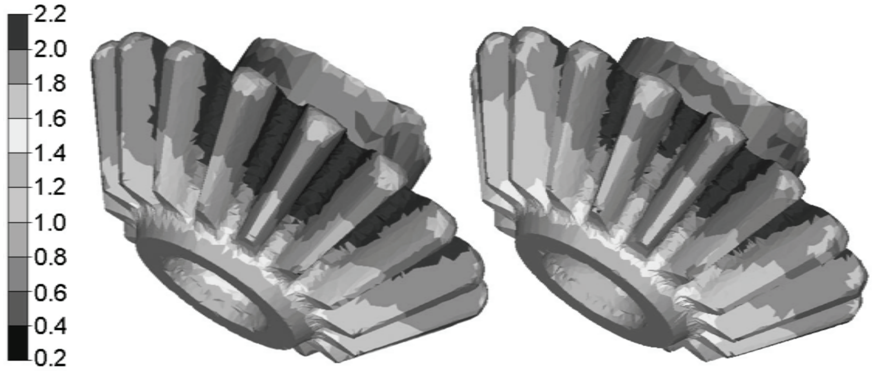

Fig. 9. 3D strain field obtained from monotonic (left) and reversible (right) forging.

The main difficulty in the monotonic closed die forging is to obtain the final shape of the product with the material properties that meet customers demands. The excessive wear of the dies is another potential problem from the technological, as well as economical point of view.

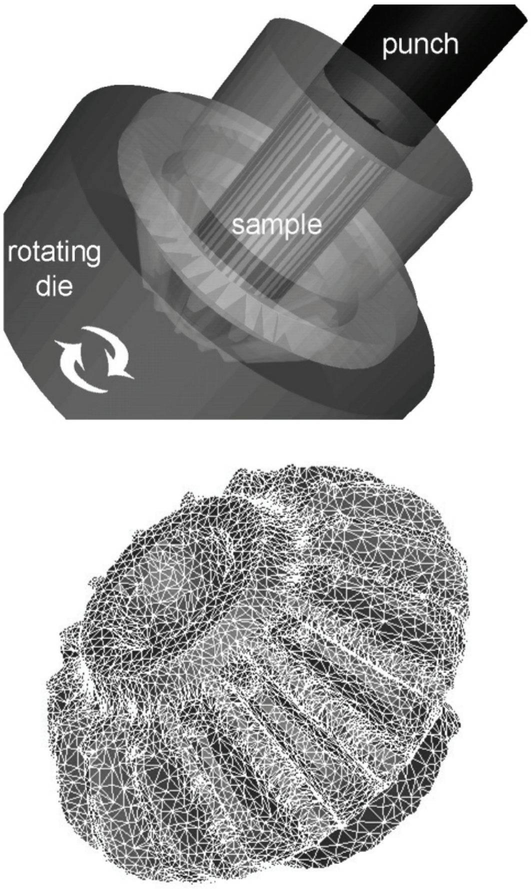

Fig. 8. a) FE model for gear wheel forging with reversible die oscillation, b) FE mesh after deformations.

It is expected that application of the reversible rotations to the die will solve these problems. The KOBO type forming will lead to better filling of the groove and will allow to obtain final product with higher accuracy in shape in comparison to monotonic forging. Additionally, it can lead to the decrease in die wear due to reduction in applied loads. To investigate mentioned possibilities a series of experimental and numerical analyses have already been done in another authors work [11]. Developed numerical model is presented in figure 8.

Examples of obtained results are presented in figures 9 and 10. Again the main attention is put on analysis of the temperature increase due to additional oscillations (figure 9). Higher temperatures observed at the circumference of the forged gear wheel directly influence stress state in the material as well as strain values. As seen in figure 10 strain field in both cases is similar, although in monotonic forging regions between gear teeth with higher strain values are clearly visible.

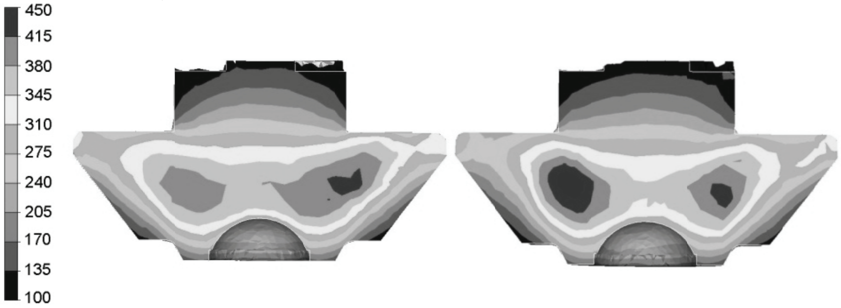

Fig. 10. *Temperature (℃) distribution at the cross section obtained from monotonic (left) and reversible (right) forging.*

4. CONCLUSIONS

As presented in all cases: simple forging, industrial extrusion and gear wheel forging, additional reversible oscillations influences material behavior during deformation. The main factor responsible for that in the FE simulations is increase in the deformation heating that is directly linked with number of oscillations. In general higher values of temperature are observed when additional oscillations are introduced, but also increase in temperature is observed when more oscillations are induced into material. This is usually obtained by reduction the press velocity and maintaining the oscillation frequency.

In real materials character of metal flow during strain patch change is affected not only by additional heat generation but also by micro shear bands initiation. Interaction of these two mechanisms lead to all the effects reported in literature [1,5]. However, as it has already been mentioned, in rheological models commonly used during numerical analysis influence of micro shear bands is neglected and only additional heat generation is taken into account. That is why, when FE modeling is used to develop an industrial technology based on the strain path change effect it is crucial to be aware that obtained differences in material flow between i.e. conventional and reversible forging are under estimated. In experimental analysis due to rapid initiation of micro shear bands obtained differences are much better pronounced.

The solution for this is development of modern multi scale models taking into account influence of micro shear band evolution. However, at this stage application of the developed approaches to simulate 3D strain path change processes lead to lengthy computational time.

ACKNOWLEDGMENT

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MODELOWANIE PROCESÓW PLASTYCZNEJ PRZERÓBKI METALI Z WYMUSZONĄ ZMIANĄ DROGI ODKSZTAŁCENIA

Streszczenie

Przez kilka ostatnich lat wiele pracy zostało włożone od strony eksperymentalnej oraz modelowania numerycznego w opracowywanie niekonwencjonalnych procesów plastycznego kształtowania metali. Efekt zmiany drogi odkształcenia wpływa na wiele istotnych własności materiałowych np. wzrost plastyczności. To z kolei umożliwia odkształcanie materiałów trudno odkształcalnych. Zalety oraz wady procesów kucia, wyciskania oraz walcowania z dodatkową zmianą drogi odkształcenia są dyskutowane w ramach niniejszej pracy w oparciu o wyniki symulacji numerycznej. Możliwość uwzględnienia w modelu MES wpływu efektów cieplnych oraz strukturalnych na makroskopowe zachowanie się materiału jest również omówione w niniejszej pracy.

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