THE ANNALS OF "DUNĂREA DE JOS" UNIVERSITY OF GALAȚI
FASCICLE V, TECHNOLOGIES IN MACHINE BUILDING,
ISSN 1221- 4566, 2009

Numerical investigation of the Bauschinger effect during the low reversal cyclic torsion, three point bending and tension/compression tests

Konrad Perzynski[1], *Lukasz Madej*[1],
Krzysztof Muszka[2] and *Maciej Pietrzyk*[1]

[1]Department of Applied Computer Science and Modelling
[2]Department of Metal Forming
Akademia Górniczo-Hutnicza, Al. Mickiewicza 30, 30-059 Kraków, Poland
kperzyns@metal.agh.edu.pl

ABSTRACT

Creation of a robust numerical model of the low cyclic deformation processes is essential for accurate predictions of the inhomogeneities occurring during industrial processes, especially when sheet materials are considered. Development of such model is the main subject of the present work. In order to evaluate material behavior under cyclic deformation conditions several simple plastometric test were selected. Particular attention is paid to the effect of the cyclic deformation on the material behavior along the radius of the deformed cylindrical sample in cyclic torsion and tension/compression tests, as well as along thickness of the sample in the three point bending. Obtained results are also compared with the commonly used in industry conventional isotropic hardening model. Finally, based on this analysis, conclusions regarding the possibility to apply investigated tests in identification of the material model parameters through the inverse analysis are drawn.

KEYWORDS: low cyclic hardening, Bauschinger effect, inverse analysis, FEM

1. INTRODUCTION

The numerical modeling of material behavior under thermo-mechanical processing conditions is widely used in both experimental research and industrial applications. Accuracy of numerical simulations depends, to a large extent, on the correctness of description of material properties, as well as on mechanical and thermal boundary conditions. Accurate evaluation of the rheological parameters in various conditions of deformation is one of the challenges in simulation. It can be said that conventional models describe properly materials subjected to deformation in a reasonably uniform and monotonic conditions [10]. However, when process with complex stress states (i.e. during reversal cyclic deformation) is considered, conventional rheological models fail to accurately describe the material behaviour. Cyclic deformation is particularly interesting from the industrial point of view because it may lead to a reduction in applied loads followed by the energy conservation. When material is subjected to severe axial deformation with the cyclic change in the strain path, micro shear band development is the major mechanism responsible for the mentioned effect. This observation is the basis of the proposed Structure Based Design of Metal Forming Operations (SBDMFO) [4] and was successfully applied to industrial scale extrusion with additional cyclic oscillations of the die [1]. Development of the rheological model to simulate this kind of processes was the subject of earlier authors works [6,7] and is not discussed in the present paper.

However, when material is subjected to a low cyclic oscillation, another interesting phenomena become important – the Bauschinger effect [3]. According to its definition, the Bauschinger effect is a transient decrease in the work hardening rate upon reversal of the loading direction. Simply, when a material is subjected to loading under tension, the yield stress (σ_t) occurs at some specific level, after that when material is reloaded under compression (σ_c), yielding occurs at the lower stress level, as it is shown in Fig. 1.

There is a number of the hardening models that do take into account this effect [8,2,5]. Review of these models can be found in authors earlier publication [9]. For the purpose of the present work a combined kinematic isotropic hardening model was selected. The obtained results are compared with the outcome from the conventional isotropic model. Short summary of the major assumptions used in this work are described in the following section.

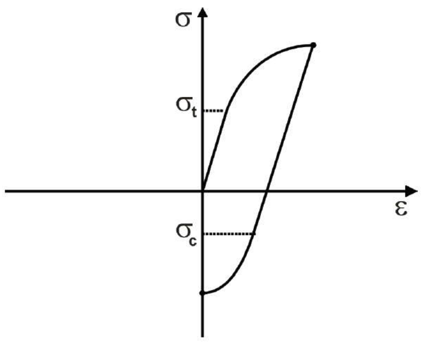

Fig. 1. Illustration of the Bauschinger effect.

2. CYCLIC DEFORMATION MODEL

As mentioned earlier, in order to solve problems which include the Baushinger effect, it is important to find an accurate hardening model. One of such models is a combination of the isotropic and kinematic hardening models. In the isotropic approach the centre of the yield surface is fixed in the stress space, while size of the surface increases. This approach is commonly used to model large plastic deformations performed in a monotonic manner. Contrary in the kinematic model the size of the yield surface is fixed, while the centre of the yield surface can move. Both approaches have their advantages and disadvantages. There is also a possibility to combine these two models and to create a combined model, where both the size of the yield surface increases and the centre of the yield surface moves in the stress space, as seen in Fig. 2.

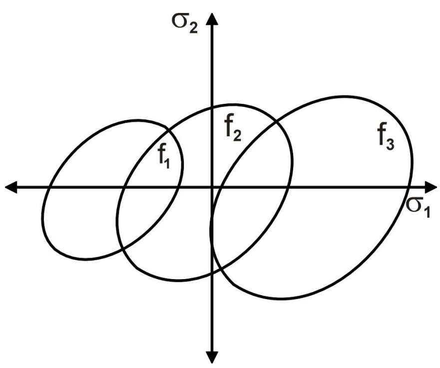

Fig. 2. Yield surface evolution in combined hardening model.

The combined model is the most complicated but, at the same time, the most accurate in description of material behaviour during low cyclic deformation. This model can be incorporated into one of the most commonly used description of the yield surfaces: the von Mises one. In this approach two state variables have to be used: the kinematic and the isotropic hardening variables. As mentioned earlier, the kinematic variable accounts for the translation of the yield surface, while the isotropic variable accounts for its change in size or expansion. Since in metallic materials the hydrostatic stress has no effect on the plastic deformation, the von Mises yield surface is defined in the deviatoric stress tensor components:

$$\dot{\varepsilon}_{ij}^{p} = \dot{\Lambda}\frac{\partial f}{\partial \sigma_{ij}} \quad (1)$$

where: $\dot{\varepsilon}_{ij}^{p}$ - plastic strain increment tensors, $\dot{\Lambda}$ - a positive scalar factor of proportionality, f - plastic potential function identical to the yield function if the associated flow rule is used.
The plastic potential function is defined as:

$$f = \sqrt{\frac{3}{2}(\hat{\sigma}_{ij}-\alpha_{ij})(\hat{\sigma}_{ij}-\alpha_{ij})} - \sigma_p - R = 0 \quad (2)$$

where $\hat{\sigma}_{ij}$ are the deviatoric components of the stress tensor σ_{ij}, α_{ij} is the backstress tensor which defines the center of the yield surface, σ_p is the initial yield point, and R is the isotropic hardening variable.
The evolution of the backstress tensor is described by the equation:

$$\dot{\alpha}_{ij} = C\frac{1}{\sigma}\left(\hat{\sigma}_{ij}-\alpha_{ij}\right)\dot{\varepsilon}_i - \gamma\alpha_{ij}\dot{\varepsilon}_i + \frac{1}{C}\alpha_{ij}\dot{C} \quad (3)$$

where C and γ are material parameters and $\dot{\varepsilon}_i$ is the equivalent strain rate defined as:

$$\dot{\varepsilon}_i = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}} \quad (4)$$

It is crucial to perform an identification of the parameters used to describe the isotropic and kinematic part of this model. An inverse analysis can be used for this purposes, what is described in the chapter 4 of the paper.

3. NUMERICAL ANALYSIS

The cyclic tests of torsion, three point bending, and tension/compression are commonly used to investigate the Baushinger effect and to analyse the material behaviour upon strain reversals (Fig. 3). Numerical models of all these tests were created in the present work and analysed for further application during the inverse analysis. All these numerical models are based on the commercial finite element Abaqus Standard software. At this stage of the research, the parameters of the isotropic part, as well as kinematic part were taken from the literature [9].

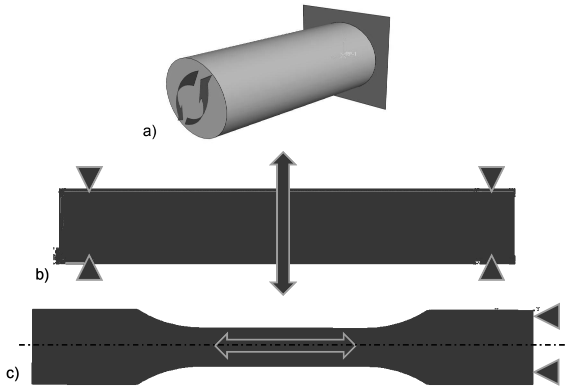

Fig. 3. Ilustration of the cyclic torsion (a), three point bending (b) and cyclic tension/compression (c) tests.

In order to demonstrate the importance of the selection of the appropriate hardening model, the comparison between the results obtained from the isotropic and combined models is presented.

The first case is the 3D cyclic tension/compression test, the sample was deformed in ten cycles. The die translation with the amplitude of 0.2 mm and frequency of 1 Hz was introduced into the FE software to realize this cyclic deformation. The results obtained from the two models, isotropic and combined, are compared in Figs. 4 and 5.

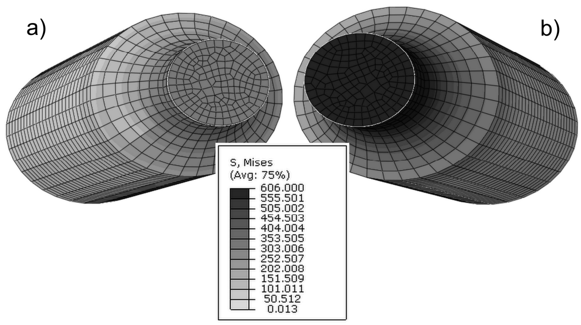

Fig. 4. Stress distribution obtained for the isotropic (a) and combined (b) models.

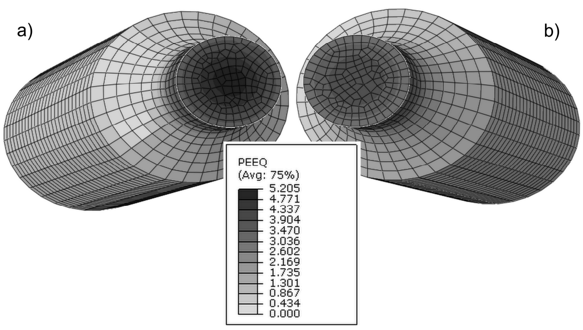

Fig. 5. Strain distribution for the isotropic (a) and combined (b) models.

As it is seen in Figs. 4 and 5, model with the combined hardening rule gives different values of strains and stresses, despite the fact that the process conditions were exactly the same in both cases. This behavior is a natural outcome from the fact that the isotropic hardening model neglects influence of the Bauschinger effect.

The second set of simulations was focused on cyclic torsion deformations only. In this simulation comparison between both models is also considered. Again ten cycles of loads were considered. It can be observed in Figs. 6 and 7 that the maximal stress and strain values occur at the circumference of the sample.

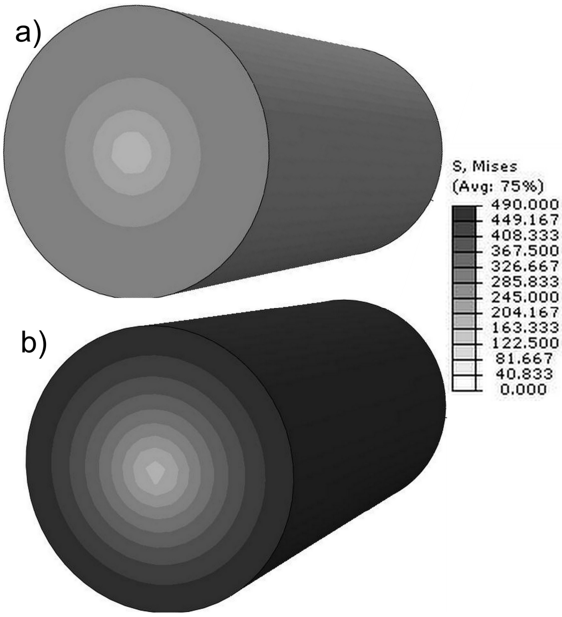

Fig. 6. Stress distribution in cyclic torsion in a) isotropic and b) combined models.

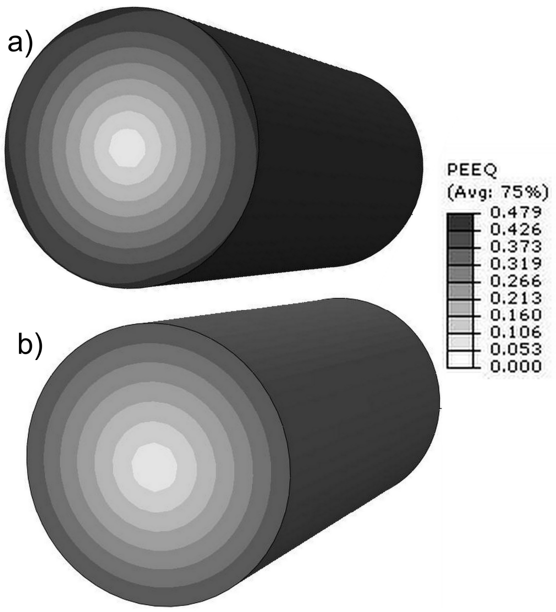

Fig. 7. Strain distribution in cyclic torsion – in a) isotropic and b) combined models.

It is also important to notice that in the centre of the sample the material remains in the elastic region. This observation is important for the industrial processes, where low cyclic deformations play crucial role, i.e. during deformation of the sheet/flat materials. Thus, another plastometric test that involves flat samples was selected to further investigate this phenomenon. The three point bending of the rectangular sample, which accurately describes behavior of the sheet/flat materials under deformation, was considered.

Comparison between both models obtained after tenth cycle are presented in Figs. 8 (stresses) and 9 (strains). In this case the displacement of the dies located in the center of the sample was assumed to be ± 2 mm. A clear distinction between the elastic and plastic regions is observed again. The centre of the sample remains in the elastic region even after tenth cycle. The regions close to middle part of the sample near the surface are characterized by significantly higher values of accumulated strains, as it is seen in Fig. 9.

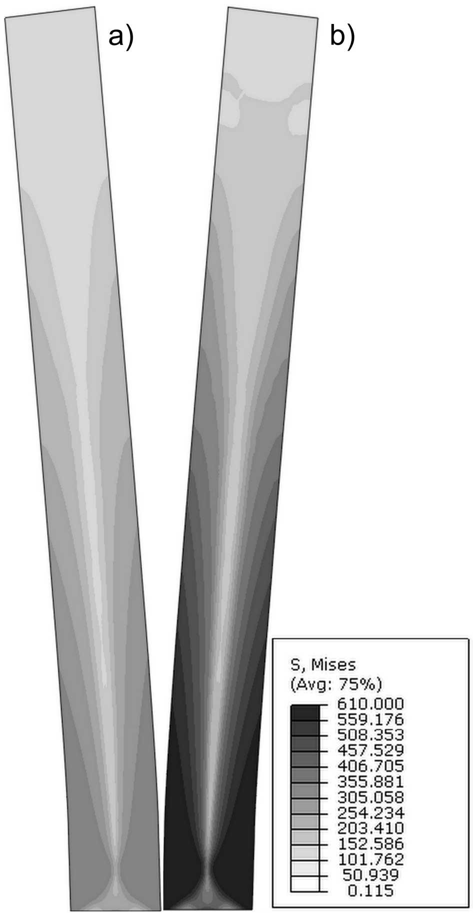

Fig. 8. Stress distribution in model with a) isotropic and b) combined hardening after ten deformation cycle.

In ordered to apply the discussed models to describe material behaviour in industrial conditions, their parameters have to be accurately identified. One of the possibilities is to use an inverse analysis [13].

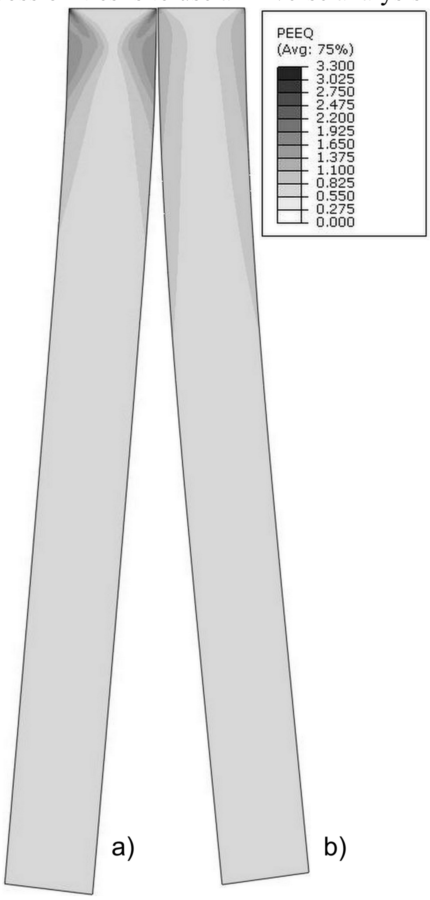

Fig. 9. Strain distribution in model with a) isotropic and b) combined hardening after ten deformation cycles.

4. INVERSE ALGORITHM

The inverse analysis is a method that eliminates an influence of disturbances occurring in plastometric tests and that allows identification of hardening model parameters independently of these disturbances. The idea is to combine experimental results with the finite element analysis and optimisation algorithms.

The inverse analysis was governed using a script that was written in Python scripting language. Python was chosen due to its capability to direct control of Abaqus models and output files. The optimisation process based on the results from experimental work was carried out in the loop until the goal function has been minimized. First, the initial hardening model parameters were chosen and introduced into Abaqus. Then Abaqus job was run and load-displacement data were taken out from the output file. The error between calculated and experimental data was calculated:

$$\Phi(\mathbf{x}) = \sqrt{\sum_{i=1}^{n} \left[\frac{F_{im} - F_{ic}(\mathbf{x})}{F_{im}} \right]^2} \quad (5)$$

where: F_{im}, F_{ic} – measured and calculated loads, n – number of sampling points in the load measurements, **x** – vector with parameters of the material model.

If the minimum of the goal function was not reached, the optimisation simplex technique was used and a new set of the model parameters was obtained and implemented into Abaqus and new job was run with the updated input. When the minimum of the goal function was satisfied, a set of the model parameters was obtained and the analysis was finished. Schematic illustration of the inverse algorithm is presented in Fig. 10.

Two of the discussed earlier plastometric tests are considered for the purposes of the inverse analysis: the cyclic three point bending and the tension/compression tests. Initial results obtained from the cyclic tension/compression test are presented in this paper. It is essential to properly select displacement values during the experiments, to avoid problem with the necking and buckling.

The comparison of the load-displacement curves obtained after four cycles from the experiment and after inverse analysis (112 iterations) is presented in Fig. 11. As it is seen in this figure there are still some discrepancies between the calculated and the experimental loads. These discrepancies are particularly large during the first compression stage. In the future, more advanced optimisation techniques will be applied, that should solve the problem of locking the solution in the local minima and improve the accuracy of the solution.

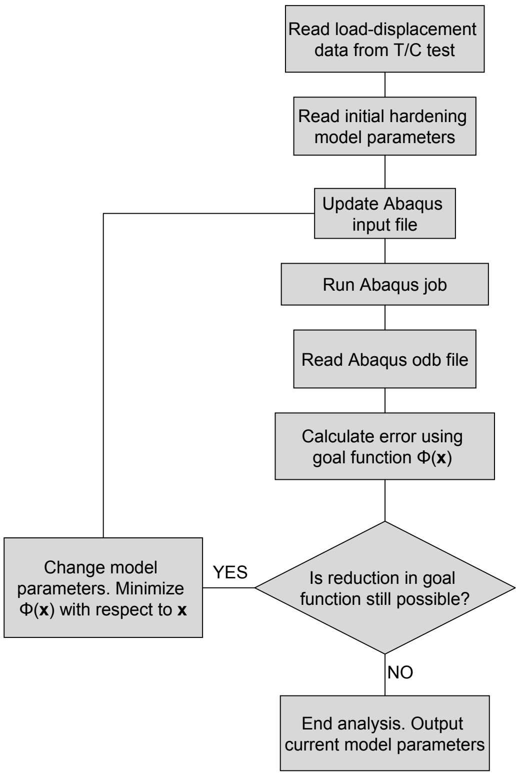

Fig. 10. Schematic flow chart of the inverse procedure used for identification of the model.

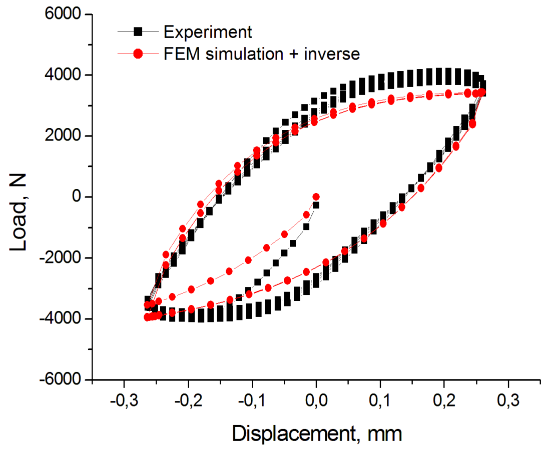

Fig. 11. Comparison of the results of the numerical experiment and the inverse analysis.

5. CONCLUSIONS

An appropriate hardening model, which accounts for the phenomena that are crucial for particular deformation process, is needed to create a reliable numerical FE model for industrial applications. An identification of the parameters of the selected model is another important issue.

The combined isotropic - kinematic hardening law that takes into account the Bauschinger effect was investigated in various plastometric tests. Results obtained from the tension/compression, torsion and three point banding test reveal weak points of the separate isotropic model and kinematic hardening model and confirm necessity of using appropriate combined hardening model.

Based on the performed analysis of the torsion and three point bending tests, regions where material remains in the elastic region during low cyclic deformation were identified. These simple numerical tests provide valuable information that helps engineers to design real industrial processes and solve problems that can appear.

A proper determination of parameters in the cyclic hardening models for selected materials, based on the experimental data, was the second goal of this work. Inverse algorithm, which combined with the three point bending experiments allows to reach this goal, is proposed in the paper. Initial parameters of the combined hardening model were identified but the accuracy was not satisfactory. Further work to obtain better agreement between numerical and experimental results has to be performed.

The better understanding of the cyclic behaviour of materials will enable creation of more robust numerical models of the low cyclic plastic deformation. This is essential for predicting inhomogeneities occurring during deformation with strain path changes.

ACKNOWLEDGEMENTS

Financial assistance of MNiSW, project SPB 22.22.110.7014, is acknowledged. One of the authors (LM) is grateful for the financial support of the Foundation for Polish Science within the Start program.

REFERENCES

[1] Bochniak, W., Korbel, A., *KOBO type forming forging of metals under complex conditions of the process*, Journal of Material Processing Technology, 134, 2003, pag. 120-134;

[2] Chaboche, J.L., Dang-Van, K., Cordier, G., *Modelization of the strain memory effect on the cyclic hardening of 316 stainless steel*, SMIRT-5, Division L., Berlin, 1979;

[3] Davenport, S.B., Higginson, R.L., *Strain path effects under hot working: an introduction*, Journal of Material Processing Technology, 98, 2000, pag. 267-291;

[4] Korbel, A., Bochniak, W., *The structure based design of metal forming operations*, Journal of Material Processing Technology, 53, 1995, pag. 229-237;

[5] Lemaitre, J., Chaboche, J.L., *Mechanics of Solid Materials*, Cambridge University Press, 1990;

[6] Madej, L., Hodgson, P.D., Pietrzyk, M., *The validation of a multi scale rheological model of discontinuous phenomena during metal rolling*, Computational Material Science, 41 , 2007, pag. 236-241;

[7] Madej, L., Weglarczyk, S., Grosman, F., *Numerical modeling of bulk metal forming processes with induced strain path change*, Computer Methods in Materials Science, 9, 2009, pag. 234-240;

[8] Mroz, Z., *On the description of anisotropic work-hardening*, Journal of the Mechanics and Physics of Solids, 53, 1967, pag. 163-175;

[9] Muszka K., Perzynski K., Madej L., *Application of the cyclic plasticity hardening law to metal forming*, Computer Methods in Materials Science, 8, 2008, pag. 165-170;

[10] Pietrzyk, M., Madej, L., Szeliga, D., Kuziak, R., Pidvysotskyy, V., Paul, H., Wajda W., W., Rheological Models of Metallic Materials, in: *Polish Metallurgy at the Beginning of XXI Century*, ed., Swiatkowski K., Komitet Metalurgii PAN, Krakow, 325-346, 2006;

[11] Szeliga D., Pietrzyk M., *Testing of the inverse software for identification of rheological models of materials subjected toplastic deformation.* Archives of Civil and Mechanical Engineering, 7, 2007, pag. 35–52;