

METAL FORMING PROCESSES CONDITIONED BY CYCLIC LOADING. A NEW CHALLENGE FOR THE THEORY OF PLASTICITY

Zenon Mróz*, Ryszard B. Peçherski**

* Polish Academy of Sciences, IPPT PAN, Swietokrzyska 21, Pl 00-049 Warszawa, Poland

** IPPT PAN, Department of Mechanics of Materials and Biomechanics/
Cracow University of Technology, Institute of Structural Mechanics, Warszawska 24,
PL 31-155 Kraków, Poland

Summary Since early works of cyclic plasticity, it was observed that stress-strain cycles of large amplitude imposed on the cold-worked specimens of metallic materials produce cyclic softening. Korbel and Bochniak proposed the improvement of a method for plastic forming operations conditioned by cyclic loading. The experimental investigations led to the identification of shear banding as the basic mechanism responsible for plastic softening. A new approach to the theory of plasticity describing the discussed above phenomena is proposed and an example illustrating its predictive power is presented. In particular, the parameters controlling cyclic loading under torsion: the amplitude of the cycle and its frequency are related with the microscopic model of shear banding.

Since early works of cyclic plasticity, it was observed that stress-strain cycles of large amplitude imposed on the cold-worked specimens of copper, steel, and aluminum alloy produce cyclic softening [1]. It was also reported that the length of the specimen increases during cyclic loading while subjected to combined tension and torsion, with the axial load maintained constant and with the alternating torque [2]. One of first attempts of the theoretical description of this phenomenon, called recently ratchetting, was proposed in [3]. Due to the importance of the latter phenomenon for the prediction of the risk of failure of structures subjected to repeated loads the cyclic plasticity theory was developed. On the other hand, the search for the applications of controlled cyclic torsion [2] for the reduction in load during the processes of drawing of copper and extrusion of lead was reported [4]. It transpired, however, that the problem is far to be solved and that the understanding of the process with cyclic strain path change requires further experimental and analytical study.

The effects of the change of strain path on the reduction of load in elementary tests of tension or compression as well as in the processes of drawing, extrusion, rolling and forging have been studied for two decades by Korbel and Bochniak [5, 6, 7]. The systematic experimental investigations, related with microstructural analysis and physical interpretation of the phenomenon, led to the identification of patterned distribution of shear banding as the basic mechanism responsible for plastic softening. Due to this observation, the search for the new energy-saving plastic forming processes of metallic materials resulted in several patents for the improvement of method for plastic forming operations conditioned by cyclic loading, called KOBO Type Forming [7]. In order to make the new operations more efficient and suitable for industrial implementations, one needs to optimize the considered forming process. This requires modelling and simulating numerically the process. The key point, which is necessary to execute this task, is the knowledge of constitutive description of material behaviour during forming operation with the cyclic change of loading scheme. The plastic flow law accounting for the effects of shear banding with the application of Armstrong-Frederick model of non-linear kinematic hardening for the approximation of the generic micro-shear banding surface was presented in [8]. However, proper understanding of the phenomenon of material softening during plastic flow, conditioned by cyclic loading with a particular amplitude and frequency, remains an unsolved and challenging problem in the recent theory of plasticity.

Our aim is to study this problem from the point of view of cyclic plasticity accounting for multiscale description of shear banding. A new approach to the theory of plasticity describing the phenomena discussed above is proposed and an example illustrating its predictive power is presented. In particular, the parameters controlling cyclic loading under torsion: the amplitude of the cycle and its frequency are related with the microscopic model of shear banding. Our task is to predict and give an assessment of the optimal ranges of these parameters from the point of view of required plastic softening.

The available results of metallographic observations reveal that in heavily deformed metals, or even at small strains if they are preceded by a change of deformation path, a multiscale pattern of shear localization modes progressively replaces the crystallographic multiple slip or twinning. Different terminology is used depending on the level of observation. The term micro-shear band is understood as a long and very thin (of order 0.1 μm) sheet-like region of concentrated plastic shear crossing grain boundaries without deviation and forming a definite pattern in relation to the principal directions of strain. It bears very large shear strains and lies in a “non-crystallographic” position. It means that micro-shear bands are usually not parallel to a particular densely packed crystallographic plane, of conventionally possible active slip system, in the crystallites they intersect. This change of deformation mode produces plastic softening. The experimental observations reveal the time and spatial organisation of dislocations and the resulting hierarchy of plastic slip processes: from coplanar

dislocation groups moving collectively along active slip systems, through slip bands to coarse slip bands, which may further transform into transgranular micro-shear bands and form clusters (packets) of micro-shear bands of the thickness of order $(10\div 100)\ \mu\text{m}$. At this level of observation, the clusters can be considered as elementary carriers of plastic strain, cf. Fig.1. It appears that the successive generations of active micro-shear bands competing with the mechanism of multiple crystallographic slips are responsible for the process of advanced plastic flow. Basing on this observation, a new description of shear banding contribution to plastic flow is proposed. The developed microscopic model of shear banding is implemented into the macroscopic model of cyclic plasticity [9]. The “lifetime” $\Delta\tau$ of the cluster of active micro-shear bands is related with the frequency of cyclic loading and the amplitude of the cycle is estimated, in terms of accumulated energy, by means of plastic shakedown theorems and the analysis of the transition from plastic shakedown to ratchetting. The nonlinear hardening rule implicitly introduces the second limit surface corresponding to the saturation of micro-stresses, which is correlated in our study with massive formation of micro-shear bands.

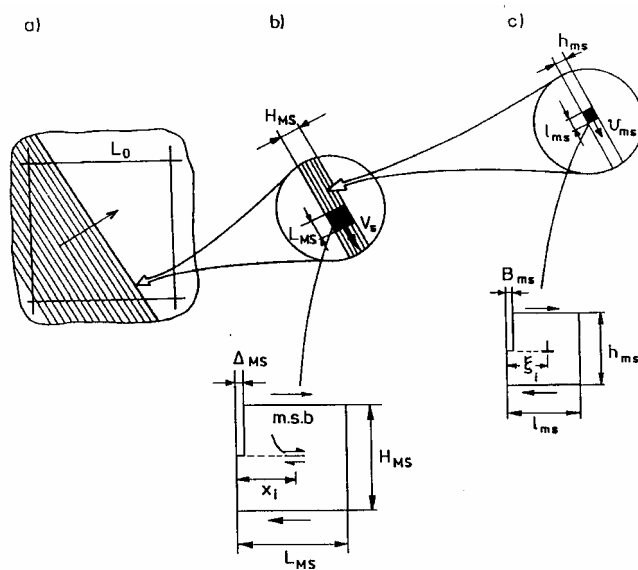


Fig. 1. Schematic view of the multiscale system of shear banding: a) The RVE of the dimension of $L_0 \approx 1\ \text{mm}$ traversed by the region of shear banding progressing in the direction pointed by the arrow. b) The cluster of active micro-shear bands with the active zone of the thickness $H_{MS} \approx (10\div 100)\ \mu\text{m}$ and the width L_{MS} being of the same order. Beneath, the fundamental mechanism of plastic shear strain generated by the active micro-shear bands operating within the active zone during their “lifetime” $\Delta\tau$, and producing the total displacement Δ_{MS} is depicted. c) The active zone of a single micro-shear band of the thickness $h_{ms} \approx 0.1\ \mu\text{m}$ and the width l_{ms} of the same order with the picture of an elementary dislocation model of plastic shear in the active zone.

Particular examples were calculated, for the case of cyclic torsion superposed upon steady tension or compression, to illustrate the relation of the parameters of micro-shear banding model with the frequency of cyclic loading and the amplitude of the cycle. The optimal ranges of these parameters from the point of view of required plastic softening were estimated. Our analysis shows that such phenomena as ratchetting and plastic softening, which can appear dangerous in cyclically loaded structures, do play beneficial role in suitably designed manufacturing processes.

References

- [1] D.S. Dugdale, Stress-strain cycles of large amplitude, *J. Mech. Phys. Solids*, **7**, 135-142, 1959.
- [2] L.F. Coffin, Jr.: The stability of metals under cyclic plastic strain, *J. Basic Eng.*, **82 D**, 671-682, 1960.
- [3] Z. Mróz, An attempt to describe the behavior of metals under cyclic loads using a more general workhardening model, *Acta Mech.*, **7**, 199-212, 1969.
- [4] L.X. Kong, L. Lin, P.D. Hodgson, Material properties under drawing and extrusion with cyclic torsion, *Matl. Sci. Engng.*, **A308**, 209-215, 2001.
- [5] J.D. Embury, A. Korbel, V.S. Raghunathan, J. Rys. Shear band formation in cold rolled Cu-6% Al single crystals, *Acta Metall.*, **32**, 1883-1894, 1984.
- [6] A. Korbel, W. Bochniak, The structure based design of metal forming operations, *J. Matl. Proces. Technology*, **53**, 229-236, 1995.
- [7] A. Korbel, W. Bochniak, KOBOType Forming: forging of metals under complex conditions of the process, *J. Matl. Proces. Technology*, **134**, 120-134, 2003.
- [8] R.B. Peçherski, Macroscopic effects of micro-shear banding in plasticity of metals, *Acta Mech.*, **131**, 203-224, 1998.
- [9] Z. Mróz, H.P. Shrivastava, R.N. Dubey, A non-linear hardening model and its application to cyclic loading, *Acta Mech.*, **25**, 51-61, 1976.