Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 1 (2009) 75–78
Procedia Engineering
www.elsevier.com/locate/procedia

Mesomechanics 2009

A virtual crystal plasticity simulation tool for micro-forming

S Wang[a], W Zhuang[b], D Balint[a] and J Lin[a,*]

[a]*Department of Mechanical Engineering, Imperial College, Exhibitiion Road, South Kensington, London SW7 2AZ*
[b]*College of Automobile Engineering, Jilin University, Changchun 130022, PR China*

Received 27 February 2009; revised 15 April 2009; accepted 17 April 2009

Abstract

The trend of increasing miniaturization of varied products and devices with a wide range of applications necessitates the forming of metallic parts with dimensions at the micron scale. In micro-forming, the stress and deformation are highly anisotropic. Hence, conventional macro-mechanics models fail to capture the important features, such as necking and bending resulting from strain localization. In this paper, a virtual integrated micro-mechanics simulation tool is presented, that was developed within the framework of Crystal Plasticity (CP) theory. With this tool, a polycrystalline Finite Element (FE) model was produced by introducing grain size, orientations and distribution patterns using VGRAIN software. ABAQUS software was used and the CP constitutive equations were implemented through a user-defined material subroutine, VUMAT. Typical micro-forming processes simulated include tension, extrusion and hydro-forming to demonstrate the effectiveness of the integrated simulation system. Finally, a map is proposed that establishes bounds of appropriate usage for different modeling techniques, namely a macro-mechanics plasticity model and a micro-mechanics crystal plasticity model, which will be useful to engineers in the metal forming industry in choosing suitable simulation tools.

Keywords: Crystal Plasticity (CP); Finite Element (FE) Analysis; Polycrystal; Micro-Forming

1. Introduction

In order to have effective metal forming processes for producing miniaturized components, appropriate design and predictive tools for simulating plastic flow of ultra-thin materials during forming are needed. The materials are usually polycrystalline in nature with dimensions on the order of microns or less. Experimental evidence, e.g. [1], indicates that the grain size exerts a dominant influence on the mechanical behavior of polycrystalline metals and alloys at these scales, which highlights the need for an efficient tool to characterize the microstructures of polycrystalline materials and correlate that with mechanical behavior via advanced constitutive relationships.

In conventional metal forming design, material deformation is usually assumed to be isotropic. Such a treatment is inappropriate for the deformation of micro-components, which is dominated by local deformations. Hence, new models are needed for micro-components that account for the heterogeneity of deformation at the micro-scale. The

* Corresponding author. Tel.: +44-0207-594-7082; fax: +44-0207-594-7017.
E-mail address: j.lin@imperial.ac.uk.

doi:10.1016/j.proeng.2009.06.020

Crystal Plasticity Finite Element (CPFE) method has been widely accepted as a valid tool for investigating the plastic deformation behavior of single crystals [2-4]. However, most present CPFE models use grains with regular geometric shapes that do not reflect the actual, complex grain structure of the material. A more physically realistic integrated framework is necessary to tackle the problem of micron-scale metal forming in a systematic way.

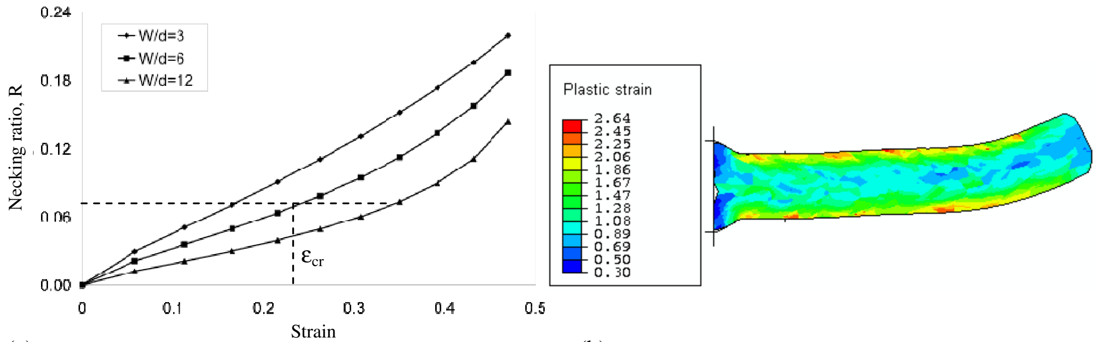
In this paper, a virtual integrated numerical simulation tool is introduced to investigate the mechanical behavior of micro-components and miniatures within the framework of Crystal Plasticity (CP) theory. Model studies were carried out for extrusion, hydro-forming and tension of micro-components to demonstrate the effectiveness of the integrated simulation system in capturing small-scale deformation features. Finally, a map is constructed from the tension results to identify regimes of appropriateness for macro-mechanics modeling techniques and the micro-mechanics CPFE model. Such a map could help engineers choose a suitable tool for micro-forming applications.

2. Integrated virtual crystal plasticity tool for micro-forming simulation

An integrated virtual crystal plasticity simulation tool has been developed [5]. The system comprises three parts: (i) a polycrystalline micro-mechanics FE model created by VGRAIN software, including specifications for grain size, orientation and their distribution; (ii) Crystal Plasticity (CP) theory to represent the mechanical behavior of the individual grains, with displacement compatibility between grains, based on the pioneering work of Taylor [6], Hill and Rice [7] and Asaro [8], and implemented using an ABAQUS user-defined material subroutine VUMAT; (iii) analysis and post processing using ABAQUS software. It should be noted that an explicit finite element calculation can be easily partitioned for solving by a number of processors. Vectorization was preserved in the writing of the VUMAT subroutine so that optimal processor parallelization could be achieved. This is important for the simulation of metal forming processes, which involve multi-component interactions

3. Case studies

In this section, several typical micro-forming processes are simulated: extrusion, hydro-forming and tension. The material used is 316 stainless steel, which has a face-centered cubic crystal structure. For all the case studies, the geometry is a thin micro-film with grain structure generated by VGRAIN software. Six different simulations with randomly generated grain patterns having the same average grain size and distribution were carried out for each study so that statistical variations could be quantified. Only a brief analysis of the deformation behavior is given here; for further details, see e.g. [9,10].



(a) (b)

Fig. 1. (a) Necking of a micro-film under tension; (b) Curving of an extruded micro-pin.

3.1. Tension of micro-films and the effect of grain size upon necking

Necking is a typical feature in micro-forming. In order to quantify the extent of necking in simulations of uniaxial tension, a necking parameter is defined as $R = (W_{max}-W_{min})/W$, where W_{max} and W_{min} are the maximum and minimum dimensions of the micro-film in the lateral direction, and W is the original width. A critical strain, ε_{cr}, is defined as the strain level when a specified amount of necking takes place, i.e. when the necking ratio achieves a predefined critical value. Fig. 1a shows the relationship between the applied strain and the necking ratio R, for three different values of the ratio of initial micro-film width to average grain size. It can be observed that necking increases with the applied strain, and also that increasing the number of grains through the film width (or, reducing the average grain size) reduces the extent of necking significantly. Hence, for a micro-film with a given width it is found that necking is a function of both the strain and the average grain size (or, the number of grains through the width). For a given degree of necking, a critical strain can be identified as shown in Fig. 1a. Predicting the maximum permissible strain such that necking is kept below a given threshold could be very important in micro-forming design.

3.2. Extrusion of micro-pins

It has been found [11] that the quality of extruded micro-pins is significantly affected by the grain size and the grain orientation distribution, or texture, of the billet material. For micro-extrusion of pins from a billet having a large grain size (e.g. 211 μm), the pin curves to one side or another; this trend is fairly repeatable. However, when the billet has a smaller grain size (e.g. 32 μm), this behavior is not observed. Since a conventional FE method cannot predict this phenomenon, a CPFE model was used to investigate the problem. In the simulation, the micro-pin is 0.57 mm in diameter with an average grain size of 211 μm, i.e. there are approximately 2 to 3 grains across the diameter of the extruded micro-pins.

Fig. 2b shows virtual extrusion of a micro-pin with contours of cumulative resolved plastic shear strain. The figure shows that curving of the pin is predicted by the CPFE simulation as in the experiment for the 211 μm grain size case. This further demonstrates the ability of the virtual CPFE simulation tool to reproduce grain size effects in micro-forming. The pin curving observed is a result of strain localization. Fig. 2b shows that the maximum cumulative shear strains occur at the free surfaces, and minimum values occur at the grain boundaries (which roughly coincide in this case with the centerline of the pin). This is caused by displacement compatibility between grains having different lattice orientations, which tends to inhibit shear in the vicinity of grain boundaries; at the free surfaces, no such displacement compatibility condition exists, making plastic shear straining occur more freely.

3.3. Hydro-forming of micro-tubes

Hydro-formed micro-tubes with wall thickness of 30-50 μm are commonly used in electronic and medical devices. In tubes this thin, there are only a few grains through the thickness, which leads to local thinning during forming. Thinning is directly related to the ratio of wall thickness to grain size of the material, and also the extent of deformation. The CPFE modeling technique was also employed for this investigation. Only a quarter section of the micro-tube is considered in the simulation, with an average of about 1 to 2 grains through the thickness.

Fig. 2a shows the profile of the hydro-formed tube section and the distribution of von-Mises stress. It can be clearly seen that the stress distribution is directly related to the grain orientations, and the wall thickness of the formed tube is not uniform. Significant thinning (necking) of the tube is apparent; the necking ratio as defined in Section 3.1 is approximately 29%. These features cannot be captured using traditional continuum FE simulations.

4. Effect of the ratio of film width to average grain size on critical strain and necking ratio

As previously stated, for a given film width the extent of necking is a function of both strain and the average grain size. Fig. 1a shows that the critical strain increases with the level of allowable localized necking. If a simulation (say, uniaxial tension) is to be performed to a given level of strain, the amount of necking predicted by CPFE must be considered allowable in order for macro-mechanics FE, which cannot capture necking, to be appropriate. Otherwise, CPFE must be used. A map that dictates regimes of appropriateness for macro-mechanics FE and CPFE, as well as the amount of strain that a component can undergo in actual micro-forming given a level of acceptable necking, can be obtained from the data in Fig. 1a. Such a map is shown in Fig. 2b, which suggests when deformation size effects become significant, and which modeling technique to use in simulating micro-forming. If, for example, R = 3% is the limiting acceptable value of necking for a certain design, the corresponding maximum allowable axial strain can be identified from Fig. 2b for a micro-film given its width and average grain size.

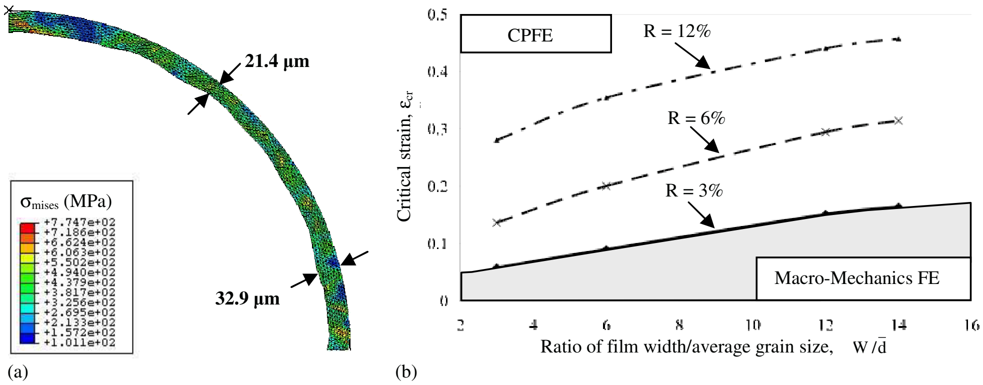


Fig. 2. (a) Hydro-forming of a micro-tube; (b) Map showing regimes of appropriateness for micro- and macro-mechanics FE.

5. Conclusions

An integrated micro-mechanics modeling system was developed to simulate micro-forming processes. The constitutive behavior of the workpiece was described by the theory of Crystal Plasticity and implemented using ABAQUS software. Typical size effects were predicted: necking of micro-films, curving of extruded micro-pins and thinning of hydro-formed micro-tubes. Lastly, a map was constructed from the data to help engineers choose a suitable tool for micro-forming applications.

References

1. Fleck NA, Muller GM, Ashby MF and Hutchinson JW. Strain gradient plasticity: theory and experiment. *Acta Metallurgica et Materialia* 1994;**42(2)**:475-487.
2. Roters F. Application of crystal plasticity FEM from single crystal to bulk polycrystal. *Computational Materials Science*. 2005;**32**:509-517.
3. Harewood FJ and McHugh PE. Comparison of the implicit and explicit finite element methods using crystal plasticity. *Computational Materials Science*. 2007;**39**:481.
4. Harewood FJ and McHugh PE, Modeling of size dependent failure in cardiovascular stent struts under tension and bending. *Annals of Biomedical Engineering*. 2007:**35(9)**;1539-1553.
5. Cao J, Zhuang W, Wang S, Ho KC, Zhang N, Lin J and Dean TA. An integrated crystal plasticity FE system for microforming simulation. *Journal of Multiscale Modelling*, 2009;**1(1)**:107-124.
6. Taylor, GI. Plastic strain in metals, *J. Inst. Met.* 1938;**62**:307–324.
7. Hill, R, Rice, JR. Constitutive analysis of elastic-plastic crystals at arbitrary strain, *J. Mech. Phys. Solids.* 1972;**20(6)**:401–413.
8. Asaro, RJ. Crystal plasticity, J. Appl. Mech. 1983;**50**:921-934.
9. Zhuang W, Wang S, Cao J, Lin J and Hart C. Modelling of localised thinning features in hydroforming of micro-tubes using crystal plasticity FE method. Int. Journal of Advanced Manufacturing Technology.
10. Wang S, Zhuang W, Balint DB and Lin J. A crystal plasticity study of the necking of micro-films under tension. *Journal of Multiscale Modelling(Accepted).*
11. Krishnan N, Cao J, Kinsey B, Parasiz SA and Li M. Investigation of deformation characteristics of micropins fabricated using microextrusion. *Paper IMECE05-81511 of the Proce. IMECE 2005: ASME Int. Mechanical Engineering Conference and Exposition*, 2005, Nov., 5-11, Orlando, FL.