A material model suitable for micro forming

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A Material Model Suitable for Micro-Forming

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Introduction

Micro-forming refers to the application of conventional forming processes to manufacture products from ultra-thin sheet materials that have thickness dimensions on the order 50-500 μm. The demand for cost effective manufacturing processes to produce an ever increasing number of miniaturized components for example in the telecommunication, medical and electronic industries requires effective predictive tools to simulate the plastic flow of this ultra-thin material during forming. This necessitates the development of a material model capable of including *material size effects*.

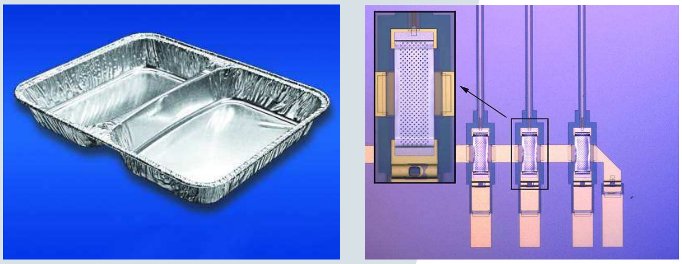

Figure 1 *Two potential applications of microforming at two technological extremes: an aluminum foil container (left), and a micro-electronic device (right).*

Objective

The objective of this research project are to:

- Implement a Strain-Gradient Crystal Plasticity material model [1] that incorporates dislocation hardening into a general purpose FEM framework.
- Experimental validation of the material model with comparisons with laboratory deformed test specimens.

Material Model Description

Material size effects arise as the geometry of the part approaches a characteristic length scale i.e. the thickness approaches the dimensions of the grain size. These size effects are captured in this material model through the inclusion of geometrically necessary dislocations (ρ_{GND}) that accumulate with increasing strain gradients. These dislocations serve two purposes: to increase the slip system hardness, and decrease the effective shear stress on a particular slip system, thereby incorporating work hardening within the model.

In the gradient enhanced single crystal plasticity model, the governing equations, evaluated in the undeformed configuration, are:

$$\nabla_0 \cdot \mathbf{T} = \mathbf{0} \qquad (1)$$

$$\rho^{\xi}_{GND} = \rho^{\xi}_{GND_0} + \mathbf{d}^{\xi\alpha}_0 \cdot \nabla_0 \gamma^{\alpha} \quad \forall \xi \qquad (2)$$

Here $\mathbf{T}$ is the first Piola-Kirchhoff stress tensor, $\rho^{\xi}_{GND_0}$ and ρ^{ξ}_{GND} are the densities of the geometrically necessary dislocations in the initial and the current time step, $\nabla_0 \gamma^{\alpha}$ is the gradient of the slip on slip system α and $\mathbf{d}^{\xi\alpha}_0$ are vectors describing the geometrical relations between the slip system α and ξ. In an FEM context, both the dislocation density and displacement terms are determined at the nodal points, representing 21 degrees of freedom.

Discussion and Future Work

Discretization of the material grain structure into representative finite elements, as shown in Figure 2, allows the calculation of the dislocation densities (ρ_{GND}), slip rates ($\dot{\gamma}^{\alpha}$) and stresses subjected to an arbitrary set of boundary conditions. For a material point subjected to plane-strain tension, the evolution of slip rates on each of the active slip systems within an FCC crystal are plotted in Figure 3, which shows the dependence of the slip system orientation with respect to the load on the relative activation of the 12 FCC slip systems.

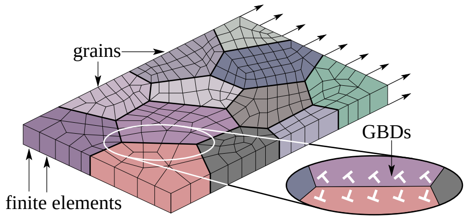

Figure 2 *Representative 3D FEM mesh of a microstructure.*

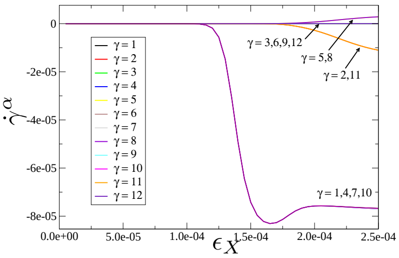

Figure 3 *Evolution of $\dot{\gamma}^{\alpha}$ with axial deformation (ϵ_X) for an arbitrary material point.*

Predictive simulations of micro-forming will require precise calibration of the material constants. This requires detailed comparisons between laboratory scale forming operations with precise knowledge of the initial crystal orientations, dislocation density, and imposed deformation. In-situ tensile testing of such a characterized thin sheet will be carried out, while tracking the evolution of strain and local crystal orientations within a Scanning Electron Microscope.

Conclusion

- Material size dependent behaviour can be incorporated through the inclusion of ρ_{GND}'s.
- FEM implementation of the material model allows the simulation of multi-grained materials.
- Further calibration of the material parameters are required for predictive calculations.

References:

[1] Evers L.P., *Strain Gradient Crystal Plasticity Based on Dislocation Densities*, Ph.D. Thesis TU/e (2003).

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