Conf-9507100--3

LA-UR-95- 1371

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

**DISCLAIMER**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

# Title: Simulation of Sheet Metal Forming Using Polycrystal Plasticity

Author(s): U.F. Kocks, A.J. Beaudoin, T. Koya, H. Uto, P.R. Dawson,
and K.K. Mathur

Submitted to: Plasticity '95
Osaka, Japan
July 17-21, 1995

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

By acceptance of this article, the publisher recognizes that the U.S. government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO. 836 R4
ST. NO. 26295/81

MASTER

# Simulation of Sheet Metal Forming Using Polycrystal Plasticity

**A. J. Beaudoin and T. Koya**
**Reynolds Metals Company**
**Richmond, VA 23219, USA**

**P. R. Dawson**
**Cornell University**
**Ithaca, NY 14853, USA**

**H. Uto**
**Sumitomo Light Metal Ind., Ltd.**
**Minato-Ku, Nagoya 455, Japan**

**K. K. Mathur**
**DeShaw Corporation**
**New York, NY 10036, USA**

**U. F. Kocks**
**Los Alamos National Laboratory**
**Los Alamos, NM 87545, USA**

Polycrystal plasticity theory provides a foundation for the introduction of anisotropy into finite element codes. The computational burden inherent in carrying a detailed microstructural description in each finite element is significant. However, recent advances in computer hardware - as well as the development of software for massive parallel architectures - enable the treatment of practical problems. In this work, experimental results are provided to highlight the effect of anisotropy on different strain paths developed in forming of aluminum sheet. Simulation of the experimental tests is performed for aluminum sheet with varying initial texture. The results of the simulations follow experimental trends.

Key Words: Polycrystal plasticity, Sheet forming, Finite element method

## 1. Introduction

### 1.1 USE OF POLYCRYSTAL PLASTICITY IN FINITE ELEMENT PROCEDURES

The introduction of polycrystal plasticity models into finite element (FE) codes is an active area of research. Current areas of application include: mechanistic treatment of polycrystals, simulations of bulk forming (e.g. rolling and drawing), and the analysis of sheet forming (a survey is given in reference [1]). Evolving computational resources - hardware and software - extend the combined treatment of macrostructure and microstructure from problems of idealized homogeneous deformations to non-uniform deformations typical of industrial processes.

There are practical benefits gained through the use of a micromechanically-based constitutive theory. Polycrystal plasticity models provide a link between the forming characteristics of a material and the texture developed through a prior thermomechanical processing history. The results of the simulations provide valuable information as to desirable (or undesirable) texture components in achieving a target deformation.

### 1.2 INTER-RELATION OF TEXTURE, STRAIN PATH, AND FORMABILITY

For a variety of aluminum alloys, the relation between formability and texture is quite dependent on strain path. For example,

- AA 2036-T4 formability in plane strain correlates inversely with $r_{90}$ (r-value in the transverse direction of the sheet) [2].
- Processing conditions were varied to produce two 5XXX series materials with nearly identical hardening rate (n-value), yield stress, ultimate stress and elongation (as measured using

routine tensile tests, Table I). Formability was evaluated using cup drawing tests (drawing) and punching of a hemispherical dome (stretch). Sheet with higher $r_{90}$ performs better in draw and worse in stretch, as compared to the sheet with lower $r_{90}$.

This experimental data suggests that the selection of an optimal texture must consider the strain path in the target deformation.

Table I - Mechanical properties of 5XXX alloy test materials

| Material | $\sigma_{yield}$ | $\sigma_{ultimate}$ | % elongation | n | $r_{90}$ | drawability | stretchability |
|---|---|---|---|---|---|---|---|
| **1** | 121 MPa | 282 MPa | 34 | 0.35 | **0.59** | 10.6 | 17.6 |
| **2** | 122 MPa | 282 MPa | 33 | 0.34 | **0.82** | 10.9 | 17.2 |

## 2. The Hybrid Finite Element Code

### 2.1 FORMULATION

The hybrid element formulation centers on two residuals [3]. A statement of equilibrium is derived from the traction balance between elements, as

$$0 = \sum_{e} \left[ \int_{B_e} \operatorname{tr}\big(\sigma \operatorname{grad}(\Phi)\big) dV + \int_{B_e} \Phi \cdot \operatorname{div}(\sigma)\, dV - \int_{\partial B_e} \Phi \cdot \boldsymbol{t}\, dA \right] \tag{1}$$

where $\sigma$ is stress, $\Phi$ are weighting functions, $t$ are tractions, $e$ indicates the sum over all elements, and $B_e$ is the element volume. A second residual is formed on the deviatoric stress due to crystal constitutive response

$$\int_{B_e} \Psi \cdot \mathrm{C}[\sigma'] dV = \int_{B_e} \Psi \cdot \boldsymbol{D}'\, dV \tag{2}$$

where C is a (linearized) fourth-order operator describing the constititutive response, $\Psi$ are weighting functions and $\boldsymbol{D}'$ is the deviatoric deformation rate.

When using polycrystal plasticity theory, the macroscale deviatoric stress is derived from the averaged response of the crystal stresses. There are two options for introduction of the crystal stresses in this hybrid formulation. One is to average the stress interpolants arising from Eq. (2) and introduce the average into the discretized form of Eq. (1); the residual Eq. (2) is formed for each crystal in the problem [3]. In this work, we opt for a second possibility and compute the averaged crystal response at each quadrature point and form a single residual of Eq. (2) for each element. In either case, the combination of distinct aggregates in each element with piecewise discontinuous shape functions for the deviatoric stress facilitate concurrent (parallel) computations.

### 2.2 INITIALIZATION OF THE POLYCRYSTAL AGGREGATE

Quantitative texture analysis results in an orientation distribution function (ODF) representing the crystallographic texture. The WEIGHTS program of popLA (preferred orientation package - Los Alamos) may then used to prepare a collection of weighted crystal orientations as a discrete sampling of the ODF. The resulting weights are sorted to identify strong contributors.

### 2.3 IMPLEMENTATION

By virtue of the data parallel nature of both the crystal constitutive calculations and hybrid element formulation, simulations of sheet forming are particularly well-suited to massive parallel architectures. Spectral decomposition of the mesh is used to facilitate iterative solution of the global system of equations. Adherence to Fortran-90, with communications performed through library routines allows for porting of the code (even to workstations). Subsets of the sorted weighted orientation files may be used to customize a problem to the memory and computational resources of a particular target architecture.

## 3. Application

The deformation behaviors of the two 2036-T4 sheet materials described above, and denoted A and B, were simulated. The $r_{90}$ values were 0.97 and 0.49 for A and B, respectively. To achieve a range of strain states of in the sheet, a routine test used to develop forming limit curves was modelled. In this test, a hemispherical punch deforms blanks of three different widths. A narrow blank leads to a state of draw, a full width blank elicits stretching, and an intermediate width gives a plane strain deformation path. In the simulations leading to the plane strain and drawing deformations, the blank was oriented such that the rolling direction lay 90° to the long axis of the specimen; also, the blank was clamped at the ends of its length. For stretching, the blank was clamped along its entire periphery. Identical hardening rules were used for the two types of sheet. Symmetry planes were defined normal to the rolling and transverse directions.

So as to demonstrate the scalability of the computer code, the three deformations were run with different numbers of elements and crystals per element. Simulations for the plane strain and stretch contained 3600 and 3750 elements with 256 and 64 grains per element, respectively. These simulations were carried out on a Thinking Machines CM-5 computer. For the case of drawing, a mesh with 208 elements and 32 crystals per element was used. The resulting problem was run on an IBM Model 3BT RS/6000 workstation.

Shown in Figures 1-3 is the sheet thinning observed in the high and low $r_{90}$ sheets for the three deformation paths. The crystal subsets used in each simulation are displayed as <111> pole figures with rolling direction along the vertical axis. As compared to material B, material A shows a greater degree of thinning in plane strain. In stretch, both materials showed similar degrees of thinning. However, the thinnest region of material A lays along the rolling direction. In contrast, the thinnest regions of material B occured along the transverse direction and 45 degrees to the rolling direction. In Figure 3, a drawing strain shows a trend opposite to that observed in Figure 1: material B thins to a greater degree than material A.

## 4. Discussion

These simulations show that the texture and deformation path interact in sheet forming. Thinning in a part may be accentuated or alleviated by the textural anisotropy in the material. Both the experimental data and simulation results indicate that relative performance in drawing and stretch/plane strain may be reversed due to material anisotropy. The combined use of finite element techniques, crystal plasticity models, and modern computer architectures enable parametric studies. The results of such studies allow one to isolate the texture effects on sheet formability.

## Acknowledgements

Support for A.J. Beaudoin and T. Koya was given by Reynolds Metals Company. Experimental data for the 5XXX and support for H. Uto were provided by Sumitomo Light Metals, Ind. The computer code was developed under the Office of Naval Research grant N00014-90-J-1810. Access to computing resources was provided by the Advanced Computing Laboratory at Los Alamos National Laboratory.

## References

1. Dawson, P.R., Beaudoin, A.J., Mathur, K.K., and Sarma, G., 1994, `Finite element modeling of polycrystalline solids', European Journal of Finite Elements, 3, 543-571.
2. Bryant, J.D., Beaudoin, A.J., and VanDyke, R.T., 1994, `The effect of crystallographic texture on the formability of AA 2036 autobody sheet', SAE Techinical Paper 940161, SAE, Warrendale, PA.
3. Beaudoin, A.J., Dawson, P.R, Mathur, K.K., and Kocks, U.F., 1995, `A hybrid finite element formulation for polycrystal plasticity with consideration of macrostructural and microstructural linking', Int. J. Plast., *in press*.

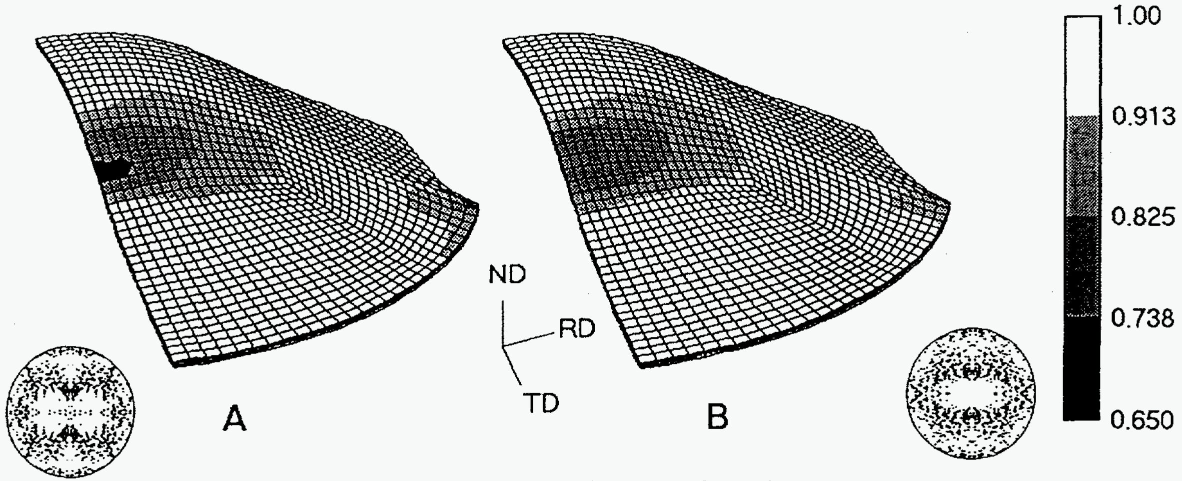

Figure 1 - Plane strain (thickness in mm)

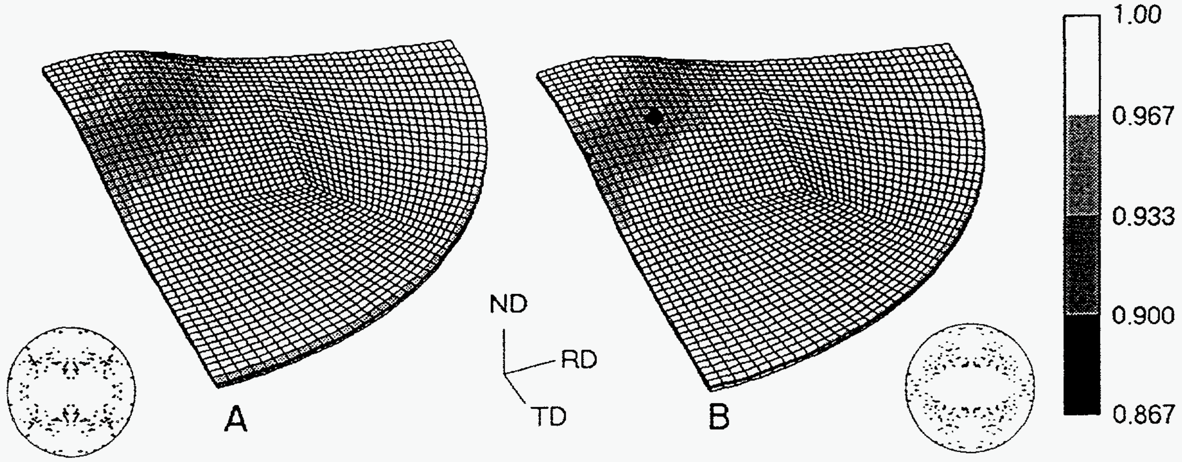

Figure 2 - Stretch (thickness in mm)

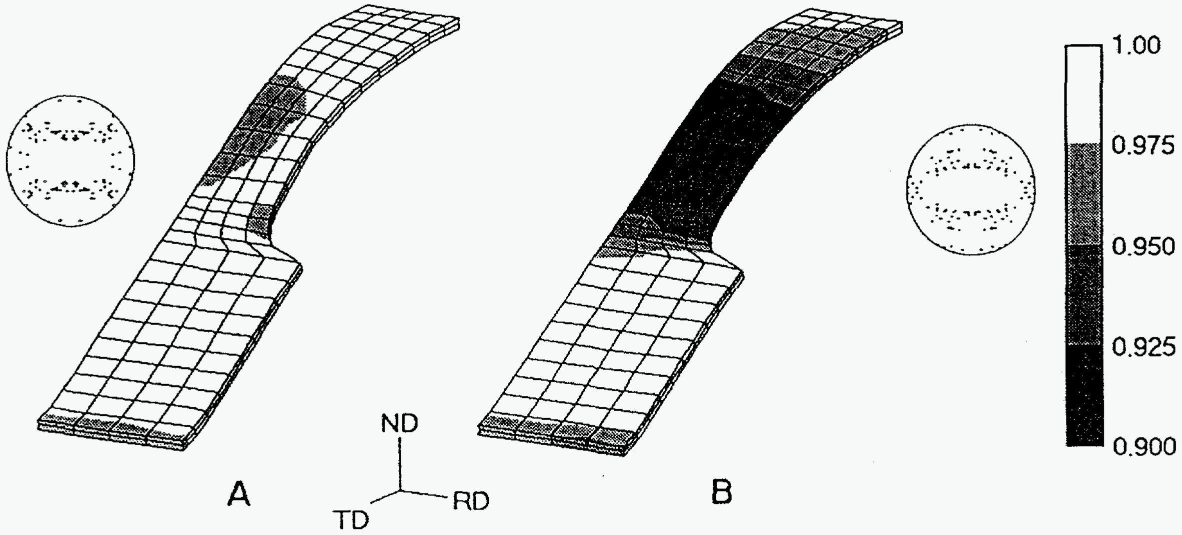

Figure 3 - Plane strain (thickness in mm)