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Forming limits of quasi-static processes

Deep drawing (axisymmetric)

Larger principal value of the Hencky strain in the sheet plane (major strain) versus smaller (minor strain), obtained with the ARGUS-system (GOM) at the IUL, Dortmund

Forming Limit Diagram (FLD)
Extension of forming limits by combination with impulse forming

Extended formability by combination of deep drawing and electromagnetic forming (K. Demir, IUL)
Extension of forming limits by combination with impulse forming

Extended formability by combination of deep drawing and electromagnetic forming (K. Demir, IUL)

Classical Forming Limit Curve is meaningless for combined and dynamical processes
Identification of suitable parameters

\[ I(t) = I_0 e^{\beta t} \cos(\omega t + \varphi) \]

Input parameters for the numerical optimization (example)

Objective function to be minimized:

\[
\min_{\lambda \in \mathbb{R}^n} \frac{1}{\text{meas } S} \int_S |s(\lambda, x) - s_{\text{opt}}(x)|^2 \, dx
\]

s.t. \( \text{dist} \left( (\epsilon_1(\lambda, t), \epsilon_2(\lambda, t)) , \partial F_t (\epsilon_1(\lambda, t), \epsilon_2(\lambda, t)) \right) \geq 0 \)
Process design by mathematical optimization

1. Initial process parameters
   \( p_1^{(0)}, p_2^{(0)}, \ldots, p_n^{(0)} \)

2. Forming Limits als Constraints

3. Optimization algorithm

- Simulation of deep drawing
- Coupled simulation of electromagnetic forming (EMF)

No: Choose new parameters

Sufficiently close to ideal shape?

Yes
1. Coupled simulation of EMF

Weak form of electromagnetic field equation

\[ 0 = \int_R \{ (\dot{a} - L^T a) \cdot a^*_\mathbf{\ast} - \nabla (\chi - a \cdot v) \cdot a^*_\mathbf{\ast} + \mu^{-1}_{\text{EM}} \sigma^{-1}_{\text{EM}} \text{curl} a \cdot \text{curl} a^*_\mathbf{\ast} \} \]

\[ 0 = \int_R \nabla \chi \cdot \nabla \chi^*_\mathbf{\ast} \]

- \( f_L = \det(\nabla \xi) (j \times \text{curl} a) \)
  - Lorentz force
- Joule heating

Weak form of momentum balance

\[ 0 = \int_{B_r} \{ \rho \ddot{\xi} - f_L \} \cdot \xi^*_\mathbf{\ast} + \int_{B_r} K(\nabla \xi)^{-T} \cdot \nabla \xi^*_\mathbf{\ast} \]

- \( \xi, v \) are unknown fields

**Unknown fields**
- \( a \) vector potential
- \( \chi \) scalar potential
- \( \xi \) deformation

Thermo-elasto-viscoplastic electromagnetic material law (Svendsen and Chanda, ‘03, ‘05)
2. Forming limits as constraints

The optimization algorithm has to care that forming limits are not violated.

How can forming limits of combined and dynamic processes be implemented?

1. Damage model
   - universal
   - accurate if well identified
   - expensive evaluation

2. Forming limit surface (FLS)
   - Depending on the process
   - fast computable

Forming limit surface (FLS) for the alloy EN AA-5083
Adapt a mathematical or physical model to experimental data.

Here: Johnsen-Cook type fracture model by Clausen et al. (2004)

\[ \varepsilon_f = (D_1 + D_2 e^{D_3 \sigma^*})(1 + \dot{\varepsilon})^{D_4} \]

with \( D_1, D_2, D_3, D_4 \) parameters, \( \varepsilon_f \) strain at fracture, \( \dot{\varepsilon} \) relative plastic strain rate, \( \sigma^* \) stress triaxiality ratio

Forming limit surface (FLS) for the alloy EN AA-5083
3. The optimization algorithm

**Basic Idea:** Use a method of descent to avoid large numbers of evaluations of the objective function.

The decending step has to be carried out such that relevant forming limits are respected.

**Problem:** Derivatives of both objective function and constrains are required.

Interior Point Method for constrained optimization.

'landscape' of the object function.
The complete algorithm

\[ f(\lambda_1, \ldots, \lambda_k + \Delta_k, \ldots, \lambda_n) - f(\lambda_1, \ldots, \lambda_k, \ldots, \lambda_n) \]

linearisation of objective function

new parameter

simulation of combined forming process

calculate objective function

no

opt?

yes

choose new parameter

generate mesh

ANSYS

+ LS-DYNA

electromagnetic forming: ANSYS and LS-Dyna

mesh generation: ANSYS

IPOPT/SQP

optimization

deep drawing: LS-DYNA

FLS

Numerical Identification of Process Parameters
An example

**Given Data**
- Sheet metal diameter: 130 mm
- Sheet metal thickness: 1 mm
- Drawing distance: 55 mm
- Drawing radius: 10 mm
- Blank holder force: 300 kN
- Work piece material: EN AA-5083
- Punch bottom radius: 20 mm
- Friction in the flange region: $\mu = 0.04$
- Ansatz for coil current: $I(t) = I_0 e^{\beta t} \cos(\omega t + \varphi)$
- Phase angle: $\varphi = -1.35381 \text{ rad}$
- Damping parameter: $\beta = -15467.3 s^{-1}$

**Finite Element mesh of the work piece**
- Number of Elements: 1780 in 5 layers
- Shape of elements: quadratic

**Simulation of EMF**
- Time step size: 1 $\mu$s
- Number of time steps: 55
- Coupling: sequentially

**Identified values**
- Amplitude: $I_0 \approx 110\,000$ A
- Angular frequency: $\omega \approx 3.8485 \cdot 10^5 \text{s}^{-1}$
Efficiency, accuracy and robustness

Controlling the algorithm

• Adapt mesh size in FE-simulation to duality gap of the optimization

• Apply trust-region type method on objective function

• Adaptive choice of the model for the constraints (FLS vs. damage model)

Derivatives

• Numerical linearization facilitates application to new problems

• However, required number of evaluations is increased

• Sometimes non-physical solutions have to be excluded by additional constraints
• Constrained numerical optimization has a potential to support the design of new forming processes

• In case of deep drawing with subsequent calibration by EMF, process chains depending on two parameters have sufficiently been identified

• The identified parameters led to extension of quasi-static forming limits

• The algorithmic framework is suitable for problems depending on larger numbers of parameters

• Simultaneous identification of both deep drawing and EMF parameters is possible

• A complete control of material flow is aimed at

• More experimental material data are required

• Many interesting questions on the mechanism of failure at high forming rates arise
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