“Various Approaches to deal with Microstructure in Simulation of Bulk Metal Forming”

Dr. Gerhard H. Arfmann, Dr. Michael Twickler
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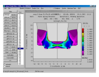
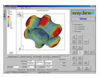
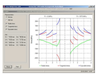
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“Various Approaches to deal with Microstructure in Simulation of Bulk Metal Forming”

Why to determine the microstructure?

The most simple Model: “Pause Time = Recrystallization“

The typical Model: “Dynamic/Static with grain growth“

The complex model: “Dislocation Based Model“

Acknowledgement

Why to determine the microstructure?

Motivation:

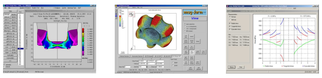
- **most realistic modeling of the forming processes in the Simulation (Material flow, Strain hardening, etc.)**
- **prove of reaching a certain specified grain structure (average grain size, max permitted grain size , etc.)**
- **provide the necessary grain structure information for subsequent further treatment (heat treatment or others)**
- **derivation of product properties**
- **information to support further experimental investigations (i.e. orientation of flow lines for ultra sonic testing)**
- **etc.**

The most simple Model: "Pause Time = Recrystallization"

Basic approach:

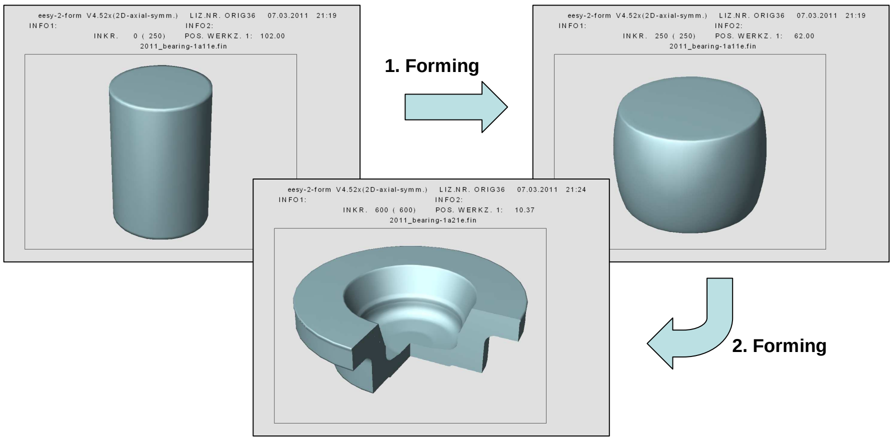
- **sufficiently high temperatures and a least energy brought in by forming result in recrystallization in the part (dynamic, static)**
- **the recrystallization reduces the deformation that is already in the part**
- **the local temperature and strain are always sufficient to enable recrystallization**
- **the pause time (transport of the part) is always sufficient to allow for complete recrystallization**
- **complete recrystatization is identical with complete reset of any deformation that is already in the part**
- **dynamic recrystallization during the forming will have no effect to the material properties nor to the material flow**

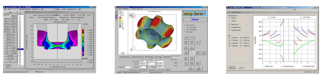
End of forming = Pause time = Complete recrystallization



The most simple Model: "Pause Time = Recrystallization"

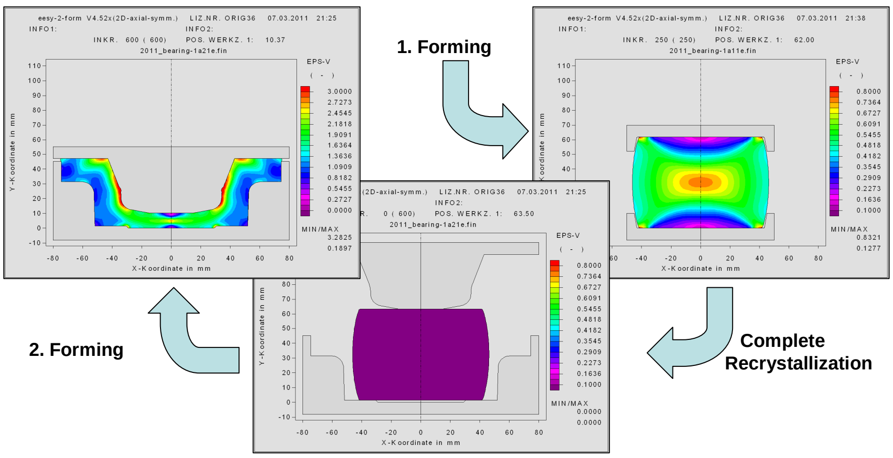
Example: Bearing Shell, 2-Step Forming at 1150°C





The most simple Model: "Pause Time = Recrystallization"

Example: Bearing Shell, 2-Step Forming at 1150°C



The most simple Model: "Pause Time = Recrystallization"

Results:

- **in a multi step forming process each step starts with completely recrystallized material behavior (there is no forming history)**
  ==> the resulting strain values often show a realistic picture of the real material situation
  ==> a basic interpretation of the actual deformation regarding the limit of formability can be performed
  ==> the calculated forming and tool loads are not influence by an accumulation of strain from previous operations

- **Information about the state of recrystallization of the material: not available**

- **evaluable information about grain size or grain size distribution: not available**

- **information about grain growth: not available**

- **further microstructure relevant results: not available**

- **influence on the used material model: none, Yield stress – strain curve remains unchanged**

The most simple Model: "Pause Time = Recrystallization"

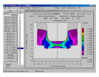
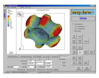
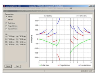
Model idea (1):

- **a model of the dynamic recrystallization can be formulated like**

dynamisch
- $D_{dyn.rek.} = f\,(D_0, \varepsilon, \delta\varepsilon/\delta t, T, \text{etc.})$ => **dyn. recryst. grain size**
- $F_{dyn.rek.} = f$ **(several process parameters) => dyn. recryst. fraction**
- **Relevance: during respectively directly after the forming**

- **a model of the static recrystallization can be formulated like**

statisch
- $D_{stat.rek.} = f\,(D_0, \varepsilon, T, t, \text{etc.})$ => **stat. recryst. grain size**
- $F_{stat.rek.} = f$ **(several process parameters) => stat. recryst. fraction**
- **Relevance: during pause time between respectively hold time after previous deformation**

The most simple Model: "Pause Time = Recrystallization"

Model idea (2):

- a model for grain growth can be formulated like

Wachstum:

$\Delta D_{xx.rek.}$ = f ($D_{xx.rek}$, T, t, etc.) with $_{xx.}$ = $_{stat.}$ or $_{dyn.}$

=> growth of the xx. recrystallized grain

Relevance: for $\Delta D_{dyn.rek}$: after the end of the dynamic recrystallization

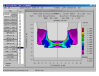
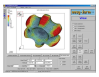
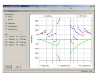
for $\Delta D_{stat.rek}$: after complete static recrystallization of the leftover grainstructure

- it is possible to find reasonable rules to allow at a certain step of time to merge the separate grain fractions like

Mischung:

$D_{0\text{-}neu}$ = f (D_0, $D_{dyn.rek.}$, $D_{stat.rek.}$, $\Delta D_{dyn.rek.}$, $\Delta D_{stat.rek.}$, $F_{dyn.rek.}$, $F_{stat.rek.}$)

=> new average of the initial grain size

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The typical Model: "Dynamic/Static with grain growth"

Model idea (3):

- the reduction of the amount of strain in the part is equivalent to the sum of the recrystallized fractions (considered locally) like

Strain Softening:

$\varepsilon_{v\text{-}neu}$ = f (ε_v, $F_{dyn.rek.}$, $F_{stat.rek.}$) => new reduced strain

Relevance: after completion of the dynamic recrystallization and during the static recrystallization

- the complex interaction between the several mechanism of microstructure change can be formulated and coded. Normally there is no strict sequence how the various models interact during a process. Knowledge is needed about:

- interaction and dependencies of the various models

- Start/Stop-conditions for the models

Dynamic/Static Model for Forming and Hold Times

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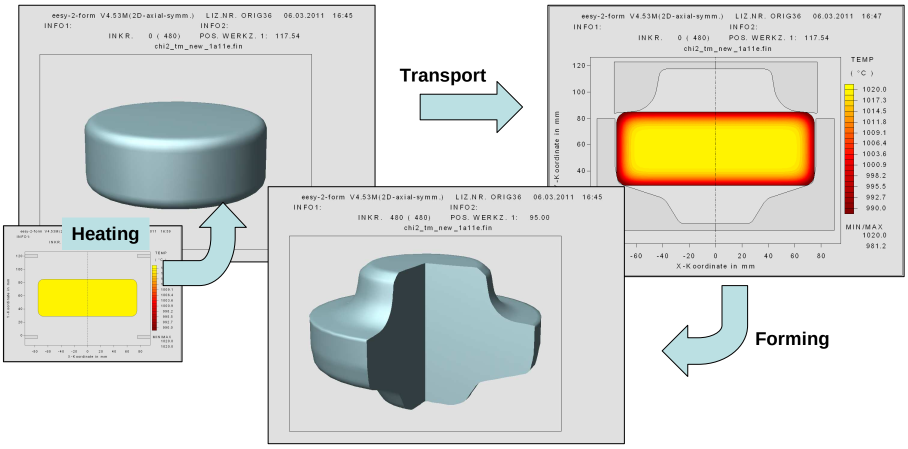
The typical Model: "Dynamic/Static with grain growth"

Example: Turbine disc made from Inconel 718, one step forming at 1020°C



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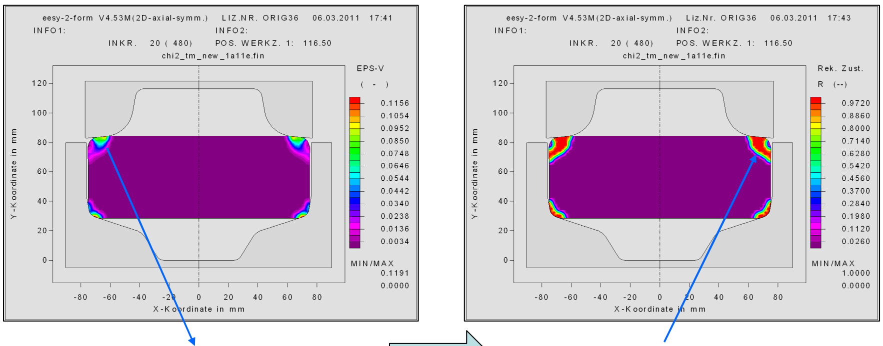
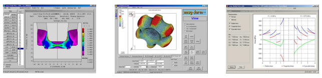
The typical model: "Dynamic/Static incl. Grain Growth"

Example: Turbine disc made from Inconel 718, one step forming at 1020°C
- results after 5% press movement

Equivalent Strain [-] **Recrystallization [-]**



Certain amount of strain → **Dynamic recrystallization (local)**



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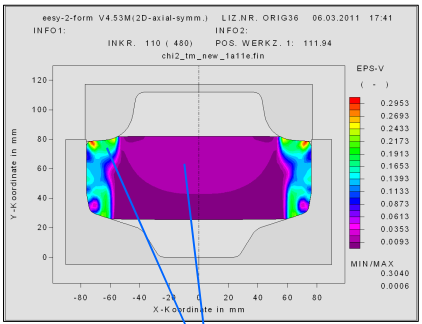
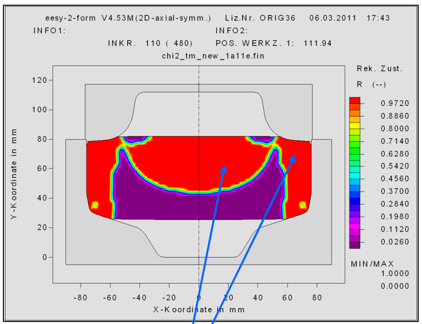
The typical model: *"Dynamic/Static incl. Grain Growth"*

Example: Turbine disc made from Inconel 718, one step forming at 1020℃
- results after 25% press movement

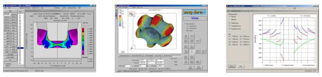
Equivalent Strain [-]



Recrystallization [-]



Certain amount of strain → **Dynamic recrystallization (local)**



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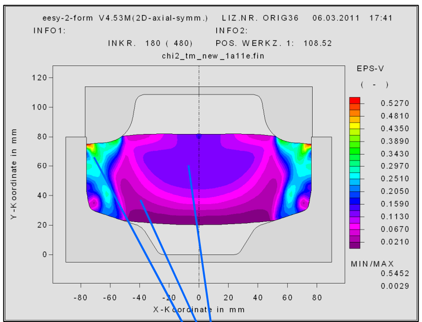
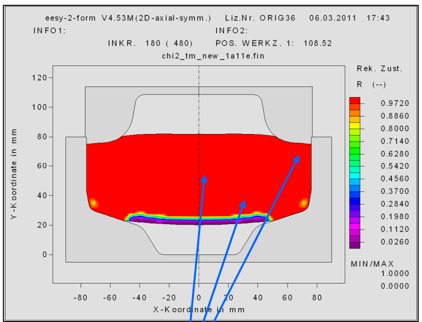
The typical model: *"Dynamic/Static incl. Grain Growth"*

Example: Turbine disc made from Inconel 718, one step forming at 1020℃
- results after 40% press movement

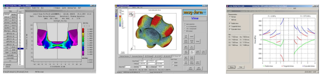
Equivalent Strain [-]



Recrystallization [-]



Certain amount of strain → **Dynamic recrystallization (local)**



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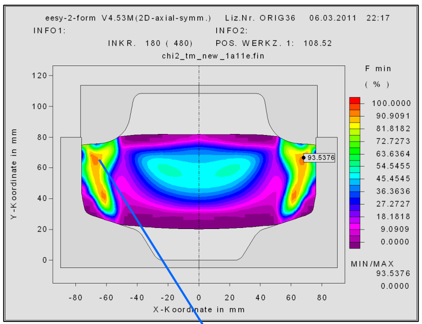
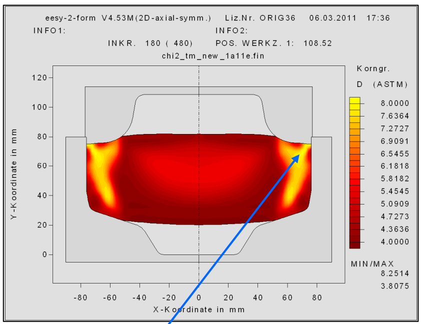
The typical model: "Dynamic/Static incl. Grain Growth"

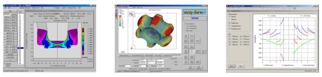
Example: Turbine disc made from Inconel 718, one step forming at 1020°C
- results after 40% press movement

Recrystallized Fraction [%] | **Grain Size [ASTM]**





High recrystallized fraction → **Fine (dyn. recrystallized) grain**



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The typical model: "Dynamic/Static incl. Grain Growth"

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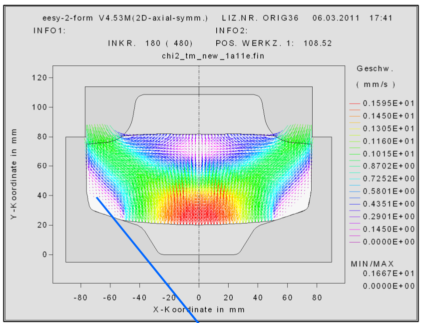
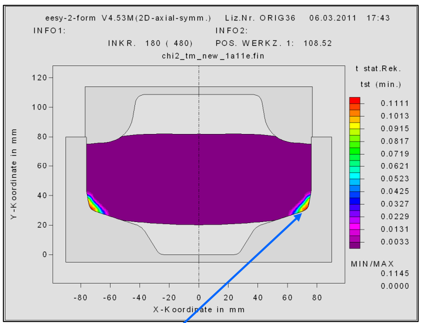
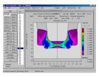
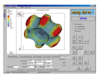
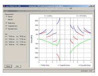
- results after 40% press movement

Material Flow [mm/sec] | **Duration of Static Recrystallization [min]**





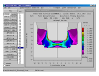
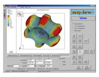
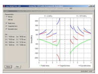
„Dead" zone, - actually no forming → **stat. recrystallization after forming**

The typical model: "Dynamic/Static incl. Grain Growth"

Results:

- **resulting strain represents the actual deformation and hardening situation (locale distribution)**
  ==> realistic calculation and evaluation of several variables like material stress, deformability, forming loads, tool loads
- **state of recrystallization: available, split in dynamic and static fraction**
- **grain size and grain size distribution : available, as global value and in it´s dynamic and static fractions as well**
- **Indication of grain growth : available, quantitative value**
- **further microstructure spec. results : available, i.e. recrystallization time, recrystallization stop, timing of growth, etc.**
- **all grain characteristics as local distribution in the part: available**
- **sustainable effects on the material model used : non, yield stress-strain curve remains unchanged**

The complex model: "Dislocation Based Model"

Model idea (1):

- **strain ε as not path independent value is no longer used as state value for the constitutive law to describe the mechanical behavior i.e.**

  $\sigma = f(\delta\varepsilon/\delta t, T, \varepsilon)$ **is no longer valid**

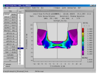
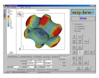
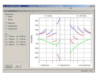
- **as new state value the dislocation density ρ is introduced like**

  $\sigma = f(\delta\varepsilon/\delta t, T, \rho)$

- **for the dislocation density an evolution equation to describe it´s development during the forming operation can be given as**

  $\delta\rho/\delta t = (\delta\rho/\delta t)^{+} + (\delta\rho/\delta t)^{-}$

  with $(\delta\rho/\delta t)^{+}$: Processes that generate dislocations
  and with $(\delta\rho/\delta t)^{-}$: Processes that reduce dislocations

The complex model: "Dislocation Based Model"

Model idea (2):

- Processes that change the dislocation density

a) dislocation generation

$\delta\rho/\delta t = M * \delta\varepsilon/\delta t \,/\, (b * L_{eff})$ mit $L_{eff} = f(\rho)$

b) dislocation reduction by spontaneous annihilation

$\delta\rho/\delta t = c_3 * M * d_{spontan} * \delta\varepsilon/\delta t \,/\, b * \rho$

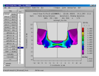
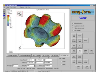
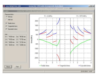
c) dislocation reduction by thermally activated climbing

$\delta\rho/\delta t = c_4 * (v_k/d_{dipol}) * \rho$ mit $v_k = f(\sigma)$ und $d_{dipol} = f(\sigma,\rho)$

- the yield stress can be calculated as depending of the dislocation density like

$\sigma_{vM} = M * (\tau_{eff} + \tau_{pass})$

with $\tau_{pass} = \alpha * b * G * \rho^{1/2}$,
with $\tau_{eff} = k_B * T / V * \text{asinh}(\text{arg})$
and with $\text{arg} = (\delta\gamma/\delta t) / (\rho_m * b * \lambda * \nu) * \exp(Q/k_B * T)$

*The complex model: "Dislocation Based Model" *)*

Model idea (3):

- the additional changes of the microstructure can be described adequate equations for

a) dynamic recrystallization,

$X_{dyn.rek} = f\,(R_{dyn.rek} , N_{dyn.rek})$

b) static recovery and static/metadynamic recrystallization,

$X_{stat.rek} = f\,(R_{stat.rek} , N_{stat.rek})$

c) precipitation during hold time and

$F_p = f\,(R_p , N_p)$

d) grain growth after complete recrystallization

$R_{gr} = f\,(R_{dyn.rek} , \delta R_{dyn.rek}/\delta t)$

Dislocation Based Material and Grain model

***) Modelling along F. Roters, MPIE Düsseldorf und L. Mosecker, U. Prahl, W. Bleck, IEHK RWTH Aachen**

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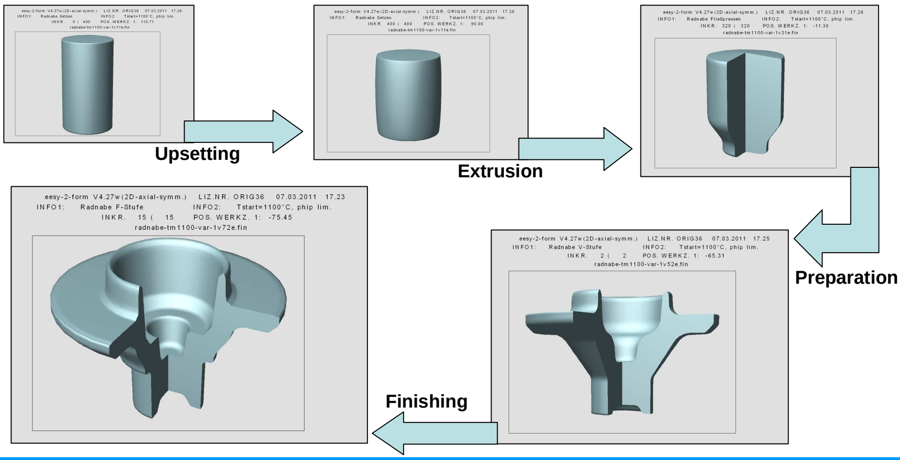
The complex model: "Dislocation Based Model"

Example: Wheel Hub, 4-step forming at T_{start} =1100°C, initial grain size: 54,8 µm



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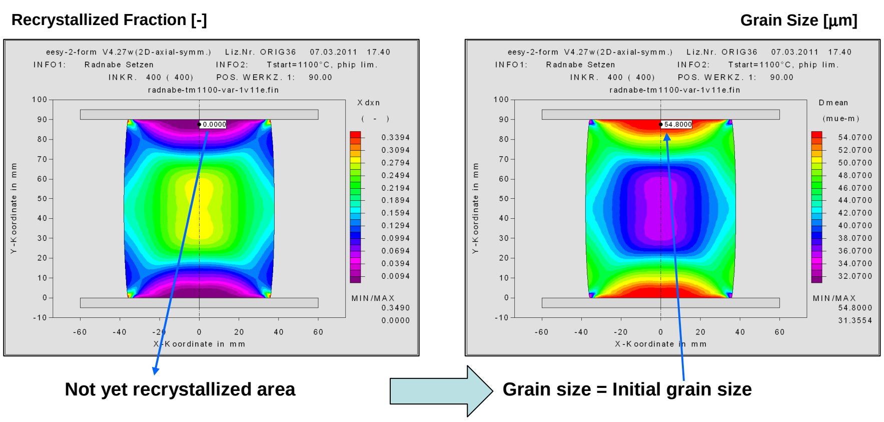

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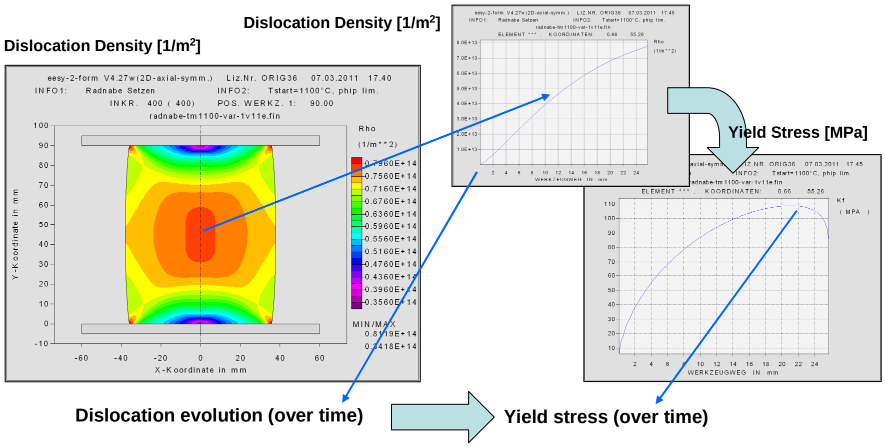

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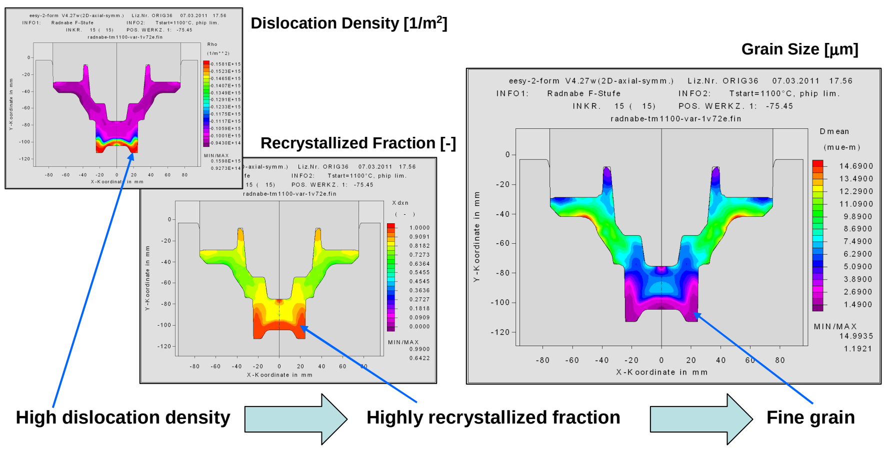
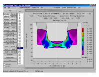
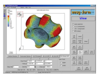
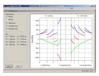
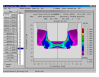
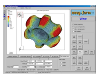
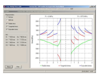


The complex model: "Dislocation Based Model"

Results:

- **a material model that describes the dependency of microstructure, yield stress and deformation**
- **yield stress: calculated based on the dislocation density and further grain structure parameters as a value independent from a measured curve**
- **state of recrystallization: available, slit in dynamic und static fraction**
- **grain size and grain size distribution: available as a general value and in its dynamic and static fractions as well**
- **Indication of grain growth: available, quantitative value**
- **further microstructure spec. results: available: i.e. amount and size of precipitations**
- **sustainable effects on the material model used: yes, the yield stress – strain curve will be determined at any time and location out of the dislocation density**

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