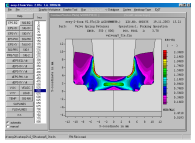
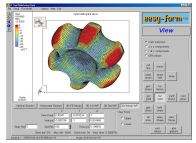
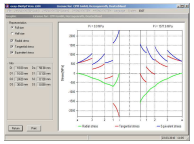




**CPM Gesellschaft für Computeranwendung,
Prozeß- und Materialtechnik**

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

Dr. Michael Twickler, Dr. Gerhard H. Arfmann
CPM GmbH, Herzogenrath

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**

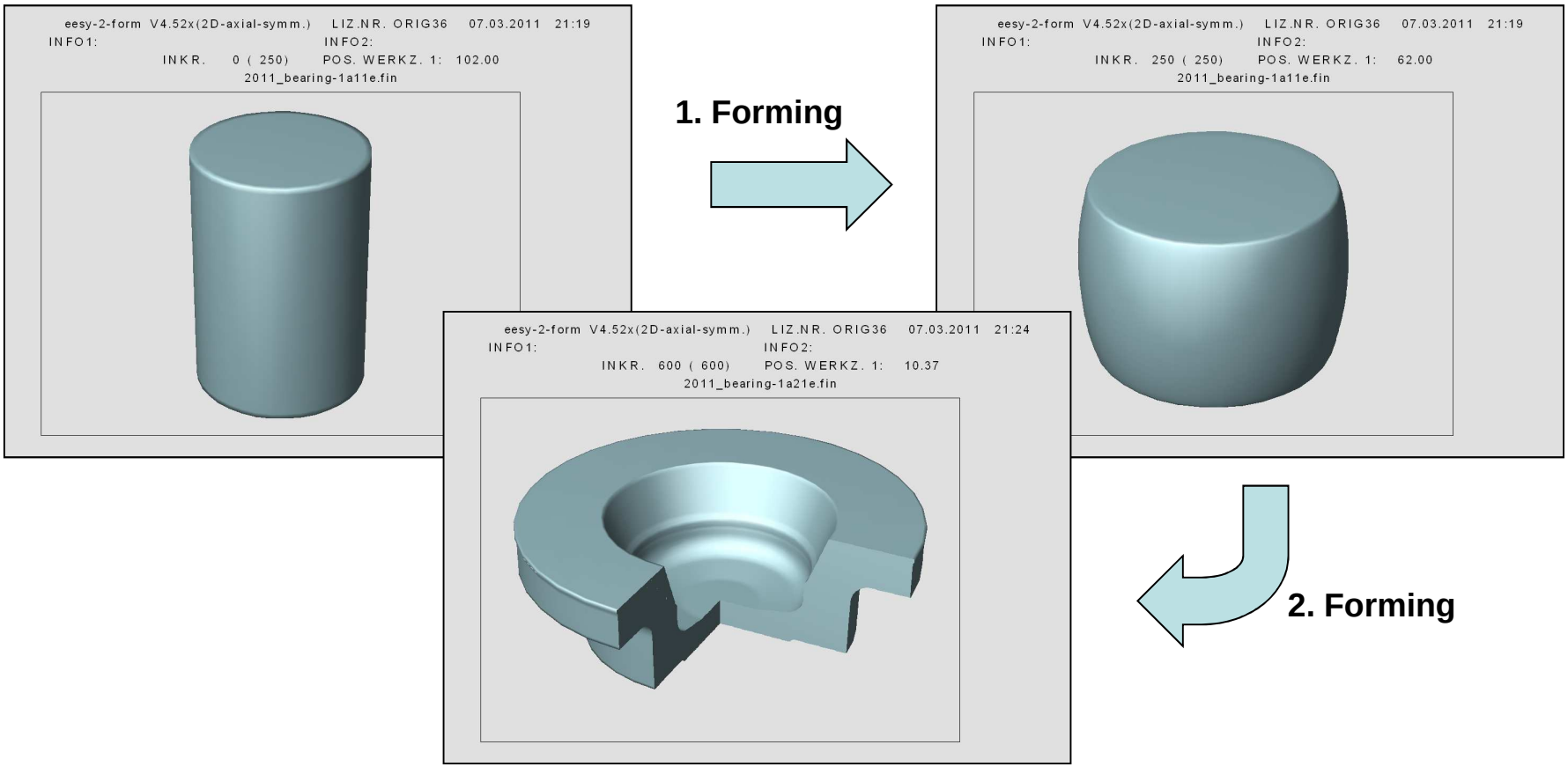
- **complete recrystatization is identical with complete reset of any deformation that is already in the part**

- **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

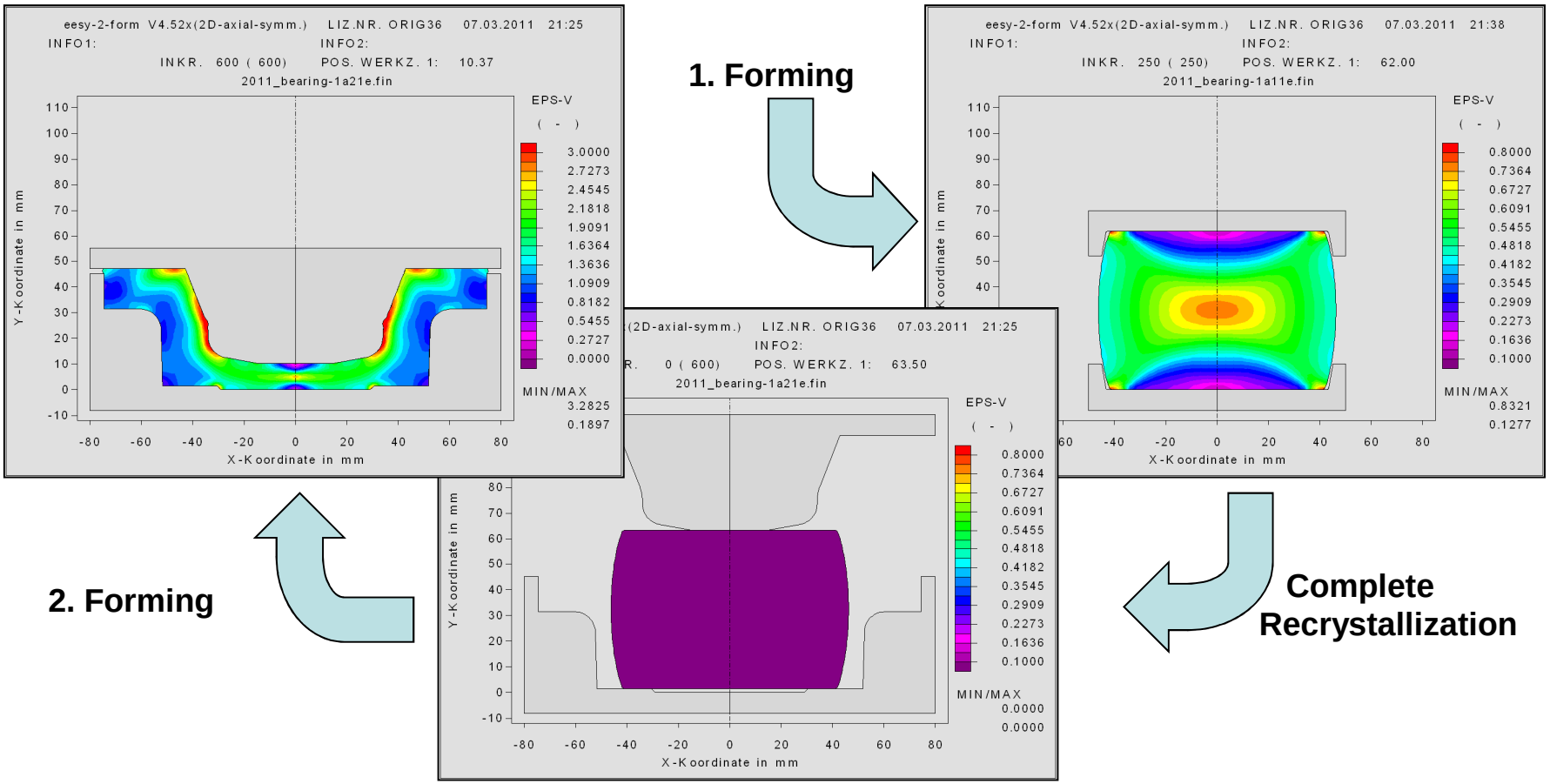
The most simple Model: "Pause Time = Recrystallization"

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
- $F_{dyn.rek.} = f(\text{several process parameters})$ => 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
- $F_{stat.rek.} = f(\text{several process parameters})$ => 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**

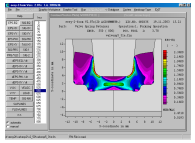
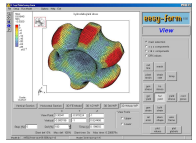
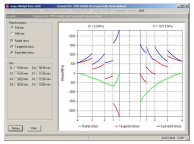
for $\Delta D_{stat.rek}$**: after complete static recrystallization of the leftover grainstructure**

- 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

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

$\varepsilon_{v\text{-neu}} = f(\varepsilon_v, F_{dyn.rek.}, F_{stat.rek.})$ **=> 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:

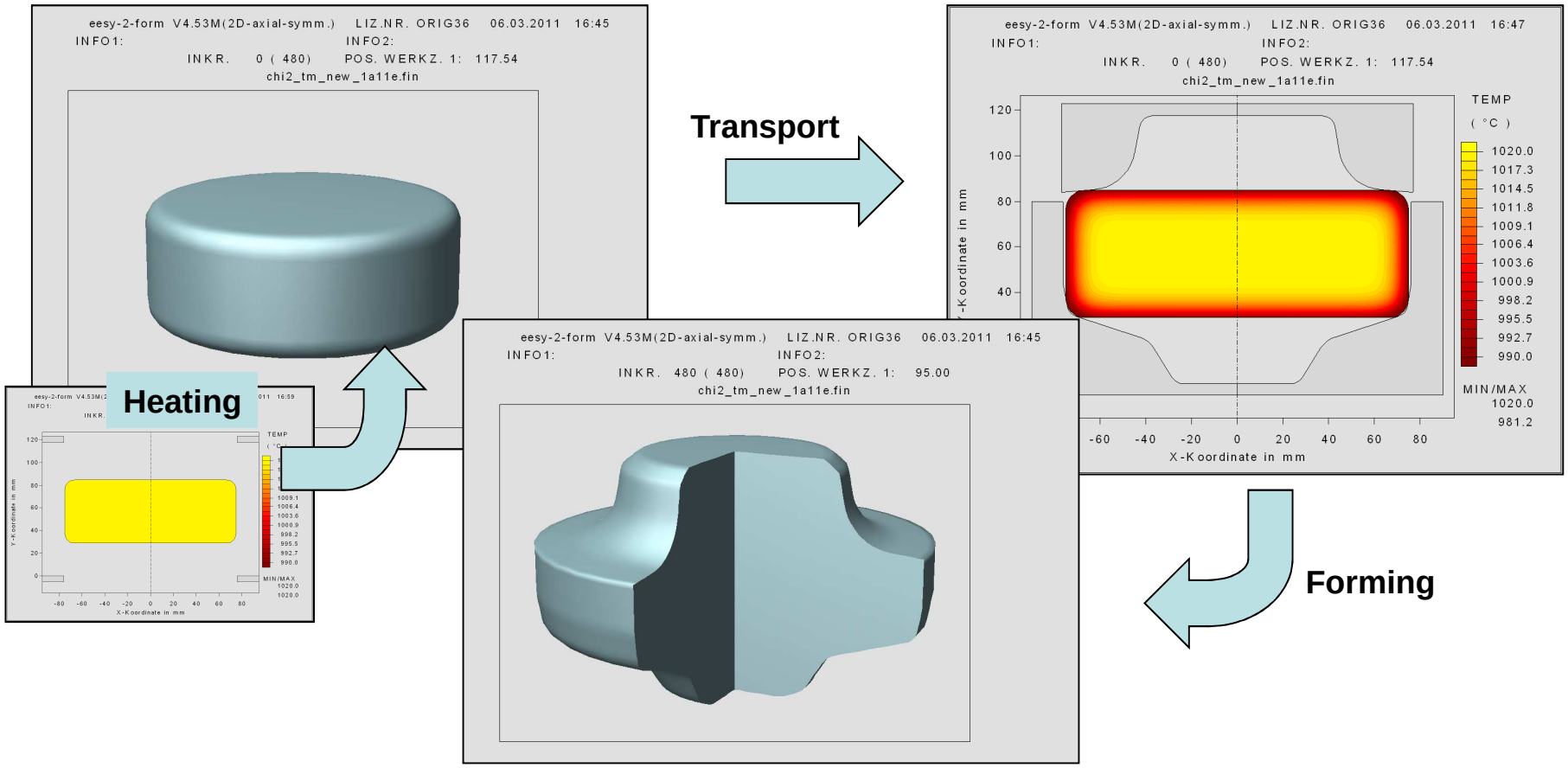
- interaction and dependencies of the various models

- Start/Stop-conditions for the models

Dynamic/Static Model for Forming and Hold Times

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

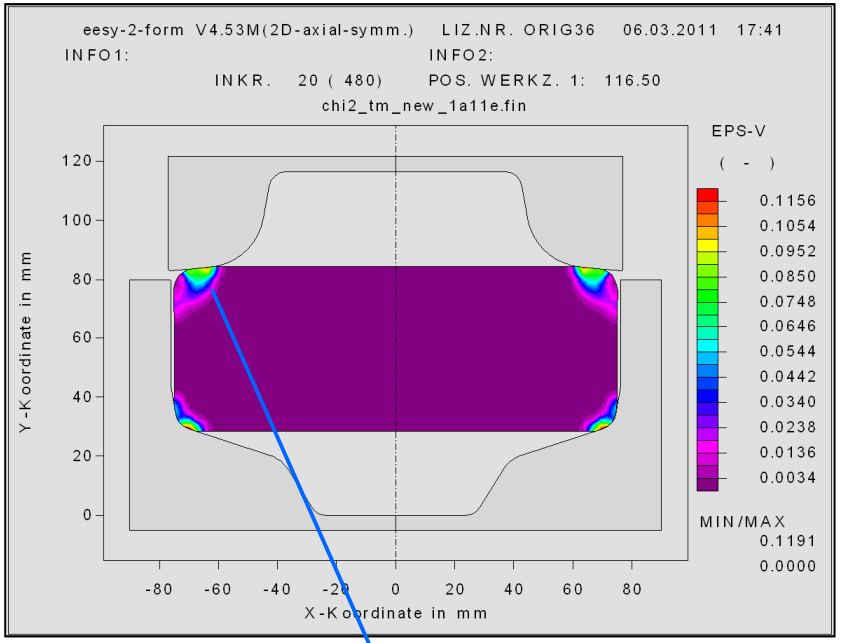
Example: Turbine disc made from Inconel 718, one step forming at 1020°C



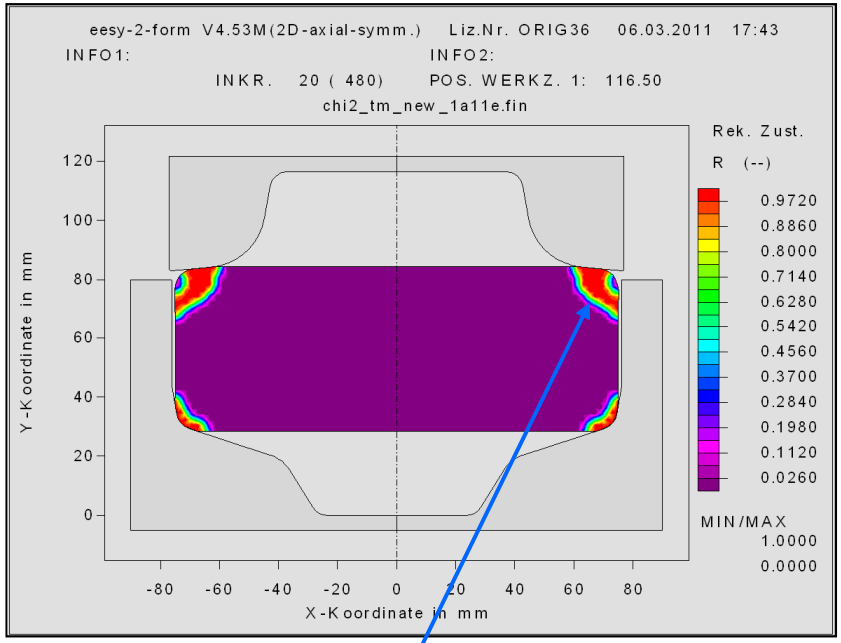
The typical model: "Dynamic/Static incl. Grain Growth"

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

Equivalent Strain [-]



Recrystallization [-]

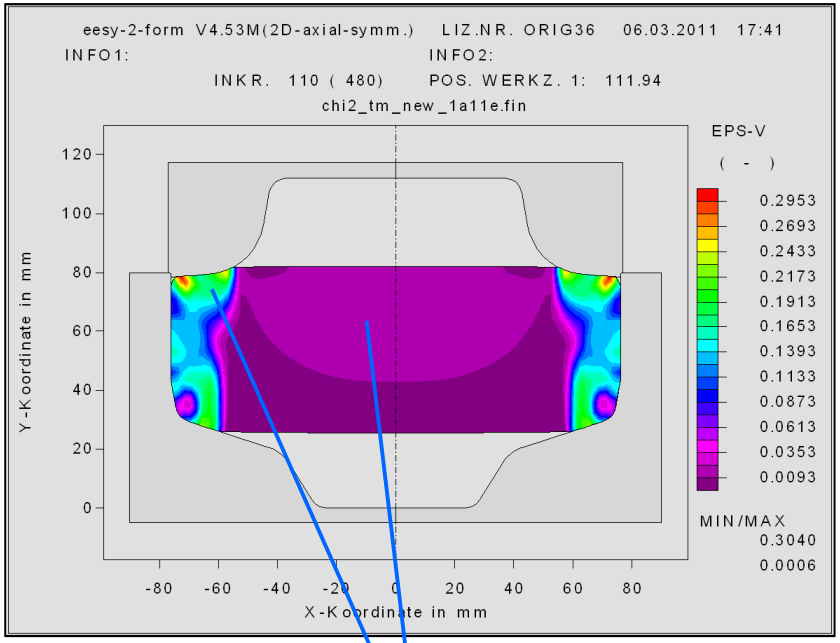


Certain amount of strain → **Dynamic recrystallization (local)**

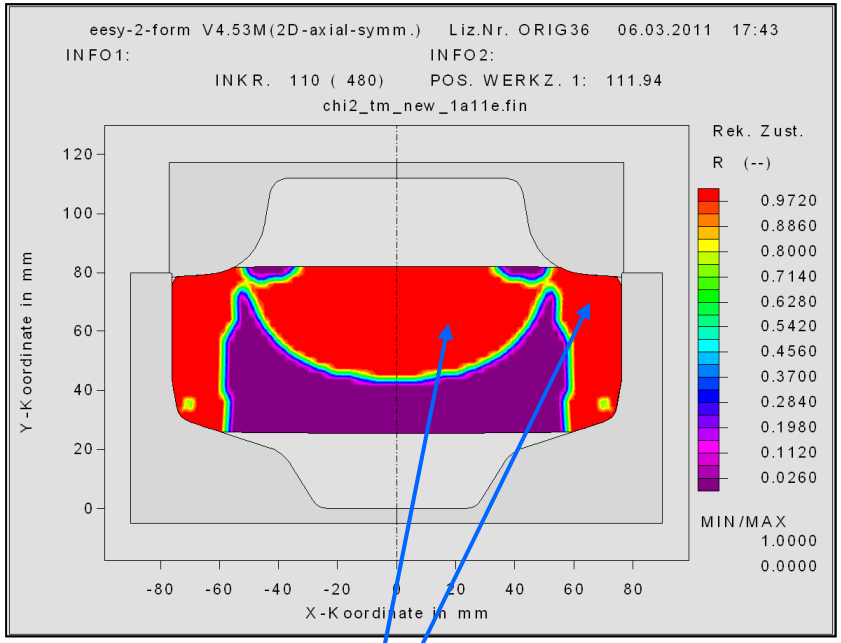
The typical model: "Dynamic/Static incl. Grain Growth"

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

Equivalent Strain [-]



Recrystallization [-]

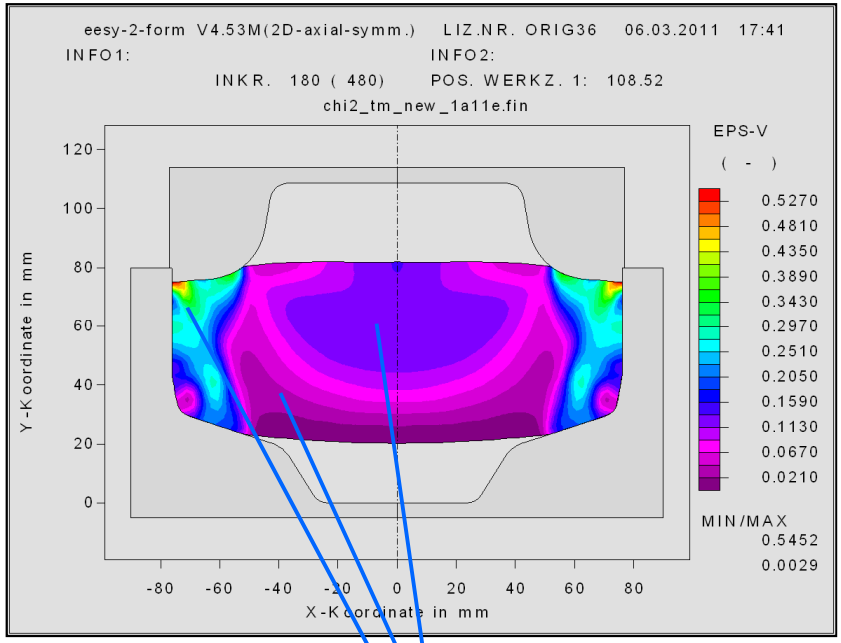


Certain amount of strain → **Dynamic recrystallization (local)**

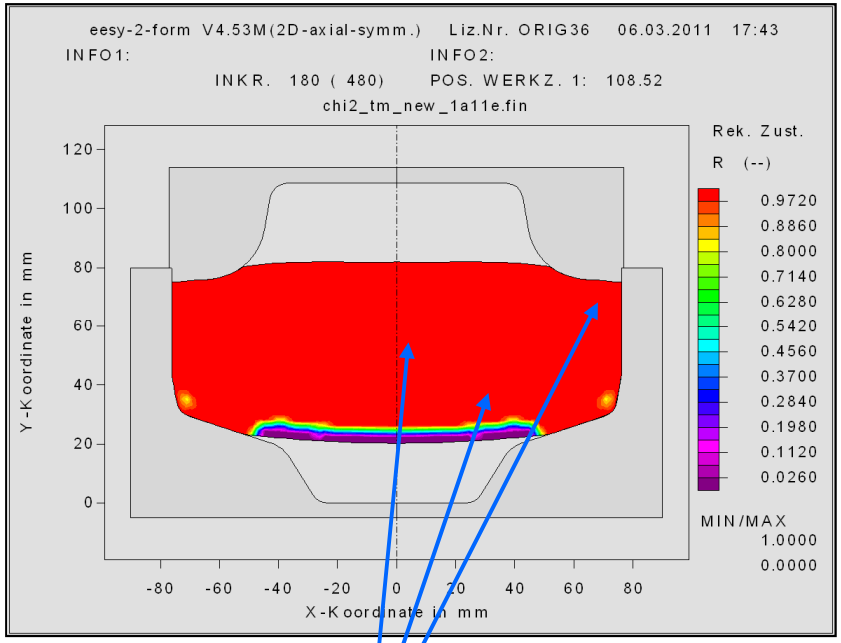
The typical model: "Dynamic/Static incl. Grain Growth"

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

Equivalent Strain [-]



Recrystallization [-]

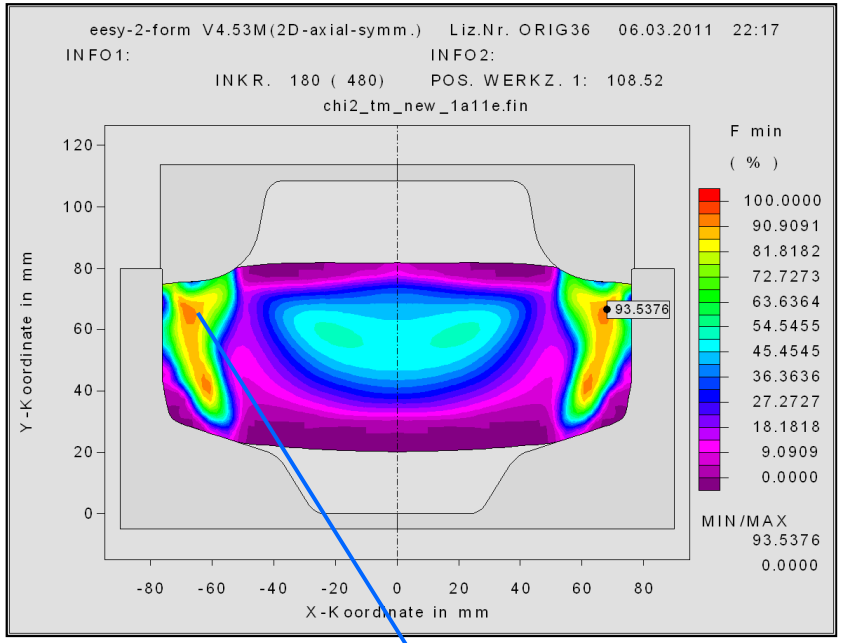


Certain amount of strain → **Dynamic recrystallization (local)**

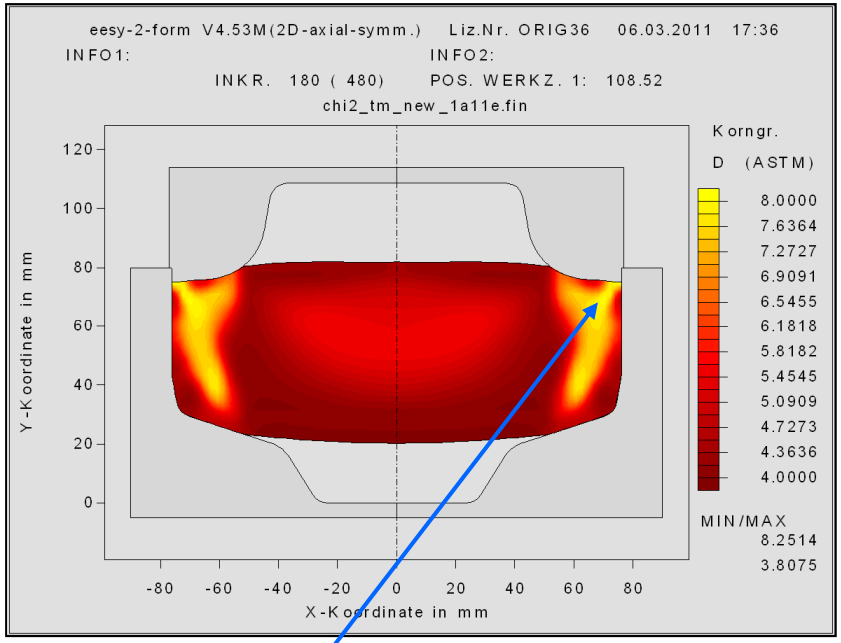
The typical model: "Dynamic/Static incl. Grain Growth"

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

Recrystallized Fraction [%]



Grain Size [ASTM]

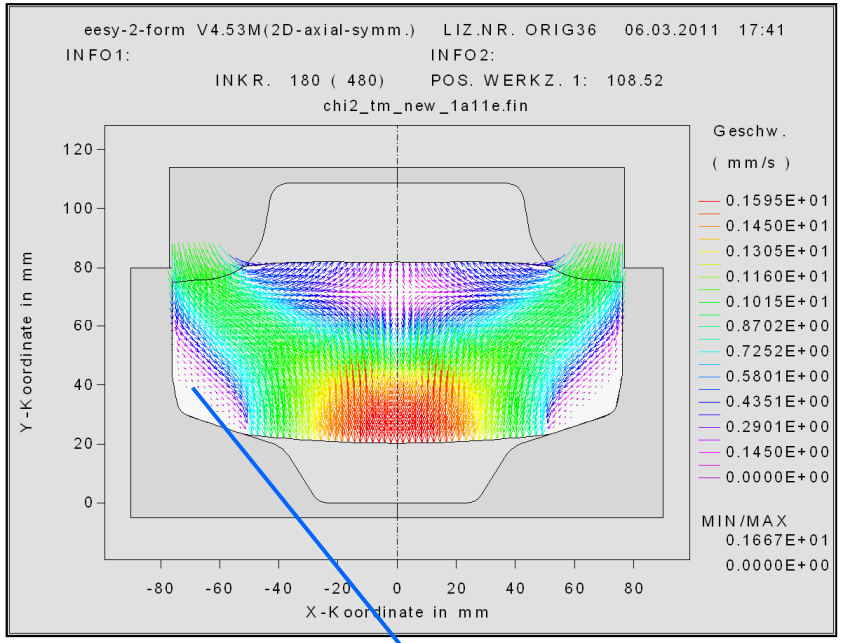


High recrystallized fraction → **Fine (dyn. recrystallized) grain**

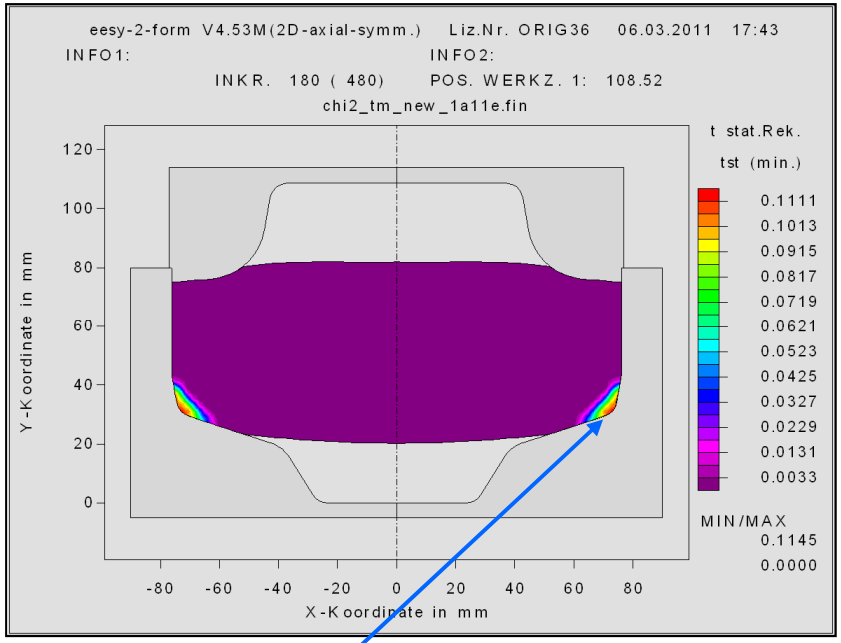
The typical model: "Dynamic/Static incl. Grain Growth"

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

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

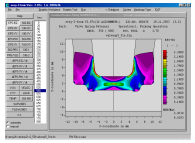
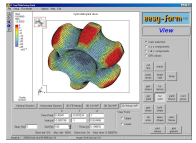
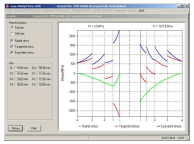
$$\sigma = f(\delta\varepsilon/\delta t, T, \rho)$$

- 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

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

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

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

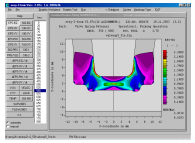
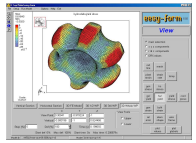
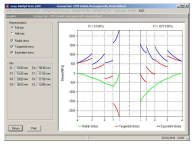
- the yield stress can be calculated as depending of the dislocation density like

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

$$\text{with } \tau_{pass} = \alpha * b * G * \rho^{1/2},$$

$$\text{with } \tau_{eff} = k_B * T / V * \operatorname{asinh}(arg)$$

$$\text{and with } arg = (\delta\gamma/\delta t) / (\rho_m * b * \lambda * \nu) * \exp(Q/k_B * T)$$

*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

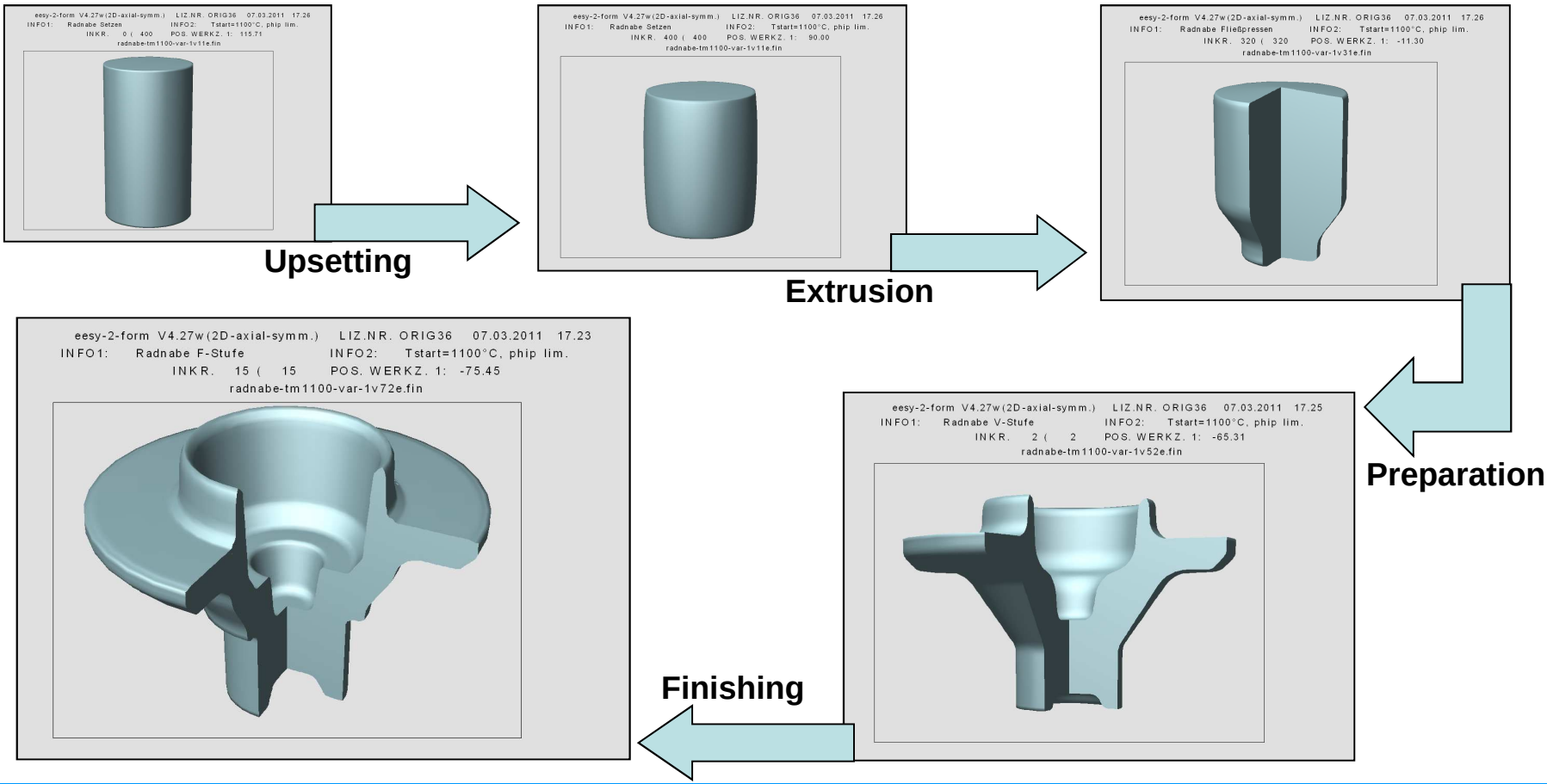
$$R_{gr} = f(R_{dyn.rek}, \delta R_{dyn.rek}/\delta t)$$

Dislocation Based Material and Grain model

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

The complex model: "Dislocation Based Model"

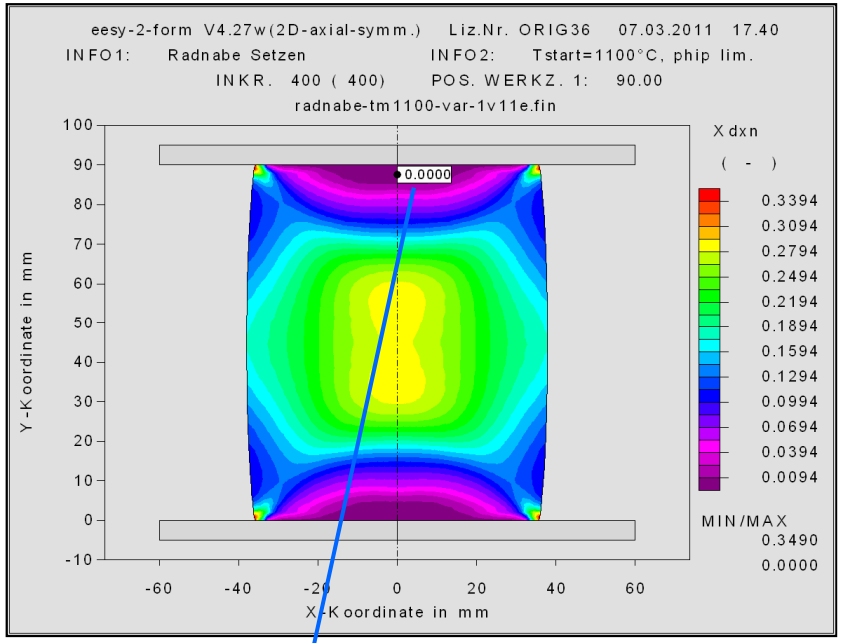
Example: Wheel Hub, 4-step forming at T_{start} =1100°C, initial grain size: 54,8 µm



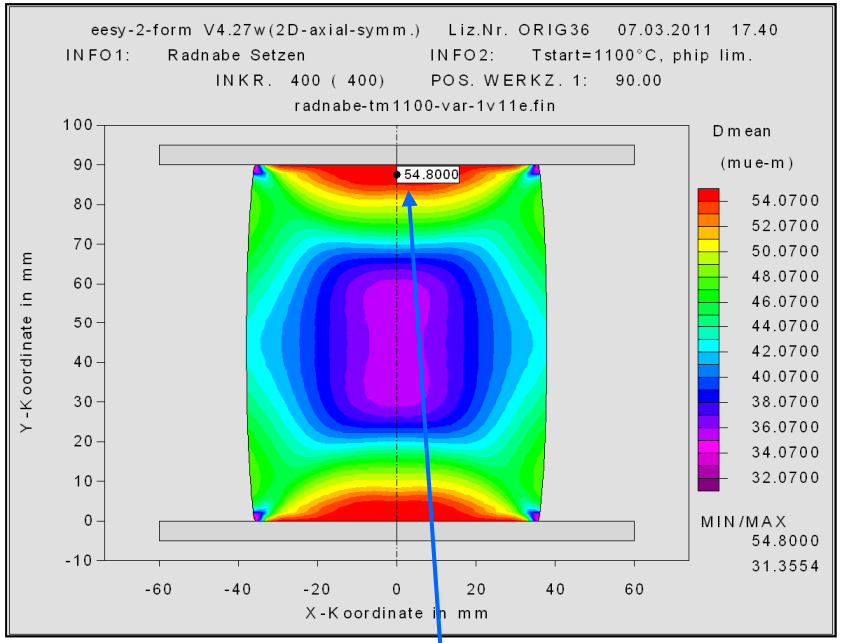
The complex model: "Dislocation Based Model"

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

Recrystallized Fraction [-]



Grain Size [µm]



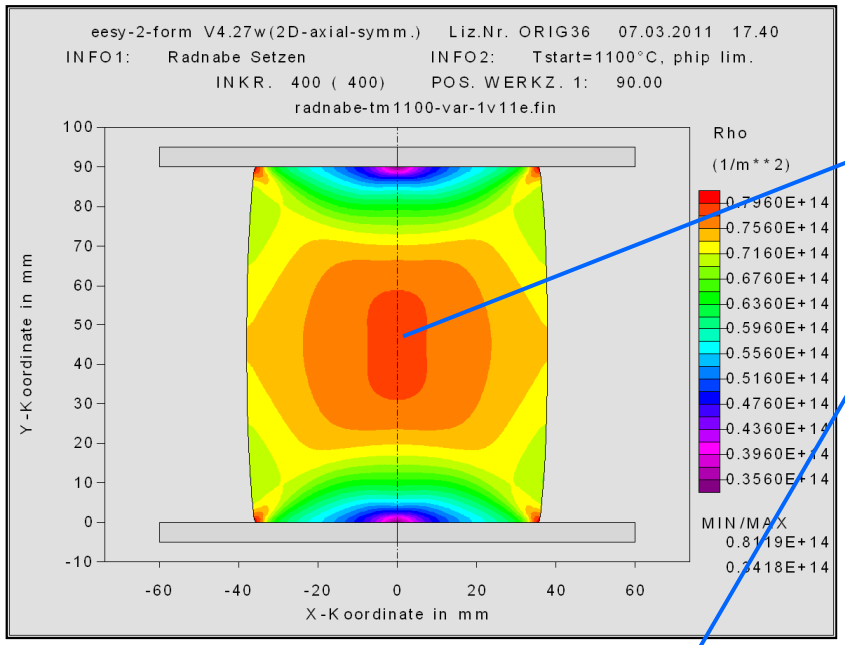
Not yet recrystallized area

Grain size = Initial grain size

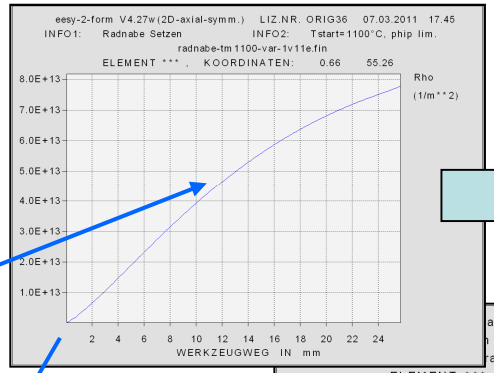
The complex model: "Dislocation Based Model"

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

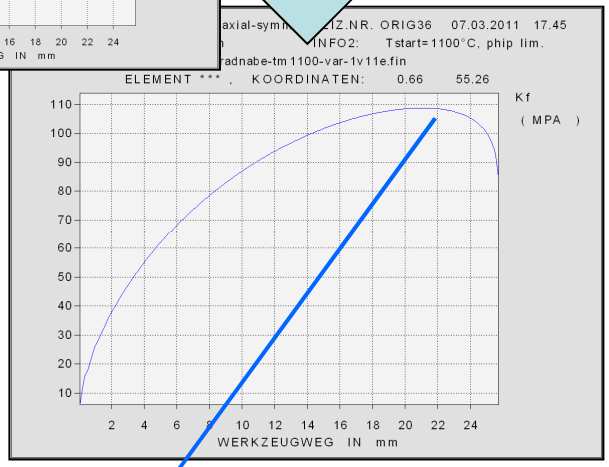
Dislocation Density [1/m²]



Dislocation Density [1/m²]



Yield Stress [MPa]

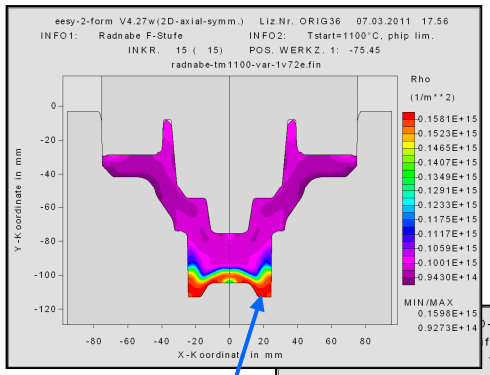


Dislocation evolution (over time) → **Yield stress (over time)**

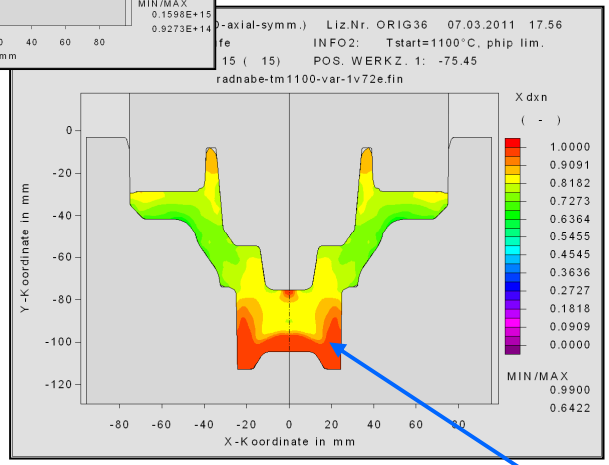
The complex model: "Dislocation Based Model"

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

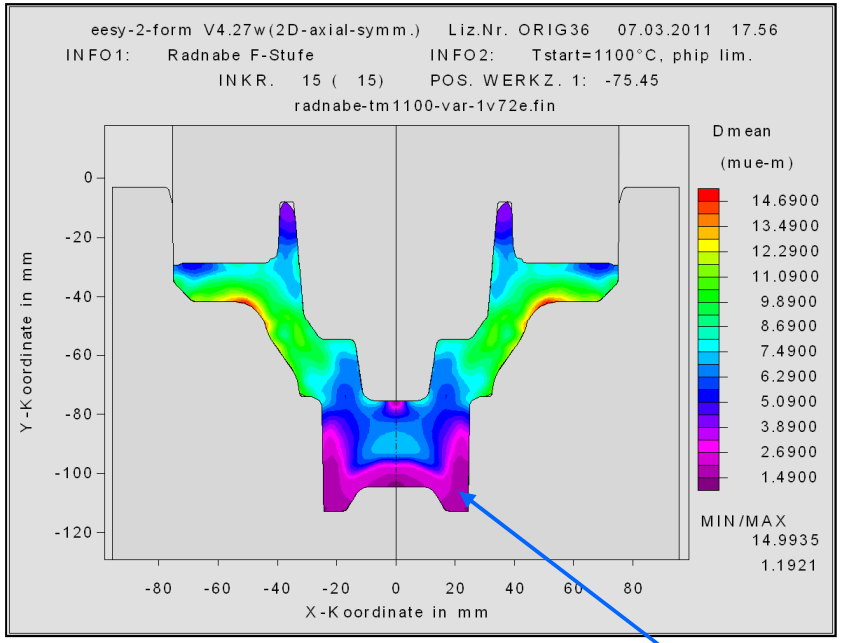
Dislocation Density [1/m²]



Recrystallized Fraction [-]



Grain Size [µm]



High dislocation density → **Highly recrystallized fraction** → **Fine grain**

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**

Acknowledgement:

The information for some of the forging parts presented were provide by **Leistritz Turbinenkomponenten Remscheid GmbH, Remscheid** and **Hirschvogel Umformtechnik GmbH, Denklingen.**

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Bundesministerium für Bildung und Forschung

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"Dislocation Based Model"

as part of the joint research project

"Mikrostrukturbasierte Modellierung des Umformverhaltens von mikrolegierten Stählen bei mehrstufigen Schmiedeprozessen".