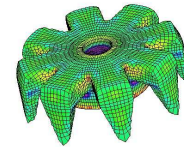
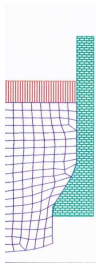
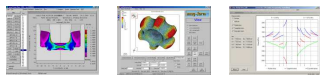


FEA Simulation and Technology by CPM



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



FEM Simulation in der Kaltumformung

Vorgeschichte

Vorgeschichte

bis in die 1980er Jahre

Großrechner, Abteilungsrechner
(Verwaltung, Finanzen, Ingenieur Anwendungen in Großbetrieben)

Einführung von Rechnern im Ingenieurbereich in der Umformtechnik

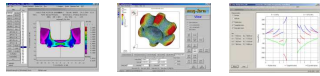
Einführung von CAD

Diverse Kleinrechner (Atari, Sinclair, Z80 etc ganz selten für
„ernsthafte“ Anwendungen)

1981 IBM PC



Wikipedia



FEM Simulation in der Kaltumformung

Vorgeschichte



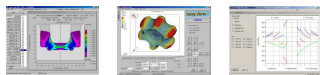
Der „reale“
Ingenieur

Der Ingenieur im Wandel

1980er



Der CA-Ingenieur



FEM Simulation in der Kaltumformung

Vorgeschichte



Der „reale“
Ingenieur



Entwicklung eines einfach zu handhabenden
Systems zur Simulation vom Massivumformung
auf zukünftigen lokalen Rechnerstrukturen



Der CA-Ingenieur



FEM Simulation in der Kaltumformung Forschungsarbeiten in den 80er Jahren

Forschungsarbeiten in den 80er Jahren

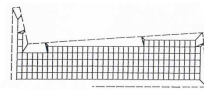
Basientwicklungen FEM (2D)

Elementtypen

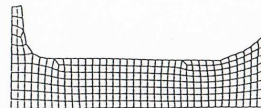


Kontaktalgorithmen

Löser von Gleichungssystemen



Vernetzungsmethoden

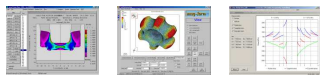


Einfache Handhabung

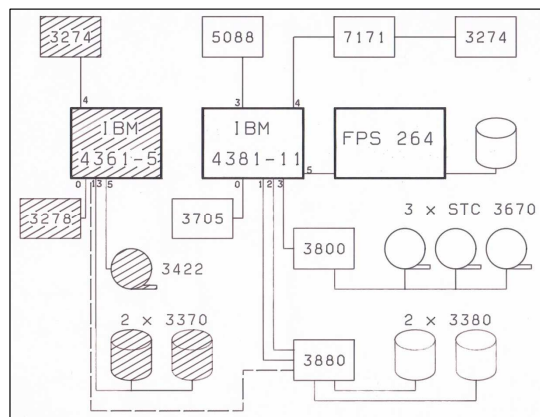
Materialgesetze

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Meeting at OBTC, 24.04.2015, Yantai, PR China

5



FEM Simulation in der Kaltumformung Forschungsarbeiten in den 80er Jahren



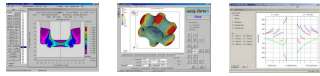
Entwicklungsumfeld in den 1980ern

Leistung ca.. 60 MFLOPS

Vergleich
Core i7,
3,47 GHz, 83,2 GFLOPS
6 Kerne

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6



FEM Simulation in der Kaltumformung Forschungsarbeiten in den 80er Jahren

Erster Prototyp eines FEM Programms zur Anwendung auch auf PC

CAPS-Finel V1.0 (1989)

2D achsen-symmetrisch und eben

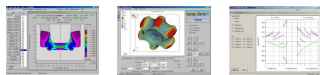
Modellierung, Simulation, Postprocessing in einem System

Einfache Benutzerführung durch Frage-Antwort Dialog

Starr-plastisches Materialgesetz

Thermische Kopplung

Automatisches Vernetzen



FEM Simulation in der Kaltumformung Forschungsarbeiten in den 80er Jahren

CAPS-Finel V1.0 (1989)

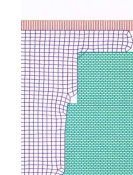
Prototyp simuliert

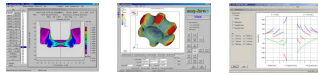
erste **industrielle Prozesse in der Warm und Kaltumformung**

Weiterentwicklung erfolgt in Richtung

- Einsatz auf PC
- Erarbeitung einer grafischen Benutzeroberfläche
(-> „Windows“ gab es noch nicht)
- Randbedingungen
- Materialdaten

Beginn von Arbeiten über Mikrostruktur mit Luftfahrtfirmen





FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

Industrieeinführung und spezielle Entwicklungen für die Kaltumformung 1990er

Entwicklung eines grafischen Interfaces und erste Installationen

Projekt der deutschen Schraubenindustrie

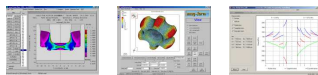
Verbesserung technologischer Module

Einfache Handhabung Mehrstufiger Prozesse

Elastische Werkzeuge

Materialdaten

Mikrostruktur



FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

Industrieeinführung und spezielle Entwicklungen für die Kaltumformung 1990er

Neuer Reibungsansatz

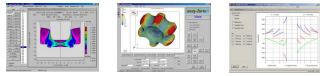
Schadenanalyse

Erste 3D Anwendungen

3D Toolbox

Neues „easy“ Design (esy-2-form, esy-form)





FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

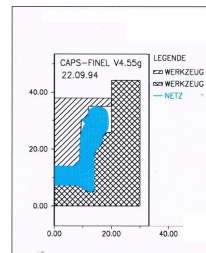
Projekt der deutschen Schraubenindustrie

Ab 1991 Aufnahme von CPM in ein Projekt des DSV

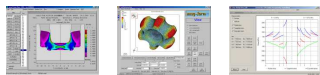
Neben Prozeßüberwachung, Stadiengangauslegung,
Pressenbewegungsablauf und Kollisionsanalyse sollte auch

Simulation
mit Hilfe der FEM

entwickelt werden.



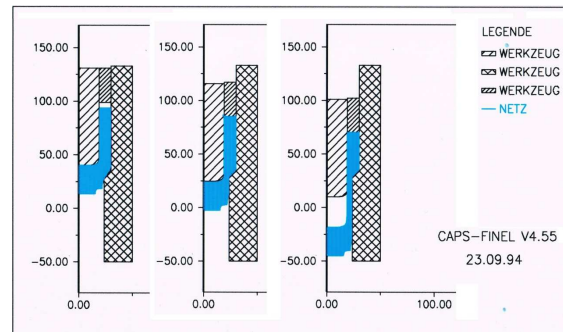
Simulation einer
Faltenbildung 1994

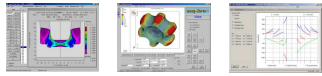


FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

Verbesserung technologischer Module

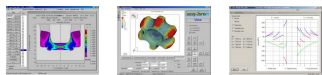
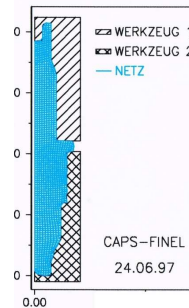
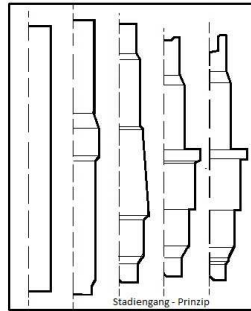
Hier: Werkzeuge mit Feder





FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

Einfache Handhabung Mehrstufiger Prozesse

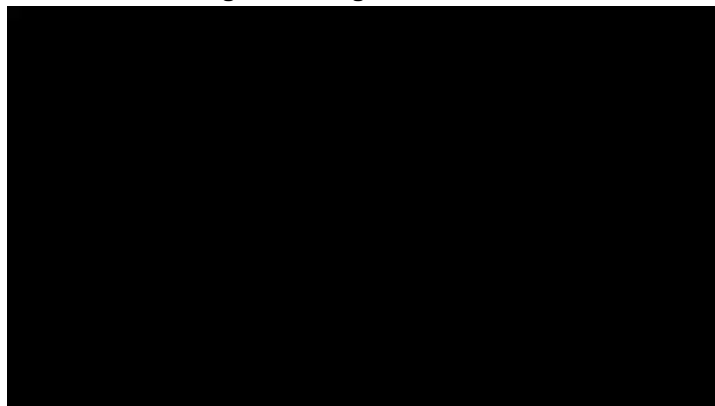


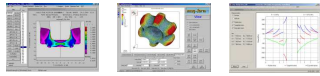
FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

Einfache Handhabung Mehrstufiger Prozesse



Zündkerze 2000



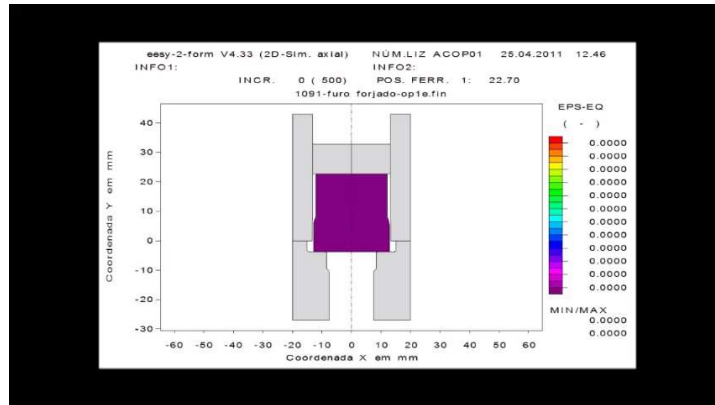


FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

Einfache Handhabung Mehrstufiger Prozesse

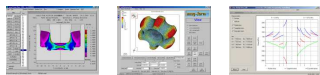


„Mehrstufen
in einer
Stufe“ mit
komplexer
Werkzeug-
bewegung



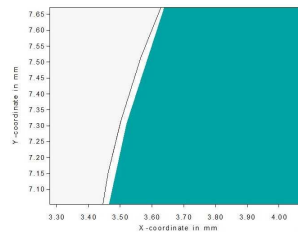
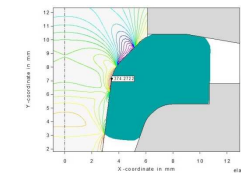
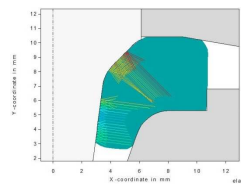
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Meeting at OBTC,24.04.2015, Yantai, PR China

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FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

Fehleranalyse



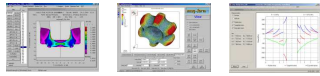
Analyse

Druck auf der Oberfläche
Axialspannung alternierend
im Werkzeug
und Erklärung
Fehlender Kontakt
während der Umformung
(keine Luft oder Öl!)

Stempelbruch beim Fertigen eines Ventildertellers

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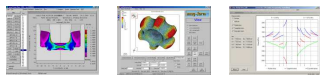
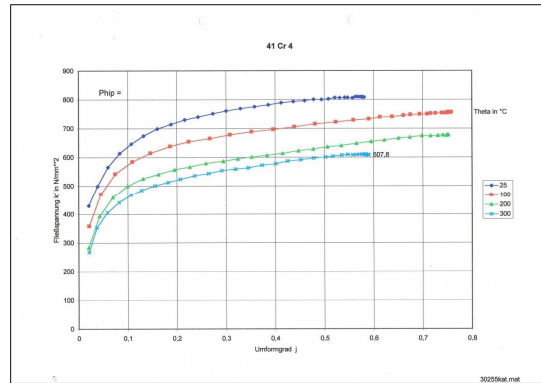
16



FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

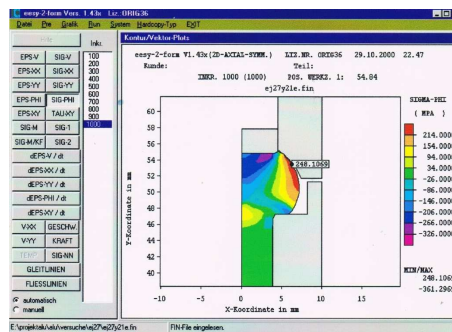
Materialdaten

Ein Projekt des Landes NRW ermöglichte es einen ersten umfassenden Bestand von Fließkurven zu ermitteln

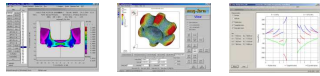


FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

Schadenanalyse

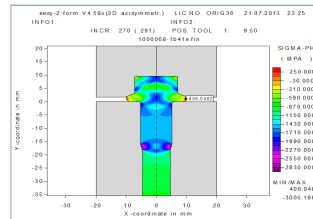
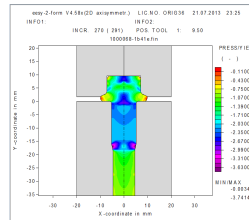


Hier Spannungsanalyse zur Erklärung eines Risses an einer Alu Schraube

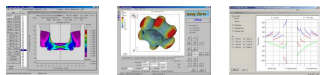


FEM Simulation in der Kaltumformung **Industrieeinführung und spezielle**

Schadenanalyse



Hier Spannungsanalyse zur Erklärung einer Aufplattung (Materialfehler)



FEM Simulation in der Kaltumformung **Vervollständigung....3D.... (2000er)**

**Vervollständigung und Ertüchtigung technologischer
Module, Werkzeuganalyse und 3D Simulation
mit automatischem generieren hexagonaler Elemente
(2000er)**

Verbesserung und Vervollständigung technologischer Module
(Kontakt, Reibung, Faltenbildung, lokal unterschiedliche Reibung...)

System zur Auslegung und Optimierung von Werkzeugen

Vollautomatisches Vernetzen (hex) in 3D

Lokale Reibungsbeschreibung

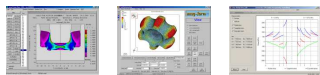
Zusätzliche oberflächennahe Analysen -> Tribosystem



FEM Simulation in der Kaltumformung Vervollständigung....3D.... (2000er)

System zur Auslegung und Optimierung von Werkzeugen

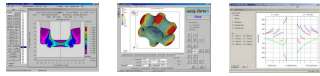
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FEM Simulation in der Kaltumformung Vervollständigung....3D.... (2000er)

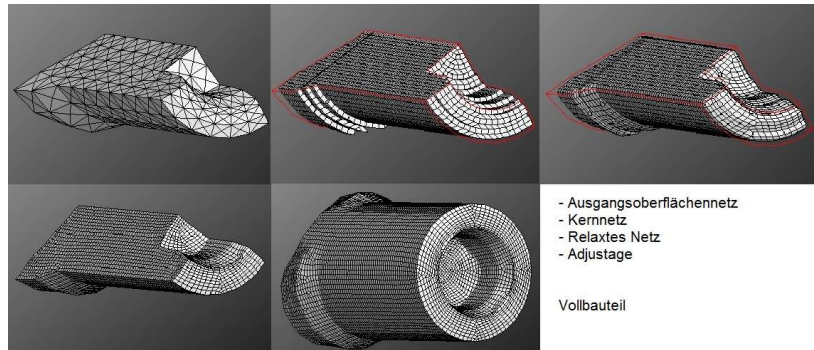
System zur Auslegung und Optimierung von Werkzeugen

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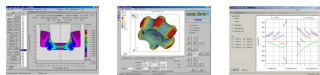
FEM Simulation in der Kaltumformung **Vervollständigung....3D.... (2000er)**

Vollautomatisches Vernetzen (hex) in 3D



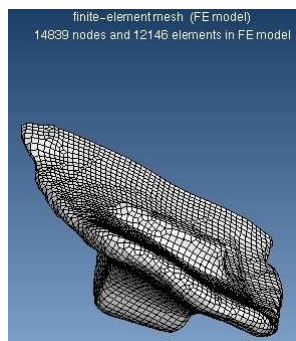
- Ausgangsoberflächennetz
- Kernnetz
- Relaxtes Netz
- Adjustage

Vollbauteil

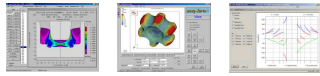


FEM Simulation in der Kaltumformung **Vervollständigung....3D.... (2000er)**

Vollautomatisches Vernetzen (hex) in 3D



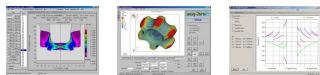
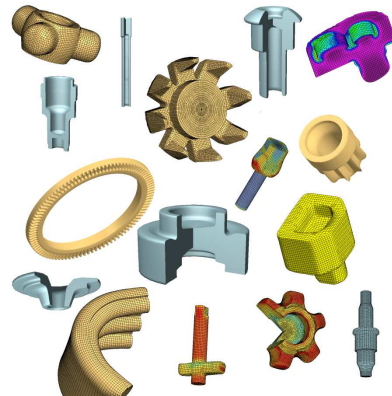
Luftfahrtteil



FEM Simulation in der Kaltumformung **Aktuelle-beispiele und Ausblick**

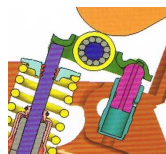
Aktuelle Anwendungsbeispiele und Ausblick

Im Folgenden werden einige
aktuell Anwendungsbeispiele
gezeigt und zukünftige
Entwicklungen angesprochen

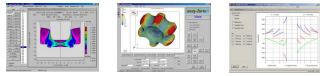


FEM Simulation in der Kaltumformung **Aktuelle-beispiele und Ausblick**

Aktuelle Anwendungsbeispiele und Ausblick

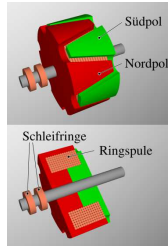


Ventilsteuerung
Ausgleichselement

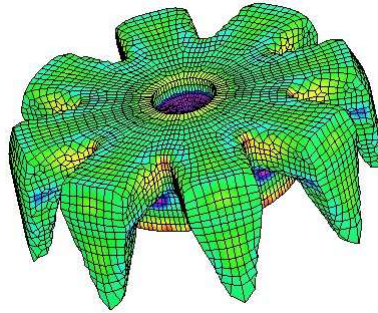


FEM Simulation in der Kaltumformung **Aktuelle-beispiele und Ausblick**

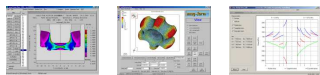
Aktuelle Anwendungsbeispiele und Ausblick



(Schenkelpolmaschine – Wikipedia)



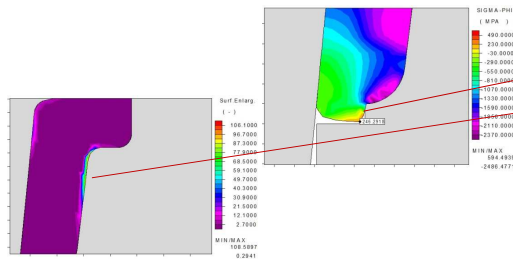
Polklaue



FEM Simulation in der Kaltumformung **Aktuelle-beispiele und Ausblick**

Aktuelle Anwendungsbeispiele und Ausblick

Aufrauhung und Riss an einem Ventildfederteller

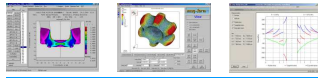


Oberflächen
vergrößerung

Umfangsspannung



Fehlerhafter Ventildfederteller



FEM Simulation in der Kaltumformung Aktuelle-beispiele und Ausblick

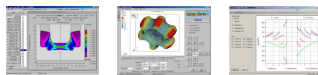
Aktuelle Anwendungsbeispiele und Ausblick



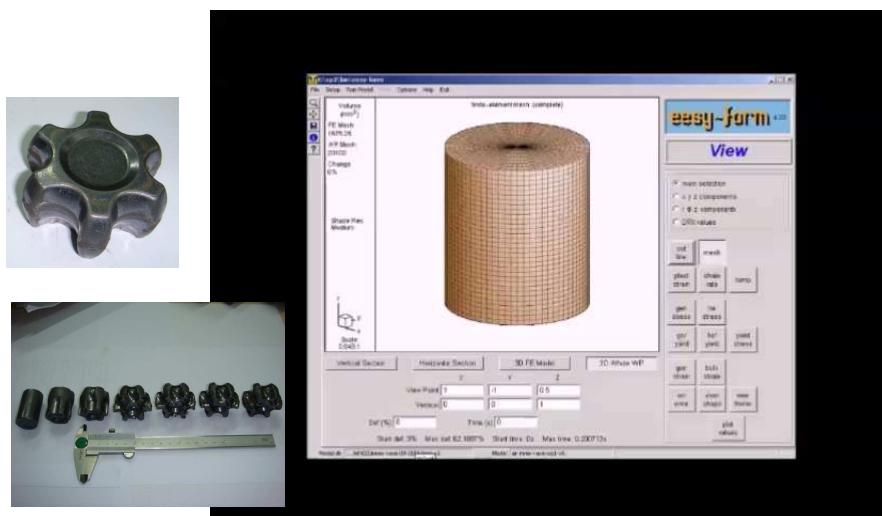
Inner Race

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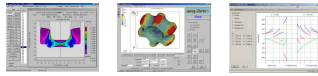


FEM Simulation in der Kaltumformung Aktuelle-beispiele und Ausblick



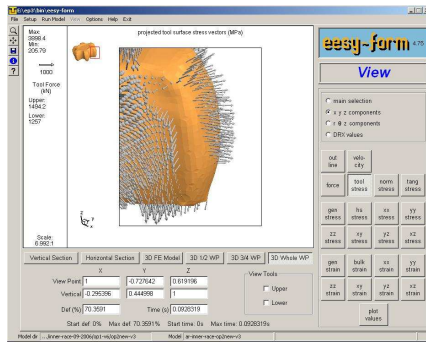
(c) 2015 Dr. Gerhard H. Arfmann, Dr. Michael Twickler
Meeting at OBTC,24.04.2015, Yantai, PR China

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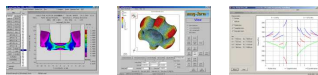
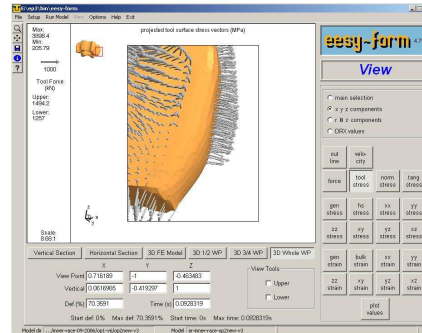


FEM Simulation in der Kaltumformung Aktuelle-beispiele und Ausblick

Aktuelle Anwendungsbeispiele und Ausblick

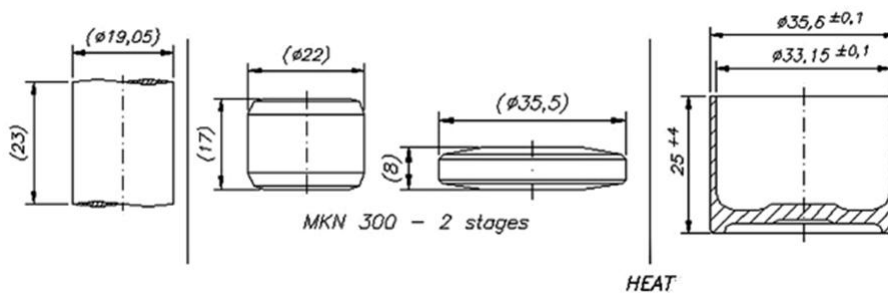


Inner Race

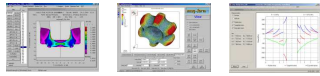


FEM Simulation in der Kaltumformung Aktuelle-beispiele und Ausblick

Aktuelle Anwendungsbeispiele und Ausblick



Ventilstößel

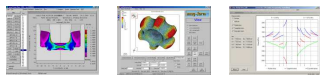


FEM Simulation in der Kaltumformung **Aktuelle-beispiele und Ausblick**

Aktuelle Anwendungsbeispiele und Ausblick

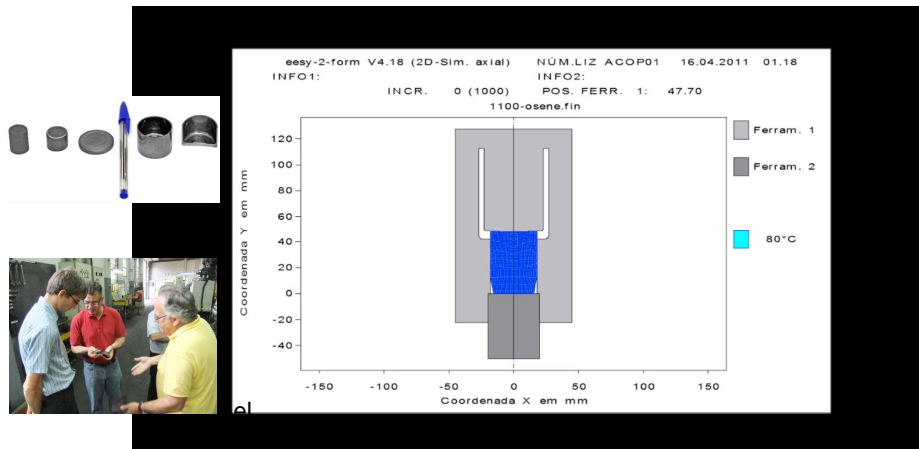


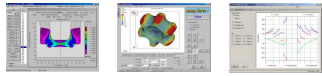
Ventilstößel



FEM Simulation in der Kaltumformung **Aktuelle-beispiele und Ausblick**

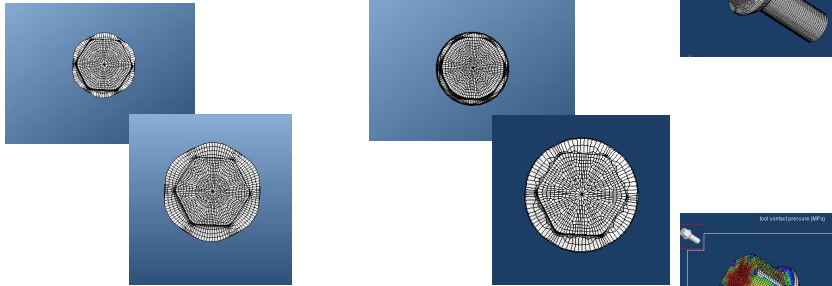
Aktuelle Anwendungsbeispiele und Ausblick



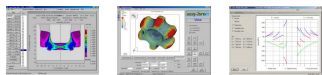
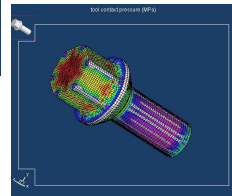


FEM Simulation in der Kaltumformung **Aktuelle-beispiele und Ausblick**

Aktuelle Anwendungsbeispiele und Ausblick

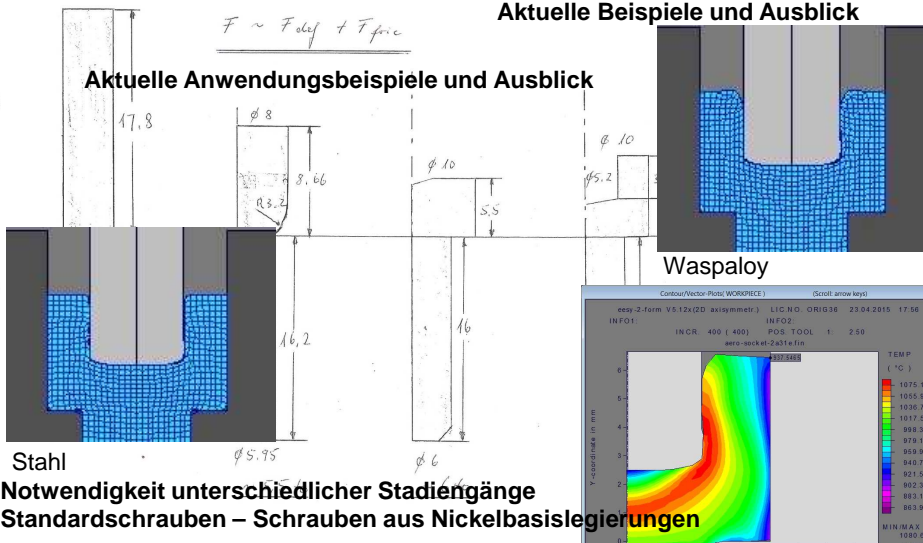


Vermeidung einer „Blume“



Aktuelle Beispiele und Ausblick

Aktuelle Anwendungsbeispiele und Ausblick

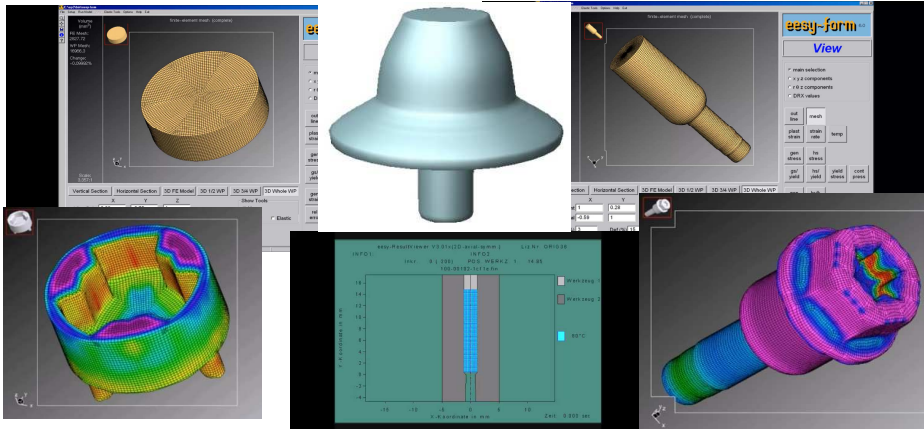
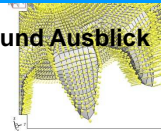


Notwendigkeit unterschiedlicher Stadiengänge
Standardschrauben – Schrauben aus Nickelbasislegierungen



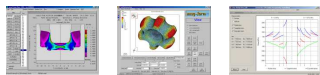
FEM Simulation in der Kaltumformung **Aktuelle-beispiele und Ausblick**

Aktuelle Anwendungsbeispiele und Ausblick



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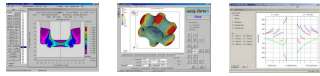
FEM Simulation in der Kaltumformung **Aktuelle-beispiele und Ausblick**

Aktuelle Anwendungsbeispiele und Ausblick



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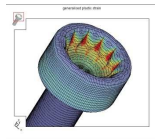
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FEM Simulation in der Kaltumformung **Aktuelle-beispiele und Ausblick**

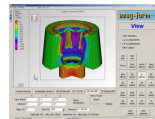
Aktuelle Anwendungsbeispiele und Ausblick

Zukünftige Entwicklungen



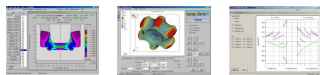
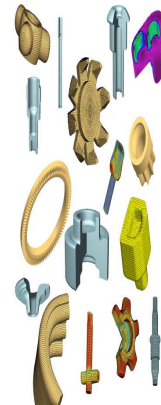
Integration der Umformtechnischen Simulation
in die gesamte Produktionskette

Vervollständigung der benötigten Materialdaten

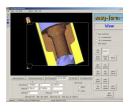


Entwicklung weiterer Teilmodule

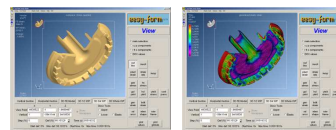
Reduzierung von umfassenden Systemen zu
hochspezialisierten, effizienten Spezialsystemen

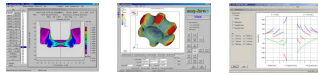


Danksagung



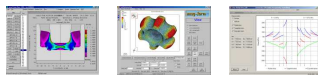
Die Autoren danken ihren Kunden, die relevante Informationen
zu den praktischen Beispielen und generelle Informationen
zur Anwendung der FEM beigetragen haben.
Solche Informationen sind sehr hilfreich, um Simulationssysteme
weiter zu entwickeln, aber auch um die sachgerechte Anwendung
der Simulationstechnik durch Vorträge wie diesen zu unterstützen.





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

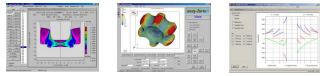
*Dr. Michael Twickler, Dr. Gerhard H. Arfmann
CPM GmbH, Herzogenrath*



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.



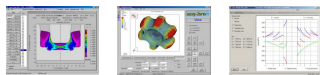
The most simple Model: "Pause Time = Recrystallization"

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 recrystallization 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

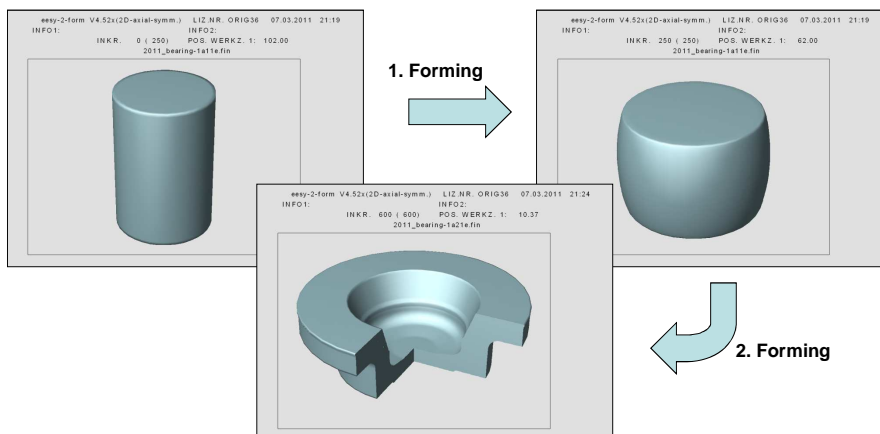


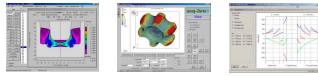
End of forming = Pause time = Complete recrystallization



The most simple Model: "Pause Time = Recrystallization"

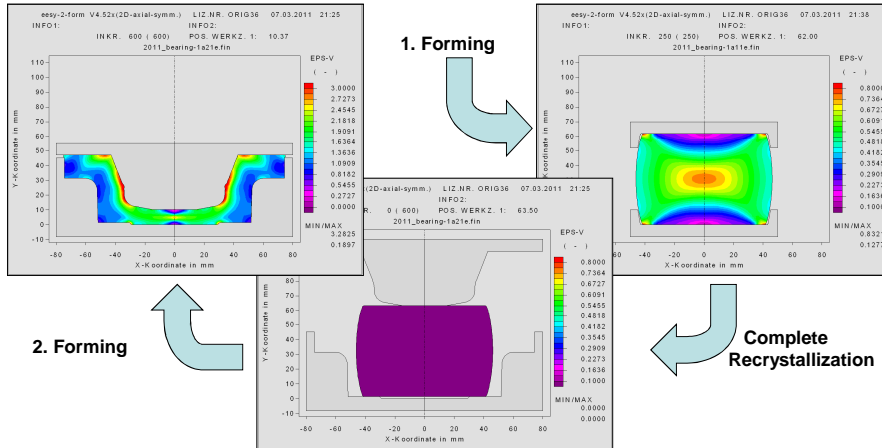
Example: Bearing Shell, 2-Step Forming at 1150°C





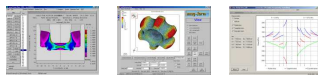
The most simple Model: "Pause Time = Recrystallization"

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



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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**

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

Model idea (1):

- a model of the dynamic recrystallization can be formulated like

dynamisch {

$$D_{\text{dyn.rek.}} = f(D_0, \epsilon, \delta\epsilon/\delta t, T, \text{etc.}) \Rightarrow \text{dyn. recryst. grain size}$$

$$F_{\text{dyn.rek.}} = f(\text{several process parameters}) \Rightarrow \text{dyn. recryst. fraction}$$

Relevance: during respectively directly after the forming

- a model of the static recrystallization can be formulated like

statisch {

$$D_{\text{stat.rek.}} = f(D_0, \epsilon, T, t, \text{etc.}) \Rightarrow \text{stat. recryst. grain size}$$

$$F_{\text{stat.rek.}} = f(\text{several process parameters}) \Rightarrow \text{stat. recryst. fraction}$$

Relevance: during pause time between respectively hold time after previous deformation



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

Model idea (2):

- a model for grain growth can be formulated like

Wachstum {

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

$$\Rightarrow \text{growth of the xx. recrystallized grain}$$

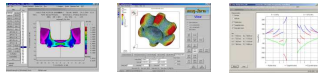
Relevance: for $\Delta D_{\text{dyn.rek.}}$: after the end of the dynamic recrystallization
for $\Delta D_{\text{stat.rek.}}$: after complete static recrystallization of the leftover grainstructure

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

Mischung {

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

$$\Rightarrow \text{new average of the initial grain size}$$



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 { $\epsilon_{v\text{-neu}} = f(\epsilon_v, F_{\text{dyn.rek.}}, F_{\text{stat.rek.}}) \Rightarrow$ new reduced strain

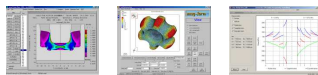
Relevance: after completion of the dynamic recrystallization and during the static recrystallization

- 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:

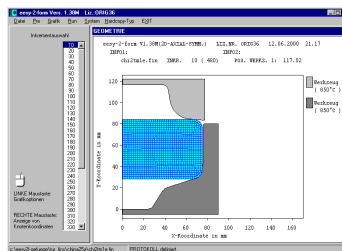
- interaction and dependencies of the various models
- Start/Stop-conditions for the models



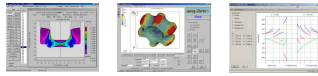
Dynamic/Static Model for Forming and Hold Times



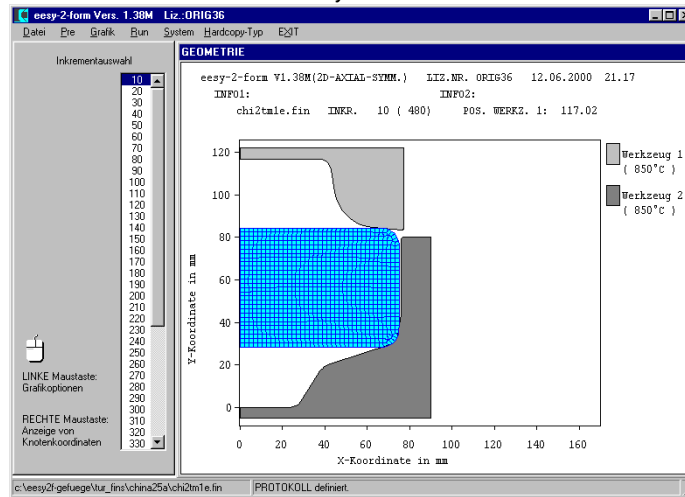
SIMULATION DER GEFÜGEENTWICKLUNG BEIM SCHMIEDEN MIT HILFE DES SOFTWARE-SIMULATIONSPROGRAMMS *eesy-2-form*



Ergebnisse von Arbeiten aus den 1990er Jahren !!!

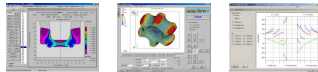


SIMULATION DER GEFÜGEENTWICKLUNG BEIM SCHMIEDEN MIT HILFE DES SOFTWARE-SIMULATIONSPROGRAMMS
easy-2-form

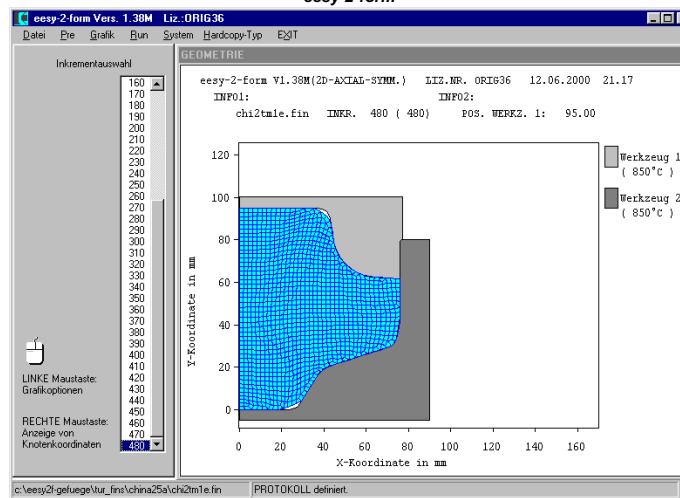


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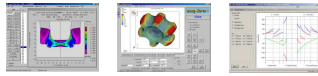


SIMULATION DER GEFÜGEENTWICKLUNG BEIM SCHMIEDEN MIT HILFE DES SOFTWARE-SIMULATIONSPROGRAMMS
easy-2-form

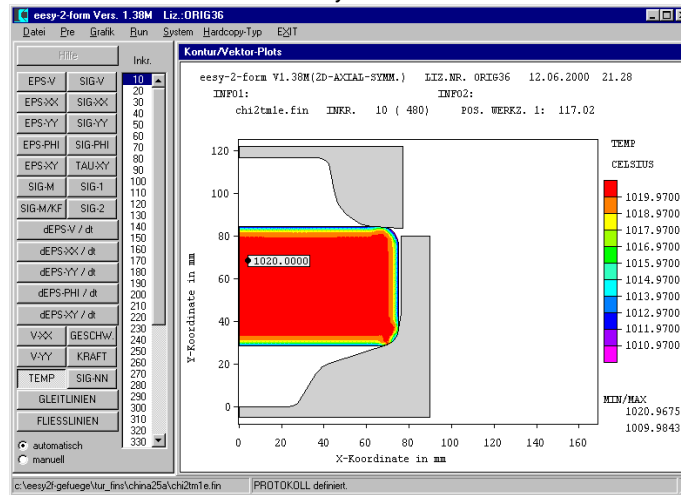


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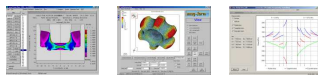


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easy-2-form**

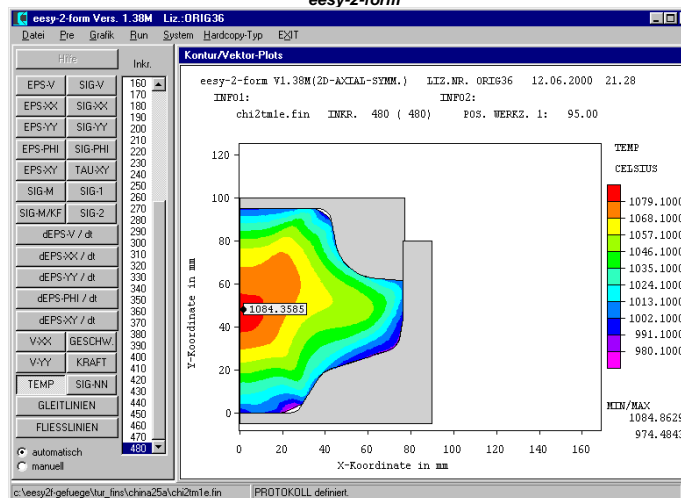


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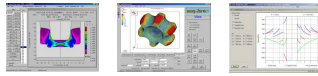


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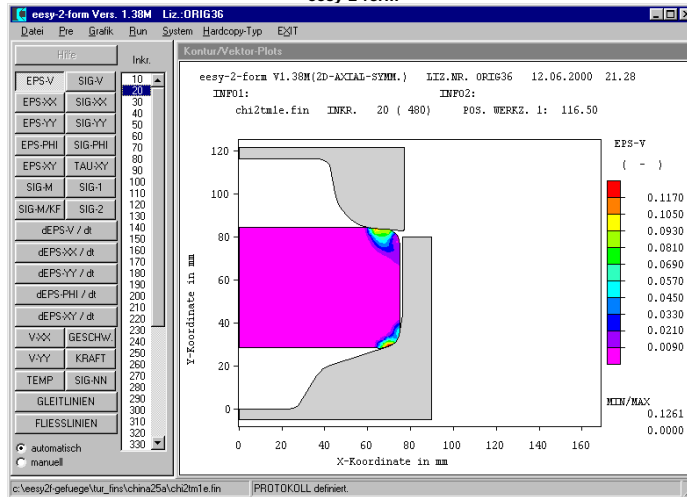


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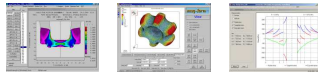


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easy-2-form

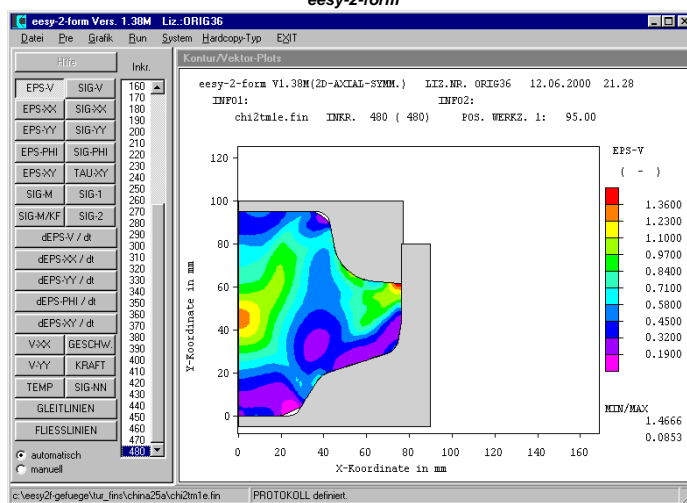


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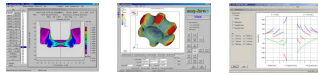


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easy-2-form

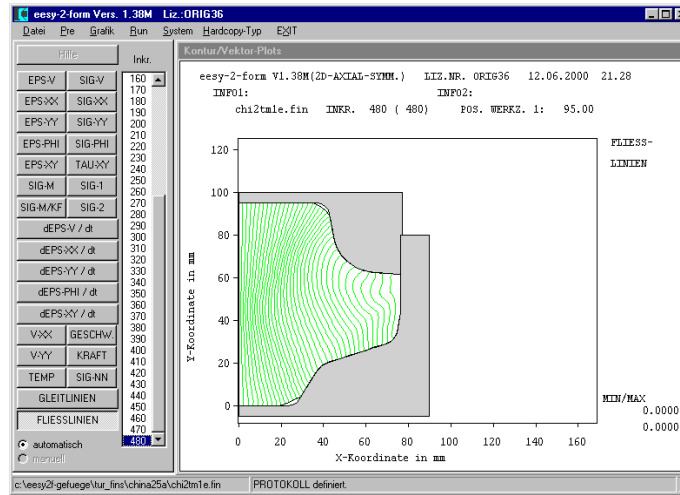


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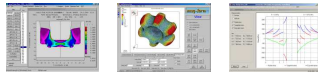


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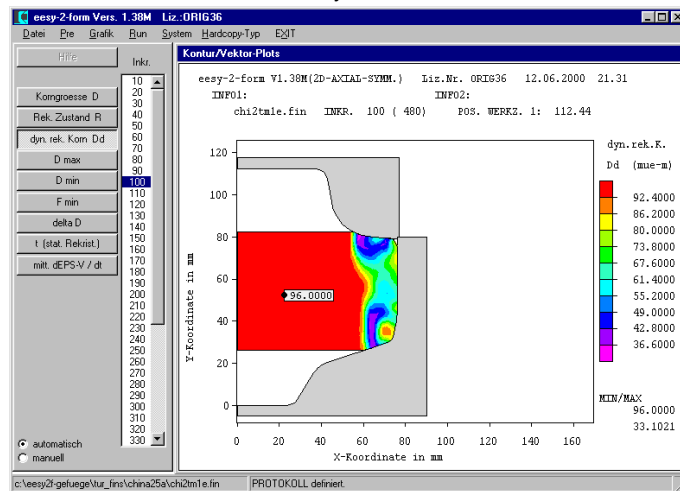


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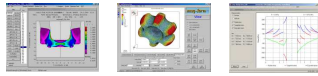


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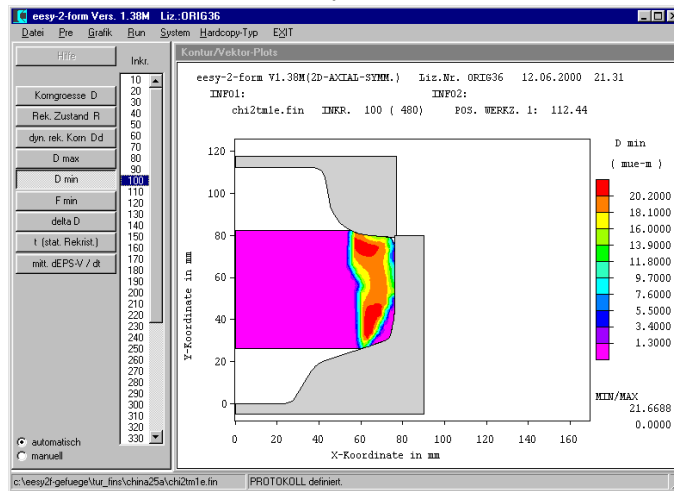


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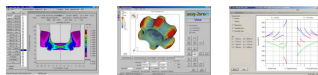


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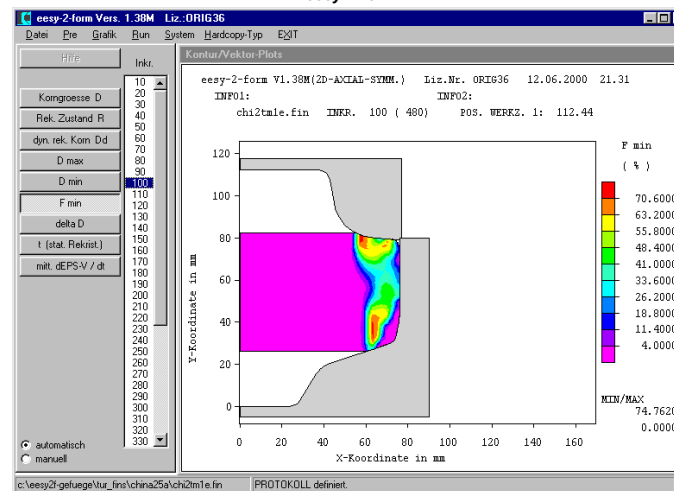


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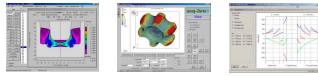


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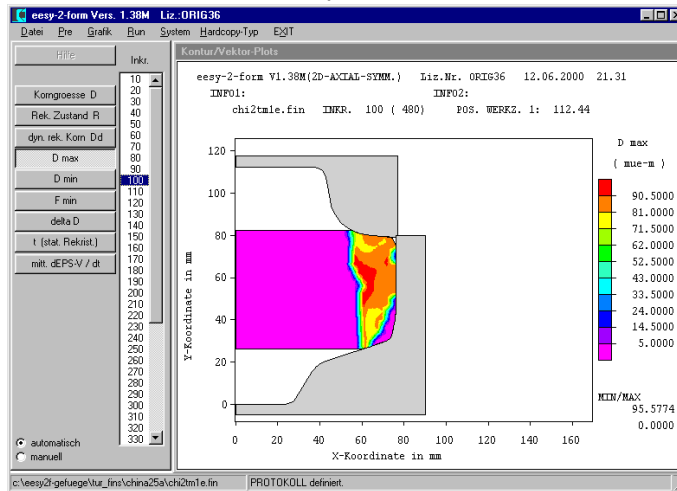


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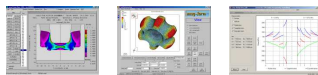


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easy-2-form

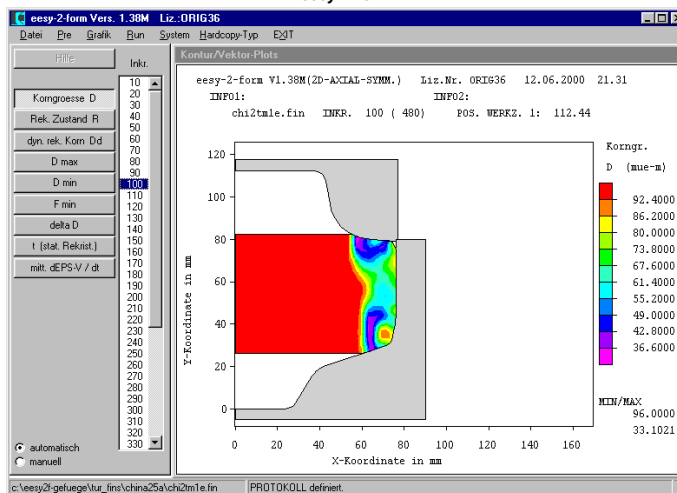


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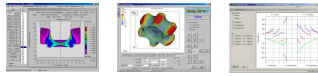


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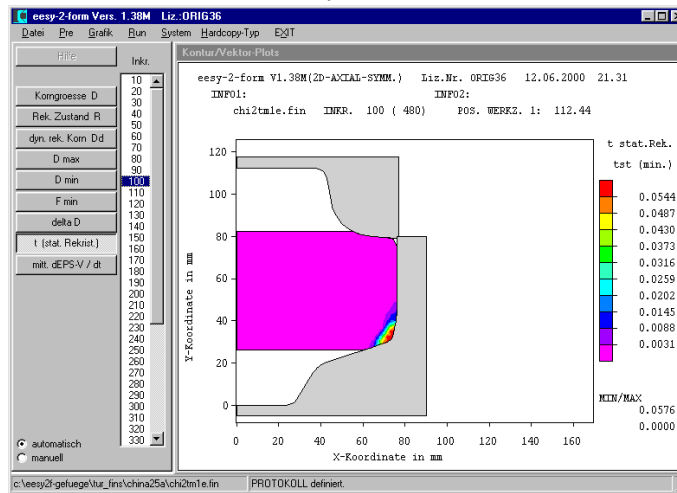


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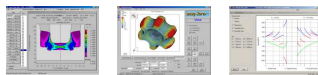


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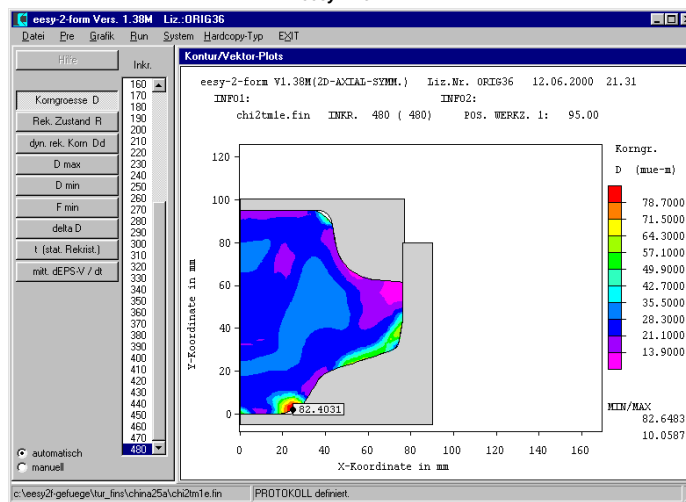


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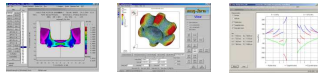


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easy-2-form

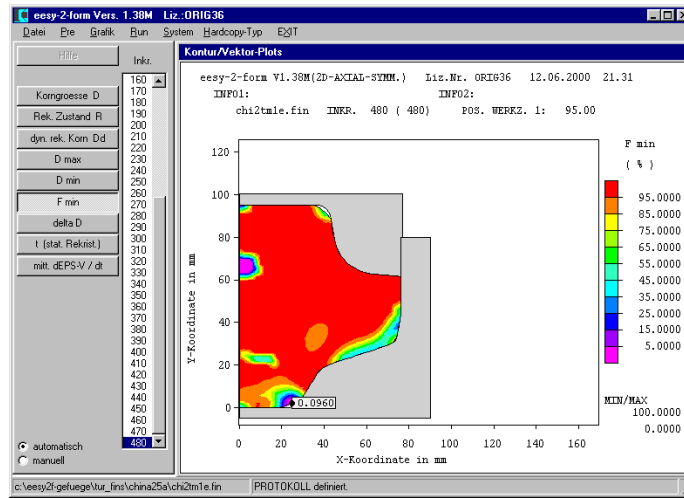


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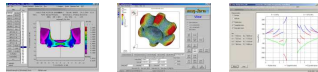


SIMULATION DER GEFÜGEENTWICKLUNG BEIM SCHMIEDEN MIT HILFE DES SOFTWARE-SIMULATIONSPROGRAMMS
easy-2-form

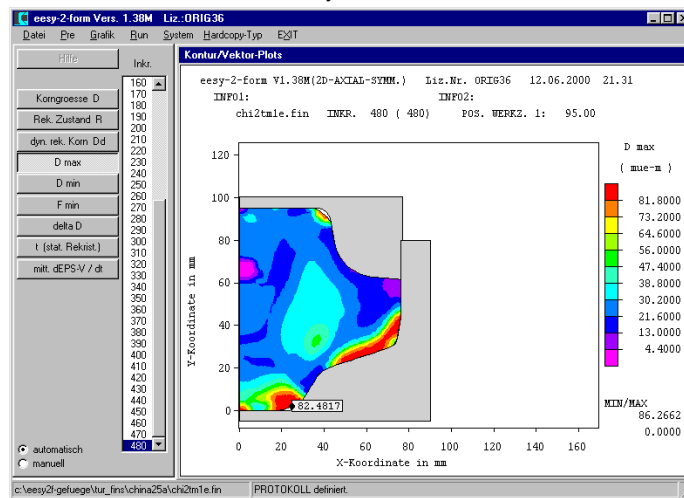


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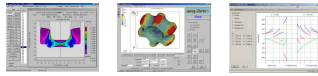


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easy-2-form

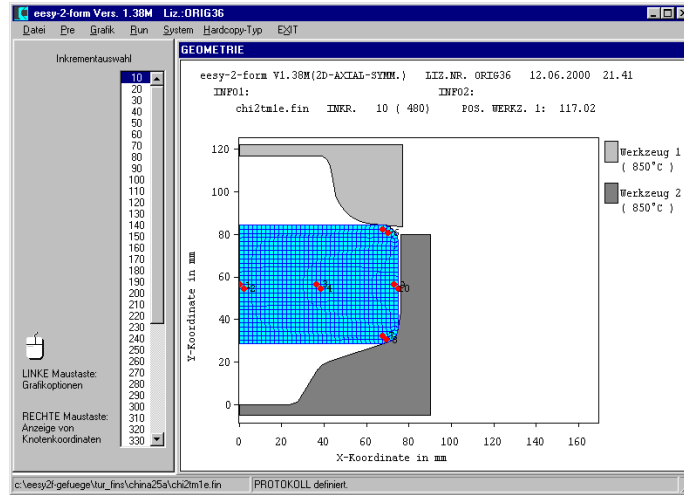


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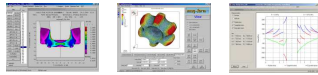


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easy-2-form

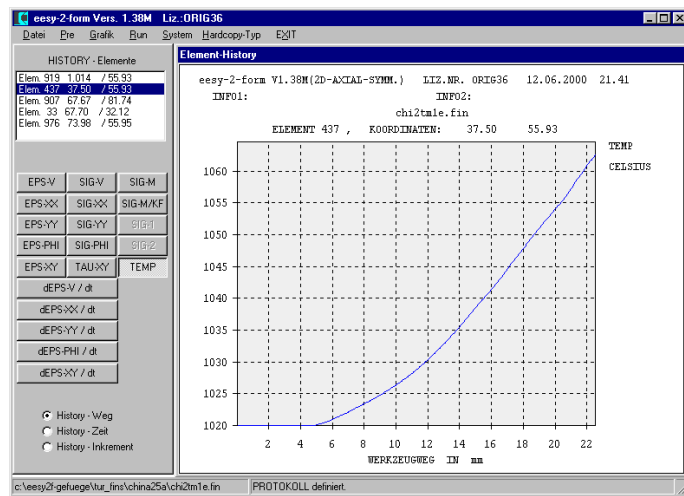


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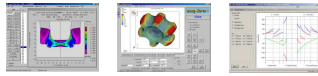


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easy-2-form

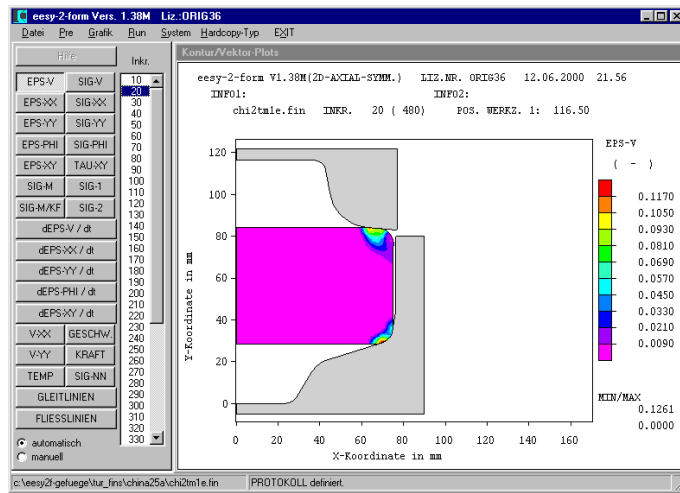


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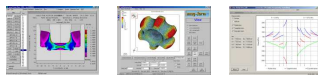


**SIMULATION DER GEFÜGEENTWICKLUNG BEIM SCHMIEDEN MIT HILFE DES SOFTWARE-SIMULATIONSPROGRAMMS
easy-2-form**

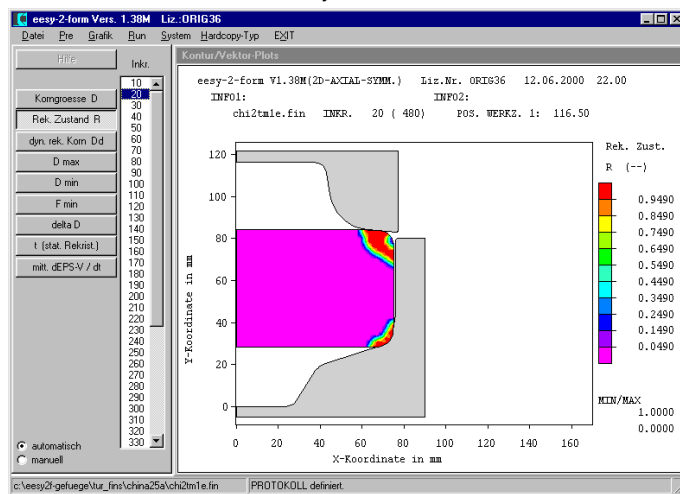


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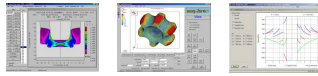


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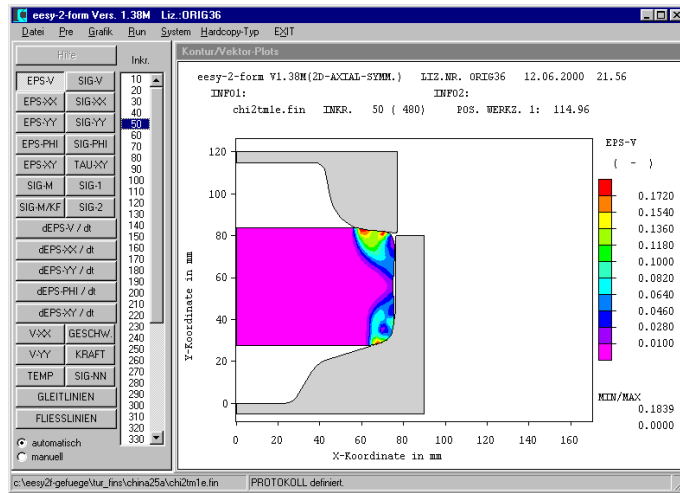


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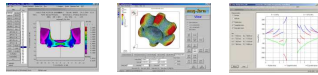


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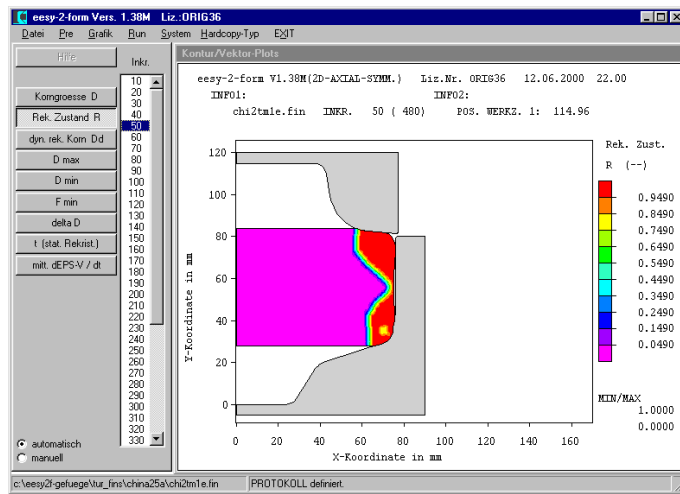


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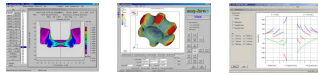


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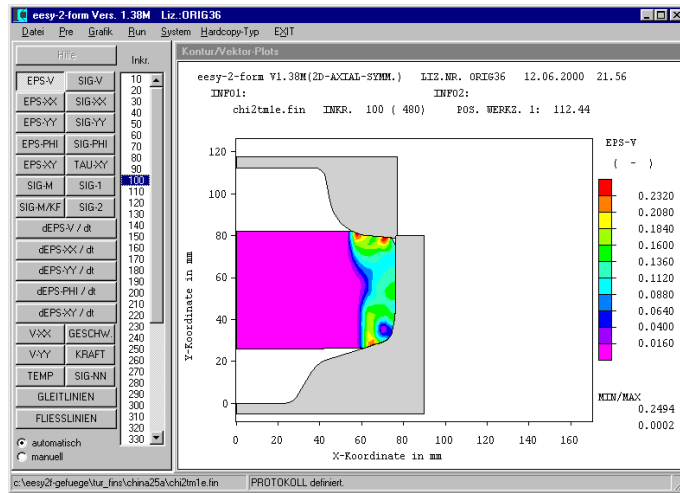


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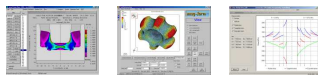


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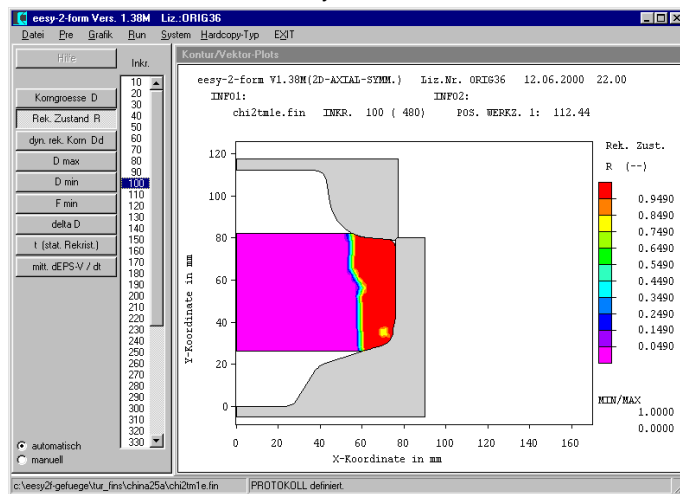


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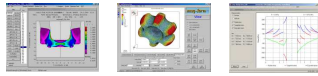


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easy-2-form**

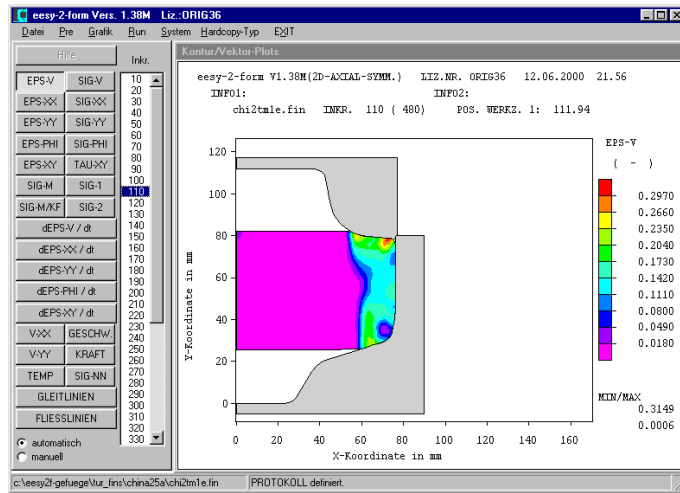


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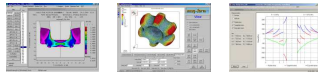


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easy-2-form**

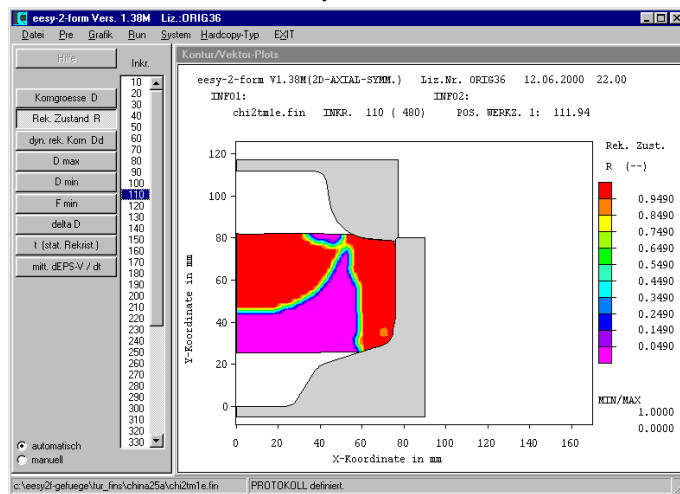


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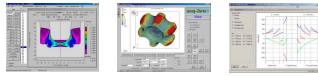


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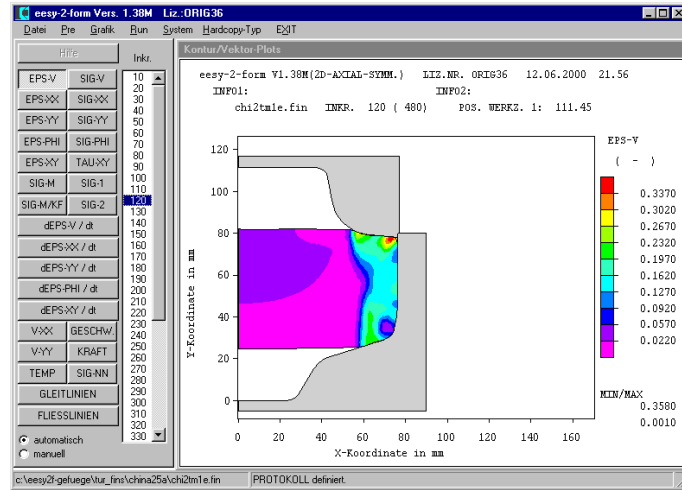


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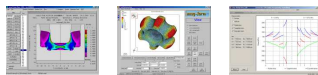


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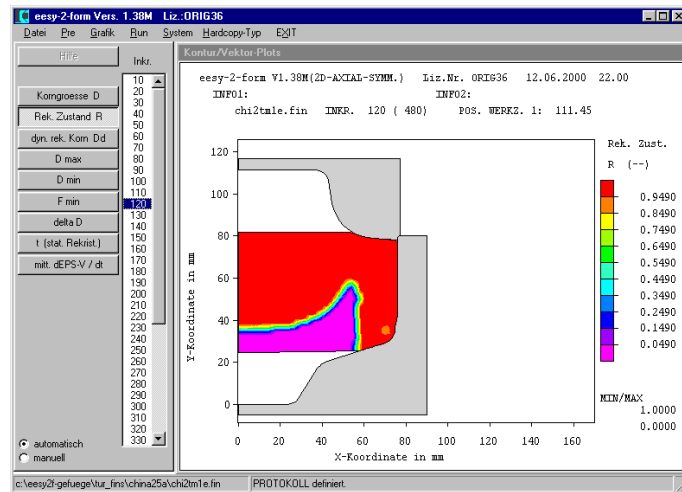


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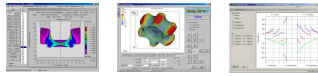


**SIMULATION DER GEFÜGEENTWICKLUNG BEIM SCHMIEDEN MIT HILFE DES SOFTWARE-SIMULATIONSPROGRAMMS
easy-2-form**

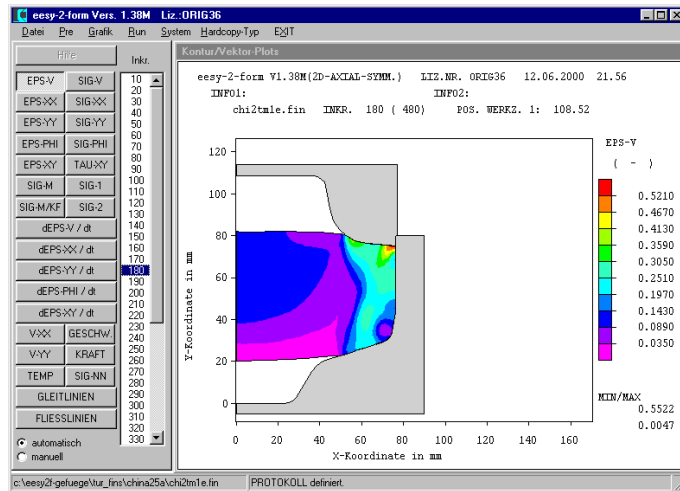


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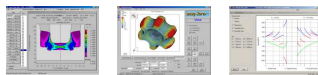
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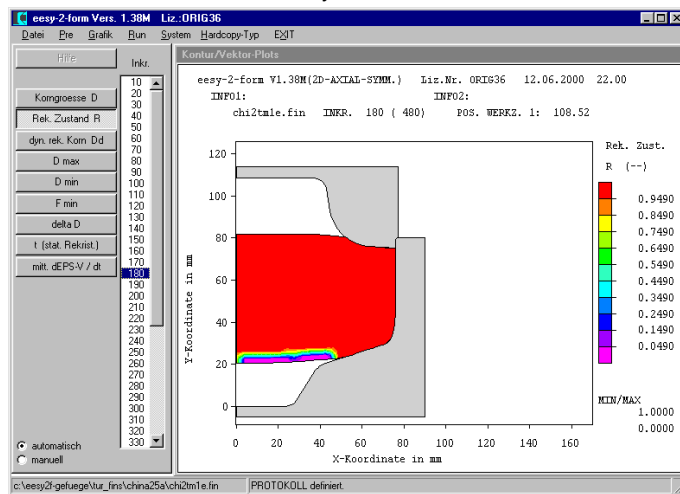
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easy-2-form



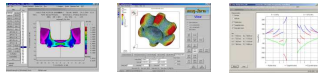
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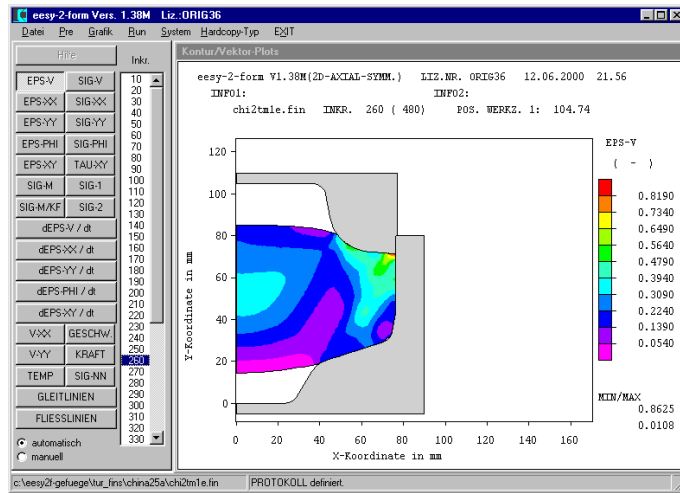
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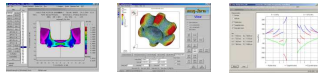


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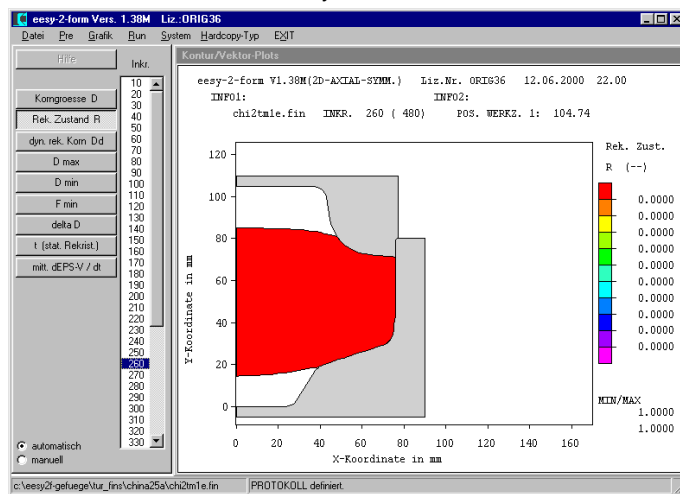


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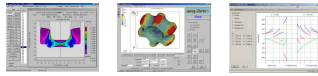


SIMULATION DER GEFÜGEENTWICKLUNG BEIM SCHMIEDEN MIT HILFE DES SOFTWARE-SIMULATIONSPROGRAMMS
easy-2-form

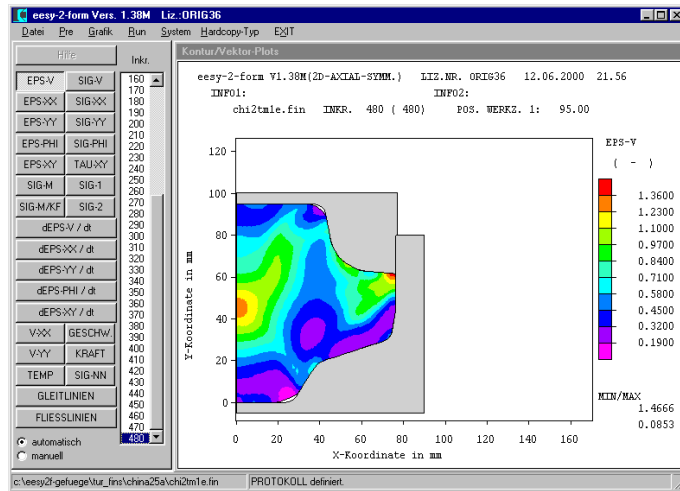


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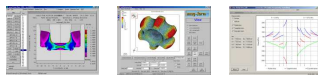


**SIMULATION DER GEFÜGEENTWICKLUNG BEIM SCHMIEDEN MIT HILFE DES SOFTWARE-SIMULATIONSPROGRAMMS
easy-2-form**

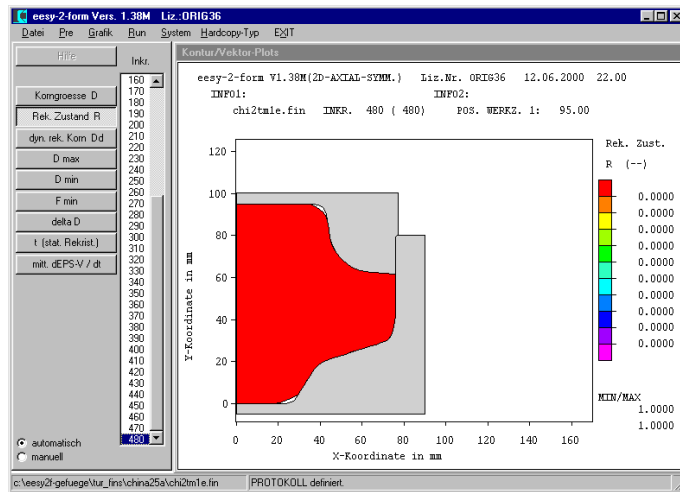


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**SIMULATION DER GEFÜGEENTWICKLUNG BEIM SCHMIEDEN MIT HILFE DES SOFTWARE-SIMULATIONSPROGRAMMS
easy-2-form**

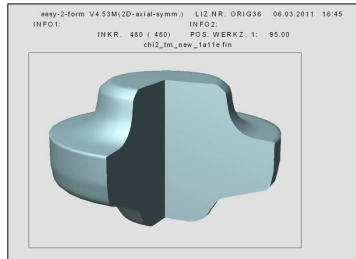


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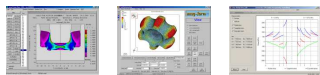
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SIMULATION DER GEFÜGEENTWICKLUNG BEIM SCHMIEDEN MIT HILFE DES SOFTWARE-SIMULATIONSPROGRAMMS *eesy-2-form*

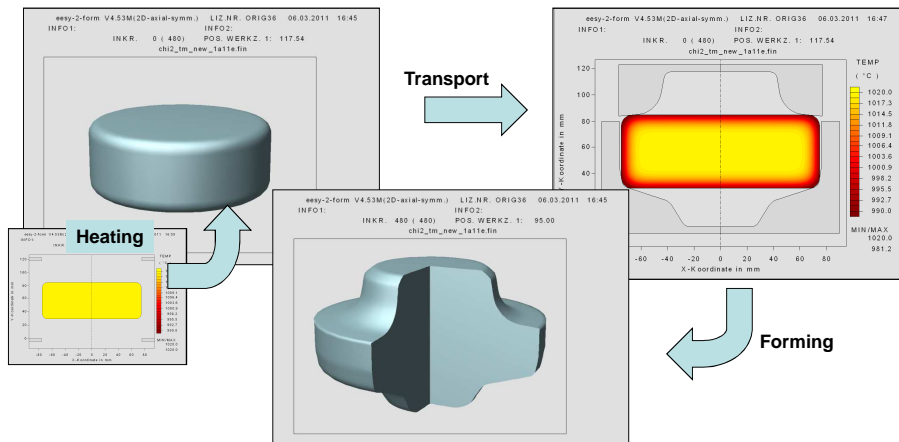


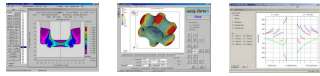
Ergebnisse von Arbeiten zusammen mit einem Kunden und
CISRI Peking aus den 2000er Jahren !!!



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

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

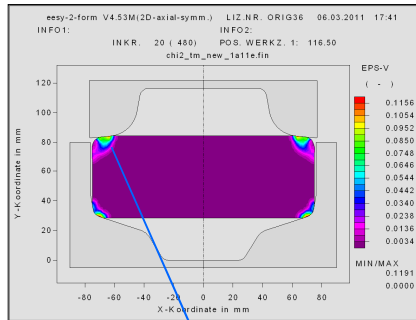




The typical model: "Dynamic/Static incl. Grain Growth"

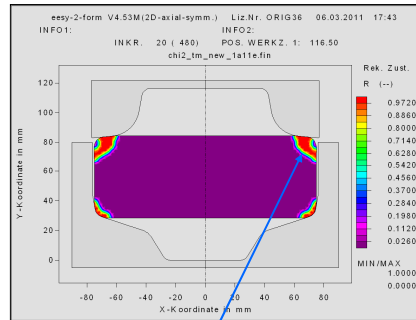
Example: Turbine disc made from Inconel 718, one step forming at 1020°C
- results after 5% press movement

Equivalent Strain [-]



Certain amount of strain

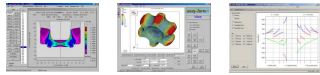
Recrystallization [-]



Dynamic recrystallization (local)

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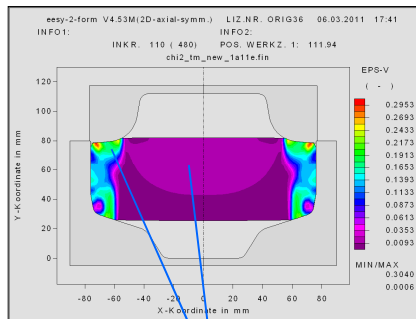
87



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

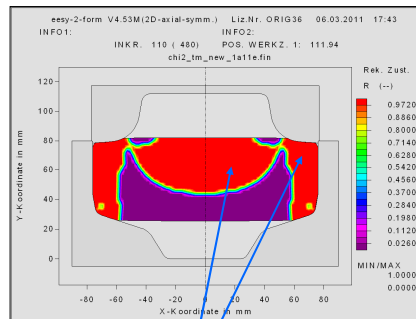
Example: Turbine disc made from Inconel 718, one step forming at 1020°C
- results after 25% press movement

Equivalent Strain [-]



Certain amount of strain

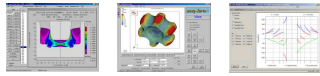
Recrystallization [-]



Dynamic recrystallization (local)

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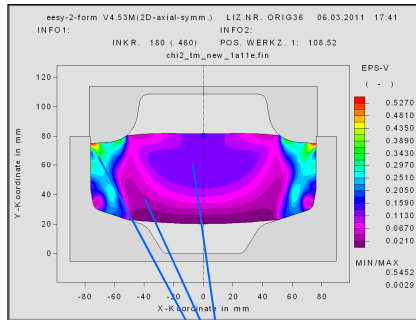
88



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

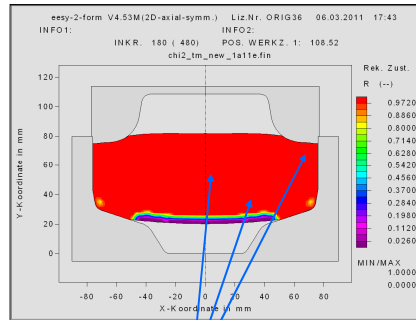
Example: Turbine disc made from Inconel 718, one step forming at 1020°C
- results after 40% press movement

Equivalent Strain [-]



Certain amount of strain

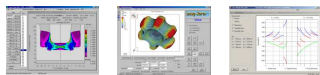
Recrystallization [-]



Dynamic recrystallization (local)

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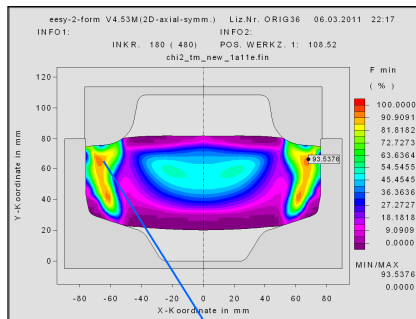
89



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

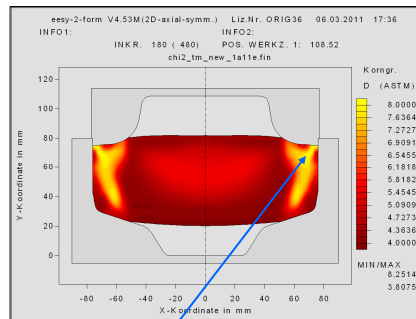
Example: Turbine disc made from Inconel 718, one step forming at 1020°C
- results after 40% press movement

Recrystallized Fraction [%]



High recrystallized fraction

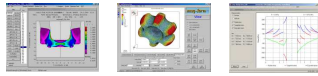
Grain Size [ASTM]



Fine (dyn. recrystallized) grain

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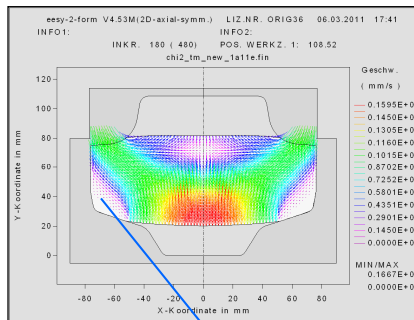
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The typical model: "Dynamic/Static incl. Grain Growth"

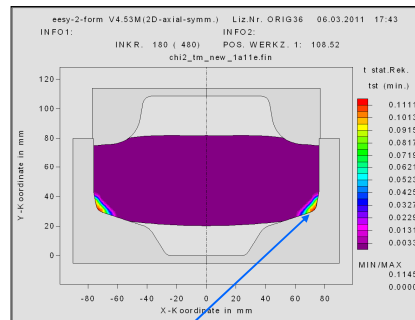
Example: Turbine disc made from Inconel 718, one step forming at 1020°C
- results after 40% press movement

Material Flow [mm/sec]



„Dead“ zone, - actually no forming

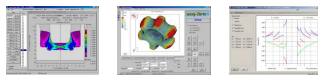
Duration of Static Recrystallization [min]



stat. recrystallization after forming

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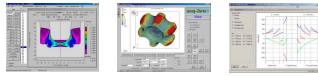
The typical model: "Dynamic/Static incl. Grain Growth"

Results:

- resulting strain represents the actual deformation and hardening situation (local 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

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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.

$$\sigma = f(\delta\epsilon/\delta t, T, \epsilon) \quad \text{is no longer valid}$$

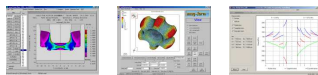
- as new state value the dislocation density ρ is introduced like

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

- 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

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

b) dislocation reduction by spontaneous annihilation

$$\delta\rho/\delta t = c_3 * M * d_{\text{spontan}} * \delta\epsilon/\delta t / b * \rho$$

c) dislocation reduction by thermally activated climbing

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

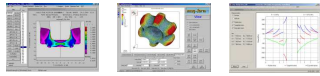
- the yield stress can be calculated as depending of the dislocation density like

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

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

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

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



The complex model: "Dislocation Based Model" *)

Model idea (3):

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

a) dynamic recrystallization,

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

b) static recovery and static/metadynamic recrystallization,

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

c) precipitation during hold time and

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

d) grain growth after complete recrystallization

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

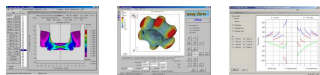


Dislocation Based Material and Grain model

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

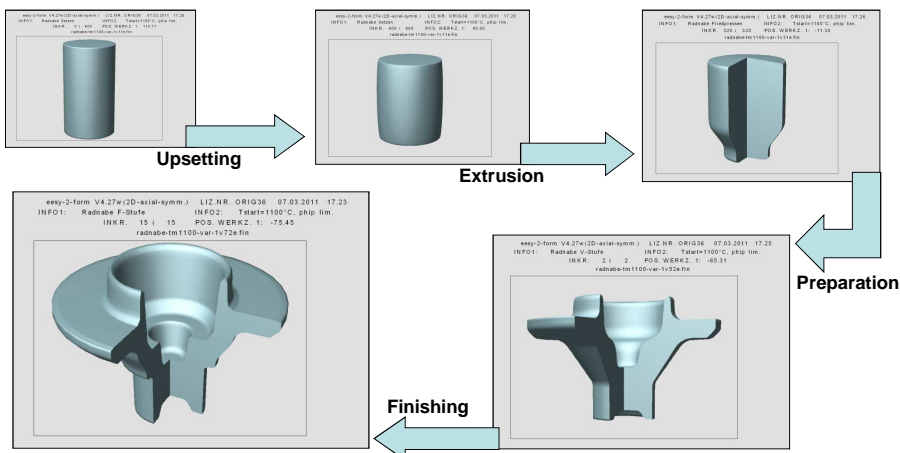
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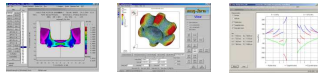
The complex model: "Dislocation Based Model"

Example: Wheel Hub, 4-step forming at $T_{\text{start}} = 1100^\circ\text{C}$, initial grain size: $54,8 \mu\text{m}$



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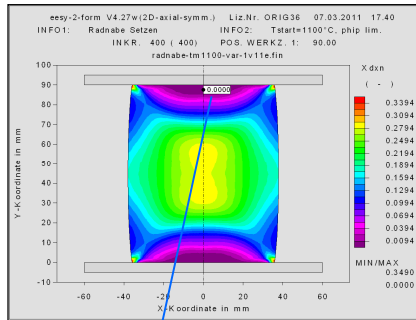
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The complex model: "Dislocation Based Model"

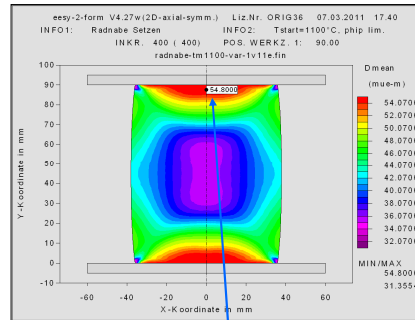
Example: Wheel Hub, 4-step forming at $T_{start} = 1100^{\circ}\text{C}$, initial grain size: $54,8 \mu\text{m}$

Recrystallized Fraction [-]



Not yet recrystallized area

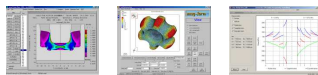
Grain Size [μm]



Grain size = Initial grain size

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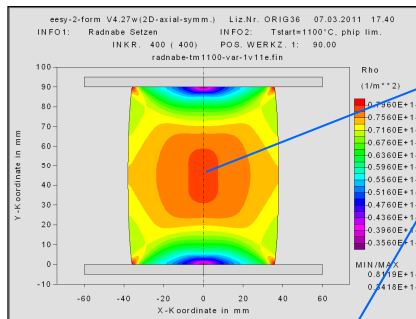
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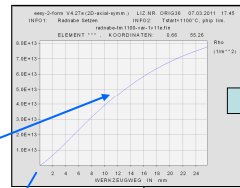
The complex model: "Dislocation Based Model"

Example: Wheel Hub, 4-step forming at $T_{start} = 1100^{\circ}\text{C}$, initial grain size: $54,8 \mu\text{m}$

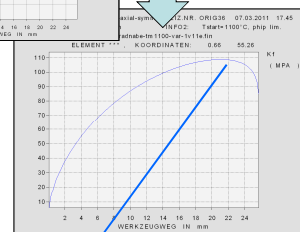
Dislocation Density [$1/\text{m}^2$]



Dislocation evolution (over time)



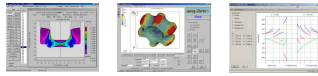
Yield Stress [MPa]



Yield stress (over time)

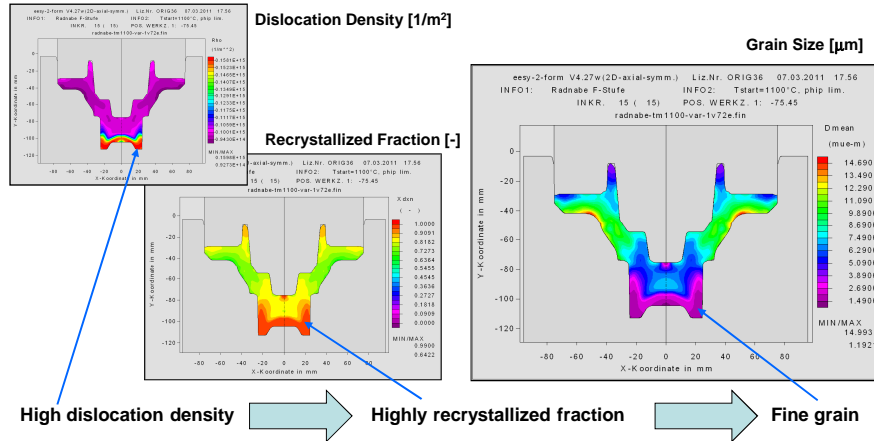
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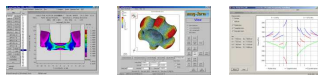
The complex model: "Dislocation Based Model"

Example: Wheel Hub, 4-step forming at $T_{start} = 1100^{\circ}\text{C}$, initial grain size: $54,8 \mu\text{m}$



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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, split 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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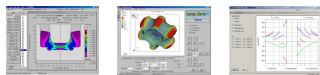


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“Dislocation Based Model”

as part of the joint research project

**“Mikrostrukturbasierte Modellierung des Umformverhaltens
von mikrolegierten Stählen bei mehrstufigen Schmiedeprozessen“.**



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