

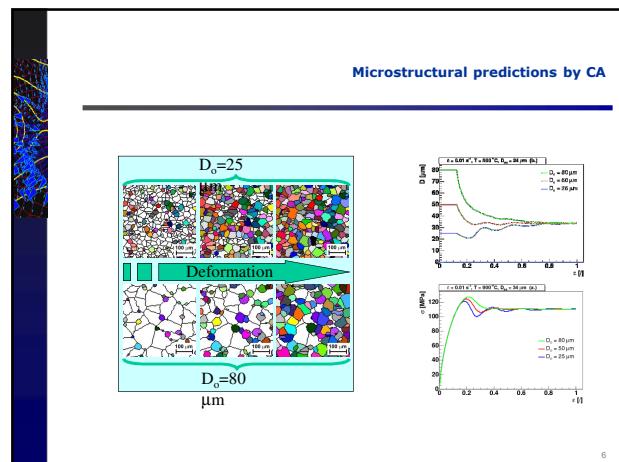
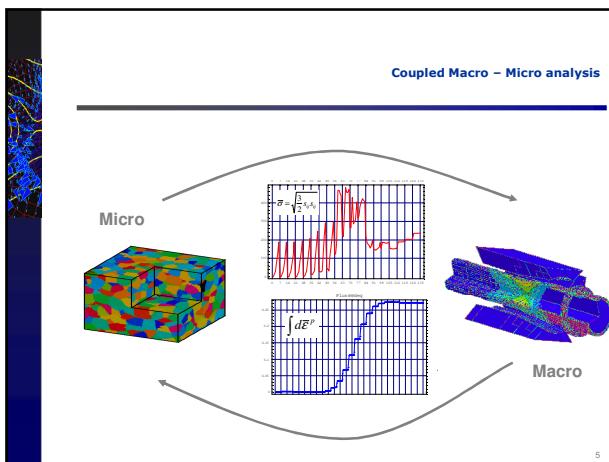
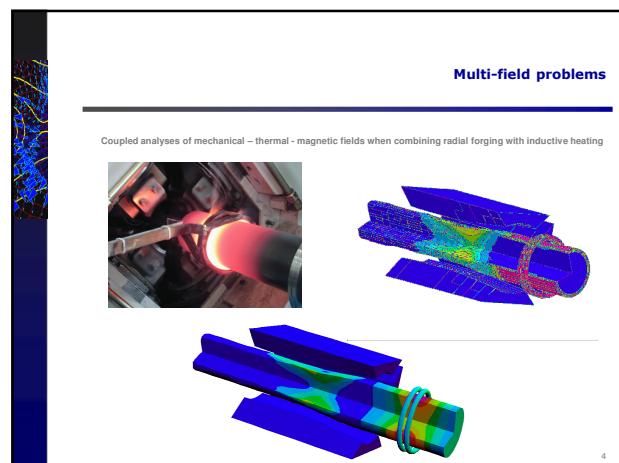
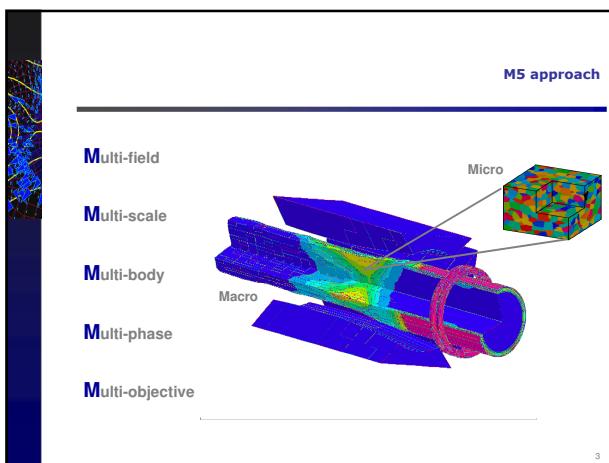
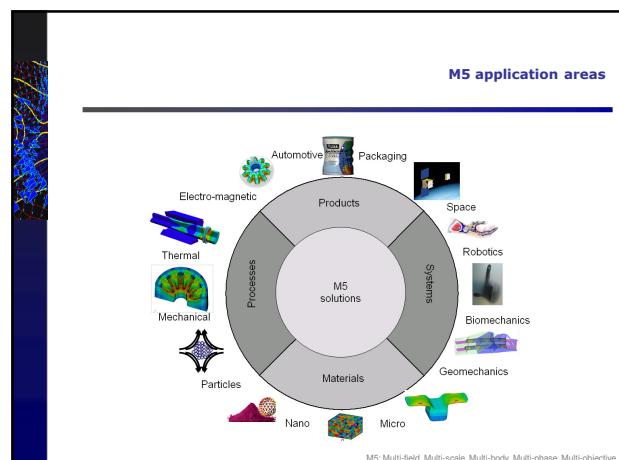
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Workshop / Radionica  
"Innovation in engineering design"  
"Inovacije u inženjerskom projektiranju"  
27-28. siječanj 2011, Sveučilište u Rijeci – Tehnički fakultet

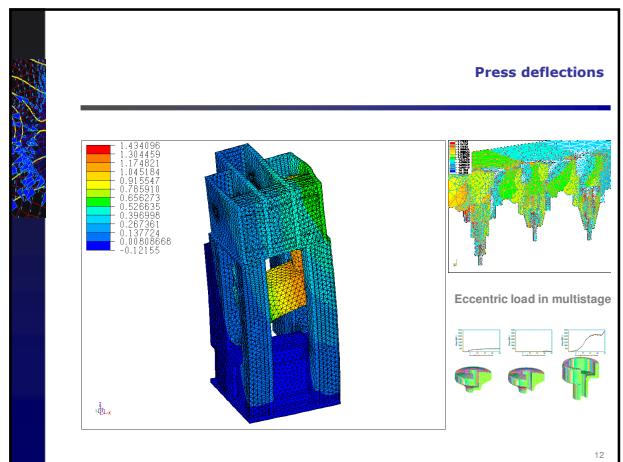
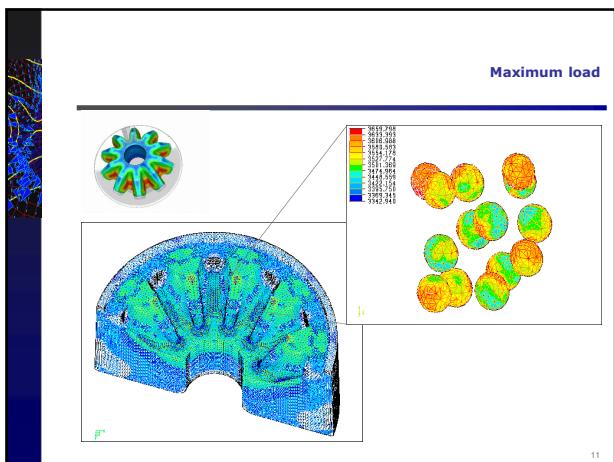
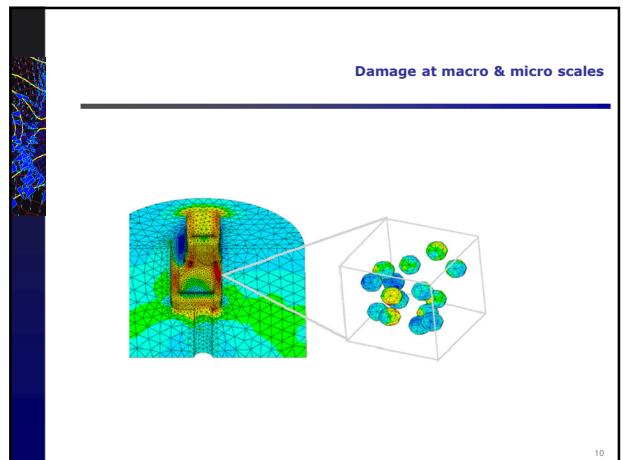
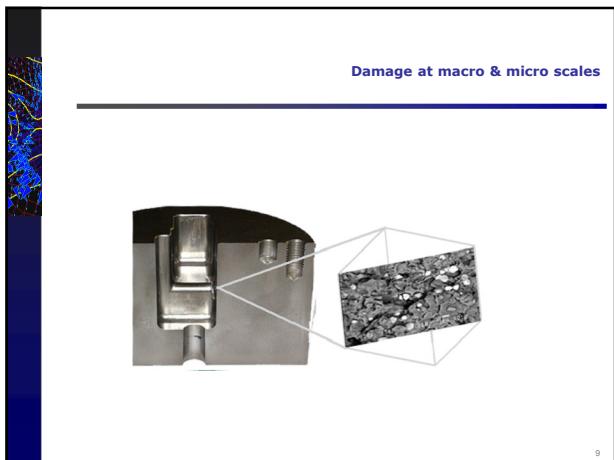
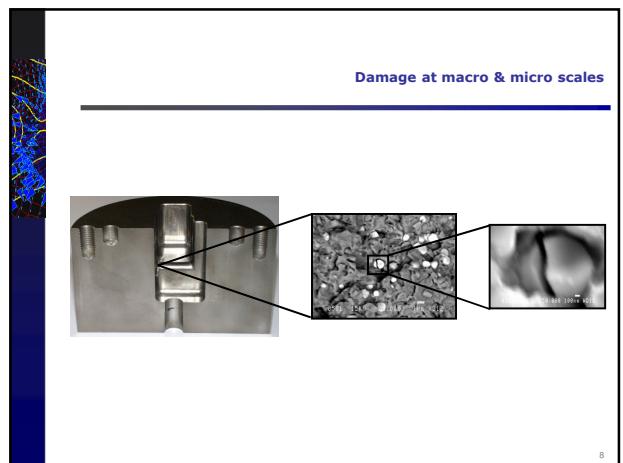
**Workshop / Radionica**  
**"Innovation in engineering design"**  
**"Inovacije u inženjerskom projektiranju"**  
27-28. January 2011, Rijeka

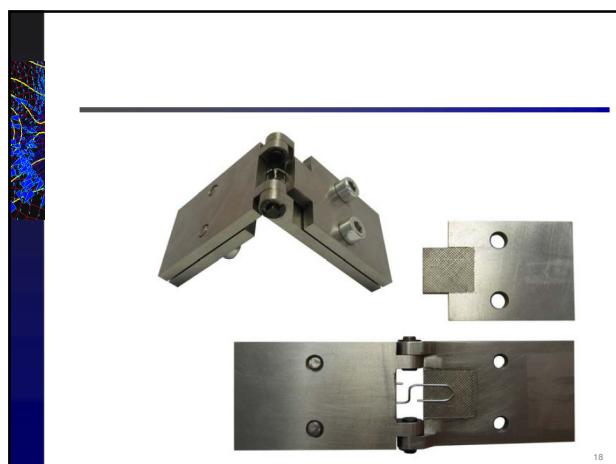
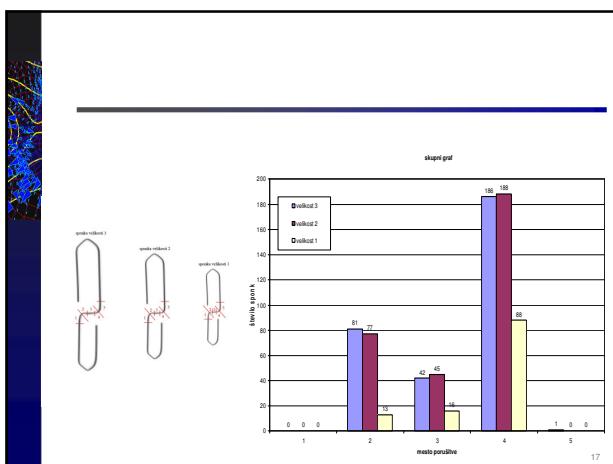
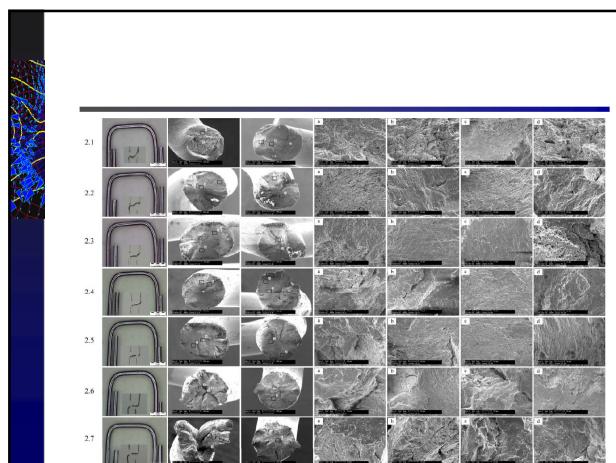
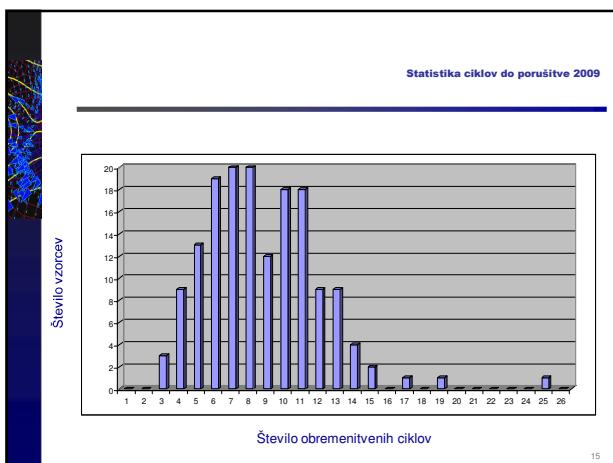
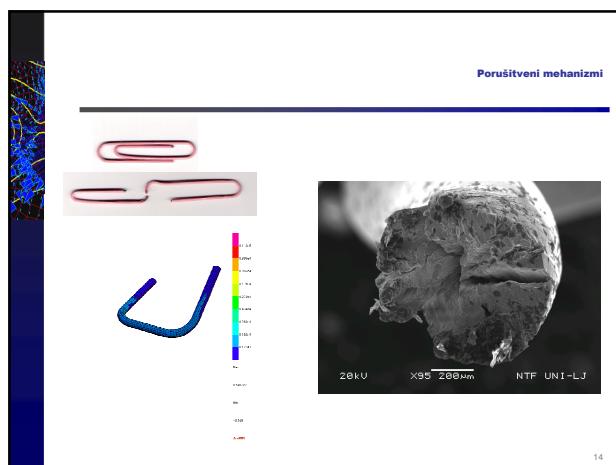
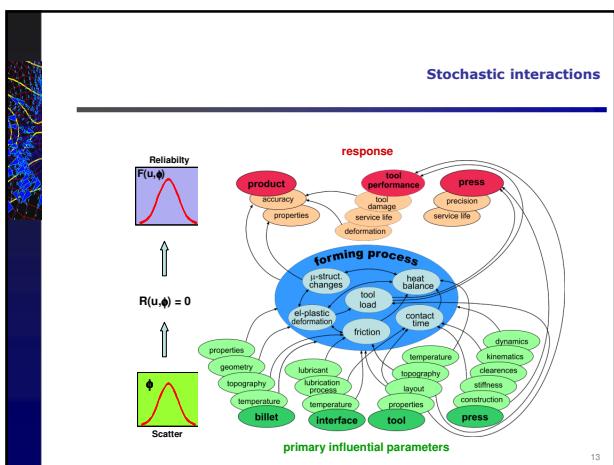
**M5 computations in production engineering and technologies**

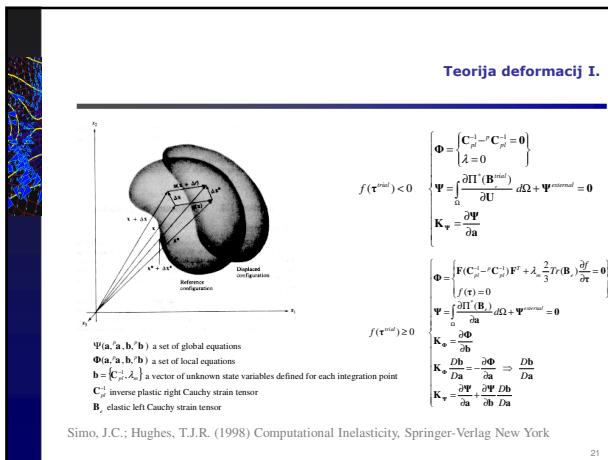
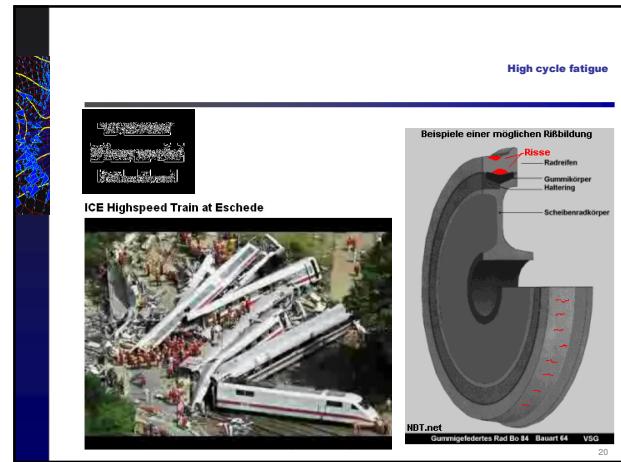
Tomaž Rodič  
University of Ljubljana, Slovenia

This project has been funded with support from the European Commission  
European Commission  
TEMPUS









**Teorija deformacij II.**

$\mathbf{B}_e = \mathbf{F} \mathbf{C}_p^{-1} \mathbf{F}^T$   
 $f = \text{yield condition}$   
 $\lambda_m = \text{plastic multiplier}$   
 $\mathbf{K}_\Psi = \frac{\partial \Pi^*(\mathbf{B}_e)}{\partial \mathbf{B}_e}$   
 $\mathbf{B}_e^{trial} = \mathbf{F}^{-1} \mathbf{C}_p^{-1} \mathbf{F}^T$   
 $\mathbf{K}_\Phi = \frac{\partial \Phi}{\partial \mathbf{a}}$   
 $\mathbf{t}^{trial} = 2 \mathbf{B}_e^{trial} \frac{\partial \Pi^*(\mathbf{B}_e^{trial})}{\partial \mathbf{B}_e^{trial}}$   
 $\mathbf{t} = \text{Kirchhoff stress tensor}$   
 $\mathbf{B}_e = \text{elastic left Cauchy strain tensor}$   
 $\dot{\epsilon}^p = \sqrt{2/3} \lambda_m$   
 $\dot{\epsilon}^p = \text{equivalent plastic strain}$

Hyperelastic Neo-Hookean Strain Energy Function

$$\Pi^*(\mathbf{B}) = \frac{\lambda}{2} (\sqrt{\det \mathbf{B}} - 1)^2 + \mu \left( \text{tr} \mathbf{B} - 3 - \log(\sqrt{\det \mathbf{B}}) \right)$$

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**Prenos topote**

$\nabla \cdot (k \nabla T) + q = \rho c_p \frac{\partial T}{\partial t}$

initial condition:  $T = T_o(x, z, y, 0)$  in  $\Omega$  and  $\Gamma$

boundary conditions:  $T = T_u(x, z, y, t)$  on  $\Gamma_u$

$k \frac{\partial T}{\partial n} = q_s$  on  $\Gamma_s$

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**Elektromagnetska polja**

Faraday, Gauss, Ampere, Maxwell's laws,

$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$   
 $\nabla \cdot \mathbf{D} = \rho$   
 $\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$   
 $\nabla \cdot \mathbf{B} = 0$

$\mathbf{H}$  magnetic field strength,  $\mathbf{J}$  current density,  $\mathbf{E}$  electric field strength,  $\mathbf{D}$  electric flux density,  $\mathbf{B}$  magnetic flux density and  $\rho$  charge density.

Magnetic Thermal Mechanical

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**Občutljivostna analiza**

---

**Residual equation**

$$R(\mathbf{U}(\phi), {}^n\mathbf{U}(\phi), \phi) = \mathbf{0}$$

**Response functional**

$$F(\phi) = G({}^1\mathbf{U}(\phi), \dots, {}^M\mathbf{U}(\phi), \phi)$$

**Design sensitivity**

$$\frac{\partial F}{\partial \phi} = \frac{\partial G}{\partial {}^1\mathbf{U}} \frac{\partial {}^1\mathbf{U}}{\partial \phi} + \dots + \frac{\partial G}{\partial {}^M\mathbf{U}} \frac{\partial {}^M\mathbf{U}}{\partial \phi} + \frac{\partial G}{\partial \phi}$$

**Sensitivity problem**

$$\frac{\partial R}{\partial \mathbf{U}} \frac{\partial \mathbf{U}}{\partial \phi} = - \left( \frac{\partial R}{\partial {}^1\mathbf{U}} \frac{\partial {}^1\mathbf{U}}{\partial \phi} + \frac{\partial R}{\partial \phi} \right)$$

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**Contact sensitivity**

---

**Total derivatives of the contact tractions**

$$\begin{aligned} \frac{\partial T_N}{\partial \phi} &= \left( \frac{\partial T_N}{\partial \mathbf{x}} \right)^T \frac{\partial \mathbf{x}}{\partial \phi} + \frac{\partial T_N}{\partial \phi} \\ \frac{\partial T_T}{\partial \phi} &= \left( \frac{\partial T_T}{\partial \mathbf{x}} \right)^T \frac{\partial \mathbf{x}}{\partial \phi} + \left( \frac{\partial T_T}{\partial \mathbf{x}} \right)^T \frac{\partial {}^n\mathbf{x}}{\partial \phi} + \frac{\partial T_T}{\partial T_N} \frac{\partial T_N}{\partial \phi} + \frac{\partial T_T}{\partial {}^nT_T} \frac{\partial {}^nT_T}{\partial \phi} + \frac{\partial T_T}{\partial \phi} \end{aligned}$$

**Total derivatives of the nodal force vector**

$$\begin{aligned} \frac{\partial \mathbf{r}}{\partial \phi} &= \left[ \frac{\partial \mathbf{r}}{\partial \mathbf{x}} + \frac{\partial \mathbf{r}}{\partial T_N} \left( \frac{\partial T_N}{\partial \mathbf{x}} \right)^T + \frac{\partial \mathbf{r}}{\partial T_T} \left( \frac{\partial T_T}{\partial \mathbf{x}} + \frac{\partial T_T}{\partial T_N} \frac{\partial T_N}{\partial \mathbf{x}} \right)^T \right] \frac{\partial \mathbf{x}}{\partial \phi} \\ &+ \left[ \frac{\partial \mathbf{r}}{\partial {}^n\mathbf{x}} + \frac{\partial \mathbf{r}}{\partial {}^nT_T} \left( \frac{\partial {}^nT_T}{\partial {}^n\mathbf{x}} \right)^T \right] \frac{\partial {}^n\mathbf{x}}{\partial \phi} + \frac{\partial \mathbf{r}}{\partial {}^n\mathbf{x}} \frac{\partial {}^n\mathbf{x}}{\partial \phi} \\ &+ \frac{\partial \mathbf{r}}{\partial T_T} \frac{\partial {}^nT_T}{\partial \phi} + \left( \frac{\partial \mathbf{r}}{\partial T_N} + \frac{\partial \mathbf{r}}{\partial T_T} \frac{\partial T_T}{\partial T_N} \right) \frac{\partial T_N}{\partial \phi} + \frac{\partial \mathbf{r}}{\partial T_T} \frac{\partial T_T}{\partial \phi} \end{aligned}$$

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**Contact sensitivity**

---

**Sensitivity pseudo load vector**



$$\begin{aligned} -\text{RHS}_{el} &= \left[ \frac{\partial \mathbf{r}}{\partial {}^n\mathbf{x}} + \frac{\partial \mathbf{r}}{\partial T_T} \left( \frac{\partial T_T}{\partial {}^n\mathbf{x}} \right)^T \right] \left( \frac{\partial {}^n\mathbf{u}}{\partial \phi} + \frac{\partial {}^n\mathbf{x}}{\partial \phi} \right) + \left( \mathbf{K} + \frac{\partial \mathbf{r}}{\partial {}^n\mathbf{x}} \right) \frac{\partial {}^n\mathbf{x}}{\partial \phi} \\ &+ \frac{\partial \mathbf{r}}{\partial T_T} \frac{\partial T_T}{\partial \phi} + \left( \frac{\partial \mathbf{r}}{\partial T_N} + \frac{\partial \mathbf{r}}{\partial T_T} \frac{\partial T_T}{\partial T_N} \right) \frac{\partial T_N}{\partial \phi} + \frac{\partial \mathbf{r}}{\partial T_T} \frac{\partial T_T}{\partial \phi} \end{aligned}$$

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**Code development system**

---

**AceGen**

```

graph TD
    subgraph Optimization_shell [Optimization shell]
        Preprocessing[Preprocessing]
        FESE[Finite element solution environment]
        SCA[Symbolic system for automatic code generation]
        Postprocessing[Post-processing]
    end
    subgraph Formulations [Formulations]
        subgraph Direct_analysis [Direct analysis]
            R_u["R('u') = 0"]
        end
        subgraph Sensitivity_analysis [Sensitivity analysis]
            du_dphi["du/dphi"]
            du_dphi["Sensitivity of response functionals dR/dphi"]
            du_dphi["Generated codes for the evaluation of element quantities"]
        end
        subgraph Element_stiffness [Element stiffness k<sup>e</sup>]
            k_e["k<sup>e</sup>"]
            k_e["Element loads r<sup>e</sup>"]
        end
        subgraph Element_sensitivity [Element sensitivity terms]
            dsigma_dphi["dsigma_dphi"]
            dsigma_dphi["Sensitivity terms of response functionals dR/dphi"]
        end
    end
    FESE --> Direct_analysis
    FESE --> Sensitivity_analysis
    FESE --> Element_stiffness
    FESE --> Element_sensitivity
    Postprocessing --> SCA

```

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**International collaboration**

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**Academic institutions**

- CIMNE - International Centre for Numerical Methods in Engineering, Barcelona (ES)
- Korea Advanced Institute of Sci & Technology (KR)
- Polish Academy of Sciences (PL)
- Polytechnical University of Catalonia (ES)
- Risø National Laboratory (DK)
- Technical University of Denmark (DK)
- Technical University of Berlin (DE)
- University College of Swansea (UK)
- University of Erlangen-Nuernberg (DE)
- University of Ljubljana (SI)
- University of Padua (IT)
- University of Stuttgart (DE)
- Technical University Clausthal

**Industrial partners**

- BAYER (DE)
- BÖHLER (AT)
- B&L MASKINFABRIK (DK)
- CORUS (NL)
- CERATIZIT (LU)
- DANFOSS (DK)
- GKN (AT)
- GRUNFOS
- IMPRESS (FR)
- IMPOL (SI)
- ISKRA-AVTOELEKTRIKA (SI)
- PLANSEE (AT)
- PSA PEUGEOT CITROEN (FR)
- ROCKFIELD (UK)
- SIAP-CARRERA (IT)
- SKODA (CZ)
- TALBOT (FR)
- TEKFOR (IT)
- THYSSEN-KRUPP-PRESTA (LI)
- UNILEVER (UK)

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**5th Framework programme**

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**FP5/GROWTH-ENLUB (2002-2006)**  
Development of new environmentally acceptable lubricants, tribological tests and models for European sheet forming industry

**FP5/GROWTH-IMPRESS (2001-2005)**  
Improvement of Precision in Forming by Simultaneous Modelling of Deflections in Workpiece-Die-Press Systems

**FP5/GROWTH-COLT (1999-2003)**  
Improvement of Service Life and Reliability of Cold Forging Tools with Respect to Fatigue Damage due to Cyclic Plasticity

**FP5/GROWTH-SCANMAP (1999-2003)**  
A validated simulation support system for the optimal design of steel shaped can manufacturing processes

30

**6th Framework programme**

**FP6-NMP-STREP-POLYCOAT (2004-2005)**  
Economical exploitation of polymer coated steel sheet in large-scale production of new can types by the European can industry

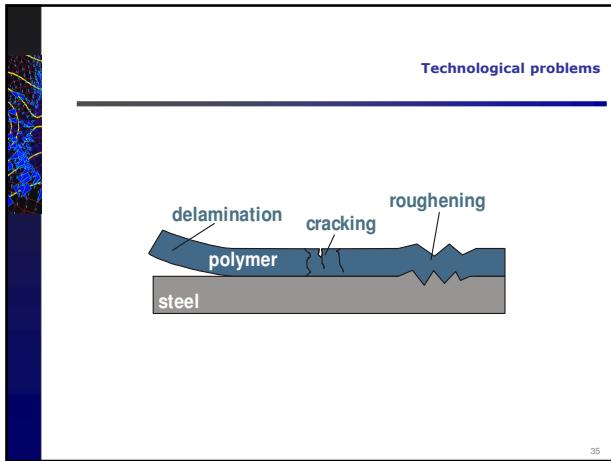
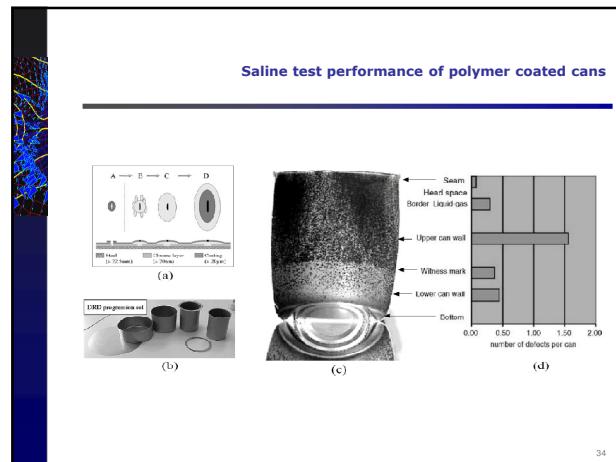
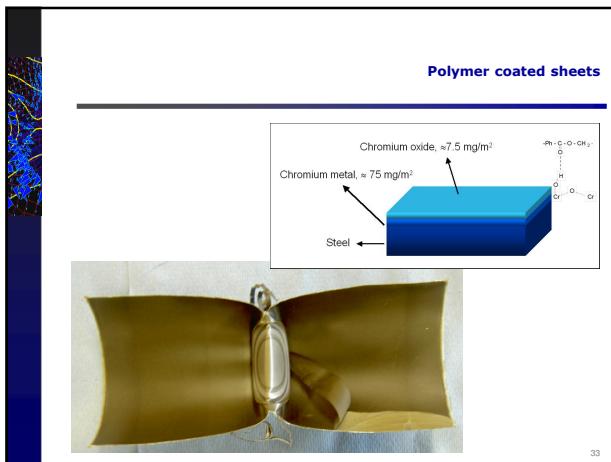
**FP6-IST/NMP-VIF-CA (2004-2008)**  
Virtual Intelligent Forging – Coordination Action within the Sixth Framework Programme

**FP6-IP- TUNCONSTRUCT (2005-2008)**  
Technology Innovation in Underground Construction – Integrated project

**FP6-NMP-STREP-PROFORM (2004-2007)**  
Transforming nano-particles into sustainable consumer products through advanced product and process formulation

**FP6-NMP-STREP-NANOBIOACT (2006-2009)**  
Nano-engineering biomimetic tactile sensors

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**Knauss-Emri model**

$$\sigma_{ik}(t, \mathbf{r}) = 3 \int_0^t K[t'(t, \mathbf{r}) - \lambda'(t, \mathbf{r})] \frac{\partial \theta(\lambda, \mathbf{r})}{\partial \lambda} d\lambda \quad S_{ij}(t, \mathbf{r}) = 2 \int_0^t G[t'(t, \mathbf{r}) - \lambda'(t, \mathbf{r})] \frac{\partial c_i(\lambda, \mathbf{r})}{\partial \lambda} d\lambda$$

$K$  ... bulk modulus,  $G$  ... shear relaxation modulus,  $t'$  ... material time

$$t'(t, \mathbf{r}) - \lambda'(t, \mathbf{r}) = \frac{1}{\lambda} \frac{d\zeta}{\Phi[T(\zeta, \mathbf{r}), \theta(\zeta, \mathbf{r})]}$$

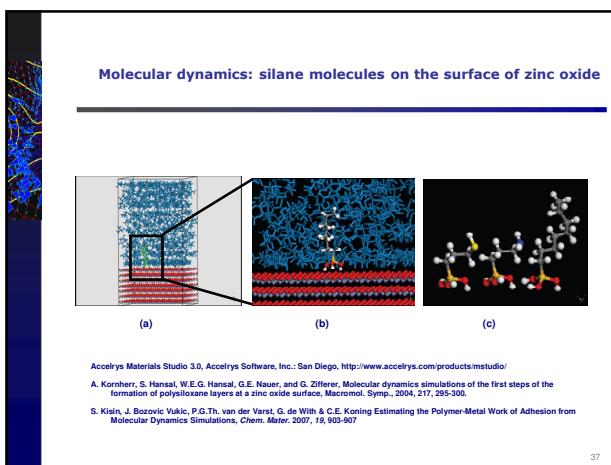
$$\log \Phi[T(\zeta, \mathbf{r}), \theta(\zeta, \mathbf{r})] = \frac{b}{2.303} \left\{ \frac{1}{f[T(\zeta, \mathbf{r}), \theta(\zeta, \mathbf{r})]} - \frac{1}{f_0} \right\} \quad \dots \text{shift function}$$

$$f[T(\zeta, \mathbf{r}), \theta(\zeta, \mathbf{r})] = f_0 + f_T + f_\theta \quad \dots \text{intermolecular volume}$$

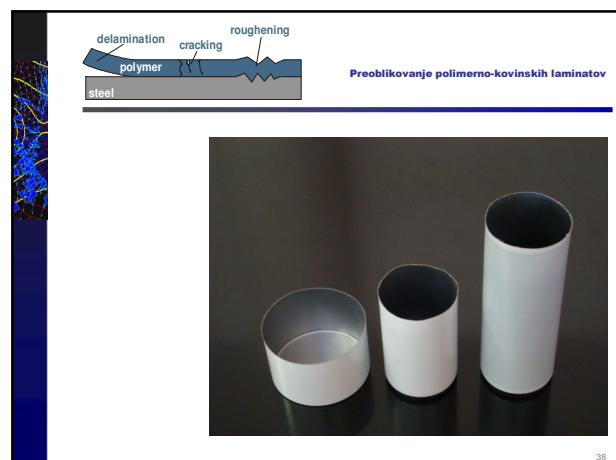
$f$  ... bulk creep compliance,  $\alpha$  ... thermal expansion

$$f_T = \int_0^t \alpha(t - \lambda, \mathbf{r}) \frac{\partial T(\lambda, \mathbf{r})}{\partial \lambda} d\lambda \quad f_\theta = \int_0^t M(t - \lambda, \mathbf{r}) \frac{\partial \sigma_{ik}(\lambda, \mathbf{r})}{\partial \lambda} d\lambda$$

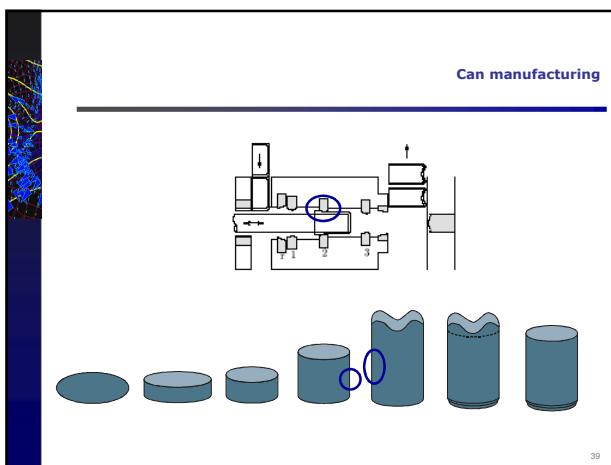
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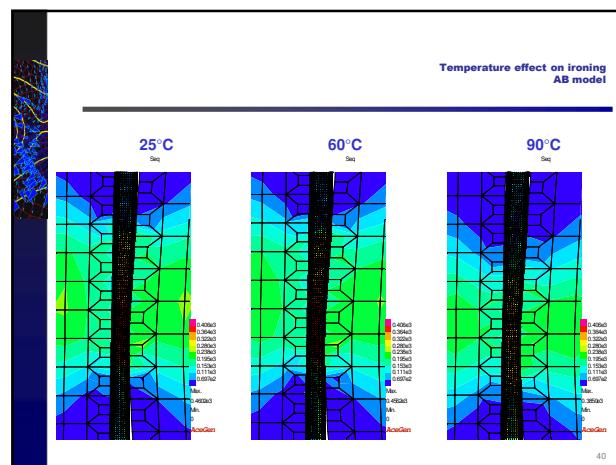
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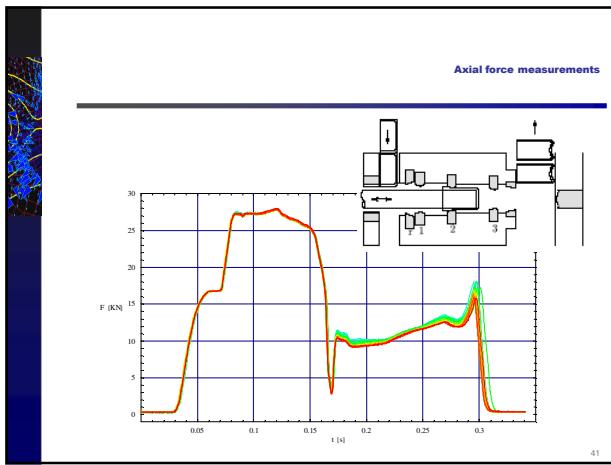
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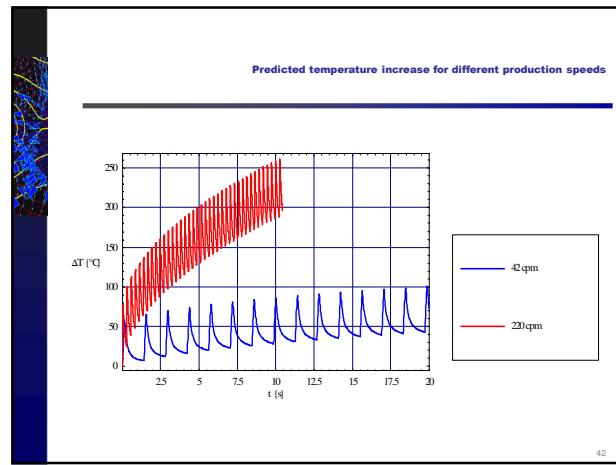
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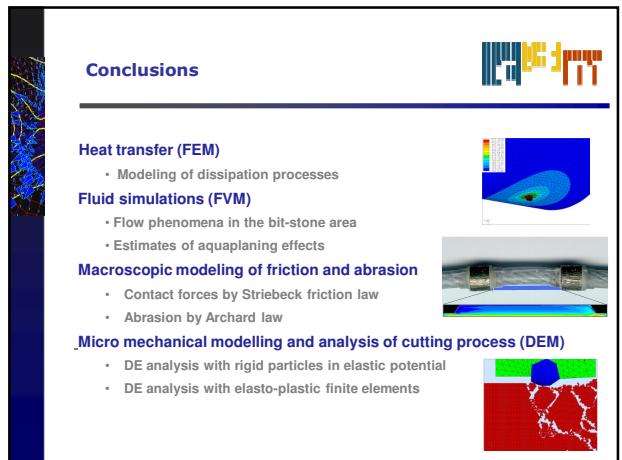
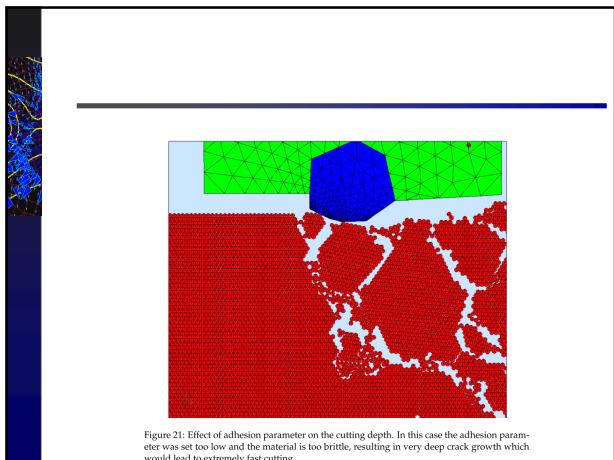
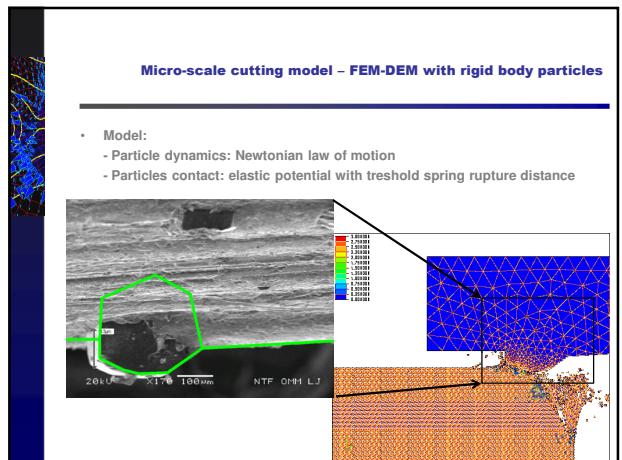
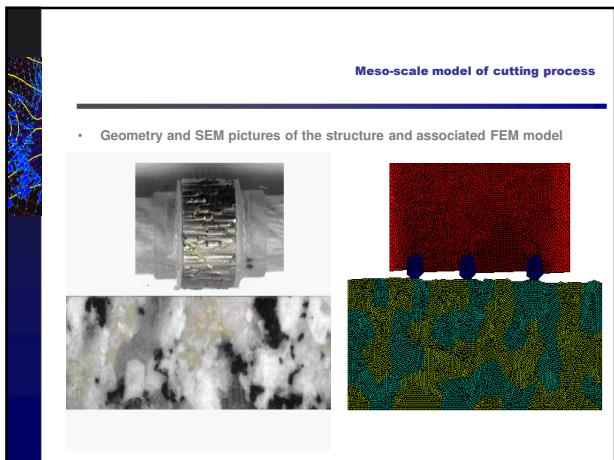
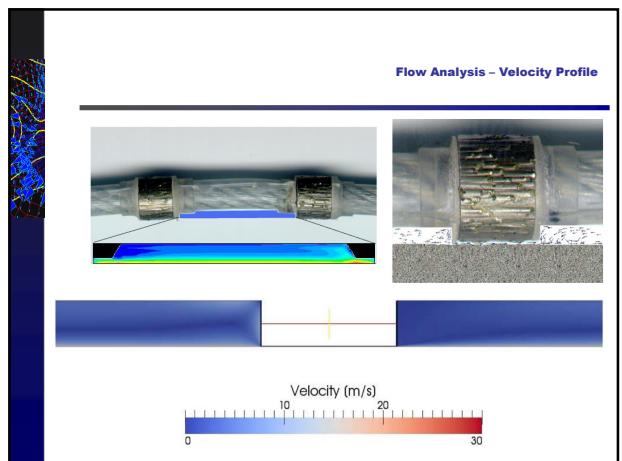
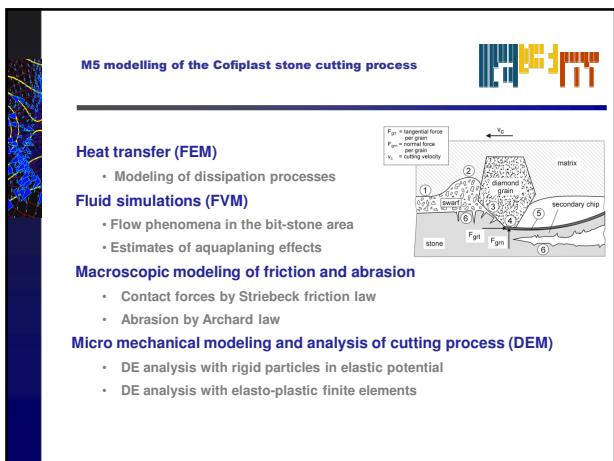
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**6th Framework programme**

**FP6-NMP-STREP-PROFORM (2004-2007)**  
Transforming nano-particles into sustainable consumer products through advanced product and process formulation

**Budget:** 3.690.40 (EU contribution 2.399.35 EUR)

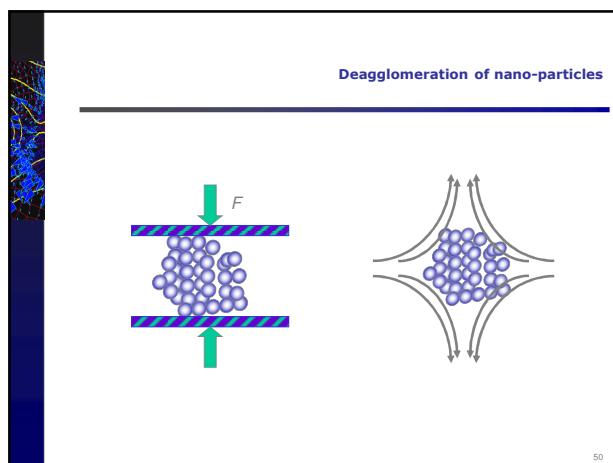
**Companies:**

- BHR Group, UK
- Bayer Technology Services, Germany
- Unilever, UK
- Rockfield Software Ltd, UK
- C3M d.o.o., Slovenia

**Universities:**

- Karlsruhe, Institute of Food Process Technology, Germany
- Loughborough, Chemical Engineering, UK
- Warsaw University of Technology, Poland
- Poznań, Faculty of Chemical Technology, Poland
- Birmingham, Chemical Engineering, UK

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**Fluid – particle interactions**

**Multi-field**

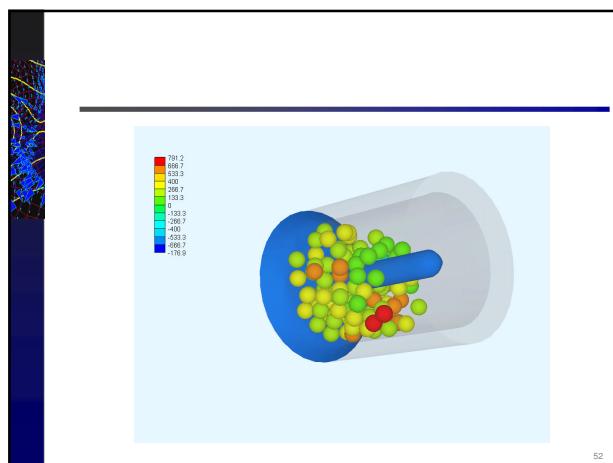
**Multi-scale**

**Multi-body**

**Multi-phase**

**Multi-objective**

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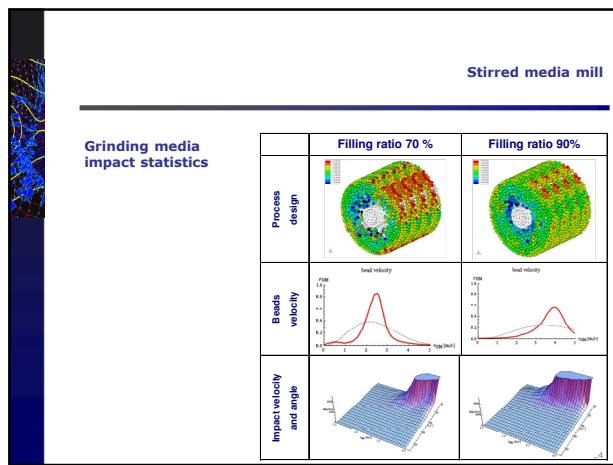


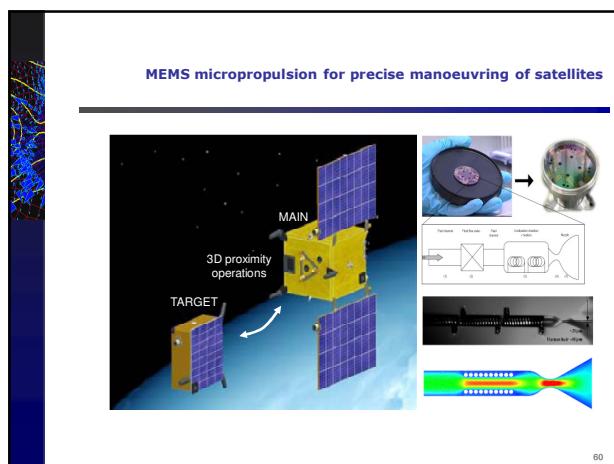
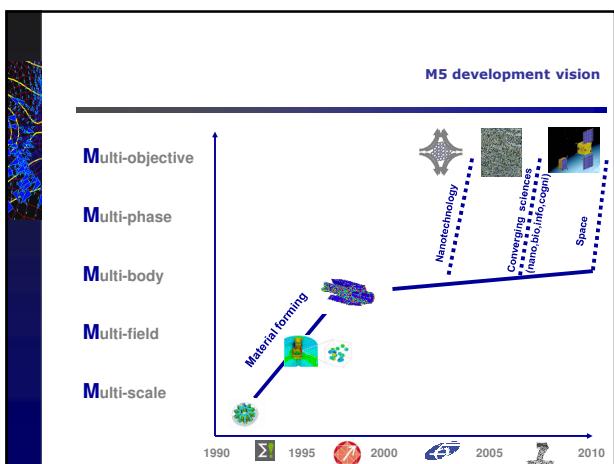
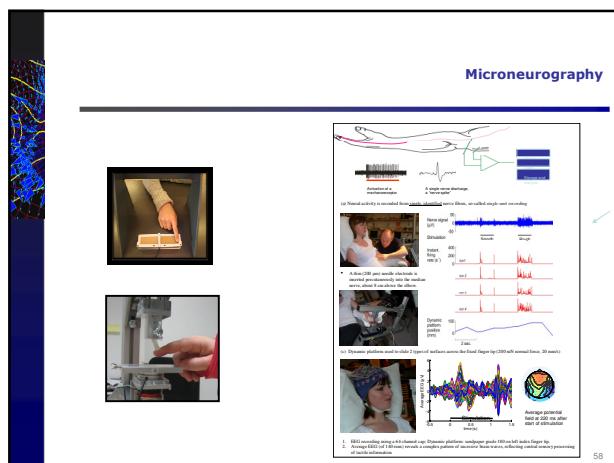
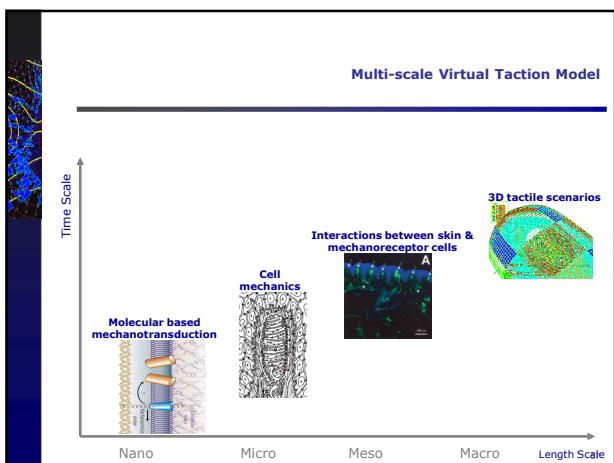
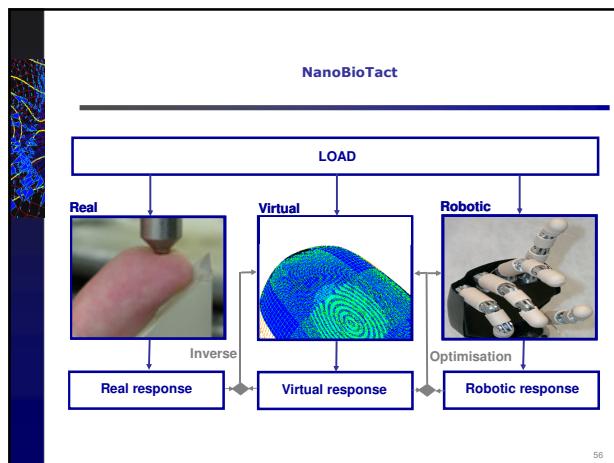
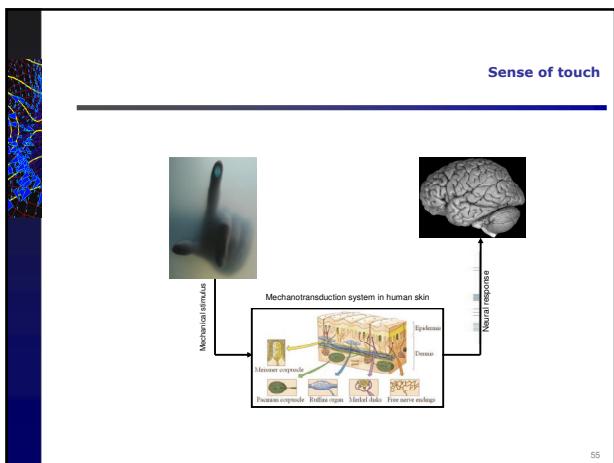
**Multi-scale model**

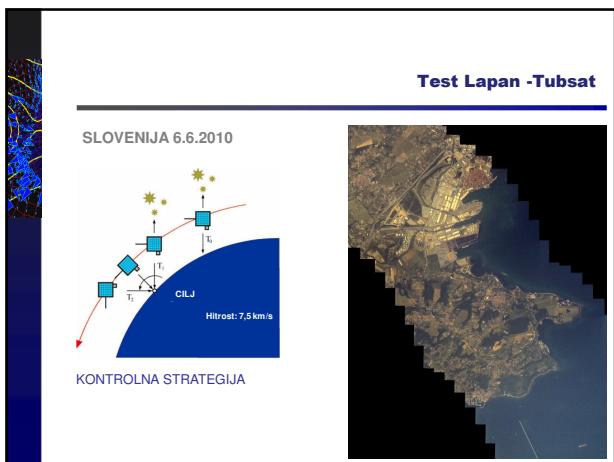
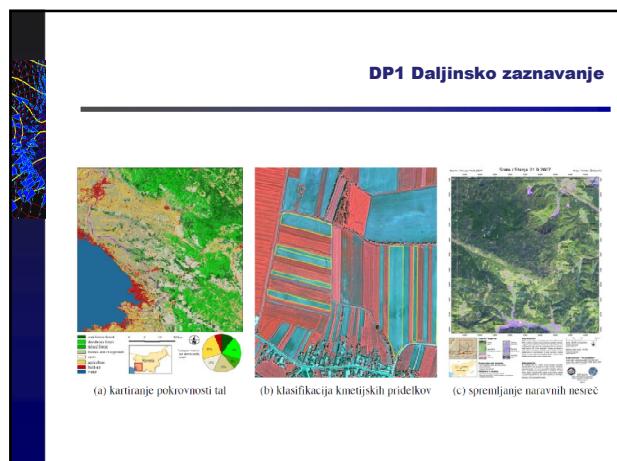
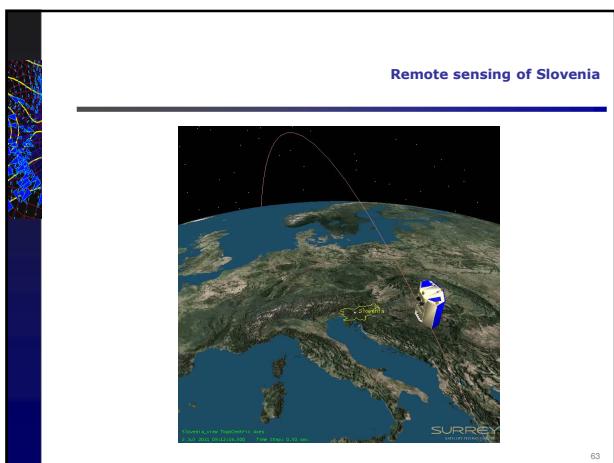
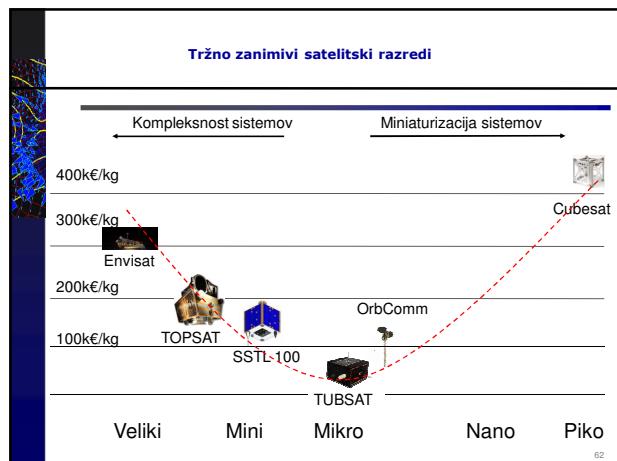
**Micro –breakage mechanisms**

**Macro – impact scenarios**

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**END**

**tomaz.rodic@space.si**

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