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# Severe Plastic Deformation in Impact Extrusion Processes

by

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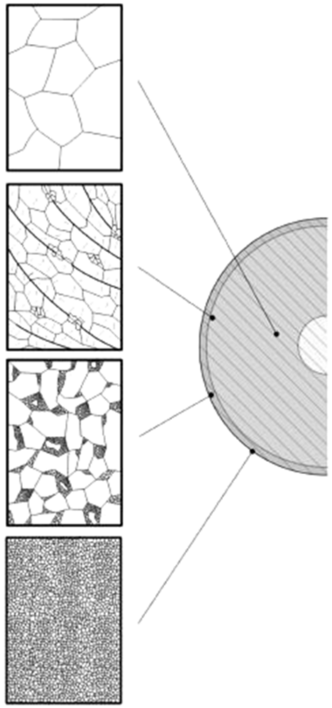
# Severe Plastic Deformation in Impact Extrusion Processes

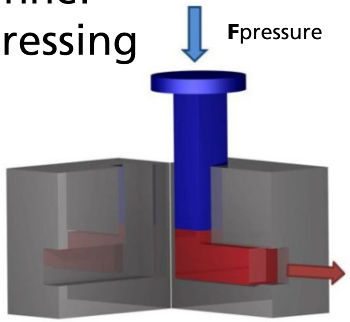



1. Introduction
2. Process Principle of Gradation Extrusion
3. Calculation of Strain
4. Evaluation of Graded Material Properties
5. Applications
6. Summary and Prospekts

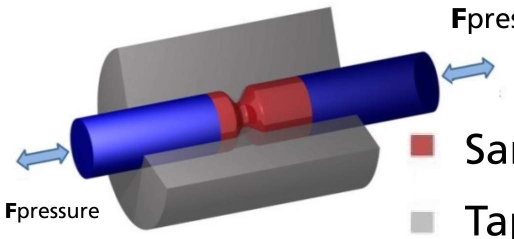
# 1. INTRODUCTION

**Severe plastic deformation (SPD)**

ECAP
Equal Channel
Angular Pressing




CEC
Cyclic Extrusion
Compression




**Equal Channel Angular Pressing (ECAP) and Cyclic Extrusion Compression (CEC)**

- Severe grain refinement (grain size below 1µm)
- Materials with improved properties
  - **Strength of material** ⇧
  - **Ductility** ⇨ ⇘
  - **Corrosion resistance** ⇧

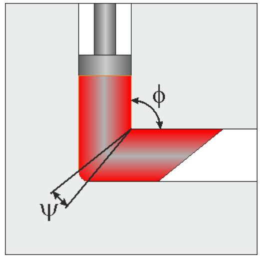
Grain refinement:
nearly **homogeneous** throughout the **complete volume**

- Limitations:
  - Low utilization factor - productivity is low

# 2. PROCESS PRINCIPLE OF GRADATION EXTRUSION

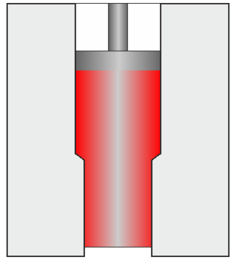
**Process principles**

- Approach
  - Combining ECAP with impact extrusion
- **Gradation die**
  - Contains additional forming area
  - Specific conditions of SPD
  - **Forming area** with several **forming elements**

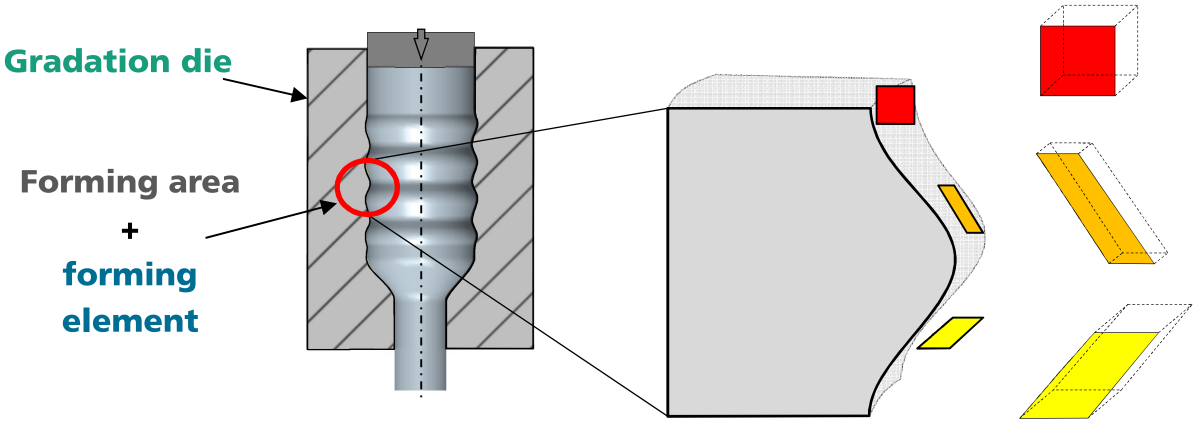



ECAP

\+



Impact extrusion

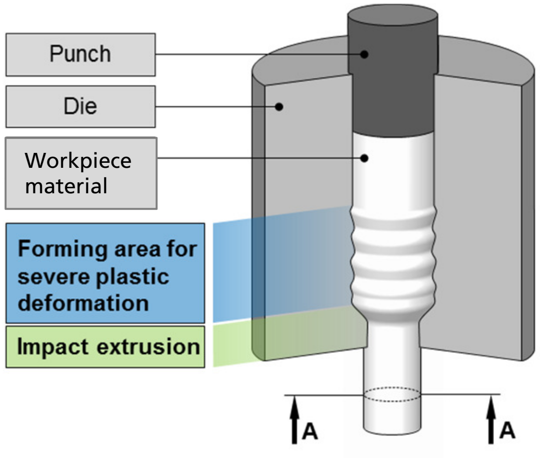



**Material deformation at a forming element in different positions**

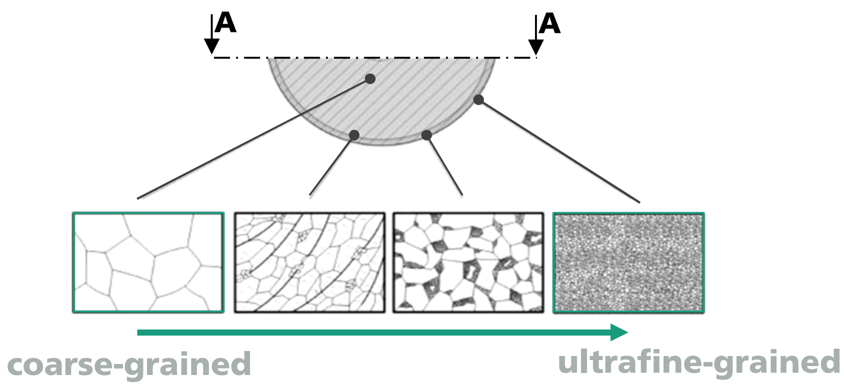
# 2. PROCESS PRINCIPLE OF GRADATION EXTRUSION

**Main properties of gradation extrusion (GE)**

- Gradation extrusion  process design




- Severe plastic deformation of the lateral area




### Influence of the die design

- Angle of element
- Length of element
- Number of stacked elements

### Peripherial layer

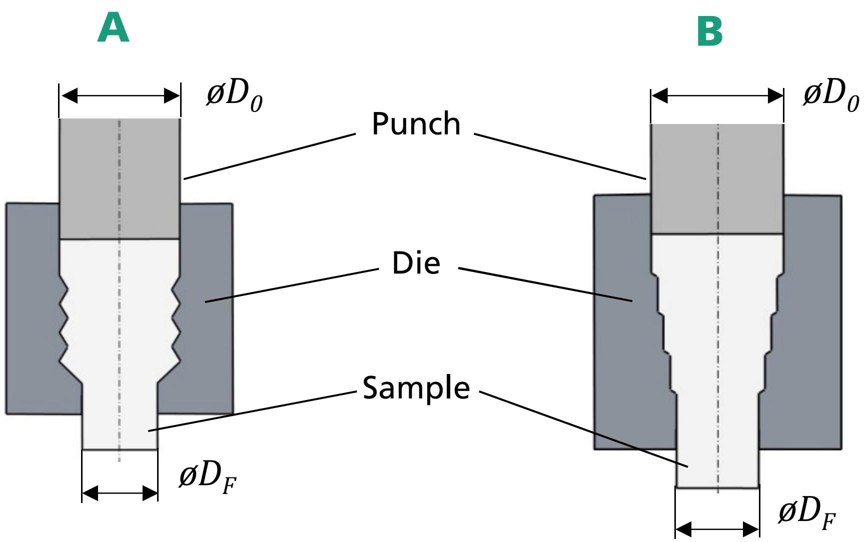
- High strength
- Delayed crack initiation
- Improved  corrosion resistance (Aluminium alloys - 7000 series)

### Core

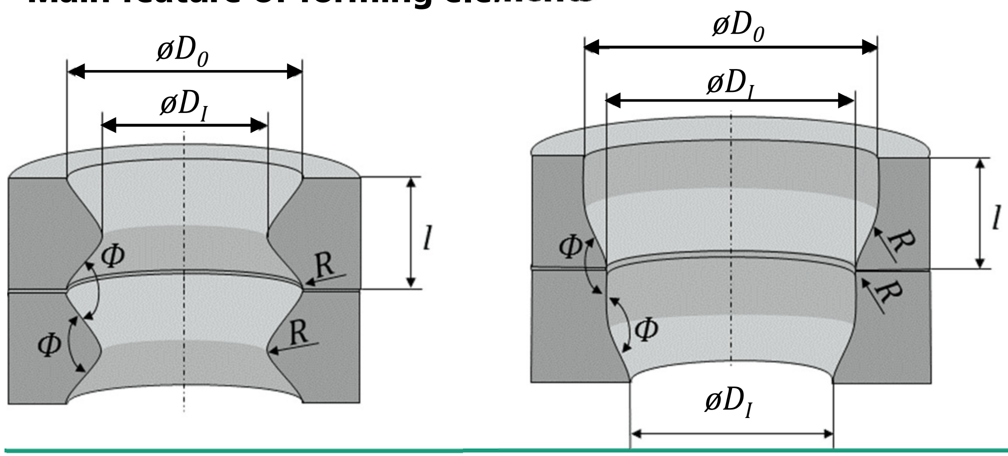
- High ductility and toughness
- Resistance to crack propagation

# 2. PROCESS PRINCIPLE OF GRADATION EXTRUSION

**Design variants of die geometries for gradation extrusion**




**Main feature of forming elements**




## Die design A

- Forming area with angled forming elements
- Undercuts
- Final diameter reduction

## Die design B

- Forming area with angled forming elements and stepwise diameter reduction
- Without undercuts
- Final diameter reduction

## Main influencing parameters

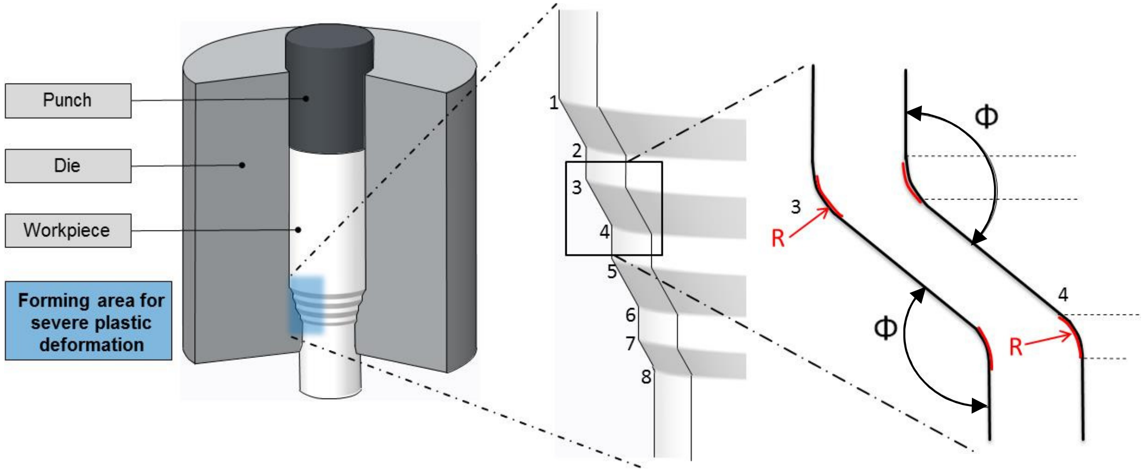
| | |
|---|---|
| Initial diameter | $D_0$ |
| Final diameter | $D_F$ |
| Inner diameter | $D_I$ |
| Radius | $R$ |
| Forming element angle | $\phi$ |
| Forming element length | $l$ |
| Number of steps | $n$ |

# 3. CALCULATION OF STRAIN

- Combining two main mechanisms:
  - **Extrusion steps** $i$
  - **ECAP steps** $j$

$$\varphi_i vIE = \ln(1 + \varepsilon_{Ai}) \qquad \varepsilon_{Ai} = \frac{{D_{I+1}}^2 - {D_I}^2}{{D_I}^2}$$

$$\varphi_i vECAP = \frac{2}{\sqrt{3}} \times \cot\left(\frac{\phi_j}{2}\right)$$




*ECAP-like deformation within gradation extrusion die*

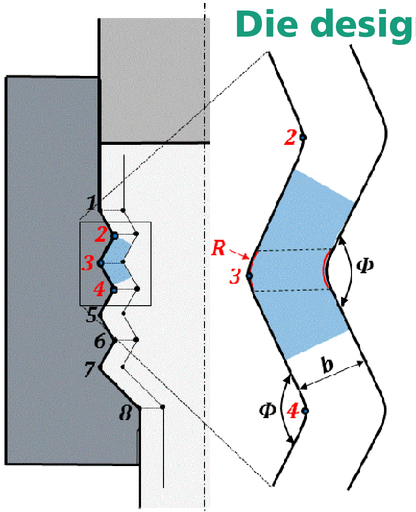
**Total effective strain**

$$\Rightarrow \varphi_v = \sum_{i=1}^{n} |\varphi_i vIE| + \sum_{j=1}^{n} |\varphi_i vECAP|$$

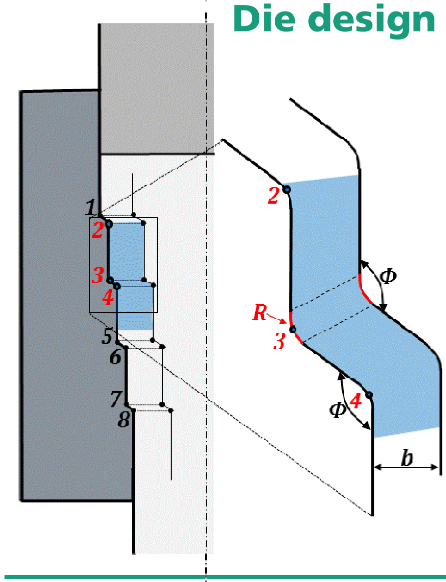
**Lateral Area only !**

# 3. CALCULATION OF STRAIN

## Die design A




## Die design B




| Element i | Diameter Change $D_i$-$D_{i+1}$ | Eff. Strain Extrusion $\varphi_i$vIE | Angle φ | Effective Strain ECAP $\varphi_j$vECAP |
|---|---|---|---|---|
| 1 | - | | 157.5° | 0.23 |
| 2-6 | Ø16 → Ø13.9 / Ø13.9 → Ø16 | -0.235 / 0.307 | 135° | 0.48 |
| 7 | Ø13.9 → Ø16 | 0.307 | 112.5° | 0.77 |
| 8 | Ø16→ Ø10 | -0.610 | 135° | 0.48 |
| | $\sum\lvert\varphi_{i\mathrm{vIE}}\rvert$ = 2.236 | | $\sum\lvert\varphi_{j\mathrm{vECAP}}\rvert$ = 3.88 | |
| Total | $\varphi_v$= 6.116 | | | |
| | | | | |
| 1 | - | | 135° | 0.48 |
| 2 | Ø16 → Ø14.5 | -0.178 | 135° | 0.48 |
| 3, 5, 7 | Ø14.5 → Ø14.5<br>Ø13→ Ø13<br>Ø11.5 → Ø11.5 | 0 | 135° | 0.48 |
| 4 | Ø14.5 → Ø13 | -0.218 | 135° | 0.48 |
| 6 | Ø13 → Ø11.5 | -0.245 | 135° | 0.48 |
| 8 | Ø11.5→ Ø10 | -0.279 | 135° | 0.48 |
| | $\sum\lvert\varphi_{i\mathrm{vIE}}\rvert$ = 0.92 | | $\sum\lvert\varphi_{j\mathrm{vECAP}}\rvert$ = 3.84 | |
| Total | $\varphi_v$= 4.28 | | | |



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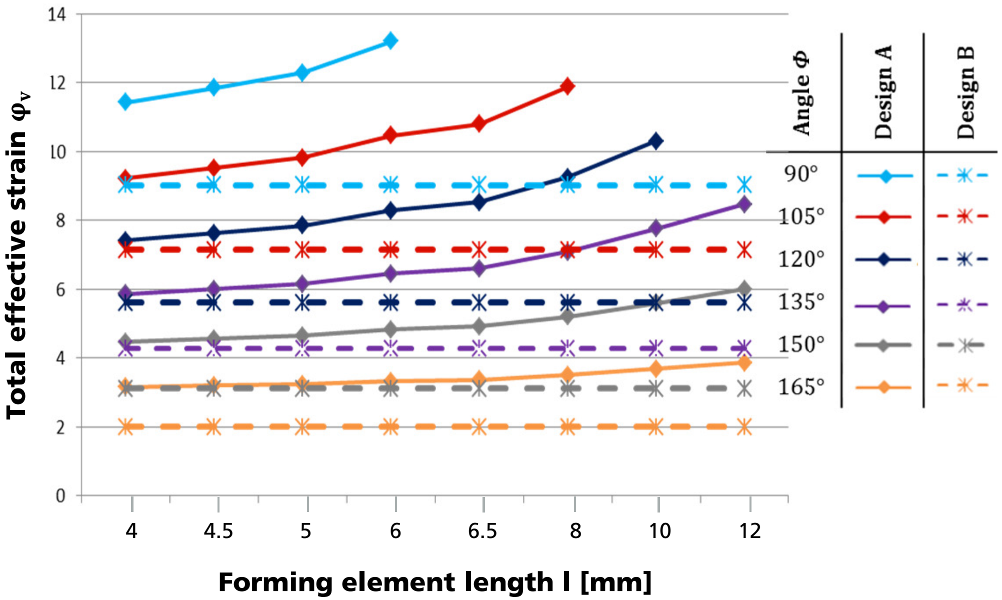
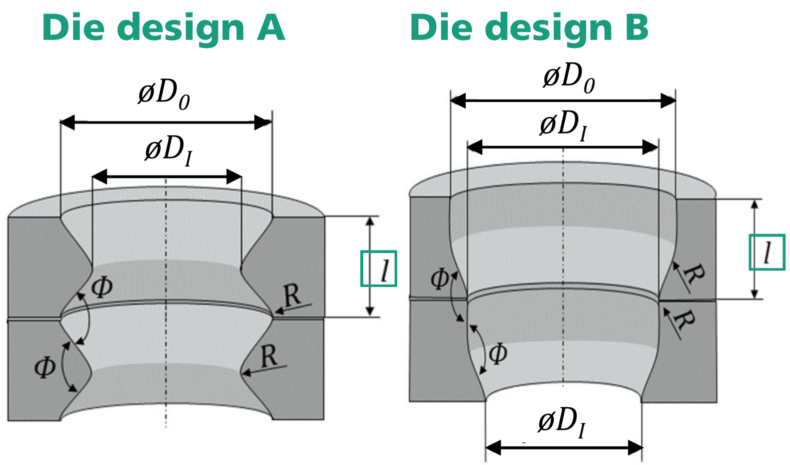
# 3. CALCULATION OF STRAIN

**Total effective strain as a function of forming element length**



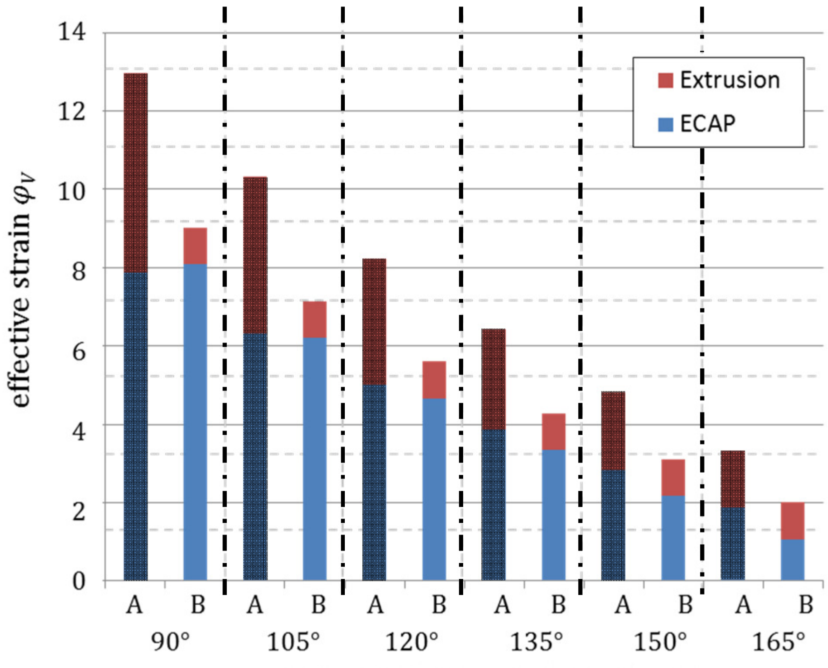



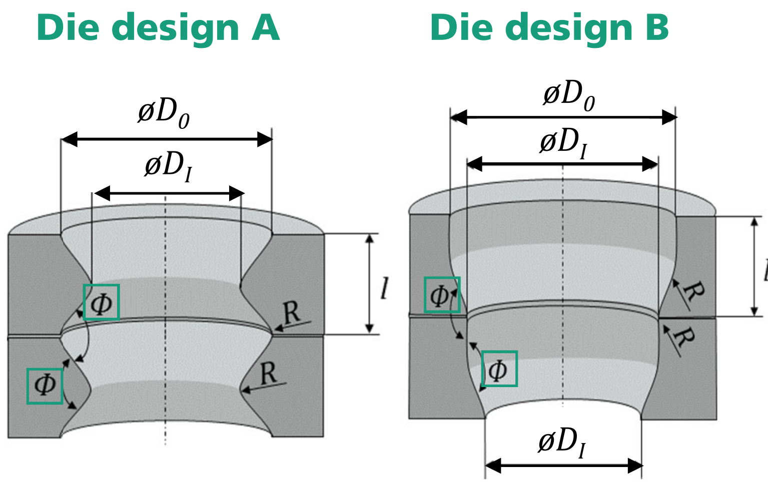

- Design A
  - Higher total effective strain $\varphi_{vA} > \varphi_{vB}$
  - Strain generation depends on angle

    angle $(\phi)$ ↓ total effective strain $(\varphi_v)$ ↑
  - Strain generation depends on forming element length $(l)$

# 3. CALCULATION OF STRAIN

**Calculated total effective strain with its shares resulting from ECAP-like deformation**



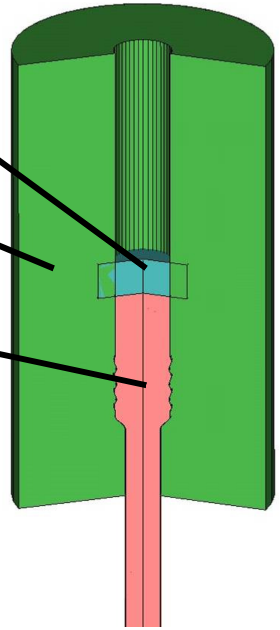




- Share of ECAP-like deformation is higher with smaller forming element angles
- Design A ➡ the amount of ECAP-like deformation is increasing with smaller angles
- Design B ➡ the amount of extrusion-based deformation is steady

# 4. FINITE-ELEMENT SIMULATION OF THE PROCESS

## Simulation setup

- Simufact Forming© 13.2
- Al-alloy EN AW-6082
- Process setup of rotationally symmetric 2D models

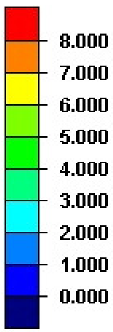


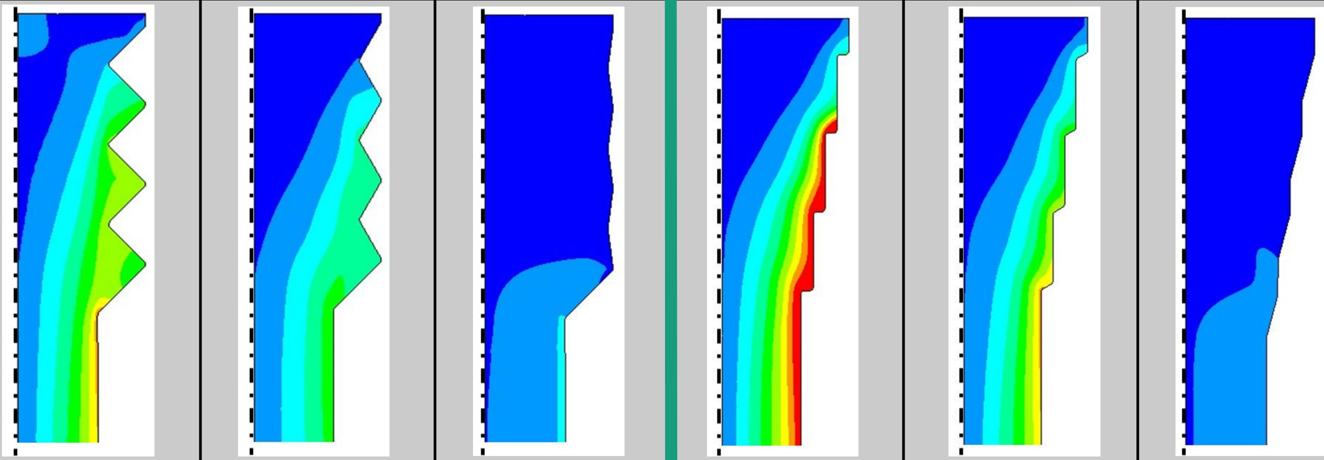

| | Approach | Parameters |
|---|---|---|
| Material flow behaviour | $k_f = K \cdot \varphi^n$ | $K = 400 \frac{N}{mm^2}$ $n = 0.094$ $R_e = 240 \frac{N}{mm^2}$ |
| Friction | Coulomb and maximum shear stress (combined) | $\mu = 0.08$ $m = 0.2$ |
| Meshing parameters | Quad-mesh | Element length 0.3 mm (7209 elements) |

| | |
|---|---|
| Flow stress | $k_f$ |
| Material-dependent coefficient | $K$ |
| Hardening exponent | $n$ |
| Yield strength | $R_e$ |
| Friction coefficient | $\mu$ |
| Friction factor | $m$ |

# 3. CALCULATION OF STRAIN

**Effective strain $\varphi_V$ [-]**

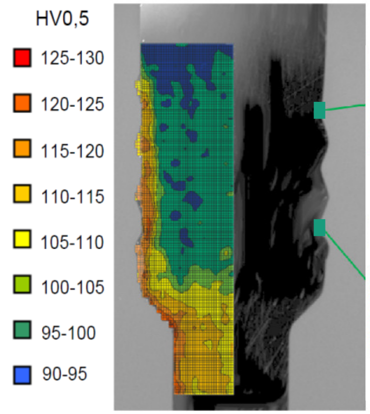



| A – 90° | A – 120° | A – 165° | B – 90° | B – 120° | B – 165° |
|---|---|---|---|---|---|
|  | | | | | |
| Analytical - Effective strain | | | | | |
| 12.2 | 9.8 | 7.8 | 9.0 | 5.1 | 2.0 |
| Simulation - Effective strain | | | | | |
| 7.2 | 5.7 | 4.8 | 9.4 | 7.0 | 1.5 |

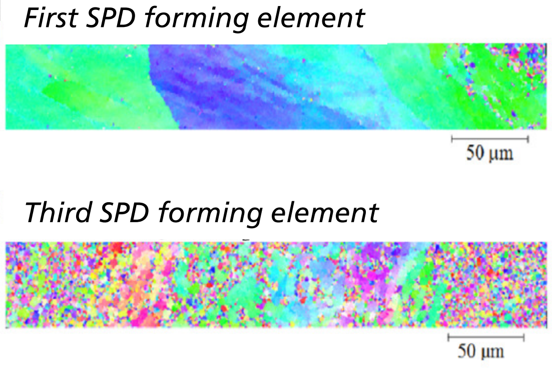
- Smaller angle → wider layer of high strain generation
  → higher strain in the lateral area
- Die design B → higher potential to create a strongly graded material

# 4. EVALUATION OF GRADED MATERIAL PROPERTIES

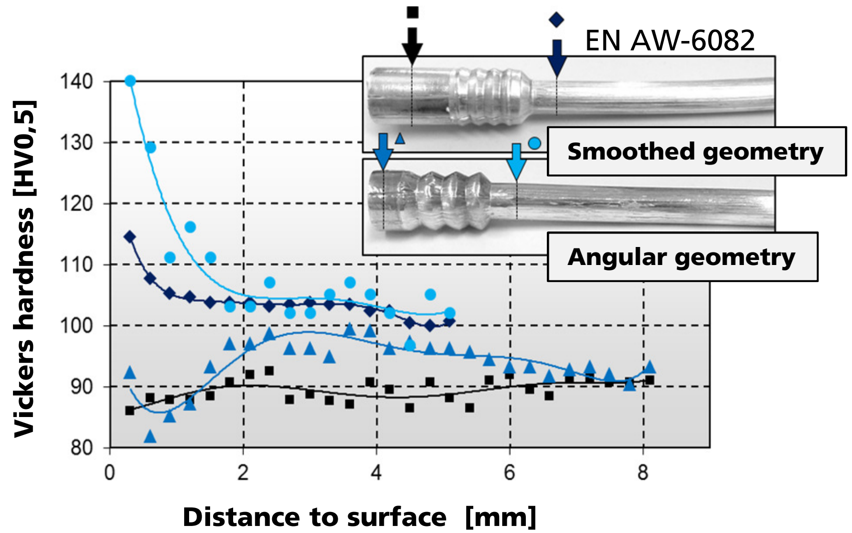
**Hardness distribution and microstructure of the Al-alloy EN AW-6082**




*Hardness distribution map*

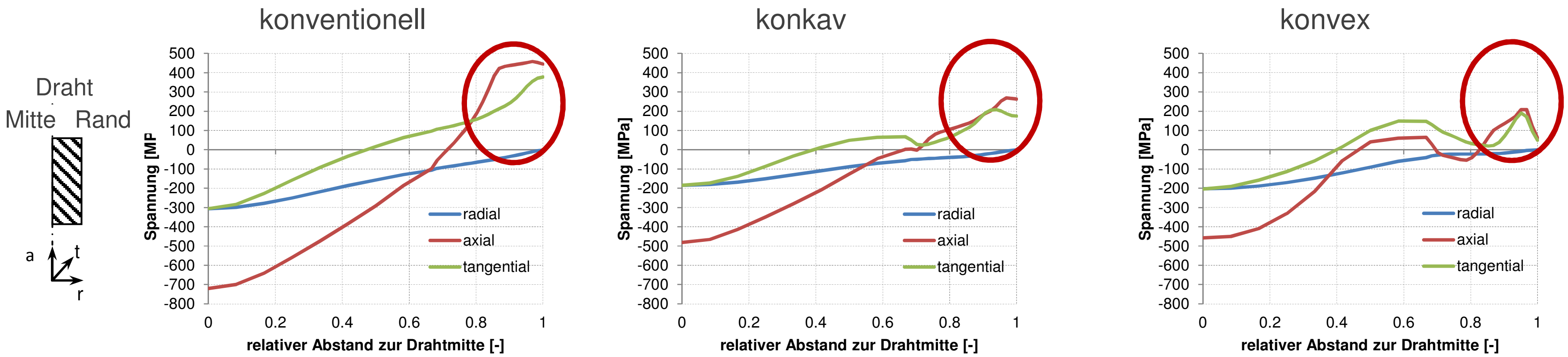



*Measurement with Electron Backscatter Diffraction (EBSD)*




- Hardness distribution correlates with the simulated effective strain distribution
- EBSD maps show grain refined microstructure
- Significant influence of **tool geometry** (angle, radius, inner diameter )
  - Hardness values lie in the range of ECAP

## Residual Stress

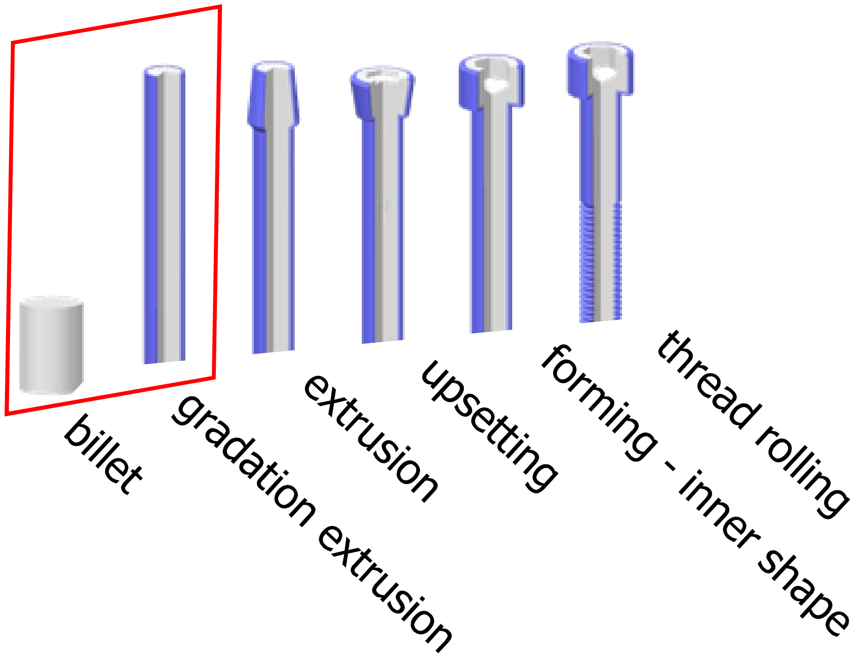


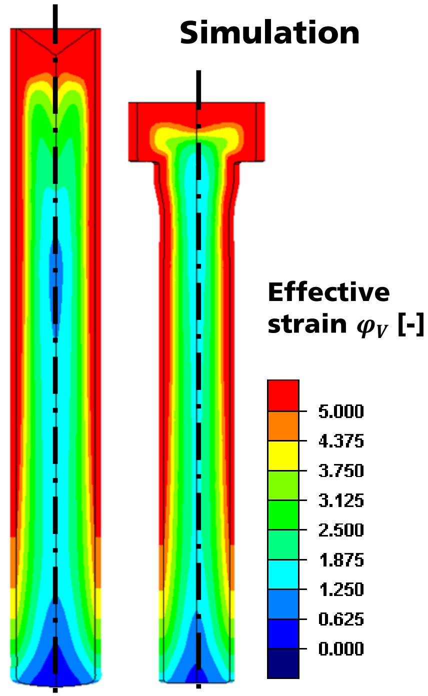
# 5. APPLICATIONS

**Process chain: producing an aluminum bolt**

- Screw with outstanding strength
- High corrosion resistance

## Process chain




**Experimental**

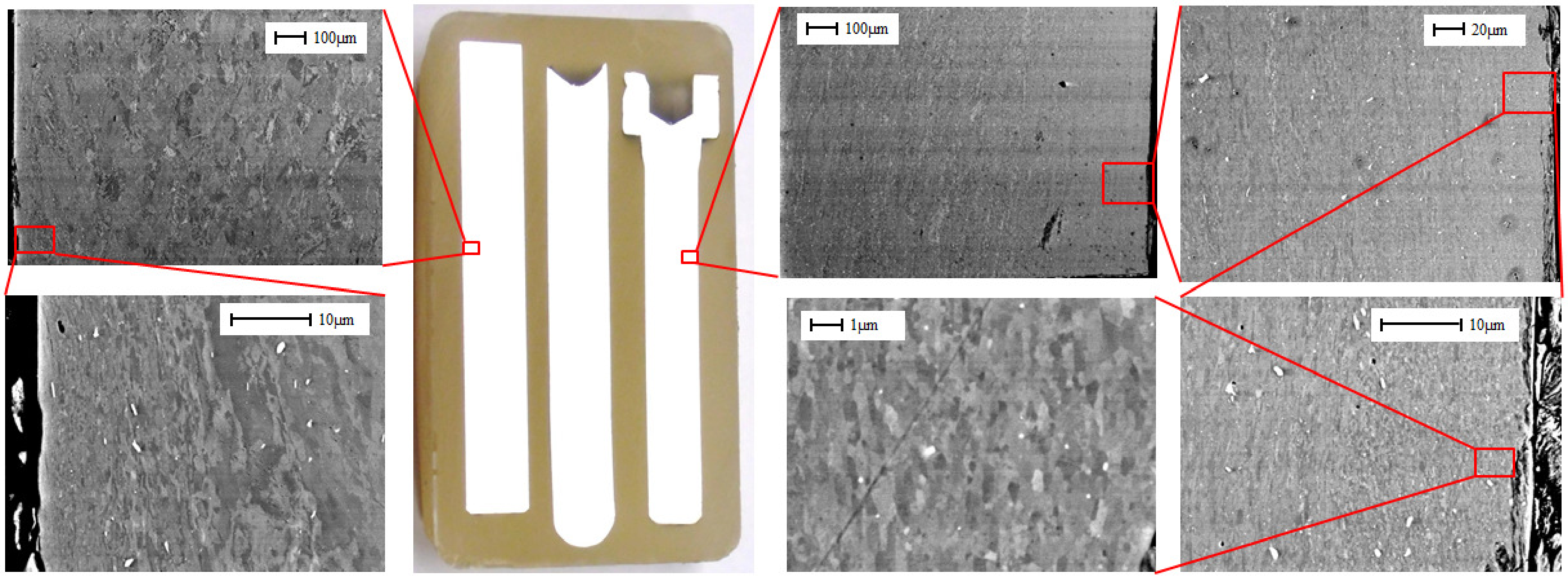
➢ Process chain - subsequent forming of graded billet

# 5. APPLICATIONS

**Process chain: producing an aluminum bolt**

- Resulting microstructure

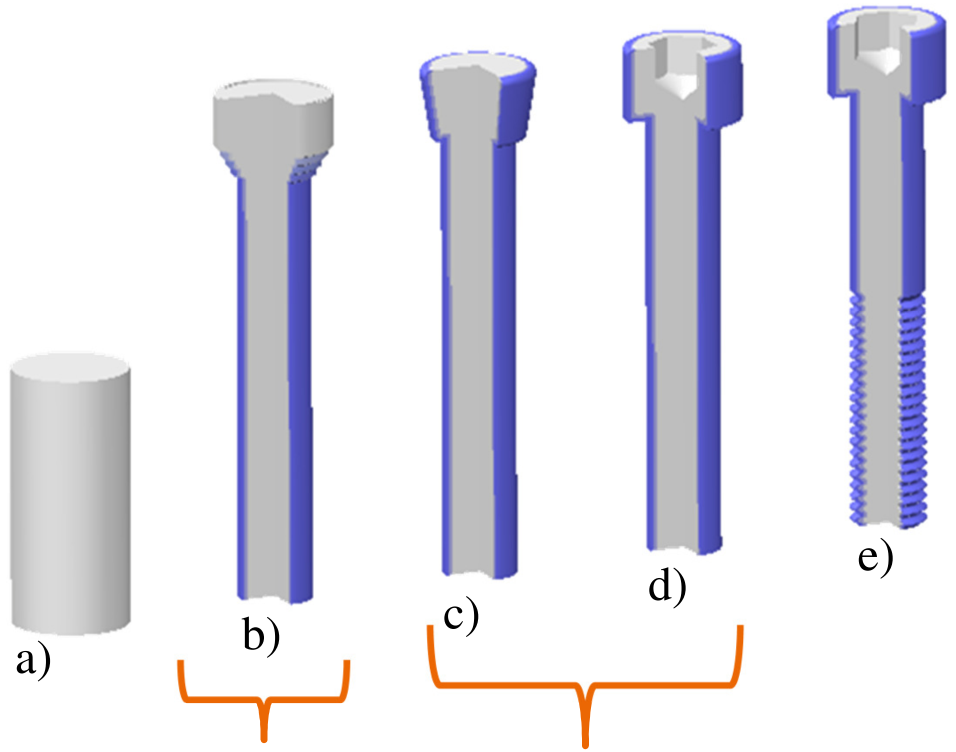
EN AW-6060




SEM images after electrolytical polishing

# 5. APPLICATIONS

**Process chain: producing an aluminum bolt**





Gradation process and diameter reduction are performed in a first die

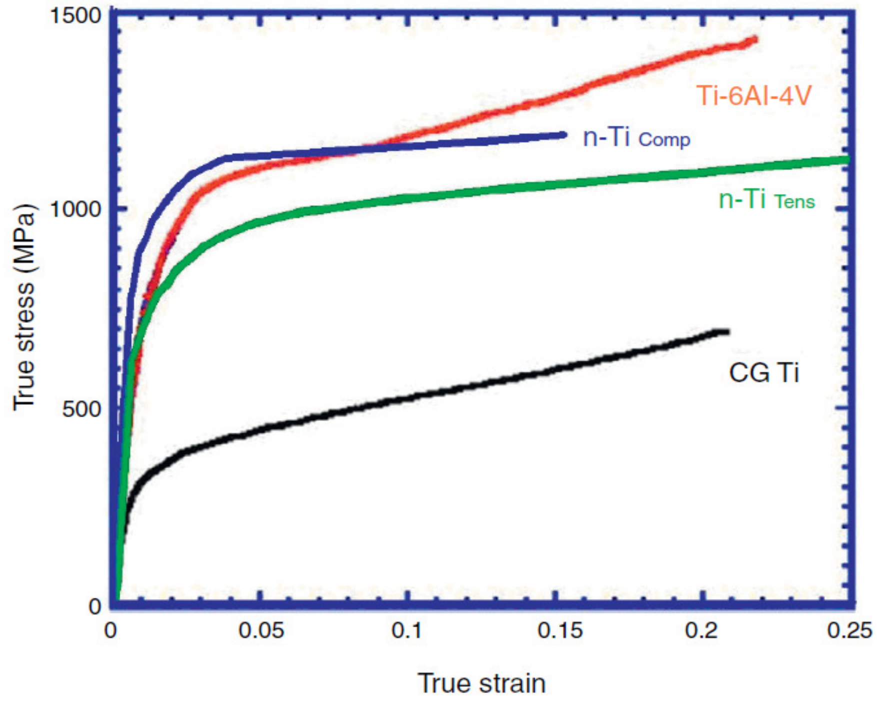
Forming steps are performed in one die

Separate thread rolling process

# 5. APPLICATIONS

**In development - medical implants (Ti Grade 2)**

*Dental implant geometries [norismedical.com]*



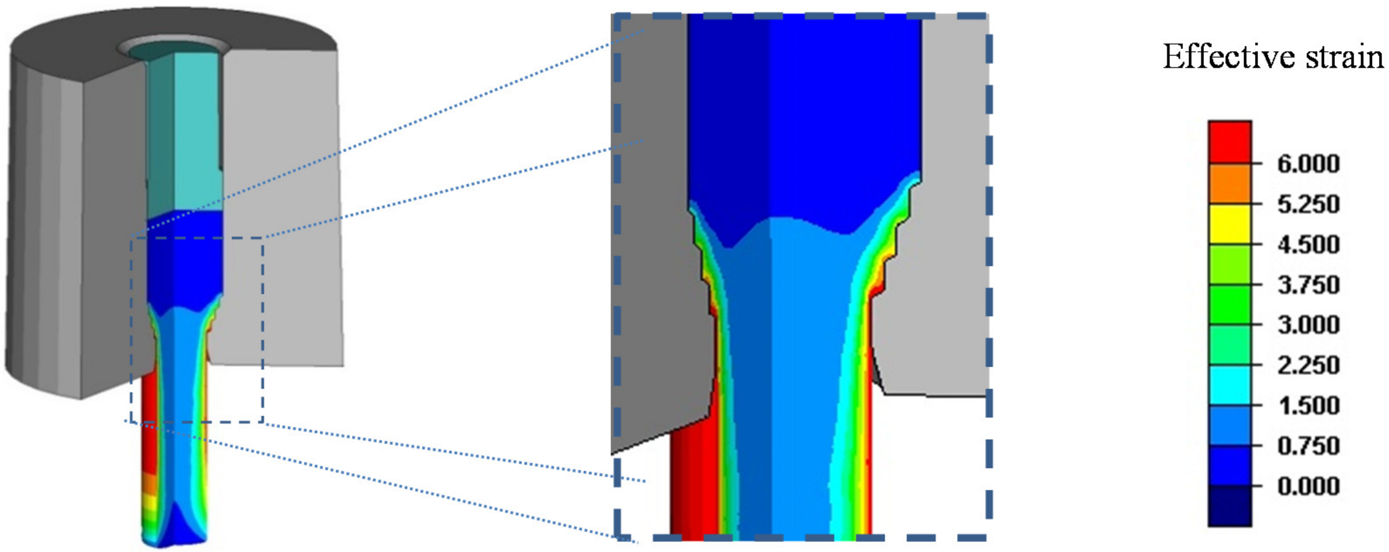

*Data: Elias, C. N.; Meyers, M. A.; Valiev, R. Z.; Monteiro, S. N.: Ultrafine grained titanium for biomedical applications: An overview of performance. Journal of Materials Research and Technology, v. 2, Issue 4, p. 340-350, Oct. – Dec. 2013.*

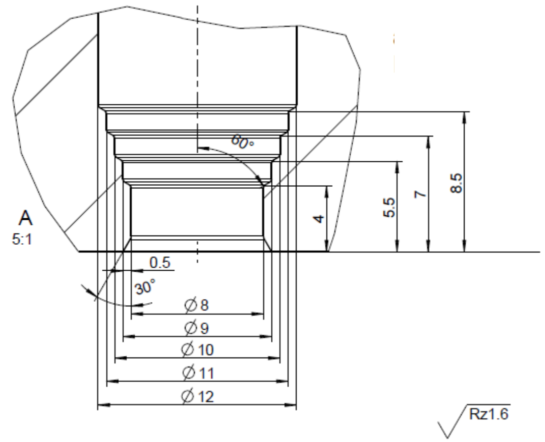
- Pure titanium instead of Ti-6Al-4V for implants
- Grade-2 titanium with strength of Ti-6Al-4V → severe plastic deformation

# 5. APPLICATIONS

**In development - medical implants (Ti Grade 2)**

## Die geometry and simulation




Lateral area

- Analytical effective strain → $\varphi_{\text{v}} = 5.5$
- FE-Simulation app. → $\varphi_{\text{vsim}} = 7$

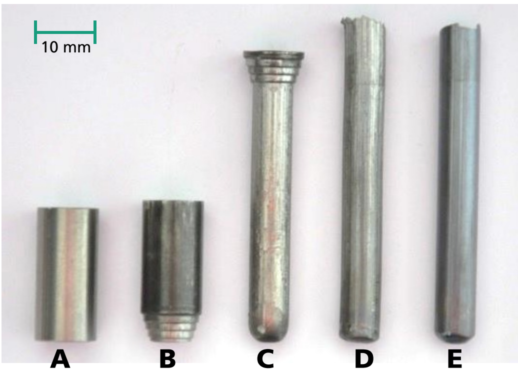
Core

- FE-Simulation $\varphi_{\text{vsim-core}} = 0.8$

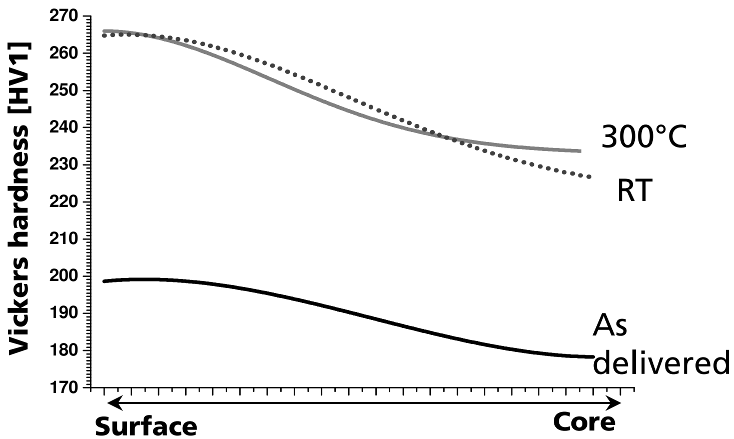
# 5. APPLICATIONS

**In development - medical implants (Ti Grade 2)**

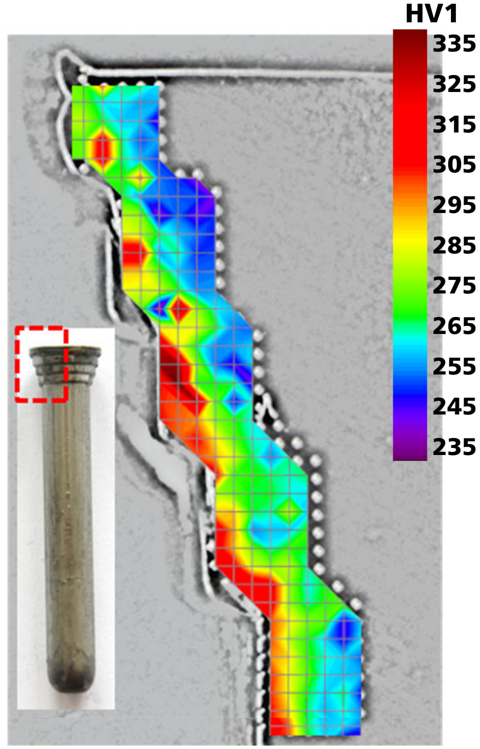
- Gradation extrusion using undercut-free geometry (**Design B**)
- Forming of titanium grade-2 successful
  - Hardening effect with gradient




*Gradation extrusion samples*




*Hardness (HV1) of the as delivered billet and extruded samples at 20°C (RT) and 300°C*



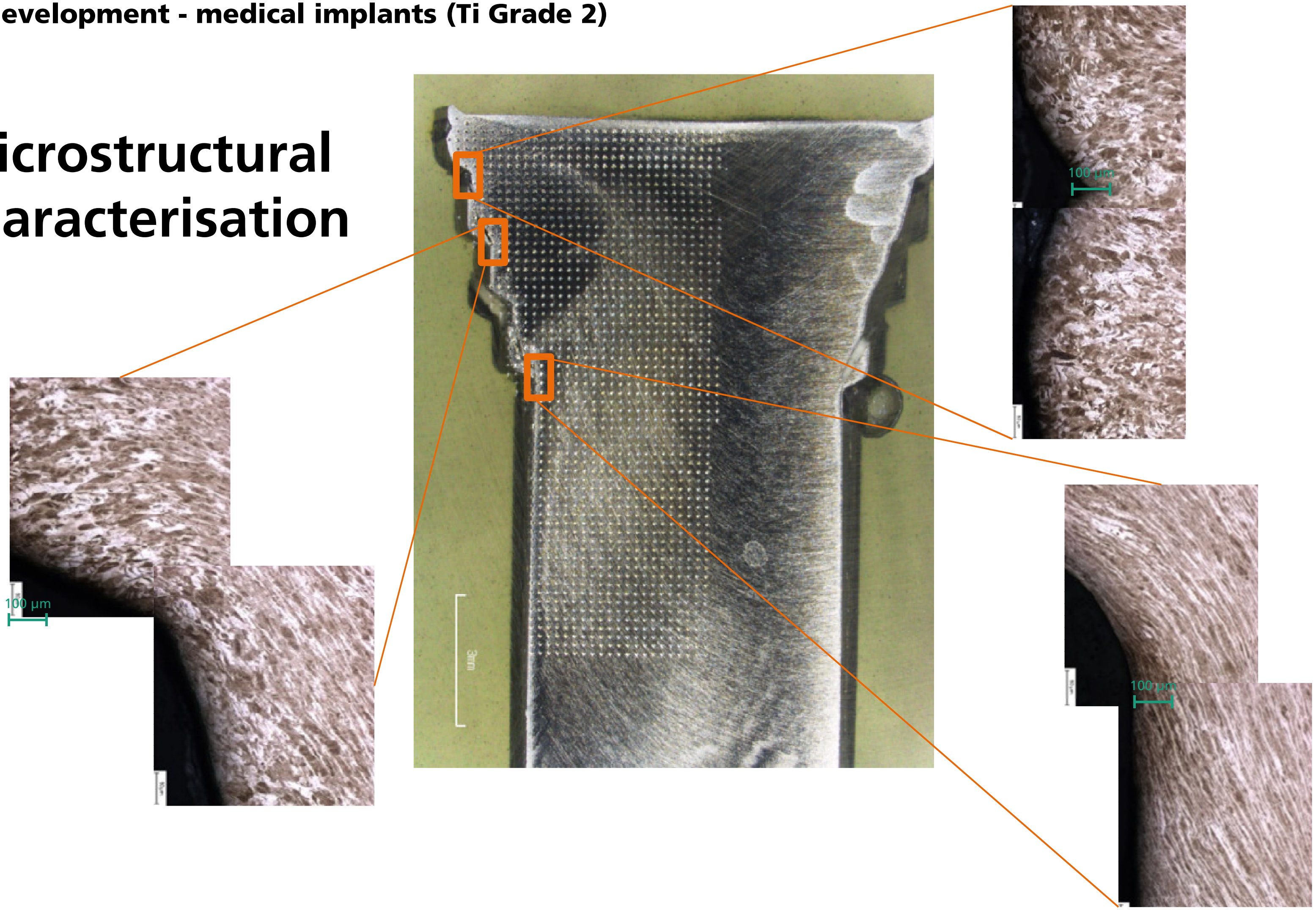

*Hardness (HV1) measuring of cross section sample III at room temperature*

| | |
|---|---|
| A | Initial billet |
| B | Sample after start of plastification |
| C | Sample almost completely processed |
| D | Sample completely formed at room temperature |
| E | Sample processed with starting temperature of 300°C |

# 5. APPLICATIONS

**In development - medical implants (Ti Grade 2)**

## Microstructural characterisation



## 5. SUMMARY AND PROSPEKTS

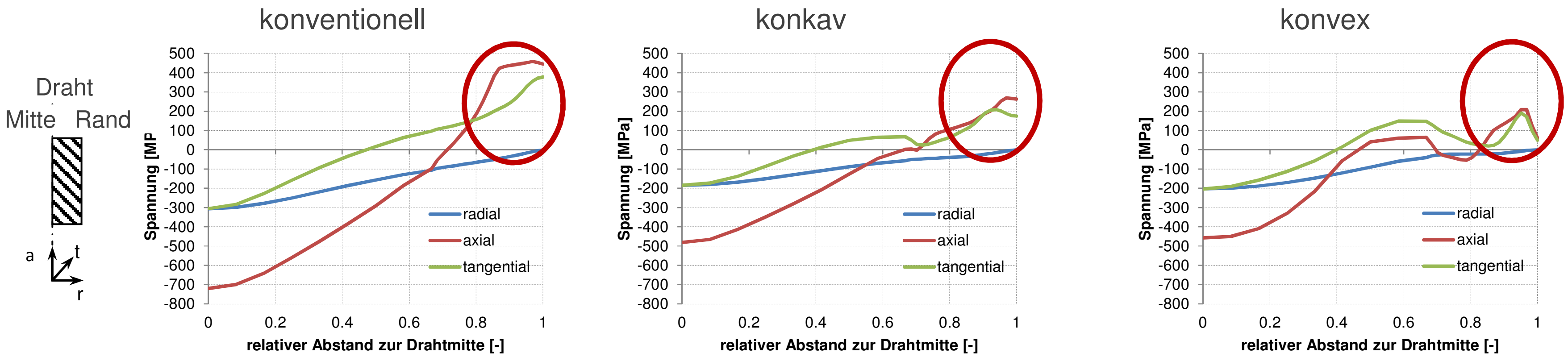
- Gradation Extrusion – process combining impact extrusion and severe plastic deformation
- SPD forming elements influencing character of deformation
  - Strain level
  - Gradient
- Microstructural analysis shows the grain refining effect
- Applications
  - Aluminum bolts
  - High strength grade 2 titanium implants

Next steps:

- Investigation of bolt properties and optimization of process chain
- Forming of implant prototypes
- Investigation of residual stress after processing

# 5. PROSPEKTS

## Residual Stress



# Thank you for your attention !

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DFG

SFB 692 – H A L S



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