

Crystalline modelling of deformation and recrystallization of an Udimet 720 superalloy during high temperature forging

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Material supplied by Aubert & Duval who cofinance this study with Ecole Centrale Paris

Outline

Context of the study

I°) The material

II°) The deformation model « Cristalecp »

III°) The recrystallization model « Reclpces »

IV°) The sequential coupling

Context of the study

Improvement of performances and energy efficiency of aircraft engines



Materials with very high mechanicals properties



Nickel base superalloy obtained by forging

Udimet 720 : Superalloy with remarkable mechanical properties at high temperature ($Re > 1000$ MPa at 800°C , low creep...)

➡ Material of replacement of the well known Waspaloy and Inconel 718 for the manufacturing of turbine discs



Material

- The Udimet 720 belongs to the family of superalloys hardened by γ' phase ($\text{Ni}_3[\text{Ti},\text{Al}]$) such as the Waspaloy
- The strength improvement results in the addition of alloying elements

Alliage	Ni	Cr	Co	Ti	Al	Mo	W	C	B	Zr
Waspaloy	base	19	13.5	3	1.4	4.2	-	0.04	0.006	0.06
Udimet 720	base	16	15	5	2.5	3	1.25	0.035	0.035	0.035

percentages
in mass

➡ The volume fraction of γ' phase reaches 43% instead of 30% for Waspaloy

➤ This strength improvement reduces inevitably ductility

➡ Sub-solvus forging required

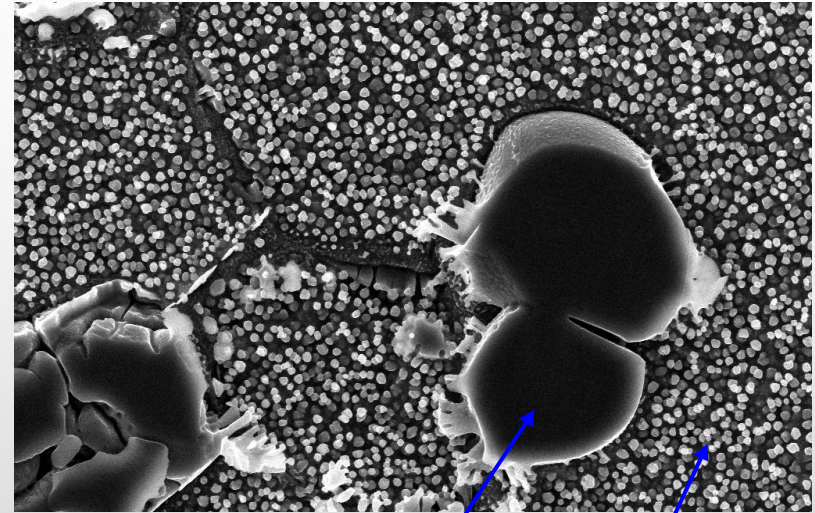
➡ Two-phase microstructural evolution during forging

Material

➤ Two phases microstructure :

- γ matrix (FCC)
- γ' hardening phase (SC)

Hypothesis: At 1100°C, secondary and tertiary γ' are solved



Primary γ'

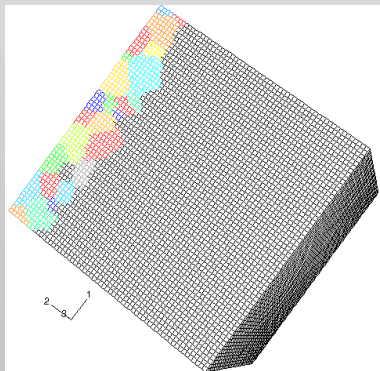
Secondary and tertiary γ'

Aims of the work

- ➔ Development of a numerical model to reproduce dynamic recrystallization
- ➔ Prediction of the microstructural evolution during forging

Deformation model : « Cristal_ECP »

- **Cristal_ECP** : Crystalline plasticity model implemented in Abaqus[®] code
- **Large transformation** : - $\mathbf{F}=\mathbf{A}.\mathbf{P}$ where \mathbf{P} plastic contribution
- $\mathbf{A}=(1+\boldsymbol{\varepsilon}).\mathbf{R}$ elastic contribution
- **Small elastic distortion ($|\boldsymbol{\varepsilon}| \ll 1$) but large rotation \mathbf{R}**
- **Deformation mechanism** : glide and recovery
- **Modelling on 3D aggregate with real microstructure obtained from EBSD**
- **In each element of the meshing** : - Crystalline orientation (Euler angles)



- Viscoplastic law
 - 12 slip systems $\{111\}\langle 110\rangle$ for γ matrix
 - 6 slip systems $\{100\}\langle 110\rangle$ for γ' precipitates
- Initial dislocation density

➡ Interaction between neighboring grains and phases are taken into account

Constitutive laws

- Schmid law on each slip system (s), in each element of the mesh

$$|\tau^s| = \tau_c^s \text{ et } \dot{\tau}^s = \dot{\tau}_c^s$$

- Viscoplastic law

$$\begin{cases} \dot{\gamma}_0^s = \frac{|\tau^s|^{n-1}}{\tau_c^s} \left(\frac{\tau^s}{\tau_c^s} \right) \text{sgn}(\tau^s) \text{ if } |\tau^s| \geq \tau_c^s \\ \dot{\gamma}^s = 0 \text{ otherwise} \end{cases}$$

$$\tau_c^s = \tau_0 + \mu b \sqrt{\sum_u a^{su} \rho^u} \quad \text{Critical shear stress}$$

- Hardening law

$$\dot{\tau}_c^s = \sum_u h^{su} |\dot{\gamma}^u|$$

- ➡ Material parameters determined by compression tests performed at several strain rate and temperature

- Hardening matrix

$$h^{su} = \frac{\mu}{2} \frac{a^{su}}{\sqrt{\sum_t a^{st} \rho^t}} \left(\frac{1}{L^u} - g_c \rho^u \right)$$

$$\text{with } \frac{1}{L^s} = \frac{1}{D} + \frac{\sqrt{\sum_{t \neq s} \rho^t}}{K}$$

- Dislocation density evolution law

$$\dot{\rho}^s = \frac{|\dot{\gamma}^s|}{b} \left(\frac{1}{L^s} - g_c \rho^s \right)$$

- ➡ The dislocation density is the state variable in the modelling

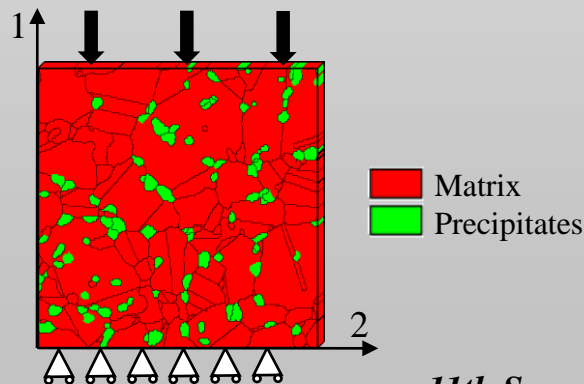
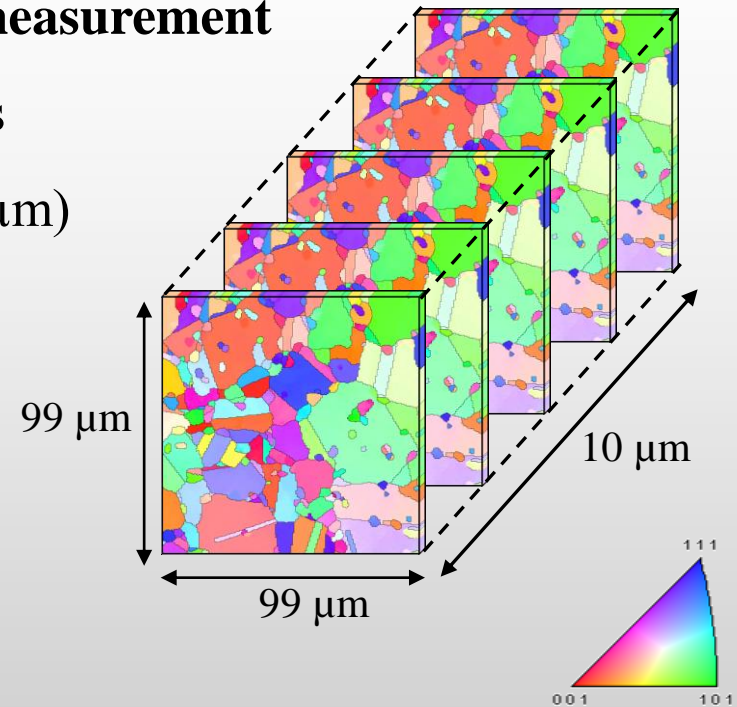
Meshing & aggregate

➤ The meshing is performed from EBSD measurement

- Aggregate composed by 5 similar layers
- Element size given by EBSD step ($0.6 \mu\text{m}$)
- EBSD map extruded in order to give a thickness of $2 \mu\text{m}$

➤ Two-phases aggregate

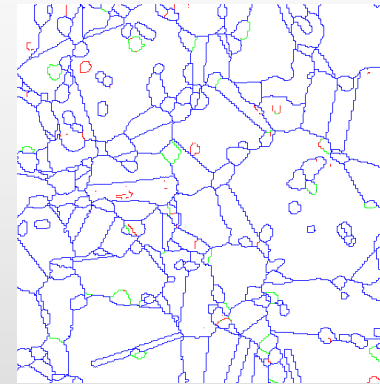
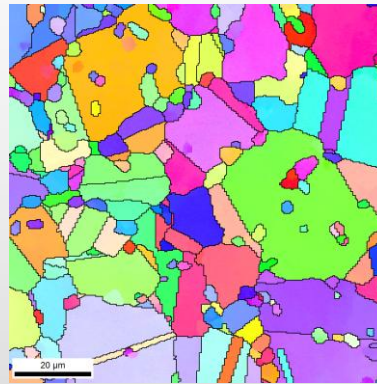
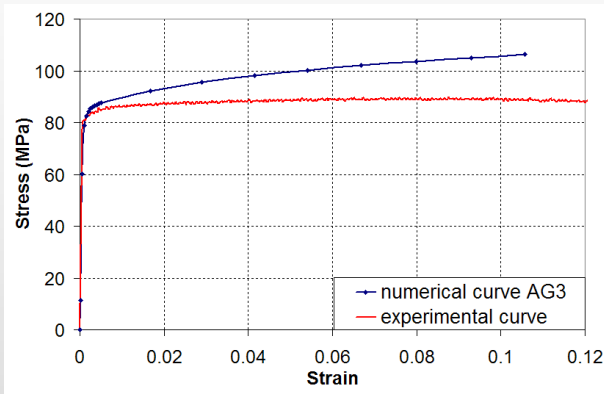
- $165 * 165 * 5$ elements (C3D8R)
- Forging boundary conditions



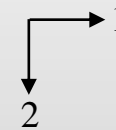
Deformation results

➤ 10% of deformation at 1100°C with $\dot{\epsilon} = 0.01 s^{-1}$

Initial microstructure

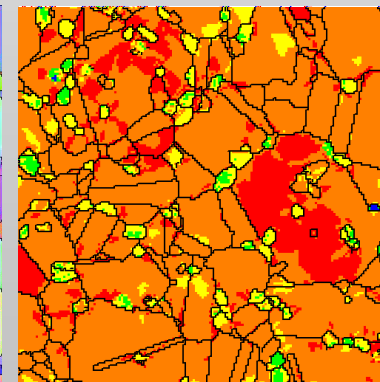
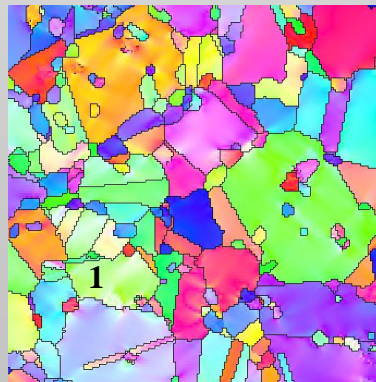
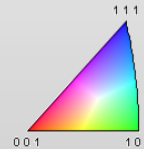


Boundaries: Rotation Angle		
Min	Max	Fraction
2°	5°	0.030
5°	15°	0.053
15°	180°	0.916



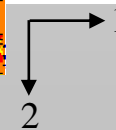
- Hardening voluntarily overestimated
- Creation of sub-boundaries
- Formation of intragranular misorientations (grain 1)
- Heterogeneous dislocation density after deformation

Deformed microstructure



Dislocation density

Min	Max	Total Fraction
3e+007	5e+007	0.001
5e+007	1e+008	0.018
1e+008	1.5e+008	0.091
1.5e+008	1.8e+008	0.744
1.8e+008	2.3e+008	0.146



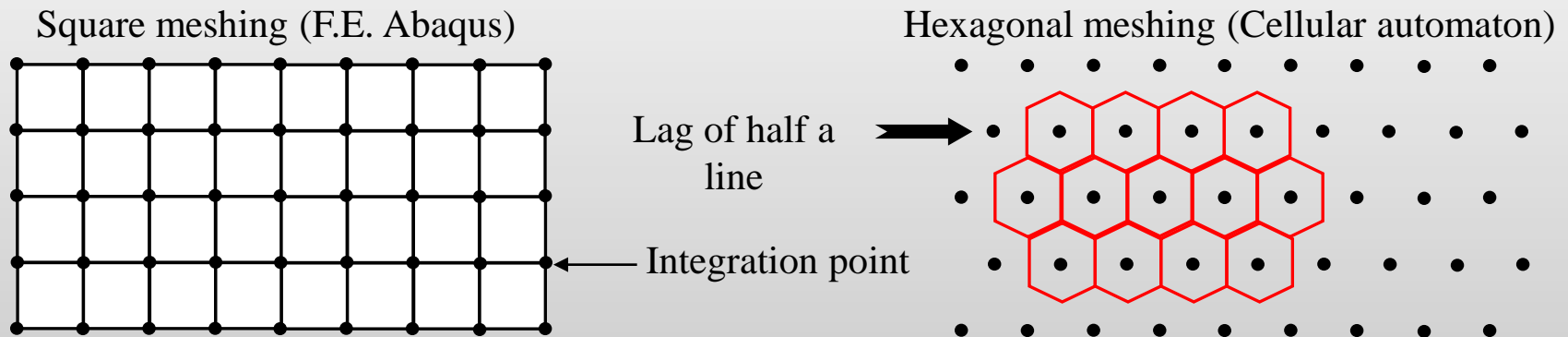
The recrystallization model « Rec_LPCES »

➤ Model of **recrystallization**

- Nucleation-growth approach

➤ Model based on the cellular automaton method

- Use of hexagonal meshing (6 neighbors for one site)



➤ Input parameters given by Cristal_ECP for each site :

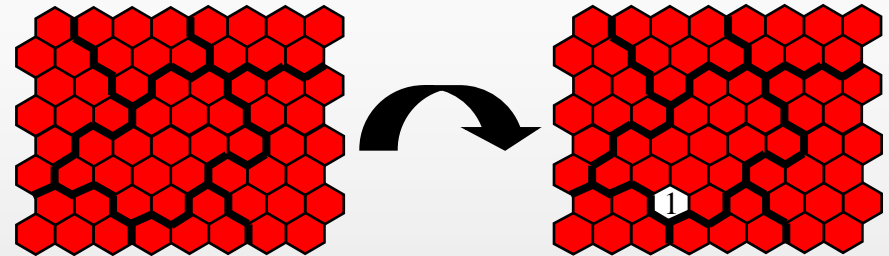
- New crystalline orientation
- Stored energy: calculated from dislocation density
- Number to identify phase

$$E_{stored} = \frac{1}{2} \mu b^2 \rho$$

Constitutive laws

➤ Nucleation

- Nucleation if $E_{\text{stored}} > E_{\text{limit}}$
- Nuclei are near the grain boundaries
- After nucleation $E_{\text{stored}} = 0$ and crystalline orientation remains the same



➤ Growth: possible for recrystallized grains

Mobility of grain boundaries

$$M^{SS'} = M_m \left[1 - \exp \left(- \left(\frac{\theta^{SS'}}{10} \right)^3 \right) \right]$$

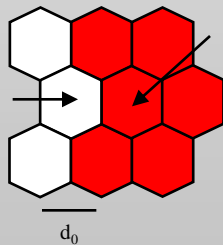
$$V = -M \Delta E$$

$$\Delta E = E_{\text{stored}} + \gamma \quad \text{where}$$

Driving force

$$\gamma^{SS'} = \begin{cases} \gamma_m \frac{\theta^{SS'}}{\theta^*} \left[1 - \ln \left(\frac{\theta^{SS'}}{\theta^*} \right) \right] & \text{when } \theta^{SS'} \leq \theta^* \\ \gamma_m & \text{when } \theta^{SS'} > \theta^* \end{cases}$$

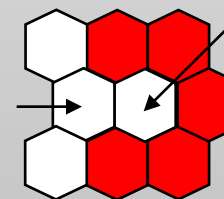
Recrystallized site
- $E_{\text{stored}} = 0$
- Orientation 1



Deformed site
- $E_{\text{stored}} \neq 0$
- Orientation 2



Recrystallized site
- $E_{\text{stored}} = 0$
- Orientation 1



Recrystallized site
- $E_{\text{stored}} = 0$
- Orientation 1

Probability of reorientation

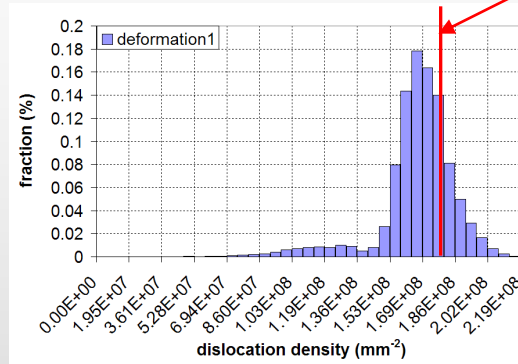
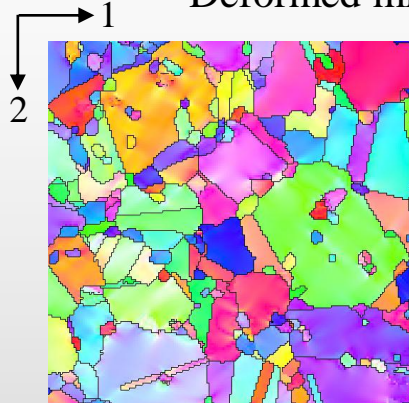
$$P^{SS'} = \frac{d}{d_0} = \frac{-M^{SS'} \Delta E t_{\text{inc}}}{d_0}$$

If $P^{SS'} >$ critical value \rightarrow réorientation

Recrystallization results



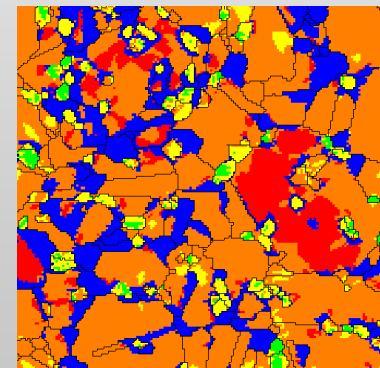
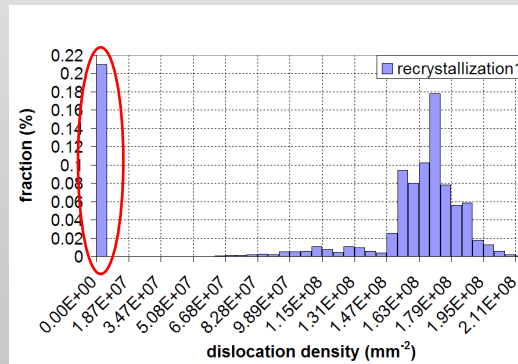
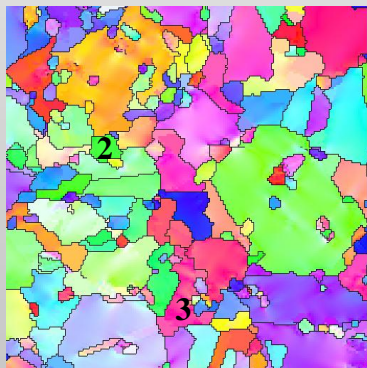
Deformed microstructure (Cristal_ECP)



**Critical value
for nucleation**

- Nucleation of all sites near the grain boundaries if $E_{\text{stored}} > 0.3 \text{ mJ} \cdot \text{mm}^{-3}$
($\rho = 1.82 \times 10^8 \text{ mm}^{-2}$)

Recrystallized microstructure



Dislocation density		Total Fraction
Min	Max	
0	1	0.210
1	1e+008	0.020
1e+008	1.5e+008	0.084
1.5e+008	1.8e+008	0.589
1.8e+008	2.2e+008	0.098

- Growth of grains (grain 2)
- Grains with sub-structure deformation (grain 3)

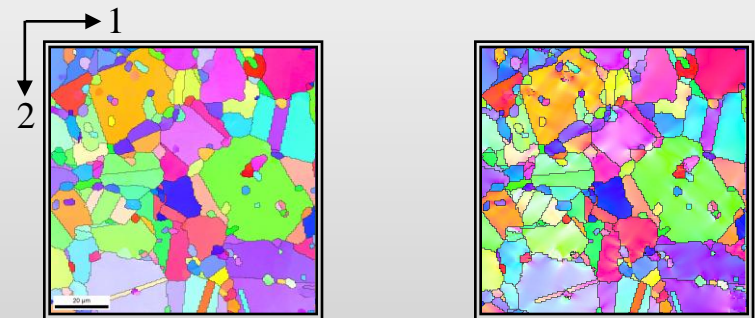
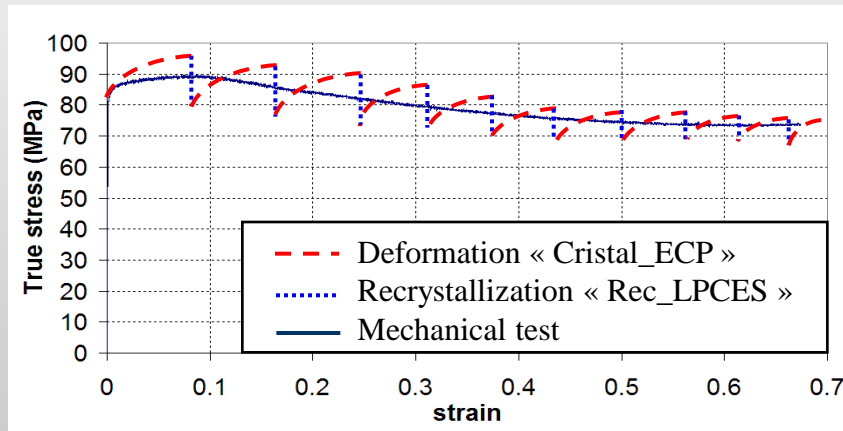
Sequential coupling to simulate dynamic recrystallization

➤ Sequential coupling of the models « Cristal_ECP » and « Rec_LPCES »

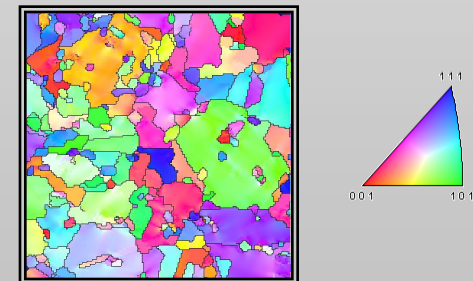
- Applied to an aggregate :

➡ To follow the macroscopic stress variation

➡ To study the microstructural evolution



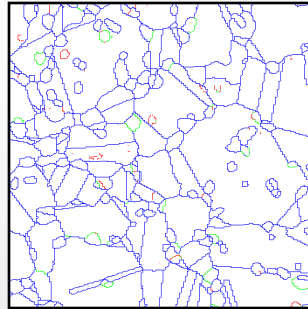
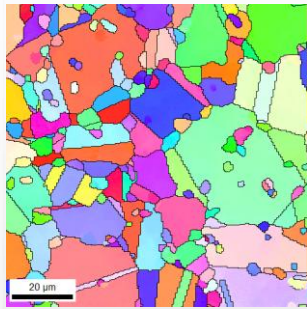
Initial microstructure Deformed microstructure



Recrystallized microstructure

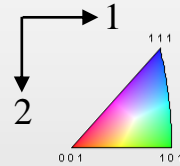
➡ Afterwards, to limit computation time the aggregate is made up of 5 layers where the sequential coupling is applied only to the intermediate layer

Sequential coupling

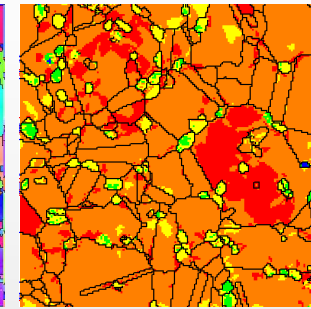
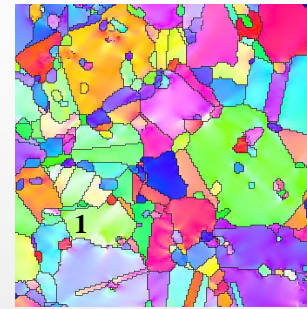


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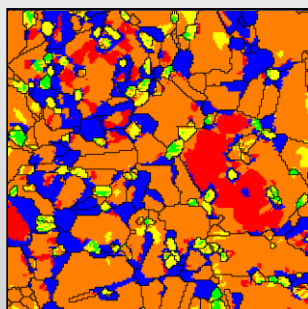
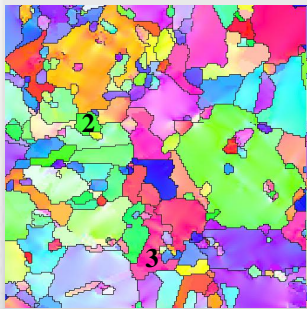


Initial microstructure


 $\epsilon = 10\%$

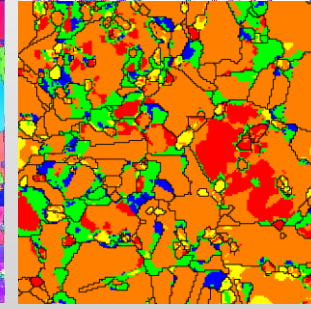
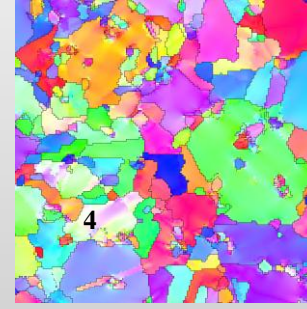
Dislocation density

	Min	Max	Total Fraction
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■	5e+007	1e+008	0.018
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Dislocation density

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 ϵ + recrystallization ϵ + recrystallization + ϵ

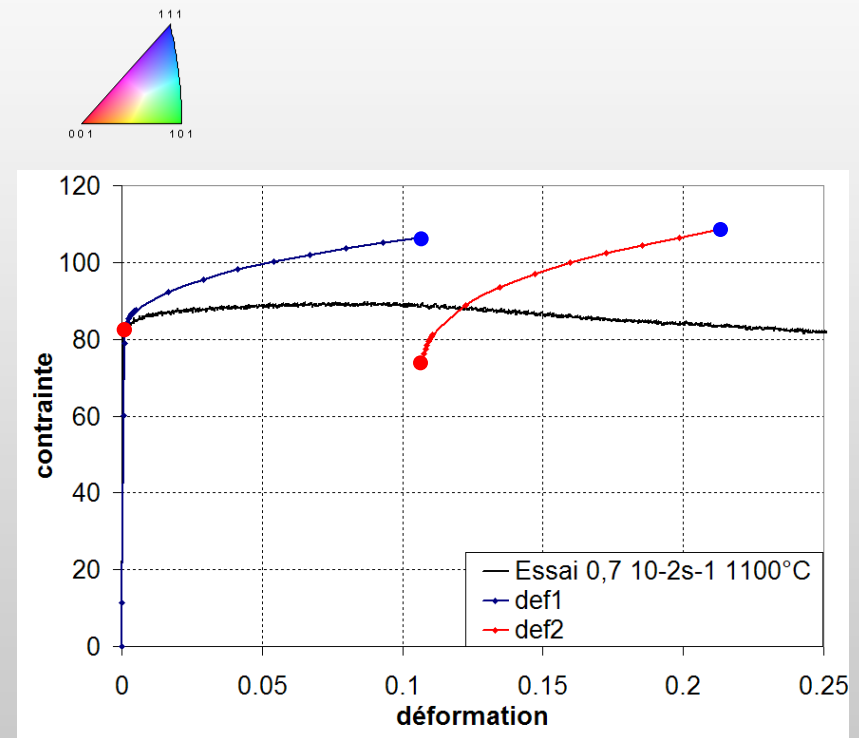
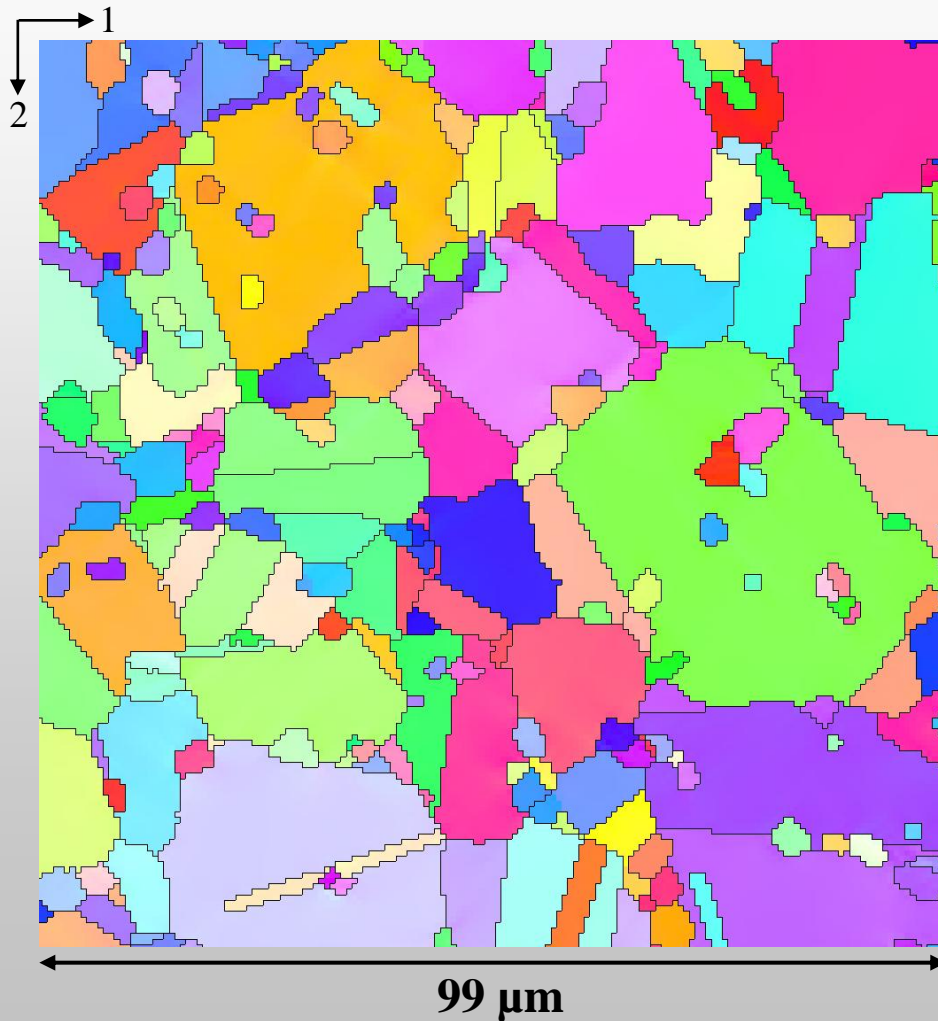
Dislocation density

	Min	Max	Total Fraction
■	2e+007	7e+007	0.041
■	7e+007	1.2e+008	0.165
■	1.2e+008	1.8e+008	0.053
■	1.8e+008	2.2e+008	0.632
■	2.2e+008	2.5727e+008	0.110

- Creation of intragranular misorientation during the first deformation
- Growth of grains and annihilation of sub-boundaries during recrystallization
- Increase of the misorientation of some sub-boundaries and evolution of the crystallographic orientation of some grains (grain 4) during the second deformation
- Evolution of dislocation densities during sequential coupling

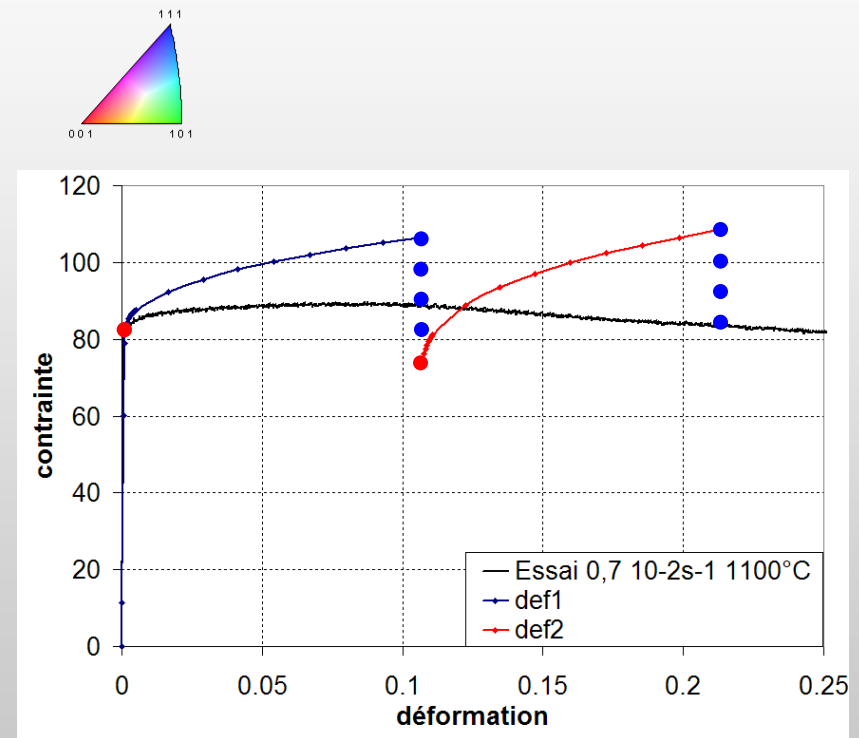
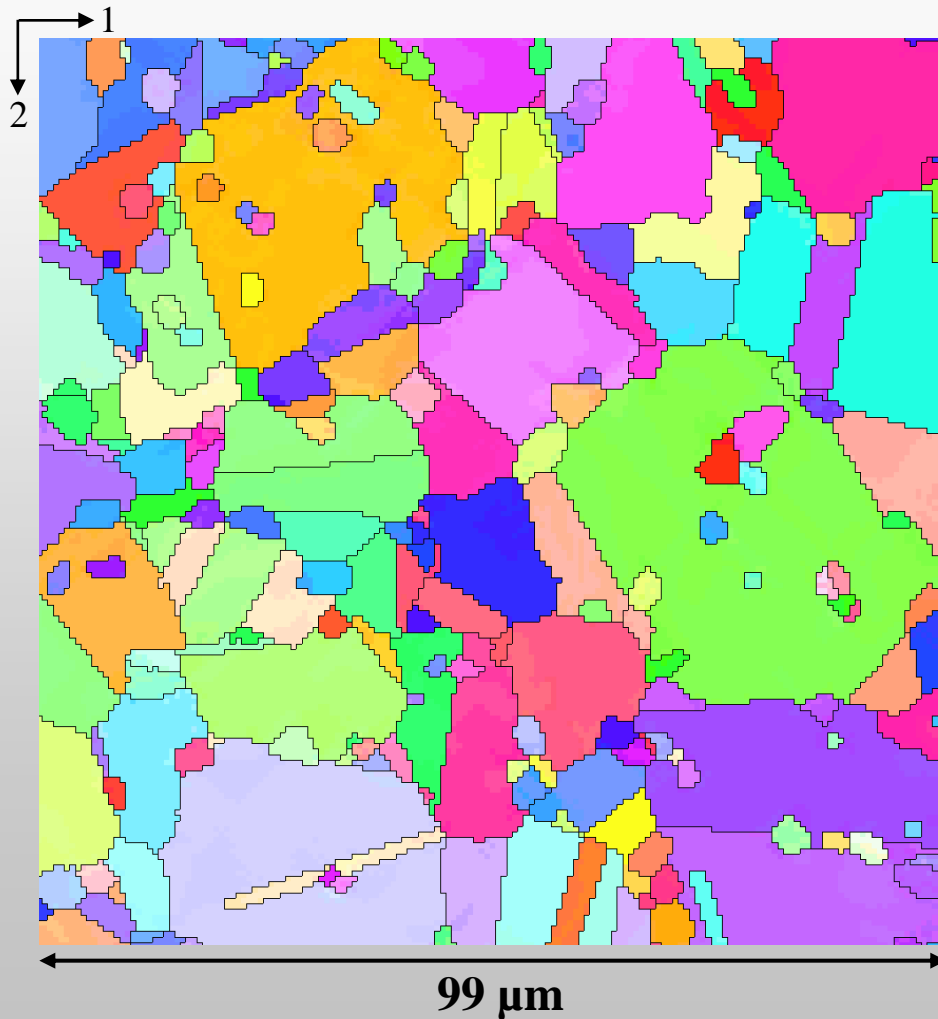
Sequential coupling

➤ After two cycles



Sequential coupling

➤ After two cycles



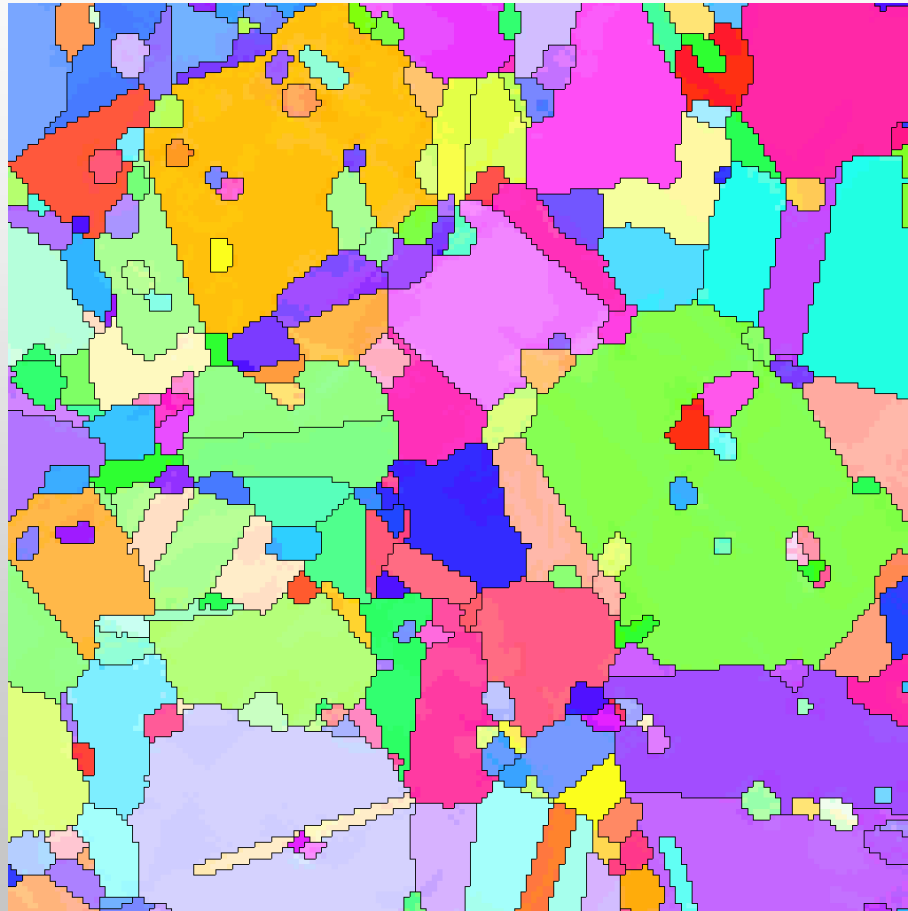
➤ Conclusion

- Development of an original simulation procedure for **dynamic recrystallization** on a two-phase material
- Prediction of stress evolution, microstructure, texture, dislocation density, stored energy ...

➤ Prospects

- Improvement of the deformation model for high temperatures
- Introduction of various recrystallization mechanisms identified during experimental analyzes (apparently DDRX for Udimet 720)
- Adjustment of the parameters to obtain a simulated stress-strain curve nearest of the experimental curve

Thank you for your attention !

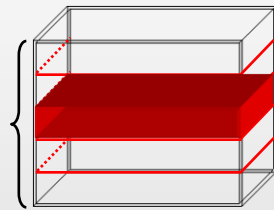


Sequential coupling

➤ Sequential coupling of the models « Cristal_ECP » and « Rec_LPCES »

Initial state : state 0

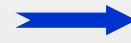
- Crystallographic orientation given by EBSD
- Unique dislocation density (ρ) per phase



1st Deformation

Deformed state : state 1

- Crystallographic orientation at state 1
- Increase of ρ
- ρ heterogeneous in the aggregate



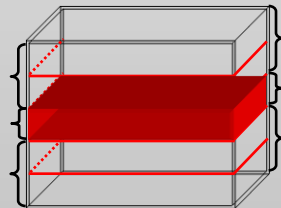
1st Recrystallization

Recrystallized state : state 2

- Crystallographic orientation at state 2
- ρ heterogeneous in the aggregate
 - Recrystallized grains : $\rho=0$
 - Deformed grains ρ : state 1

Input

- Layers at state 0
- Layer at state 2
- Layers at state 0



2nd Deformation

output

- Layers at state 1
- Layer at state 3
- Layers at state 1

Deformed state : state 3

- Crystallographic orientation at state 3
- Increase of ρ
- ρ heterogeneous in the layer