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Development and Validation of a Dynamic and Static Recrystallization Model for Microstructural Prediction of AA6060 Aluminum Alloy with Qform

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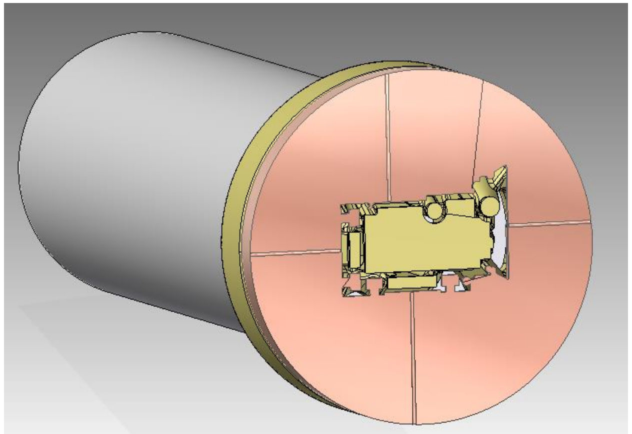
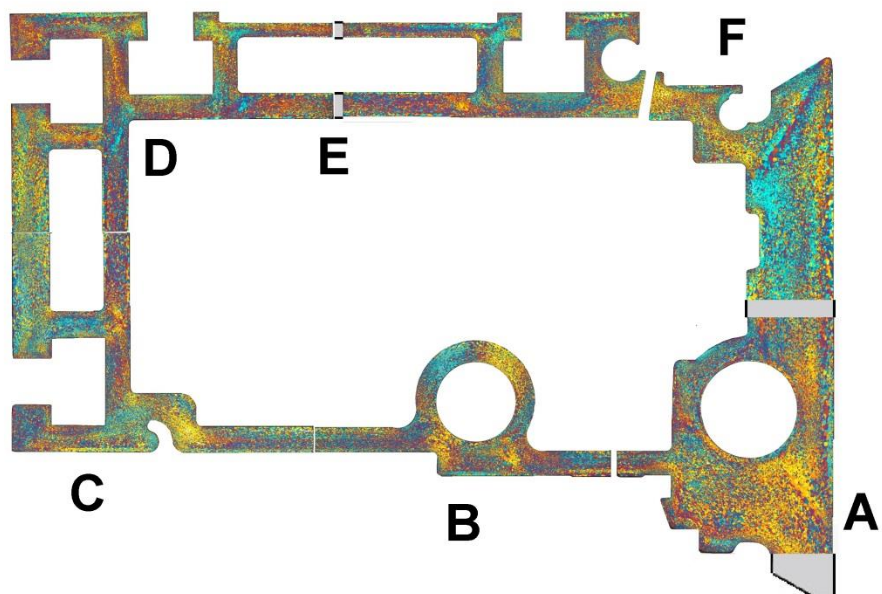
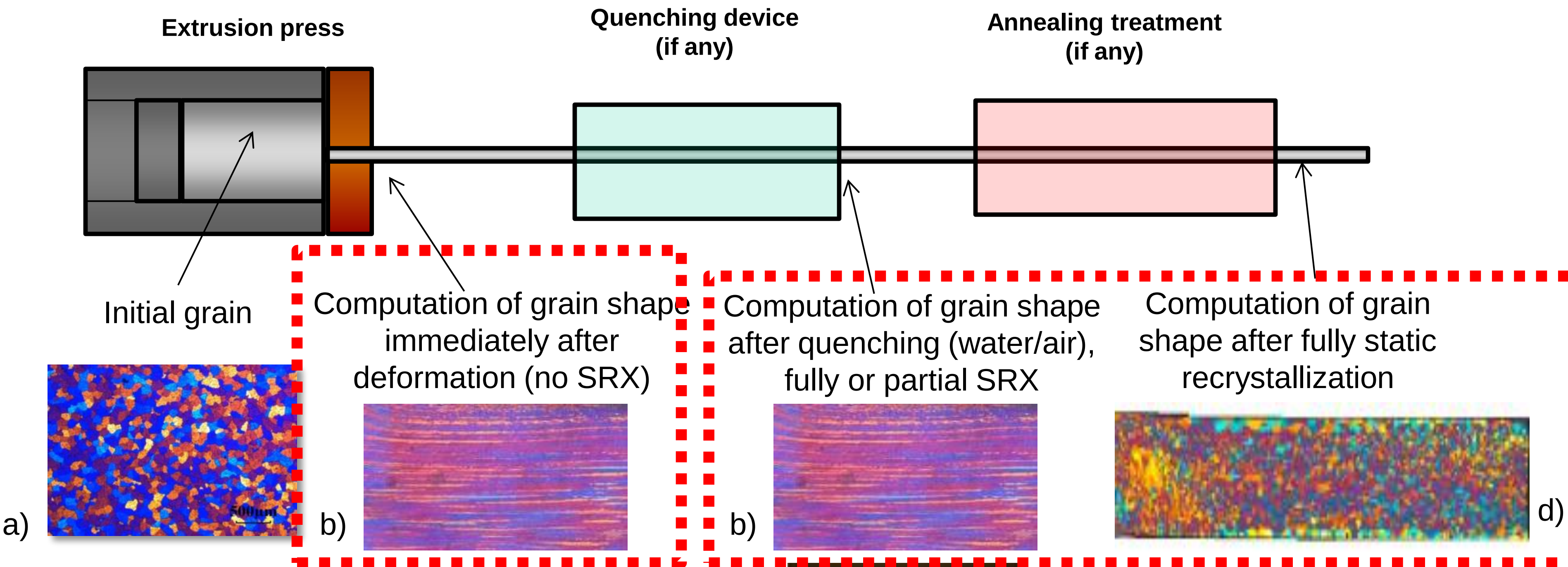
Aim of the research

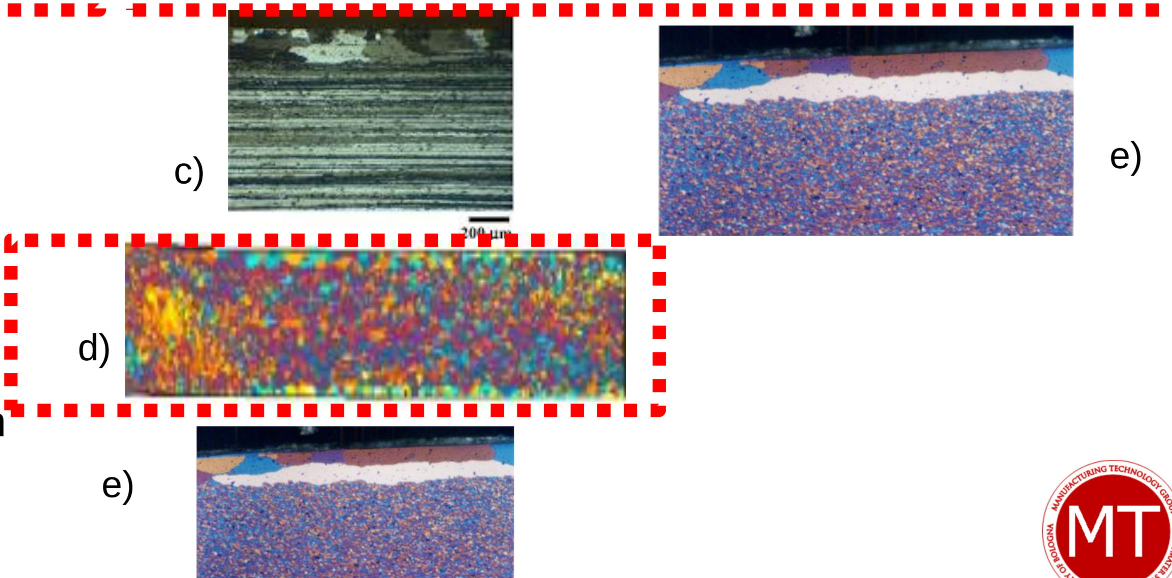
Prediction of final grain size in real 3D industrial profiles through FEM simulation at die design stage





Research steps





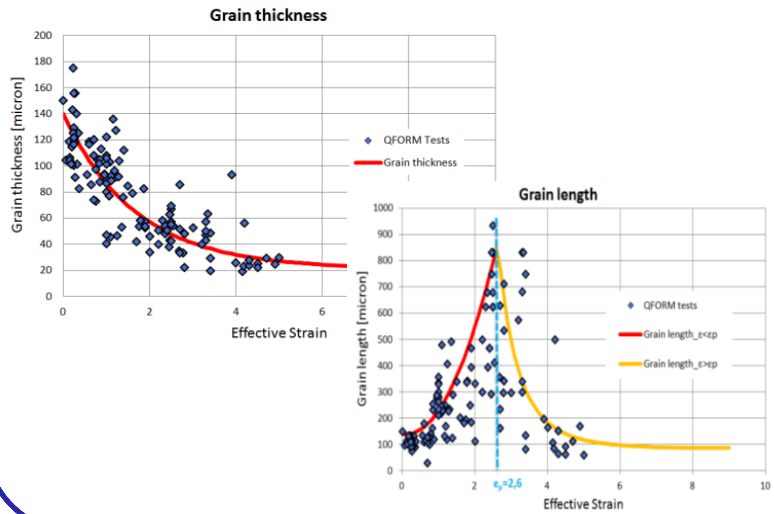
a) Cast material
b) Fibrous structure
c) Partially recrystallized
d) Fully recrystallized
e) Peripheral grain coarsening/Abnormal grain growth

Aim of paper

Development of a model within Lagrangian FE Code Qform to predict the grain evolution of 6xxx-series aluminum alloys during Dynamic Recrystallization (DRX) and Static Recristallization (SRX)

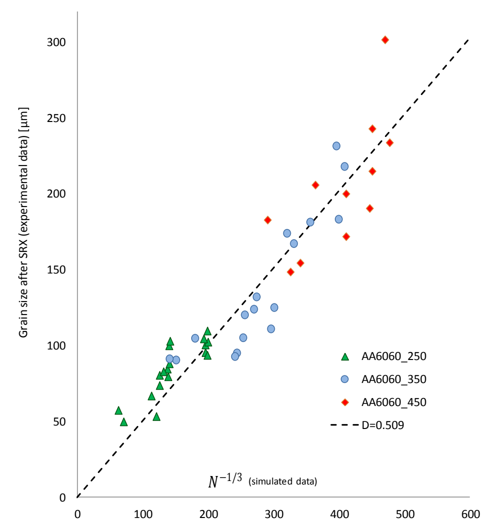
DRX Model

Validation of a theoretical model for the grain size and shape evolution of **6060** and **6082 aluminum alloys** previously developed.



SRX Model

Implementation and evaluation of a static recrystallization model proposed for **6060 aluminum alloy.**



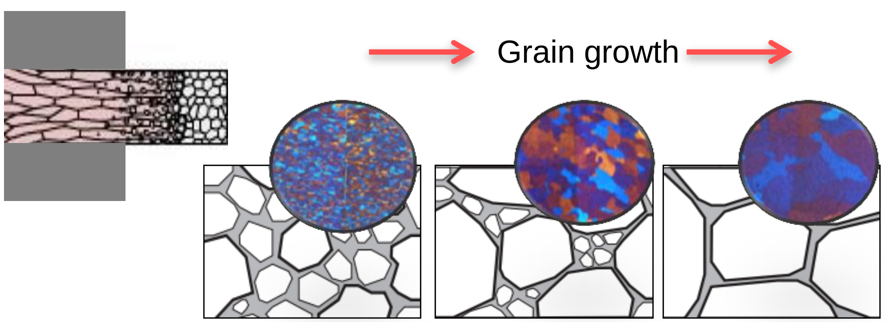
Recrystallization models in alluminum alloys

Recrystallization

Formation of a new grain structure in a plastically deformed material.

Static recrystallization (SRX)

Grain evolution/growth after dynamic recrystallization



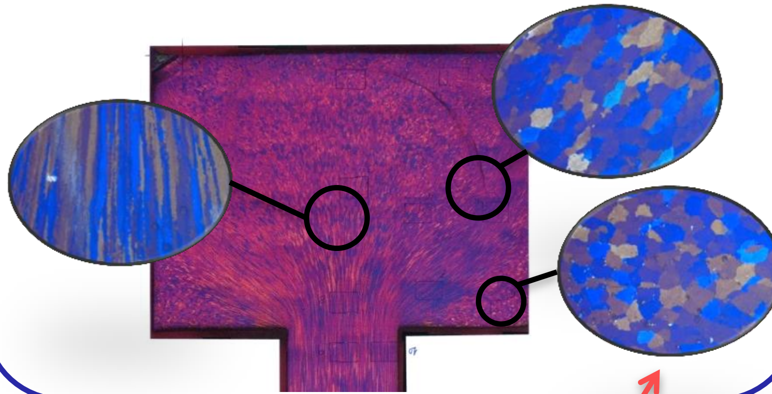
Peripheral Coarse Grain structure (PCG) or Abnormal Grain Growth

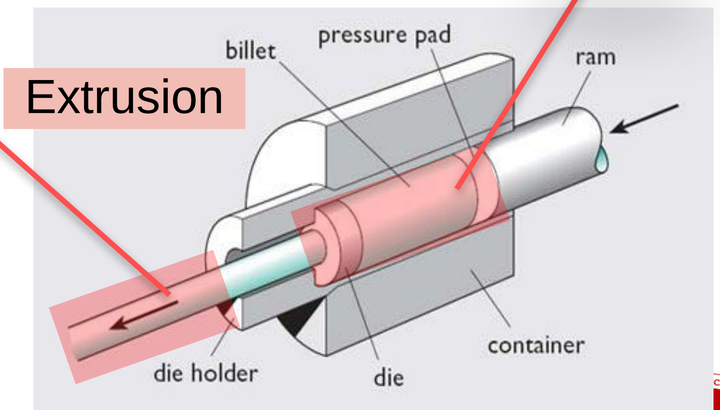
Abnormal grain growth in the peripheral surface of the profile in extrusion processing, while the remaining parts of the profile maintain a fibrous structure.

Dynamic recrystallization (DRX)

Approaches that involve the production of new grains during hot deformation processes

- •CDRX: continuous dynamic recrystallization
- •GDRX: geometric-dynamic recrystallization

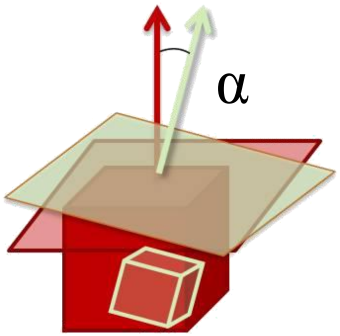




Dynamic recrystallization (DRX)

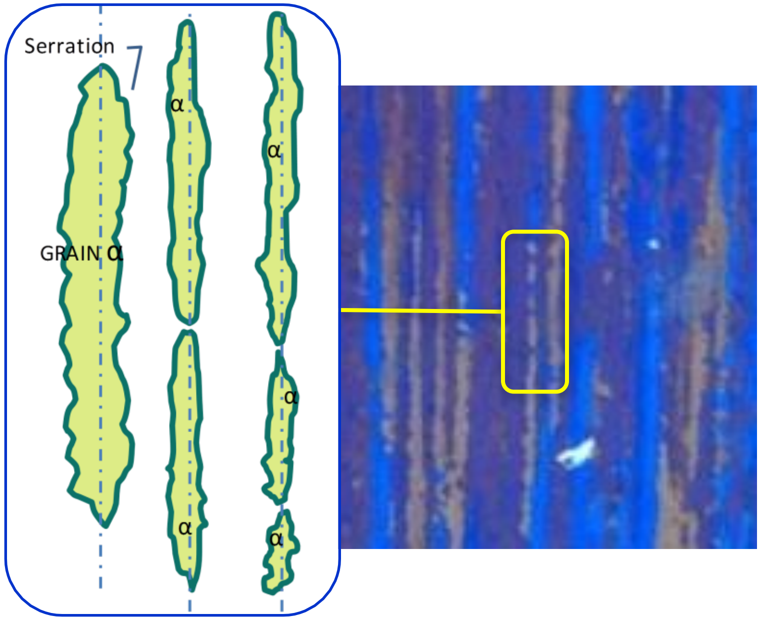
Continuos Dynamic Recrystallization (CDRX)

The misorientation **α** of subgrains increases with the progressive application of a macroscopic deformation, till a difference greater of 15° (critical value) between subgrains

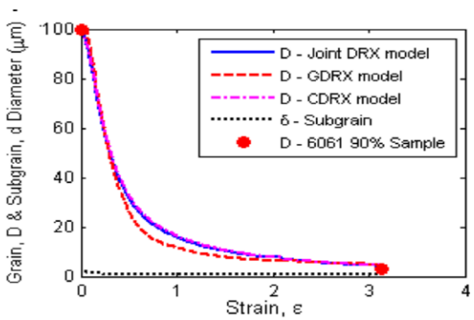


Geometric Dynamic Recrystallization (GDRX)

When the thinning of high angle serrated grains is reduced till a thickness in the order of twice the subgrain size, the grain “pinch- off “ in two or more parts.



Joint Dynamic Recrystallization (JDRX)



Combination between CDRX and GDRX (De Pari theory)

Luigi De Pari Jr., Wojciech Z. Misiolek, Theoretical predictions and experimental verification of surface grain structure evolution for AA6061 during hot rolling, *Acta Materialia* 56 ,6174 (2008) .

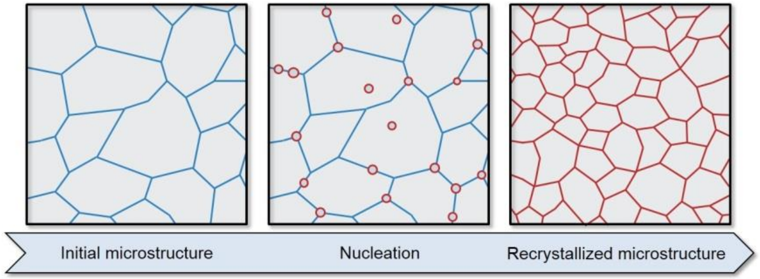
Static recrystallization (SRX)

Static recrystallization (SRX)

"Static recrystallization is the process in which a deformed material is transformed into a strain free Structure. This occurs by the nucleation of strain free regions (nuclei) which grow and eventually replace the original deformed matrix"

(D.J. Srolovitz, G.S. Grest, M.P. Anderson, Acta Metall. 34 (1986) 1833-1845.)

•This process is mainly driven by temperature, strain and strain rates, stored energy, chemical structure and alloying elements.
•The stored dislocation energy allows the growth of nuclei
•More stable structure is produced
• Achievement of a lower dislocation density than in the deformed structure



Peripheral Coarse Grain structure (PCG)

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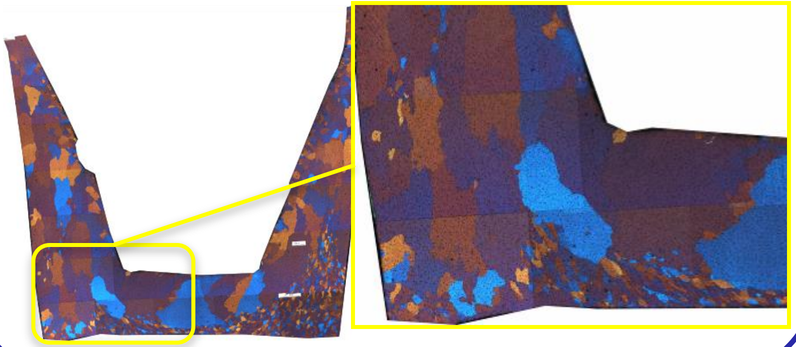
- PCG structure is a undesirable microstructure because causes a high deterioration of profile properties, in particular strength, deformability, and corrosion resistance.
- It is due to the complex, unclear interaction of several factors: extrusion conditions (strain, strain rates, temperatures), cooling process, chemical composition, homogenization treatment.
- A unified model able to predict abnormal grain growth is currently still under study, and will not be included in the present work.
- Specimens where PCG occurred, were not included in the present work.



JDRX model

- **δ** : subgrains size
- **Z**: Zener-Hollomon parameter
- **N**: density of recrystallization sites
- **d_t** :thickness of grains
- **d_l** :length of grains

$$Z = \dot{\bar{\varepsilon}} \exp\left(\frac{Q}{RT}\right)$$

$$\frac{1}{\delta} = C(\ln Z)^n$$

$$N = \frac{4C_d}{\delta^2 (d_t + d_l)}\left[e^{\bar{\varepsilon}} - e^{-\bar{\varepsilon}} + 1\right]$$

$$d_t = (d_0 - 2.5 \cdot \delta_{SS})(\mathbf{k_1})^{\bar{\varepsilon}} + 2.5 \cdot \delta_{SS}$$

$$d_l = \mathbf{k_2}\bar{\varepsilon}^2 - \mathbf{k_3}\bar{\varepsilon} + d_0 \quad \text{for } \varepsilon < \varepsilon_p$$

$$d_l = \mathbf{k_4}\bar{\varepsilon}^{-\mathbf{m}} + 10 \cdot \delta_{SS} \quad \text{for } \varepsilon > \varepsilon_p$$

C=3.364E-09 [m^{-1}],

n=5.577,

Q=161000 J/mol (Activation Energy)

$\dot{\bar{\varepsilon}}$:effective strain rate

R=8.341J/mol (Universal gas constant)

T :absolute temperature in ° K

C_d =1.48·10^{-4} (calibration constant)

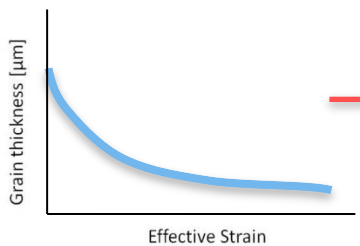
d_0 =137 µm (undeformed grain size)

δ_{ss}= 8,4 µm (subgrain size at the steady state condition)

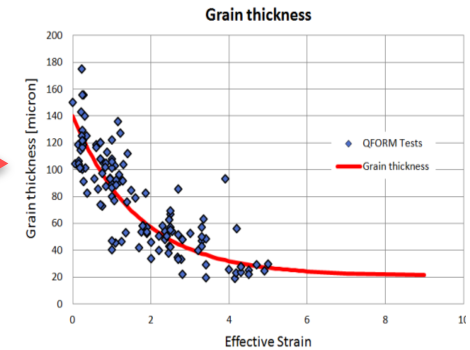
ε: Von Mises effective strain

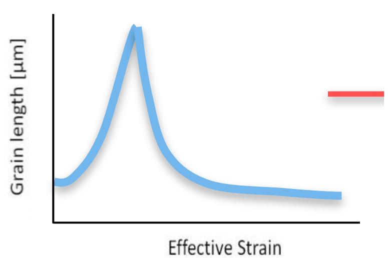
ε_p :critical level of strain for the starting of pinch-off

Coefficients **k_1**, **k_2**, **k_3**, **k_4**, **m** and **ε_p** were determined by authors in a previous work[1]



k_1= 0.55





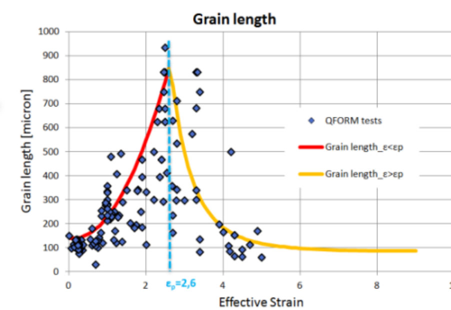
k_2=114

k_3=25

k_4=9E04

m=4.9

ε_p=2.6



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[1] Bandini, C., Reggiani, B., Donati, L., and Tomesani, L., "Code validation and development of user routines for microstructural prediction with Qform," *Materials Today: Proceedings,* Vol. 2, 2015, pp. 4904–4914.

SRX model

δ : subgrains size

Z: Zener-Hollomon parameter

N: density of recrystallization sites

d_t :thickness of grains

d_l :length of grains

d_{rex}: static recrystallization grain size

C=3.364E-09 [m^{-1}],

n=5.577,

Q=161000 J/mol (Activation Energy)

$\dot{\bar{\varepsilon}}$:effective strain rate

R=8.341J/mol (Universal gas constant)

T :absolute temperature in ° K

C_d =1.48·10^{-4} (calibration constant)

d_0 =137 μm (undeformed grain size)

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$$Z = \dot{\bar{\varepsilon}} \exp\left(\frac{Q}{RT}\right)$$

$$\frac{1}{\delta} = C(\ln Z)^n$$

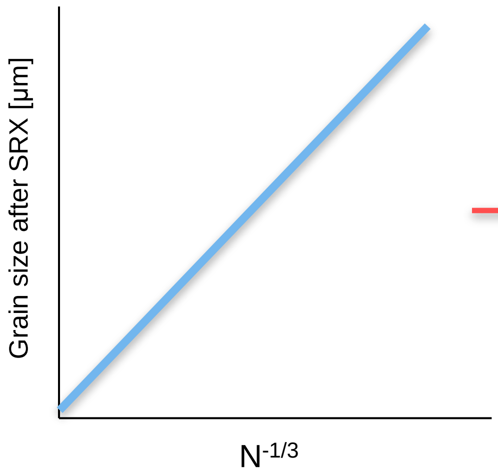
$$d_t = (d_0 - 2.5 \cdot \delta_{SS})(k_1)^{\bar{\varepsilon}} + 2.5 \cdot \delta_{SS}$$

$$d_l = k_2 \bar{\varepsilon}^2 - k_3 \bar{\varepsilon} + d_0$$

$$d_l = k_3 \bar{\varepsilon}^{-m} + 10 \cdot \delta_{SS}$$

$$N = \frac{4C_d}{\delta^2 (d_t + d_l)} \left[e^{\bar{\varepsilon}} - e^{-\bar{\varepsilon}} + 1 \right]$$

$$d_{rex} = \mathbf{D}\, N^{-\frac{1}{3}}$$

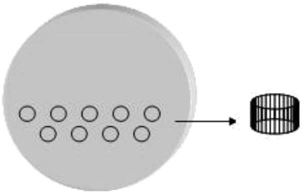


Coefficients **D** was evaluated by comparing the results of simulations with experimental data

Experimental plan

Material AA6060
fully homogenized
d_0 =137 µm

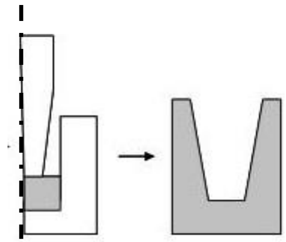
Material AA6082
fully homogenized
d_0 =152 µm

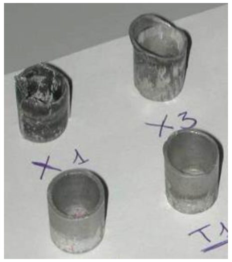


Different extrusion temperature:
250° C, 350° C,
450° C, 550 ° C

Different ram speed: 0.1mm/sec,
5 mm/sec

Hot backward extrusion

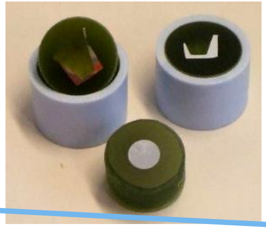


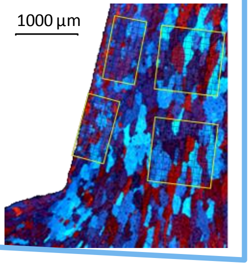


Water quenching

Microstructural analysis

Morphology and grain size after **dynamic recrystallization**

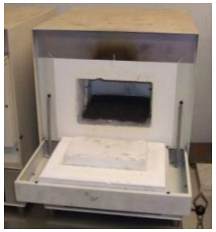


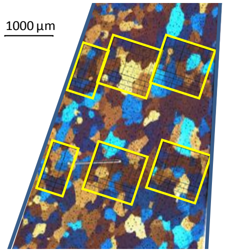


Only on AA6060 alloy specimens

Annealing heat treatment (550° C 30min)

Morphology and grain size after **static recrystallization**





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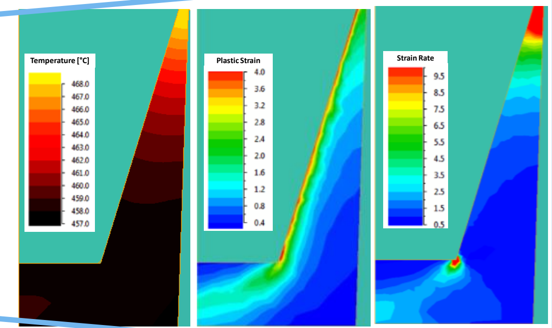
TU Delft
Delft University of Technology

Numerical plan

FEM Simulation (QForm)

Temperature
Strain
Strain rate

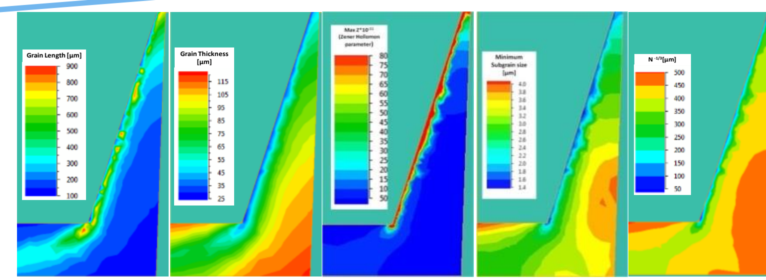


User routine

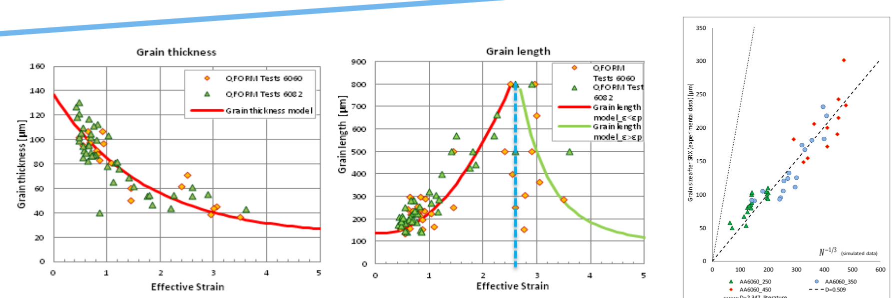
FEM Simulation (QForm)

For AA6082 samples: d_t, d_l

For AA6060 samples: d_t, d_l, max Z, minδ, $N^{-1/3}$



Comparison between simulated and experimental results



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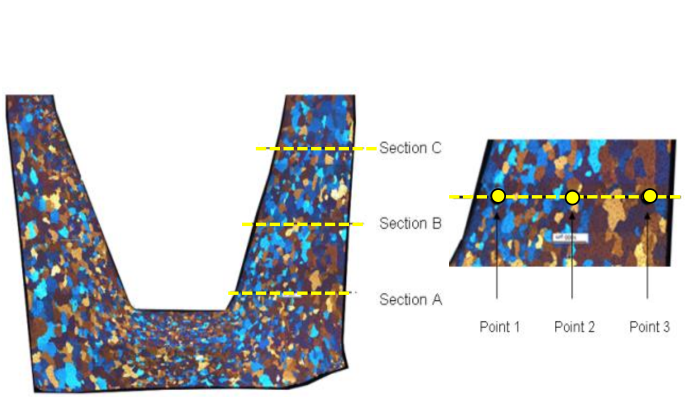
Processing and methods

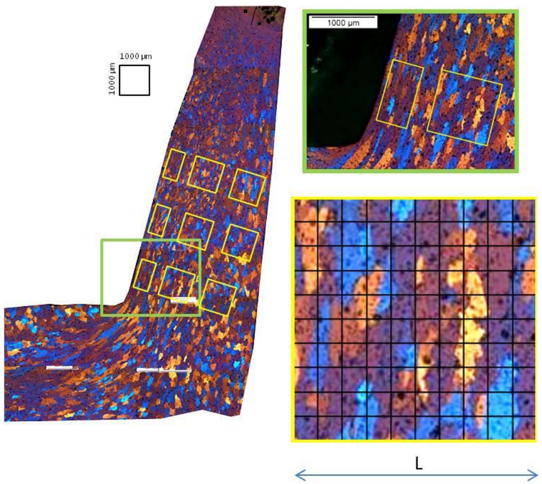
8 different hot backward extrusions for each alloy.

Selection of 9 small areas (500/1000 µm X 1000 µm) in the micrographs.

Grain size calculation through ‘line interception’ method.

Ram speed [mm/s]	Temperature [°C]	AA6060 specimen code	AA6082 specimen code
0,10	250	60_250_01	82_250_01
0,10	350	60_350_01	82_350_01
0,10	450	60_450_01	82_450_01
0,10	550	60_550_01	82_550_01
5	250	60_250_5	82_250_5
5	350	60_350_5	82_350_5
5	450	60_450_5	82_450_5
5	550	60_550_5	82_550_5

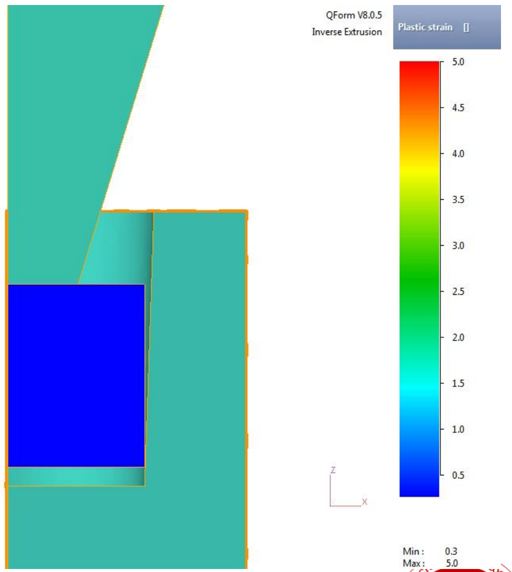




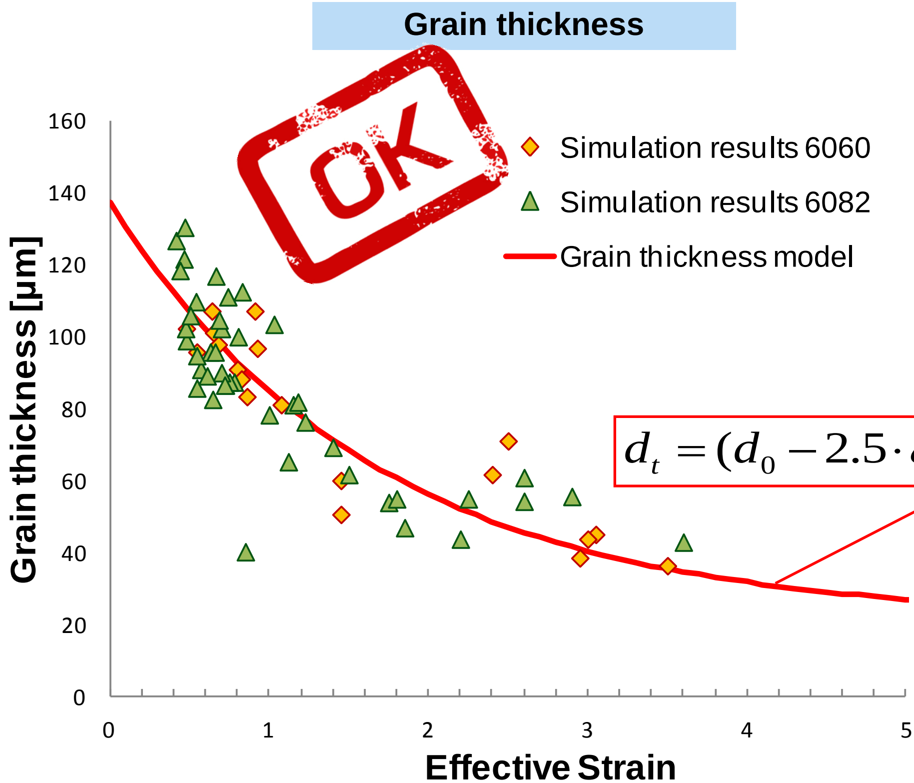
Simulation parameters setting

Pre –processing:
- ✓ 3D approach by simulating 1/4 specimen.
- ✓ Hensel –Spittel flow stress formulation implemented through a user routine.
- ✓ Levanov friction conditions with friction factor m = 0.3 (ring test data), n=1.25 (exponent).
- ✓ Simple heat exchange was set on all billet-dies surfaces.
- ✓ HTC steel-aluminum fixed at 11000 W/(m^2K).
- ✓ Rigid fixing set on bottom tool basement.
- ✓ Mesh adaptation in workpiece due to strain and due to velocity.

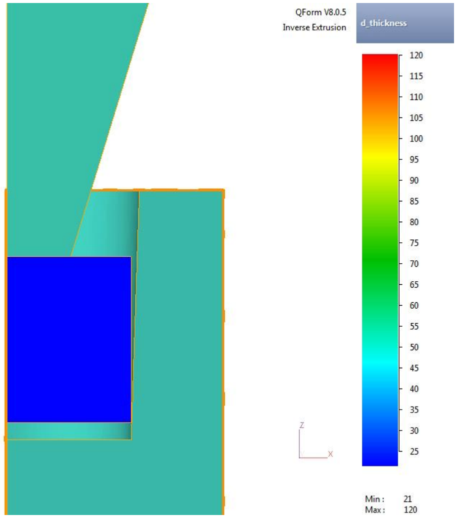
Post –processing:
- ✓ Implementation of dynamic and static model through user routines.

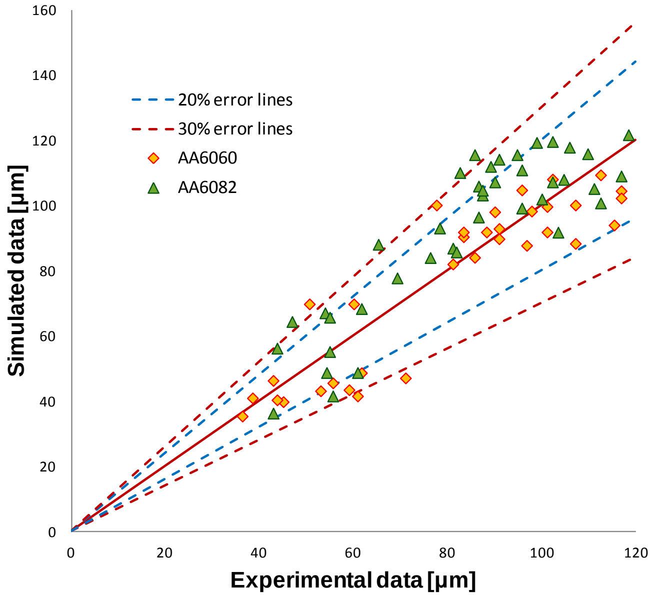


JDRX model: simulations results



$$d_t = (d_0 - 2.5\cdot\delta_{SS})(0.55)^{\bar{\varepsilon}} + 2.5\cdot\delta_{SS}$$



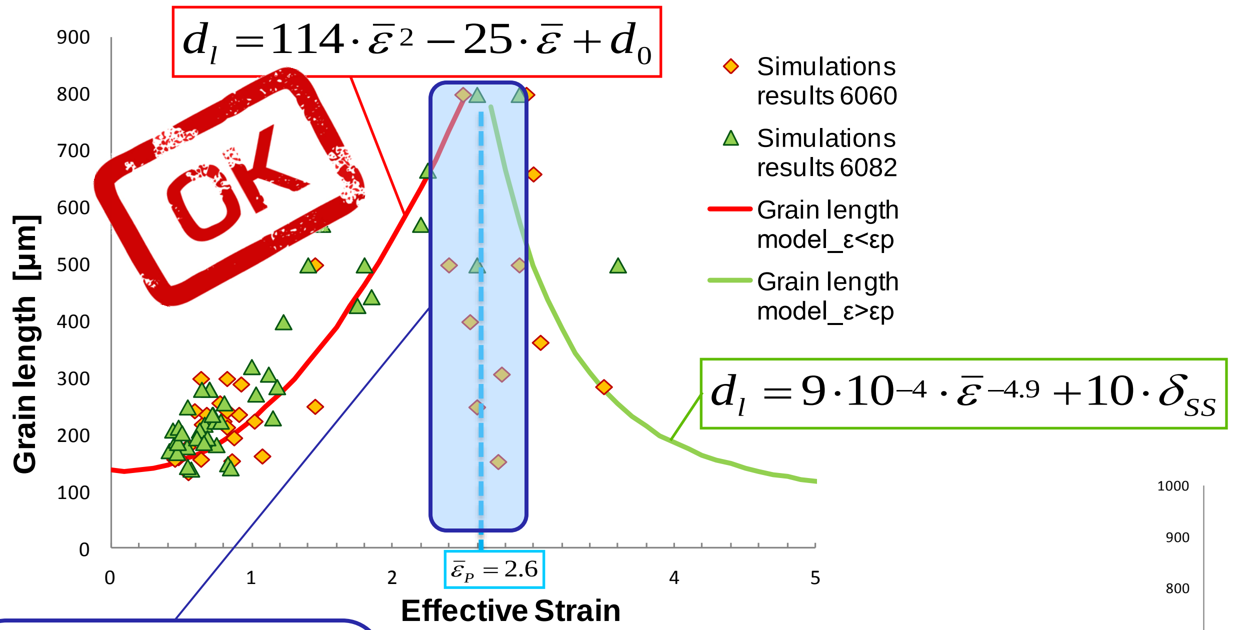


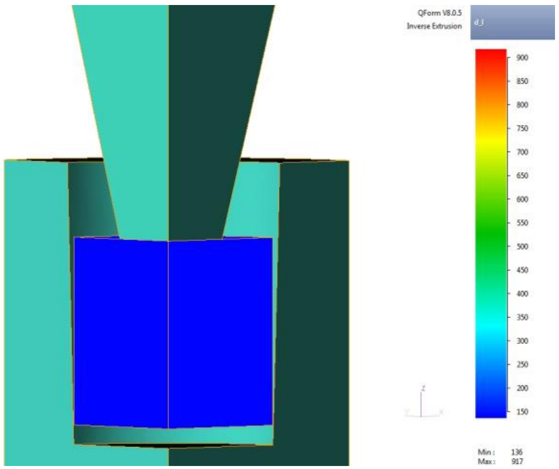
The good agreement is clearly visible by the experimental simulation charts.

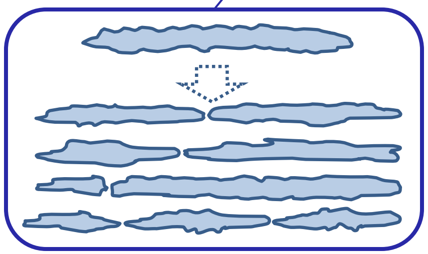
75.3 % of dots within the 20 percent error lines, and 91% within the 30 percent.

JDRX model: simulations results

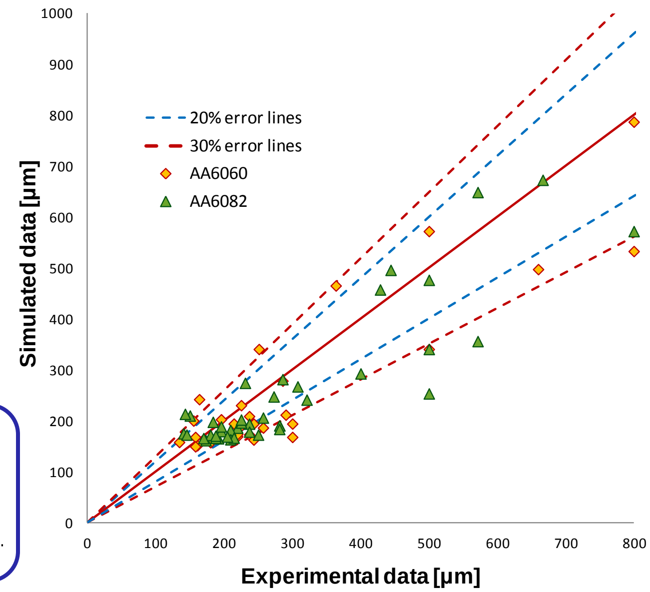
Grain length







High dispersion at ε=εp=2.6 due to the occurrence of the **"pinch-off" effect**: the grain splits into two or more parts, the separation can take place at any point of the grain, thus producing grains of statically different and variable lengths.



Apart from pich-off phenomena there is

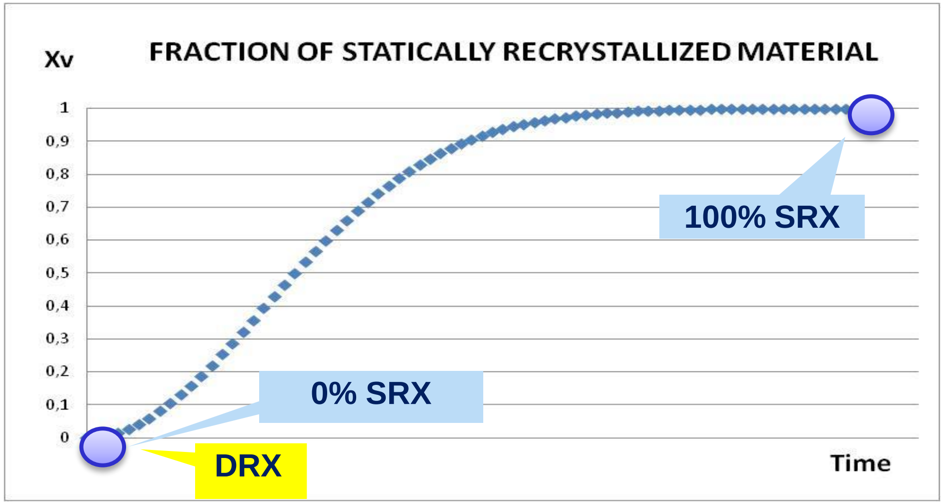
good agreement beetween proposed model and numerical results:

55.5 % of dots within the 20 percent error lines, and 77.5 % within the 30 percen

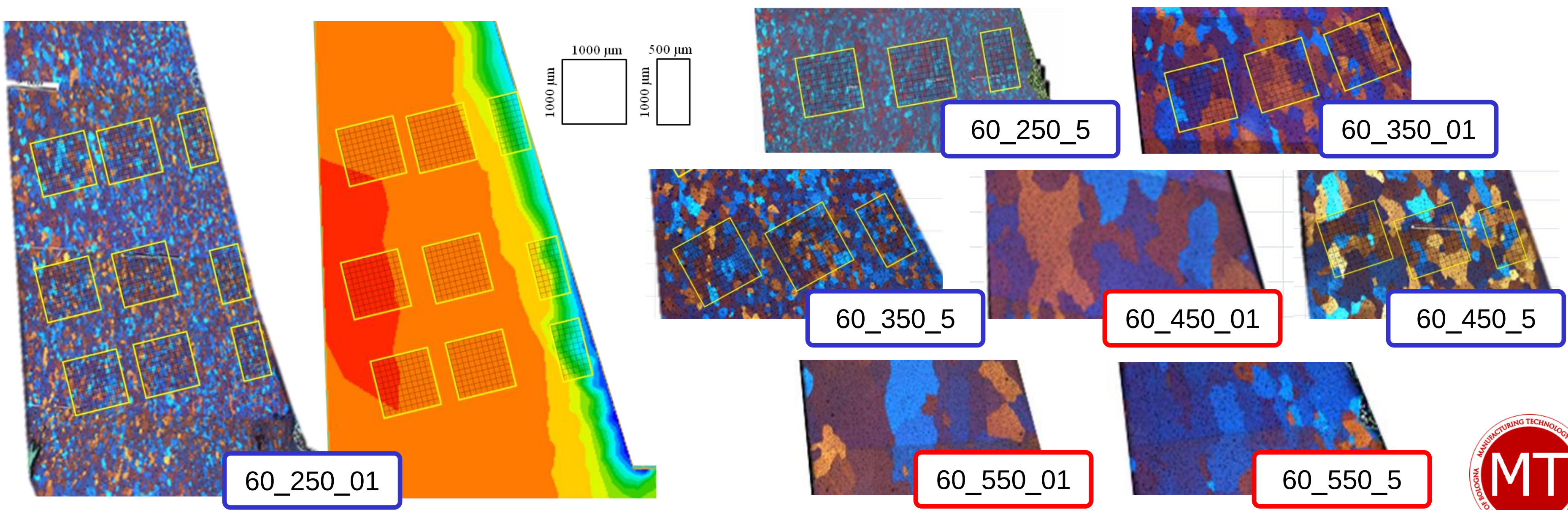
JDRX model: experimental data

Heat Treatment after extrusion:
SOLUTION SOAKING + T6 TEMPER

1) Solution heat treatment at 580° C for 30 minutes



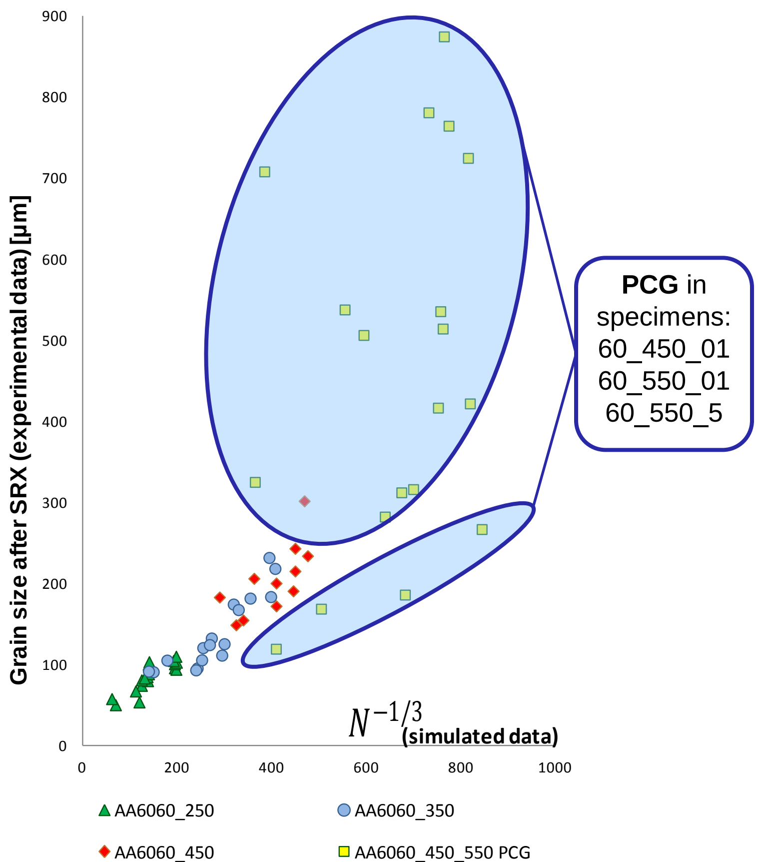
Evaluation of grain size after 100% SRX in 9 areas of specimens through 'line interception' method.



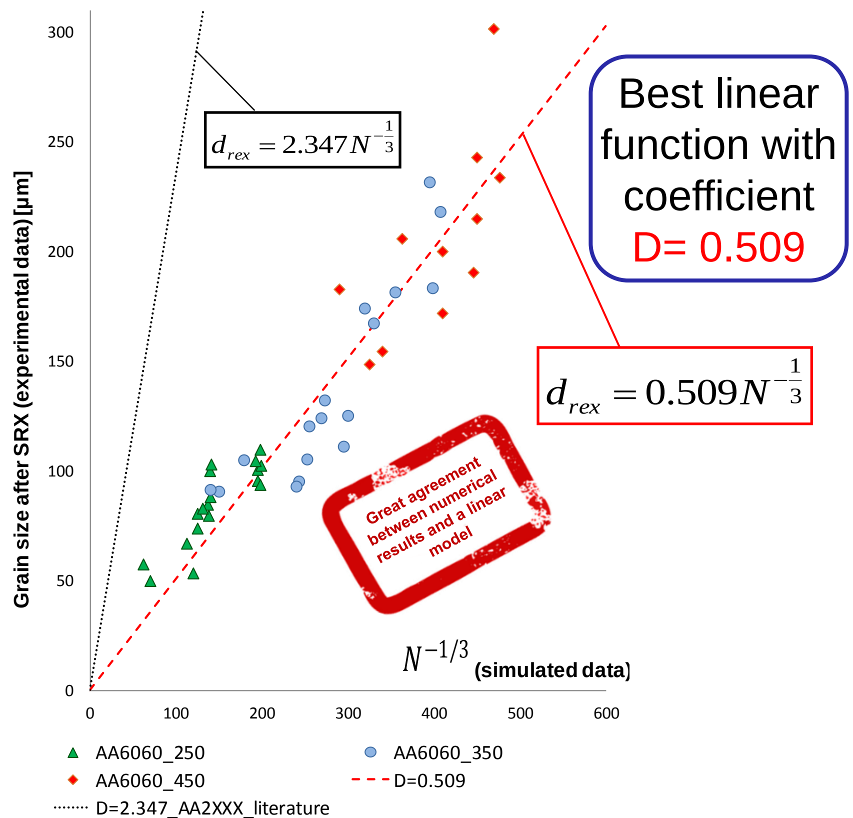
SRX model: simulations results

The values of $N^{-1/3}$ parameter obtained from user routine calculation were plotted over recrystallized grain size (d_{rex}) experimentally measured.

Coarse grain (PCG) included



Coarse grain (PCG) not included



Calibration coefficient
$D_{AA6060} \neq D_{AA2014-AA2024}$

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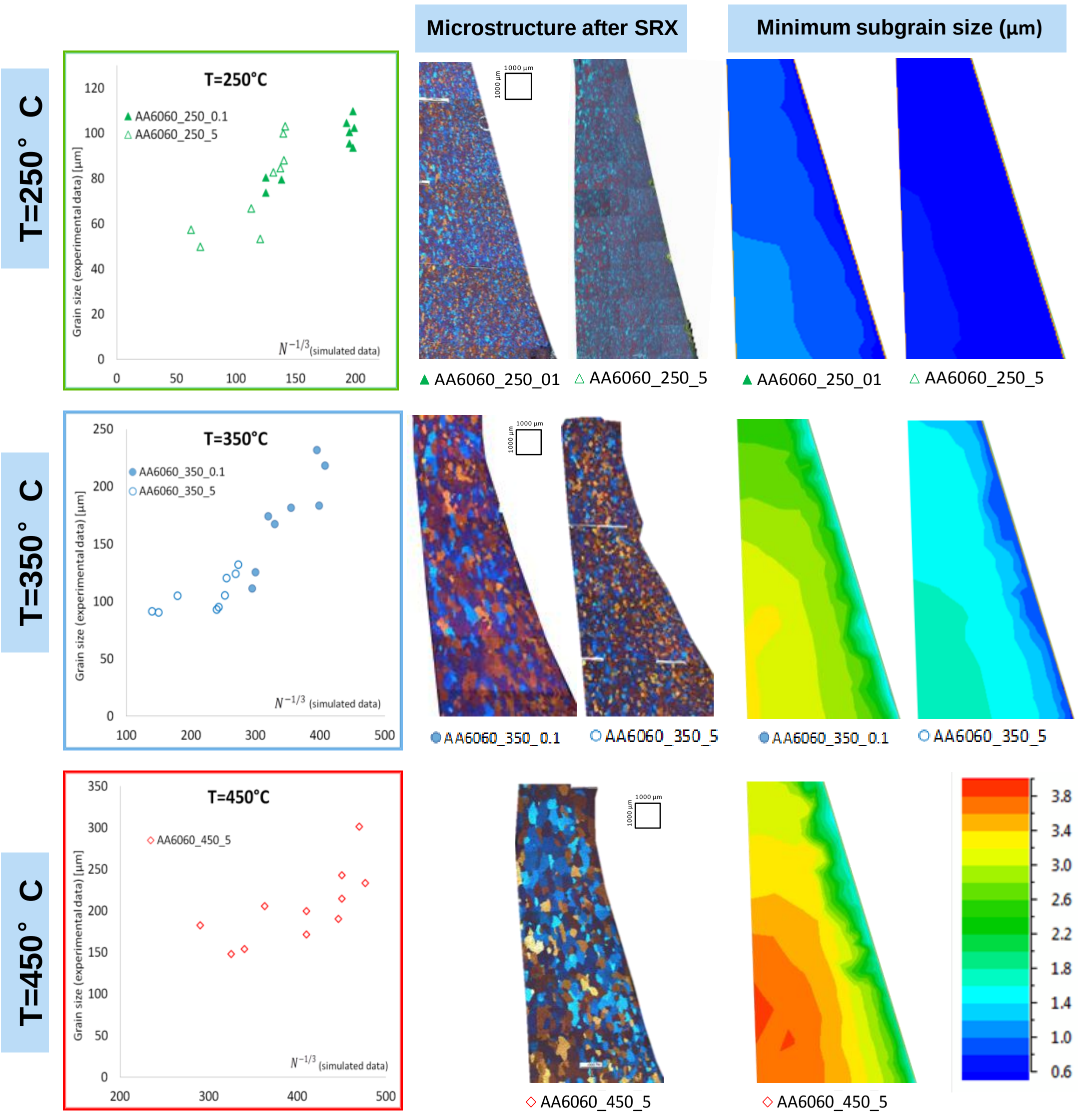
SRX model: simulations results



Evident connection between the temperature of material and the SRX phenomenon

As reported in literature:

-when increasing strain rates or reducing deformation temperature the density of nucleation sites increases, and consequently the number of growing grains, thus limiting the maximum dimension that each single grain may achieve

- at constant levels of deformation, the subgrain and the fully recrystallized grain sizes increase with increasing of temperature;

D=0.509 is a reasonable value of the calibration constant

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Conclusions

Dynamic recrystallization

Validation in QForm Code of the analytical model for grain evolution prediction, previously presented by the authors and valid for entire AA6XXX aluminium alloy series.
Good agreement between numerical results calculated by means of the implementation of a user-routine and experimental data.

$$d_t = (d_0 - 2.5 \cdot \delta_{SS})(0.55)^{\bar{\varepsilon}} + 2.5 \cdot \delta_{SS}$$

$$d_l = 114 \cdot \bar{\varepsilon}^2 - 25 \cdot \bar{\varepsilon} + d_0 \quad \text{for } \varepsilon<2.6$$

$$d_l = 9 \cdot 10^{-4} \cdot \bar{\varepsilon}^{-4.9} + 10 \cdot \delta_{SS} \quad \text{for } \varepsilon>2.6$$

Extension of the model to 3D industrial profiles and hybrid recrystallization conditions.

Static recrystallization

The comparison between experimentally determined grain size and computed results has shown a direct proportionality between d_{rex} and $N^{-1/3}$ parameters.
For AA6060 aluminium alloy is found

$$d_{rex} = 0.509 N^{-\frac{1}{3}}$$

Both micrographs and numerically computed results reveal the influence of temperature and ram speed on subgrain and static recrystallized grain size.

The difference between D_{AA6060} =0.509 and D_{AA2XXX}=2.347 evidence **the impossibility of determining a unified model for all aluminum alloys,** due to the great influence of chemical structure and alloying elements in SRX mechanism.

Thank you for your kind attention…