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Isabelle BOBIN[1], Isabelle POITRAULT[2] , Marc BERNACKI[3], Evelyne GUYOT[1], Aurore MASCARO[1] and Benjamin MARTIN[1]

[1]AREVA Creusot Forge – 6 Allée J. Perrin – 71200 Le Creusot - France
[2]INDUSTEEL, ArcelorMittal, CRMC, 71200 Le Creusot - France
[3] MINES ParisTech, PSL Research University, CEMEF – Centre de mise en forme des matériaux, CNRS UMR 7635, CS 10207 rue Claude Daunesse 06904 Sophia Antipolis Cedex, France

Abstract

The grain size of the austenitic stainless steel is an important issue for parts such as primary pipes in nuclear power plants and more globally for metal forming. Having tools which can predict at least the final grain size distribution for these materials is strongly required.

It is in this frame that ACF worked for several years with other industrial and academic partners such as INDUSTEEL CRMC, Aubert & Duval, Ascometal, CEA Valduc and CEMEF Mines ParisTech on the simulation of the recrystallization (ReX) of 304L austenitic stainless steel. Recent developments allowed simulation in a full-field context of the static recrystallization (SRX) of 304L stainless steel including a crystal plasticity formulation in a finite element (FE) context in order to model precisely the grain deformation anisotropy. This crystal plasticity model includes a decomposition of the dislocation density in SSDs (Statistically Stored Dislocations) and GNDs (Geometrically Necessary Dislocations). Including the GNDs gave better results on the localization of the strain but also allowed to define more relevant nucleation criteria. During and after ReX, the grain growth phenomenon due to capillarity effects is also modelled. To take into account capillarity effects enables to reproduce precisely the final microstructure morphology (shape of the grains, equilibrium angles at multiple junctions...). This full-field approach gives very good results for the modelling of 304L stainless steel SRX.

In parallel, at plants, forging and rolling processes need to be simulated in order to optimize fabrication sequences in terms of material distortion capability versus rheological properties of these materials and in terms of grain size with potential impact on ultrasonic inspection performance. In order to verify the process capability, a reduced ¼ scale component of 304L stainless steel primary pipes has been fabricated in a similar forging sequence. Study of the recrystallization aspect at different locations of the component was part of the objectives of the project.

The paper gives a view of all combined approaches: theoretical approach by recrystallization modeling as well as simulation of forging and rolling sequences with Forge® software (coupled to a mean-field metallurgical model called Thermide) and fabrication of a reduced scale part with nozzles as a test before the fabrication of the final component.

Keywords

Recrystallization, stainless steel, metallurgical mean field model, finite element full field modeling, forging, rolling.

1. Introduction - Context

AREVA Creusot Forge (ACF) is specialized in hot forging processes on large dimensional ingots. Typical weights of ingots between 20 up to 260 tons are forged either on a 9000 t press

with manipulator, or on an 11300 tons press, under temperatures from 700 to 1300°C. Those ingots are aimed at nuclear and non nuclear markets.

INDUSTEEL, subsidiary of ArcelorMittal, is specialized in the fabrication of heavy plates. Plates are produced from ingots or continuous casting slabs with a thickness range 3 to 950 mm. Whereas, rolling is efficient to achieve the required quality for thinner plates, it is not sufficient when higher thickness have to be considered or when very stringent mid-thickness quality is required. By associating both techniques of forging and rolling, it is possible to produce heavy plates with a very high quality from the point of view of internal quality, but also with very homogeneous mechanical properties, while keeping the same geometrical qualities as a classic rolled plate : precise size, flatness and surface finish.

For both companies, to be able to predict the grain size is very important for the austenitic stainless steel parts which have to respect high mechanical properties, such as for the yield strength at hot temperature. Besides, the controls by Ultrasoning Testing (UT) also require structures with fine grain. Microstructure with fine grain is of course difficult to obtain for massive parts where long heating periods with no phase transformation, have to be counterbalanced by static, dynamic and post-dynamic recrystallization which take place during forging and rolling.

In rolling or open die forging, the deformations obtained are heterogeneous and vary in quite large proportions depending on the type and size of the tools, the conditions of tool/material rubbing and the deformation level. The photograph in Fig. 1 shows a macro-etching obtained after an experimental compression on a specimen made of 304L stainless steel and illustrates the heterogeneity effects of deformation [Pisseloup, 2000].

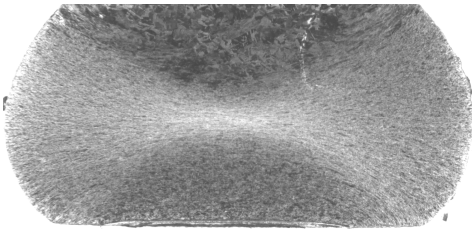


Fig. 1: Macro-etching after compression test on a 304 stainless steel sample.

The mean grain size obtained is then very different between the highly deformed areas (central part) and the dead areas in contact with the tool that are only slightly deformed. To obtain as homogeneous as possible microstructure, the optimization of the tool shape, the pass depth and the forming sequence, by numerical simulation is needed for each type of products. Numerical tools able to predict the final mean grain size or even the grain size distribution of these materials are also strongly required. It is in this frame that several French compagnies worked together since several years with French research laboratory such as CEMEF - Mines ParisTech, on the simulation of the recrystallization of 304L austenitic stainless steel (see Table 1) using mean field models but also full field approaches.

AISI	Euronormes	C	Si	Mn	Cr	Mo	Ni	S
304 L	X2 CrNi 18-9	0.03	< 1	< 2	18-20	/	8-12	0.03

Table 1 : Chemical analysis of stainless steel 304L (weight %).

2. Mean field model

As already explained, the way in which microstructures are described is inherently linked to the type of microstructure evolution model which can be either very simplified recrystallization approaches using analytical/phenomenological models as Jonhson–Mehl–

Avrami–Kolmogorov (JMAK) approaches [Avrami, 1939] where the microstructure is reduced to a scalar value such as a mean grain size or a recrystallized fraction or very elaborate full field approaches where all the characteristics of the microstructure and the evolving interfaces are described [Rollett, 1992], [Bernacki, 2008] (one of these approaches will be described in the section 4).

An intermediate framework could consist to the prediction of the distribution of such significant state variables without modeling explicitly the microstructure [Montheillet, 2009]. In 2007, in a context of a multipartners ANR program (Areva, Industeel, CEA, Cemef Mines ParisTech, TSV, ENSAM, UB), a new mean field approach (Thermide) [Logé, 2011], dedicated to the dynamic discontinuous recrystallization modeling has been developed. Classical mean field approaches are based on the definition of a homogeneous equivalent medium (HEM) interacting with all representative grains and therefore defining their evolution. The states variables defining the HEM themselves evolve as a volume average of the representative state variables.

Thermide approach was innovative in sense that two HEMs instead of one are considered in its formulation. Microstructure is synthetized as recrystallized representative grain (RX) and non-recrystallized representative grains (NR). The evolution of a representative grain will depend on the surface fractions of grain boundaries with the various combinations of RX and NR HEMs on either side, these surface fractions evolving themselves as long as a steady state is not reached. Representative grains are described by their radius (grain shape is assumed circular) and their dislocation density. Topological information is then incorporated into the model by prescribing the relative weight of the HEMs as a function of their volume fractions. This procedure allows accounting for the well-known necklace structures. Equations and discussions, in 304L stainless steel DDRX context, of the model are described in [Logé, 2011]. Moreover, efficiency of the Thermide model in context of prediction of grain size distribution for 304L during pure grain growth regime is detailed in [Fabiano, 2013], [Fabiano, 2014]. Some industrial validations and discussions are presented in the next section.

3. Validation on industrial fabrication

In order to verify the mean field model Thermide, industrial validations have been realized in INDUSTEEL and AREVA NP. Two examples are presented below.

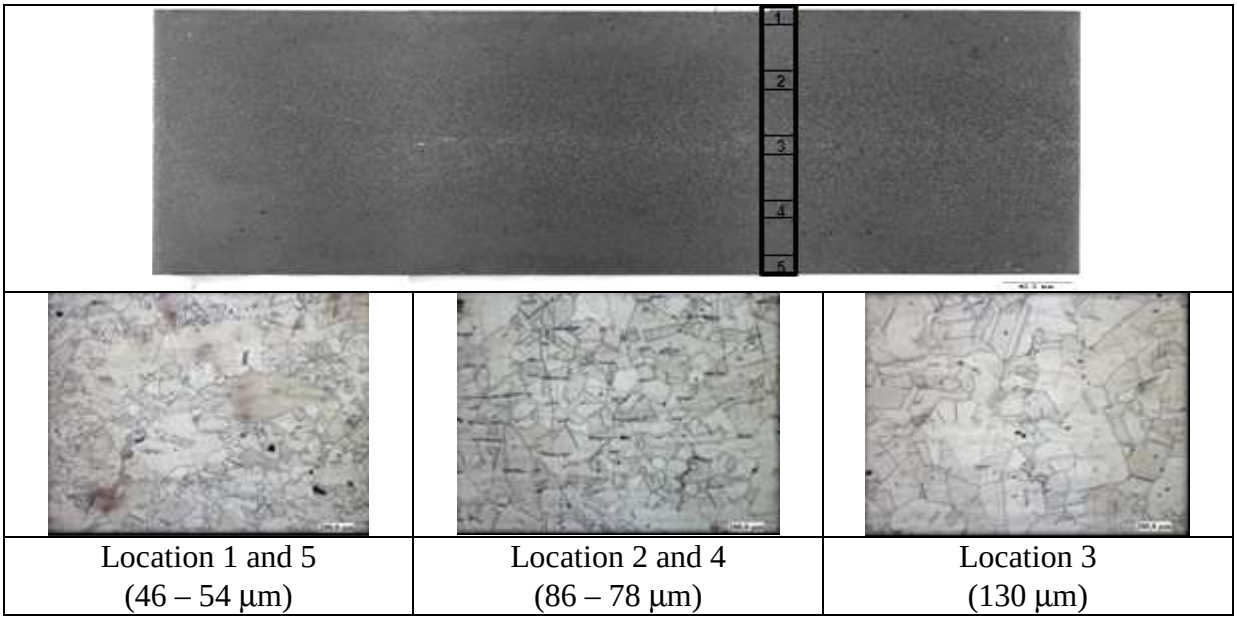
3.1. Hot rolling of thick plates in INDUSTEEL

Thermide model have been tested on an hot rolling with 38 passes (initial thickness 570 mm and final thickness 155 mm), see Fig. 2.

Fig. 2 : Hot rolling of thick plate.

A wedge of the plate has been cut through the full thickness. Macro-etching has been achieved on surface of this sample (see Fig. 3) to determine the grain structure. Specimens were taken off at various locations through the thickness (upper surface, T/4, T/2, 3T/4, below surface) to identify the grain size and the recrystallized volume fraction. The results show that

the grain size is more important at mid-thickness. The recrystallized fraction is between 80 and 100%.



Location 1 and 5 (46 – 54 µm)	Location 2 and 4 (86 – 78 µm)	Location 3 (130 µm)

Fig. 3 : Microstructures through the thickness of the 155 mm plate (average grain size).

Digital simulation of hot rolling sequences has been performed with FORGE® software taking into account the Thermide model. The Fig. 4 illustrates the comparison between simulation and experimental data concerning grain size results.

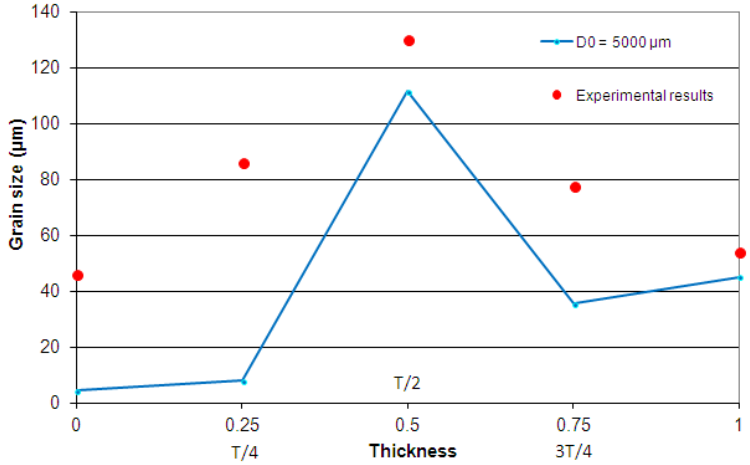


Fig. 4 : Comparison between results from Thermide model and observations.

Thermide model is able to forecast the general trend, but the gap between measures and calculation remains important.

3.2. Primary pipes mock-up in AREVA NP

AREVA has manufactured for many years the different X2CrNi19-10N2 (304L) main coolant lines (MCL) for nuclear reactors. Those lines (see Fig. 5) connect the reactor vessel to the other components (steam generator, pressurizer, pumps).

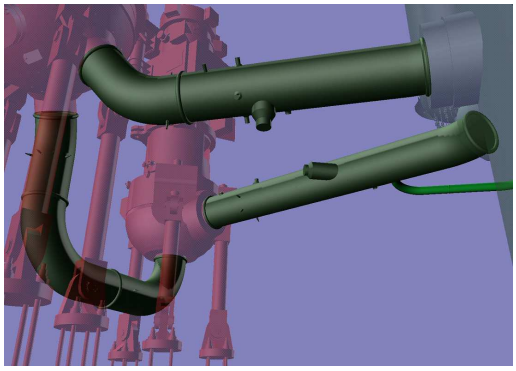


Fig. 5 : MCL location into the reactor vessel.

They could include bends and integrated nozzles (see Fig. 6) requiring particular design and manufacturing operations. The typical dimensions are: 8 m long for a diameter of 1 m and a wall thickness of 80 mm.

Fig. 6 : MCL examples and location of MCL critical areas.

The MCL manufacturing is technically challenging due to the competition between the complex shapes and the material behaviour (competition between forging temperature and grain growth). Beyond dimensions respect, it is important to control the grain size evolution all along the process through dynamic and static recrystallization. The objective is to have a final mean grain size compatible with the mechanical properties and UT capability (components 100% inspected).

Even if today AREVA Creusot Forge masters this components manufacturing, the new equipment invested in 2013 (9000 t hydraulic press and manipulator), allowed to propose improvements concerning as well as initial ingot weight, time production, or final mean grain size. Thanks to this new press with higher force, and the manipulator (reducing handling time and increasing production rate), a new production sequence is now possible with less forging steps and with a new upsetting operation favourable to the forging ratio and thus to the recrystallization phenomenon.

To perform this evolution AREVA Creusot Forge has built a R&D study through numerical simulations and experimental forging operations on a ¼-volume scaled mock-up.

The studied component was a main coolant line with two integrated nozzles and a bent part. The critical areas in terms of mean grain size mastering and UT capability, are the main opposite side and the extremity of the nozzle (see Fig. 6).

3.2.1. Forging sequence optimization

A new forging sequence taking into account the new press characteristics and allowing a reduction of the heat number has been defined by the ACF forging experts, and then computed with FORGE® software. The operations have been optimized in terms of press effort and forging velocity, dimensions, temperature mapping, end forging temperature, strain repartition, heat number reduction and die sizes.

3.2.2. ¼ Scale mock-up simulation

To experimentally validate the effective interest of recrystallization Thermide model available in the Forge software, a reduced scale mock-up has been defined to represent a similar forging sequence. The objective was to have comparable results between the mock-up and the main coolant line in terms of temperatures, strains and final mean grain size. We focused only in the main interesting zone from the UT point of view that is to say the integrated nozzle area. To take into account the scale factor, numerical simulation was used to adapt the manufacturing parameters (heating and forging) for both cases (the 40 ton mock-up and the 150 ton MCL component) and to optimize the different recrystallization steps which contribute to the final grain size:

- dynamic recrystallization : reduction of grain size by nucleation during deformation,
- static recrystallization : hardened grain nucleation and growth,
- grain growth during heating in furnace. The grain doesn't grow anymore in not previously forged areas if the heating temperature remains below the forging temperature.

Adaptation of the strains, the strain rates and the temperatures appeared as essential in order to control and to be able to reproduce on both components the same mean grain size (the other parameters being the same).

The results show locally a bimodal repartition of grain size (ASTM 1 and 5-6), corresponding to a dynamic material recrystallization at the nozzle location, where the recrystallization process has been enhanced by a local upsetting operation. This bimodal result could not be reached by a mean field model resulting in an average grain size, but by a full field model.

3.3. Comments on Thermide

If it is clear that the mean field approaches such as the Thermide model are a step forward to the global understanding and modeling of recrystallization phenomena; it is also obvious that these models must always be improved and/or optimized according to the material, the range of thermomechanical conditions and the metallurgical regime (SRX, DDRX, GG…) considered. An alternative to "case by case" mean field models (and subsequent expensive experimental studies) lies in full field approaches as described in the next section.

4. Full field approach

The first attempts to use the finite element (FE) method for metal forming simulation were achieved by several scientists with their pioneer works in the seventies, treating the feasibility of simple geometries in two dimensions. More than ten years after, three-dimensional computations were attempted on very simple geometries. Under the pressure of industrial needs and taking advantage of the rapid increase of affordable computer performance, many developments were tested in laboratories and introduced in commercial codes. Today there is still a strong demand from many companies to introduce more realistic physical behavior as illustrated by the development of mean field models such as Thermide model (see previous section). In this kind of approaches, selecting representative material parameters (grain size, inclusions, phase percentage, precipitates, etc.) are considered in an average way to identify physical laws which govern the evolution of these parameters, and their influence on the mechanical behavior. As detailed previously, this macro framework is quite convenient for coupling thermal, mechanical and physical computation, but it remains limited and needs for a given material a large amount of experiments to identify the physical laws describing microstructure evolution for large range of thermomechanical conditions.

On the other hand, computation at the microscale level is now possible and is developed for a potentially more realistic description of materials under the concept of "full field approach". Micro modeling is potentially much more accurate but, due to heavier computer cost at the

local micro level, direct coupling with macro thermal and mechanical simulations seems limited to 2D problems and simple parts, even with large clusters of computers. One way to view the short term applications is to use micro modeling of material in post processing, to predict microstructure evolution for a limited number of locations in the work piece, neglecting coupling effects. Another method is to use the micro approach to help identification and improvement of mean field models.

The brief following summary illustrates some development realized concerning these topics for 304L. Success in the integration of multiscaling modeling activities requires effective means to organize the data defining the structure, and its variability over many scales, and to facilitate its access by a heterogeneous collection of modelling tools. This requirement will be addressed through the use of a modeling system referred to here as the Digital Material.

A precise procedure to generate complex 2D and 3D statistical virtual microstructures in a finite element (FE) context has been developed. This technique based on Laguerre-Voronoï tessellation and advancing front method, level-set or phase field description of the interfaces and anisotropic meshing adaptation was validated for some REVs. Most precisely, it was illustrated, in [Hitti, 2012], [Fabiano, 2013] and [Fabiano, 2014], the capability of the procedure to generate and to immerge, in a FE context, equiaxial statistical poycrystal by respecting an imposed initial grain size distribution. The methodology developed in terms of virtual generation and implicit description of the interfaces is illustrated in Fig. 7.

A new FE framework, based on a level set description of grain interfaces, has been developed to model 2-D or 3-D primary recrystallization, including the nucleation stage [Bernacki, 2008], [Bernacki, 2009], [Logé, 2008]. It was first briefly described in [Bernacki, 2008] for very simple microstructures. It was then improved to be able to deal with more realistic 2-D and 3-D microstructures and to make the link with stored energies induced by large plastic deformations [Bernacki, 2009], [Logé, 2008].

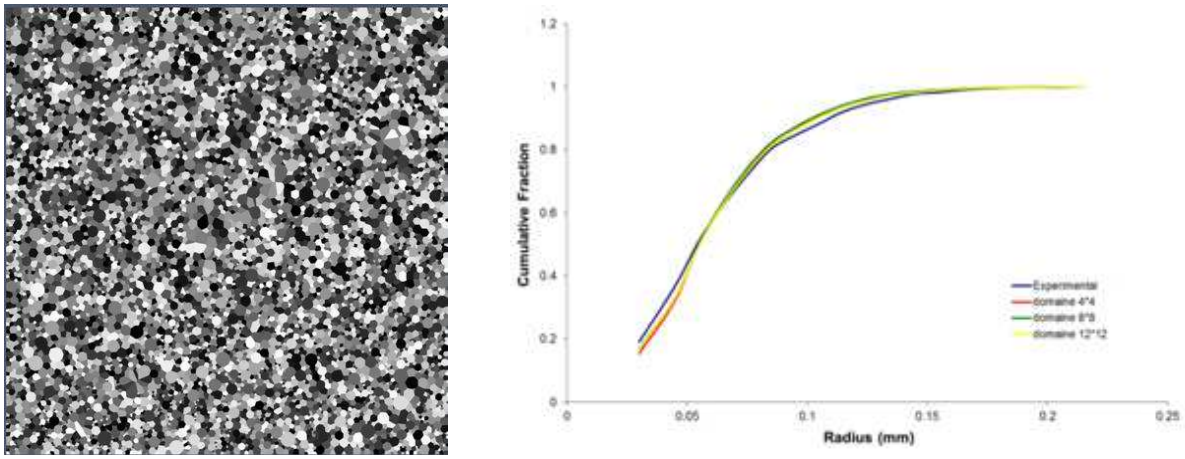


Fig. 7 : (left) A 2D digital microstructure made of 8294 grains obtained using a Laguerre-Voronoï method, based on a 304L steel experimental grain size distribution (domain size: 12 mm x 12 mm): (right) comparison between experimental grain size distribution and numerical ones for different size of REV.

Anisotropic meshing and remeshing techniques were used to accurately describe interfaces, both for the modeling of plastic deformation using crystal plasticity, and for updating the grain boundary network at the recrystallization stage. It was shown, in particular, that the distribution of stored energy in the polycrystal resulting from plastic deformation led to deviations from the JMAK theory. The proposed framework has been shown to avoid

kinematic incompatibilities between level set functions, i.e. it prevents the appearance of vacuum or overlapping regions. Most recently, capillarity effect and Zener pinning phenomenon were also added to the model [Bernacki, 2011], [Fabiano, 2013], [Fabiano, 2014], [Agnoli, 2014]. Moreover it was also proved that high anisotropy of grain boundary energy could be taken into account in the considered formalism [Jin, 2014].. These different developments are currently used to bring a better understanding of abnormal grain growth or impact of twin interfaces in ReX and GG which can not be predicted by mean field approaches as far as to improve mean field models used in FE code.

Moreover, thanks to the maturity of these developments and the improvement of their numerical cost [Scholtes, 2015], [Shakoor, 2015], a new commercial code, Digi-μ® software dedicated to recrystallization modeling in full field context, associated with the FORGE® software, is under development thanks to a consortium composed by AREVA Creusot Forge, INDUSTEEL ArcelorMittal, Safran, Timet, Aubert&Duval, CEA Valduc, Transvalor and Cemef Mines ParisTech (see Fig. 8 below).

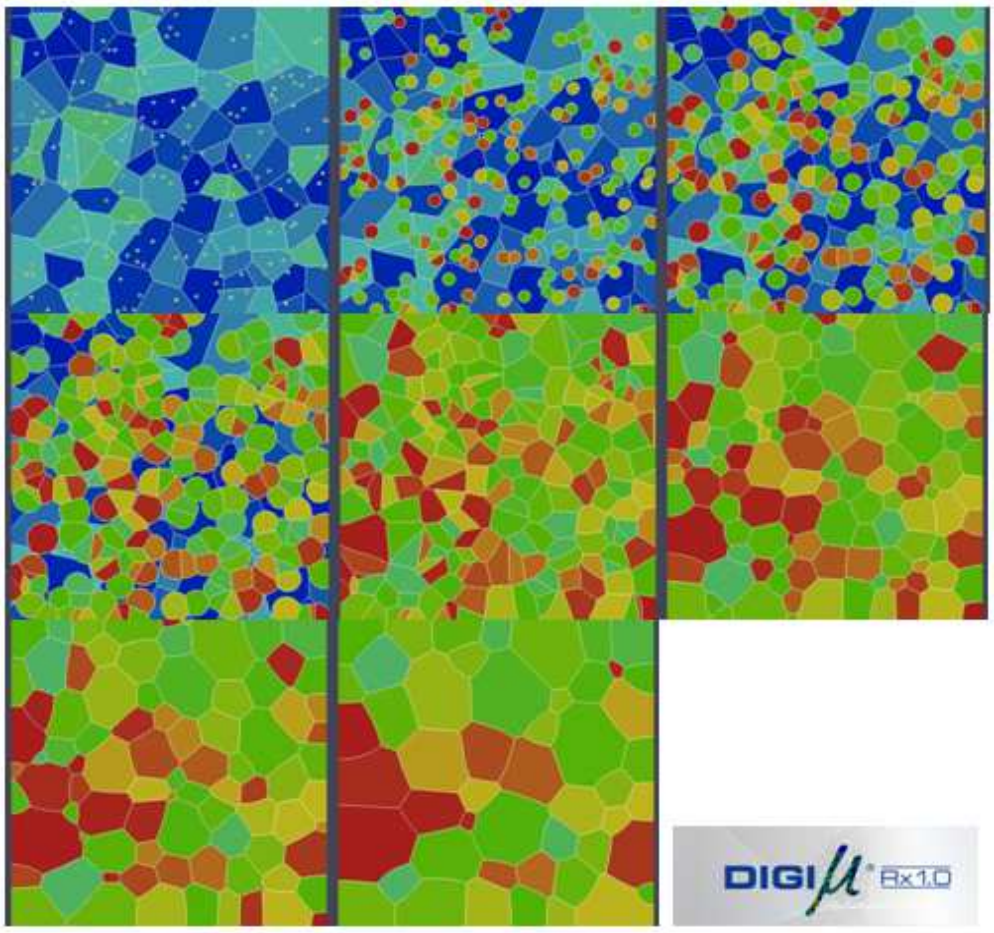


Fig. 8 : Modeling of site-saturated nucleation in 304L, from top to bottom and left to right : primary recrystallization and subsequent grain growth modeling [Fabiano, 2013].

For 304L, these numerical tools have been extensively used for comparison with the Thermide model [Fabiano, 2014] and linked to CPFEM calculations in order to predict accurately static recrystallization (with validation thanks to experimental results). Fig. 9 illustrates a 3D- 304L static recrystallization case with a site-saturated configuration.

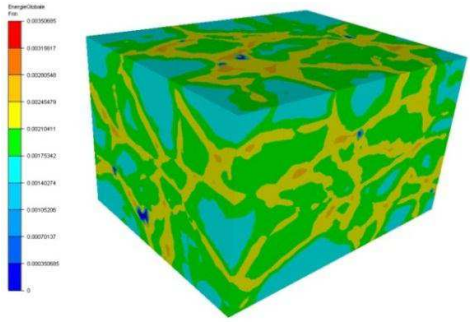
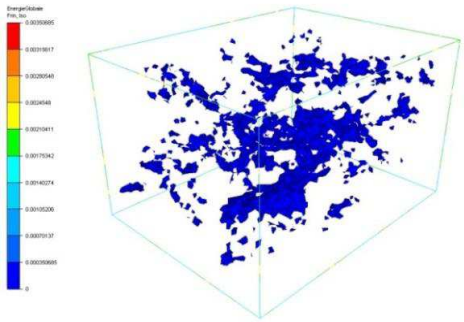
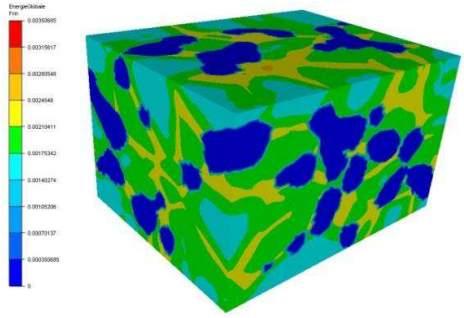
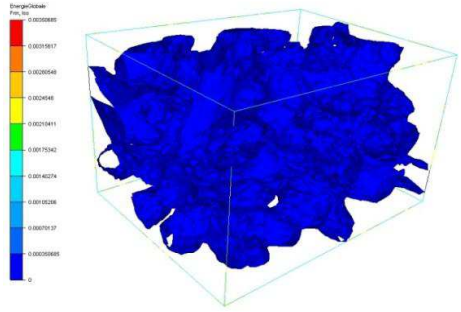
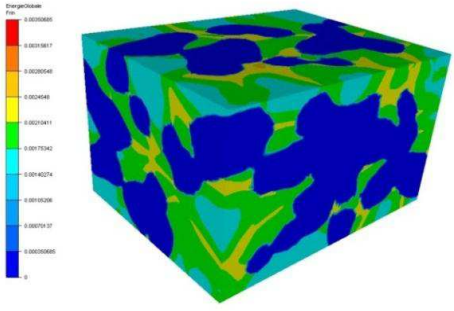
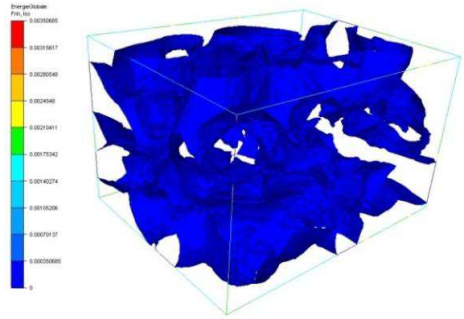
Xv	Internal Energy	Recrystallization front
0%		
50%		
75%		

Fig. 9 : 3D recrystallization simulation based on CPFEM simulation results considering both statistically stored dislocations and geometrically stored dislocations (blue part corresponds to the ReX front) [Fabiano, 2013].

5. Conclusions

The objective of industrial partners is to provide the best possible quality for the final product of their customers with the shortest delivery time. In this aim, the development of numerical models able to predict microstructure evolution, recrystallization and grain growth at the mesoscopic scale is nowadays of prime importance. These digital models will allow to be very reactive to new markets with enough high confidence in the proposed manufacturing sequences and parameters. In the future, the development of these digital methods will be going on being supported by industrial companies.

6. Acknowledgements

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