Modelling of solids undergoing large deformations within the scope of the four dimensional formalism. Improvement of numerical simulations of manufacturing processes.

Work environment for the PhD student:

The University of Technology of Troyes (UTT)

UTT is a French institution of higher education established in 1994. It is today one of the largest engineering schools in France. Over 2,500 students are registered at the University, enrolled on undergraduate, postgraduate and doctoral study programs. In the renowned yearly ranking of French magazines, UTT takes enviable positions. More detailed information is available on http://www.utt.fr/en/about-utt.html.

The LASMIS research team

The ICD/LASMIS team has a significant experience in the field of shot-peening, of residual stresses modelling, of residual stresses measurements, of nano-indentation and of advanced modeling of the behavior of materials. Our team cooperates with industrial partners such as Renault, Peugeot SA, SNECMA or Turbomeca (Safran Group) and academic partners such as University Paris VI, University of Reims, ENSAM or INSA de Lyon, in the field of process modeling together with experimental characterization and understanding of physical phenomena. For more details, see: http://lasmis.utt.fr/fr/index.html.

Moreover this research project is part of the global research policy on risk management of the joint research laboratory UMR 6281 of CNRS (French National Research Council) and UTT established in January 2010.

PhD advisor:
Dr. Benoît Panicaud, 37, obtained a Master of Engineering from Engineering School of La Rochelle (EIGSI) in 2001 and a Master of Physics and Mechanics of Materials from University of Poitiers in 2001. He defended his PhD in University of La Rochelle in 2004, on the coupling between chemical and mechanical effects during high temperature oxidation. After a postdoctoral position in University of Marseille on the mechanical effects on semi-conductors, he became assistant professor in UTT in 2006. He is now full professor. Information can be found on http://www.researchgate.net/profile/Benoit_Panicaud. He is responsible of the mechanical engineering department. He is also fully involved in different research projects of LASMIS due to its modeling skills.

Collaboration with:
Dr. Emmanuelle Rouhaud, 48, obtained a Master of Engineering from University of Technology of Compiègne (UTC) in 1990 and a Master of Engineering from Washington University (Saint-Louis, USA) in 1990. She defended her PhD in Washington University in 1993. Then she became assistant professor in UTT in 1994, when the university was created. Information can be found on http://www.researchgate.net/profile/Emmanuelle_Rouhaud. She is currently in charge of the Prestress Engineering Team of LASMIS.

Available equipments

- Finite Element codes (ABAQUS, Z-Set for which source code is available).
- High level computing facilities.
- Every PhD student shares an office with other PhD students. A personal desk is offered to each PhD student along with a personal computer and full personal access to the internet and bibliographic data bases.
Short description of the project

At University of Technology of Troyes (UTT), the research axis in mechanics within the Charles Delaunay Institute (ICD) / Laboratory of Mechanical Systems (LASMIS) has acquired a recognized expertise for the modelling of materials behaviour. The LASMIS is indeed at the origin of several models that, applied to the simulation of manufacturing processes, permit to consider a complete virtualisation of the line production/manufacturing. One of the essential points of this work is based on a multiphysical approach including thermodynamics to describe any real complex motion of the matter. Some strong couplings are taken into account between the thermal aspects, the elasto-visco-plastic aspects and the damage aspects. These models have proved their efficiency to simulate and to optimize various manufacturing processes such as forming, shot peening, machining.... Besides, even based on the principles of thermodynamics of continuous media, the existing macroscopic models are finally more phenomenological than physical. One of the long term project is thus to propose models based on a micro-mechanical approach. This "dimension" should also be integrated within the project to obtain the most coherent mathematical formulation with accurate physical contents.

The correct description undergone by matter in the scope of these finite transformation models is therefore a necessity to master a realistic kinematics. In classical mechanics approaches, its representation uses a so-called “objective” description and in particular several types of objective derivatives to evaluate the variations versus time. For a suitable numeric resolution, it is also necessary to associate an adequate configuration of the deformable environment. It remains the difficulty therefore to choose the correct objective derivative and its associated configuration.

We propose to use the formalism of general relativity that, thanks to its four-dimensional description in curvilinear space-time, guaranteed a so-called "covariant" description (that is to say valid whatever the frame of reference) of the matter’s transformation. Thus, the goal of the project is to verify the interest of such an approach and to solve the difficulties that remain yet with the notion of objectivity. It is worth noting that we want to apply this covariant principle to transformations that correspond to those of classical mechanics of continuous media (that means without any relativistic effect and in particular for speeds that remain always significantly inferior to the speed of light).

What we propose in this work is decomposed in three distinct steps:

- The first step of this work will consist, while being based on the tools of the general relativity, to get a four-dimensional formulation for different macroscopic behaviour models (hypo - and hyper – elasticity, plasticity, viscosity of polymers), with an interpretation of the different components of such a relation.
- In a second part, a computation in the Zset code (Zébulon) will permit to validate this approach numerically through a demonstrator's realization. The target is to compare the results with already existing macroscopic formulations in finite transformations. A validation, in collaboration with regional industrial partners, is considered in the setting of manufacturing processes modelling, such as metal forming with shot peening for which huge finite distortions are observed.
- Thereafter, a generalization for a mechanical behaviour models, in a four-dimensional micromechanical approach, will be considered to transpose this approach to the continuous damage of ductile materials taking into account the microscopic mechanisms of plasticity (slip systems, orientation of grains, internal stresses). The importance of the objectivity principle is essential in this setting. The realism of simulations that aims to improve the reliability of the structures while reducing their mass depends on the degree of confidence for the description of the underlying mechanisms.
Context and state of the art

In order to test durability in service of the structure parts or to simulate the forming of complex parts, it is spilled today in different industries (aeronautics, cars...) to use numeric simulators. Such an approach is useful and did not stop improving during the last 20 years. The target of these modellings is always to value the resistance of a piece or a structure, resistance to the failure or to fatigue in a context of mass optimization and costs reduction. Nevertheless, the precision wished to account for the physical phenomena depends mainly on two factors limiting:
- The calculation time bounded to the complexity of such model, to the chosen algorithmic scheme and to the power of calculators.
- The physical content himself, bound on the one hand to the diversity of the phenomena occurring and on the other hand to the considered scales of resolution.

Some fundamental and applied works are in progress in many laboratories, academic but also industrial ones, to improve these limits. Taking into account of finite transformations for continuous media became a necessity. The correct description of these finite distortions constitutes an essential point to hang realistic kinematics behaviour. The correct description of the kinematics behaviour constitutes yet an open problem mainly to choose correct grandeurs used in the behaviour law that must describe the mechanical behaviour undergone by matter. Approaches are often minimalists to take in account this kinematics effect. It is achieved of various ways:
- while replacing the grandeurs in behaviour laws by infinitesimal associated rates of transformation (tangent approach), that brings back the problem to a succession of infinitesimal transformations;
- while using "objective“ grandeurs in behaviour laws and especially while replacing the derivatives of quantities in the behaviour laws by objective derivatives, that means corrected of one kinematics term for all finite transformations (what proves to be more realistic);
- while associating to the behaviour model a more or less artificial non linearity corresponding to the kinematics effect, for a given solicitation;
- while considering, from a lower scale, the evolution of the microstructure that influences the macroscopic mechanical behaviour: for example, the evolution of the anisotropies due to the rotation of grains in a metallic polycristal enables to understand the macroscopic rotation of the representative elementary volume.

Unfortunately, none of these solutions enables to answer completely the problem for finite distortions, because of the multiplicity of mechanical behaviours (elastic, plastic, with or without damage) and because of difference from the considered materials (metals, polymers, ceramic, composites). Each of the previously proposed solutions has advantages and inconveniences that will not be list here. For a merely macroscopic survey, it is recognized currently that the best approach uses (among others) are the use of objective grandeurs [Lemaître and Chaboche, Doghi, Badreddine], because based on a methodology thermodynamically compatible. It introduces the objectivity principle on which we are going to come back forward. A particular problem remains the construction of objective quantities and especially the choice of the objective derivatives [Sidoroff, Doghi, Badreddine].

The objectivity constitutes so a “new” principle of the 3D mechanics of the continuous medium whose interest fully appears only for the construction of the behaviour laws in finite transformation. It corresponds to the invariance of laws, whatever the considered observer bounded to the material (material frame indifference). The objectivity of grandeur depends on its nature and its kind of representation: eulerian or lagrangean. A more delicate problem occurs when one tries to define an objective derivative. It is indeed possible to define several sorts of objective derivatives: either in rotation, either convectives. The use of the first one is often chosen in order to avoid the use of curvilinear coordinates. In this case, the choice of derivative in rotation leads to an infinity of possible derivatives, corresponding to an infinity of possible intermediate turned configurations (Jaumann, Green-Naghdi,...), objective and associated to an infinity of rigid observers bound to matter (gotten by a rotation in relation to the present configuration). It raises three questions that make yet currently debate:
- What is the good objective derivative?
- Is it possible to reach these intermediate configurations experimentally to lead to some measurements?
- How can we limit the calculations time in numerical simulations, associated to this intermediate
stage used to express the behaviour model?

These questions clearly lead to a conceptual dead end.

Within the of research axis in mechanics of the Charles Delaunay Institute (ICD) / Laboratory of Mechanical Systems (LASMIS) of University of Technology of Troyes (UTT), these problems are investigated. Indeed, the LASMIS has developed calculation models bound notably to finite element analysis software ABAQUS and ZéBuLoN, permitting to simulate efficiently virtual forming processes in the case of elastoplastic materials. The originality of such works is to take into account of the strong multiphysical couplings between the thermal aspects, the elastoviscoplastic aspects and the damage aspects. These coupled models, once computed, showed their efficiency to simulate and to optimize various manufacturing processes. The relevance of such an approach has already been demonstrated through lots of phD thesis achieved at the laboratory [Hammi, Marriage, Lestriez]. For all these works is asked the problematic of grandeurs objectivity chosen in mechanical behaviour relations and the choice of the intermediate configurations chosen for numerical scheme.

The problem of objectivity of the chosen quantities in behaviour laws and the description of the kinematics also arises in the setting of the micromechanical approach developed at LASMIS. Even based on the principles of thermodynamics of continuous media, the existing models are today eventually more mathematical than physical. For example, one of the limits of this inductive approach comes from the anisotropy taken into account through a phenomenological formulation. A thesis [Hfaiedh] has been achieved to test those elastoplastic models in finite distortions with ductile damage while considering a scale transition method, as well as to validate experimentally on particular material (Copper). Another thesis [The Joncour] is currently under realization to validate these experimental and numeric approaches on duplex stainless steels. The existence of clearly independent quantities whatever the observer would be greatly beneficial to these works for which the description of the local kinematics is essential.
Methodology proposed for the PhD thesis

For this project, we propose to consider the objectivity as a consequence of the tensorial tools used. Therefore, it is necessary to redefine the tensorial tools. This problem already has a solution in another branch of physics: general relativity [Landau and Lifshitz, Boratav and Kerner]. Einstein clearly proved how tools can be build to consider invariant grandeurs whatever the observer (bound to matter or not). It is therefore necessary to use some four-dimensional tensors. The 4D covariance, intrinsic feature of the 4D tensors, induces then in their non-relativistic limits the invariance feature by change of reference of the 3D tensors of the mechanics of continuous media. Several difficulties occur then in this choice:

- the theoretical extension in four dimensions of the classical quantities of the MMC usually used in three dimensions;
- the intrinsic use of grandeurs in 4D curvilinear coordinates. The use of the convective approach (at least on the spatial part) permits to recover some approaches proposed in 3D [Malvern, Eringen]. It offers a double advantage: to associate the finite transformation of matter to the most general observer change (for one Gauss point) and "to gather" the eulerian and lagrangean approaches.

In a particular way, the covariant derivatives of the 4D approach becomes the natural and unique derivatives permitting to correct properly and without ambigusness the kinematics of matter, whatever is the finite transformation. Such a methodology is in progress within the laboratory [Panicaud and Rouhaud, Rouhaud and Panicaud], since two publications have been submitted in international journals with reading committee.

The proposed work will consist in defining the bases of a physical and numerical modelling of the problem for mechanical systems solicited in finite distortions. Currently, some international works showed the theoretical relevance of such a 4D approach for mechanics of continuous media [Lamoureux, Williams]. Some questions are nevertheless yet extensively open. Indeed, many of these works stand mainly in the setting of the tools of special relativity. It does not allow their use therefore in interesting particular cases and excluded the use of curvilinear reference whose interest is the description of convective and non-inertial transformations. We wish therefore, to develop a systematic approach of the tools of general relativity (metric tensor 4D, symbols of Christoffel 4D, covariante derivative 4D) for simple solicitations in a first time (shearing, tensile load...), then for more complex ones in a second time.

The treatment of different classic behaviours will be done. First, the problem of elasticity will be considered in order to show the contributions of such an approach. In this non-dissipative case, three approaches are possible [Sidoroff]: elastic, hyper-elastic and hypo-elastic will permit to construct different behaviours. It will be notably important to consider precisely the use of the thermodynamics in a 4D context (hyper-elastic approach). Indeed, although researches are advanced for the fluid matter, relativity and thermodynamics of solid matter is less efficient because the inertial effects only appear in finite transformations. We propose to redefine clearly, in this context of application, the needed physical tools.

Finally, the plastic behaviour will be treated. We have then to introduce dissipative phenomena. This specific behaviour leads to several difficulties. In agreement with researches led at LASMIS, we wish an approach of plasticity based on the thermodynamics of the irreversible processes. The generalization to four dimensions of this thermodynamics including the dissipative processes will be therefore an important stage of the present work. Besides, the use of functional mathematics (yielding potential and state potential), having particular properties as the convexity and the normality, imposes a specific survey of the problem in four dimensions and especially in curvilinear coordinates.

The third and last part of this work will consist in writing properly the numeric problem. A computation of the different theoretical cases will be led on the software Zset© calculation (Zebulon code of the Ecole des Mines) available within the laboratory. The advantage of this code is that it is relatively flexible and open. While considering the methodology previously established, it will be necessary to achieve the calculations of the kinematics part in 4D, then to project the 3D components that will be able to be treated under Zset©. A proof of feasibility will be tested while considering a certain number of simple cases, as the bending case. A validation, in collaboration with regional industrial partners, is considered in the setting of the modelling of the formatting of sheet metal by shot peening for which one observes finite distortions.
References
Please consult the papers written by B. Panicaud and E. Rouhaud on research gate. The references in the text above are: