MASTER
MATERIALS SCIENCE AND ENGINEERING

Track MAGIS

Updated: 2022/10/24

Master 2 : Track « Materials and Engineering Sciences in Paris » – MAGIS

The objectives of this program are to provide students with a deeper understanding of materials science & engineering and solid mechanics fundamentals and to impart a better knowledge of recent developments in the field, for advanced industrial applications and innovative processes. This track provides an education in the mechanics of materials. It focuses on the relationships between processes, materials, microstructures, and mechanical properties for advanced industrial applications and innovative processes.

The track « MAGIS » is divided into core courses and the choice of one elective sub-track to choose among 4 :

- Elective 1 (E1) : Damage and fracture of materials and structures
- Elective 2 (E2) : Metal processing and additive manufacturing
- Elective 3 (E3) : Life cycle of polymers and composite materials
- Elective 4 (E4) : Machining and simulation

Semester 3		ECTS	E1	E2	E3	E4
EQUALIZATION TEACHING UNITS (common to all students, optional but highly recommended)	**30 h**	**0**				
CORE COURSES (common to all students)	**150 h**	**18**				
Material Sciences	30 h	3				
Materials constitutive equations and thermodynamic of solids	30 h	3				
Numerical methods for continuum mechanics	30 h	3				
Advanced experimental methods	30 h	3				
Research project		3				
Scientific communication in foreign language		3				
OPTION (3 mandatory units + 1 unit to be choosen)	**120 h**	**12**				
Fracture mechanics	30 h	3	O			
Damage and fracture of polymers and composites	30 h	3	O			
Continuum damage mechanics	30 h	3	O	X	X	X
Plastic strain processing	30 h	3	X	O	X	O
Metal additive manufacturing	30 h	3		O		
Numerical simulation for metal processing	30 h	3		O		
Durability and recycling of polymers and composite materials	30 h	3			O	
Processing of polymers and composites	30 h	3	X	X	O	X
Mechanical behavior of polymers	30 h	3			O	
Multi-physical approach of cutting, materials and material integrity	30 h	3				O
Advanced machining and its applications	30 h	3				O
Dynamic behaviour and failure of materials	30 h	3	X	X	X	X
Algorithmic modelling of physical processes	30 h	3	X	X	X	X
Fatigue of materials	30 h	3	X	X	X	X
Eco-materials	30 h	3	X	X	X	X
Total S3	**300 h**	**30**				
Semester 4 Internship (minimum 5 months) 30 ECTS *		30				
Total du M2	300 h	60				

O : mandatory teaching unit for the given option
X : optional teaching unit for the given option

CONTINUUM MECHANICS

Equalization course

The course is optional but highly recommended
The course is taught in English

Coord. **Véronique Aubin** (veronique.aubin@centralesupelec.fr, CentraleSupelec)

Objectives

This basic course has the aim of providing insight in the fundamental concepts of kinematics and the different stress measures in order to formulate the equilibrium of a deformable body undergoing a finite motion. The necessary complements on tensor algebra and analysis are reviewed at the beginning of the course. Starting from the finite deformations framework, the more familiar small transformations are deduced by linearization. In particular, a discussion on the objectivity (frame indifference) of the physical quantities introduced is proposed. A proper understanding of the mechanical concepts used throughout the course requires mathematics of tensor algebra and tensor calculus. The symbolic (modern) notation is typically used, completed by the index notation at the appropriate point. The last part is devoted to linear elasticity with a brief discussion of finite elasticity. Some examples of application are finally given. This course should provide the student of the master MAGIS with a reasonable background in mechanics to learn efficiently more specific subjects during the semester.

Content

Chapter 0. Tensor algebra

- Body, configuration and motion – Material and spatial description
- Material derivative, velocity, acceleration
- Deformation gradient, deformation tensors and invariants
- Polar decomposition, Volume and area change– Conservation of mass – Distortion
- Homogeneous deformations and motion of rigid body
- Linearized kinematics – Small displacements and tensor of infinitesimal strains
- Deformation rate
- Objectivity of kinematics quantities

Chapter 2. Kinematics of continuous media

- Body, configuration and motion – Material and spatial description
- Material derivative, velocity, acceleration
- Deformation gradient, deformation tensors and invariants
- Polar decomposition, Volume and area change– Conservation of mass – Distortion
- Homogeneous deformations and motion of rigid body
- Linearized kinematics – Small displacements and tensor of infinitesimal strains
- Deformation rate
- Objectivity of kinematics quantities

Chapter 3. Stress and equilibrium

- Body and contact forces – Postulate of Cauchy
- Translational and rotational equilibrium of a continuum
- Properties of the Cauchy stress tensor – Deviatoric and pressure components
- Examples of stress states
- Piola-Kirchhoff stress tensors
- Objective stresses – Principal of virtual work

Chapter 4 : Elasticity and applications

- Recalls on infinitesimal and linear elasticity
- Elasticity tensor in material and spatial description
- Examples of applications

References

- Bonet J. and Wood R. D., Nonlinear continuum mechanics for finite element analysis, Cambridge University Press, 2000
- Botsis J. et Deville M., Mécanique des milieux continus: une introduction, Presses Universitaires Romandes, 2005
- Curnier A., Mécanique des solides déformables (Tome 1), Presses Universitaires Romandes, 2004†
- Fung Y. C. and Pin Tong, Classical and computational solid mechanics, World Scientific Publishing Co. Pte. Ltd. 2001
- Gurtin M., An introduction to Continuum Mechanics, Academic Press, 1981
- Haupt P., Continuum Mechanics and Theory of Materials, Springer, 2000 †
- Holzapfel G.A., Nonlinear Solid Mechanics, John Wiley & Sons, LTD, 2000
- Lemaitre J. et Chaboche J. L., Mécanique des matériaux solides, Dunod, 1988
- Simmonds J.G., A Brief on Tensor Analysis, 2nd edn, Springer-Verlag, New York, 1994

† : advanced books

MATERIALS AND METALLURGY

Equalization course

The course is optional but highly recommended
The course is taught in English

Coord. **Anne-Françoise GOURGUES-LORENZON** (anne-francoise.gourgues@mines-paristech.fr, MINES Paristech)

Objectives

This course aims at refreshing students' knowledge about basics in materials science. Microstructure-property relationships are the core subject of this course, especially, mechanical properties that are addressed in the master curriculum. The 15-hour course is very interactive, so that the students will check acquired skills in real time.

Chapter 1. Fundamentals about microstructure of materials

- Introduction to the various families of materials: starting from in-service properties. Origin, typical values of these properties (Young's modulus, thermal expansion, melting temperature...) .
- Atomic bonding. Crystal state. Amorphous state (and glass transition). Basics of crystallography.
- Microstructure of metal alloys, of ceramics: solid solution, grains, texture, phases.
- Defects in materials: vacancies, dislocations, interfaces (and interfacial energy), cavities, inclusions...

Chapter 2. Formation des microstructures : outils thermocinétiques

- Basics of phase transformations from the material's point of view.
- Basics of thermodynamics (thermodynamic potentials, equilibrium phase diagrams)
- Basics of kinetics: nucleation, growth, Avrami equation, thermal activation.
- Non-diffusive phase transformations.

Chapter 3. Processing of materials: a few examples

- Objective of processing steps for different families of materials.
- Ferrous alloy metallurgy (steelmaking) : electrical route, ore route. Solidification, crystal growth, solidification-induced microstructures, solidification defects.
- Cementitious materials.
- Glass manufacturing: the role of viscosity.

Chapitre 4. Linking microstructure to mechanical strength - Heat treatments

- Application to heat treatments of metal alloys; iron-carbon equilibrium diagram, TTT and CCT diagrams of steels, associated microstructures.
- Case study on precipitation: heat treatments of aluminium alloys.
- Application 1: automotive steels.
- Strengthening: solid solution strengthening; grain size strengthening (Hall-Petch equation); strain hardening; precipitation strengthening. Quantification of all of these contributions.
- Application 2: nickel-base superalloys for aircraft turbine blades.

Chapitre 5. Polymer processing and microstructures

- Introduction to polymers: macromolecules. 2D, 3D networks.
- Configuration (tacticity), conformation
- Amorphous state. Random coil.
- Crystal state: crystal structure of polymers.
- Microstructures : crystal lamellae, spherulite
- Evolution of modulus with temperature: glassy state, viscoelasticity, rubbery state, viscous flow. Interpretation of dynamic mechanical analysis measurements.
- Fibres: natural fibres, synthetic fibres : microstructures, properties (stiffness).

MATERIALS SCIENCE

Core course

The teaching unit is mandatory. ✔
The teaching unit is taught in French.
The teaching unit is taught in English.

Outline

3 ECTS / 30h/ 10 sessions of 3 hours

Courses : 13h Exercises : 13h Practice : 4h

Coord. **Véronique Favier** (veronique.favier@ensam.eu, ENSAM Paris)

Team

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Objectives

This teaching unit aims at clarifying the relationships between the structure of materials and their mechanical properties. In materials science, multiscale modelling is developing rapidly and requires an in-depth understanding of the physical basis of materials behaviour so that for instance new materials with optimal properties can be created. Therefore it is aimed at relating the desired properties of a material to the structure of the material from the atomic scale (10-10m) to the scale of the microstructure (10-4 m). From this point of view, the field is at the intersection between mechanics and physics. In this teaching unit, metallic materials, polymers and material that possess and internal length scale such as nano-structured materials, metallic foams or bones will be specifically considered..

Targets

A solid knowledge in material science becomes essential when working within the field of processin of existing or new materials, and of structural design, in particular when complex, non-linear material behaviours are encountered. In industry, this is mainly relevant for the material selection when a new system is designed, for the choice of the best process to obtain optimized properties for a given application, and for the development of new materials and processes for emerging applications. The relevant industrials sectors are diverse, ranging from transportation, energy production, construction to electronics or health !

Topics

- Polymers : 3 sessions
- Metals : 4 sessions
- Nano-Materials and biological materials : 2 sessions
- One session for practice (numerical or experimental).

References

- D. François, A.Pineau, A. Zaoui, (1993), Comportement mécanique des materiaux, tomes 1 et 2, Hermes, Paris
- J. Friedel, (1964), Dislocations, Pergamon, Oxford.
- J.P. Hirth, J.Lothe, (1968), Theory of dislocations, Mac Graw Hill.
- D. Jaoul, (1965), Etude de la plasticité et application aux métaux, Dunod, Paris.
- D. Hull, J. Bacon, (1984), Introduction to dislocations, International series on materials science and technologie, Pergamon, Oxford.
- H. H. Kausch et col.(2001), Matériaux Polymères. Propriétés Mécaniques et Physiques, Traité des Matériaux vol. 14. Presses Polytechniques et Universitaires Romande Lausanne.
- G. Kostortz et col. (2001), Phase Transformations in Materials, Wiley-VCH, Weinheim.

Content

Session 1 : Polymers, course

Introduction to polymers and macromolecules . Molecular architecture and classification of polymers. Applications. Relationships between microstructure and mechanical and optical properties.

Session 2 : Polymers, course and Exercise

Time-temperature equivalence, linear viscoelasticity and rubber elasticity. Effect of temperature on the mechanical properties of polymers.

Session 3 : Polymères, TD

Plasticity and fracture mechanisms of polymers. Case study : observation of damage mechanisms, crazes and shear bands

Session 4 : Metals, course and exercise

Stresses : crystalline metal behaviour – Crystal plasticity: slip systems, resolved shear stress, Schmid law, Non-Schmid effects. Case of polycrystals and role of the texture - Exercises : Yied surface for single crystal in tensile-torsion loadings, Effect of crystal orientation, application to textured polycrystal

Session 5 : Metals, course and exercise

Dislocations : The theoretical critical shear stress, edge and screw dislocations, Burgers vector, stress field of a straight dislocation, Strain energy of a dislocation - Exercices : Forces between dislocations and consequences...

Session 6 : Metals, course and exercise

Structural and work hardening – Multiplication of dislocations by Franck-Read sources, Interaction between dislocations and point defects/precipitates (cutting and Orowan mechanisms - Exercices : Single-crystal work hardening.

Session 7 : Metals, course and exercise

Strain rate – Kinematics of the single crystal : single and multiple slips, Additional deformation mechanisms : geometrically necessary dislocations, climb, cross slip, twinning and others… - Exercices : Dissociation of perfect dislocations, Suzuki effect, Applications to industrial alloys

Session 8 : Scale effects in materials, nanostructured materials, course

Nano-structured materials and nono-objects. Evolution law of the dislocation density with plastic strain. Grain size effects in polycrystals the Hall Petch law and the deviations to this law for nano-crystalline materials.

Session 9 : Scale effects in materials, nanostructured materials, course and exercise

Exercice: Geometrically necessary dislocations and second gradient models. Image force associated to a free surface and its effect on the flow of dislocations in nano-objects. Course: The behaviour of organics or metallics foams (bone, biological materials, and new metallic materials) How the internal structure of a material modifies its macroscopic behaviour.

Session 9 : Scale effects in materials, nanostructured materials, show

Numerical simulation of the dynamics of dislocations in nanostructured materials / Numerical simulation of the behaviour of a collection of grains (polycristal) and using a crystal plasticity formulation.

MATERIALS CONSTITUTIVE EQUATIONS AND THERMODYNAMIC OF SOLIDS

Core course

The teaching unit is mandatory.
The teaching unit is taught in French.
The teaching unit is taught in English.

Outline

3 ECTS / 10 sessions of 3 hours

Course : 15h Exercises : 15h Numerical practice : 4h

Coord. **Rodrigue Desmorat** (rodrigue.desmorat@ens-paris-saclay.fr, ENS Paris-Saclay)

Team

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Objectives

The main models that are used to describe the thermo-mechanical behaviour of solid materials – all along the life of a structure – are presented in the general framework of the continuum thermodynamics with internal variables.

Targets

The aim is to learn how to choose, identify and, if necessary, develop, the best model to describe the thermo-mechanical behaviour of materials during the numerical simulation of manufacturing processes or of in-service structure life.

Topics

- (An)isotropic thermo-elasticity
- Continuum thermodynamics with internal variables
- Modelling of thermo-elastoplastic and thermo-elastoviscoplastic behaviour
- Continuous damage
- Thermodynamics of fracture
- Numerical exercise : Kinematic vs isotropic hardening. Application to the cyclic behaviour of a mini-structure

References

- Mécanique des matériaux solides, J. Lemaître et J.L. Chaboche, Dunod, 2004.
- Mechanics of solid materials, J. Lemaître et J.L. Chaboche, Cambridge Univ. Press, 1994.
- Mécanique non-linéaire des matériaux, J. Besson, G. Cailletaud, J.L. Chaboche, S. Forest, Hermès, 2001.
- Advanced Fracture Mechanics, M. Kanninen, C. Popelar, Oxford University Press, 1985.

Content

First session

- Course 1 : (An)isotropic thermo-elastic behaviour and continuum thermodynamics principles.
- Exercise 1 : 1-D viscoelasticity with internal variable.

Second session

- Course 2 : Linear and non-linear visco-elasticity : phenomenology, mechanisms, modelling, identification.
- Exercise 2 : Anisotropic elasticity.

Third session

- Course 3 : Continuum thermodynamics with internal variables.
- Exercise 3 : 3-D viscoelasticity (with internal variables vs. functional formulation).

4th session

- Course 4 : Thermo-elastoplastic behaviour : phenomenology, mechanisms, modelling, identification (1st part).
- Exercise 4 : Plasticity criteria.

5th session

- Course 5 : Thermo-elastoplastic behaviour : modelling, identification (2nd part).
- Exercise 5 : 1D elasto-plasticity.

6th session

- Course 6 : Thermo-elastoplastic behaviour : modelling, thermodynamics, identification (3rd part).
- Exercise 6 : 1D elasto-viscoplasticity.

7th session

- Course 7 : Thermo-elastoviscoplastic behaviour : phenomenology, mechanisms, modelling, identification.
- Exercise 7 : Elastoplasticity under non-proportionnal loading.

8th session

- Course 8 : Continuous damage.
- Exercise 8 : Tangential operator.

9th session

- Course 9 : Thermodynamics of fracture.
- Exercise 9 : Damage (uniaxial case).

10th session

- Course 10 : Introduction to porous media.
- Exercise 10 : Introduction to porous media.

Evaluation

Written examination.

NUMERICAL METHODS FOR CONTINUUM MECHANICS

Core course

The teaching unit is mandatory.
The teaching unit is taught in French.
The teaching unit is taught in English.

Outline

3 ECTS / 10 sessions of 3 hours

Courses: 10 sessions of 1h / Exercises : 4 sessions of 2h / Practice : 6 sessions of 2h

Team

Coord. **Andrea Barbarulo** (andrea.barbarulo@centralesupelec.fr, CentraleSupelec)

Guillaume Puel, CentraleSupelec, gguillaume.puel@centralesupelec.fr

Objectives

This course presents numerical methods in structural computations and mechanics of materials. The discussed topic is structured in two large parts: (i) Nonlinear-Structural Computations and (ii) formulation and implementation of complex material laws in programs for structural computations. The objectives are therefore to provide the students with (i) basic knowledge to perform numerical computations (essentially using the finite element method) and (ii) advanced knowledge of implementing a material behavior in standard finite element programs.

Targets

The course is dedicated to engineering jobs in design research and development for various industries, such as aeronautics, transportations, civil, mechanical or electrical engineering. Theses industries employ and produce currently complex materials involving microscopic and macroscopic scales.

There is a frequent need to employ structural computations in order to evaluate the stress, strain or damage fields. In the past, most of the structures have been computed in the elastic domains. However, present applications demand more and more that the behavior of structures should be estimated in complex nonlinear situations. The present lectures are devoted to give the proper tools to the students in order to respond efficiently for these type of questions.

Bibliography

- Besson, J., Cailletaud, G, Chaboche, J.-L., Forest, S.,Mécanique non-linéaire des matériaux, Hermes (2001)
- Besson J., Billon N., Cantournet S. - Matériaux pour l'ingénieur, Editions Mines, 2006
- Bonnet M, Frangi A. - Analyse des solides déformables par la méthode des éléments finis, Editions de l'Ecole Polytechnique, 2006
- Constantinescu A, Korsunsky AMK – Elasticity with Mathematica, Cambridge University Press, 2007
- Dhondt, G., The Finite Element Method for Three-Dimensional Thermomechanical Applications, 2004
- Hughes, T. J. R. Finite Element Method - Linear Static and Dynamic Finite Element Analysis
- Prentice-Hall, Englewood Cliffs, 1987
- Georges Cailletaud - Modélisation mécanique d'instabilités micro-structurales en viscoplasticité cyclique à température variable (Note technique ONERA) (Broché - 1979)
- Simo, J. C. and Hughes, T. J. R. Computational Inelasticity, Springer 1999
- Suquet P. - Rupture et plasticité, Editions de l'Ecole Polytechnique, 2006

Content

Session 1 : Review of the finite element method (Course + Exercises)

Balance equations for elastic bodies. Principles of virtual strains. Minimum Principles and weak formulation of the equlibrium.

Session 2 : The Finite Element Method in linear elasticity (Course + Practice)

Construction of the approximate elasticity, Discret system of equations and its numerical resolution. Static and Dynamic balance. Boundary conditions and computations of the reactions. Numerical computations of stress intensity factors. Computation of the energy release rate.

Session 3 : Solids with nonlinear material behaviour (Course + Exercises):

Review of large strains. Nonlinear equations and Newton type iterative algorithms.

Session 4 : Solids with nonlinear material behaviour (Course + Exercises):

Review of elastoplastic material behaviour. Nonlinear equations and Newton type iterative algorithms.

Session 5 : Solids with elastoplastic material behavior: local aspects (Course + Practice)

Computation of an elastoplastic structure: problem definition. Local integration of the constitutive law. Examples.

Session 6 : Solids with elastoplastic material behavior: integration algorithm (Course + Practice)

Programming of an example.

Session 7 : Solids with elastoplastic material behavior: identification of the material behaviour (Course + Practice)

Testing possibilities. Problem formulations and identification techniques. Sensitivity computations.

Session 8 and 9 : Programing Exercices (Practice)

Session 10 : Exam

Evaluation :

Written examination and Continuous control – homework, numerical projects

Computer Programs :

Castem, Zebulon, Calculix, Abaqus / Scilab, Matlab, Mathematica

ADVANCED EXPRIMENTAL METHODS

Core course

The teaching unit is mandatory.
The teaching unit is taught in French.
The teaching unit is taught in English.

Coordinateur : Hubert Olivier
olivier.hubert@ens-paris-saclay.fr

Pedagogical team :

- Hubert, Olivier, Professeur des Universités, CNU 60, ENS Paris-Saclay (olivier.hubert@ens-paris-saclay.fr)
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Procedure and organisation :

Courses: Experiments for the study of mechanical behavior of materials (Machines, specimens, PID) Sensors and measurement (Principles of measurement, signal conditionning and numerization) Experimental plans Field Measurements – Digital Image Correlation (DIC – 2D/3D)) Numerical methods - field identification of properties Techniques for the analysis of the microstructure of materials (microscopy, X-ray diffraction)

Tutorials: tensile strengthening (elasticity, plasticity), thermomechanical, damage; heat treatments; image correlation; DTA / DSC; additive manufacturing; metallurgical analyzes, optical microscopy / SEM / TEM; electron diffraction.

Pedagogical objectives :

Content:

Solving a problem related with the mechanics of materials usually requires a precise knowledge of the material constitutive behaviour, and more generally of the basics properties of the material. The property that is aimed at being characterized determines the machine, the shape of the sample, the measurements techniques and also the identification algorithms. This course provides an overview of the classical experimental techniques employed in a material testing laboratory. It also aims at providing an insight into the development of advanced experimental methods, in particular full field measurements (especially kinematic), 1D, 2D, 3D et 4D. And finally it aims also at providing essential working methods that are required in the field of testing, such as estimating the uncertainties and the errors of data sets, or data fields, the spatial or temporal resolution etc... Emphasis will be placed on tutorial work, whose completion, analysis of results and writing will be evaluated by the teachers of the course. An exam will assess the culture acquired in the field of experimental techniques by the student during the semester.

Skills:

Acquire the technical knowledge and skills associated with traditional and modern tools for measuring the behavior of materials

Complementary skills :

Digital Image Correlation, microscopy (optical, SEM, TEM), X-ray diffraction; All Learning (analysis, writing and synthesis) essential for the training of researchers and senior executives.

Prerequisites :

Continuum mechanics, elasticity, thermic, metallurgy (basic).

Bibliographie :

- Grédiac, M., Hild, F. (éditeurs). Mesures de champs et identification en mécanique des solides. Traité MIM. Hermes. 2011.
- Grédiac, M., Hild, F. (éditeurs). Full-field measurements and identification in solid mechanics (edited) Publisher ISTE / Wiley. 2013
- F. Hild, S. Roux. Digital image correlation, in Optical Methods for Solid Mechanics. A Full-Field Approach, ed. by P. Rastogi, E. Hack (Wiley-VCH, Weinheim, 2012), pp. 183-228.
- Benard, J., Michel A, Philibert J., Talbot J., (1984). Métallurgie générale, ed. Masson (France). Cullity B.D.,(2rd edition 1976), Elements of X-Ray Diffraction,

RESEARCH PROJECT

Core course

3 ECTS / 30 h

Courses : 9h Practice : 21h

Team

Coord. **Xavier Colin** (xavier.colin@ensam.eu, ENSAM Paris)

Objectives

This teaching unit aims at leading a research project from a scientific but also management point of view.

Apart from exceptions, the research project aims at preparing the internship. If the research project is well-led, you will be able to start experimental, theoretical or numerical studies right from the beginning of the internship.

Over the teaching unit, project management methods and tools are taught. A course on "how to find scientific publications on a given subject" and "how to write a research bibliography" is proposed. The main part of the teaching unit is dedicated to practice. You will have to choose a scientific research subject among proposals. For this subject, you will have to read literature results and then clarify the remaining scientific issues. Finally, you will have to propose some methods and tools to contribute to solving the scientific issues. A teacher-researcher, called "supervisor", will help you for your project. Another teacher-researcher will assess your work.

Website useful for the course

Dominique Jaccard's website with a lot of ressources.

Assesment of the research project

Your work is assessed via a written report and an oral presentation in front of a poster. It means that you will explain your work to a scientific commitee during a poster session. You can write and speak using the language of your choice (English or French). As a consequence, two marks will be given to assess your work and you will know the average of these two marks.

In addition, you will have to write a one-page summary in a foreign language (French for anglophone students and English for francophone students). This assessment allows to check your summarization capabilities and your written level in a foreign language. Finally, you will have to write a document describing the management of your project to assess your ability to plan a project, to keep an analytical distance from the scientific issue, to think about the human and technical means to achieve the project. These last two items will be assessed by two other marks which will be incoporated to the final mark of another teaching unit called "Scientific communication in a foreign language".

Uploading

How to write the research project report ?
How to write the one-page summary in a foreign language ?
How to write the project management document ?

FRACTURE MECHANICS

Elective 1

The teaching unit is mandatory.
The teaching unit is taught in English.

Outline

3 ECTS / 30 h

Courses : 15 h	Exercises : 3 h	Practice : 6 h	Conferences : 6 h

Team

Coord. **Thilo Mogeneyer** (thilo.morgeneyer@mines-paristech.fr, Mines ParisTech)

Objectives

This teaching unit covers the broad topic of structural integrity which is founded on the mechanics of fracture, and is concerned with the reliability, durability and security of structural components of any scale, geometry or material. It is aimed at presenting and practising efficient and up-to-date engineering designs methods when defects or cracks are present (damage tolerance approaches) for various fracture mechanisms.

Targets

Fracture mechanics is employed in industrial applications when the failure of a component could have catastrophic consequences, such as losses of human lives or an ecologic disaster for instance. This is the case of mass transportation (trains or planes), energy production and in particular nuclear powerplants and the industries concerned with the production, the transportation or the recycling of toxics (oil industry, chemical industry). In these industrial fields, the risk of failure is not acceptable, therefore it should always be assumed that the existence of a defect is possible, even if its probability is very low, and determine at which conditions this defect can't be at the origin of a catastrophic failure.

Topics

- Linear elastic fracture mechanics, mode I and mixed mode
- Non linear fracture mechanics
- Mechanisms of failure : ductile, brittle, fatigue and related models
- Numerical practice: Calculation of K, J and T, case study of real catastrophic failure events
- Experimental Practice: observation of stress fields in a cracked sample of PMMA (photoelasticimetry)

References

- Mécanique de la rupture fragile et ductile, Jean-Baptiste Leblond, Hermes Science Publications (2003), Etudes en mecanique materiaux
- Comportement mécanique des matériaux : viscoplasticité, endommagement, rupture, D. Francois, A. Pineau, Hermes Sciences Publication (1993)
- La simulation numérique de la propagation des fissures, S. Pommier, A. Gravouil, N. Moës, A. COmbescure, Hermes Sciences Publication (2009)
- Fatigue of Materials, S. Suresh , Cambridge University Press, (1998)

Content

Session 1 : introduction, linear elastic fracture mechanics (LEFM)

Introduction, Griffith's theory, elastic singularities, asymptotic development, linear elastic fracture mechanics (LEFM), KI, KII, KIII and T.

Session 2 : Exercises

Analysis of the results of a tensile test on a pre-cracked sample: KIC, case study of a real failure event. Notions of toughness and of potential energy release rate…

Session 3 : Numerical Practice. Determination of SIF

For the same sample geometry that will be used in the experimental practice session, computations of of stress intensity factors, displacements, stresses, J integral and interactions integrals.

Session 4 : LEFM for tridimensionnal probles (loading and geometry)

Mixed mode fracture, I, II and III. Bifurcation criteria in linear elastic fracture mechanics. Role of non-singular terms for the crack path stability. 3D cracks with curved crack front. Surface singularity (when a 3D crack front intersect a free surface), interface singularity.

Session 5 : Non-liear fracture mechanics

How plasticity modifies the loading conditions at crack tip, from a microscopic point of view (disclocation emission and shielding effect at crack tip) and from a macroscipic point of view (Irwin's plastic zone, J integral and HRR field)

Session 6 : Experimental practice

Observatiin using the scanning electron microscope of typical fracture surfaces (ductile, brittle and fatigue). Initiation and arrest toughness measurements, in mode I and Mixed mode conditions.

Session 7 : Mode I fatigue crack growth

Fatigue failure for complex loading conditions. Physical mechanisms of crack extent in fatigue. Paris law and domain of application. Application: prevision of the fatigue life of an aerospace component. Effect of variable amplitude loadinds, history effects. Design methods.

Session 8 : Mixed Mode fatigue crack growth

Ductile failure and fatigue crack growth under mixed mode loading concicions. Examples of torsion failures of contact fatigue failures. Effect of friction on fatigue crack growth.

Session 9 : Novel tools and concept for predictinig crack growth in brittle or ductile materials

Mesh size effect, fatigue and ductile fracture, non-local models, Levels sets and X-FEM.

Session 9 : Conference, ductile fracture

Ductile fracture and design rules for industrial components, global and local approaches of ductile fracture.

DAMAGE AND RUPTURE OF POLYMERS AND COMPOSITES

Elective 1

The teaching unit is mandatory.
The teaching unit is taught in English.

Outline

3 ECTS / 30 h

Team

Coordinator : **Federica Daghia** (federica.daghia@ens-paris-saclay.fr, , ENS Paris-Saclay)

Instructors :

- **Lucien Laiarinandrasana** (lucien.laiarinandrasana@mines-paristech.fr, Mines ParisTech)
- **Sebastien Joannes** (sebastien.joannes@mines-paristech.fr, Mines ParisTech)
- **Federica Daghia** (federica.daghia@ens-paris-saclay.fr, ENS Paris-Saclay)
- **Cristian Ovalle Rodas** (cristian.ovalle_rodas@mines-paristech.fr, Mines Paris-Tech)

Objectives

The aim of the course is to discover the damage and fracture mechanisms of polymers and polymer matrix composites at different scales, and to learn about the appropriate modelling approaches. Specific aspects developed in the course include the extension of fracture mechanics concepts to large and viscoplastic deformations, statistical approaches for fibres' characterization, the damage mesomodel for laminated composites, thermo-mechanical aspects and ageing of elastomers.

Targets

Polymers and polymer matrix composites occupy an increasing part of the market in different industrial applications, especially in the transportation industry. It is therefore important to understand, and to be able to predict, the degradation and failure of these materials. Due to their specificities (large deformations and viscosity for polymers, complex and hierarchical microstructure for composites), the study of these materials require specific tools, both from the point of view of characterization and of the appropriate modelling approaches, which often involve different scales of observation and scale transition techniques.

Topics

- Polymers : extension of classical fracture mechanics concepts to polymers (large deformations, viscosity), deformation and damage mechanisms in link with their microstructure.
- Polymer matrix composites : damage and fracture at different scales - fibre/matrix, ply/interface, laminate.
- Rubbers : damage and fracture behaviour under monotonic and fatigue loading, including thermal considerations.

References

- Mechanical Behaviour of Materials - François, D, Pineau, A, Zaoui, A, Springer (2012)
  - Volume I : Micro- and Macroscopic Constitutive Behaviour
  - Series : Solid Mechanics and Its Applications, Vol. 180
  - Volume II : Fracture Mechanics and Damage
  - Series : Solid Mechanics and Its Applications, Vol. 191, chapter 10
- John A. Nairn, Polymer Matrix Composites, Chapter 13, R. Talreja and J-A. Manson, eds., in press (2000) Volume 2 of Comprehensive Composite Materials, A. Kelly and C. Zweben, eds., Elsevier Science

Content

Each session lasts 3 hours, it can include classical course as well as exercise sessions.

Session 1 (Lucien Laiarinandrasana)

Fracture mechanics applied to polymers: limitations of linear elastic fracture mechanics due to large transformations, viscoelastic and viscoplastic behaviour and non-linearities.

Session 2 (Lucien Laiarinandrasana)

Deformation and damage mechanisms in polymers classes in link with their microstructure observed by fractography and 3D observations.

Session 3 (Lucien Laiarinandrasana)

Fracture mechanics concepts for polymers: essential work of fracture and effects of viscosity.

Sessions 4 (Sebastien Joannes)

Characterization of single fibres: failure mechanisms at the fibre's scale, statistical aspects, multi-scale models.

Sessions 5 (Sebastien Joannes)

The unidirectional ply with continuous aligned fibres: anisotropy, symmetry classes, failure mechanisms in the fibres and transverse directions.

Session 6 (Federica Daghia)

Notions on laminated composites: stacking sequence, modelling of the overall behaviour, couplings (normal/shear, membrane/bending).

Session 7 (Federica Daghia)

Damage mechanisms at the ply's and at the laminate's scale: load redistribution and final failure, multiple cracking, delamination.

Session 8 (Federica Daghia)

The damage mesomodel for laminates: ply and interface models, illustrations.

Session 9 (Cristian Ovalle Rodas)

Mechanical behaviour of elastomers: hyperelasticity. Influence of the manufacturing process.

Session 10 (Cristian Ovalle Rodas)

Fatigue behaviour of elastomers: Wohler's curves, damage initiation mechanisms, thermomechanical and ageing aspects.

CONTINUUM DAMAGE MECHANICS

Elective 1 and optional course

The teaching unit is mandatory.
The teaching unit is taught in English.

Outline

3 ECTS / 30 h

Courses : 15 h   Exercises : 15 h

Team

Coord. **Rodrigue Desmorat** (rodrigue.desmorat@ens-paris-saclay.fr, ENS Paris-Saclay)

Objectives

To give a review of damage models for different materials (metal and alloys, concrete and glass, composites, elastomers) and different applucations (e.g. rupture under monotoni loading conditions, fatigue, dynamic fragmentation). To give the fundamentals for the numerical implementation of constitutive damage models.

Targets

This course of advanced modeling prepares engineers and young researchers for future design methods based on Damage mechanics concepts. Fields : aircraft and space industry, energy industry, car industry, civil engineering.

Bibliography

- Mechanics of Solid Materials, J. Lemaitre, Cambridge University Press, 1990
- A Course on Damage Mechanics, J. Lemaitre, Springler-Verlag,1992 Engineering Damage Mechanics: Ductile, Creep, Fatigue and Brittles Failures, J. Lemaitre and R. Desmorat, Springer, 2005
- Mécanique non linéaire des matériaux, J. Besson, G. Cailletaud, J.-L. Chaboche, S. Forest, Hermès-Lavoisier, 2001

Content

- A - Probabilistic description
    1. Probabilistic description of the degradation and failure of britlle and quasi-brittle materials.
    2. Analysis of the transition between single and multiple fragmentation.
    3. Introduction to Poisson point processes. Weibull model.
- B - Phenomenological model in the thermodynamiccs framework
    1. Marigo and Mazars damage models.
    2. Lemaitre type damage models : effective stress concept, stored energy damage threshold, damage evolution laws, isotropy/induced anisotropy (damage tensors).
    3. Different behavior in tension and in compression.
    4. Micro-defect closure effect or quasi-unilateral conditions.
    5. General thermodynamics framework for hysteresis, fatigue and damage
- C - Gurson Type models
    1. GTN model for ductile failure
    2. Gurson-Rousselier-Lemaitre unified thermodynamics approach
- D - Localization and instabilities
    1. Bifurcation analysis. Perturbation analysis. Regularisation and non local models
- Written examination

METAL ADDITIVE MANUFACTURING

Elective 2

The teaching unit is mandatory.
The teaching unit is taught in

Coord. **Morgan Dal** (morgan.dal@ensam.eu, ENSAM Paris)

Outline
3 ECTS / 30 h

Objectives

This course provides a rigorous formation for the students in casting and miscellaneous techniques (powder metallurgy, welding, thixoforming, thermal spraying…), physical mechanisms and induced microstructure (1) to model and simulate these processing and (2) to predict the in-life mechanical properties of components.

Targets

This program focuses on liquid, semi-liquid metal processing: casting (sand casting, die casting), powder metallurgy (sintering, metal injection moulding…), welding, high energy processes …. This course will be used in order to optimize the manufacture processing to obtain the right properties for a specific application. Current industrial areas are aeronautics, transportation, nuclear engineering, energy, biomedical engineering, structures…

Topics

- Solidification of ferrous and non-ferrous alloys and mechanical behaviour during processing : 3 sessions
- Applications to high energy beam processing with and without tool/material contact : 5 sessions
- Temperature and thermal flux in fluid metal processing : 2 sessions

Content

Session 1 : Thermodynamics – Phase diagrams – Kinetics of phase transformation – Microsegregation – Development of microstructure – defects

Session 2 : High solidification rate and others types of solidification (ultrafine structure, amorphous structure, defects, polymer crystallisation …

Session 3 : Semi-solid rheology.

Session 4 : Coatings & Materials by Thermal Spraying– Technologies and processing.

Session 5 : Coatings & Materials by Thermal Spraying – Properties of coatings.

Session 6 : Laser Materials Processing (1) : overview on different laser processes (basic physical processes, interaction modes, thermal aspects).

Session 7 : Laser Materials Processing (2) : Microstructures, defects and resulting properties.

Session 8 : Powder metallurgy. Technologies and processing -: Microstructures, defects and resulting properties.

Session 9 : Thermal phenomena – heat sources modelling –Heat exchange modelling (contact surface and heat transfer).

Session 10 : experimenTal measurements and identification/inverse methods

PLASTIC STRAIN PROCESSING

Elective 2, Elective 4 and optional course

The teaching unit is mandatory.
The teaching unit is taught in

Coord. **Franck Morel** (franck.morel@ensam.eu, ENSAM Angers)

Outline

3 ECTS / 30 h
Courses : 10 sessions de 3h
Exercises : Aucun
Practice : Aucun

Team

- Jean Lou LEBRUN (jean-lou.lebrun@ensam.eu)
- Franck MOREL (franck.morel@ensam.eu)
- Nathalie BOZZOLO (nathalie.bozzolo@mines-paristech.fr)
- Rodrigues DESMORAT (rodrigue.desmorat@ens-paris-saclay.fr)
- Thierry PALIN-LUC (thierry.palin-luc@ensam.eu)
- Ivan IORDANOFF (ivan.iordanoff@ensam.eu)

Objectives

This course provides a rigorous formation for the students in physical mechanisms and induced microstructure during forming operations and machining coupling mechanical and thermal effects (1) to model and simulate these manufacturing processing and (2) to predict the in-life mechanical properties of components.

Targets

This program focuses on solid materials processing: sheet forming operations (rolling, stamping, light cutting …), bulk materials forming operations (forging, extrusion, drawing …) and machining. This course will be used in order to optimize the manufacturing processing to obtain the right properties for a specific application. Current industrial areas are aeronautics, transportation, nuclear engineering, containers, structures…/P>

Topics

- Transformations in solid metals and mechanical behaviour during forming processing: session 1 to 4.
- Tribology : session 5 to 6.
- Role of residual stress and microstructural heterogeneities on final properties of parts : session 7 to 10.

Content

Session 1 :

Phase transformation and precipitation (JLL).

Session 2 :

Recovery and recrystallisation (YC).

Session 3 :

Strain induced textures et dislocation structures (YC).

Session 4 :

Temperature-dependent elasto(visco)plastic constitutive equations for high temperatures, high strain rates and large strains (RD): Johnson-Cook, Norton-Hoff, Thermal activated constitutive equations, integration of damage, extension to finite transformations.

Session 5 :

Presentation of the historical tribological contact characterisations : friction coefficient, Block model and its extensions, wear models. - Experimental and physical limitations involved by these phenomenological approaches.

Session 6 :

Generic description of contacts, notion of third body, description of material and heat flows with the help of a discrete element model – Proposition of a generic methodology, based on expérimental and numerical studies to establish appropriate contact behavior laws. Examples of experimental set up used in material forming studies. Exemple of numerical tools.

Session 7 :

Residual stress origin and calculations in simple forming operations –Residual stresses after forming and heat treatments – Advanced techniques for residual stress experimental analysis (JLL).

Session 8 :

Residual stress and microstructural heterogeneities effects on deformation, static strength, corrosion, physical properties ... (JLL).

Session 9 :

Material Integrity and fatigue behaviour (FM): Background fatigue limit criteria - Effect of surface state, residual stresses and microstructural heterogeneities.

Session 10 :

Illustrations : processing operations-fatigue properties-correlations (machining, forging, casting, surface heat treatments …)(FM).<

Evalutation :

Written exam.

Bibliography

- “Simulation of wear through mass balance in a dry contact”, Fillot, N., Iordanoff, I., Berthier, Y., Journal of Tribology 127 (1), pp. 230-237 (2005)
- “Thermal Study of the Dry Sliding Contact With Third Body Presence”, Richard, D., Iordanoff, I., Renouf, M., Berthier, Y., Journal of Tribology, 130, (10 pages) (2008)
- “Background on friction and wear”, Berthier Y., , Handbook of materials behavior models. Lemaître. Academic Press, Background on friction and wear. Vol.Chap 8. p.676 -699 (2001)
- “Physique et Mécanique de la mise en forme des métaux”, Ecole d’Eté d’Oléron dirigée par F. Moussy et P. Franciosi, Paris : Presses du CNRS : IRSID, XiV-645p (1990)

NUMERICAL SIMULATION OF METAL PROCESSING

Elective 2

The teaching unit is mandatory.
The teaching unit is taught in French

Coord. **Etienne Pessard** (etienne.pessard@ensam.eu, ENSAM Angers)

Pedagogic team :

- Yessine. Ayed, Ensam Angers (Yessine.AYED@ensam.eu)
- Amine. Ammar, Ensam Angers (Amine.AMMAR@ensam.eu)
- Julien Artozoul, Ensam Angers (Julien.ARTOZOUL@ensam.eu)
- Idriss Tiba, Ensam Angers (Idriss.TIBA@ensam.eu)
- Aude Caillaud, Ensam Angers (aude.caillaud@ensam.eu)
- Etienne Pessard, Ensam Angers (Etienne.Pessard@ensam.eu)

Description of the Teaching Unit

Outline
3 ECTS / 30 h
Cours magistral : 10 h
Travaux dirigés : 10 h
Travaux pratiques : 28 h

Objectives

This program focuses on modelling and simulation tools to metal processing analyse. Students and specialists will use current commercial softwares dedicated to specific processing operations to address the reliability and the relevance but also the limits of these commercial softwares. A rigorous formation for the students in casting and forging

physical mechanisms and induced microstructure (1) to model and simulate these processing and (2) to predict the in-life mechanical properties of components.

Targets

This course can be directly applied to liquid, semi-liquid and solid metal processing: casting (sand casting, die casting), bulk materials forming operations (forging, extrusion, drawing …) The objective is to acquire knowledge allowing to optimize these processes using numerical simulation software. Current industrial areas are aeronautics, transportation, nuclear engineering, energy, biomedical engineering, containers, structures …

Topics

- Introduction : to processing modelling
- CM1 : How to establish thermomechanical and metallurgical couplings ?
- CM2 : Fom the geometry of the component to the processing simulation : meshes and numerical aspects
- Materials data generation and identification
- CM3 : Materials data : experiments on thermomechanical simulator (GLEEBLE)
- CM4 : Specific experiments for casting process.
- CM5 : Specific experiments for forging parameters
- Industrial examples – Numerical simulation of the processing
- How to use commercial codes (e.g. PROCAST, QUICKCAST, ForgeNXT)
- Presentation of the studied example
- How to prepare the modelling ?
- Numerical simulations and part manufacturing
- Results analysis and comparison between experimental and simulation results

DURABILITY AND RECYCLING OF POLYMERS AND COMPOSITE MATERIALS

Elective 3

The teaching unit is mandatory.
The teaching unit is taught in English

Outline of teaching unit

3 ECTS / 30 h

Lectures : 13h30 Tutorials : 4h30 Practical works : 8h

Team

Coord. **Xavier Colin** (xavier.colin@ensam.eu, ENSAM Paris)

Xavier Colin , ENSAM Paris, Xavier.COLIN@ensam.eu
Lucien Laiarinandrasana, PSL, lucien.laiarinandrasana@mines-paristech.fr
Bruno Fayolle, ENSAM Paris, bruno.fayolle@ensam.eu

Objectives

To provide to students an overview of the required theoretical concepts for assessing the lifetime of polymeric material engineering components in service conditions.

To show an application of these tools in selected industrial cases.

To tackle the problem of polymer recycling.

Targets

In a first time designed for resisting to static and dynamic loadings, polymer structures are now considered for long term applications (typically for several dozens of years) in more and more aggressive environmental conditions. Designers, familiarized with the domain of mechanical modelling, are more and more fond of kinetic models allowing us to introduce the time factor in the design. Classical approaches, based on the (often unfounded) use of Arrhenius law or other totally empirical models, are less and less compatible with the present requirements of design and one can observe a strong industrial pressure in favour of the development of models for lifetime prediction. The recent activities of the different teachers' laboratories show well this renewed interest.

Topics

In this course, it not envisaged to make an exhaustive presentation of all types of ageing susceptible to take place in service conditions. This course is aimed to present a general approach for lifetime prediction, applicable to all type of ageing problem of a polymeric material engineering component, and to show the high heuristic value of this approach for selected industrial applications. With this intention the course will be divided into three main parts. In a first part, the most current chemical ageing mechanisms (oxidation, hydrolysis) and their corresponding chemical kinetics will be described. In a second part, a peculiar attention will focus on embrittlement mechanisms at the local and global scales in the absence of mechanical loading. Once the structural embrittlement state well defined, its consequences on the material mechanical properties will be described. The knowledge of the constitutive relations governing the material behaviour will allow the characterization of appropriate concepts of fracture mechanics to be used, in order to assess the residual lifetime of the engineering component. This approach will be applied in selected industrial cases operated in the respective teachers' laboratories.

Content

- Oxidation mechanisms, hydrolysis.
- Transport properties of molecular species.
- Diffusion/reaction coupling.
- Stabilization mechanisms.
- Chain scissions and crosslinking.

- “Hindered” shrinkage of the degraded superficial layer.
- Consequences on mechanical properties.
- Slow crack growth mechanisms in polymers.
- Fracture mechanics for creeping solids: global approach and introduction to local approach.
- Embrittlement of PE pipes used for the transport of drinking water.
- Creep damage and failure of extruded tubes subjected to internal pressure.
  - Chemical ageing mechanisms, kinetic aspects – L 4h30 T 3
  - Local and global embrittlement – L 4h30 T 1h30
  - Application of fracture mechanics concepts to polymers - L 6h T 3h
  - Introduction to polymer recycling - L 1h30
  - Selected industrial problems - TP 6h

Examples of Mater projects and PhD theses :

- Thermal ageing of epoxy matrix composites (EADS, 2006/09).
- Thermal ageing of PBD matrix propellants (SNPE, 2004/07).
- Long term properties of hdPE sheaths for pontoon bridges (LCPC, 2007/10).
- Thermal ageing of hybrid composite strings used for the reinforcement of electrical wires (EdF, 2007).
- Development of models for lifetime prediction for synthetic cables (EdF, 2008/11).
- Ageing of PE and Ethylene/propylene copolymers electrical cable insulators in nuclear environment (EdF, 2003/06).
- Recycled PET for food packaging: experimental approach and kinetic modelling (2005/08).
- Impact of water quality on ageing of innovative products for synthetic material plumbing (CSTB, 2008/11).
- Damage and crack growth under creep of extruded polyethylene : local approach – global approach (GdF 2000/03).
- Aging effect on creep crack initiation and growth in HDPE (2010/09).
  - Aeronautics and space :
  - Civil Engineering :
  - Electricity :
  - Nuclear :
  - Food packaging :
  - Fluid transport :

Marking

Personal work : Analysis of scientific papers / experimental or computing work. Two formatted A4 pages + oral presentation (15 min).

Bibliography

- X. Colin, B. Fayolle, L. Audouin, J. Verdu & X. Duteurtre, dans « Vieillissement et durabilité des matériaux », Série Arago 28, édité par G. Pijaudier-Cabot, OFTA, Paris, Chap. 3, p. 65, 2003.
- H.B.H. Hamouda, M. Simoes-Betbeder, F. Grillon, P. Blouet, N. Billon, R. Piques, "Creep damage mechanisms in polyethylene gas pipes", Polymer 42 (2001) 5425-5437.
- H. Ben Hadj Hamouda, L. Laiarinandrasana, R. Piques, "Fracture mechanics global approach concepts applied to creep slow crack growth in a medium density polyethylene (MDPE)", Engineering Fracture Mechanics 74 (2007) 2187-2204.

PROCESSING OF POLYMERS AND COMPOSITES

Elective 3 and optional course

The teaching unit is mandatory. ✔
The teaching unit is taught in English

Outline of teaching unit

3 ECTS / 30 h

Lectures : 6 courses of 3h | Tutorials : 4 courses of 1h30 | Practical works : 1 course of 4h

Team

Coord. **Gilles Regnier (**gilles.regnier@ensam.eu, ENSAM Paris)

Emmanuel Baranger, ENS, baranger@lmt.ens-cachan.fr
Corinne billerault, IFOCA, corinne.billerault@ifoca.com
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Cyrille Sollogoub, ENSAM Paris, Cyrille.SOLLOGOUB@ensam.eu

Objectives

Show the distinctive features of polymer processing (viscoelastic behavior, kinetics of state transitions, influence of micro- and nanofillers).

Have an overview of the induced micro- and nanostructure to better understand properties.

Know application field and limits of industrial process simulation codes.

Targets

Organic materials and composites are taking an increasing part in manufactured products. Their processing optimisation needs simulations on specific codes based on several hypothesis. The predictions are highly dependent on these hypothesis and the lectures aim to show what can bring an intensive use of codes like REM3D or Moldflow for injection molding simulation. The present limits linked to the complexity of induced microstructures will be discussed.

Exemples of 4-months Master projects :

- Thermoforming simulation of aeronautical PMMA windows (Saint-Gobain 2008).
- Debindering simulation of injection molded ceramic parts (Snecma 2007).
- Thermoelastic properties of injection molded polymers reinforced by fibers (Legrand 2006, Bosch 2008).
- Rheology of polymers reinforced by carbon nanotubes (2007).
- Viscoelastic properties of a PE reinforced by nanoclay particles (2007).

  - Aeronautics :
  - Génie électrique / Automobile :
  - Nanotechnologies :

Topics

- Rheothining visqueux behavior.
- Viscoelasticity in flow.
- Induced microstructures.

- Kinetic modelling.
    - Polymer processing - L 3h
    - Rheology in the liquid state - L 3h, T 3h
    - Crystallisation - L 1h30, T 1h30
    - Microscopic or nanometric fillers (fibers, carbon nanotubes, …) and nanostructuration - L 6h
    - Induced thermoelastic behavior - L 1h30, T 1h30
    - Injection molding - L 3h
    - Injection molding simulation of thermoplastics on MOLDFLOW® code - TP 4h

Marking

Personal work : Analysis of scientific papers / experimental or computing work. Two formatted A4 pages + oral presentation (15 min).

BibliographY

- Agassant J.F. et al., La mise en forme des matières plastiques, Tech & Doc, 1996.
- Etienne S., David L., Introduction à la physique des polymères, Dunod, 2002.
- Macosko C., Rheology: principles, measurement and applications, VCH publishers, 1994.
- Ward I.M., Structure and Properties of oriented polymers, Chapman & Hall, 1997.

MECHANICAL BEHAVIOR OF POLYMERS

Elective 3

The teaching unit is mandatory. ✔
The teaching unit is taught in English

Outline

3 ECTS / 30 h

Courses : 19h30 Exercises : 6h Practice : 4h

Team

Coord. **Bruno Fayolle** (fayolle.bruno@ensam.eu, ENSAM Paris)

- Etienne Barthel, PSL, etienne.barthel@espci.psl.eu
- Antoine Châteauminois, PSL, antoine.chateauminois@espci.fr
- Justin Dirrenberger, ENSAM Paris, Justin.DIRRENBERGER@ensam.eu
- Bruno Fayolle, ENSAM Paris, bruno.fayolle@ensam.eu
- Patrick Heuillet, LRCCP, heuillet@lrccp.com
- Alba Marcellan, PSL, alba.marcellan@espci.fr

Objectifs

This teaching unit aims at giving the knowledge bases of different polymers behaviors allowing the choice and the use of the right material in applications where weight, stiffness, fracture strength or chemical resistance are the challenging parameters. The master of the complex behaviors of polymers is the only way to be able to substitute metals by organic or composite materials.

Targets

Aerospace, Automotive both for both design and technical parts, Offshore, Civil Engineering in particular for coatings and sealants, Electricity as insulating materials, Packaging and Conditioning, Fluid transport (drinking water, gas). Sports and leisure, microelectronics. Health (prosthetic devices, tissue engineering).

Topics

- Linear viscoelasticity, creep and relaxation, dynamic behaviour, time-temperature equivalence, molecular mobility (J. Diani L 4h30 – T 1h30 – P 4h00)
- Show the molecular/physical interpretation of hyperelasticity theory applied on elastomers, then introduce finite strain formalism (A. Marcellan and L. Laiarinandrasana L 6h)
- Analyse the specificity if linear and non linear fracture mechanics applied on polymers (L. Laiarinandrasana L 3h)
- Describe the mechanisms of plasticity and fracture at the microscopic scale, establish the relations between chemical structure, polymeric architecture and plastic deformation mechanisms (C. Creton L 3h – T 1h30)
- Introduce the basic concepts of elastic adhesive contacts on polymers (A. Chateauminois L 4h30 – T 1h30)

Evaluation

Articles analysis : report (2 A4 pages) and oral presentation.

Bibliographie

- Rheology : principles, measurements and applications, C. Macosko, VCH publishers, 1994.
- An introduction to the mechanical properties of solid polymers, I.M. Ward et D.W. Hadley, Wiley, 2002.

MULYI-PHYSICAL APPROACH OF CUTTING, MATERIALS AND MATERIAL INTEGRITY

Elective 4

The teaching unit is mandatory.
The teaching unit is taught in French
The teaching unit is taught in English

Outline

3 ECTS / 30 h
Lectures : 16h Tutorials : 8h Practical works : 8h

Team
Coord. **Guillaume Fromentin** (guillaume.fromentin@ensam.eu, ENSAM Cluny)

Pedagical team :

- Gérard POULACHON, Professeur des Universités, Arts et Métiers, Cluny, gerard.poulachon@ensam.eu
- Frédéric ROSSI, Maître de Conférences, ENSAM, Cluny, frederic.rossi@ensam.eu
- José OUTEIRO, Maître de Conférences HDR, ENSAM, Cluny, jose.outeiro@ensam.eu

Procedure and organisation:

Course 1 – Cutting, High Speed machining and Analytical Models: orthogonal cutting principles, description of tool geometry, description of the cutting zone, Albrecht's & Merchant's theories, analytical modeling of cutting forces.

Course 2 – Thermal aspects of cutting: instrumentation and modeling.

Course 3 – Machinability of difficult-to-cut materials & Interaction material-process: Physical phenomena around the cutting edge, built-up edge, tribological aspects during metal cutting.

Course 4 – Numerical modeling and simulation of subtractive machining: introduction; fundamental aspects of numerical simulation; constitutive laws, friction and contact laws; simulation of chip morphology (separation of material); boundaries conditions; validation; FEM software dedicated for cutting simulation, case study.

Course 5 – Surface Integrity (SI): Introduction and definitions; surface defaults; residual stresses; microstructure and phase transformations; experimental techniques to evaluate the surface integrity; modeling and simulation of SI.

Pedagogical objectives:

The objective is to analyze the thermomechanical phenomena in the vicinity of the tool tip and its consequences on the integrity of the machined surface. These phenomena will be observed at mesoscopic and microscopic scales, based on experiments and numerical simulations of the cutting operation.

Content:

- Fundamentals notions and theory of cutting by material removing.
- Machinability of difficult-to-cut materials, such as those encountered in the aeronautical, automotive and nuclear sectors.
- Determination of the validity fields of the cutting parameters for a given tool and material.
- Qualification of new generation cutting tools and validation of new metallurgies of work materials.
- Implementation of numerical simulation and experimental means dedicated for understanding the thermomechanical phenomena of cutting.
- Analysis of the surface integrity of machined parts, including evaluation of mechanical, metallurgical and topographic conditions.

Skills:

Notions of the machining process; Numerical methods ; Continuum mechanics ; Thermal theory.

Bibliography:

- Jan Eric Stahl, Metal cutting -Theory and models, Printed by Elanders, 2012.
- M.A. Davies, T. Ueda, R. M'Saoubi, B. Mullany, A.L. Cooke, On The Measurement of Temperature in Material Removal Processes, CIRP Annals, Volume 56, Issue 2, 2007, Pages 581-604.
- I.S. Jawahir, E. Brinksmeier, R. M'Saoubi, D.K. Aspinwall, J.C. Outeiro, D. Meyer, D. Umbrello, A.D. Jayal, "Surface Integrity in Material Removal Processes: Recent Advances", CIRP Annals - Manufacturing Technology, keynote paper, Vol. 60/2, pp. 603-626, 2011.
- J. Outeiro "Residual Stresses in Machining", in Book "Mechanics of Materials in Modern Manufacturing Methods and Processing Technique", Edited by V. Silberschmidt, Elsevier, 2019.
- Viktor P. Astakhov, "Metal Cutting Mechanics" Edited by CRC Press, 1999. ISBN 0-8493-1895-5.
- David A. Stephenson, John S. Agapiou, "Metal cutting theory and pratice", edited by Marcel Dekker 1999. ISBN 0-8247-9579-2.
- Graham T. Smith, "Cutting Tool Technology", edited by Springer. ISBN 978-1-84800-205-0.

ADVANCED MACHINING AND ITS APPLICATIONS

Elective 4

The teaching unit is mandatory.
The teaching unit is taught in

3 ECTS

Pedagogical team

Coord. **Guillaume FROMENTIN** (gerard.poulachon@ensam.eu, ENSAM Cluny)

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DYNAMYC BEHAVIOR AND FAILURE OF MATERIALS

Optional course

The teaching unit is optional
The teaching unit is taught in English.

Team

Coord. **Bastien Durand** (bastien.durand@ens-paris-saclay.fr, ENS Paris-Saclay)

Pedagogical objectives:

The course deals with the mechanical behavior of engineering materials (metals and foams) under dynamic loading conditions. The mechanical wave propagation study is the key of this field.

Content:

The course first gives the theoritical background necessary to understand wave propagation (characteristic method in Lagrange Diagram, Rankine & Hugoniot relations). This knowledge is relevant for future engineers and researchers working on problems that involve the dynamic loading of structures and materials.

The course also gives experimental (Hopkinson bars) and numerical (ABAQUS) abilities.

Concerned fields: energy absorption in vehicles, military applications, high-speed machining...

Prerequisites:

MAGIS core courses

References:

Kolsky, H., 1963, Stress Waves in Solids, Clarendon Press, Oxford.

Meyers, M.A., 1994, Dynamic behavior of materials, John Wiley & Son Inc.

Zhao, H., 2004, Cellular materials under impact loading, Amas-edition, Warsaw.

Procedure and organization:

ELASTIC WAVES:

- Simple tensile and compressive waves;
- Hydrostatic and deviatory waves in a 3D medium;
- Confined tensile and compressive waves;
- Torsion waves;
- Bending waves;
- Tensile and compressive waves in plates;
- Theoretical study of the compression Hopkinson bar technique;
- Wave dispersion in a bar due to lateral inertia.

ELASTIC PLASTIC WAVES:

- Piece by piece linearity;
- Lagrange diagrams.

RANKINE & HUGONIOT EQUATIONS AND COMMON EQUATIONS OF STATE:

- Conservation equations;

- Application to elasticity;
- Waves in polytropic gases and in highly compressed solid materials (shock front theory, Rayleigh line);
- Application to non-compressive fluid mechanics (Bernoulli relation);
- Foam dynamic behavior.

VISCO-ELASTIC WAVES

EXPERIMENTAL WORK:

- Dynamic shear test on a glue joint using tensile Hopkinson bars;
- Strain gauge measurement processing to determine forces and velocities;
- Digital Image Correlation to determine local displacements.

NUMERICAL WORK:

- Use of a finite element software (ABAQUS-CAE);
- Numerical study of elastic-plastic waves in solid materials and in foams;
- Numerical study of wave dispersion.

ALGORITHMIC MODELLING OF PHYSICAL PROCESSES

Optional

The teaching unit is optional
The teaching unit is taught in French.

It can be easily followed by English speaking students

Coord. **Olivier Hubert** (olivier.hubert@ens-paris-saclay.fr, ENS Paris-Saclay)

Pedagogic team :

- Hubert, Olivier, Professeur des universités, CNU60, ENS Paris-Saclay (olivier.hubert@ens-paris-saclay.fr)
- Lorong Philippe, Professeur des universités, CNU60, ENSAM (philippe.lorong@ensam.eu)
- Ranc, Nicolas, Professeur des universités, CNU60, ENSAM (nicolas.ranc@ensam.eu)
- Guilhem, Yoann, Maître de conférences, CNU 60, ENS Paris-Saclay.(Yoann.guilhem@ens-paris-saclay.fr)

Schedule and practical organisation :

- Course 1A: Typology of multiphysics couplings (local, global, strong, weak), unified formulation of balance equations and constitutive laws (mass conservation, momentum, energy); Chemical diffusion, heat, phase change
- Course 1B: Elliptical, parabolic and hyperbolic problems (algorithms, convergence and stability).
- Course 2A: Solving multiphysic problems using finite differences, explicit, implicit scheme, theta-scheme
- Course 2B: Thermo-mechanics of plasticity: static, fatigue, measurement, simulation.
- Course 3A: Change of scale for the simulation of free deformations: Shape memory alloys, magneto-mechanics, electro-mechanics.
- 3B project session: Presentation / choice of projects
- Project session 4: Validation of numerical project objectives, validation of formulations
- Sessions 5-10: Numerical projects.

Pedagogical objectives

Content:

The final objective is to propose a typology of multi-physical problems encountered in mechanics of materials, to present the methods and algorithms which make it possible to build an associated numerical model, and to implement these concepts through a numerical project (strong coupling with spatial-temporal evolution of the modelled physical fields).

Skills:

1 / Acquire the knowledge allowing to choose, identify and possibly develop, the most suitable model to describe one or more multiphysic couplings;

2 / Acquire the knowledge allowing to choose, identify and possibly develop, the numerical method most suited to the resolution of the targeted problem;

Complementary skills :

- matlab language, python
- writing of a scientific article
- oral presentation of work.

Prerequisite:

Continuum mechanics, elasticity, thermics, programming elements.

Bibliography:

- Mécanique des matériaux solides, J. Lemaitre et J.L. Chaboche,A. Benallal, R. Desmorat, Dunod, 3e Ed. 2009.
- Mechanics of solid materials, J. Lemaitre et J.L. Chaboche, Cambridge Univ. Press, 1994.
- Mécanique non-linéaire des matériaux, J. Besson, G. Cailletaud, J.L. Chaboche, S. Forest, Hermès, 2001.
- Modélisation numérique en sciences et génie des matériaux, Traité des matériaux (Tome 10), M. Rappaz, M. Bellet, M. Deville, Presses Polytechniques et Universitaires Romandes, Lausanne.

ECO-MATERIALS

Optional

The teaching unit is optional
The teaching unit is taught in 🇬🇧

3 ECTS

Coord. **Martin Poncelet** (martin.poncelet@ens-paris-saclay.fr, ENS Paris-Saclay)

Pedagogic team :

- Carole CHARBUILLET, Ensam Chambery (Carole.CHARBUILLET@ensam.eu)
- Imade KOUTIRI,Ensam Paris (Imade.KOUTIRI@ensam.eu)
- Bertrand LARATTE , Ensam Bordeaux (Bertrand.LARATTE@ensam.eu)
- Cyrille SOLLOGOUB, Ensam Paris (Cyrille.SOLLOGOUB@ensam.eu)
- Martin PONCELET, ENS Paris-Saclay (martin.poncelet@ens-paris-saclay.fr)
- Anne-Francoise Gourgue, Mine-ParisTech (anne-francoise.gourgues@mines-paristech.fr)
- Mateusz BOGDAN (mateusz.bogdan@arep.fr)

Keywords : Resource limitation, environmental impact, recycling, sustainability, optimization, additive manufacturing.

This course focuses on the environmental impact of the use of materials, and ways to reduce it.

The course begins by addressing the issue of constraints in the choice of materials. Beyond the simple economic cost, there are the restriction of resources (geological limitations, politics), legal frameworks (national, international) and the setting up of recycling channels (both constraint and partial solution of the limitation problem). More generally than the environmental impact of a material, the question of estimating the impact of an entire product (thus including its materials, but also its manufacturing processes and, in general, its entire life cycle) arises. What methods exist to quantify this impact?

A description of the technical, ecological and geostrategic issues, as well as recycling and reuse solutions for two main families of materials is then proposed. These are, on the one hand, the family of metals, from heavy production (steel, aluminium) to precious metals and rare earths, and, on the other hand, the family of polymers, natural, derived from hydrocarbons or biosourced.

Finally, the current avenues aimed at reducing the use of materials will be presented: functionalization (a material fulfils several functions), topological optimization (less material used for the same performance), additive manufacturing techniques (allowing a reduction in the quantity of material used during production). A critical look at the entire additive manufacturing process will be proposed, including the development of consumables and the post-treatment of parts.

The track MAGIS is in partnership with ENSAM Paris and Université Paris Saclay. The courses take place either at ENSAM Paris (151 boulevard de l'Hôpital – 75013 Paris) and at Université Paris Saclay (ENS Paris-Saclay, CentraleSupelec)

Contacts

Mention Materials Science and Engineering :

Lola Lilensten & Vincent Guipont, heads (contact.master-sgm@psl.eu)

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Track Magis : Thilo Morgeneyer (thilo morgeneyer@mines-paristech.fr)

- Elective 1 (E1) : Damage and fracture of materials and structures
  Thilo Morgeneyer (thilo morgeneyer@mines-paristech.fr) – MINES ParisTech

- Elective 2 (E2) : Metal processing and additive manufacturing
  Morgan Dal (morgan.dal@ensam.eu) – ENSAM Paris

- Elective 3 (E3) : Life cycle of polymers and composite materials
  Bruno Fayolle (fayolle.bruno@ensam.eu) – ENSAM Paris

- Elective 4 (E4) : Machining and simulation
  José Outeiro (jose.outeiro@ensam.eu) – ENSAM Cluny

Welcome Desk PSL : welcomedesk@psl.eu / 01 75 00 02 91

The Welcome Desk helps internaitonal students for administrative procedures and boosts up their everyday life.

A bilingual team organizes different activities throughout the year. Touristic joggings, cultural visits...there is something for everyone! At these events international students meet other students, both internationals and Parisians who are part of the PSL network, improve their French and discover the different parts of Paris.

For more information, Facebook page: Welcome to Paris and to PSL!