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# PhD Yearbook | 2021

# DOCTORAL PROGRAM IN MECHANICAL ENGINEERING

Chair:
Prof. Daniele Rocchi

The PhD Programme in Mechanical Engineering of Politecnico di Milano offers top-level knowledge in one of the most profitable sectors in Italy and Worldwide; it is a key instrument to access leading enterprises and to achieve prominent positions in large international companies devoted to research and development, innovation and design. The primary employment market is composed of leading companies and organizations dedicated to innovation, research and technical development, high-tech SMEs and governmental departments. Our Programme currently ranks 15$^{th}$ in the world according to QS World University Rankings (Mechanical, Aeronautical & Manufacturing Engineering 2021).

As for career perspectives, a recent survey (run by Politecnico in 2020) showed that our PhD Candidates are 97% employed after one year, in national and international companies and academic and non-academic research institutions, engaged in innovation, research and technical development. On average, the survey showed that people earning our PhD title are paid 35% more than the corresponding employees with a master title.

Within our Programme all Doctoral Candidates follow a minimum path of three-years, which includes specific courses and lectures, held by Faculty members and foreign professors and experts: in particular, our candidates have access to a series of research seminars delivered monthly by international top-level faculty (Mecc PhD Lectures) and to full courses provided by European and non-European academic experts leading to the obtainment of ECTS. They also experience in-depth research, lab activities and active cooperation with international industries, institutions and research groups. With this background, our Doctorates are able to blend the exactness of scientific knowledge with the ability to deal with management and industrial issues. In this view, their scientific profiles are suitable for prestigious positions at national and international level within universities and research institutions, large industrial and consulting companies, SMEs.
In the following pages 11 abstracts belonging to PhDs of the 30$^{th}$(1), 31$^{st}$ (1), 32$^{nd}$ (3) and 33$^{rd}$ (6) doctoral cycles (defended in 2020 and 2021) are proposed. They represent a good overview of the international vocation of our PhD Programme, with a third of them having being developed by international fellows. Female presence accounts for almost 25%.
Nearly 100% of the PhDs were supported by fellowships provided by the Italian Government, Industries, and European and National projects.

**RESEARCH AREAS**

The PhD Programme in Mechanical Engineering covers a number of different disciplines, being devoted, in particular, to innovation and experimental activities in six major research areas. All doctoral thesis displayed in the following pages belong to one of these areas:
***Dynamics and vibration of mechanical systems and vehicles****:* this research line is organized into five research areas, namely Mechatronics and Robotics, Rotodynamic, Wind Engineering, Road Vehicle Dynamics, Railway Dynamics. It features modelling of linear and non-linear dynamic systems, stability and self-excited vibrations, active control of mechanical systems, condition monitoring and diagnostics.
***Measurements and experimental techniques:*** the Mechanical and Thermal Measurements (MTM) group has its common background in the development and qualification of new measurements techniques, as well as in the customisation and application of well-known measurement principles in innovative fields. MTM major research focus is oriented towards the design, development and metrological characterisation of measurement systems and procedures, the implementation of innovative techniques in sound/vibrations, structural health monitoring, vision, space and rehabilitation measurements.
***Machine and vehicle design:*** this research area is involved in advanced design methods and fitness for purpose of mechanical components. Advanced design methods refer to the definition of multiaxial low and high cycle fatigue life prediction criteria, and the assessment of structural integrity of cracked elements, the prediction of fatigue life criteria of advanced materials as polymer matrix composite materials (short and long fibres), the definition of approaches to predict the influence of shot peening on fatigue strength of mechanical components. Gears, pressure vessels and helicopter components are dealt with. Optimal design and testing of vehicle systems create a synergism between the theoretical and the experimental researches on ground vehicles.
***Manufacturing and production systems:*** this research field gives relevance to the problem of optimal transformation of raw materials into final products, addressing all issues related with the introduction, usage, and evolution of technologies and production systems during the entire product life-cycle. PhD activities, in particular, are developed within the following research fields: Manufacturing Processes (MPR), Manufacturing Systems and Quality (MSQ).
***Materials*:** this area is focused on the study of production process and characterization of materials, for structural and functional applications. Excellent research products were obtained both on fundamental research topics (e.g. nanostructured materials, foamed alloys, chemical phenomena in liquid melts, microstructural design etc.) and on applied research (e.g. failure and damage analysis, texture analysis, high temperature behaviour, coatings for advanced applications, etc.). The research projects carried out in recent years addressed specifically the following research topics: Steelmaking and Metallurgical Processes, Advanced Materials and Applied Metallurgy.
***Methods and tools for product design*:** two main research topics are addressed in this field: PLM-Product Lifecycle Management, which includes process modelling, engineering knowledge management, product innovation methods, systematic innovation principles and methods, topology optimization systems,

and data/process interoperability, and Virtual Prototyping, which includes virtual prototyping for functional and ergonomics product validation, haptic interfaces and interaction, reverse engineering and physics-based modelling and simulation, emotional engineering.

**LABORATORIES**

One of the key elements of our Doctoral Programme is represented by our laboratories; we feature some of the most unique, active and innovative set-ups in Europe: Cable Dynamics, Characterization of Materials, DBA (Dynamic Bench for Railway Axles), Dynamic Testing, Dynamic Vehicle, Gear and Power Transmission, Geometrical Metrology, High-Temperature Behaviour of Materials, La.S.T., Manufacturing System, Material Testing, Mechatronics, MI_crolab Micro Machining, Microstructural Investigations and Failure Analysis, Outdoor Testing, Physico-Chemical Bulk and Surface Analyses, Power Electronics and Electrical Drives, Process Metallurgy, Reverse Engineering, Robotics, SIP (Structural Integrity and Prognostics), SITEC Laser, Test rig for the Evaluation of Contact Strip Performances, VAL (Vibroacoustics Lab), VB (Vision Bricks Lab), Virtual Prototyping, Water Jet, Wind Tunnel.

**INTERNATIONALIZATION**

We foster internationalization by strongly recommending and supporting candidates' mobility abroad, for short-term study and research periods up to 18 months. Our Institution is member of Idea League (www.idealeague.org) ,Alliance4Tech (www.alliance4tech.eu) and ENHANCE (https://enhanceuniversity.eu/), three strategic partnerships with leading European Technical Universities.
We also promote, draft and activate European and extra-European Joint Degrees, Double PhDs and Joint Doctoral Thesis (Cotutelle); our Department is actively involved in EU-based and governmental third-level education agreements such as H2020, Erasmus Mundus and China Scholarship.
We have ongoing agreements with MIT (Progetto Rocca), Shanghai Jiao Tong University (Double PhD), École Centrale de Paris (Cotutelle), Delft University of Technology (Double PhD and Cotutelle), TUM (Cotutelle), ETH Zurich (Cotutelle), RWTH Aachen (Double PhD), Laval University (Double PhD), Qatar University (Double PhD), Northwestern Polytechnical University (Double PhD), Universiteit Antwerpen (double PhD) and Peter the Great St Petersburg Polytecnical University (Double PhD).
We also have ongoing collaborations within a wider international network, that includes some of the highest-level and best-known universities all over the world, such as the University of California at Berkeley (US), Imperial College London (UK), Tsinghua University (CN), University of Michigan (US), École Polytechnique Fédérale de Lausanne (CH), Norwegian University of Science and Technology (NTNU), University of Southampton (UK), Technical University of Denmark (DK), Pennsylvania State University (US), Chalmers University of Technology (SE), Virginia Tech (US), Technische Universität Berlin (DE), Warsaw University of Technology (PL), The University of Sheffield (UK), Politècnica de València (ES), Xi'an Jiao Tong University (CN), Tongji University (CN).

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# POWDER DEVELOPMENT OF LEAD-FREE PIEZOCERAMICS MATERIAL FOR ADDITIVE MANUFACTURING TECHNOLOGY

**Ruben Beltrami** - Supervisor: Nora Francesca Maria Lecis

In the last decades, 3D printing additive manufacturing has attracted the attention of the scientific and engineering community. In fact, these new technologies have emerged as one of the most interesting technologies for designing and production of innovative materials. Additive manufacturing 3D printing of different types of materials (from metals and plastics to ceramic) has allowed a versatility in design and realization never seen before. Today, 3D printing is one of the most promising technology able to change production paradigms and transform the manufacturing industry. The production process starts from a 3D model CAD design file with the consequent conversion to STL format (stereolitography), which consists in the object slicing into virtual layers printable in 2D, with different techniques, by the 3D printers. Binder Jetting 3D printing is one of the emerging additive manufacturing technologies, in which the object is printed with the aid of a chemical binder and then heat-treated for densification (figure 1). With respect to ceramic materials and more precisely piezoelectrics, additive manufacturing technology offers new possibilities of part designing and thus innovative applications. For instance, just think on the next internet of things (IoT) industrial revolution and the new needs and challenges that we will have to face from the manufacturing point of view.

Piezoelectric materials are the basis for a large number of devices including sensors (pressure, force and vibration), accelerometers, actuators and transducers but only few of them are used in applications as piezoelectric devices. Nowadays, the most important piezoelectric material applied in the practice is Lead Zirconate Titanate (PZT). In fact, this ferroelectric ceramic material guarantees excellent performances thanks to its high piezoelectric properties and high Curie temperature. Nevertheless, Pb represents a serious hazard for human health leading scientific community to develop alternative lead-free piezoelectric materials. Among the others, Potassium-Sodium Niobate (KNN) system is one of the most promising, due to its high piezoelectric constant and high Curie temperature although its piezoelectric properties are not still comparable with those of PZT. The aim of the PhD project was to study the 3D printing feasibility of lead-free piezo-electric ceramic powder using binder jetting technology. This challenging target was achieved through a dual pathway: lead-free piezoelectric powder synthesis and study of the most important parameters in binder jetting 3D technology. First, $K_{0.5}Na_{0.5}NbO_3$ (KNN) was synthetized by solid-state reaction through mechano-chemical activation and sol-gel method. Second, stainless steel (316L) and alumina ($Al_2O_3$) were used as powder testing materials for studying binder jetting 3D printer technology and its fundamental parameters. Finally, a KNN sample was 3D printed, poled and tested obtaining a working piezoelectric disc proving the usability of binder jetting technology even for advanced ceramics (figure 2).

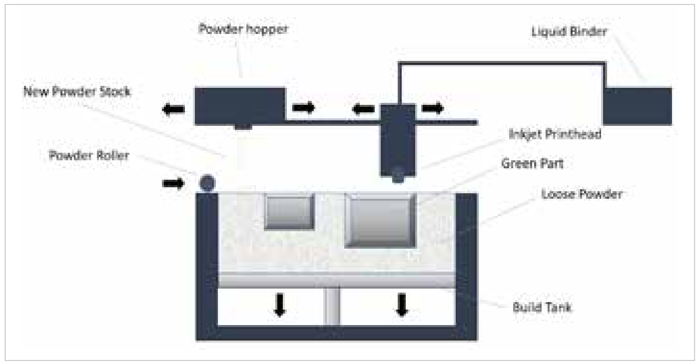


Fig. 1 - Binder jetting 3D printing process..







Potassium sodium niobates (KNN) was successively 3D printed with binder jetting technology for the first time thanks to the optimized powder synthesized by mechano-chemical and sol-gel method. In particular, in order to increase the sinterability and the piezo characteristics, KNN mechano-chemical powder and sol-gel powder were mixed in different ratio (0 to 20 % wt. of sol-gel). Sol-gel powder with its higher reactivity works as liquid-phase during sintering making easier densification and improving piezoelectricity. This is a remarkable result because it demonstrates the possibility to use a low melting phase identical to the main material improving both the density and the piezoelectricity. Despite the non-use of pressure techniques to densify the material, KNN discs obtain by only printing and sintering have shown a good relative density (75%) and piezoelectric activity (d33 ~ 73 pC/N).

In conclusion, several improvements are still required for wide industrial application, such as improvement of the powder geometry (e.g. spherical powders), optimization and standardization of powder synthesis with enhanced piezoelectric features and adoption of alternative heat treatments (spark plasma sintering or hot isostatic pressing) to obtain reliable and reproducible products.

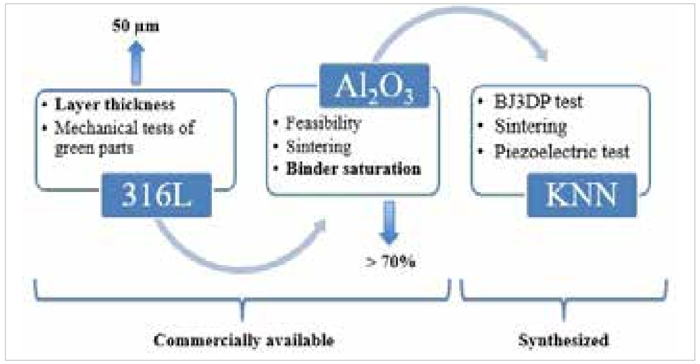


Fig. 2 - Experimental steps for KNN binder jetting 3D printing.

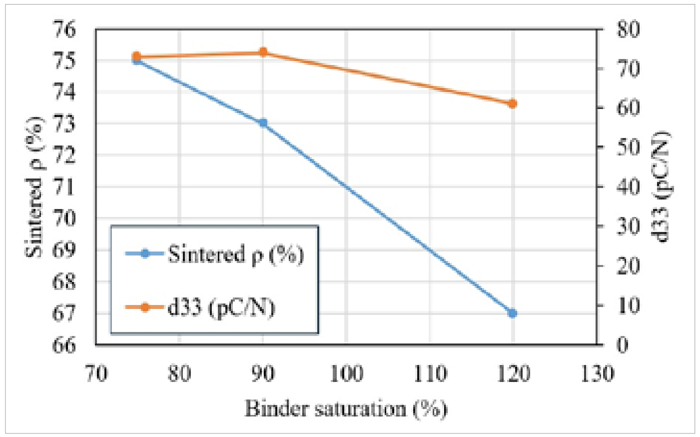


Fig. 3 - $d_{33}$ (pC/V) and sintered density (%) of KNN binder jetted samples at different binder saturation.

# FORMULATION AND TESTING OF A BIOLOGICALLY-INSPIRED DESIGN METHOD TAILORED FOR INDUSTRIAL APPLICATIONS

**Alessandro Bianciardi** - Supervisor: Gaetano Cascini

**Introduction**

Over the last decade and a half increasing attention of the scientific community has been given to biologically-inspired design (BID), the process of selecting and emulating natural forms, processes and systems to generate innovative design. The potential for bio-inspired innovation is however still largely untapped. In particular, BID methods and tools are not yet largely utilized within the industry, a sector with high potential for turning bio-inspired ideas into marketable innovation.

The use of BID methods imply costs for populating biological knowledge repositories, so as to increase the space for bio-inspired solutions, as well as costs for processing this knowledge to be utilized in analogical transfer and ideas generation.

How should a BID method and tool looks like to be of more interest of and exploitable by the industry?

**Objectives**

The objectives of the research were:

1) To develop a framework of innovation model which would enhance the synergy between BID and the innovation process so as to increase the effectiveness of BID as tool for innovation;
2) To identify the type and amount of biological information which should be considered in a BID tool and how to structure it so as to increase its effectiveness and be more suitable for the industry.

**Methodology**

In order to answer the question, two main methodological approaches were followed:

1) An exploration of natural evolutionary process and, by analogy, extraction of design principles to formulate innovation models more aligned with natural principles, where the ideation process is a continuous multi-stakeholders participative process;
2) A review of literature on BID to identify key factors affecting BID effectiveness and based on these, extract possible solving strategies which led to the formulation of BID methods' Design Principles.

**Results**

Based on the principles identified above, the following outputs were conceived:

1) The *Evolutionary Innovation Model* (EIM) which is a conceptual Open Innovation/Coopetitive innovation model;
2) The *Guild-based BID method* (GB-BID), which consists in a method to set up databases of biological solutions to generate bio-inspired ideas of interest for industrial applications.

The GB-BID method, differently from already existing BID methods, is:

Sectoral: conceived to be customized for specific industrial sectors;

Open: conceived to promote Open Innovation/Coopetitive models;

Problem-based: biological information are processed to be meaningful and useful for specific target groups (sectors) with specific problems;

Multi-level: able to generate solutions of different levels of abstraction of the problem;

Inclusive: biological information is stored in formats, which can allow participation of non-technicians to the ideation process.

To test and validate the method, a GB-BID Database has been designed for the Separation Technology sector. It is populated with more than a hundred relevant biological solutions responding to the function "to separate". The database was tested via a series of ideation workshops with different target groups (mixed background, engineering students and separation technology experts) and the development of case studies. The workshops highlighted the potentiality of the GB-BID database to generate bio-inspired ideas for complex problems by expert and non-expert users. Among the case studies produced, to be mention:

1) A modular solar desalination system to produce water to regenerate degraded land was designed emulating how the Mangrove Ecosystem develops and grow (Fig1). A system of 10 desalination units to irrigate organic incubators for degraded soil was successfully pilot tested in Cyprus. The unit produces 2-3.5 L/d/m$^2$ of water depending on weather conditions. Its efficiency is comparable with currently existing solar stills units available in the market but its cost is estimated to be 50% lower.
2) 2 An anti-bacterial micro surface morphology, emulating shark's dermal denticles and fish epithelial cells, was designed. The morphology was reproduced on metallic mold via micro electrical discharge machining and imprinted on polymeric material (Fig2). The surface, tested in an accredited laboratory with different species of bacteria, shows between 15 to 30 days delay in bacterial colonization.

**Conclusions:**

The results achieved so far by this research give indication that a BID method/tool with the attributes of the GB-BID method can indeed be beneficial to industrial practitioners for industrial applications. Attributes which are not explicitly present in other BID methods/tools.

In particular, it has been demonstrated that the GB-BID method allows:

- Generating bio-inspired ideas in ideation workshops of knowledge-based as well as mixed target groups;
- Extracting design principles to evaluate existing technology vis-à-vis natural principles and steer sectoral research toward innovative bio-inspired solutions;
- Producing various and novel design concepts for solving sectoral problems.

Fig. 1 - Modular desalination system inspired by Mangrove Ecosystem

Fig. 2 - The anti-bacterial pattern (right) inspired by fish epithelial cells (left)

# ON THE DEVELOPMENT OF A UNIFIED FRAMEWORK FOR LOAD AND STRUCTURAL HEALTH MONITORING

**Luca Colombo** - Supervisor: Marco Giglio

Co-supervisor: Claudio Sbarufatti

Structural safety is a critical aspect in many engineering fields and applications, from large civil infrastructures to mechanical and aeronautical components. In the last years, many efforts have been put by scientific and industrial communities to develop a new framework for assessing structural integrity, generally known as Structural Health Monitoring (SHM). SHM should allow real-time, automatic evaluations of the structures' health state based on a network of permanently installed sensors, leading to considerable operative cost reductions and improved safety margins. However, several complications limit SHM systems and anomaly identification techniques implementations in the industry, and the variability of operational and environmental conditions is one of the most challenging. Furthermore, the structure's mechanical behavior and the feature extraction from the recorded signals are markedly affected by the operational variability, potentially producing health misclassification. Consequently, the variability of signal features might hamper the SHM system's ability to detect damage, potentially producing false alarms.

This thesis addresses load variability in anomaly identification by exploiting load monitoring algorithms to reconstruct changes in the operational condition or to produce the desired output (e.g., strain field) automatically adapting to load variations. The aim is to define a unified framework to reconstruct the real external load spectra or the internal strain field in a structure and provide information about its actual health state. Load monitoring extension to anomaly identification considers that the algorithm, leveraging on a vector of input strain measures, always reconstructs a strain field compatible with the healthy structure geometry. If a geometrical modification not included in the model occurs, e.g., damage, it induces non-compatibility between measured and reconstructed strains in a test position near the damage. Two load monitoring algorithms are considered for testing the method numerically and experimentally, i.e., the inverse Finite Element Method (iFEM) and the Calibration Matrix Approach, modifying and enhancing the algorithms state of the art.

The iFEM reconstructs the displacement and strain fields of a structure based on discrete strain measures without prior knowledge of the material and loads. An anomaly index is defined as the percentage difference between an equivalent strain read at a test sensor position and the corresponding iFEM reconstruction in the same position. The latter allows establishing a load-adaptive baseline based on the anomaly index, highlighting the actual health state independently from the applied load and without training requirements. The damage position can also be inferred considering multiple test positions. A plate subjected to multiple loads and cracks is considered for numerical verification.

Even though the iFEM formulation is general for any arbitrary geometry and constraints, the definition of the correct boundary conditions is not trivial for structures subjected to non-ideal constraints. Thus, the linear boundary superimposition of the effects is proposed to weight the contribution of different basic models approaching the real structure's behavior. Experimental verification is performed with a composite reinforced plate subjected to impact damage and compressive fatigue test, verifying the shape sensing reconstruction with non-ideal boundary conditions and multiaxial loading. Damage detection and localization of delaminations are also verified through a Mahalanobis distance, highlighting discrepancies with respect to the load-independent baseline.

As logistic constraints impede strain sensor installation in all the desired locations, Smoothing Element Analysis (SEA) and polynomial fittings are investigated for pre-extrapolating the structure strain field. After a sensitivity analysis on the input strain pre-extrapolation, the iFEM displacement reconstruction is validated with three lasers' independent measurements of a composite plate subjected to a compressive buckling condition.

The Calibration Matrix approach, on the other hand, estimates a set of loads from discrete strain measures through a "calibration" or "influence" matrix, and it is extended for inverse-direct estimation of the full strain-field, automatically compensating temperature variations. An "observability" metric is defined, allowing one to verify load and temperature estimations capability with different sensors grid before physical testing. The method is validated numerically and experimentally with a UAV experiencing different aerodynamic pressure fields. Experimental validation is performed in the laboratory on-ground and with real flight tests under varying flight maneuvers and environmental conditions. Damage development in the wing-winglet interface is also highlighted with a divergent trend between measured and reconstructed strains.

Finally, since SHM systems rely on distributed sensing, sensor network optimization is crucial for maximizing detection capability at a reduced cost. Multi-objective optimization is regarded to consider cost minimization and classification performance maximization when designing a sensor network for SHM. An optimal statistical detector is developed, and the detection capability is derived accordingly. The relative importance of a minimum cost strategy compared to maximum classification performances is analyzed in detail, providing insights into the consequences, in terms of costs and probability of detections, of choosing one strategy over the other. The method is numerically verified on a simple case study composed of a damaged plate under tension.

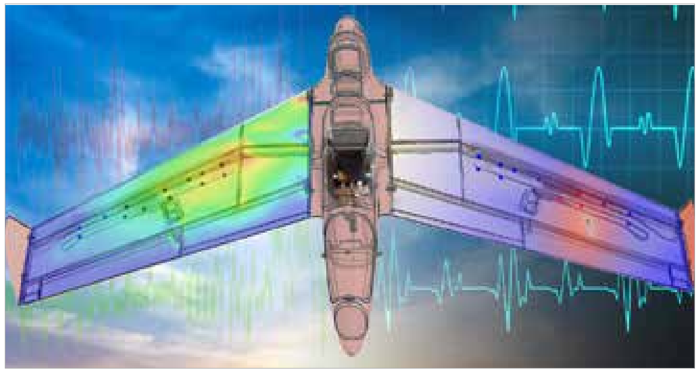

Fig. 1 - Example of load and damage identifications

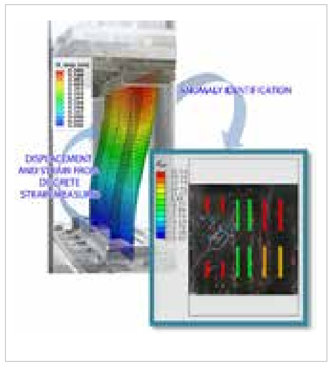

Fig. 2 - Example of shape sensing and anomaly identification with the iFEM.

# INVESTIGATION OF HYBRID EFFECTS OF CNT AND NANOCLAY IN TAILORING MECHANICAL AND ELECTROMECHANICAL PROPERTIES OF EPOXY BASED NANOCOMPOSITES

**Ali Esmaeili** - Supervisor: Claudio Sbarufatti

Many studies have been reported in the literature on multifunctional properties of epoxy based nanocomposites reinforced with carbon nanotubes (CNTs), indicating the mechanical and piezoresistive performance of the material are strictly dependent on the microstructure resulting after manufacturing. More recently, fewer attempts have been reported of production of ternary state nanocomposites where addition of nanoclay (NC) is suggested as a means to increase mechanical properties. However, a combined investigation of mechanical and piezoresistive behavior of ternary state nanocomposites remained unaddressed. Therefore, the synergetic effects of single walled carbon nanotubes (SWCNTs) and double- walled carbon nanotubes (DWCNTs) and montmorillonite (Shelsite 30B) platelets on the mechanical and piezoresistive performances of the epoxy are addressed in this study. The project was divided into two main phases. In the first phase, different CNTs morphologies (SWCNTs and DWCNTs) and weight concentrations (0.25-0.75 wt.%) were used. This was important to find out the appropriate CNTs loading along with identifying the optimum manufacturing procedure for phase 2, thus, methodological approaches used in phase 2 were optimized based on the outcomes in phase 1. For the second phase, CNTs content was kept constant while two different nanoclay loadings were used for the ternary states. In fact, the nanocomposites were prepared in two different states, i.e. the binary state, including 0.1 wt.% CNTs, and the ternary states, including 0.1 wt.% CNT and two levels of NC (0.5 wt.% and 1 wt.%). SEM, FESEM, and XRD were used for the microstructural analysis of the materials while tensile and mode I fracture tests were performed for mechanical and piezoresistive characterizations. In overall, by taking into consideration of multifunctional properties including tensile strength, fracture toughness, electrical conductivity and sensitivity, it was stated out that the ternary nanocomposites developed in phase 2 demonstrated better performance compared to the ones produced in phase 1. In fact, low tensile strength along with high variations observed in phase1, raised questions for the effective exploitation of CNTs in multifunctional properties enhancement. On the other hand, highly monotonous outcomes especially for tensile strength without sacrificing other properties indicated the effective exploitation of nanofillers in tailoring material performances in phase 2. The addition of nanoclay to CNTs doped epoxy resulted in better CNTs dispersion, hindering CNTs re-agglomeration. Significant increase in critical stress intensity factor ($K_{IC}$) and critical strain energy release rate ($G_{IC}$) compared to the neat epoxy was obtained for the hybrid nanocomposites developed in phase 2 due to crack bridging and crack deflection mechanisms. Because of the improved CNTs dispersion, the electrical conductivity of the ternary state materials increased substantially with respect to the binary nanocomposite. The hybrid nanocomposites also manifested higher piezoresistive sensitivity and a more robust signal in tensile and fracture tests, respectively.

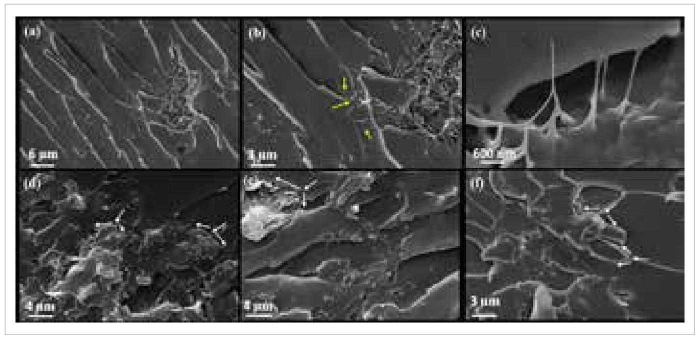


Fig. 1 - Toughening mechanism: (a-c) crack deflection and crack bridging for DWCNT doped epoxy, (d-f) crack deflection for DWCNT/nanoclay doped epoxy. Crack propagation took place from right to left in all panels.

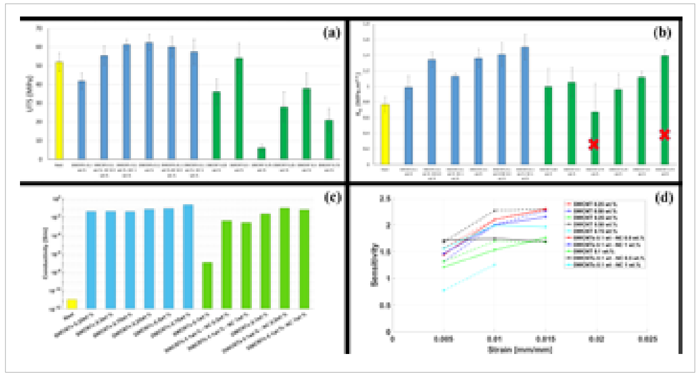


Fig. 2 - Combined global results in phase 1 and 2: (a) tensile strength, (b) $K_{IC}$, (c) Impact strength, (d-e) electrical conductivity, (f) sensitivity

# DESIGN AND CONSTRUCTION OF A HIGH ACCURACY FIELD MAPPER FOR LONGITUDINAL GRADIENT BENDING MAGNETS

**Paola La Marca** - Supervisor: Marco Tarabini

Synchrotron light sources are large accelerator facilities able to produce high-brilliance X-rays. This emission is obtained bringing changed particles (electrons or positrons) to energies of the order of GeV and imposing them a quick change of their trajectory direction. Generally, particles run in a storage ring and their trajectory is steered in the circular segments using bending magnets, which trigger the synchrotron light emission. The photon beam is supplied to scientists by means of output beam-lines tangential to the main ring, where experimental stations are built for different application fields, such as fundamental physics, material characterization, classification of chemical compounds, biologic and pharmaceutical applications, such as proteins sampling or micro-organisms investigation. The quality of the generated particle and photon beams is directly related to the quality of the generated magnetic fields. For this reason, magnet technology and design techniques are driven by the requirements of beam optics, which are reduction of the beam spot to increase the brilliance, but keeping emission spectra as wide as possible from infra-red to hard X-rays. With the introduction of Multi-Bend-Achromat (MBA) lattices, the presence of several small bending sections allows a reduction of the beam emittance. In order to keep the beam energy required to emit photons in the hard X-rays region, high fields in small magnets are required. This can be achieved with longitudinal gradient bending magnets, called superbends, that generate field profiles with a gradient along the particles trajectory with a peak in the middle of the beam path. While conventional dipoles generate homogeneous vertical fields, in superbending magnets, or, more in general, in longitudinal gradient magnets, field shape is more complex and field quality requirements are strict. To assess then the outcome of the design process, it is required to measure in operating conditions the magnetic field along the beam path, with particular interest on the following properties: field components profile, thus the magnetic induction vector in the three Cartesian directions, peak location with respect to the mechanical references of the magnet assembly, field integral along the beam trajectory, magnetic field effective length, mainly the extension of the field profile outside the magnet, both to calculate the effective cumulated field that the beam will be subjected to and to limit cross talk between two adjacent magnets. To check the performances of the generated field, magnetic measurement techniques for field mapping are present in literature, in particular Hall effect based sensors. Miniaturized high performances Hall probes offer sensitive areas limited to 100 µm, allowing point-like measurements, and normally guarantee an instrumental uncertainty of 0.1% of the field range, that for calibrated commercial sensor is 2 T. Further developments in the semi-conductor and integrated circuits technology allowed the realization of 3D Hall sensors which can be used to simultaneously measure all three components of the induction vector. These sensors are inserted in the magnet aperture to measure one or more field components in specified locations, thus it is required the use of a mechanical manipulator able to track the probe position in the magnet frame and record per each point the field vector components. Hall probe measurement benches for particle accelerators magnet are widely used in many research centers, both for the characterization of normal and superconducting magnets as well as for the inspection and tuning of undulators. In most of the cases, the positioning system is a stiff, over-dimensioned structure, with a long arm carrying the probe to the measurement location. The design of the bench is generally limited by the choice of a high-accuracy positioner in order to neglect all the mechanical error sources in the final uncertainty budget, such as positioning uncertainty due to non-perfect axis geometry, vibration, non-synchronization between position and Hall voltage reading. This approach reduces then the uncertainty budget to the sensor performances, introducing relevant design effort (mechanical but also monetary) and it lacks of a proper knowledge of the effect of these design choices on the final quantity of interest which is the bench measurement uncertainty. This thesis is focused on the development of a generalized and comprehensive measurement model which includes the mechanical structure, in order to create a coupled mechanical-magnetic model which can be used for the estimation of the uncertainty and it can guide in the selection of the instrument configuration in the design phase. The coupled model is built analytically and requires a detailed kinematic description of the manipulator in order to include all the geometrical errors of each axis and describe their impact on the end-effector positioning, and a magnetic field distribution model. In this work, the kinematic chain is analysed as a Multi-Body-System (MBS), in which n rigid bodies are connected with prismatic or cylindrical joints, defining a local frame on each body and a global frame for the complete system. This approach allows to build consecutive transformation matrices in homogeneous coordinates, named Homogeneous Transformation Matrix (HTM), including location and angular errors for each sub-system. Furthermore, the magnetic model is introduced together with the sensor one: in this work, field multipoles expansion is used for the formulation. From the coupled model, it is possible to obtain the measurement function, which relates the input influence quantities to the measurand. The measurement model is used to propagate the effect of the error sources statistical distribution to the measurement outcome, thus allowing the estimation of its probability distribution function, using Monte Carlo simulation. This method can be generalized to any kinematic type robot and magnetic field distribution and it is used to perform an uncertainty driven mechanical design. During the last three years, this technique has been developed and used for the realization of a field mapper for magnets that will be used for the upgrade of the Swiss Light Source (SLS-2) at Paul Scherrer Institut in Switzerland. The Compact Field Mapper (CFM) is a 3D Cartesian robot and it will be operated for serial measurements of normal and superconducting magnets as well as permanent ones which provide a longitudinal gradient. The main requirement on the system performances concerns an instrumental uncertainty of 10 – 50 units, with 1 unit being  of the maximum expected field value. This bench is designed estimating the target positioning uncertainty to fulfil the requirements regarding the measurement performances. The kinematic model of the open chain is built to forecast the positioning uncertainty of the robot end effector, taking into account 21 geometrical and assembly stages errors and introducing the Hall probe as mechanically defined element with sensors location and orientation tolerances related to the packaging specifications. Additionally, a numerical model of the bench is introduced to introduce flexible joints among each pair of stages and to estimate the natural frequencies and associated modes; furthermore, this model is used to investigate the efficiency of the bench foundations in environmental vibration rejection. This latter contribution is included in the kinematic model together with the additional effect of position recording delays which are due to the acquisition trigger lag. The magnetic field description is coupled to the mechanical one to provide a complete measurement model which propagates the uncertainty of the input quantities to process yield, according to the Guide of Measurement Uncertainty. The CFM construction is then performed following a rigorous assembly procedure assisted by the use of a optical Coordinate Measurement Machine to limit and characterize the stages errors. To experimentally validate the numerical model, a volumetric map scan is performed for the robot end-effector and a reference magnet is instead used to qualify the measurement chain. Both verifications lead to a validation of the developed models, characterizing the CFM positioning uncertainty of 36 µm and magnetic measurement uncertainty of 15 units, including the non-compensated systematic sources. To complete the bench characterization, different measurement techniques are compared to its results to assess the performances in first and second order integral values, integrated gradient and center location. Finally, an additional study on the temperature effects and the importance for its compensation in Hall probe measurements is presented. The presented method is proved to be efficient to assess the effect of the mechanical structure on the measurement process and to guide the design of the bench, targeting the uncertainty budget and balancing the contribution of the Hall sensor without worsening its performances and avoiding over-tolerancing of the manipulator.

# METALLURGICAL DEVELOPMENT OF HIGH-PERFORMANCE BIODEGRADABLE TWINNING-INDUCED PLASTICITY STEELS

**Sergio Loffredo** - Supervisors: Maurizio Vedani, Diego Mantovani

Atherosclerosis is one of the most common diseases in humans, consisting in formation of a fibrofatty plaque on an arterial wall, obstructing blood flow. In order to restore the normal lumen diameter, a tubular metallic mesh, known as stent, is implanted inside the diseased artery by inflation of a balloon mounted on the guiding catheter. Metallic materials are normally used to manufacture stents since they have very high strength and ductility, preventing device failure upon expansion. Moreover, such materials must not cause any harmful reaction from the body.

Stents are traditionally corrosion resistant, meaning that they will stay inside the patient for its entire lifetime. However, clinical evidence showed that an artery is capable of supporting itself after 6-8 months from stent implantation, meaning that the device is no longer needed after this timespan. For this reason, biodegradable stents were developed. Currently, both polymeric and Mg-based biodegradable stents are available on the market, but they have significantly larger dimensions with respect to their permanent counterparts, limiting implantation only to large arteries and increasing the risks of forming a blood clot (thrombosis). This limitation in size is due to the poor mechanical properties of polymers and of Mg alloys, which are significantly lower to those of the commonly used stainless steels and Co-Cr alloys.

Twinning-induced plasticity (TWIP) steels could solve this limitation in biodegradable stents, since their mechanical properties are comparable to those of Co-Cr alloys and they are sensitive to chloride corrosion. However, it was found that a stable corrosion layer forms during degradation of such steels, preventing full device dissolution from occurring.

This thesis aimed at developing a strategy for preventing stabilization of the corrosion layer without affecting the outstanding mechanical properties of TWIP steels. To do so, this project explored the addition of 0.4% wt. Ag to a Fe-16Mn-0.7C (wt. %) alloy. This amount of Ag was chosen to promote corrosion by galvanic coupling without affecting either mechanical or biological properties.

A production process for the alloys was successfully developed. In order to have a better correlation with industrial practice, the retained production process was casting from pure elements, followed by solubilization treatment and hot rolling. Atomic absorption spectroscopy analyses confirmed that casting allowed to obtain the targeted alloy composition.

After having developed the production process, the effect of Ag on the mechanical properties was assessed. The presence of Ag caused a reduction in elongation at failure from 55% to 42% without significantly affecting strength. X-ray diffraction (XRD) analyses showed that the inclusion of Ag promoted formation of ε-martensite at high levels of plastic deformation in addition to the normally found austenite. Since this phase has a hexagonal close packed (HCP) structure, which has a much lower number of slip planes available for dislocations to glide with respect to the face centered cubic (FCC) structure of austenite, this could explain at least in part why the presence of Ag caused a reduction in elongation at failure.

Furthermore, microstructural analyses by scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD) revealed that the Ag-containing alloy promoted a significantly finer grain structure with respect to the Ag-free counterpart. Being the thermo-mechanical history of the two alloys exactly the same, a hindering effect of Ag on the recrystallization kinetics was hypothesized.

This hypothesis was tested by applying several annealing treatments with varying temperatures and durations on both alloys in the cold rolled state. Vickers microhardness analyses revealed that the presence of Ag did not alter the overall recrystallization kinetics. Moreover, no effect of time nor of treatment temperatures below 600°C was detected. Analysis of the recrystallized fraction was carried out by EBSD as a function of the local lattice misorientations detected in each grain. It was observed that the presence of Ag prevented full recrystallization of the material after a treatment at 800°C for 10 minutes.

In addition, analysis of the variation in Schmid factors (SF) revealed that the presence of Ag promoted a broader distribution, with the grains showing the lowest SF values having a {111} orientation. Being this orientation the preferential one for twinning in TWIP steels, it can be deduced that dislocations would saturate more quickly in the presence of Ag, giving a further explanation for the reduction in ductility.

Aiming at developing a biodegradable metal, validating that the addition of Ag effectively improves the corrosion behavior of the studied TWIP steel is primordial. First of all, since a stent is plastically deformed upon expansion, the effect of plastic deformation was studied by performing 14-day static immersion tests in Hanks' modified salt solution (HMSS) and putting the samples in a $CO_2$-rich environment in order to better simulate the conditions encountered in a human artery. SEM analyses showed that neither the presence of Ag nor plastic deformation altered the corrosion behavior, with cuboid-like degradation products (DPs) attached to the surface of the material, forming a porous corrosion layer. XRD allowed to identify such DPs as $MnCO_3$. Finally, potentiodynamic polarization tests revealed that the presence of Ag did not alter the electrochemical characteristics of the material.

In order to assess the role of Ag on the evolution in corrosion mechanism over time, immersion tests ranging from 3 to 180 days in duration were carried out using the same conditions outlined above. It was observed that the presence of Ag did not alter the corrosion rate at all times. In the first 14 days of immersion, corrosion proceeded steadily, with a corrosion rate (CR) around 0.15 mm/year. However, after 28 days, CR decreased at 0.10 mm/year, for then attaining negligible values after 60 days. This situation remained stable after 120 and 180 days of immersion. SEM analyses showed that, after 3 days, the surface was completely active, with some voids around Ag particles, indicating that galvanic coupling effectively took place. After 7 days, the first nuclei of DPs started to appear, leading to growth of the already observed cuboids after 14 days. XRD analyses once again confirmed that such cuboids were $MnCO_3$. After 28 days, the cuboids clustered into a nearly compact layer. In addition, flake-like DPs deposited on top of them, identified by XRD as FeO·OH. After 60 days, part of this layer detached and left place to deposition of a thin layer of phosphates, very similarly to what was detected in animal studies of Fe-based biodegradable metals. Part of the older layer remained attached in a varying fashion between replicates. After 120 days, $MnCO_3$ and FeO·OH once again deposited on top of the thin phosphate layer. The situation remained unchanged after 180 days.

From the results obtained in this work, two main conclusions can be drawn. First, the addition of Ag caused a reduction in ductility due to the combined effect of second-phase particles, formation of ε-martensite during plastic deformation and preferential development of {111} grains during recrystallization annealing. It must be kept in mind that the elongation at failure remained largely superior to the minimum requirement of 25%. Secondly, the evolution in corrosion mechanism of TWIP steels in pseudo-physiological environments was well understood, explaining the limited duration of the effect of Ag and the different DPs that attach to the surface. Further works should focus on surface modifications to modify the surface/environment interface, together with biological validation of the system and development of a manufacturing process for stents made from TWIP steels.

# ADVANCED MECHANICAL DESIGN WITH METAL SNAP-FIT FEATURES

**Stefano Monti** - Supervisor: Mario Guagliano

The traditional design process of industrial products is based on the so-called Over-The-Wall approach, according to which the designer defines the component characteristics (geometry, surface finishing, assembly procedure, etc...), exclusively based on his/her own creativity. Then, the manufacturing engineer must take care of its realization. This kind of design procedure leads to a significant waste of resources, mainly due to the continuous adjustments introduced into the product design. Continuous adjustment needs to be introduced into the product design to fit the chosen manufacturing process. Other possible issues could be encountered during the assembly phase. For this reason, in last decades, a new design methodology called Concurrent Engineering was developed. Through the Concurrent Engineering Approach, people from different departments should contribute into the design of the product. The main advantage stands in the possibility of addressing issues related to design, production, assembly, use and disposal of the product since the early stage of the design process. This changing in the paradigm of the industrial design implies an important reduction of resource consumption in the consecutive phases. Some studies have demonstrated that nearly 70% of product cost is determined through the choices taken in the design stage. Based on the Concurrent Engineering design concept, several techniques called Design for X (DfX) were developed. The Design for X is a collection of different design methodologies, each of them focused on a specific aspect in the component life cycle. For example, assembly, manufacturing, or disassembly phases; other examples could be the environmental impact of the product, reliability, and so on. The Design for Assembly (DfA) methodology was introduced during the '70s. Introduction of the last century, but was seriously used later, when the increased power of computers made possible to fully exploit the concepts of DfA. One of the basic ideas behind DfA considers the identification of potential design changes evaluating the assembly time for each assembly action. This design optimization process leads to a significant reduction of the assembly cost. Contemporary, the assembly time could be used as parameter to compare the different design solutions. The assembly efficiency can be calculated in order to obtain a quantitative evaluation of the improvements and identify the most suitable design choice. There are a lot of possibilities to realize a mechanical joint of parts, among them the one preferred by DfA is the snap-fit system. Snap-fit is an integrated attachment system, in which the joining elements are extracted (or better, realized) onto the component surface. This means that the joining elements are comprised in the parts to be connected. The assembly of snap-fit systems is very fast, and since there is no need of adding external elements, the mating time (that is the engagement process during the assembly) is strongly reduced. Even the number of parts to be assembled decreases, since snap-fits do not need any external element to be introduced. The mechanics of snap-fit joints is related to the flexibility of its features, generally called Hook and Slot. More in detail, during the mating phase (that is the assembly procedure), both hook and slot are elastically deformed. When the parts to be connected reach the final mating position the Hook and Slot initial configuration is restored, realizing the joint. Traditionally, polymers are more suitable to be used to realize snap-fit features than metallic materials, for the good flexibility and formability. Metals are stiff and the traditional manufacturing processes are not able to realize complex shapes in an economic and sustainable way. However, in last decades several innovative manufacturing processes entered in the industrial practice, like laser cutting, waterjet. based on CNC systems and introducing different methods to cut the material. These processes are able to exploit a strong flexibility on the shapes that can be realized since they take advantage of beam-like tools, instead of physical tools as for the machining process. Considering the lack of snap-fit solution on materials other than plastics and the availability in the practice of very versatile manufacturing technologies, it is interesting to develop snap-fit joining systems to be applied on metallic materials, and this is the basic idea fi the present thesis. The products, on which snap-fit will be applied, can be obtained both from metal sheets and metallic tubular. The idea is to develop a series of snap-fit features that can be used on metal parts, creating a full designed solution, for which its functionality can be proved by apply the developed solution on specific case studies. Once the specific snap-fit feature design has been finalized, an experimental campaign is performed, to estimate its mechanical performance. In order to reach this goal, there are some intrinsic issue for snap-fit-to-metals relationship that in the past prevented the diffusion on snap-fit technology to be used on metals and must be solved in order to find a potential path of innovation. The encountered issues have been analyzed and solved through the contradiction analysis taken from the Theory of Inventive Problem Solving, whose Russian acronym is TRIZ, that, oppositely to what happens with polymers, brought to conceptually and physically separate the material region responsible for the engagement/disengagement phases and a different resistant region acting once the joint has been realized that has to assure joint stability and integrity. This process was composed by different steps: investigation and selection of traditional and most used snap-fit features for polymers; functional analysis; contradiction model applied to the chosen snap-fit feature; definition of a potential way for solving the problem. At the same time, a state-of-the-art research was performed to identify potential solutions already discovered and presented to the public domain. The investigation not only concerned scientific papers and books, since the joining technology is strongly related to the industrial practice, it is necessary to perform a patent investigation. Although different solutions have been found, no one introduced a strong innovation on the snap-fit technology. This evidence opens the path for the development of novel metallic snap-fit features. Once understood the potential way of development for the new snap-fit technology, the topology optimization process has been used to identify a more appropriate shape for the snap-fit feature. In this sense, starting from an already existing snap-fit feature, widely adopted in the practical use, it is possible to derive a new design that can be applied on metal. Then, the outcome of the contradiction analysis has been introduced, generating the conceptual design of the novel snap-fit feature. Starting from the novel concept of metallic snap-fit, some different features are developed and applied to specific case studies. The developed snap-fit solution provides the following assembly conditions: fixed joint, removable joint, assembly for welding process. Based on the evidence derived by the case studies, used to prove the effectiveness of specific snap-fit solution, the snap-fit technology moved from the idea of a specific and well-defined feature to a more general concept, that would take not only the snap-fit elements, but also the whole part to be assembled. Finally, a series of experimental campaign are presented with the aim of characterizing the mechanical performance of the novel joint solution, both considering the limit load and the failure mechanism. The outcome of the experiments shows that metallic snap-fit presented in this thesis are able to provide a fail-safe behavior. This leads to the possibility of introducing metallic snap-fit to become a self-standing joining solution.

# IMPROVED RESIDUAL LIFETIME PREDICTION FOR RAILWAY AXLES UNDER SERVICE CONDITION

**Amir Pourheidar** - Supervisor: Stefano Beretta

Railway axles are safety components whose failure could result in catastrophic consequences. Furthermore, there is a growing need to optimize the costs and operations associated with inline inspections throughout the working life. Despite the great number of studies, standards requires that axles be designed against fatigue limit. By such an approach, even if a high level of safety has been achieved, it is not possible to move forward in terms of optimizing the design and all costs associated with manufacturing and in-service operations. As a result, the conventional design against infinite life is increasingly being complemented by the relatively modern, damage tolerant approach, which can account for the axle's deterioration or damage over time. Damage tolerance means that fatigue cracks may develop, but in order to prevent axle failures, these cracks have to be detected before they grow up to a critical size. As a result of appropriate analysis, the residual lifetime and, consequently, an adequate inspection plan, can be defined, to increase safety.

Even though the damage-tolerant approach is well-known, it is still relatively new in the railway sector, and there are open issues for improving the crack growth algorithms. The aim of this Ph.D. thesis was to try to improve a few of them by adopting the newly devolved knowledge about the development of the closure offered by the cyclic R-curve concept.

The first step was to conduct an experimental campaign to evaluate the cyclic R-curve. Along the way realizing the limitation of the current experimental technique for R-curve determination led to the development of a new experimental procedure. Shown in Figure. 1 the R-curve obtained adopting the new procedure was compared with the R-curve evaluated from the potential drop technique and a good agreement was found between the two curves. Exploiting the R-curve concept, a new design root for assessment of the endurance limit from micro-defected specimens was presented along with the subsequent experimental validation.

The performed experiments on full scale railway axles in presence of micro notches under fretting fatigue condition were analyzed in terms of the fatigue test results and crack propagation path obtained from fractographic evidence by the means of FEM analysis (See Figure 2). It was shown that the onset of fatigue propagation can be predicted in relation to the threshold condition expressed by the cyclic R-curve and the predictions were fully consistent with the experiments.

The periodicity of inspections is determined on the basis of the propagation lifetime of a given initial defect, therefore, the key point was the development of an accurate crack growth model to calculate the residual lifetime of an axle under service loads. The application of the cyclic R-curve concept implemented in the Modified NASGRO equation for describing the crack growth behavior of an arbitrary crack length on evaluating the residual lifetime of an axle subjected to the realistic load spectrum was investigated. Shown in Figure 3, the predictions by the Modified Nasgro equation coincide well with the full-scale axle test results while the conventional NASGRO equation leads to a significant overestimation of residual lifetime.

The random factors and uncertainties must be addressed when evaluating the reliability under fatigue crack growth. Finally, a statistical model for reliability analysis of the railway axles to account for the dispersion of the crack propagation lifetime of the railway axle subjected to a realistic load spectrum was developed by adopting the R-curve concept. Shown in Figure. 3 the variability of the R-curve treated in a simplified random variable approach is leading to a sufficient variability of the residual lifetime.

In terms of applications, the results obtained by employing the cyclic R-curve concept provides more engineering tools for evaluating the failure probability of axles in service and, consequently increasing the safety of the axles while optimizing the life cycle cost of axles by proposing a sophisticated inspection plan.

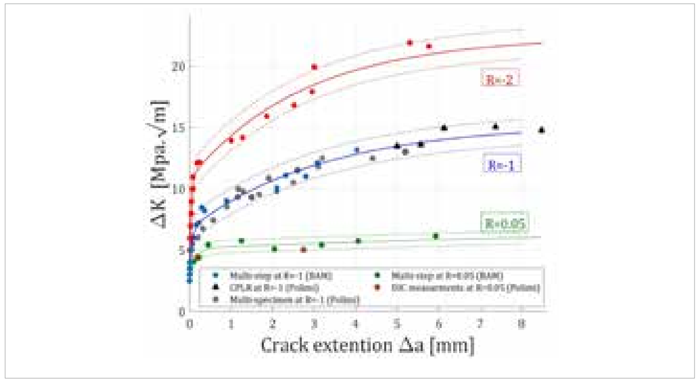


**Fig. 1 - Comparison of obtained cyclic R-curve at different R ratios and confirming different test techniques.**

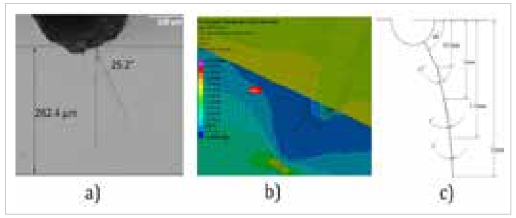


**Fig. 2 - Fretting fatigue analysis: a) fractographic evidence of crack at notch tip; b) the crack path modeling by the means of FEM; c) predicted crack growth path**

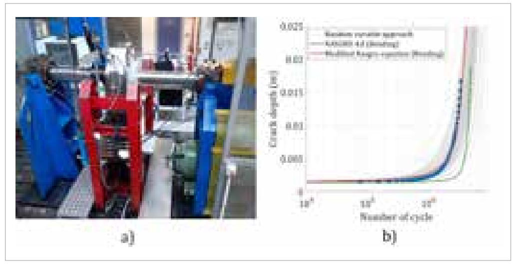


**Fig. 3 - Residual lifetime analysis: a) Full-scale axle crack propagation experiments; b) Residual lifetime predictions using Nasgro equation and modified Nasgro equation adopting R-curve concept together with the investigation of the R-curve scatter effect on the residual lifetime predictions.**

# TOPOLOGICAL AND NON-RECIPROCAL WAVE PROPAGATION IN STIFFNESS MODULATED MATERIALS

**Emanuele Riva** - Supervisor: Francesco Braghin

This PhD work combines theoretical and experimental investigations on elastic wave propagation in stiffness modulated materials, in the attempt to dominate the mechanical energy flow in structures. This novel class of materials is generally made of a periodic pattern of unitary elements, or *unit cells*, arranged along relevant dimensions, which can be either spatial or temporal. In other words, the systematic application of periodicity on the physical and geometrical parameters, affects the dynamics governing wave propagation, which reflects on the manifestation of interesting behaviors that are not typically achievable in nature. In this context, this PhD work focuses on how simple harmonic modulations can be exploited in the quest of robust and nonreciprocal transport of elastic waves, which are behaviors of technological relevance for applications involving wave propagation, such as nondestructive evaluation and realization of mechanical logic circuits, among others. Specifically, the main goals of this research are: *(i)* the development of an elastic analogue of an electric diode, in which elastic wave propagation is supported along one direction only (i.e. from a point A to a point B, but not vice-versa); *(ii)* the development of elastic waveguides that are able to transmit elastic signals efficiently (without signal distortion) between an emitter A and a receiver B in the plane and in a controllable manner, which is not generally achievable in conventional waveguides. The understanding of these two phenomena has important implications in engineering applications and have been elusive for many years from the experimental perspective.

In the first part of this thesis, novel analytical and numerical methods for the dynamic analysis of a generic space-time varying medium are presented. It is shown that, for this class of modulated materials, nonreciprocal wave propagation is supported along specific directions, which, in analogy with the electrical counterpart, can be exploited for the implementation of novel devices that operate as a mechanical diode. The theory is applied to discretely modulated space-time varying beams and plate structures. Then, the concept is experimentally validated through the realization of a stiffness modulated beam with periodically placed piezoelectric patches controlled by shunting circuits, as shown in the experimental setup illustrated in Fig. 1. In particular, the stiffness of consecutive piezo-patches is locally altered through phase shifted control signals applied to switching circuits, which allow to establish a left or a right traveling Young's modulus profile in the material, according to the switching frequency $f_m$ sign. This non-zero momentum in the material is responsible for the nonreciprocal behavior, which can be observed in the experimentally measured wave-field in Fig. 2 for an excitation at 10 kHz and for $f_m$. According to the author's best knowledge, the achieved results constitute relevant progress with respect to the state of the art in the field. Also, in contrast to alternative solutions, the configuration presented in this PhD work is compact and easily scaled for the implementation of novel devices operating at the micro-scale.

The second part of this work is focused on robust transport of elastic waves through topologically non-trivial structures, which rely on the exploitation of a synthetic dimension, emerging from a relevant higher-order parameter space and mapped in a physical domain (spatial or temporal). In other words, it is demonstrated that one-dimensional mechanical structures support the formation of edge-localized modes, either at the left or at the right boundaries, depending on a relevant parameter . When such a parameter is varied along a second physical dimension, such as space (see Fig. 3(a)) or time, the modal shape transforms from being a left (right) to a right (left) localized mode, as shown in the response illustrated in Fig. 3(b). It is indeed demonstrated that, thanks to the system topology, wave propagation occurs from one edge to the other and it is scattering-immune in presence of sharp bends, and therefore suitable for the implementation of mechanical delay lines, wave routing and de-multiplexing. The study of this phenomenon is carried out theoretically and verified experimentally - for the first time in mechanics - through the realization of a square-wave modulated plate with smoothly varying properties along the wave propagation direction and through the realization of a 1D beam with temporally varying parameters in time.

Several are the challenges have been faced in this PhD work, ranging from numerical to experimental aspects. Theoretical problems have been addressed through numerous tools, such as **Finite Element Method** (FEM), *Assumed Modes Method* (AMM), *Finite Difference Time Domain* (FDTD) simulations, *Plane Wave Expansion Method* (PWEM) applied to multi-physic problems, with the aim to acquire physical insight before the experimental design and validation. In addition, the experimental challenges have been addressed rigorously, exploiting consistent and suitable measurement and testing methods. Specifically, the theoretical studies performed are experimentally validated, by measuring wave propagation in transient regime, as well as the standing mode formation in standing regime through a 3D *Scanner Laser Doppler Vibrometer* (SLDV).

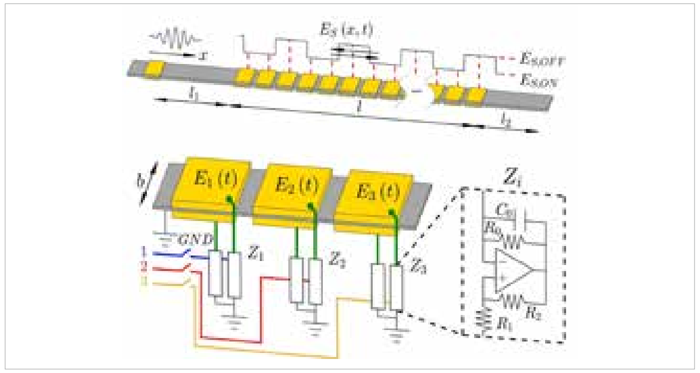

Fig. 1

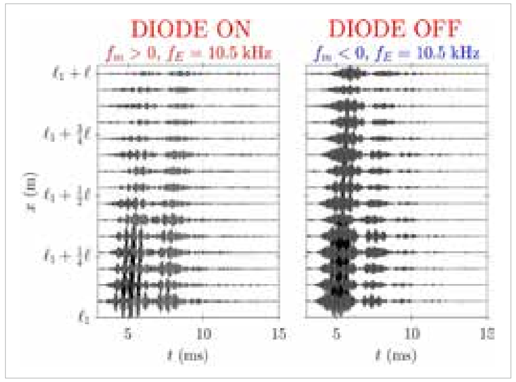


Fig. 2 - Experimentally measured wave-field along the space-time stiffness modulated beam.

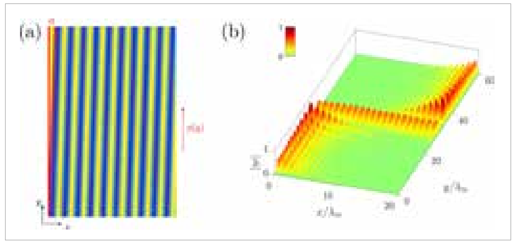

Fig. 3 - (a) Schematic of a stiffness-modulated plate with a smoothly varying parameter. (b) Left to right transition of the edge state.

# THERMAL FATIGUE OF LASER POWDER BED FUSION PROCESSED AL ALLOYS

**Zahra Sajedi** - Supervisor: Maurizio Vedani

Thermal Fatigue (ThF) is a phenomenon that deteriorates the service life of components due to the exposure to fluctuating thermal cycles. The repeated modification of temperature results in nucleation and propagation of cracks and eventually in part failure. This is due to the effects of thermally induced strains that partially hinder, locally or on the full size-scale, the expansion and contraction of the part. Arising thermal strains result in thermal stresses and the repetition of this condition causes ThF within the components. In many real applications, thermal stresses are superimposed with mechanical stresses induced by the presence of external pressure or mechanical loads. When the component is exposed to thermal cycles and at the same time to external cyclic strains or loads, the fatigue phenomenon is known as Thermo-Mechanical Fatigue (TMF).

The most influencing parameters on ThF resistance of a component are: material properties, including thermal conductivity, thermal expansion coefficient, elastic modulus, poisson's ratio, high-temperature strength and creep resistance, operational conditions such as the upper and lower temperature values, temperature range, heating and cooling rates and holding periods at peak temperatures, environmental conditions, part geometry and surface conditions. Temperature range can cause amelioration or worsening of ThF resistance by diminishing or increasing the effects of creep and oxidation on fatigue life. The increase in the upper temperature of the thermal cycles may result in a more severe oxidation, creep strain and microstructural changes due to the phase coarsening or recrystallization. Example of parts that undergo such a condition in automotive industry are mainly exhaust systems, cylinder heads and pistons. In power plants, ThF conditions are met in high and intermediate pressure rotors of steam turbines. Especially for these components, the damage that arises from this condition can additionally be superimposed to effects of creep and oxidation.

ThF and TMF life in Al-Si alloys is mainly affected by microstructural properties such as dendrite arm spacing, spatial distribution pattern of the Al-Si eutectic phase, also considering size and shape of the Si particles and precipitation and solution strengthening conditions of the Al matrix. It has been established that the cooling rate experienced during solidification in cast process of Al alloys has a great influence on ThF, indirectly affecting the presence of porosity, the dendrite arm spacing and morphology of the intermetallic phases.

Laser Powder Bed Fusion (L-PBF) process, also known as Selective Laser Melting (SLM), is an additive manufacturing technology that is capable of producing integrated complex parts with similar or even higher mechanical properties with respect to the conventional methods. In L-PBF process, a laser beam is used to selectively melt a layer of powder, based on a 3D digital model. During the process, the powder bed and the underlying layers down to a certain depth are melted/re-melted, resulting in complete consolidation into a solid volume. The main advantages of this technique in comparison to conventional processes are design freedom and the capability of producing light weight structures.

All these factors drive the attention on L-PBF for the design of high-performance parts for the aerospace, automotive and biomedical sectors. Integrity of parts has a great impact on mechanical properties, hence on safety and reliability. Defects in parts produced by L-PBF can be divided in two categories: surface features such as balling, partially melted powder particles and spatters and volume defects, including porosity and cracks. Porosity in turn can be process-induced or powder-induced. Process induced pores can be of different types, such as those due to lack of fusion, keyhole formation or shrinkage. Powder induced pores with spherical shapes, can form due to the entrapment of the inert gas during gas atomization, which can translate directly to the printed component.

Although several studies focused on ThF and TMF behavior of cast Al alloys are available in the literature, to the author's knowledge, the ThF and TMF behavior of L-PBF processed Al alloys have not been reported in the literature yet. The hypo-eutectic AlSi7Mg (A357) alloy was selected for this research due to its high strength-to-weight ratio, low density and a narrow solidification range, that makes it a suitable candidate for many applications in transportation and aerospace sectors, not only by conventional casting methods but also by additive manufacturing technologies.

In the first part of this research, the ThF of A357 alloy processed by Laser Powder Bed Fusion (L-PBF) is investigated using a Gleeble® 3800 equipment. The material is thermo-mechanically tested in the artificially aged condition. Microstructural and mechanical behavior of the alloy was investigated, and it was found that by keeping fixed the minimum and maximum temperatures of thermal cycles between 100 and 280°C, the fatigue life of the alloy deteriorates significantly by increasing the applied constant load from 90 to 120 MPa. Fractographic analyses showed the occurrence of ductile fracture nucleated from large process-induced pores and numerous fine dimples created due to plastic deformation. Results based on the analysis of the elasto-plastic behavior of the material at high temperature showed that the inelastic strain of the broken samples was about 5 times higher than that of the run-out samples. Hardness drop occurred in all specimens after ThF experiments due to coarsening of the strengthening phases and modification of the Si-rich particles.

In the second part of this study, a comparative research has been carried out on the ThF behavior of A357 alloy processed either by sand casting or L-PBF. Both alloy conditions were cycled within three temperature intervals with a lower temperature of 100°C and upper limits of 200, 240 and 280°C, in presence of a constant uniaxial tensile load. Three tensile loads of 110, 120 and 150 MPa were applied for each temperature range in order to explore the effect of both thermal cycling and concurrent tensile load on ThF resistance. Both alloys showed a similar ThF lifetime when exposed to temperature cycles from 100 to 200°C under all the three tensile loads investigated, while the L-PBF A357 alloy tested to the highest temperature limits of 240°C and 280°C comparatively revealed an improved ThF resistance than the cast counterpart. Microstructural analyses on the cross-sections of both samples revealed that a large amount of strain was accumulated close to the fracture regions and several micropores and microcracks were developed in these areas. Microcracks preferentially nucleated at eutectic Si and Fe-bearing coarse intermetallics in the ThF tested cast alloy, while they propagated from the sharp corners of the process-induced pores in L-PBF samples. Moreover, several micropores are formed at the edges of the fragmented silicon particles in the network in L-PBF alloy that accelerate the failure process.

# PREDICTIVE MODELS FOR HIGH-VELOCITY IMPACT

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There has always been a strong interest in engineering of impact resistant structures and a large amount of research has been conducted in this field. Ballistic shields are intended at protecting valuables and lives from external threats. To reach this aim, they are designed to have high perforation resistance from impacting objects. This design requirement is primarily obtained at a cost of increasing the weight of the shield. On the other hand, lightweight shields are desired in case of both vehicle and personal protection. Therefore, the design of a ballistic shield is usually an optimization process which is achieved by the combination of layers of different materials: metals, fiber-reinforced composites and ceramics. The most significant example is the Small Arms Protective Insert. This is a ballistic shield which combines a hard front layer, usually made with ceramic tiles and a backing layer, in fiber-reinforced composite or ductile metal, to achieve excellent perforation resistance with relatively low weight. Predictive models are a basic tool in the design of mechanical components since they lead to the reduction of costs related to experimental tests and to a better comprehension of the physical phenomenon. Furthermore, the optimization of a ballistic shield would require the evaluation of a large number of combinations of impactor types, impact conditions and target configurations. This task would be almost impossible to be completed exploiting only experimental tests.
The main scope of this thesis is to develop and assess new methods for the simulation and optimization of multi-layered ballistic shields. This is a problem of terminal ballistics in the category of high-velocity impact which is roughly classified with impactors with velocities ranging from 500 m/s to 2000 m/s. Both analytical and numerical models are useful tools in an optimization process.
Analytical models are based on simple equations and usually involve several assumptions and they require far less computational resources. Analytical models are developed for a specific threat target system, thus their predictive capacity for a different threat or target is rather limited. For this reason, in this thesis the effort was focused on the development of an analytical model for high-velocity impact against a double-layered ceramic/composite target which is representative of the Small Arms Protective Insert. This aim was reached by and intermediate step where an improved analytical model for high-velocity impact on fiber-reinforced composite was developed. This analytical model overcome the main limitation of this category of analytical models, which is the assumption of rigid impactor. Afterwards, this model was implemented in an analytical model for ceramic/composite shields by adding a front layer of ceramic material.
Numerical models require more computational resources but are more accurate. Furthermore, once constitutive models of the materials are calibrated, they can be adopted to several geometries, thus on different configurations of multi-layered shields. Therefore, the research activities focused on the calibration of constitutive models for metals, fiber-reinforced composites and ceramics. The numerical models followed the common approach based on the FE method and with element erosion. The FE method is not suited to deal with large deformations and fracturing. For this reason, element erosion is implemented to remove overstrained elements from the analysis and avoid locking of the calculation. In this thesis it was shown that, while this approach guaranties satisfactory results in case of monolithic targets, it is not suited to deal with more complex problems, such as the multi-layered targets. For this reason, the SPH was adopted, which, being a meshless method, is suited to deal with large deformations. The SPH method was exploited for the discretization of soft-core bullets which are subjected to large deformation and fracturing during high-velocity impact. A FE coupled to SPH method was developed for modeling fracturing for ceramics. This approach was found to be more appropriate than the common FE method for modeling high-velocity impact on ceramic, especially when they constitute the front layer of a multi-layered target.
The accuracy of the predictive models was improved, going in the direction of increasing the capabilities of an optimization approach of multi-layered ballistic shields. The capability of predicting large deformations in soft-core bullets was improved both in analytical and numerical models.
The SPH method was successfully implemented where the FE method failed to provide accurate results, showing the necessity of exploiting and assessing meshless methods for the numerical simulation of high-velocity impact. Finally, the experimental tests necessary for the calibration and validation of the predictive models led to a better comprehension of the static and dynamic response of materials commonly used in the manufacturing of ballistic shields, namely the high-strength steel Ramor 500, the aluminum alloy 6061-T6, the fiber-reinforced composite plain weave Kevlar®29/Epoxy and the ceramic Alumina.

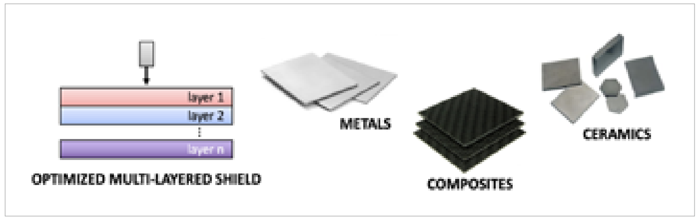


Fig. 1 - Optimized multi-layered ballistic shield manufactured with layers of different materials

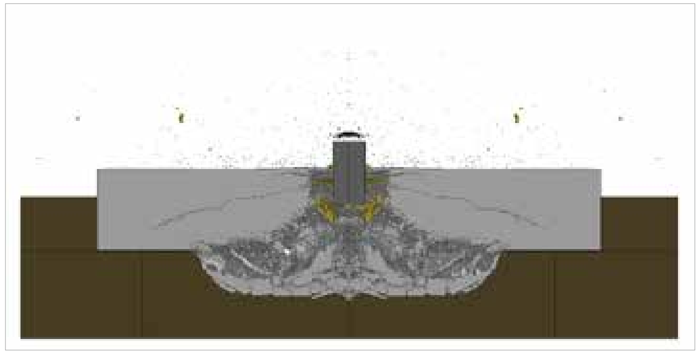

Fig. 2 - FE coupled to SPH numerical model for the simulation of fracturing of ceramics