UNCLOAK

Uncovering microstructural heterogeneity effects of metal-matrix composites on dynamic instabilities and plastic shocks

PhD position in Research Grant funded by:

Ministry of Science and Innovation of Spain
National Research Agency

PURPOSE

The purpose of UNCLOAK is to unravel the mechanisms that govern the formation of instabilities and plastic shocks, leading to the fracture of ductile Metal Matrix Composites (MMCs) subjected to impact loading. This challenge remains unresolved in Solid Mechanics and demands a disruptive, multidisciplinary, and multiscale approach that integrates the latest advances in Manufacturing Engineering and Materials Science with Continuum Mechanics. This fusion aims to open new avenues in the design and analysis of protective structures. To address this challenge, we have devised a three-pronged approach encompassing singular experiments, large-scale computations, and novel theories. These methodologies will be applied to tackle three canonical dynamic fracture problems frequently used to assess the energy absorption capacity of materials under impact: (1) spalling, (2) shear banding, and (3) fragmentation. In MMCs, the microstructure significantly influences the fracture toughness by activating diverse failure mechanisms under different loading conditions. UNCLOAK seeks to establish a comprehensive research program that ultimately explains the influence of microstructural heterogeneity on dynamic plastic localization and failure.

PhD Research

Spalling, shear banding and fragmentation of metal-matrix composites: experiments and modelling

Host

University Carlos III of Madrid

Supervisors

Dr. José A. Rodríguez-Martínez
Dr. Guadalupe Vadillo
Dr. José Reinoso

Synopsis

The dynamic behaviour of materials presents a pervasive challenge for various industries, including automotive, aircraft, aerospace, and civilian-security sectors, where structural elements frequently encounter a wide range of exceptionally severe mechanical forces. Some specific examples include: (i) Components used in satellites must be designed to withstand hypervelocity impacts from space debris. (ii) Crashworthiness structures in ground vehicles are designed to absorb energy during accidents and crashes. (iii) Protective structures in critical buildings such as embassies, governmental facilities, and military bases are required to provide defence against blasts and attacks, safeguarding high-ranking officials, troops, and key infrastructures. Continuous efforts are made to develop new structural solutions to meet these demanding requirements, positioning the transportation and security industries at the forefront of technological innovation. Notably, these industrial sectors play a crucial role in the European economy and society, as emphasized in the "Civil Security for Society," "Digital, Industry and Space," and "Climate, Energy and Mobility" clusters of the Horizon Europe Research and Innovation program, as well as in the "Materials and Components" category of the European Defence Fund.

Materials used to construct energy absorption structures often exhibit heterogeneity in their microstructure, resulting in variations in their macro-scale mechanical properties, which significantly impact localization and fracture behavior. Composite materials serve as a quintessential example of heterogeneous materials, wherein a quasi-homogeneous matrix is reinforced with a distribution of particles and/or fibers, leading to anisotropic and non-homogeneous properties. Consequently, their failure modes heavily depend on the microstructure and the interdependence of microstructural features with the bulk material. Moreover, when subjected to dynamic loading, the propagation of stress waves induces spatial and temporal variations in stress and strain fields, resulting in the formation of plastic shocks and phenomena like strain localization, voids cavitation/collapse, adiabatic shear banding, and multiple necking. These dynamic instabilities arise abruptly, rendering them largely uncontrollable and unpredictable. Consequently, they lead to the ultimate fracture of the material and eventual structural collapse, thereby limiting the energy absorption capacity of protective structures when exposed to impact loading.

In this research, our main objective is to investigate the mechanisms that govern the formation of plastic shocks and dynamic fracture in MMCs materials, with a focus on three canonical problems: **spall fracture** in plate-impact tests, **dynamic shear banding** in direct impact experiments on cylindrical specimens, and **high-velocity impact fragmentation** of rings. Aluminum/Silicon-Carbide and Aluminum/Boron-Carbide have been preliminarily selected as the MMCs to be studied.

In the **plate-impact tests**, we will use a gas gun to launch a high-speed projectile (plate) against a stationary target (plate). During impact, compression shock waves will be generated in both plates, which will then reflect as rarefaction (tensile) waves when reaching the free surfaces. The meeting point of these tensile waves, known as the spall plane, will experience very large tensile stresses, leading to ductile (spall) fracture of the target due to the growth and coalescence of defects and voids caused by the high triaxiality and significant local plastic deformation. We will vary the impact velocities in intervals of 50 m/s, ranging from 250 m/s to 650 m/s. The velocity of the free surface of the targe will be measured with a PDV system to obtain the spall strength of the materials tested. In the **dynamic shear banding tests**, we will perform direct impact on shear-compression samples using a hardened-steel projectile with flat faces launched at velocities ranging from 150 m/s to 450 m/s. The samples will have a diameter of 10 mm and a length of 20 mm with a machined slot to induce shear band inception. Two orientations for the slot will be investigated: 45° (maximum shear) and 35.26° (zero stretch). High-speed cameras will be used to record the experiments, enabling us to obtain timeresolved information on the nucleation time, propagation speed, and trajectory of the shear band. For the **dynamic fragmentation tests**, a thin ring will be axially penetrated by a circular cross-section projectile with a conical nose and trunk diameter greater than the inner radius of the ring. The projectile will be made of tempered manganese steel to minimize deformation during the test. This problem exhibits radial symmetry, which minimizes the propagation of waves along the circumferential direction of the sample. As the impactor advances, it induces a progressive hoop stretching of the ring until localization occurs in the form of multiple necks, eventually leading to the fragmentation of the sample. Impact velocities will vary in intervals of 50 m/s, from 250 m/s to 650 m/s. The radial expansion velocity of the ring will be measured with a PDV system to obtain the characteristic loading rate of the experiments. To address these problems, we will conduct **simulations using ABAQUS Explicit**, employing both homogenized micromechanical and phenomenological macroscopic constitutive approaches. For this purpose, we will develop custom **user subroutines** to implement these constitutive models into ABAQUS. These models will be calibrated using specific characterization experiments conducted as part of this research. This research effort will harness the unique capabilities of the University Carlos III of Madrid and the University of Seville, integrating experimental and computational resources to tackle this fundamental problem in Solid Mechanics, pushing the boundaries of technological innovation.

Research outputs

- **Novel experimental techniques** to perform dynamic fragmentation, shear banding and spall fracture experiments.
- **Development of multiscale finite element models** to obtain insights into the mechanisms which control plastic shocks and dynamic fracture of heterogeneous materials.

The recruited researcher will have access to the unique facilities of the Impact Laboratory of the Department of Continuum Mechanics of the University Carlos III of Madrid, with all the equipment required to perform plate-impact, dynamic shearing and fragmentation experiments: gas guns to launch strikers at velocities as high as 800 m/s, three high speed cameras with filming rate up to 2.1 Mfps to record the tests, 1 photon doppler velocimetry system and 1 oscilloscope with a sampling rate of 20 Gs/s. In addition, the recruited researcher will have access to all the computational resources of the Nonlinear Solid Mechanics group, including licenses of ABAQUS, Matlab and Mathematica, and several workstations.

Multidisciplinary / international research approach

Experiments – he/she will master singular impact testing techniques using the unique facilities of the IMPACT Laboratory of the UC3M. **Theory** – he/she will be trained in formulation and calibration of constitutive models for MMCs, with emphasis on mean-field homogenization approaches. **Computations** – he/she will learn stress integration algorithms for implementation of constitutive and fracture models into finite element codes (including Phase Field), advance scripting for generation of finite element models and image processing techniques for importing microstructures into finite element models.

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Research stays - he/she will conduct **research stays** at the University of Seville under the supervision of Dr. José Reinoso to implement phase field fracture approaches to model impact failure of MMCs.

Training activities

The successful candidate will have access to the PhD program of the **University Carlos III of Madrid** as well as to the training activities organized by the Nonlinear Solid Mechanics group. These activities include, among others:

- **Attendance to prestigious international conferences** on Solid Mechanics.
- **Attendance to technical courses** on materials science and continuum mechanics organized by different prestigious institutions, e.g. the International Center of Mechanical Sciences (http://www.cism.it/).

Benefits

The successful candidate will be employed for 4 years within the framework of a prestigious research grant and receive a generous **financial package.**

Key publications

Czarnota, C., Jacques, N., Mercier, S., Molinari, A., 2008. Modelling of dynamic ductile fracture and application to the 150 simulation of plate impact tests on tantalum. Journal of the Mechanics and Physics of Solids 56, 1624-1650.

Czarnota, C., Mercier, S., Molinari, A., 2006. Modelling of nucleation and void growth in dynamic pressure loading, 152 application to spall test on tantalum. International Journal of Fracture 141, 177-194.

Lin, Z., Lingcang, 182 C., Yinglei, L., Jianxiang, P., Fuqian, J., Dongquan, C., 2004. Simplied model for prediction of 183 dynamic damage and fracture of ductile materials. International Journal of Solids and Structures 41, 7063-7074.

Roy, G., 2003. Vers une modelisation approfondie de l'endommagement ductile dynamique. Investigation experimentale 196 d'une nuance de tantale et developpements theoriques. Ph.D. thesis. University of Poitiers, France.

Zhang, H., Ravi-Chandar, K. On the dynamics of necking and fragmentation - II. E effect of material properties geometrical constraints and absolute size. *International Journal of Fracture*. 2008; 150, 3-36.

Rodríguez-Martínez, J.A., Molinari A., Zaera R., Vadillo G., Fernández-Sáez, J. The critical neck spacing in ductile plates subjected to dynamic biaxial loading: On the interplay between loading path and inertia effects. International Journal of Solids and Structures. 2017; 108: 74–84.

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Nieto-Fuentes, J. C., Virazels, T., Jacques, N., Rodríguez-Martínez, J. A . Gas gun driven dynamic expansion of 3D-printed AlSi10Mg rings. International Journal of Impact Engineering, 2023, 180, 104556.

Nieto-Fuentes, J. C., Espinoza, J., Sket, F., Rodríguez-Martínez, J. A. High-velocity impact fragmentation of additively-manufactured metallic tubes. Journal of the Mechanics and Physics of Solids, 2023, 174, 105248.

Nieto-Fuentes, J. C., Jacques, N., Marvi-Mashhadi, M., Nsouglo, K.E., Rodriguez-Martinez, J.A. Modeling dynamic formability of porous ductile sheets subjected to biaxial stretching: Actual porosity versus homogenized porosity. International Journal of Plasticity, 2022, 158, 103418.

Vishnu, A.R., Nieto-Fuentes, J. C., Rodríguez-Martínez, J. A. Shear band formation in porous thin-walled tubes subjected to dynamic torsion. International Journal of Solids and Structures, 2022, 252, 111837.

Vishnu, A. R., Marvi-Mashhadi, M., Nieto-Fuentes, J. C., Rodríguez-Martínez, J. A. New insights into the role of porous microstructure on dynamic shear localization. International Journal of Plasticity, 2022, 148, 103150.

Marvi-Mashhadi, M., Vaz-Romero, A., Sket, F., Rodríguez-Martínez, J. A. Finite element analysis to determine the role of porosity in dynamic localization and fragmentation: Application to porous microstructures obtained from additively manufactured materials. International Journal of Plasticity, 2021, 143, 102999

Profile

We are looking for highly motivated early-stage researchers with the following profile:

- Hands-on mentality, good organizational and communication skills.
- Proactive attitude and ability to work both independently/autonomously and within a team.
- Good communication skills in English.
- Willingness to travel.

Required educational level

Degree	Master degree or equivalent
Degree field	Engineering: civil, mechanical, aerospace

Career stage

Early stage researcher or 0-4 years (Post graduate)

Specific qualifications

Candidates should have a solid background in Continuum Mechanics, Experimental Mechanics, Dynamic Behavior of Materials, Mathematics and Programming.

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Professional and/or research experience

We will particularly consider those candidates with proven experience in technological and/or research activities. Publication/s in journals indexed in the Journal of Citation Reports will be especially welcomed.

Letter of motivation

The candidates must provide a letter of motivation where they clearly state why, under their point of view, they should be enrolled in UNCLOAK.

References

At least one recommendation letter from the scientist/s who mentored the candidate during her/his master studies is required. The letter must clearly expose the profile of the candidate with emphasis in the qualities which make her/him suitable for being recruited in UNCLOAK. Additional recommendation letters from any other professor/professional will be most welcomed.

Flexible working conditions

We are committed to provide flexible hours and home working conditions for researchers having family obligations. The following web-site contains relevant information **related to the EU equal opportunities policy** https://ec.europa.eu/info/aid-development-cooperation-fundamental-rights/your-rights-eu/know-your-rights/equality/non-discrimination_en. Moreover, the web-site http://www.partnerjob.com/ facilitates geographic mobility by providing help to find a job for an accompanying partner.

Contact details

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The application period closes on August 21st, 2023