LEM3 LABORATOIRE D'ÉTUDE DES MICROSTRUCTURES ET DE MÉCANIQUE DES MATÉRIAUX

anr agence nationale de la recherche

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Master internship towards a doctoral project in Metz (France)

Mechanical behavior and microstructure characterizations of irradiated MAX phases and high-entropy MAX phases

for the new generation of nuclear reactors

The intern (then the doctoral researcher) will be part of the team for the HEIRMAX project (*Development of High Entropy, Irradiation Resistant MAX Phases*), which is funded up to 712 k€ by the ANR (French National Agency for Research) over 48 months.

Nuclear energy is crucial for achieving energy autonomy and reducing greenhouse gas emissions. To enhance the safety of current reactors and develop new generations, it is essential to create novel materials with optimized properties.

MAX phases, compounds with the formula $M_{n+1}AX_n$ (n = 1, 2, or 3), have a hexagonal nanolayered structure composed of M_6X octahedrons interleafed with A atom layers [1,2]. They possess a unique combination of metallic and ceramic properties, such as machinability, high thermal stability, and resistance to corrosion.

Some MAX phases also exhibit good resistance to irradiation damage and low neutron activation. MAX phases like Cr_2AlC, Ti_2AlC, and Ti_3SiC_2, do not interact with liquid sodium, making them suitable for certain Generation IV nuclear reactors. Cr_2AlC is additionally resistant to oxidation in pressurized water reactor conditions. These properties make MAX phases excellent candidates for various nuclear applications, including core structures, fuel cladding, and zircalloy coating for enhanced accident tolerant fuel. As MAX phases in core structures and fuel cladding are exposed to high neutron fluence, their irradiation behavior has been extensively studied. Ti_2AlC and Ti_3SiC_2 show promises for high-temperature nuclear applications, but their microstructure tends to evolve under neutron or ion irradiation. It degrades the mechanical properties and damage resistance of MAX phases, requiring improvements in radiation resistance for long-term reactor operation.

High-entropy MAX phases, which incorporate 3 to 5 elements in M or A constituents, have gained attention. High-entropy alloys and ceramics offer unique physical and chemical properties due to solutes with different atomic radii and valence electrons. By tuning the composition of MAX phases towards higher complexity, it is possible to develop high-entropy MAX phases with improved stability under irradiation, combining desired nuclear application properties with enhanced mechanical strength and radiation resistance.

The objective of the doctoral project initiated by this master internship will be to evaluate the initial mechanical properties of both conventional and high-entropy MAX phases. Their evolution under irradiation will be investigated by means of micro-mechanical tests, required considering the size of sample and the irradiation depth of few µm. Hardness and plasticity behavior will be determined by nano-indentation and micro-compression, respectively. The toughness will be evaluated using SEM *in-situ* microcantilever bending tests. The results will allow determining the potential of improvement in mechanical properties after irradiation of high-entropy MAX phase in comparison to conventional MAX phases.

[1] M.W. Barsoum, T. El-Raghy; AMERICAN SCIENTIST, 2001 (89)
[2] A. Guitton; PhD thesis, Université de Poitiers, France, 2013
[3] D.J. Tallman; PhD thesis, Drexel University, USA, 2015

Your skills

The following qualifications are required:

- Master in materials sciences or related fields
- Good knowledge in materials science and mechanical behavior
- Knowledge in characterization of microstructures using electron microscopy.

The following qualifications are beneficial:

- Experience with computation languages such as Python or MatLab

We offer

A 6-month paid master's internship (≈600€/month) that can be followed by a 36-month full-time PhD position. The doctoral contract is ideally starting on October 1, 2024, but with flexibility to begin earlier. The contract includes health coverage and paid holidays. The position offers a dynamic international environment and close supervision by senior scientists. The opportunity to develop experimental skills such as micromechanical testing, etc. is available to foster a career in academia or industry. The gross salary for the PhD position is approximately 2530 €/month[1].

[1] The median gross salary in France is 2500 €/month (source: French Ministry of Employment, https://code.travail.gouv.fr/outils/simulateur-embauche).

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The doctoral school:

As PhD student, you will be registered at the Université de Lorraine and will be part of the C2MP (***C**himie, **M**écanique, **M**atériaux, **P**hysique*: Chemistry, Mechanics, Materials, Physics) doctoral school. You will have the opportunity to benefit from a wide range of training programs during your PhD.

The local team of HEIRMAX:

- **Prof. Olivier BOUAZIZ**, Full professor at Université de Lorraine, expert in metallurgy.
- **Dr. Julien GUÉNOLÉ**, CNRS research scientist, expert in materials plasticity and atomistic simulations. [www.julien-guenole.fr]
- **Dr. Antoine GUITTON**, tenured associate professor HdR at Université de Lorraine & Adjunct Associate Professor at Georgia Institute of Technology school of Materials Science and Engineering (USA), expert in microscopy and materials plasticity. [www.antoine-guitton.fr]

Host laboratory of the doctoral researcher:

The LEM3 laboratory (***L**aboratoire d'**É**tude des **M**icrostructures et de **M**écanique des **M**atériaux:* Laboratory of Study of Microstructures and Mechanics of Materials) is a joint research center of the Université de Lorraine, the French National Center for Scientific Research (CNRS), and the engineer school Arts et Métiers. LEM3 is one of the largest research institutes for the physics of materials and engineering in France. It is located in Metz, near the tripoint along the junction of France, Germany, and Luxembourg, and forms a central hub for science in Europe. Over 250 scientists from France and around the world work at LEM3 to perform world-class research in materials science, mechanics, and processes. By conducting both fundamental and applied research, researchers at LEM3 work on long-term solutions for the major challenges facing society, industry, and science.

Advantages of working at the LEM3:

As a valued member of our team, you will have access to the comprehensive social protection system in France, including:

- **Universal healthcare coverage:** Universal healthcare coverage: Our comprehensive healthcare system ensures that all necessary medical treatments, including doctor visits, prescription drugs, and hospital stays, are covered with a reference reimbursement rate of around 90% on average (thanks to the *Alsace/Moselle* local regime).
- **Generous annual paid leave:** Take advantage of the LEM3's generous annual leave policy, which allows you to take up to 45 days of annual leave to recharge and rejuvenate.
- **Retirement pensions:** Contribute to the French retirement system and enjoy a pension when you reach retirement age.
- **Unemployment benefits:** when your contract ends, you may be eligible for unemployment benefits to help you cover your expenses while you search for new employment.
- **Sickness benefits:** If you are ill or injured, you may be eligible for daily sickness benefits to cover your lost income.
- **Maternity, paternity, and family leave:** Take time off to care for your family and bond with your new child.
- **Professional training and development opportunities:** Take advantage of the many professional training and development opportunities available in France, to improve your skills and advance your career.
- **Free education:** Education is free in France for children up to 18 years old.
- **Personalized housing allowance:** Assistance for housing costs for low-income individuals.
- **Participation in your public transportation subscription:** 50% of your subscription fees to public transportation for your commute will be supported by the Université de Lorraine.

It is important to note that the level of financial assistance provided by the state may vary depending on your income and the composition of your household.

- **Opportunity for teaching:** There may be the opportunity for you to teach at the Université de Lorraine, which includes an additional salary for this responsibility.

Application:

Please send a detailed CV, a cover letter, and transcripts of your bachelor's and master's degree to the three email addresses provided in the header. Recommendation letters are not required, but please include the contact information of your references.

Applications without the requested attachments may not be considered.