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**INNOVATIVE ACCIDENT-TOLERANT FUEL CLADDING MATERIALS:
THE H2020 IL TROVATORE PERSPECTIVE**

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ABSTRACT: *The Fukushima Daiichi event has demonstrated the need for improved nuclear energy safety, prompting amongst other efforts the development of accident-tolerant fuels (ATFs), which are expected to overcome the inherent technical shortcomings of the standard zircaloy/UO₂ fuels. The main objective of the IL TROVATORE project is to optimize and validate, in an industrially-relevant environment, some of the most promising ATF cladding materials for use in light water reactors. The ATF cladding material concepts proposed in IL TROVATORE are expected to demonstrate significant improvement in performance when compared to the current fuel cladding materials, thus helping to take a critical step towards an improved energy safety worldwide. To achieve its ambitious objectives, IL TROVATORE relies on academic excellence and industrial support, while also involving standardization bodies and nuclear safety regulatory authorities to accelerate the transfer of key innovation to market. Since the IL TROVATORE project is put forth to address a pressing global challenge, it is an international collaboration between Europe, the USA and Japan.*

KEYWORDS: *accident-tolerant fuels (ATFs), fuel cladding materials*

I. INTRODUCTION

Safety, reliability and economic considerations have always been the driving force for the continuous improvements in nuclear fuel system performance. Today's light water reactor (LWR) fuels are based on the UO₂/zirconium alloy system, which achieved full maturity and excellent performance records after several decades of research, return of experience and steady technological advancements. The tsunami following the Great East Japan Earthquake in March 2011 caused a prolonged station blackout (SBO) of the Fukushima Daiichi plants, followed by core meltdown, hydrogen explosion and release of radioactive matter beyond the power plant containments. The material and immaterial consequences of this event prompted international discussions on the necessity of enhanced accident tolerance in LWRs, as it is reflected, for example, in the amended European Nuclear Safety Directive (Council Directive 2014/87/EURATOM of July 2014).

When compared with the standard UO₂/zirconium alloy system currently used, nuclear fuel systems with enhanced accident tolerance (Ref. 1) can tolerate loss of active cooling in the reactor core for considerably prolonged periods during design-basis accidents (DBA) and design extension conditions (DEC) (also known as "severe accidents", SA), while

maintaining or improving the fuel performance during normal operation and operational transients (“anticipated operational occurrences”, AOO). Enhanced accident tolerance includes reduced steam reaction kinetics, lower hydrogen generation rate, delayed core degradation and reduction of the initial stored energy in the core, while retaining acceptable cladding and fuel thermomechanical properties, fuel-clad interactions, and fission product behaviour.

Efforts directed towards ATF development are deployed at both national and supranational levels. In February 2017, the European Commission evaluated favorably the H2020 project IL TROVATORE (“Innovative cladding materials for advanced accident-tolerant energy systems”). IL TROVATORE gathers thirty organizations from Europe, the USA and Japan with the aim of accelerating ATF cladding material development, in response to the pressing global societal and industrial demand for enhanced nuclear energy safety in the current generation LWRs. IL TROVATORE aims at optimizing and validating some of the most promising ATF cladding material concepts in industrially-relevant conditions. The present paper describes the material down-selection process and key performance indicators implemented in the IL TROVATORE project.

II. MATERIAL DOWN-SELECTION IN H2020 IL TROVATORE

II.A. Initial ATF Cladding Material Pre-selection

IL TROVATORE focuses on innovative fuel cladding material concepts with potential for enhanced accident tolerance; these materials have achieved an experimental proof-of concept and have also undergone validation in the lab, at least for some of the key fuel cladding properties. A critical pre-selection of candidate materials with the potential to address the stringent requirements of the ATF cladding application has already been performed, taking into account the latest global academic and industrial achievements. The ATF cladding material concepts to be further studied in IL TROVATORE are:

1. *Select SiC/SiC composite concepts* produced by different processing routes and with different performance-defining fiber/matrix interfaces. Apart from their refractoriness, the great advantage of SiC/SiC composites is their damage tolerance, i.e., the fact that they exhibit pseudo-ductile fracture with high strain at failure ($\epsilon_f > 0.5\%$) in contrast to the brittle fracture of monolithic SiC ($\epsilon_f < 0.1\%$).
2. *Coated cladding material concepts* are considered an appealing (near-term) technology, since their performance will rely on the performance of the well-known/commercial substrate clads that are expected to remain largely unaltered by the applied coatings. Both coatings and coating/substrate interfaces will be tailored to guarantee reliable performance in application-relevant conditions. IL TROVATORE will not evaluate all ‘mature’ coated ATF cladding material concepts, as some of them are currently being evaluated in other research reactors or might soon be evaluated in power reactors. Under the IL TROVATORE initiative, the following substrate-specific coating types are considered:
 - a. Nanolaminated ternary carbide coatings (MAX phases and solid solutions thereof) with tailored composition and microstructure to achieve adequate high-temperature stability and oxidation resistance. MAX phases are capable of self-annihilation of radiation-induced defects at elevated temperatures representative of accidental scenarios. Moreover, some MAX phases have demonstrated remarkable self-healing of cracks in oxidizing environments.
 - b. Nanocrystalline oxide coatings engineered to the needs of the end application. Some of the considered oxide coatings have already demonstrated high-temperature stability, radiation tolerance and capacity for self-repair of mechanical damage, but have not yet been validated in an industrially-relevant environment (water, neutrons) or under LOCA conditions (high-temperature steam). Other oxide coatings have already shown excellent corrosion resistance in water and high-temperature steam, but have not yet been studied with respect to radiation tolerance.
3. *GESA surface-alloyed clads* that form in-situ thin oxide scales capable of providing corrosion and wear protection to the substrate clad. The GESA (Gepulste ElektronStrahl Anlage) process is used to surface-modify commercial clads by means of an intense pulsed electron beam; the structural and chemical material modification is limited in depth (30–50 μm), thus ensuring no deterioration of the bulk properties of the surface-alloyed fuel cladding material.
4. *Oxide-dispersed-strengthened (ODS) iron-chromium-aluminum (FeCrAl) alloy clads* should ideally combine the high-temperature oxidation resistance of FeCrAl alloys with the superior resistance of ODS ferritic alloys to irradiation creep and swelling. Strengthening the FeCrAl matrix by incorporating oxide dispersoids is expected to allow the reduction of the cladding thickness, neutralizing the neutronic penalty associated with the use of Fe-based alloys instead of zircaloy.

II.A.1. SiC/SiC composite clads

Some of the recent progress in the development of leak-tight SiC/SiC composite cladding tubes is shown in Figs. 1a-1b for the DEMO-NITE SiC/SiC clads developed by OASIS (Organization of Advanced Sustainability Initiative for Energy System/Material), MuroranIT, Japan, and in Figs. 1c-1e for the “sandwich” SiC/SiC clads developed by CEA, France. The DEMO-NITE process uses a polymer-based slurry of SiC nano-powders to infiltrate SiC fibers that have been CVD-coated with pyrolytic carbon (Ref. 2); the intermediate SiC/SiC materials (green sheets → prepreg sheets → preforms) turn into fully-densified tubes based on the transient eutectic process by means of pressure-assisted sintering methods (hot pressing, hot isostatic pressing). The CEA “sandwich” SiC cladding concept contains a thin (50-100 μm) metallic liner between two layers of SiC/SiC composites (Fig. 1c) (Ref. 3); the middle metallic layer, which is Nb or Ta in fuel cladding concepts for Gen-IV gas-fast reactors (Gen-IV GFRs), will be tailored to meet the needs of the ATF cladding application. Cladding tubes can be produced with different fiber braiding patterns (Fig. 1e), so as to tailor the material mechanical properties.

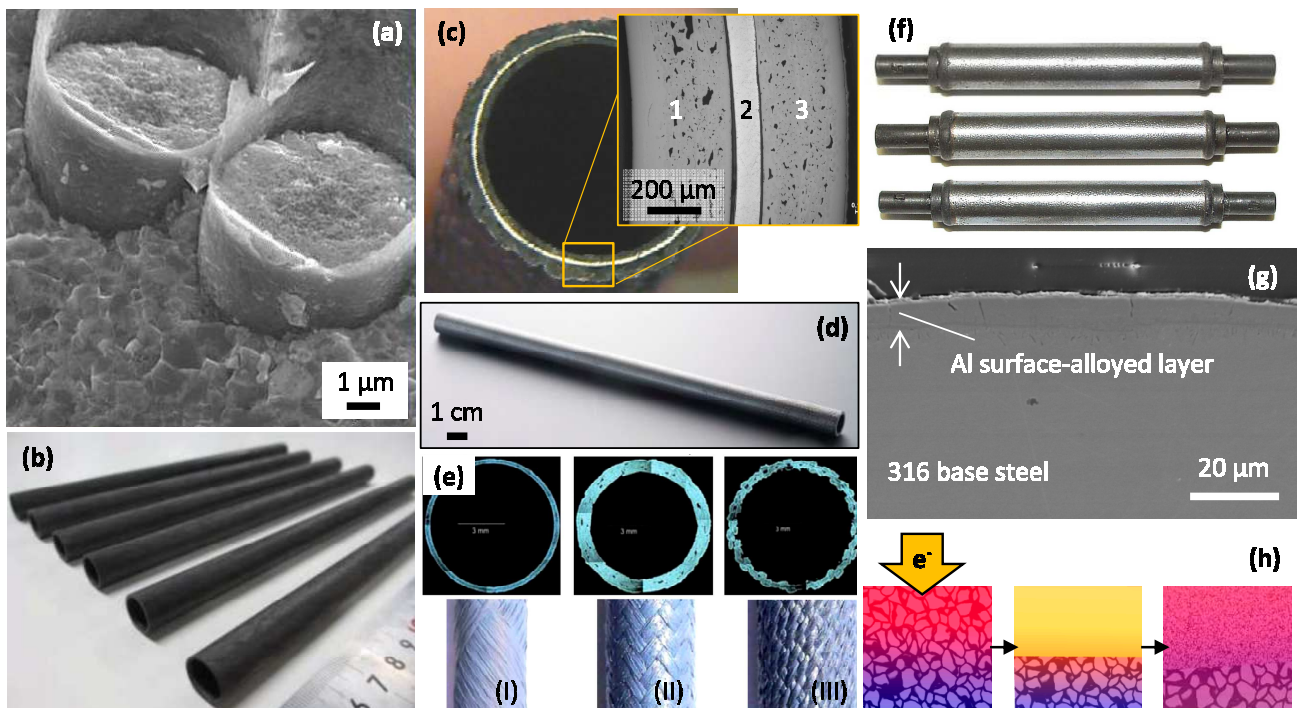


Fig. 1. DEMO-NITE SiC/SiC cladding: (a) fracture surface showing fiber pull-out, fiber & matrix micro-crystallinity and perfect densification; (b) tubes. The CEA SiC “sandwich” concept: (c) tube cross-section showing (1) an inner SiC/SiC layer, (2) a middle metallic layer, and (3) an external SiC/SiC layer; (d) tube; (e) SiC/SiC layouts with different braiding patterns: (I) filament winding, (II) 2D braiding, and (III) 3D braiding. (f) GESA FeCrAlY-coated DIN 1.4970 stainless steel cladding tubes exposed at 600°C for 8500 h to liquid LBE with 10^{-6} mass% oxygen. (g) GESA Al surface-alloyed 316 stainless steel exposed at 600°C for 10000 h to liquid LBE with 10^{-6} mass% oxygen. (h) GESA process of surface modification by an intense pulsed electron beam: volumetric heating → formation of a melt layer → restructured surface-alloyed layer.

II.A.2. GESA surface-alloyed clads

The GESA process (Ref. 4) has already been successfully applied to modify steel clads intended for use in Gen-IV lead-fast reactors (Gen-IV LFRs). For example, the surface-alloyed stainless steels DIN 1.4970 and 316 (Figs. 1f-1g) have been exposed for long times to liquid lead-bismuth eutectic (LBE) at high temperature (600°C) without suffering the typical liquid metal attack, due to the in-situ formation of a protective alumina scale. Typically, the GESA process involves the deposition

by plasma spraying on the steel surface of a FeCrAl coating (20-40 μm -thick), followed by melting of the coating by intense pulsed electron beam; the restructured surface-alloyed layer acts as a ‘reservoir’ layer of Al atoms that enables the in-service formation of an alumina scale (Fig. 1h). This technology has been upscaled to 1 m-long tubes; its suitability for the targeted ATF application relies on the chemistry of the applied coating and the hydrothermal stability of the oxide scale that will form in service. It is believed that the latter can be improved, if necessary, by the co-deposition of the appropriate dopants during the first stage of the GESA process; dopant co-deposition is expected to improve the oxide scale hydrothermal stability, presumably by dopant grain boundary decoration during the restructuration of the surface-alloyed layer.

II.A.3. MAX phase-coated clads

The MAX phases are a fascinating class of layered solids with hybrid metallic-ceramic behavior and properties that depend on stoichiometry, which is given by the general formula $M_{n+1}AX_n$, where M is an early transition metal, A is an A-group element, X is C or N, and n typically takes the values 1, 2 or 3. MAX phases form solid solutions on the M, A and X sites; solid solutions may often have better properties than the ‘parent’ MAX phases (Ref. 5). For example, the thermal stability of the $(\text{Nb,Zr})_4\text{AlC}_3$ solid solution (Ref. 6) is better than that of the starting Nb_4AlC_3 ; the thermal stability of the former is comparable to that of refractory metals W and Mo (Fig. 2f). The fact that many of the properties of the MAX phases (e.g., deformability, thermal stability, oxidation resistance, etc.) can be tailored by producing solid solutions makes them quite versatile materials; for example, $(\text{Zr,Ti})_2\text{AlC}$ (Figs. 2b-2c) has an improved oxidation resistance compared to the ‘parent’ Zr_2AlC (Fig. 2a).

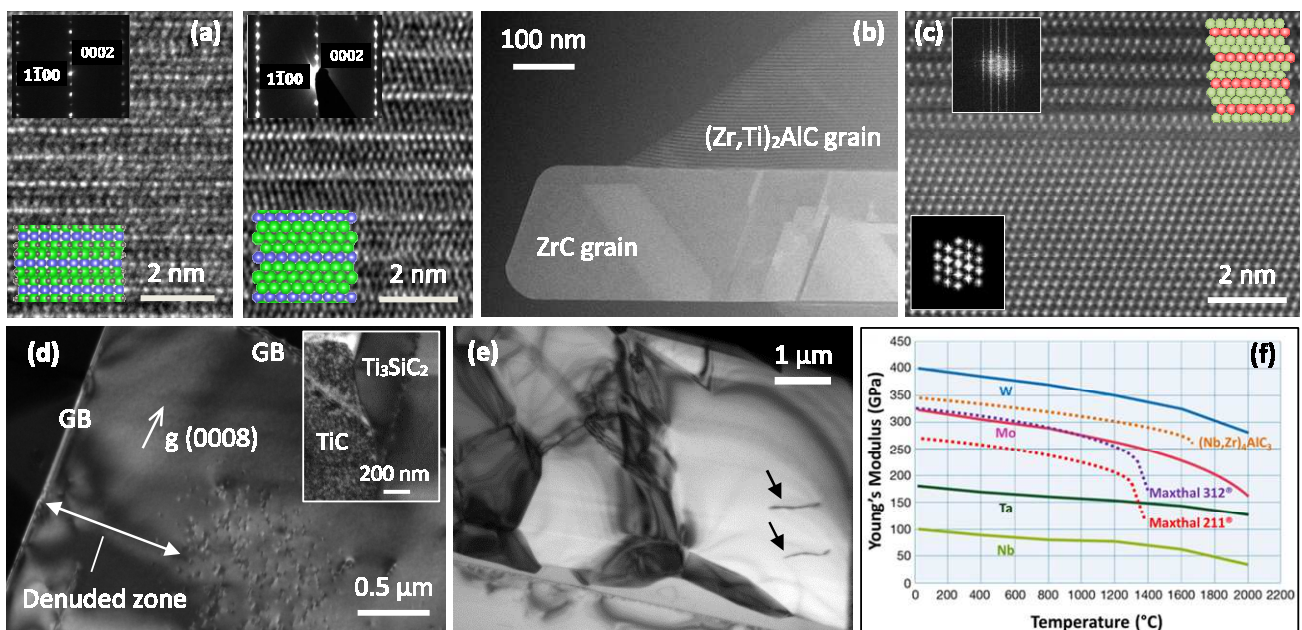


Fig. 2. (a) MAX phases in the Zr-Al-C system (left: Zr_2AlC ; right: Zr_3AlC_2) are the basis for the development of oxidation-resistant solid solution coatings with financially-acceptable neutronic penalty. Producing phase-pure MAX phases and solid solutions thereof is often challenging: STEM images of a $(\text{Zr,Ti})_2\text{AlC}$ MAX phase grain next to a ZrC ‘impurity’ grain (b) and the interface between them (c). (d) Neutron-irradiated Ti_3SiC_2 at $\sim 735^\circ\text{C}$ to 3.4 dpa: large defect-denuded zones are established next to MAX phase grain boundaries (GBs), which act as potent radiation-induced defect ‘sinks’; the Ti_3SiC_2 MAX phase grain appears less damaged than the neighboring TiC grain (inset). (e) Neutron-irradiated Ti_3SiC_2 at $\sim 1085^\circ\text{C}$ to 3.4 dpa: the grains appear devoid of defects, except from few isolated dislocations (arrows). (f) Comparison of the high-temperature stability of select MAX phases (commercial Maxthal 211[®] & 312[®] produced by Sandvik, Sweden, and $(\text{Nb,Zr})_4\text{AlC}_3$ solid solution) with that of refractory metals tungsten (W) and molybdenum (Mo).

The MAX phases exhibit better high-temperature radiation tolerance than their respective binary carbides: an example is given in the inset of Fig. 2d, which shows a highly-damaged TiC grain next to a defect-free Ti_3SiC_2 grain, both irradiated at $\sim 735^\circ\text{C}$ to 3.4 dpa. The fact that the MAX phases are capable of effective self-annihilation of radiation-induced defects at elevated temperatures ($700\text{--}1100^\circ\text{C}$; Figs. 2d-2e) makes them promising coating materials for ATF clads. Producing phase-pure MAX phases is challenging, as the produced MAX phase-based materials often contain non-negligible amounts of ‘parasitic’ phases (Figs. 2b-2c) that can lead to differential swelling-induced intergranular cracking under neutron irradiation. The aim of MAX phase research in this project is to synthesize phase-pure, compositionally- and microstructurally-tailored MAX phases that will subsequently be applied as coatings on commercial clads. MAX phase coatings have already been successfully deposited on different substrates via plasma vapor deposition techniques (Ref. 7) and cold spraying (Ref. 8); similar low-temperature coating deposition approaches will be adopted in this project, so as not to alter the substrate clad microstructure and bulk properties. The coating/substrate interfaces in the candidate MAX phase-coated clad concepts will be engineered to ensure reliable in-service performance under both nominal and transient/accidental operation conditions.

II.A.4. Oxide-coated clads

High-quality nanocrystalline alumina (Al_2O_3) coatings have been successfully made by pulsed laser deposition (PLD). These coatings, often vitreous in the as-deposited state, started immediately crystallizing under heavy ion irradiation (dual ion beam of 12 MeV Au^{5+} and 18 MeV W^{8+}), maintaining their crystallinity up to high dpa levels (20-150 dpa; no delamination was observed up to the maximum achieved displacement dose of 450 dpa; Figs. 3b-3c). These coatings have demonstrated a remarkable resistance to mechanical (even impact) damage, as shown by the adherence of the nano-impacted coating to the substrate (Fig. 3d). TEM analysis has shown that the crack-like features in Fig. 3d are filled with vitreous matter, indicating that these coatings might have a remarkable ability to self-repair mechanical damage (Ref. 9). The in-service irradiation of impacted/damaged coatings is expected to result in crystallization of the vitreous matter filling the crack-like features, thus resulting in coatings with remarkable self-healing capacity.

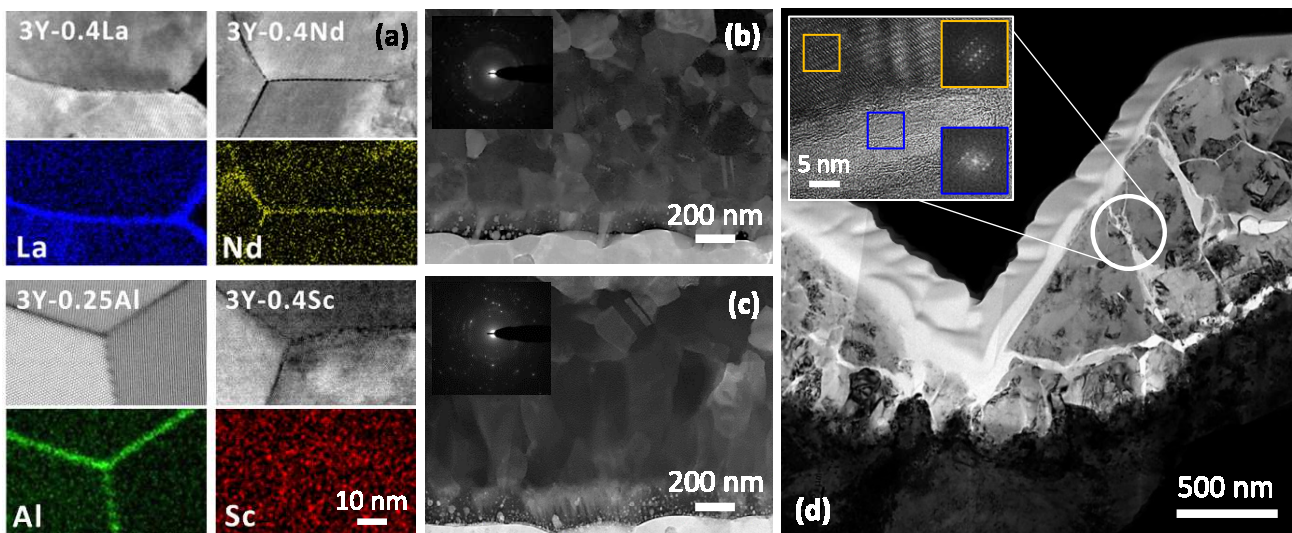


Fig. 3. (a) Dopant-specific grain boundary decoration in 3Y-TZP (3 mol% yttria-stabilized tetragonal polycrystalline zirconia). Grain boundary decoration of 3Y-TZP ceramics by La^{3+} , Nd^{3+} and Al^{3+} dopants increased their hydrothermal stability; grain boundary decoration – and consequently improvement of the hydrothermal stability of the doped oxides – could not be achieved by adding Sc^{3+} . TEM images of heavy ion-irradiated amorphous Al_2O_3 coatings made by PLD show nanocrystalline domain formation – 20 dpa (b) and growth – 150 dpa (c). (d) TEM data of a nano-impacted, heavily ion-irradiated (150 dpa) Al_2O_3 coating deposited by PLD: crack-like features are filled with vitreous matter as result of impact-induced local amorphisation.

If needed, the resistance of the nanocrystalline oxide coatings to hydrothermal ageing could be improved by the co-deposition of select dopants that segregate preferentially at grain boundaries during radiation-enabled crystallization. The concept of improving the hydrothermal stability of oxides by grain boundary engineering has been demonstrated by the addition of various dopants to 3Y-TZP (3 mol% yttria-stabilized tetragonal polycrystalline zirconia) dental ceramics: some of the added dopants (La^{3+} , Nd^{3+} and Al^{3+}) effectively decorated the material grain boundaries (Fig. 3a), thus preventing the intergranular diffusion of water species that is considered responsible for hydrothermal ageing (Ref. 10). The composition of the oxide coatings will be substrate-specific (other oxides are foreseen for conventional clads, such as zircalloys, and other for innovative clads, such as SiC/SiC composites) and the substrate/coating interface in each coated system will be engineered to guarantee reliable in-service performance under both nominal and transient/accidental operation conditions.

II.A.5. ODS-FeCrAl alloy clads

Oxide-dispersed-strengthened (ODS) iron-chromium-aluminum (FeCrAl) alloys produced by mechanical alloying are very promising candidate ATF cladding materials, due to their excellent oxidation resistance in steam up to 1450°C and their appealing mechanical properties (high strength, good resistance to irradiation creep and swelling) (Ref. 11). Their oxidation resistance is attributed to the combined Al and Cr content of the FeCrAl matrix (both Al and Cr form protective oxide scales), while their mechanical performance is associated with the distribution of ultra-fine dispersoids in the FeCrAl matrix (Fig. 4a); these dispersoids are capable of pinning dislocations, resulting in high yield strengths at all temperatures. Strengthening the FeCrAl matrix by incorporating oxide dispersoids is deemed necessary for these clads, since they must be manufactured with reduced thickness (< 400 μm) to compensate for the neutronic penalty associated with the use of Fe-based alloys instead of zircalloys.

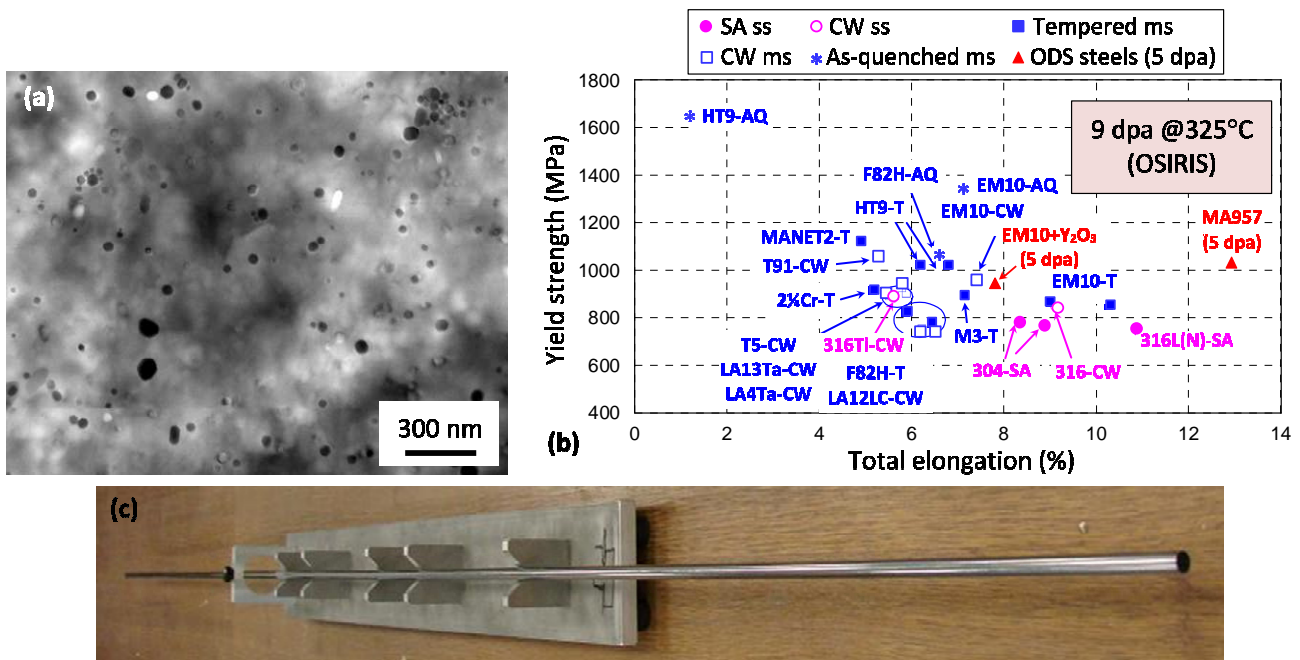


Fig. 4. ODS-FeCrAl alloys: (a) TEM image a certain FeCrAl alloy with nanosized oxide dispersoids – dark particles – dispersed in the grey FeCrAl matrix. (b) Yield strength vs. total elongation for alloys (ss: stainless steels; ms: martensitic steels; SA: solution-annealed; CW: cold-worked; AQ: as-quenched; T: tempered) irradiated at 325°C in the OSIRIS research reactor up to 9 dpa; the ODS alloys (MA957 & EM10+Y₂O₃) exhibit appreciable residual ductility at a dose of 5 dpa. (c) Fe-14Cr ODS tube produced at CEA Saclay (outer diameter = 10.7 mm; wall thickness = 0.50 mm).

In the past 15 years, the development of the ODS fuel clads has mainly targeted Gen-IV sodium-fast reactors (Gen-IV SFRs) and Gen-IV supercritical water reactors (Gen-IV SCWRs). The previously achieved progress in ODS fuel cladding tube fabrication (Fig. 4c) will be exploited to develop ODS-FeCrAl alloys suitable for the ATF application. At present, the international community is mainly studying ODS-FeCrAl alloys with ~5% Al and 12-20% Cr: the highest end of the Cr range favors oxidation resistance, while 12-15% Cr is expected to limit the formation of the brittle α' -Cr-rich phase upon neutron irradiation at low temperatures. The neutron irradiation tolerance of ODS alloys appears to be very satisfactory, both in terms of microstructural stability and mechanical property retention after irradiation (Fig. 4b), which is an additional motivation for the ongoing development of various ODS-FeCrAl alloy grades.

II.A.6. Predictive modeling activities

The reliable prediction of the long-term in-service behavior of the candidate ATF cladding concepts studied in this project demands the development of robust predictive models that are based on the understanding and accurate simulation of the damage accumulating in the material's lifetime. To that end, various approaches will be tried, one of which relies on the use of the FEMME (Finite Element Microstructure Mesh-free) fracture model to simulate the thermomechanical degradation and deformation process to failure of complex fuel cladding materials (Ref. 12), such as the SiC/SiC composites studied in this project. The FEMME model uses microstructure-related input acquired by means of 3D imaging (micro-computed X-ray tomography, μ XCT, combined with digital volume correlation, DVC) to simulate in-service damage evolution in a cost-and time-effective manner (Fig. 5).

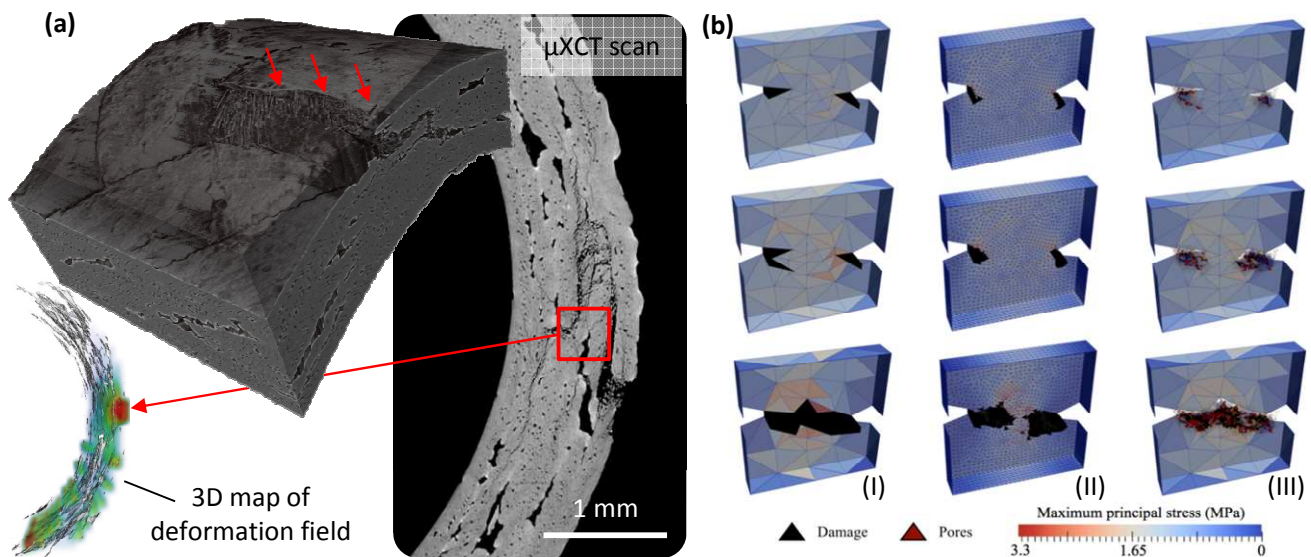


Fig. 5. (a) The mechanical damage (arrows) in a SiC/SiC composite cladding tube is revealed in the high-resolution (0.7- μ m voxel size) μ XCT scan of the tube cross-section; the 3D impression of the deformation field around the site of mechanical damage is given by DVC. (b) The FEMME (III) 3D simulation of thermomechanical damage evolution provides a comparable level of discretization (accuracy) as a fine finite element model (II), but at the low computational cost of a coarse finite element model (I).

II.B. ATF Cladding Material Screening before Neutron Irradiation in BR2

This section describes the ATF cladding material down-selection process in IL TROVATORE prior to the irradiation in BR2 (Belgian Reactor 2) at SCK•CEN. The BR2 irradiation campaign aims at providing validation of the best ATF cladding concepts in an industrially-relevant environment, i.e., under neutron irradiation up to a maximum displacement of 7 dpa in PWR-like water. The candidate ATF cladding material candidates and their joints/welds will be irradiated simultaneously in

BR2, so as to pinpoint the most suitable material(s) for the targeted application, thus expediting the transfer of the anticipated key innovation to market. The first 2 years of the project will be dedicated to the optimization of the pre-selected ATF cladding material concepts described in the previous section. The timely optimization of the candidate ATF cladding material concepts prior to the irradiation in BR2 – scheduled for two full years – is a prerequisite for the success of the project, the principal aspiration of which is to deliver proof-of-concept ATF cladding materials that have been already validated in an industrially-relevant environment. Material optimization in IL TROVATORE is expected to help establishing a culture of accelerated materials development (AMD), which relies on the continuous feedback between *application-driven material design, material production* and *material performance assessment under application-relevant conditions*. The successful implementation of the AMD approach relies on *high throughput material screening* to reliably assess material performance prior to its demonstration in actual industrial conditions. Examples include ion and proton irradiation to assess the radiation tolerance of innovative nuclear materials prior to neutron irradiation, and judiciously-chosen modeling approaches (atomic-scale, thermodynamic, finite element).

The down-selection of the ATF candidate cladding materials to be irradiated in BR2 will rely on the outcome of a *set of critical screening tests* that aim at assessing:

1. Resistance to aqueous corrosion at nominal operation conditions (specific exposure conditions): materials are expected to demonstrate a step improvement in corrosion rate when compared to commercial zircaloy clads;
2. Resistance to high temperature steam oxidation (specific exposure conditions): materials are expected to demonstrate a step improvement in steam oxidation resistance when compared to commercial zircaloy clads;
3. Hermeticity of sealed tubes: it includes the permeability of the bulk material to critical elements, in particular helium and tritium, and the demonstration of suitable end-plug joining techniques (i.e., welding or similar); and
4. Acceptable irradiation tolerance: materials and their constituents must show no decomposition or unacceptable swelling upon ion/proton irradiation to dpa levels relevant for the envisaged fuel cladding application.

III. KEY PERFORMANCE INDICATORS IN H2020 IL TROVATORE

The ATF cladding material concepts considered in IL TROVATORE have already reached an adequate level of technological maturity (TRL 3 – experimental proof-of-concept demonstrated and/or TRL 4 – technology validated in the lab). Their suitability in addressing the ATF challenge will be assessed at two moments during the project lifetime: (a) at the end of the 2nd year (month 24) and (b) at the end of the project (month 54). In month 24, the optimized ATF clads that have successfully passed the pre-screening critical tests mentioned in the previous section, thus demonstrating a minimum threshold performance, will be allowed to partake in the BR2 irradiation. In month 54, the one or more proof-of-concept ATF clads that performed satisfactorily during the BR2 irradiation (i.e., achieved TRL 5 – technology validated in an industrially-relevant environment) will be considered fit to embark on the next step towards deployment, which will be the demonstration of fuel-cladding compatibility. The IL TROVATORE project foresees a limited number of fuel/cladding compatibility tests between the best ATF cladding material candidates and standard LWR fuels, such as UO₂ and MOX (mixed oxide fuels).

IV. INVOLVED PARTIES IN H2020 IL TROVATORE

Table I presents the H2020 IL TROVATORE beneficiaries. Apart from the beneficiaries entrusted with performing the foreseen R&D tasks, three expert advisory committees were established to ensure that the IL TROVATORE scientific & technical (S&T) objectives will be reached within the project timeframe (duration: 4.5 years; kick-off date: 1st October 2017), i.e., a scientific advisory committee (SAC), an end users group (EUG), and a standardisation advisory committee (STC).

The SAC involves prominent members of the international scientific community with recognised expertise in disciplines that relate closely to the project R&D activities. The SAC experts have the necessary qualifications/experience to peer-review the appropriateness and robustness of the research approaches adopted by the project partners, helping to ensure scientific excellence. The EUG involves industrial experts that can communicate to the project beneficiaries the stakeholder knowledge and industrial expectations, in particular relative to ATF cladding material performance requirements, thus helping the project to achieve its S&T objectives. Moreover, the EUG involves nuclear safety regulators and experts involved in the development of Gen-IV systems that envisage the use of similar materials with those studied in the project. The STC involves experts associated with standardisation bodies and, more specifically, with standardisation activities on nuclear materials and advanced ceramics similar to some of the fuel cladding material concepts studied in the IL TROVATORE project. The STC experts provide feedback on existing and/or developing standards, assess the standardisation potential of the project results,

and offer recommendations on the appropriate standardisation strategy leading to the development of new standards (material specifications, material test methods).

TABLE I. H2020 IL TROVATORE beneficiaries.

[‡] Project Coordinator

| No. | Beneficiary Organization Name | Short Name | Country |
|-----|---|------------|---------|
| 1 | Studiecentrum voor Kernenergie – Centre d’Etude de l’Energie Nucléaire [‡] | SCK•CEN | Belgium |
| 2 | Katholieke Universiteit Leuven | KU Leuven | Belgium |
| 3 | Rheinisch-Westfälische Technische Hochschule Aachen | RWTH | Germany |
| 4 | Karlsruher Institut für Technologie | KIT | Germany |
| 5 | Helmut-Schmidt-Universität – Universität der Bundeswehr Hamburg | HSU | Germany |
| 6 | Technische Universität Dresden | TUD | Germany |
| 7 | Plansee Composite Materials GmbH | PLANSEE | Germany |
| 8 | Gesellschaft für Technische Thermochemie und –physik mbH | GTT | Germany |
| 9 | Joint Research Centre – Directorate G-Nuclear Safety and Security | JRC | Germany |
| 10 | Deutsches Zentrum für Luft- und Raumfahrt e.V. | DLR | Germany |
| 11 | Linköpings Universitet | LiU | Sweden |
| 12 | Kungliga Tekniska Högskolan | KTH | Sweden |
| 13 | Sandvik Materials Technology AB | SMT | Sweden |
| 14 | Westinghouse Electric Sweden AB | WH SE | Sweden |
| 15 | The Chancellor, Masters and Scholars of The University of Cambridge | UCAM | UK |
| 16 | The Chancellor, Masters and Scholars of The University of Oxford | UOXF | UK |
| 17 | Imperial College of Science, Technology and Medicine London | ICL | UK |
| 18 | The University of Manchester | UoM | UK |
| 19 | The University of Huddersfield | UoH | UK |
| 20 | National Nuclear Laboratory | NNL | UK |
| 21 | Rolls-Royce Power Engineering plc | RR | UK |
| 22 | Université de Poitiers | UP | France |
| 23 | Commissariat à l’Énergie Atomique | CEA | France |
| 24 | École Normale Supérieure Cachan | ENSC | France |
| 25 | Electricité de France S.A. | EDF | France |
| 26 | Association Française de Normalisation | AFNOR | France |
| 27 | Politecnico di Torino | POLITO | Italy |
| 28 | Istituto Italiano di Tecnologia | IIT | Italy |
| 29 | Drexel University | DU | USA |
| 30 | Kyoto University | KU | Japan |

V. CONCLUSIONS

The conventional “cook and look” approach cannot be adopted, if accident tolerant fuel (ATF) systems are to be implemented in the current generation of nuclear reactors. Accelerated material development strongly relies on physics-based approaches to expedite the development, demonstration and licensing processes for innovative fuel cladding materials. This need is not only reflected in the contemporary efforts to improve the nuclear energy safety via the development of ATF cladding materials, but it also regards the deployment of future generation systems (Gen-IV, fusion). The envisaged developments in the IL TROVATORE project intend to validate specific candidate ATF cladding concepts in an industrially-relevant environment, thus helping to take a critical step towards an improved nuclear energy safety worldwide.

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the results presented here as indicative of the state-of-the-art achievements in the development of the ATF cladding material concepts to be studied in the project. Due to the large number of involved persons, not all contributors could be named.

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