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Summary Report of the Fifth Workshop on Structural Materials for Innovative Nuclear Systems

8-11 July 2019
Kyoto, Japan

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;

– to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

Foreword

The Expert Group on Innovative Structural Materials (EGISM) was created in 2008 under the auspices of the Nuclear Science Committee (NSC) and the Working Party on Scientific Issues of the Fuel Cycle (WPFC) to conduct joint and comparative studies to support the development, selection and characterisation of innovative structural materials that can be implemented in advanced nuclear fuel cycles under extreme conditions such as high-temperature, high-dose rate, corrosive chemical environment and long-service lifetime.

One of the objectives of the expert group is to organise a series of workshops on structural materials for innovative nuclear systems (SMINS) in order to stimulate an exchange of scientific information on current and innovative materials research programmes for different advanced nuclear systems with a view to identifying and developing potential synergies. The workshop covered fundamental studies, modelling and experiments on innovative structural materials including cladding materials for the range of advanced nuclear systems such as thermal/fast systems, subcritical systems, as well as fusion systems. This document presents a summary of the presentations given during the workshop and of the various discussions held during the sessions and panel discussions.

Acknowledgements

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List of abbreviations

ACTOF	Analysis of options and experimental examination of fuels with increased accident tolerance
ADS	Advanced data structure
AFA	Alumina forming alloys
ATF	Accident-tolerant fuel
AM	Additive manufacturing
AMME-TF	Advanced Manufacturing and Materials Engineering Task Force
ANSTO	Australian Nuclear Science and Technology Organisation
APT	Atom probe tomography
BCC	Body-centred cubic
BWR	Boiling water reactor
CAS	Chinese Academy of Sciences (China)
CEA	Le Commissariat à l'énergie atomique et aux énergies alternatives (Alternative Energies and Atomic Energy Commission, France)
CFETR	China Fusion Engineering Test Reactor
CIEMAT	Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (Center for Environmental and Technological Energy Research, Spain)
CNRS	Centre national de la recherche scientifique (National Centre for Scientific Research, France)
CRP	Co-ordinated Research Programme
CVD	Chemical vapour deposition
DBTT	Ductile-to-brittle transition temperature
DFT	Density functional theory
DLI-MOCVD	Direct liquid injection – metalorganic chemical vapour deposition
DOE	Department of Energy (United States)
EATF	Enhanced accident-tolerant fuel
EBSD	Electron backscatter diffraction
EERA	European Energy Research Alliance
EGISM	Expert Group on Innovative Structural Materials
ENEA	L'Agenzia Nazionale per le Nuove tecnologie, l'Energia e lo Sviluppo economico sostenibile (National Agency for New Technologies, Energy and Sustainable Economic Development, Italy)
F/M	Ferritic/martensitic

GEMMA	GEneration IV Materials MAturity
GIF	Generation IV International Forum
HEA	High-entropy alloys
HTGR	High-temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
ICME	Integrated computational materials engineering
INL	Idaho National Laboratory (United States)
INSPYRE	Investigations Supporting MOX Fuel Licensing in ESNII Prototype Reactors
JAEA	Japanese Atomic Energy Agency
JPNM	Joint Programme on Nuclear Materials
KAIST	Korea Advanced Institute of Science and Technology
KI	Kurchatov Institute (Russia)
KIT	Karlsruhe Institute of Technology (Germany)
KTH	Kungliga Tekniska högskolan (KTH Royal Institute of Technology, Sweden)
LANL	Los Alamos National Laboratory (United States)
LBE	Lead-bismuth eutectic
LOCA	Loss-of-coolant accident
LWR	Light water reactor
M4F	Multi-scale modelling for fusion and fission materials
MATISSE	Methods and tools for integrated sustainability assessment
MEGAPIE	Megawatt pilot target experiment
MMLC	Multi-metallic layered composite
MSR	Molten salt reactor
MTA	Magyar Tudomanyos Akademia (Hungary)
NEA	Nuclear Energy Agency
NITE	National Institute of Technology and Evaluation (Japan)
NPP	Nuclear power plant
NSC	Nuclear Science Committee, NEA
ODS	Oxide-dispersed strengthened
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory (United States)
PIE	Post-irradiation experiment
PKA	Primary knock-on atom
PSI	Paul Scherrer Institute (Switzerland)

PVD HIPIMS	Physical vapour deposition by high-power impulse magnetron sputtering
PWR	Pressurised water reactor
R&D	Research and development
RAFM	Reduced activation ferritic/martensitic
RHEA	Refractory high entropy alloy
RIS	Radiation-induced segregation
SCK•CEN	Research Centre for the Applications of Nuclear Energy (Belgium)
SEM	Scanning electron microscopy
SFR	Sodium fast reactor
SMINS	Structural materials for innovative nuclear systems
SMR	Small modular reactor
TEM	Transmission electron microscopy
TMT	Thermo-mechanically treated
XRD	X-ray diffraction
UNIST	Ulsan National Institute of Science (Korea)
VHTR	Very high temperature reactor
WPFC	Working Party on Scientific Issues of the Fuel Cycle, NEA

Introduction

Since 2007, the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) has organised a series of workshops on structural materials for innovative nuclear systems (SMINS). The fifth meeting, held from 8-11 July 2019 in Kyoto (Japan), was hosted by the Kyoto University and the Japanese Atomic Energy Agency (JAEA) in co-operation with the International Atomic Energy Agency (IAEA) and the European Energy Research Alliance (EERA) through the Joint Programme on Nuclear Materials (JPNM).

The main purpose of this workshop was to stimulate an exchange of scientific information on current and innovative materials research programmes for different advanced nuclear systems with a view to identifying and developing potential synergies. The workshop covered fundamental studies, modelling and experiments on innovative structural materials including cladding materials for the range of advanced nuclear systems such as thermal/fast systems, subcritical systems, as well as fusion systems.

During the workshop, the following topics were discussed:

- fundamental studies;
- advanced processes and materials;
- metal alloys for advanced systems.

Fundamental studies focused on the identification of mechanisms driving the response of materials under the environmental conditions expected in advanced nuclear systems. These mechanisms may have acted at the atomic or higher scale and the application of multi-scale approaches, together with related problems of scale bridging or numerical methods, were of special interest.

Advanced processes and materials included topics such as high-entropy alloys, functionally graded materials, nano-grained materials, grain boundary engineered materials, nano-precipitation-strengthened materials, oxide-dispersion strengthened materials (ODS) and micro-laminates, MAX phases, numerical design of materials and processes. Accident-tolerant fuel cladding in light water reactor (LWR) systems were also within the scope of the meeting. Processing and joining focused on novel and advanced methods (including coatings) for the production of materials for nuclear systems: for instance, additive manufacturing (AM), laser sintering and innovative joining techniques for similar and dissimilar materials.

In line with this topic, a specific panel discussion was held on “on how to fast track innovative materials through to application”.

Metal alloys for advanced systems included in- and out-of-core applications with the scope of data availability and gaps; experimental and modelling needs for specific components or degradation modes; the link between fundamental research, fine characterisation and experimental protocols; mechanical properties; ion and neutron irradiation experiments and their post-irradiation experiments (PIE); corrosion tests associated with fine interface analysis and/or irradiation experiments and/or mechanical tests.

The workshop received 120 abstracts. In total, 105 participants from 19 countries and 2 international organisations attended and the final number of presentations amounted to 109 (39 oral presentations and 70 posters) with 16 invited speakers.

Each section of this report briefly summarises the presentations and discussions held during each workshop session.

The workshop materials (i.e. presentations and book of abstracts) can be accessed by workshop participants on the NEA website: www.oecd-nea.org/SMINS-5.

Overview of the programmes (Session I)

Session I, on national and international programmes, was divided into four parts, with two or three presentations held every morning. As such, the session was chaired by a different person every day.

International perspectives from several current programmes were presented:

Tai Asayama (JAEA, Japan) gave an overview of the Japanese Programmes on Materials for Innovative Nuclear Systems. The focus was on the large Japanese experience in fabricating, testing and preparing standards for Fe-Cr ODS steels for sodium fast reactor (SFR) high burn-up fuel cladding on data acquisition and high-temperature material property equations for supporting SFR structural materials codification and safety evaluation and on research and development (R&D) for a commercial high-temperature gas-cooled reactor (HTGR).

Lorenzo Malerba (JPNM co-ordinator) described the vision of the Joint Programme on Nuclear Materials of the European Energy Research Alliance. The EERA JPNM currently brings together 52 European public research organisations and represents an important, and so far successful, co-ordination umbrella for activities on materials for innovative nuclear systems. Investigations Supporting MOX Fuel Licensing in ESNII Prototype Reactors (INSPYRE), GEneration IV Materials MAturity (GEMMA) and Multi-scale Modelling for Fusion and Fission Materials (M4F) are Euratom-funded projects of the JPNM. In the near future, JPNM will foster a European joint programme on nuclear materials co-funded by Euratom and its member states.

Stuart Maloy (LANL, United States) gave insights into US Department of Energy (DOE) research on advanced reactor clad materials. The DOE pursues the ultimate goal to support different reactor concepts by making available advanced materials immune to fuel, neutrons and coolant interactions under specific environments. A new heat of HT-9 with controlled interstitial concentration is being developed and tubes made from radiation tolerant nanostructured ferritic alloys rods are being processed and tested.

Erich Stergar (SCK•CEN, Belgium) provided an update of the MYRRHA project. In September 2018, the Belgian Government decided upon launching the construction phase of MYRRHA in Mol with a budget secured for: i) building the up-to-100 MeV accelerator MINERVA; ii) further design R&D and licensing of the reactor and of the up-to-600 MeV accelerator; and iii) the operational expenses of MINERVA up to 2038. In support of MYRRHA, the R&D programme is mainly directed at identifying materials issues, assessing materials properties and qualifying materials using experimental facilities.

Manuel Pouchon (PSI, Switzerland) gave an overview of the nuclear materials research in Switzerland. Though Switzerland is phasing out of nuclear power, research is still active in support of nuclear power plant (NPP) lifetime extension, nuclear waste management and fusion. PSI capabilities in terms of beam lines including a shielded beam line for handling radioactive materials and a companion hot lab were illustrated with the example of in situ high-speed X-ray diffraction (XRD) characterisation of ODS made by additive manufacturing with laser melting.

Yugang Wang (Peking Uni., China) provided a status of the fusion reactor materials R&D activities in China that are mainly driven by the China Fusion Engineering Test Reactor (CFETR). A preliminary roadmap was drawn up to match the engineering design and construction requirements of CFETR, which encompasses many projects on plasma-facing materials like W- and Cu-based alloys, on structural materials like reduced activation ferritic/martensitic (RAFM) and ODS steels, on the breeding blanket for tritium management and on supporting experimental and numerical platforms.

Pietro Agostini (ENEA, Italy) described the European GEMMA Project, which comprises work on the technical readiness level of steels for Generation IV prototype reactors under investigation in Europe, on the compatibility with coolants and on neutron irradiation effects. The programme, launched two years ago, is now bringing its first results. Examples include materials development like alumina forming alloys (AFA) steels, pulsed laser deposition, detonation gun and GESA surface treatments, mechanical tests in environment and neutron-diffraction stress measurements on thick welds.

Mikhail Veshchunov (IAEA) detailed the status of the IAEA Co-ordinated Research Programmes (CRPs) on Ion-accelerator Simulation and Theoretical Modelling of Radiation Effects (SMoRE-2) and on Analysis of Options and Experimental Examination of Fuels with Increased Accident Tolerance (ACTOF). This second CRP was completed last year. New upcoming CRPs were presented on “Fuel Materials for Fast Reactors” and “Testing and Simulation of Advanced Technology Fuels”.

Lyndon Edwards (GIF) described the activities carried out within the Generation IV International Forum framework under the Task Force on Advanced Manufacturing and Materials Engineering (AMME-TF). A survey covering current and potential uses of advanced manufacturing in the nuclear industry was sent out to targeted stakeholders. Results showed that there is strong support for collaborative work. The techniques identified as having the greatest potential were cladding and surface modification followed by welding and joining and metal additive manufacturing. Most of the respondents agreed that approval by codes and standards organisations is an obstacle to adoption. Finally, cost is only seen as a moderate issue.

Fundamental studies (Session II)

Session II included five presentations addressing various aspects of the observation and physical understanding of damage accumulation in nuclear materials.

Cristelle Pareige (CNRS, France) presented new data and analyses by atom probe tomography (APT), PAS and transmission electron microscopy (TEM) of ion- and neutron-irradiated model FeCr steels from the European Methods and Tools for Integrated Sustainability Assessment (MATISSE) Project in relation to radiation hardening. Preferential segregations of Ni, Si, P and clustering were identified at specific nano-features like dislocation loops.

Lorenzo Malerba (CIEMAT, Spain) detailed refinements in modelling the radiation-induced formation and evolution of Mn, Ni, Si, P-rich clusters in ferritic/martensitic (F/M) FeCr steels. The approach couples density functional theory (DFT) data on point defect and cluster stability with the kinetic Monte Carlo method for transport calculations. These theoretical predictions agree qualitatively well with experimental evidences on model steels.

Pär Olsson (KTH, Sweden) addressed irradiation primary damage in structural materials at the quantum scale. The rationale was to improve the description of displacement cascades by using a dynamic model accurate for significant valence electrons but less computationally intensive than a complete treatment in quantum mechanics. The developed dynamic potential switching method, named LAVAX code, is ready to use, effective even if still rather costly in computational terms.

Alexander Ryanazov (KI, Russia) introduced the irradiation facility at the KI cyclotron and the experimental method for measuring swelling in tungsten under carbon-ion irradiation with a Mo mesh. Considerations were developed on the effective damage rates as a function of the reactor neutron spectrum.

Yuping Xu (CAS, China) described the development methods to reduce tritium permeation based on the system Fe-Cr-Al that produces alumina layer by oxidation. The performance of as-oxidised and irradiated barriers were evaluated.

The discussion that followed revealed that using simplified systems in terms of size, number of chemical elements and microstructure is helpful to bridge the gap between the characteristic scales of experimental studies and of numerical simulations. To move this forward, improvements in designing and controlling experiments should be searched for. In parallel, modelling can be refined by taking into account the microstructural inhomogeneity, such as elemental segregation and heterogeneities and the chemical effects with many interrelated elements in an attempt to capture complex properties beyond the accurate description of the dislocation network.

Oxide-dispersion strengthened alloy (Session III)

Sesssion III included three presentations, which focused on the most important issues in R&D of ODS steels: phase stability of oxides, welding techniques and fabrication process.

Akihiko Kimura (Kyoto University, Japan) reported experimental results on the phase stability of three sorts of Fe14Cr-ODS ferritic steels, which were irradiated with 6.4 MeV Fe ions with peak dose up to 150 dpa at 30° and 200°C. Hardening was assessed by nanoindentation. All ODS steels were hardened by ion irradiation. The 20 dpa ion irradiation can induce dissolution of the nano-oxides at room temperature. This radiation-induced dissolution, which depends on irradiation temperature, may be influenced by cascade overlapping at a high dpa rate.

Jian Gan (INL, United States) described recent work on pressure resistance welding for MA957 ODS tubes. Burst tests were carried out for different weld conditions and micro X-ray 3D scans, scanning electron microscopy/electron backscatter diffraction (SEM/EBSD), TEM, APT were used to identify the weld quality. Limited grain growth and uniform distribution of oxide particles were observed in pressurised water reactor (PWR) zones. X-ray CT scans show some incomplete bond regions but the current PWR conditions will be further optimised.

Qingzhi Yan (University of Beijing, China) presented the status of a novel fabrication process for ODS-like steels by casting. Y-Ti-O particles or precipitates are approximately 1-5 nm with Y content lower than 0.3wt%. Higher strength, lower ductile-to-brittle transition temperature (DBTT) and longer creep rupture life were measured as compared to the base material without Y addition. Adequate welds were obtained by electron-beam and thin wall tubes were produced by cold rolling, which show acceptable deformability.

Accident-tolerant fuels (Session IV)

Various options of cladding materials for accident-tolerant fuels (ATFs) were presented in Session IV including new alloys, coated materials and composites. These different options were presented at various stages of development together with performance results.

Shinichiro Yamashita (JAEA, Japan) presented the current status and future prospect of LWR ATF R&D in Japan. Both, FeCrAl-ODS and SiC composites have been selected as promising candidates for advanced fuel components with enhanced accident tolerance. The objective is to finalise the R&D programme by 2022. Results were presented concerning the fabrication of thin wall tubes of FeCrAl ODS as well as a performance study for boiling water reactor (BWR) applications (mechanical tests on irradiated and non-irradiated samples). Concerning SiC composites, R&D on corrosion behaviour for BWR was performed using Cr coated chemical vapour deposition (CVD) SiC and Ti-coated CVD SiC. The best behaviour was obtained on Ti-coated CVD SiC. R&D was also performed on SiC composites for PWR. Tests under loss-of-coolant accident (LOCA) conditions in a PWR showed good results compared to Zr-based alloy.

Fanny Balbaud (CEA, France), presented developments performed in France in the field of advanced surface treatments. Results obtained on zirconium alloy cladding coated by an external chromium layer by physical vapour deposition by high-power impulse magnetron sputtering (PVD HIPIMS) were presented showing very good results both in nominal and accidental conditions for PWR. Up-scaling of the deposition process is ongoing. An industrial prototype has been built with a capacity of treatment of 10 claddings at scale 1. Other developments concern MAX phase coatings. Internal amorphous chromium carbide coatings are also investigated for zirconium alloy cladding by the direct liquid injection – metalorganic chemical vapour deposition (DLI-MOCVD) process showing promising results. Finally, coatings performed by laser metal deposition for cobalt free hard facing materials were presented.

Changheui Jang (KAIST, Korea) presented results on the performance of alumina forming duplex stainless steels as ATF cladding materials. A nominal composition was determined allowing coexistence of austenite, ferrite and nickel aluminide. The formation of a protective oxide layer was observed in both normal and accidental conditions. Satisfying mechanical behaviour was also obtained. Thin cladding tubes (0.3 mm thickness and 1.6 m long) were successfully fabricated by pilgering.

Akira Kohyama (NITE Corporation, Japan) presented three different neutron irradiation programmes ongoing in the Halden reactor on SiC/SiC claddings produced by nano-infiltration. A very good corrosion behaviour of the NITE SiC/SiC was observed. Helium gas leak tightness of the cladding was observed using eddy current measurements. A drop tower type mechanical test was developed in the Halden hot lab.

Tae Yong Kim (UNIST, Korea) presented work on multi-metallic layered composite (MMLC) for ATF cladding. The different layers above the Zr alloy are: an intermediate layer to prevent the formation of Fe-Zr intermetallic, a Fe-12Cr-Si alloy layer to improve accident tolerance, a CRUD (deposited corrosion products) barrier coating. The elaboration of the MMLC cladding was achieved by successive steps of bonding, HIP, machining, co-extrusion and pilgering. The final material is constituted of successive layers: Zr alloy/Ti/V-Cr-Ti/FeCrSi. Oxidation resistance of FeCrSi alloy was evaluated at 1 200°C under H_2O and Ar gas showing excellent corrosion resistance. CRUD deposition resistance was also evaluated on TiN coated cladding showing reduction of deposition. Ion irradiation tests were performed with Si ions. No segregation was observed in the FeCrSi and Ti layers but some segregation of Ti and Cr was observed in the Zy-4 grain boundaries.

Advanced processes and materials (Session V)

In Session V, both innovative materials and coatings were discussed as well as new processes to produce these materials.

Advanced materials

In the field of heavy liquid metal corrosion, Alfons Weisenburger (KIT, Germany) presented different solutions to mitigate corrosion with alumina forming alloy:

- Development of FeCrAl alloys with incorporation of reactive elements (Y, Zr, Hf, Mo): It was observed during corrosion tests in liquid lead that reactive elements foster the alumina formation and that a certain Al/Cr ratio is required for alumina formation.
- Development of alumina forming austenitic steel: $FeCr_{12\text{-}16}Al_{2.5\text{-}4}Ni_{20\text{-}29}$. Different generations of alloys were developed using thermo-dynamic calculations showing very good corrosion results in liquid lead. Small punch test showed a ductile behaviour of all the samples tested.
- High-entropy alloys (HEAs) design and manufacturing: $FeCr_{20\text{-}30}Al_{3\text{-}6}Ni_{20\text{-}37}$. Different compositions were tested and various microstructures were obtained depending on composition. After immersion in liquid lead at 600°C, formation of AlCr rich protective oxide scale was observed for most of them. Further work is needed.

Emmanouil Stavroulakis (University of Manchester, United Kingdom) presented work on functionally graded materials produced by hot isostatic pressing to eliminate dissimilar metal welds by replacing them with functionally graded transition joints. The chosen system was SA508 Grade 3 (bainitic steel)/316L. Microstructural characterisations as well as mechanical tests were performed on first heats of materials. Dramatic increase in hardness and strength was observed together with loss of ductility in intermediate compositions of 316L and SA508 Grade 3. Formation of laths was observed as a result of element diffusion between the two phases. Composition limits were determined for formation of the α-Fe lath constituent.

Bo Shiuan Li (University of Oxford, United Kingdom) presented the development of refractory high-entropy alloys elaborated by arc casting: TiVNbTa and TiVCrTa. Ion irradiation tests were performed to evaluate the irradiation resistance of these alloys. Microstructural analysis, nanoindentation tests and micro-cantilever bending tests were performed. Results showed that the crystal structure for the two refractory high entropy alloys (RHEAs), TiVNbTa and TiVCrTa, is mostly body-centred cubic (BCC) in the as-cast state. Nanoindentation serves as a quick screening test for investigating irradiation-induced hardening. Thermally-stable microstructure must be achieved before conducting HT irradiation/nanoindentation experiments.

Advanced processes

Pascal Aubry (CEA, France) presented additive manufacturing (AM) activities for nuclear applications. Numerous technologies are being evaluated such as powder bed fusion (selective laser melting, electron beam melting), laser cladding (plasma transfer arc, direct metal deposition), wire (laser) with the number of parts required: maintenance for operational conditions, repair, continuity of the production chain, function integration, complex shapes. Application within the nuclear industry sets specific requirements in terms of material issues, codification/regulation, robustness of the AM process. Other limitations of AM are the size of components, the production time and finishing. Several issues need to be addressed such as link process/microstructure for parameter optimisation, addition of structure, of function, replacing, rebuilding, repair, production of demonstration parts, design optimisation, production of HEA and graded materials (direct metal deposition).

Alfons Weisenburger (KIT, Germany) presented the steel surface alloying process, which is another way (alternative to the development of new steels also presented by KIT) of developing alumina forming steels by coating the surface with Al or with an Al containing alloy and then melting the coating and surface layer of the steel using the GESA process (pulsed intense electron beam). A thin protective alumina layer was obtained that protected the steel during corrosion tests in liquid lead or Pb-Bi up to 600°C and 10 000 hours, except at 550°C, raising the question of an optimal Al/Cr content.

Metal alloys for advanced systems (Session VI)

The presentations in Session VI mainly addressed the development and characterisation of improved metal alloys and/or the understanding of metal damage modes like irradiation embrittlement and environmental compatibility.

Improved metal alloys

Marta Serrano (CIEMAT, Spain) reported an ongoing study on modified T91 F/M steel by thermo-mechanical treatments. The thermo-mechanically treated material (TMT) consists of austenitising at 1 227°C, rolling to 20% at 900°C and tempering for 2 hours at 740°C with a view of enhanced creep properties. The resulting microstructure has been characterised in detail. A uniform distribution of MX precipitates was obtained and the creep strength is improved. However, the steel ductility is decreased. An optimum balance between creep properties and ductility should be sought for low-stress applications.

Akira Hasegawa (Tohoku Uni., Japan) presented a study on effects of low concentration of helium on the tensile properties of tungsten for fusion systems. Up to 20 appm helium was implanted, which is similar to first wall values at 5 years. A reduced DBTT and an increased recrystallisation temperature were observed in the implanted regions as compared to the AR tungsten.

Thierry Auger (CNRS, France) described the work to identify and better understand the intermediate temperature embrittlement in high Cr, high W, nickel alloys envisioned as advanced structural materials for a molten salt reactor (MSR) where W replaces Mo. The investigated NiCrW alloys tend to exhibit inter-granular cracking at 700-900°C. This tendency is reduced in fine-grained alloys and when grain boundary oxygen segregation is minimal.

Ondrej Muransly (ANSTO, Australia) reviewed the activities planned at the Australian Nuclear Science and Technology Organisation (ANSTO) in support of Generation IV systems. The materials under scrutiny for MSRs are austenitic steels and Ni-based alloys. Very high temperature reactor (VHTR) materials focus on Alloy 617, graphite and TiAl.

Irradiation embrittlement

Yong Dai (PSI, Switzerland) described the analyses of solute elements and spallation transmutants in F/M steels after irradiation to 9 and 20 dpa with high-energy protons and spallation neutrons. Enrichment was observed at grain boundaries and at precipitate-matrix interfaces like with Ca up to 0.1%. The effect of such an enrichment on embrittlement needs further clarification.

Arnaud Courcelle (CEA, France) presented new results of the PIE of neutron-irradiated austenitic steel up to high fast neutron doses. Ring tension tests were performed at room temperature (RT) with fracture mechanism investigated by SEM on fractured specimens. These data allow quantitatively correlating embrittlement and swelling. Ductility was significantly reduced at 4% swelling and above due to inter-granular and trans-granular fracture. A micromechanical modelling was developed based on the growth and coalescence of irradiation-induced voids. The model allows for a reliable prediction and may be improved by including the fuel clad chemical interaction and the variation of swelling across the wall thickness.

Environmental compatibility

Nariaki Okubo (JAEA, Japan) introduced the specific materials issues for the beam window and cladding in an advanced data structure (ADS) core. Materials research at JAEA covers mechanical tests in oxygen-controlled liquid lead bismuth alloy and the influence of irradiation on compatibility with lead-bismuth eutectic (LBE), which is investigated through ion irradiation followed by corrosion tests. During these tests, SS316 and T91 behave differently. Outlooks include testing with megawatt pilot target experiment (MEGAPIE) and STIP irradiated specimens.

Márton Kiraly (MTA EK, Hungary) described the activities of Hungary in support of the ALLEGRO gas-cooled fast reactor addressing the effect of pure helium and He mixed with H_2, CH_4 and N_2 at 1 000°C on the ring tensile strength of 15-15Ti austenitic steel. Burst experiments at high temperature were also reported.

How to fast track innovative materials through application (Panel discussion)

Four speakers first presented thematic speeches to introduce the topic of the panel discussion.

Franck Tancret (University of Nantes, France) presented Integrated Computational Materials Engineering (ICME) vs. Integrated Computational Alloy Design. ICME, by chaining models in series, is intrinsically limited by propagation of uncertainties. In fact, it can be used as a tool, combined with experiments, for incremental design. On the other hand, computational alloy design needs fast models, working in parallel with tools such as machine learning. Examples given of "Intelligence guided exploration of alloy systems" included:

- Determination of the best nominal composition of a commercial super alloy within its patent range: this was performed by multi-objective optimisation using data mining/machine learning for strength and creep resistance; thermo-dynamic calculations for phase constitution, oxidation resistance and processability; and empirical equations for cost and density.
- Design of high-entropy alloy: optimisation in >16 element compositional space of "high-entropy alloys" to maximise strength and minimise density.

In the following discussion, it was highlighted that accurate predictions require accurate models and accurate data, but for complex properties such as toughness and fatigue, the current models and data basis are insufficient for machine learning tools.

Frédéric Schuster (CEA, France) presented the opportunities for advanced manufacturing technologies in an integrated approach to low-carbon energy, including nuclear. Although seemingly different, nuclear with long timescales, low competition, need for developing science to predict materials' long-term behaviour and renewables with fast feedback, intense competition and low-cost processes may develop synergies.

Indeed, cross-cutting opportunities exist in manufacturing, characterisation tools, simulation, durability studies. Examples include additive manufacturing (repair, remanufacturing, optimised components, basic studies) in a circular economy approach, advanced coating technologies, enhanced accident-tolerant fuel (EATF), fuel clad interaction, corrosion, nano-manufacturing and hybridation of processes. Robust processes are required and tools are needed for up-scaling and evaluating emerging processes (and hybrid processes) that enable new designs.

Finally, to answer the panel discussion question, "How can we accelerate materials and process developments?", different examples were presented:

- combinatorial synthesis to accelerate thin film developments in connection with numerical design;
- laser engineering net shaping: a new approach for the design of new alloys;
- numerical simulation of new processes: example of DLI-MOCVD development;

- generation of data bases for emerging processes, like AM;
- process optimisation assisted by artificial intelligence.

In the field of advanced manufacturing, there is potential for co-operation with international research and education organisations.

Steve Zinkle (ORNL, United States) presented the roles of ion and neutron irradiations to evaluate and qualify innovative structural materials for nuclear energy applications.

Ion and neutron irradiations offer complementary capabilities for accelerating the development and qualification of new high performance structural materials. However, complete "emulation" of neutron irradiation effects by ions and vice-versa is problematic (impossible) due to dose rate and primary knock-on atom (PKA) spectrum effects. The example of the multiple "temperature shifts" for different microstructural components [cavities, dislocation loops, precipitates, radiation-induced segregation (RIS), etc.] was developed.

In all cases, ion irradiations are an indispensable scientific tool to help guide and validate the development of physics-based comprehensive models of radiation effects aiming to:

- identify fundamental radiation effects phenomena;
- explore damage rate and He/dpa effects on microstructural evolution, volumetric swelling, etc.

William Weber (University of Tennessee, United States) presented results on irradiation-induced defect production and microstructure evolution in tunable concentrated solid-solution alloys. Concentrated solid-solution alloys consist of multiple elemental species, exhibit extreme intrinsic chemical disorder and lattice distortion raising the question of tunable defect properties (modified migration barriers, high defect recombination probability, limited atomic diffusion, etc.). Therefore, systematic study of concentrated solid-solution alloys was presented using modelling at the electronic and atomistic level showing:

- effects on electronic structure and short range, non-periodic energy landscape at atomic scale;
- identification of alloys predicted to have improved resistance to swelling due to enhanced recombination of interstitials and vacancies in damage cascades.

The results of these calculations were confirmed by experimental studies in single crystals, ODS alloys and nano-crystalline alloys.

Synthesis of the panel discussion

The presentations were followed by an open and active discussion between panellists and participants. The main points raised during the discussion are the following:

- To qualify a new material, one needs bulk materials: these can be produced, but the testing and characterisation of these is a bottle-neck that requires money and a workforce.
- Designers can provide the "push" for innovation:

  - ATF developments are driven by safety, but there is a big impetus for innovation when it also reduces cost; innovation in structural materials is also more challenging.
  - Round robin activities, which can be considered within the NEA/EGISM, can accelerate new tools and methods; and ion irradiation and additive manufacturing could be themes of round robin activities.
  - If new materials can be developed and demonstrate improved properties, user interest will grow. New manufacturing processes will lead to the development of new properties.
- Is the nuclear industry less visionary than it used to be?
  - Why is there little or no innovation in LWR, except in fuels?
  - The nuclear industry is not strongly engaged in new systems, but there may be a push? for innovation, e.g. in small modular reactor (SMR) systems, if the materials community works and communicates with designers and the regulators.

Poster session

Most topics at the SMINS workshop are displayed in the form of poster presentations. The poster session was held on the evening of 9 July with posters on display all day. Each poster presenter was given the opportunity for a short oral presentation with the support of one or two slides in order to introduce the key issues of the topics. Specific time slots were allocated for these short 3-minutes presentations on Monday 8 July and Tuesday 9 July.

For the first session, 25 short presentations were given. 20 posters specifically focused on experimental investigations and 5 on modelling studies. The second session held 35 short oral presentations on advanced materials and manufacturing processes including ATF, metal alloys and their degradation mechanisms, irradiation programmes and facilities. Many presentations included irradiation experiments, the majority of which used ion beams with very limited research on long and costly neutron irradiations. The number of poster presentations from research institutions, national laboratories and universities was well balanced.

Attendance in the poster room was excellent, which stimulated animated and fruitful exchanges around the posters. The evening poster session was successful in terms of promoting discussions inspired by scientific interest. The poster session was a highlight of the SMINS workshop.