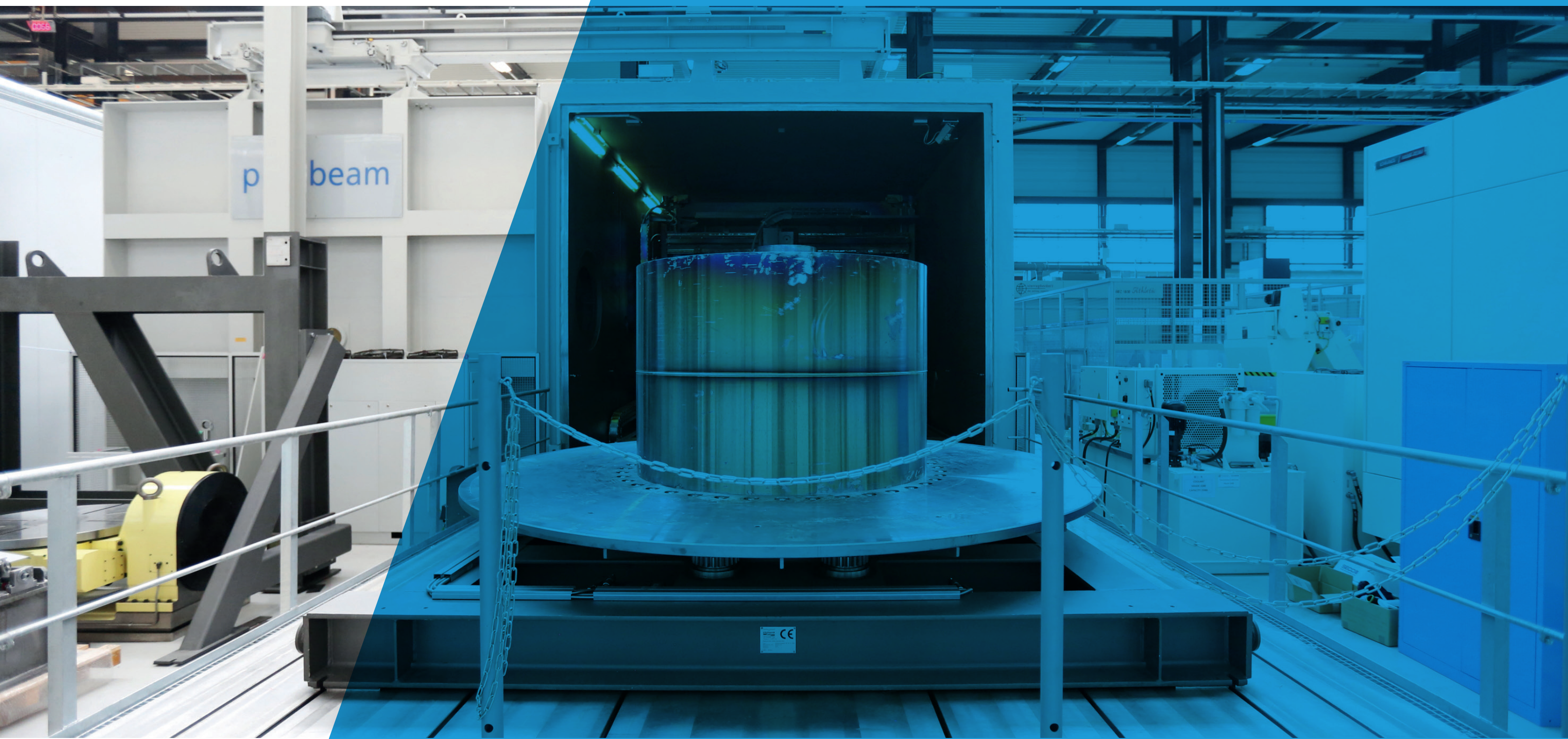
WORLD NUCLEAR ASSOCIATION



Advanced Manufacturing of Nuclear Components

Accelerating the harmonized development of codes and standards

Cooperation on Reactor Design Evaluation and Licensing Mechanical Codes and Standards Task Force

Title: Advanced Manufacturing
of Nuclear Components
Produced by: World Nuclear Association
Published: September 2022
Report No. 2022/004

Contents

Contributors to the report

Technical Author & Project Coordinator

Ronan Tanguy, World Nuclear Association

Industry Project Contributors

Damien Couplet, Engie Tractebel
Ekaterina Svistunova, Rosatom RusAT
Mejido Hajjaj, EDF
Oliver Martin, EC Joint Research Centre
Steve Jones, NAMRC
Thomas Geneves, Framatome

Supply Chain Working Group Contributor

Nathan Paterson, World Nuclear Association

Reviewers

Byung-Chan Na, World Nuclear Association
Cécile Petesch, CEA
Damien Couplet, Engie Tractebel
Frédéric Beaud, EDF
Nawal Prinja, Jacobs
Steven Lawler, Frazer-Nash Consultancy

Foreword

The World Nuclear Association's Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group was established in 2007 to promote the development of a worldwide regulatory environment where internationally standardized reactor designs can be widely deployed without major design changes due to national regulations.

The Mechanical Codes and Standards Task Force (MCSTF) of the CORDEL Working Group was set up in 2011 to collaborate with the Standards Development Organizations Board and the Multinational Design Evaluation Programme (MDEP) Codes and Standards Working Group (CSWG) on the international convergence of mechanical codes and standards related to the design of nuclear power plant components important to safety. The MCSTF's collaboration with regulators is now through the Committee for Nuclear Regulatory Activities (CNRA) of the OECD Nuclear Energy Agency (NEA). The MCSTF has focused on three areas: qualification of non-destructive examination personnel; fatigue analysis and design rules; and non-linear analysis design rules.

Abbreviations and acronyms

AFCEN	Association française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières électro-nucléaires (French Association for the Rules Governing Design, Construction and In-Service Inspection of Nuclear Plants)
AFCN	Agence fédérale de contrôle nucléaire (Belgian Nuclear Regulatory Agency, Federaal Agentschap voor Nucleaire Controle, FANC)
ASME	American Society of Mechanical Engineers
ASN	Autorité de sûreté nucléaire (French Nuclear Safety Authority)
ASTN	American Society for Testing and Materials
BPVC	Boiler and Pressure Vessel Code
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (French Atomic Energy and Alternative Energies Commission)
CNRA	NEA Committee on Nuclear Regulatory Activities
CNSC	Canadian Nuclear Safety Commission
CORDEL	Cooperation on Reactor Design Evaluation & Licensing Working Group of the World Nuclear Association
EC	European Commission
EPRI	Electric Power Research Institute
FOAK	First-of-a-kind
IRSN	Institut de radioprotection et de sûreté nucléaire (French Institute for Radiological Protection and Nuclear Safety)
ISO	International Organization for Standardization
MCSTF	Mechanical Codes & Standards Task Force of the World Nuclear Association CORDEL Working Group
Nuclear AMRC	Nuclear Advanced Manufacturing Research Centre
NEA	Nuclear Energy Agency of the OECD
NUCOBAM	Nuclear Components Based on Additive Manufacturing (SNETP)
OECD	Organisation for Economic Co-operation and Development
RCC-M	Règles de conception et de construction des matériels mècaniques des ilots nucléaires PWR (Design and Construction Rules for the Mechanical Components of PWR Nuclear Islands)
RCC-MRx	Règles de conception et de construction des matériels mécaniques des installations nucléaires hautes températures, expérimentales et de fusion (Design and Construction Rules for Mechanical Components of Nuclear Installations: High-temperature, Research and Fusion Reactors)
RusAT	Rusatom Additive Technologies
SDO	Standards developing organization
SNETP	Sustainable Nuclear Energy Technology Platform
UK ONR	United Kingdom Office for Nuclear Regulation
US DOE	United States Department of Energy
US NRC	United States Nuclear Regulatory Commission
WGCS	NEA Working Group on Codes and Standards

Technical nomenclature

CAD	Computer-aided design
NDE	Non-destructive examination
NDT	Non-destructive testing
PWR	Pressurized water reactor
R&D	Research and development
SMR	Small modular reactor
SSC	Structures, systems, and components

Tables

Figures

Executive summary

Advanced manufacturing techniques are of great interest to the nuclear industry as they enable the realization of complex designs, whilst improving the quality and safety of components and reducing the time and cost involved in their manufacture. These techniques have seen rapid development and deployment in many industries but their applications to nuclear power are still at an early stage. Such applications include the repair of equipment or replacement of parts in existing plants, the procurement of new components or manufacture of integral products. These may have nuclear safety functions and may form integral parts of the reactor pressure vessel, notably for small modular reactor (SMR) projects.

The interest in nuclear applications of advanced manufacturing was confirmed by a survey of members of the World Nuclear Association's Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group. National regulators such as the US Nuclear Regulatory Commission, UK Office for Nuclear Regulation and the Canadian Nuclear Safety Commission, as well as other international organizations, have also shown interest in the topic and are aiming to set requirements and guidelines to review the emerging applications of the technologies to the nuclear industry. Standards developing organizations (SDOs) are launching committees to prepare standards supporting these manufacturing techniques (*e.g.*, the ASME Subgroup on Materials, Fabrication and Examination).

However, challenges remain in demonstrating the quality and reliability of materials produced through advanced manufacturing techniques under both normal and accident conditions. Qualification methodologies are being developed to overcome these issues and enable the codification of advanced manufacturing techniques. The development of these codes and standards in a harmonized manner is essential for factory-based international deployment of SMRs.

CORDEL's Mechanical Codes and Standards Task Force (MCSTF) therefore proposes that more efforts and resources should be put into collaborative projects that aim to develop and advance new proposals for advanced manufacturing techniques to code development committees. This will accelerate their development and enable codification to support reactor deployment schedules. More standards developing organizations should adjust their approach to codification, as AFCEN have done, to promote innovation. The nuclear industry also should engage early with regulators and work alongside them to develop common approaches to the regulation of advanced manufacturing techniques and their use within the nuclear supply chain.

1 Introduction

This report presents ongoing and completed advanced manufacturing projects in the nuclear industry. The challenges faced by these projects regarding the application of codes and standards as well as in obtaining regulatory acceptance could serve as examples for the wider integration of advanced manufacturing techniques into the global nuclear supply chain. These projects were carried out in Belgium, France, Russia, UK and USA and cover a variety of regulatory regimes and codes and standards.

The report features three main sections: an overview of advanced manufacturing techniques that are being considered for nuclear applications; a selection of advanced manufacturing nuclear projects and the challenges they encountered with regard to codes and standards, and regulation; and the advances and innovations needed within the nuclear supply chain.

Finally, the report provides recommendations for the nuclear industry to adopt advanced manufacturing techniques and benefit from their many advantages.

2 Advanced manufacturing for nuclear applications

2.1 Electron beam welding

Electron beam welding is a fusion welding procedure that uses a stream of high kinetic energy electrons to bond two materials. The electrons impact the parent materials, thereby heating them instantaneously so that they melt and flow together. The way the materials are bonded, notably without the need for a filler, means that electron beam welding provides extremely strong and accurate welds.

The electron beam is produced by a cathode, heated by a tungsten filament to the point that it emits electrons. The resulting electrons initially have very low kinetic energy (in the eV range) and must be accelerated by electric fields and focused by magnetic fields until they reach the power density levels required to melt the parent materials (of the order of 107 W/mm2) (1). The whole process must take place in a vacuum to prevent the electrons from colliding with gases. This requirement limits the applications of electron beam welding as large components require proportionally large vacuum chambers. Recent advances have enabled the electron beam to be enclosed within a vacuum box placed by the side of the parent materials, thereby negating the need for the whole workpiece to be placed within a vacuum chamber.

Electron beam welding has great potential for nuclear applications not only due to the strength, accuracy, and depth of its resulting welds but also to the much shorter welding times and automation. The Nuclear Advanced Manufacturing Research Centre (NAMRC) has estimated that using electron beam welding to manufacture reactor pressure vessels for small modular reactors (SMRs) in a factory setting could cut welding times by a factor of 10 (2) and costs by 85% (3).

2.2 Hot isostatic pressing

Hot isostatic pressing (HIP) is a manufacturing process that uses a combination of high temperature and pressure (>1000°C and >100MPa) to densify powdered materials into near-net-shape parts or components. This reduces the need for both machining and welding, offers the possibility of complex shapes of components while also providing materials with homogeneous and fine microstructures, which tends to improve material properties and inspectability for large components compared to powdered material without HIP. Machining is not completely eliminated however, as it is required to remove the skin hardening effect seen by powder metal HIP and to achieve the final surface finish.

The HIP process follows five key stages. Firstly, metal powder of the required specification must be procured, for nuclear applications this is typically 316L stainless steel, grade 91 steel, SA508 or Tristelle 5183 steel with an appropriate particle size distribution and morphology. The second stage is the design and fabrication of the canister which is to be loaded with metal powder, and which provides the shape of the component that is being manufactured. This is the most challenging part of the process as not only does the canister have to account for shrinking of up to 30% during the HIP process but many welds must be performed manually. The third stage is the loading of the canister, during which it is vibrated

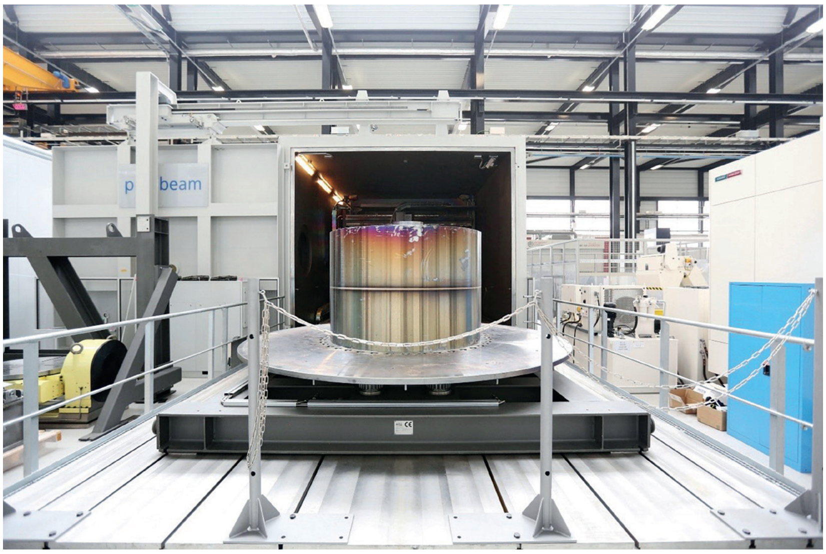


Figure 1. Electron beam welding of SA508 Gr3.Cl 2 steel (NAMRC)

to remove any gaps, thereby maximizing the packing density of the powder. The HIP cycle is the fourth stage, during which the canister and powder are exposed to very high temperature and pressure for two to four hours. The final stage is the removal of the canister either by machining or via acid pickling (4).

Nuclear applications of HIP include the manufacture of large Class 1 nuclear safety components such as reactor vessel heads, steam plenum and their access ports and transition shell sections. HIP can be used to produce lingots of material that can be further extruded into plates or other shapes. HIP has also been employed to immobilize radioactive waste products and encapsulate spent fuel (5).

2.3 Diode laser cladding

Weld overlay cladding is a commonly used process to protect metal components from corrosion and wear. A layer of corrosion-resistant alloy is welded over component sections that are exposed to challenging environments and conditions. Diode laser cladding (DLC) is a recently developed alternative to arc-based classic methods (manual metal arc, gas tungsten arc, gas metal arc, submerged arc, *etc.*) which offers many advantages over the previously mentioned methods due to the reduced amount of cladding material required, a smaller heat-affected region and a faster cladding process.

DLC uses a high-power diode laser (order of 10kW) to melt a powdered metal onto the surface of the component where it then cools and forms the protective cladding. DLC enables the production of very high quality cladding layers which have low porosity, very low dilution, and a uniform surface (6).

There are many potential nuclear applications for DLC on safety-classified components such as the reactor pressure vessel, nozzles, primary circuit pipes and other components that are subjected to the harsh corrosive environments found within a nuclear reactor.

DLC is also sometimes referred to as diode laser overlaying.

2.4 Additive manufacturing

Additive manufacturing, also commonly known as 3D printing, is a technique that constructs objects by depositing material layer by layer as opposed to traditional techniques that typically create parts via the removal of surplus material in processes such as machining which are referred to as subtractive manufacturing. This means that less material is required to manufacture parts using additive manufacturing, thereby reducing the costs involved and the amount of waste generated. The additive manufacturing process is controlled by computers that typically work directly from a CAD file thereby enabling the creation of precise geometric shapes. This level of control allows manufacturers to create objects that were previously impossible to produce opening new possibilities for designers to improve the mechanical performance of parts while reducing their weight.

Multiple additive manufacturing processes exist, however this report only covers those that have applications to produce structural components for nuclear plants.

2.4.1 Directed energy deposition

Directed energy deposition (DED) uses a nozzle to deposit melted material (typically metal powders or wires) onto a surface upon which it solidifies as it cools. The nozzle is mounted on a multi-axis arm that can move along the x, y, and z axes (7). While it is possible to use DED to produce complete parts, it is more commonly used to repair or add additional material to existing parts.

DED is also known as laser-engineered net shaping, directed light fabrication, direct metal deposition and 3D laser cladding when a laser is employed as the heat source. Other heat sources can also be used, such as electron beam welding, plasma arc or shielded metal arc welding.

Figure 2. Diode laser cladding processing of a pressure vessel lower dome (NAMRC)

2.4.2 Powder bed fusion

Powder bed fusion (PBF) uses a laser, an electron beam, or a thermal print head to melt and fuse a powdered material (metal or polymer) into a shape. A thin layer of the powdered material is spread by a roller before being exposed to the heat source that melts it to fuse it to the layer beneath it. Excess powder is then removed before the steps are repeated for the next layer.

Several additive manufacturing techniques are categorized as PBF but differ by the method used to apply the heat. These are direct metal laser melting, direct metal laser sintering, electron beam melting, selective heat sintering and selective laser sintering.

2.4.3 Cold spray

Cold spray is a solid state additive manufacturing process developed in the 1980s. Dynamic cold gas spraying, more commonly known as cold spray, is a process for making deposits by exposing a metallic or dielectric substrate to a high-speed jet (300 to 1200 m/s) of small particles (1-50 μm) accelerated by means of a supersonic flow of a compressed gas.

This process is based on the acceleration of particles via the injection of a compressed gas into a de Laval nozzle. This gas is generally preheated to temperatures that can reach 800°C to increase the speed at the nozzle outlet.

The particles remain in the solid state and are deposited at high speed on a substrate. The formation of the deposit is carried out by stacking particles which undergo a very significant and very rapid plastic deformation on impact.

The method can be attached to an industrial robotic arm or a manual system and has attractive portability. By using multiple passes, the possible deposition thicknesses are greater than those obtained from layering processes and by direct deposition.

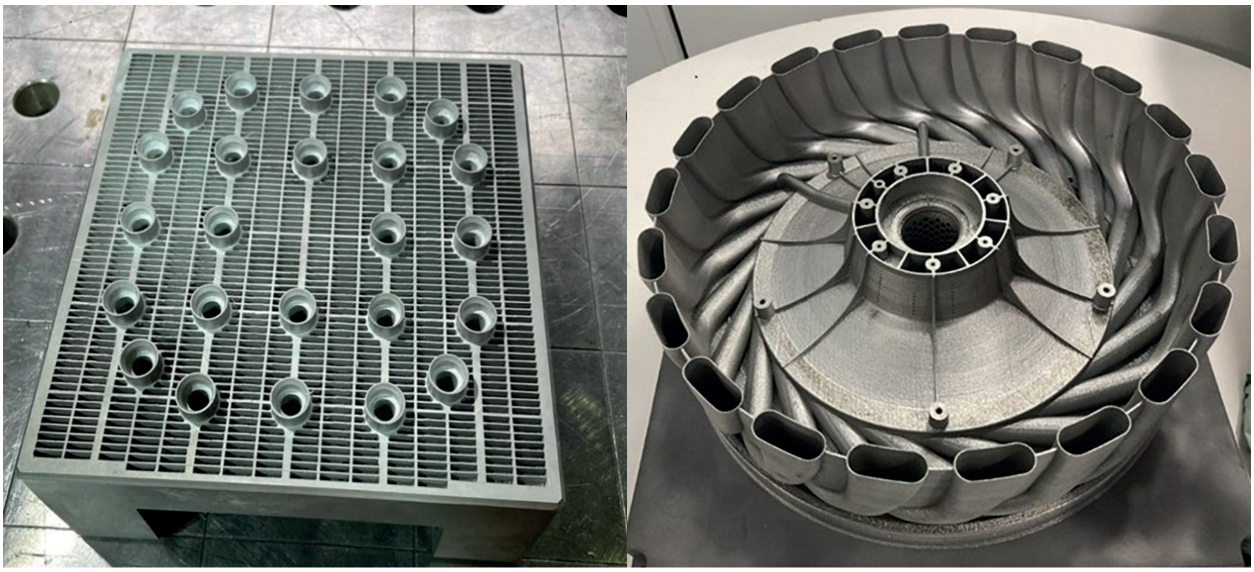


Figure 3. Fuel debris filter and pump impeller produced using powder bed fusion (RuSAT)

3 Nuclear advanced manufacturing insights

3.1 Engie

3.1.1 Project overview

Within the Engie group, Tractebel and Laborelec have been involved in the development of additive manufacturing for several years, principally using powder bed fusion (PBF) technology.

This technology is already employed outside of the nuclear industry, but its use is not yet widespread within the nuclear industry, notably for the manufacture of safety related pressure components. Engie aims to produce specific ad-hoc pieces as replacements for components in operational nuclear power plants that are either obsolete or difficult to procure. Obsolescence can occur for several reasons; either because the original manufacturer is no longer in business, the component has been discontinued, the cost of the component has become prohibitively expensive, or the lead times have increased to the point of being incompatible with plant operational needs.

PBF is a mature technology which has been mastered by Laborelec. The principal challenges in the implementation of PBF in the nuclear industry reside in the design, and the qualification of both the process and the final product.

Challenges arise for the design if the original detailed drawings and specifications cannot be found. This is unfortunately the case for some components that were procured over 40 years ago, for which it is not always possible to gather all the information needed. In such cases, new requirements must be developed, based on current regulations, practices for equivalent components, and using reverse engineering.

Qualification is required to demonstrate that the PBF manufacturing process can deliver the required component in a reproducible way, and that both its properties and quality will comply with the demands applicable to the relevant nuclear safety classification.

The additive manufacturing process has been optimized to produce a material with equivalent properties to material produced with traditional processes (*e.g.*, forging), that also satisfies typical C&S. Further research and development (R&D) are still needed to identify the type of tests that must be performed on specimens and on the final product to confirm that the required quality has been achieved. The material's response to long term degradation mechanisms such as fatigue, thermal ageing, and exposure to ionizing radiation must also be proven to be acceptable.

Tractebel and Laborelec are active contributors to the SNETP NUCOBAM project, an international project supported by the European Commission and funded by the Euratom H2020 programme. NUCOBAM is covered in more detail in Section 3.4.

In another project, for a Belgian NPP, Tractebel also made innovative use of materials and manufacturing techniques that are not commonplace in the nuclear sector: steel piping was replaced with piping made of glass reinforced epoxy. This required an equally strict and extensive qualification programme to demonstrate the quality of the product, of its fabrication and its installation on site, which employed chemical bonding instead of welding. The main challenges faced during this project were the limited availability of regulations and applicable nuclear specific standards for such materials and their application to nuclear piping.

3.1.2 Codes and standards related challenges

ASME BPVC is the mandatory code for the construction and in-service inspection of safety related pressure equipment for Belgian NPPs. The use of other codes is allowed provided it is supported by code reconciliation studied and the AFCN have approved their use.

The use of glass reinforced epoxy piping is based on an ASME code case, which was adapted to Belgian needs following discussions with the regulator. Specific instructions were developed in Belgium, based on recommendations from the manufacturer and industrial standards specifically relating to the material.

The qualification process for the glass reinforced epoxy was developed by Tractebel and was based upon the following:

- Manufacturer's instructions and experience for the material
- ASME code case and other industrial standards
- Analysis, bibliography study and experience feedback regarding the behaviour of the material in a nuclear environment

A specific in-service inspection program was also defined considering the degradation expected on this material, based on scientific analysis, and learning from experience.

The use of components or material obtained from additive manufacturing for nuclear safety related equipment is not yet exhaustively regulated in the nuclear C&S.

Some requirements exist for other AM technologies (*e.g.*, welding, powder metallurgy / hot isostatic pressing) but they do not cover all specificities of additive manufacturing. ASME is currently working to develop criteria for the qualification and acceptance of additive manufacturing components for pressure equipment. Work is in progress to define requirements for nuclear applications.

In Belgium, the use of components produced by additive manufacturing for safety related components must be approved by the Safety Authorities. The lack of established code or standard makes it difficult to identify the criteria that the Licensee or the manufacturer must meet and equally what could be acceptable to the Safety Authorities to maintain the same level of quality and reliability provided by a component manufactured by traditional means. An internationally recognized code or standard, or at least a guidance, supported by strong technical justifications, would assist the implementation of additive manufacturing technology into the nuclear industry.

Many parameters can affect the final quality of a product fabricated using additive manufacturing techniques. Multiple experimental results are therefore needed to identify the impact of each parameter. Work completed to date has so far provided such data for widely employed metals (*e.g.*, stainless steel 316L), but gaps remain for other metals. Another aspect to be considered is that each manufactured component is unique and, because of its shape and build plan, could present different characteristics to those of another component produced by the same additive manufacturing process.

Qualifying processes remains challenging as rules must be simultaneously generic whilst covering all specific aspects of the manufacturing processes. A large amount of experimental data is therefore required to substantiate the qualifications, a significant part of which has not yet been gathered. In the light of this lack of data and uncertainties, examinations and testing play an increasingly important role in confirming the quality of the manufactured component. Traditional examination methods such as non-destructive testing (NDT) may be difficult to implement or might not always be appropriate as there are also material properties that are specific to the additive manufacturing process which must be verified. Further development of testing and examination technologies and their related acceptance criteria is therefore required.

The chemical and mechanical properties of materials produced by additive manufacturing at the point of manufacture have been well studied and characterized for some metals, but knowledge will need to be developed regarding its long-term integrity. Further R&D must therefore be conducted to demonstrate that the components produced by additive manufacturing satisfy requirements with regards to ageing and the degradation mechanisms they are subjected to whilst in service in a nuclear environment, thermal ageing, fatigue, and irradiation. This research and demonstrations will form part of the qualification file of for equipment produced using additive manufacturing.

3.1.3 Regulatory related challenges

The general principle in Belgium is that, if a new manufacturing technology is to be used, it must be approved by the national regulator, the Agence Fédérale de Contrôle Nucléaire (AFCN). The Licensee (Plant Owner) and the Safety Authorities agree on a process to qualify and validate the new technology and the obtained products, including preliminary qualification tests, surveillance during the manufacturing, examinations and related acceptance criteria, and a specific follow-up program during operation. There is no detailed regulation for this approach, and it is based on a case-by-case agreement.

For the use of piping in glass reinforce epoxy, this process was followed successfully.

For additive manufacturing, no official discussion has yet started with the Safety Authorities, as no real case is envisaged for the moment, waiting for more maturity of the technology and its qualification in nuclear. As mentioned above, the existence of recognized C&S on the topic would ease the discussion.

3.2 Rosatom RusAT

3.2.1 Project overview

Rosatom is currently developing new business areas alongside its traditional nuclear business, including wind power, composite materials, nuclear medicine, waste management, oil and gas services, digital transformation, international logistics and additive technologies.

To unite all Rosatom's additive manufacturing capabilities, Rosatom created a subsidiary; Rusatom – Additive Technologies, abbreviated to RusAT, which coordinates the activities of all Rosatom subsidiaries that are involved in this business. RusAT is focused on four key areas: the manufacturing of 3D printers and their components, the production of materials and metal powders for additive manufacturing, the development of software for additive systems and services, and additive manufacturing printing services.

As part of Rosatom, RusAT, pays great attention to the development of additive manufacturing applications in the nuclear energy sector. RusAT is currently working on four additive manufacturing technologies for nuclear applications; powder bed fusion, direct metal deposition, plasma, and arc wire additive manufacturing for printing with metal wire, and electron beam additive manufacturing. These technologies are used for manufacturing of parts with complex geometries, such as equipment components, spare parts for NPPs and fuel assembly components.

Innovative materials enable the production of parts with improved properties and lower weight. For example, using additive manufacturing to produce reactor vessel internals allows for an increased number of cooling channels to reduce heat and consequently extend a component's life cycle and increase its reliability. RusAT's operations extend across all aspects of additive manufacturing, including the development of numerous modes of additive manufacturing using a variety of materials, such as titanium, stainless steel, heat-resistant steel, powder, and wire materials; out-of-pile tests of check specimens; tests in ion-accelerator tube, as well as neutron irradiation testing in a reactor to confirm characteristics and properties of 3D printed components.

RusAT's is pursuing the following objectives with their additive manufacturing projects:

- Confirmation of physical, mechanical, and corrosive properties of materials for the additive manufacturing of nuclear components.
- Adjustment of various additive manufacturing technologies and 3D printing modes to be used for the nuclear energy sector.
- Validation of additive manufacturing technologies for the nuclear industry.
- Design optimization of nuclear components to be 3D printed.
- Development of specific additive manufacturing technologies and equipment for nuclear applications.
- Obtaining an approval from regulatory authorities for additive manufacturing as a feasible production method for nuclear applications.

RusAT uses additive manufacturing to produce critical and non-critical components, *e.g.*, powder bed fusion (PBF) technology to print components with complex geometries, such as guide cards, dust filters and anti-debris filters. The mechanical properties of parts printed by PBF equipment are comparable to those produced via conventional casting methods. PBF technology allows RusAT to remove the need for tooling, and reduce the time required for R&D and manufacturing, in addition to weight reduction as component strength can be enhanced through complex structural elements and internal parts, as well as high utilization of powder material.

Direct metal deposition (DMD) technology is used by RusAT for the additive manufacture of heavy shields with diameters of up to 2 meters and measuring 1 meter in height. This technology is very useful to produce large-sized products with complex geometries. The DMD process allows manufacturers to quickly change the composition of the metal by injecting different types of metal powders. DMD technology is especially well suited to the rapid repair of old or worn components made of titanium, steel, aluminium, or copper.

Quality control and qualification procedures are essential to all additive manufacturing technologies employed by RusAT and are not only relevant to the components produced with the use of additive manufacturing, but also to the powder feedstock, testing and process monitoring. RusAT is currently working these topics, and notably examining nuclear specific challenges for parts produced by additive manufacturing, such as irradiation damage and stress corrosion cracking.

RusAT has encountered challenges with regards to standardization of additive manufacturing within the nuclear energy sector as specific nuclear standards for additive manufacturing do not exist yet. The lack of standards slows down the rate of adoption of additive manufacturing technologies within the sector. One of RusAT's key objectives is therefore to prove to the regulatory institutions that additive manufacturing is a feasible, sustainable, and reliable manufacturing method that can be successfully implemented in nuclear projects. RusAT is currently benchmarking the performance of parts produced via additive manufacturing against those produced using conventional methods to substantiate the case for including additive manufacturing within nuclear standards. In addition to this work, RusAT is pursuing regulatory approval for the use of additive manufacturing within the nuclear sector by undertaking pilot projects that will build a knowledge base and a library of application cases.

3.2.2 Codes and standards related challenges

RusAT strongly believes that standardization is an essential enabler for the implementation of new technologies. Russian and international practices have previously differed for traditional methods of production. These differences are due to the fact that for a long-time development in Russia and at the international level occurred in parallel and consensus was not reached with regards to certain topics. RusAT therefore aims to avoid a similar outcome for additive manufacturing and seeks to minimize differences.

In pursuit of this objective, RusAT pays a lot of attention to standardization. First, RusAT actively contributes to the work of the Russian national technical committee (TC) for standardization TC 182 "Additive technologies". RusAT also acts as a developer of national standards for additive manufacturing in Russia. One of RusAT's goals is the implementation of best available practices from ISO and ASTM standards, as well as development of national standards in conformance with ISO and ASTM International.

In recent years, the focus of RusAT's work was standardization of the laser PBF process. The following Russian national standards were published as an output of this work:

- GOST R 57588-2021 Additive technologies. Equipment for additive processes. General requirements.
- GOST R 59184-2020 Additive technologies. Selective laser melting equipment. General requirements.
- GOST R 59036-2020 Additive technologies. Production based on selective laser melting of metal powders. General provisions.
- GOST R 59038-2020 Additive technologies. Confirmation of quality and properties for metal products.
- GOST R 59035-2020 Additive technologies. Metal powder compositions. General requirements.

The approval of standards for directed energy deposition (DED) additive manufacturing is planned soon. A significant effort is currently also underway to harmonize Russian national standards with international standards, such as ISO and ASTM.

Russian standards currently only cover general issues, there are few or no requirements for specific products or specific technologies, even for non-nuclear products. RusAT has identified the following main gaps in C&S:

- Standard terminology is insufficient and is not consistently implemented in practice.
- There are no technical specifications standards for raw materials, thus no requirements for product performance, packaging, and transportation requirements.
- There are no technical specification standards for products manufactured through a combination of both traditional and additive manufacturing.
- There are no uniform approaches for the testing of components or parts, for example production of samples for further physical and mechanical tests.
- Some AM processes are not mentioned in standards, so there are no standardized requirements for them.
- There are no standardized requirements for additive manufacturing personnel.
- There is a lack of safety standards for additive manufacturing.

Further gaps will likely be identified as additive manufacturing and the standardization of AM are still emerging topics for industrial applications. These gaps should be filled as the technologies mature and experience is gained following sufficient practice and use in industrial settings.

3.2.3 Regulatory related challenges

The Federal Technical Regulation and Metrology Agency (Rosstandart) is the Russian federal government agency that serves as the national standardization body of the Russian Federation. The federal agency carries out general management of the system of technical committees (TC) for standardization based on which standards are developed. For additive manufacturing the relevant technical committee is TC 182 "Additive technologies" of which RusAT is an active member and contributor.

3.3 NAMRC/NuScale Power

3.3.1 Project overview

The Nuclear Advanced Manufacturing Research Centre's (NAMRC) mission is to support the UK Government's delivery of low-carbon and low-cost electricity through innovative solutions and creation of a nuclear savvy supply-chain.

One of its major research and development projects is the US DoE sponsored Small Modular Reactor programme, where NAMRC works in partnership with EPRI and NuScale Power. The programme's aim is to reduce the manufacturing cost of a NuScale SMR reactor pressure vessel (RPV) by 40% and demonstrate the feasibility of manufacturing the RPV in under twelve months (8) (9) (10).

NAMRC's research strategy has identified four key advanced manufacturing strands where a concerted effort in adopting an integrated programme provides significant benefit in reducing costs, lead-times, energy usage and CO_2 generation, whilst simultaneously improving product quality and in-service performance:

- Solid-state forming and bonding
- Laser heat source processing - welding, overlaying and additive manufacturing
- Modularisation and standardisation
- Codes, standards, and specifications

Solid-state forming and bonding (SSFB) research into the combined use of powder metallurgy and hot isostatic pressing technology (PM+HIP), using nuclear grade structural and corrosion steels, provides prospects for increased design freedom and modular configurations. Concurrently, from a performance perspective, improved directional and through-thickness (Z-grade) properties and dissimilar metal bonding capability is achieved, along with augmented inspection characteristics resulting from improved homogeneity. Further benefits include improved 'product-to-point-of-use' ratios, reduced energy, and material utilisation, and removing the need for excessive profile envelopes.

In addition to the SSFB R&D, NAMRC is applying the use of single pass autogenous electron beam welding (EBW) to nuclear grade and PM+HIP steel sections with less than 110mm thickness. This process offers significant benefits including reductions in processing times, the elimination of machined groove joint profiles, external pre-heating, and hydrogen bake-out processing. Typical reductions in processing times (pre-heat, welding, and inspection) are greater than 80% for the main RPV circumferential weld, assuming a "right first time" output when using conventional arc welding techniques. Autogenous welding methods not only remove the need for filler metal use, thereby reducing the weight of the RPV (by around 325kg in this example) but also allows the component to maintain nearly all its chemical homogeneity (~1% losses occur through some elemental vaporisation). The preservation of its homogeneity allows novel heat treatments to virtually eliminate the weld's macrostructure to underwrite the expansion period for in-service inspection.

In addition to this dramatically reduced production time, EBW uses significantly less energy than traditional welding processes. In this instance a single pass circumferential weld in 110mm thick SA508 Gr3. Cl 2 steel (see Figure 4) resulted in an energy saving of 1.1GJ, or 303kWhr, and 71kg of CO_2 equivalent emissions (calculated based upon the UK's electricity mix) making it a valuable asset to help manufacturers reach their Net Zero commitments.

NAMRC has also been investigating the modularization of EBW equipment which offers game-changing capabilities, not only for nuclear components but for production equipment too, *e.g.*, modular in-chamber vacuum systems. Moreover, modular 'local-to-product vacuum' systems further reduce cost and lead-times, but such developments have been difficult to translate to first of a kind reactor design, due to the perceived performance risk from current data available in the nuclear sector. Successes in EBW research completed in the offshore wind sector, notably at Dogger Bank, should also be highlighted to showcase the benefits it can bring to the nuclear industry.

With regards to quantum heat source processing, NAMRC's research into laser-based corrosion resistant overlaying and hard face overlaying is challenging existing designs and methods, where excessive thicknesses are required to achieve acceptable dilution and elemental transfer levels.

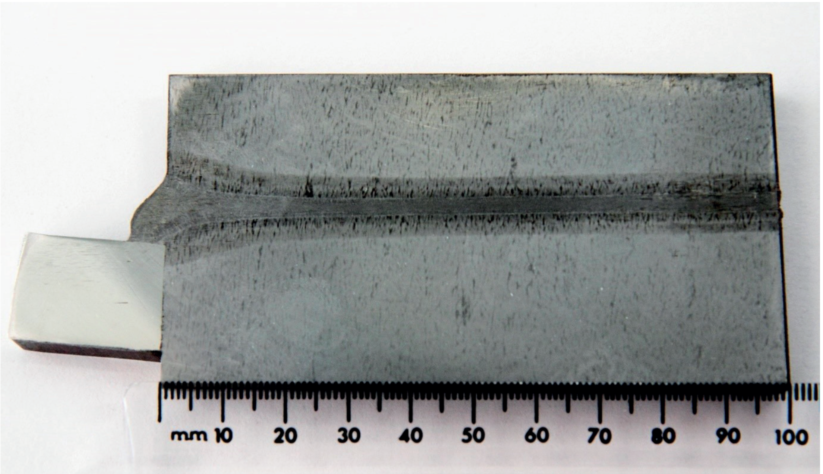


Figure 4. Electron beam weld of 100mm SA508 Gr3.Cl 2 steel (NAMRC)

The use of diode laser cladding (DLC) produces very low dilution (<10%) levels, minimized substrate disruption, and improved material utilisation to form corrosion barriers that are approximately 3mm thick. When employed in combination with robotic articulation, this technology results in reduced distortion, and enables the overlaying of thinner substrates in multiple orientations. These capabilities provide manufacturers and vendors with additional repair and rework options.

Whilst DLC exhibits deposition rates between three and six times lower than established mechanized arc and resistance methods, a 70% reduction in total energy accompanied by a CO_2 mass reduction of 495kg is achieved by overlaying a simple 2.8m diameter x 3m length strake. However, to embed this technology in the nuclear industry requires designers and regulators to change their mindset on corrosion resistant overlaying thicknesses that reflect a dilution and element transfer criteria rather than established oversizing to achieve lifetime passivation. Furthermore, NAMRC research involving laser cleaning technology to remove surface contaminates immediately prior to welding or overlaying is showing potential promise. The use of nano and picosecond pulse width periods produces significant peak-power to remove extraneous materials, so further research in assessing metallurgical degradation is needed, but promising results are being exhibited.

These technologies, combined with robotic articulation offer significantly improved overlaying capability and pre-cleaning cycle times, and removes the use of harmful chemicals.

In summary, developing new technology requires the supply-chain to have the appetite and support to adopt innovative technologies. It is also important that they have a comfortable and open relationship with regulators, therefore regular updates and the sharing of appropriate historical challenges should be sought, this will help innovators assess and address similar matters well in advance.

Improvements are required to bridge the gap between industry and standards developers. Volunteers supporting and developing codes and standards are needed, and funding from government should be made available to research and technology organizations and industry to develop them.

Analysis and, where appropriate, adoption of data and practices developed within other safety critical sectors should be sought, as well as research into probabilistic analysis, and machine learning systems to migrate from a ‘design by rule’ to a ‘design by analysis’ philosophy.

3.3.2 Codes and standards related challenges

NAMRC is currently developing a code-case submission into the ASME BPVC Section III committee to enable the wider nuclear industry to benefit from the adoption of EBW in manufacturing. The codification is not the only barrier however, further efforts and funding will be required to reach widespread deployment notably investment in national equipment qualification facilities to accelerate performance assessments

3.3.3 Regulatory related challenges

Research and development organizations recognize the importance of aligning their R&D

outputs and outcomes towards advancing solutions to convince national regulators of their safety and reliability to function as prescribed. An increased transparency of matters that have affected delays in reactor deployment, which subsequently increases the public's perception of the nuclear industry being costly, unsafe, and bureaucratic, would significantly improve its efficacy. Access to critical data from not only national databases but a global repository via an anonymized platform would help researchers and designers to overcome those three key issues that could improve turnaround times in producing code cases. Therefore, an incentivized initiative should be considered that aids developers and the supply chain in identifying, navigating through, and overcoming common priorities, based on past exploits and future activities in moving to a standardized resolution, which would reduce the barriers to market and the public's perception of a 'nuclear premium'.

The use of advanced technologies such as PM+HIP would, for example, reduce the level of cold work into a product or component through the progression of near net shaped forming methods. Furthermore, combining this with the use of technologies capable of completing overlaying or dissimilar weld metal joints (DWMJs) with one chemistry type applied with low-stress-low distortion technologies, will improve resistance to certain premature failure mechanisms, *e.g.*, intergranular stress corrosion cracking, primary water stress corrosion cracking and underclad cracking. However, other issues that may occur as barriers to applying such technology could be the lack of understanding that may arise from the effect of induced cavitation on and across DWMJs overlayed surfaces, and the level of protection/longevity that may be reduced as a result. This latter example is one such reason for an improved engagement with vendors and regulators in understanding more clearly the 'true' effects that arise from plant operation.

3.4 European cooperation – NUCOBAM project

3.4.1 Project overview

The NUCOBAM (Nuclear Components Based on Additive Manufacturing) project involves a consortium of 13 European organizations and is led by the French Alternative Energies and Atomic Energy Commission (CEA) through the Sustainable Nuclear Energy Technology Platform (SNETP). The four-year project started in October (11).

The scope of the NUCOBAM project covers additive manufacturing qualification for nuclear applications, specifically laser powder bed fusion (L-PBF) as it is the most widely and commonly used additive manufacturing method in several industries and therefore the one for which the greatest amount of practical experience is available. NUCOBAM consortium members own and run additive manufacturing equipment and provide the additively manufactured bulk material and components for the project test programme.

The main goal of the NUCOBAM project is the development of a qualification methodology or process for additively manufactured components for usage as safety-classified structures, systems, and components (SSCs) for nuclear installations. All safety-classified SSCs in nuclear installations must comply with stringent regulations through nuclear codes and standards. Components produced via additive manufacturing and that are intended to be used for safety-classified SSCs in nuclear installations are no exception. The qualification methodology that will be developed from the NUCOBAM project is intended to ensure that additively manufactured components comply with nuclear codes and standards. At the end of the project, the NUCOBAM consortium plans to submit the completed and final version of the qualification methodology to nuclear codes and standards committees and working groups with the aim of incorporating the qualification methodology into nuclear codes and standards.

The NUCOBAM consortium issued a first draft of the qualification methodology within the first year of the project, based primarily on consortium members' practical experience with L-PBF, existing guidance and standards on additive manufacturing (also from non-nuclear industries) and requirements from nuclear codes and standards.

The qualification methodology will be refined throughout the project based on results from the project's test programme and possible new guidance, so that a final version of the qualification methodology will be available at the end of the project (October 2024). It also accounts for requirements in traditional manufacturing nuclear codes and standards. These elements have guided the structure of the methodology and helped define its chapters: metallic powder procurement & assessment of powder characteristics, qualification of the additive manufacturing process, the additive manufacturing process itself and quality control monitoring, post-heat treatment of additive manufactured components, inspection & tests of material, component finishing, non-destructive examination (NDE) of the finished components.

There remains some uncertainty on the level of detail to which each aspect should be covered in the qualification methodology and on how prescriptive the final qualification methodology should be for all these aspects. The required level of documentation for all these aspects (process qualification in particular) also still requires (re-)consideration. The NUCOBAM consortium expects that the test results will help to resolve these issues.

The additive manufacturing of bulk material and components for the project test programme and preceding tasks (*e.g.*, powder procurement and characterization, agreeing on process parameters) required extensive discussion and coordination efforts by the involved NUCOBAM partners.

3.4.2 Codes and standards related challenges

The nuclear codes and standards that are followed in the project and to which the qualification methodology is primarily aligned to are RCC-M and ASME BPVC Section III (code modifications will also be proposed to RCC-MRx). Besides these, the NUCOBAM consortium also considers, to a lesser extent, codes for non-nuclear pressure vessels, notably EN 13445, for requirements on pressure vessels in general, since EN 13445 is referenced in nuclear codes and standards with RCC-MRx being a prominent example of this.

In the qualification methodology significant references are made to existing standards for additive manufacturing, primarily the ISO/ASTM 52900 standard and additional ASTM standards related to additive manufacturing (*e.g.*, ASTM F3184, F3434, F3303, F3301, F3122, F2971). Standards and guidance documents on additive manufacturing by the Society of Automotive Engineers (*e.g.*, AMS 7000A) and the American Welding Society (*e.g.*, AWS D20.1/D20.1M) are also referenced in the current draft of the qualification methodology.

The development of a qualification methodology or process for additively manufactured components for use as safety classified SSCs for nuclear installations is the main goal of the NUCOBAM project.

Nuclear codes and standards do not cover additive manufacturing yet. In the case of the ASME BPVC several code cases related to additive manufacturing exist (*e.g.*, ASME CC 20-254). As previously mentioned, it is the aim of the NUCOBAM project to issue a qualification methodology for additively manufactured components so that they comply with the requirements of nuclear codes and standards.

Additive manufacturing itself and related aspects (*e.g.*, component design, documentation needs, powder characterization, inspection & testing) are well covered by existing standards, for example ISO/ASTM 52900. The NUCOBAM consortium does not see an immediate need to supplement these documents. The challenges of additive manufacturing are technical, notably the determination of which machine and process parameters to apply to achieve a stable and repeatable additive manufacturing process.

3.4.3 Regulatory related challenges

Technical support organizations to safety authorities such as the IRSN are involved in the NUCOBAM project, however regulators are not directly involved. Their expectations with regards to the use of additive manufacturing to produce safety-classified SSC for nuclear installations will be however considered through an end-user-group and through the regulatory texts. Several regulators have lately published documents on their expectations towards the use additive manufacturing such as the ASN and US NRC (11) and these will be considered in the further development of the qualification methodology.

3.5 EDF – Framatome

3.5.1 Project overview

Framatome, part of the EDF group, designs and manufactures nuclear steam supply systems, equipment, services, and fuel. It is currently also developing advanced manufacturing processes.

The combined use of powder metallurgy and hot isostatic pressing (PM+HIP) has been studied for several years through both internal and collaborative projects. This technology provides significant advantages compared to traditional manufacture such as enhanced material properties and improved inspectability while also being more time and cost efficient. PM+HIP also facilitates design improvement, as nozzles can integrated into parts rather than being welded on. The development programme led by EDF and Framatome addressed the creation of material data files that cover stainless steels, low alloy steels, and hard-facing materials. The programme showed that nuclear components such as pipework (see Figure 5), pump impellers and bi-metallic junctions can be manufactured using PM+HIP. This has led to a commercialization programme that is currently supported by parametric studies on the influence of powder composition, process related defects and weldability on the outcome of PM+HIP manufacturing.

Laser powder bed fusion (L-PBF) is a promising process for the manufacture of small components, spare parts, and specific tools. The following topics are being explored for L-PBF:

- Development of skills in additive manufacturing oriented design.
- Identification and control of key manufacturing parameters, with the support of the supply chain, and the use of gloveboxes for machining irradiated materials.
- Compilation of data files for materials of notable interest (316L, Alloy 718, 17-4 PH, uranium).
- Identification of process specific defects and development of NDE techniques.

Framatome has led the introduction of additively manufactured fuel components into operating nuclear power plants, such as material test rods for Gösgen or channel fasteners at Browns Ferry, and for the replacement of worn parts (valve handle for example). Framatome was also the first industrial company to produce uranium fuel using the L-PBF process. Framatome has developed a roadmap for the deployment of fuel components which should lead to use of such components in outages in the mid-to-late 2020s. Framatome is also an active contributor to the NUCOBAM project (see Section 3.4).

The cold-spray process has been identified as a potential solution for repairing (instead of replacing) metal parts, and as a suitable solution to 3D print nuclear fuel. EDF R&D and Framatome acquired a cold spray facility in 2019 to study the process. Objectives have been defined for the examination of a wide range of materials, such as stainless steels, titanium alloys, copper alloys, carbides, and uranium alloys. For each of these, the following studies will be undertaken:

- Optimization of the manufacturing process to produce coatings with the required structural properties (density, adhesion, surface roughness, microstructures, *etc.*).
- Behaviours of the components while subjected to in-service conditions (mechanical properties, corrosion resistance, *etc.*).
- Development of specific coatings for the parts (properties, gradient, *etc.*).
- Use of the process for the repair of components and parts.

The scope of these feasibility studies must be expanded however, to include qualification and controllability, as needed for nuclear industrial applications. Work on the development of fuel prototypes for a nuclear research reactor is underway, for example.

Wire arc additive manufacturing is the final advanced manufacturing process under consideration as it has potential for the repair, modification and even manufacture of large parts.

As wire arc additive manufacturing builds on well-established welding expertise, its development path is shorter and focuses on the following points:

- Identification of appropriate welding wires for low alloyed steels and austenitic stainless steels
- Management of heat input and distortions through numerical simulations
- Production of welding programmes from CAD files taking deposition rules into account

EDF R&D and Framatome have dedicated additive manufacturing laboratories equipped with tungsten inert gas welding and gas metal arc welding processes. Current research aims to develop an understanding of the relationship between operating parameters and the quality of manufactured parts. Initial work has enabled the development of optimized toolpaths (*ex-nihilo* or from CAD files) for a given part geometry. As the manufactured parts must have no metallurgical nor mechanical defects, EDF and Framatome developed instrumentation with real-time temperature control. The surface temperature of the part is monitored using bi-chromatic pyrometers and infrared cameras and is provided as an input to the welding robot so it automatically pauses its work until a target temperature has been reached. A subsequent initiative examining toolpath correction is in progress as the path the robot takes can diverge from the programmed toolpath. Work is therefore ongoing to implement a way to adapt programmed work to the actual situation during the process.

The development of wire arc additive manufacturing is supported by the Additive Factory Hub initiative that brings together major French industrial entities and by the French government through the France Relance post-Covid-19 recovery plan.

3.5.2 Codes and standards related challenges

The supply and manufacture of nuclear equipment is carried out either according to the RCC-M nuclear code or to European harmonized standards depending on its safety classification.

The RCC-M code does not currently contain any technical specifications relating to the use of advanced manufacturing processes. European standards relating to pressure equipment also do not include advanced manufacturing processes.

Given the growth of these new processes and their advantages in terms of component quality, cost and manufacturing time, actions have been taken to incorporate their codification and standardization into RCC-M code and European standards.

With regard to the RCC-M code, a paragraph (M 116) has been introduced in the 2020 edition to allow the specific use of a manufacturing process that is not currently referenced in the code. This paragraph requires the provision of a procurement specification, a justification for the use of the material and a qualification process/procedure. Parts produced according to this new paragraph will enable AFCEN to accumulate feedback and experience and ultimately enable it to introduce technical specifications for advanced manufacturing into the code.

With regard to European standards, a draft standard (EN 13445-14) related to the manufacture of pressure equipment components by additive manufacturing methods is being developed and is scheduled for publication in 2024.

The principal difficulty with these new processes and in particular additive manufacturing is to define the qualification methodology as well as the parameters that can affect the quality of the component (grade, process, machine used, heat treatment). It is therefore necessary to:

- Define the material requirements in terms of chemical composition and mechanical characteristics,
- Guarantee the mechanical characteristics in the volume of the component and therefore the representativeness of the acceptance tests,
- Ensure the controllability of the components,
- Ensure the weldability of the components,
- Define any additional requirements applicable to nuclear pressure equipment.

In addition to the definition of the qualification methodology, the use of additive manufacturing in the nuclear industry requires data related to the materials and their behaviour in service and through the plant's lifetime (ageing, corrosion, *etc.*). Ongoing projects (NUCOBAM, EN 13445-14) seek to address these points, in relation to the qualification methodology and in-service performance.

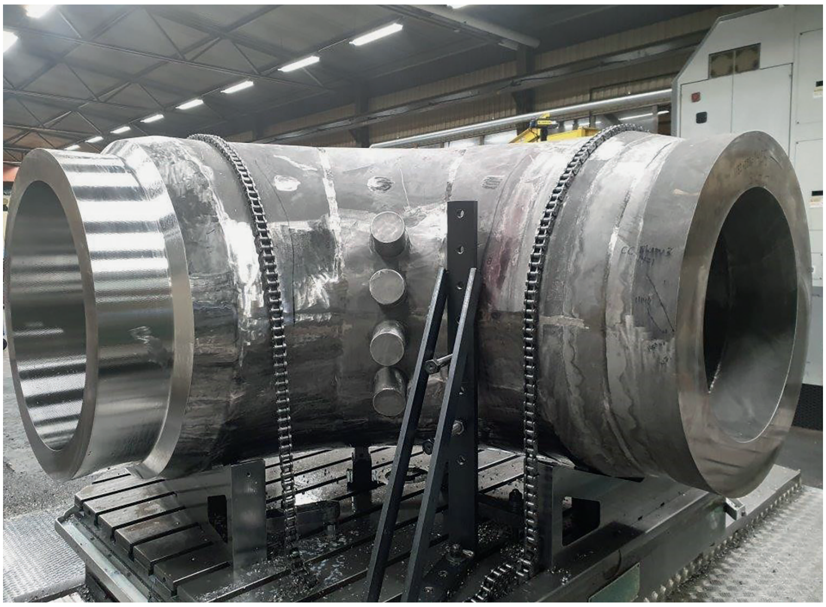


Figure 5. Piping elbow manufactured using HIP process (EDF/Framatome)

3.5.3 Regulatory related challenges

The use of advanced manufacturing (PM+HIP and additive manufacturing) for classified nuclear applications will require prior validation by EU notified bodies and the nuclear safety authority (ASN). Notified bodies were also informed of PM+HIP projects in progress.

Projects relating to the qualification of new processes aim to integrate notified bodies as early as possible, to work alongside them and ensure that the qualification will able to pass conformity assessments.

EDF has chosen to initially use additive manufacturing for non-safety related on-site use-cases. This will enable it to compile technical data from manufacturing and in-service experience before extending its use to safety-classified use-cases. This approach would allow EDF to work alongside suppliers in this goal, and provide IRSN with feedback over time.

4 Enabling supply chain innovation

4.1 Context and business models

Advanced manufacturing methods have the potential to enhance the nuclear industry supply chain by optimizing the production of high-quality components, which are, in some cases, quicker to produce, more cost-competitive and have better material properties than conventionally produced components. This could enhance the performance of existing plants and the ability to manufacture SMRs, advanced reactors and microreactors. Ultimately the potential efficiencies gained by implementing advanced manufacturing processes may significantly reduce capital costs. Within the existing fleet there are some supply chain challenges related to access to replacement parts for obsolete components and for warehouse inventories.

To enable the adoption of advanced manufacturing techniques, since around 2010 there have been significant public and private investment in programmes designed to bring advanced manufacturing methods into the nuclear supply chain. These programmes have built upon the lessons and insights from the earlier deployment of advanced manufacturing techniques in other industries such as aeronautics, oil and gas, transport, and industrial tooling.

Further uptake of advanced manufacturing methods within the nuclear supply chain will be driven by combining them with other innovative practices such as advanced computational analysis, modelling, and simulation to accelerate the qualification of advanced manufacturing processes for key nuclear components.

4.2 Bringing advanced manufacturing to the nuclear industry

The application of advanced manufacturing methods in the nuclear supply chain can provide significant opportunities for both suppliers and licensees.

Enhanced performance and design characteristics

With the use of advanced manufacturing methods such as additive manufacturing, equipment suppliers will be able to provide components with complex geometries that can have additional structural stability, less use of material and additional functions such as built-in filtration, compared with conventionally-produced components. Advanced manufacturing can support quicker design development through mock-ups and prototypes that have more design and performance characteristics to the end design.

Use of new materials and lean manufacturing process

Advanced manufacturing methods provide new fabrication, assembly, surface treatment possibilities and even hybrid material structures. These can enable new suppliers and collaborations to enter the nuclear industry, reduce the time needed to manufacture nuclear equipment compared to traditional methods, and support enhanced quality assurance with greater predictability in the manufacturing process.

Enhanced equipment health monitoring and predictive maintenance

The ability to have complex geometries with integrated sensors within equipment or systems will provide operators with the potential for real-time information on performance which will allow preventive maintenance and possibly autonomous operations. Such functionalities are considered key areas of the operational strategy of several SMRs and advanced reactors.

Faster and more consistent manufacturing processes leading to high-quality products

When coupled with advanced modelling and simulation of the manufacturing process, there are considerable opportunities to enhance the qualification and quality assurance of manufactured equipment. This would ultimately improve the cost competitiveness of high value and traditionally long lead time components.

Enabling collaboration and competitive supply chain offerings

Public and private investment in collaborative projects have advanced considerably since around 2015. In addition to the projects outlined in Section 3, the following sample collaborations highlight how several organizations involved in the nuclear supply chain are working towards greater use of advanced manufacturing techniques in the nuclear industry.

Table 1. Advanced manufacturing initiatives and collaborators

Project/initiative	Collaborators
Advanced Manufacturing and Materials Engineering Task Force (AMME-TF) (12)	Generation IV Forum
Pump impeller replacement at Krško nuclear plant (13)	Siemens, Nuklearna Elektrarna Krško (NEK)
Roadmap for Regulatory Acceptance of Advanced Manufacturing Methods in the Nuclear Energy Industry (14)	Nuclear Energy Institute
National Lab 3D Prints Key Component for Kairos Power's New Molten Salt Reactor (15)	Oak Ridge National Laboratory, Kairos Power
Westinghouse 3D printing trials reveal cost savings for all reactor types (16)	Westinghouse Electric Company
Transformational Challenge Reactor Program (17)	Oak Ridge National Laboratory
3D-printed nuclear fuel elements (18)	Gösgen Nuclear Power Plant, Framatome
Binder jet printed refractive materials (19)	Ultra Safe Nuclear Corporation, Oak Ridge National Laboratory

These, and other collaboration projects and initiatives, highlight the following points:

- Early regulatory involvement in the projects lowers the time taken to reach the demonstration phase.
- Near-term demonstration projects should be focused on components of lower risk/safety function and design complexity.
- When the scope includes clear industrial outcomes, there are greater opportunities to leverage both public and private funding in the project deployment.
- Public funding of industrial development programmes within national laboratories are accelerating the near-term commercialization of advanced manufacturing methods.

There is a growing interest in using some SSCs that are fabricated using advanced manufacturing techniques in the nuclear industry. The table below presents examples of such SSCs:

Table 2. SSCs produced by advanced manufacturing techniques

Item	Advanced manufacturing process	Material	Manufacturer
Pump impeller	Powder bed fusion (selective laser sintering)	Metallic (not specified)	Siemens (13)
	Powder bed fusion	316L	RuSAT
Valve (body)	Additive manufacturing (not specified)	Stainless steel	Neles (20)
Thimble plugging device	Powder bed fusion	316L	Westinghouse (21)
Channel fastener	Powder bed fusion	316L	Framatome (22)
Vessel cladding	Diode laser cladding	Stainless steel & nickel alloys	NAMRC
Large and small vessels	Powder metallurgy - hot isostatic pressing, electron beam welding	316L, SA508	NAMRC
Heavy shielding	Direct metal deposition	Metallic (not specified)	RusAT
Terminal block	Powder bed fusion	316L	Engie Laborelec
Debris filter	Powder bed fusion	Metallic (not specified)	RusAT

5 Conclusion

The wide variety of applications presented in this report demonstrate the potential of advanced manufacturing techniques to reduce costs whilst enhancing performance and safety in the nuclear sector. Advanced manufacturing could address some of the current nuclear supply chain challenges such as production of spare parts, obsolescence issues, reverse engineering, and component modernization.

Despite the differences with non-nuclear industries that have successfully implemented advanced manufacturing, such as aeronautical, transport and the power sector, introducing these techniques into nuclear supply chains should require similar approaches.

Components produced using advanced manufacturing techniques have already been put into operation in nuclear reactors; however these are small components that do not have safety-classified functions such as debris filters, channel fasteners and thimble plugging devices. Their lack of safety function has enabled them to be deployed whereas large Class 1 components must await codification and regulatory acceptance before they can be introduced into nuclear power plants.

Many parties are currently working on developing both nuclear and non-nuclear codes and standards for a wide variety of advanced manufacturing techniques. There would be potential cost savings in coordinating these efforts, notably to resolve technical challenges regarding qualification. An initiative aimed at sharing the underpinning principles of qualification at the ISO level appears feasible based upon previous experience. The NUCOBAM project's approach of developing a qualification procedure that is compatible with existing ASME and AFCEN requirements is another promising avenue for harmonization.

The industry partners that have contributed to this report aim to have common principles for qualification of advanced manufacturing techniques. Harmonized or equivalent codes and standards for these technologies would enable manufacturers to produce components for multiple markets thereby creating more resilient supply chains and would enable the export of production line-built small modular reactors.

Additionally, advanced manufacturing would provide a solution to the current supply chain challenges such as long lead times, warehouse inventories, as well as to issues concerning obsolescence and component modernization. The development of digital technologies will complement the deployment of advanced manufacturing techniques – notably artificial intelligence, which will support the prediction of advanced new material properties and assist in optimizing advanced manufacturing methods (23).

The development of codes and standards for advanced manufacturing will help to build regulatory confidence in this area. Prescriptive regulators require the codification of the techniques to incorporate them into their regulations and goal-based regulators require the vendor to demonstrate the safety cases of the engineering rules. Wider discussion on the different regulatory approaches and associated challenges facing emerging reactor designs can be found in the CORDEL report, *Different Interpretations of Regulatory Requirements* (24).

The current gaps in codes and standards present an opportunity for harmonization: aligning international code requirements for advanced manufacturing would help to ensure the success of the global SMR market. Furthermore, without them, the economy of series production that SMRs promise are unlikely to be achieved.

CORDEL therefore recommends the following actions:

- Organizations engaged in reactor design and reactor materials research should dedicate enough resources to accelerate the development of codes and standards to align codification with their deployment schedules.
- SDOs should adopt the AFCEN approach outlined in Section 3.5.2 to enable their codes and standards to allow the use of unreferenced advanced manufacturing processes.
- The nuclear industry should support collaborative international projects to develop harmonized advanced manufacturing techniques aligned to multiple codes and standards.
- Regulators should work collaboratively with the nuclear industry to develop common approaches to the regulation of advanced manufacturing techniques and their use within the supply chain.

References

1. M. St. Węglowski, S. Błacha and A. Phillips, *Electron beam welding – Techniques and trends – Review, Vacuum*, 130 (2016)
2. Nuclear AMRC, University of Sheffield, *Intelligent Fixtures for Optimised and Radical Manufacture – Project Report*, NI1066-REP-01 (2019)
3. Scott Birch, Electron beam welding could cut reactor build costs by 85%, *Reuters Events*, (11 December 2019).
4. H.V. Atkinson and S. Davies, *Fundamental Aspects of Hot Isostatic Pressing: An Overview*. Metallurgical and Materials Transactions A, 31A (December 2000)
5. Martin W. A. Stewart *et al., The Use of Hot-Isostatic Pressing to Process Nuclear Waste Forms*, Proceedings of the ASME 2009 12th International Conference on Environmental Remediation and Radioactive Waste Management (October 2009)
6. S. Barnes et al., *High Power Diode Laser Cladding*, Journal of Materials Processing Technology, 138 (July 2003)
7. I. Gibson, D. Rosen and B. Stucker, *Additive Manufacturing Technologies – 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, Chapter 10: Directed Energy Deposition Processes*, Springer, 978-1-4939-4455-2 (2015)
8. Electric Power Research Institute, *Small Modular Reactor Vessel Manufacture and Fabrication, Phase 1—Progress*, 3002015814, Technical Update (October 2019)
9. Electric Power Research Institute, *Small Modular Reactor Vessel Manufacture and Fabrication, Phase 1—Progress (Year 2)*, 3002019335, Technical Update (April 2020)
10. Electric Power Research Institute, *Program on Technology Innovation: Small Modular Reactor Vessel Manufacture and Fabrication, Phase 1—Progress (Year 3)*, 3002021037 (2021)
11. Sustainable Nuclear Energy Technology Platform (SNETP), Nuclear Components Based on Additive Manufacturing (NUCOBAM) information leaflet
12. Lyndon Edwards, *Advanced Manufacturing and Materials Engineering Task Force (AMME-TF)*, Virtual 15th GIF-IAEA Interface Meeting (June 2021)
13. World Nuclear News, *Siemens prints part for Krško plant*, (9 March 2017)
14. Nuclear Energy Institute, *Roadmap for Regulatory Acceptance of Advanced Manufacturing Methods in Nuclear Energy Industry* (May 2019)
15. US Department of Energy Office of Nuclear Energy, *National Lab 3D Prints Key Component for Kairos Power's New Molten Salt Reactor* (11 August 2020); Oak Ridge National Laboratory, *As ORNL builds novel reactor, nuclear industry benefits from technology* (28 May 2020)
16. Karen Thomas, *Westinghouse 3D printing trials reveal cost savings for all reactor types*, Reuters Events (25 January 2017)
17. Benjamin Betzler, *Additive Manufacturing in the Nuclear Reactor Industry*, Encyclopedia of Nuclear Energy (2021)

18. World Nuclear News, *3D-printed fuel parts complete initial irradiation cycle* (5 November 2020)

19. World Nuclear News, USNC licenses 3D printing for reactor component manufacture (11 Januray 2022)

20. TVO, *Valve produced using 3D printing technology tested in Olkiluoto* (5 May 2021)

21. World Nuclear News, *Westinghouse unveils 'industry first' with 3D-printed component* (5 May 2020)

22. World Nuclear News, *3D-printed components in service at TVA reactor* (10 August 2021)

23. J. Blevins and G. Yang, *Machine learning enabled advanced manufacturing in nuclear engineering applications*, Nuclear Engineering and Design, 367 (October 2020)

24. World Nuclear Association, *Different Interpretations of Regulatory Requirements* (December 2021)

World Nuclear Association
Tower House
10 Southampton Street
London WC2E 7HA
United Kingdom

+44 (0)20 7451 1520
www.world-nuclear.org
info@world-nuclear.org