ADDITIVE MANUFACTURING PAVES THE WAY TO ENHANCED PERFORMANCE OF FRAMATOME FUEL ASSEMBLIES

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ABSTRACT

New component designs – which could be not manufactured up to now – might enhance the utilization of fuel assemblies.

This new design can be realized by Additive Manufacturing (AM). AM has already been used to revolutionize parts of other industries and the use of this technology in the manufacturing of fuel assembly components should remove many constraints.

Framatome has launched several years ago an extensive development project to assess the value of using such technology in Nuclear fuel manufacturing.

The focus of this paper is a review of the results obtained at Framatome on structural metallic components manufactured by Selective Laser Melting, as part of the development project on AM. The qualification of the technology and the accompanying material characteristics include a range of out-of-pile tests and subsequent in-pile tests.

1. Introduction

The present paper focuses on components of fuel assemblies for Light Water Reactors (LWR), manufactured using Additive Manufacturing technology. This technology will greatly benefit the LWR operators which Framatome provides with Fuel Assemblies.

1.1 Current challenges for FUEL

New component designs – which could be not manufactured up to now – might enhance the utilization of fuel assemblies.

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Framatome has launched several years ago an extensive development project to assess the value of using such technology in Nuclear fuel manufacturing.

In the past, many concepts could not be transferred into industrial products as conventional manufacturing technologies limited design freedom and implementation. For example, the efficiency of debris filters could be improved but the necessary design changes are restricted by manufacturing and assembling requirements.

The technology which will help to overcome current design limitations is called Additive Manufacturing (often simply called “3D-Printing”, abbreviated AM) and has already been launched to revolutionize parts of other sectors.

Sectors that already benefit from using AM and have similar requirements and materials to Nuclear are Energy (incl. non-nuclear), Aviation, Defence and Transportation.

1.2 Overview of the activities within Fuel Business Unit of Framatome

All Framatome AM projects are integrated into one single program to assure that all market needs are considered.
This means that the following departments are involved:

- Engineering and Design
- Laboratories for analysing materials under different conditions (incl. post-irradiation)
- Prototyping laboratories to develop, adapt and implement manufacturing technologies
- Test facilities for analysing the thermal-hydraulic and mechanical performance
- Production facilities
- Sales and after-sales-service
- External Cooperation with main partners involved in Research in the Nuclear Industry field and with universities.

Some projects – like the project for characterisation of materials – have been running for several years.

2. Why AM for Fuel Assemblies?

2.1 Advantages in Design

Development of new product designs requires changes in the environment to overcome current constraints. Additive Manufacturing has the capability to open access to design approaches which would have been rejected in the past. With the use of AM these designs can now be manufactured and in the long run will allow completely new design for fuel assemblies.

Currently, AM demonstrates its strength with parts of low quantity and high complexity [2], [3]. A component's complexity is often the limiting factor, especially when looking at components where the value is given by their thermal-hydraulic performance.

The immediate benefits for the utilities are, for example, to improve and individually adapt filter geometries in Bottom Nozzles (aka. Lower Tie Plates) to achieve the lowest failure rate due to debris in accordance with adequate pressure loss.

2.2 Advantages in responsiveness

Through the implementation of AM the time to market for newly adapted products can be reduced. This is the case for different approaches:

- Fast prototyping to accelerate development process
- Fast supply of tools and fixtures for quick response time in production
- Fast manufacturing of components [1]

Especially for the third approach it is important to make use of the option to print complete components at once, i.e. to reduce the total amount of parts needed for the production of the component. Consequently, the process chain is significantly shorter and the direct manufacturing time decreases as the production of the assembly is concentrated to one step.

In fact, even more time can be saved, since other activities require less effort [2]:

- Amount of drawings and specifications
- Coordination of suppliers (incl. Quality Management, Contracts, Audits etc.)
- Preparation of tools and auxiliaries
- Qualifications
- Transportation
- Assembling
- Documentation

3. Our Path to implement AM

3.1 Overview of introduction procedure

For the introduction of the new manufacturing technology, three main sectors are considered (see figure 1). Full use of the new opportunities can be made only if these sectors are pushed in parallel.

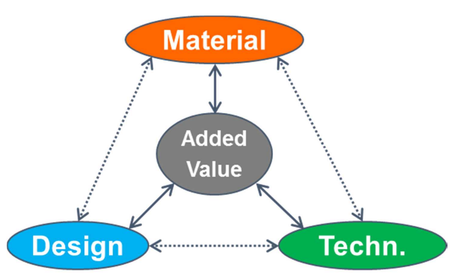

Fig 1: The magic triangle for Added Value of AM

Goals of "Material":

- Define acceptance criteria for additively manufactured components,
- Gain data on properties with and without irradiation.

Goals of "Technology":

- Set standards for procurement of parts

- Find the best technical solution for manufacturing and inspection (robust process)
- Consider the complete manufacturing process
- Bear in mind that industrialization is the target

Goals of “Design”:

- Improve existing components towards performance and reliability
- Longer term approach to take maximum benefit through innovative features

In order to assure proper design, a paradigm shift in the engineering/design departments is necessary. The designers need to be trained how to design new or adapted components for AM.

From another perspective, four levels of introduction are of importance:

- Technology
- Products
- Licensing
- Organisation (operation)

3.2 Chosen technology – Selected Laser Melting (SLM)

In general, AM is defined as manufacturing methods of joining materials to create components, usually layer upon layer, as opposed to subtractive manufacturing methods like milling, drilling or lathing [1].

One of the first technologies chosen by Framatome was the SLM process which builds the components within a powder bed that is fused with a laser layer-by-layer [3]. As this process works without shaping tools like moulds it gives the opportunity of high design freedom accompanied by customization of the design to meet specific needs without making additional investment in special tooling.

When comparing SLM to conventional production processes, e.g. casting, forging or milling, there are significant differences with respect to properties of the part. These differences can be severe challenges for the implementation of the technique in our industry. The following items are the most pronounced differences, however, this list does not claim to be exhaustive [2]:

- Porosity/density: Trapped gas from the production process or incomplete fusion of metal powder can lead to internal imperfections. The effect of these imperfections on static and dynamic mechanical properties as well as environmental degradation (primary water corrosion etc.) needs to be understood and considered.
- Surface quality: The roughness of surfaces in as-printed condition is governed by different factors, such as the stepwise build-up of the part or adhesion of partially molten powder particles to the sample surface. These effects must be understood and considered in the design, but might also be beneficial in special cases.
- Residual stresses: As the part is formed by sequentially melting and solidifying metal powder using a scan pattern, the resulting residual stresses (and potentially also distortion of the part) are governed by the scan strategy. In addition a proper heat treatment is necessary to reduce stresses prior to further machining.

3.3 Manufacturing Process

Each step of the process chain needs to be considered to maximize the benefits provided by AM. The designer of a component has to consider each step to assure a proper quality of the final product. Figure 2 shows the fundamental manufacturing process.

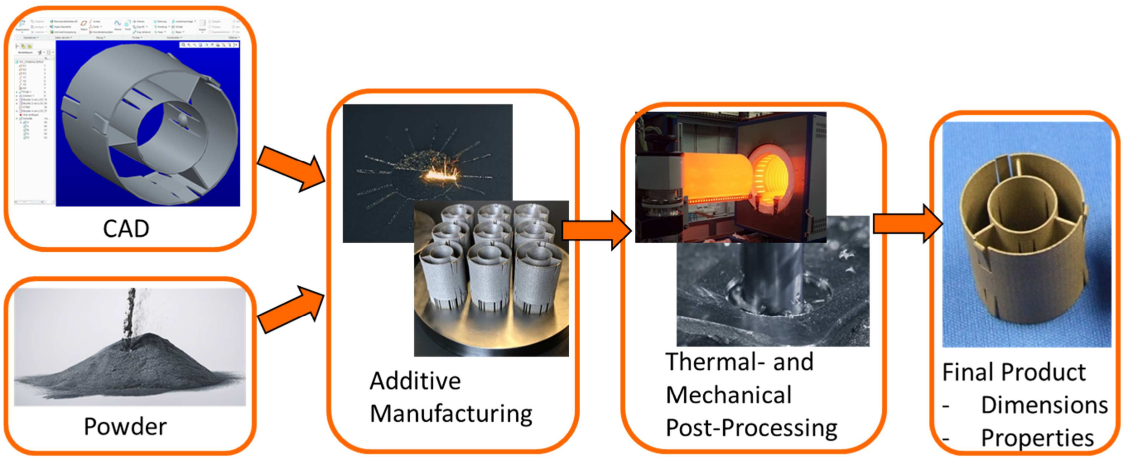

Fig 2: Main steps in Additive Manufacturing

The fabrication and procurement of powder is not discussed in this paper, but it is necessary to mention its importance as one parameter that is decisive for the quality of the AM-Process.

Typical steps in Post-Processing include [2]:

- Heat treatment to improve material properties
- Machining of functional surfaces and
- General surface finishing

Until the manufacturing process is qualified, further QA-Tools are planned to assure that the final product fulfils the specification. These are especially:

- Accompanying tensile samples to test material properties
- Accompanying density cubes to analyse the density
- Accompanying process monitoring to assure proper fusion of the metal powder and
- Subsequent application of computer tomography

Especially the use of computer tomography is important to ensure that the fusion of the powder was successful at all layers.

The shortened process chain using AM as the main manufacturing technology will have an impact on the complete management of supply chains.

3.4 Application Domains

There are many possibilities how to start looking for possible applications. For using AM within the Business Unit FUEL four domains were identified (internal Roadmap):

- Fuel products and core components
- On-site services tooling and production of spare parts
- Manufacturing equipment
- Rapid Prototyping and manufacturing of test components to support development

In the long run domain 1 (Fuel products) is the most important objective.
The focus of the current development project is on structural components made of stainless

steel and nickel-base alloys.

In order to further utilize the advantages of AM in the Fuel Assembly (FA) load chain, it is possible to realize a hybrid design which means to pre-manufacture a part with traditional technologies and then print directly upon the surface the necessary geometry [4][4].

Examples for potential components are

- Short-term: Grids for Upper Tie Plates (for Boiling Water Reactor, s. figure 3), Filter (s. figure 4) and Channel fastener
- Long-term: Intermediate Flow Mixing Grids

Fig 3: Grid for UTP made with AM

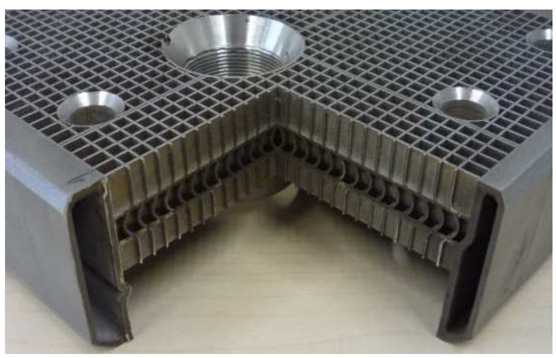

Fig 4: Cross section of a filter with evolutionary improvement (3D curves)

Regarding the Service Tooling and spare parts for spent fuel assemblies it is possible to introduce AM rather quickly if there is no significant irradiation intensity or duration. The results with test samples, tests with additional identical components and subsequent quality assurance using computer tomography will pave the way. Figure 5 shows a clamping gripper to pull defective fuel rods out of quivers.

Fig 5: Tools to grab fuel rods

The use within production sites for maintenance, fixtures, tooling and gauging to support the ramp-up of new products and to improve existing processes is already started. Figure 6 shows exemplary a box for mounting accelerometers for transportation monitoring.

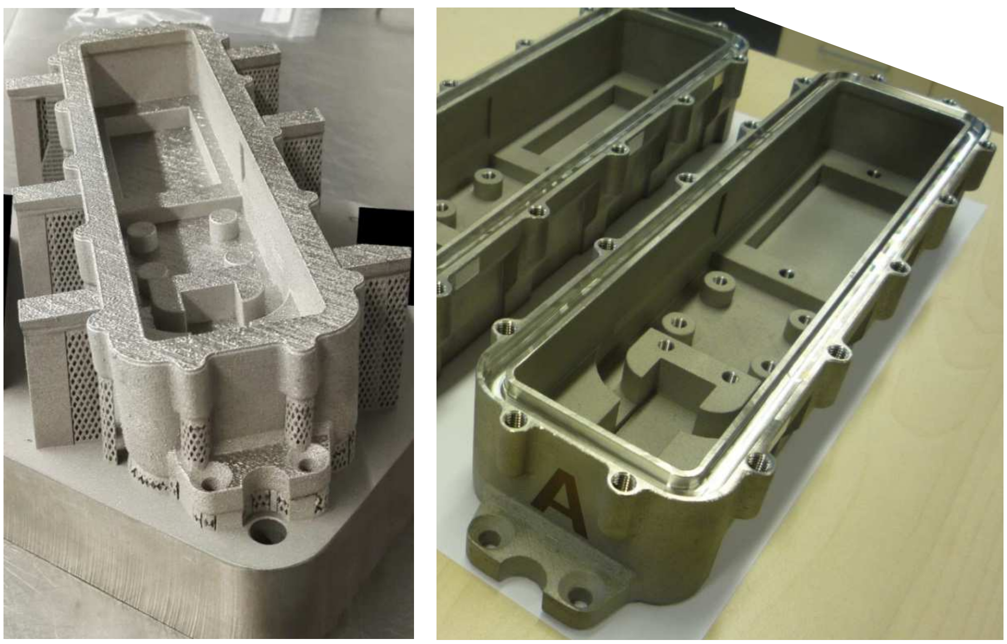

Fig 6: Fixture for sealed mounting of accelerometers to monitor transportation
(directly after printing and after finishing)

The fourth domain is the so called Rapid Prototyping supports product development independent of whether the product will be manufactured conventionally or additively for later use in the reactor. The rapid prototyping allows fast testing of new design ideas. However the influence of some characteristics like surface quality needs to be analysed and correlations need to be derived (e. g. for tests on the thermal hydraulic performance like the mounting for single rod flow testing as shown in figure 7).

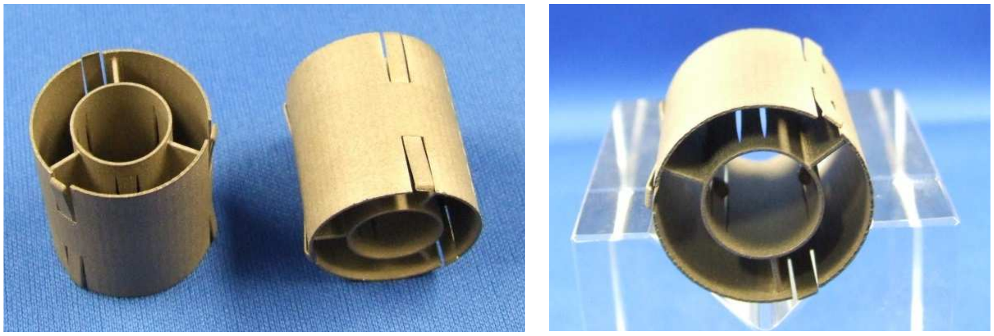

Fig 7: Mounting for a single rod flow testing

3.5 Testing and qualification

The focus of this paper is on components made of stainless steel and nickel-base alloys. Qualification of the technology and the accompanying material characteristics have the highest priority. Therefore it is done by an integrated concept including the assessment of potential suppliers, a range of out-of-pile tests and subsequent in-pile tests. The out-of-pile tests already show promising results for mechanical behaviour and corrosion that suggest a viable path towards qualification and use of AM for fuel components. The results regarding visual appearance, corrosion behaviour and mechanical properties of heat treated stainless steel 316L are sufficient and close to the results of forged material.

The samples made of stainless steel 316L meet the ASTM A276 [5]~~[5]~~ and RCCM M3301 [6]~~[6]~~ requirements with respect to minimum yield stress, ultimate tensile stress and elongation (see figure 8 and 9).

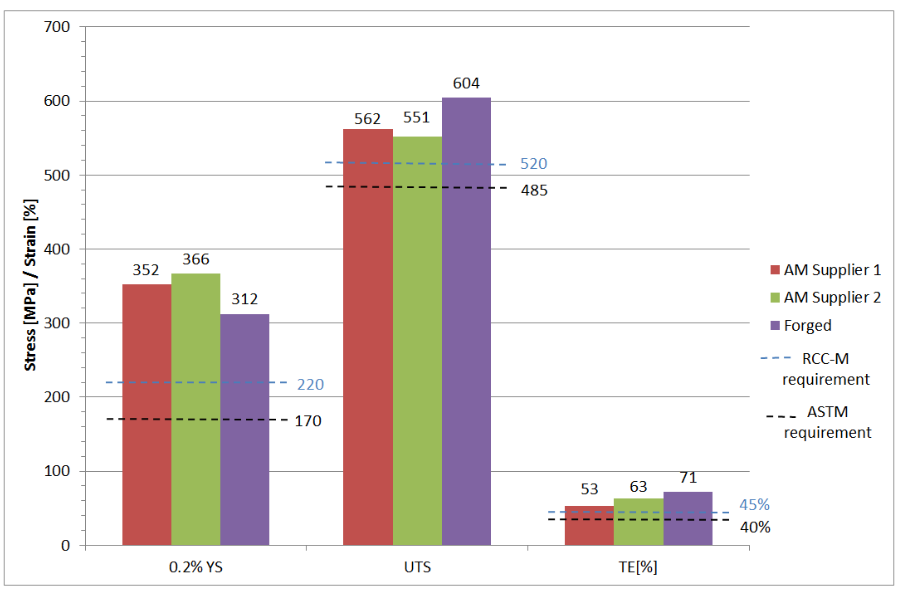

Fig 8: 0.2% Yield strength, ultimate tensile strength and total elongation of additively manufactured and forged 316L at room temperature

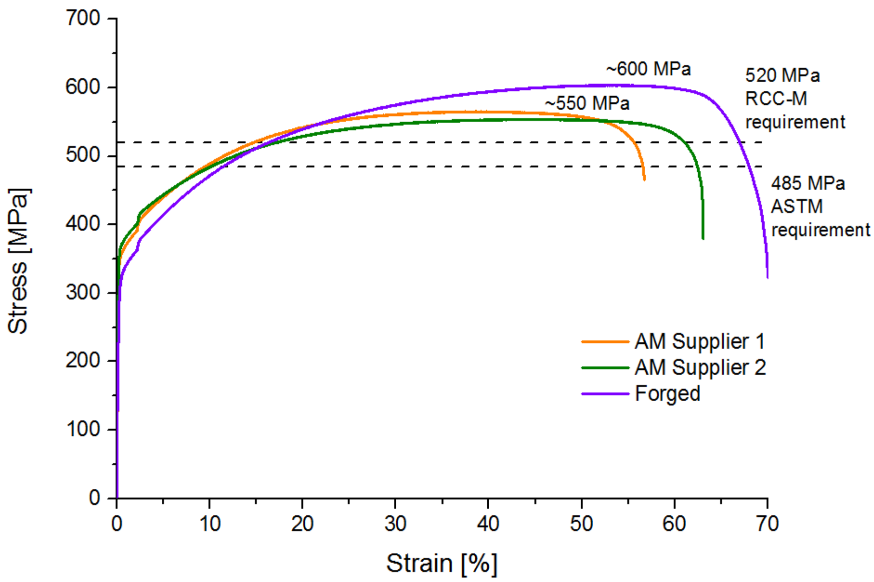

Fig 9: Stress strain diagram of additively manufactured and forged 316L at room temperature

Goal of the irradiation campaign is to gain data on properties of stainless steel and nickel-base alloys produced by SLM after exposure to neutron field and PWR primary coolant. Derived from this a base line of relevant material properties can be established as a function of irradiation history.

The samples which will be used for the irradiation program are shown in figure 10. In order to address the anisotropy of printed components, tensile specimens were manufactured in the unfavourable direction (load direction perpendicular to the layer interface).

Fig 10: Samples for out of pile testing

4. Conclusion

Additive Manufacturing already shows that it can help to reach new levels in performance and reliability in other sectors. The implementation to nuclear fuel assemblies is ongoing and will improve the product itself and the time to market of new designs. In the long run it will even allow customization of products based on specific needs. The often repeated need for “Design to Cost” (DtC) and “Design to Manufacturing” (DtM) is replaced by “Design to function” – without compromising the ideas DtC and DtM.

Framatome has the knowledge to direct the use of AM in the best way and to assure the best quality.

Applications in which components are not exposed to irradiation like spare parts, service equipment and manufacturing equipment can be implemented rather soon. The same applies to components which are not parts of the safety-related load chain.
In order to extend the use of AM beyond these fields, extensive work has been launched to:

a) Understand the behaviour of AM material under in-pile conditions
b) Master the AM process as well as the necessary post-processing to achieve a good and reproducible part quality and
c) Change the design process to benefit from freedom and flexibility gained by AM

5. References

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