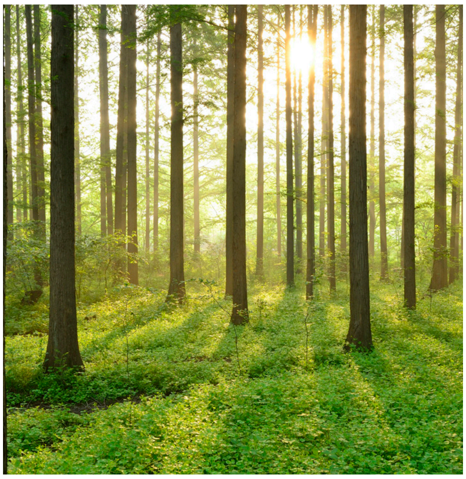
# METAL ADDITIVE MANUFACTURING IN NUCLEAR APPLICATIONS

REPORT 2020:699



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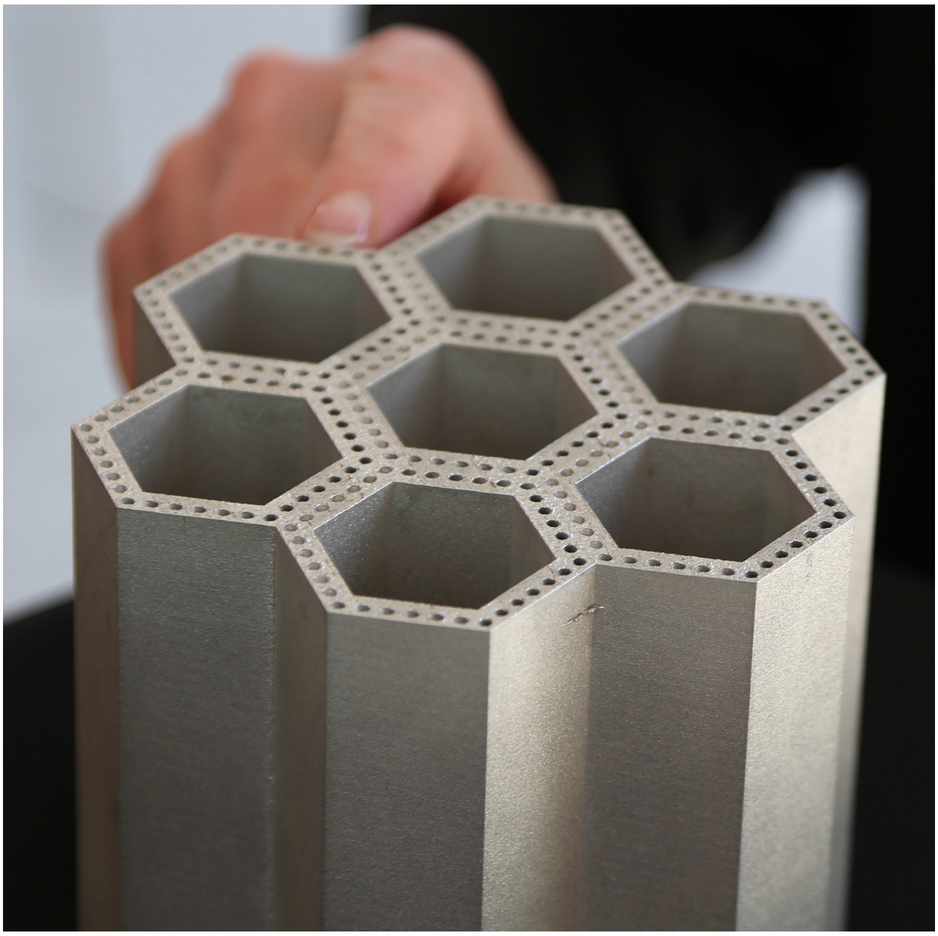

Energiforsk

# Metal Additive Manufacturing in Nuclear Applications

## Main outcomes from Energiforsk webinar

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# Foreword

**Advanced manufacturing methods are developing rapidly for different kinds of applications and materials. One of these interesting technologies is Additive Manufacturing. It started out as a technology for manufacturing small items in a limited number of materials, and it has grown to encompass large components in many different materials**

So far, additive manufacturing (AM) has only been used in a number of pilot cases in the nuclear industry. This is however likely to change as the technology has become more mature and there are multiple ongoing activities to develop technologies, materials, qualification, quality control/monitoring, post treatment and more. In time, it is believed that it will be possible to print some spare parts on demand.

Energiforsk arranged a webinar on September 23, 2020, to summarize the current knowledge regarding opportunities and challenges for an increased use of AM technology in the nuclear sector. The webinar program was developed by Pasi Puukko at VTT Technical Research Centre of Finland. Documentation in the form of slides and videos of some presentations are found on the Energiforsk web. The webinar was arranged by the Energiforsk Digitalization in nuclear program, financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstad Energi.

# Sammanfattning

**Additiv tillverkning skapar nya möjligheter inom kärnkraftssektorn, då den möjliggör tillverkning av reservdelar utifrån behov samt tillverkning av komplexa geometrier i ett enda stycke. Trots att tekniken har uppenbara fördelar, finns det också flera öppna frågor och utmaningar som måste lösas innan tekniken kan utnyttjas till fullo. För att öka kunskapen och medvetandet om additiv tillverkning ordnade Energiforsk ett webbseminarium "Metal Additive Manufacturing in nuclear applications" den 23. september, 2020. Sammandraget nedan på engelska lyfter fram huvudpunkterna från detta mycket lyckade seminarium.**

De viktigaste observationerna och höjdpunkterna vad gäller additiv tillverkning (AM) beskrivs nedan, plockade ur webinarets presentationer. En mer detaljerad sammanfattning står att läsa i det andra kapitlet i denna rapport.

De viktigaste drivkrafterna för AM-användning i kärnkraftssektorn är relaterade till digital lagerhållning/digitala reservdelar och möjligheterna att uppnå kortare ledtider, men också relaterat till att vissa komponenter inte längre tillverkas av traditionella leverantörer. Dessutom är snabb reparation av slitna eller skadade komponenter en intressant möjlighet.

För närvarande har AM-standardiseringen många luckor som begränsar användningen av AM-teknik. Standardiseringsorganisationerna utvecklar dock aktivt nya standarder för att fylla i många av luckorna. Några kärnkraftsspecifika AM-standarder finns inte ännu. Avsaknaden av tillräcklig standardisering identifierades som en nyckelfråga, som fördröjer användningen av AM inom kärnkraftsindustrin.

Pilottester och typexempel för industriell användning spelar en viktig roll i acceptansprocessen, de är extremt viktiga för både slutanvändare och myndigheter. Det finns några godkända och några pågående fall: 3D-tillverkat vattenpumpshjul, operativt i ett kärnkraftverk (Krsko, Slovenien); EPRI och Westinghouse Code Case (Record 20-254); ASME 316L L-PBF datapaket och typfall. ASME HIP-typfall (godkänt av US NRC 2019). En pluggningsenhet, tillverkad av 316L av L-PBF, installerad i kärnkraftverk mars 2020.

Kvalitetssäkrings- och kvalificeringsförfaranden är mycket viktiga. Nyckelfrågan är vilken kvalitetsnivå som krävs för att uppfylla kraven på prestanda och säkerhet. Utformning av acceptanskriterier och kvalitetsindikatorer för pulverråvara, men också för icke-kritiska och kritiska komponenter skulle hjälpa os framåt på detta område. Inom kvalitetskontrollen är det bästa tillvägagångssättet för nuvarande att kombinatera olika tekniker, dvs. destruktiv och icke-destruktiv testning samt processövervakning. Man bör också vara medveten om att additiv tillverkning är mycket mer än bara 3D-utskrivning: man bör också behärska materialkunskap, design för AM, kvalitetssäkring, efterbehandling och hälso- och säkerhetsaspekter.

Förutom det som sagts ovan, kommer mervärdet för AM-användning från designfasen. Detta gäller särskilt då fokus är på komplexa multifunktionella komponenter. Med smart design kan produkterna göras mer hållbara, lättare och i vissa fall även med andra nyttor exempelvis att designen bidrar till minskat behov av tryckluft eller hydraulolja i komponentens tillämpning.

# Summary

**Additive manufacturing (AM) can bring new opportunities for the nuclear energy sector, with the ability to print spare parts on demand and manufacture complex geometries in one piece. Although there are obvious benefits, there are also several open issues and challenges needed to be addressed to utilize the full potential of additive manufacturing. To increase the awareness of this topic, Energiforsk organized a webinar "Metal Additive Manufacturing in nuclear applications", on September 23rd, 2020.**

In following, key findings and highlights, extracted from the webinar presentations, are shortly presented. More detail information of presented topics is summarized in second chapter of this report:

Main drivers for AM utilization in the nuclear industry are related to digital warehousing (digital spare parts) and capabilities to achieve shorter lead times, as well as obsolescent part management. In addition, rapid repair of worn or damaged components is an interesting opportunity.

Currently, the AM standardization has many gaps that limit the adoption of the AM technologies. However, the standardization organizations are actively developing new standards to address many of the gaps. Nuclear industry specific AM standards do not yet exist. The gaps in standardization was recognized as one key issue slowing down the AM utilization in nuclear.

Code Cases and demonstrators play a vital role in the adoption process, they are extremely important for both utilities and authorities. There exist some completed and on-going cases: 3D printed water pump impeller, operational in nuclear power plant (Krsko, Slovenia); EPRI and Westinghouse Code Case (Record no 20-254); ASME 316L L-PBF data package and Code Case. ASME HIP specific Code Case (approved by US NRC 2019). A Thimble Plugging Device, made of 316L by L-PBF, installed in NPP March 2020.

Quality assurance and qualification procedures are of high importance. The key question is what the required quality level is to fulfil the performance and safety requirements. Formulation of acceptance criteria and quality indicators for powder feedstock, but also for non-critical and critical components would help in this path. In quality control, the current best approach is the combination of various technologies, i.e. destructive and non-destructive testing and process monitoring. One should be also aware of that additive manufacturing is much more than just 3D printing: one should master also material knowledge, design for AM, quality assurance, post processing and health and safety aspects.

Finally, the added value for AM utilization comes from the design phase. This is especially true when focus is on complex multifunctional components. With smart design the components can be more durable, save on material and also bring other benefits for example reduced need of compressed air or hydraulic oil when the component is in use.

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# 1 Introduction

Additive manufacturing can bring new opportunities for nuclear energy sector, with the ability to print spare parts on demand and manufacture complex geometries in one piece. However, there are also many challenges, for example lack of relevant standards and reasonable few nuclear energy relevant case studies.

Due to technological development and increased productivity, costs related to metal additive manufacturing (AM) have reduced, and various new industrial sectors are currently in process to study and adopt additive manufacturing in their manufacturing portfolio.

In the nuclear energy sector, there are two clear drivers for applying AM: the capability to manufacture very complex geometrics; and the possibility to manufacture spare parts on demand without long lead times. The operational lifetime of Nuclear Power Plant (NPP) is long, and availability and long lead times of obsolete spare parts is becoming an increasing issue. In the extreme, this causes prolonged and costly downtimes for NPP´s. Therefore, additive manufacturing offers an attractive alternative for spare part manufacturing.

To increase the awareness of this topic, Energiforsk organized a webinar "Metal Additive Manufacturing in nuclear applications", on September 23rd, 2020. The target group for the seminar was persons working with maintenance, material research and plant development in the nuclear sector and persons in the additive manufacturing industry that would like to meet with the nuclear industry.

This report summarizes the main findings and highlights from the webinar. Webinar was co-organized with VTT Technical Research Centre of Finland Ltd, where VTT's responsibilities were related mainly on the webinar program building, recruiting the speakers and moderating the event. VTT researchers also wrote this report.

# 2 Main findings and highlights from the webinar

In following, each presentation is briefly summarized, and key takeaways are highlighted. Following subtitles refers to presentation titles in chronological order.

## 2.1 WELCOME REMARKS

**Monika Adsten**, Research Area Director from Energiforsk, welcomed all participants for the webinar. She presented Energiforsk mission and some major activities to accomplish this mission. Energiforsk is owned by trading- and transmission organizations for electricity, heat and gas and it is active in entire field of energy. Energiforsk facilitates and communicates energy related R&D through collaborative actions with industry, authorities, suppliers, universities, consultants and other stakeholders. Nuclear portfolio activities in 2020 covers a wide variety of topics from Concrete related topics to Digitalization in nuclear. From these, the latter one includes the webinar reported in this report, as one action. Overall vision in this sector is to reduce maintenance and operation costs, increase availability and make nuclear attractive to industry.

After Monika's short presentation, **Pasi Puukko**, Research Team Leader from VTT, introduced himself briefly and VTT as multi-technological RTO. He also introduced the webinar program briefly. The common thread and theme of the program was to cover all relevant aspects related to utilizing metal additive manufacturing in nuclear sector, therefore covering topics starting from AM design and ending in post-processing. In addition, various views for AM utilization were given by utility and authority perspectives.

The seminar program was structured such that the presenters were available during breaks, facilitating discussions in smaller groups. This was considered to be a very practical arrangement.

## 2.2 INDUSTRIAL AM FOR ENERGY APPLICATIONS

The first keynote presentation was given by Senior Key Expert **Pajazit Avdovic** from Siemens Energy. Siemens has long history in both energy sector and utilizing additive manufacturing for it. There has been turbine manufacturing in Siemens Swedish facility Finspång since 1913. Metal additive manufacturing has increased since the first machine installation in 2009, currently there are more than 40 machines operational worldwide. Main drivers for AM utilization are 1) shorter time-to-market and lead time, 2) less resource intensive production process, 3) environmental benefits due to reduction of greenhouse gas emissions and 4) flexibility for design of parts. From customer point of view, additional befits are related mainly to improved maintenance services: obsolescence management, spare parts on demand and faster repairs.

Some interesting references were given. AM manufactured gas turbine burner is a well-known example of laser powder bed fusion (L-PBF) manufactured component and has been in commercial operation since 2018. Some major benefits include part consolidation from 13 parts and 18 welds to one integrated part, reduction of lead time by 23 weeks and enabling higher flexibility.

Another, *nuclear specific example was first 3D printed water pump impeller, operational in nuclear power plant* (Krsko, Slovenia). As an obsolete part with not existing original supplier, the part was reverse engineered and AM qualified. The main driver was significant lead time reduction. In addition to these two examples, Pajazit presented also cases related to gas turbine blade, high pressure hydraulic manifold and oil sealing rings.

Siemen's vision is to develop Additive Manufacturing towards autonomous AM through the increased intelligence and machine learning tools. Pajazit also highlighted that *additive manufacturing is much more than just 3D printing: one should master also material knowledge, design for AM, quality assurance, post processing and health and safety aspects*, to mention some.

## 2.3 DESIGN FOR ADDITIVE MANUFACTURING

Next presentation was given by **Erin Komi**, Additive Manufacturing Specialist from Etteplan Oyj. One of her key statement was that *added value for AM utilization comes from design and to accomplishing this, teamwork of various experts is needed*. In AM design workflow, it is important to choose and fix certain key aspects, like material and manufacturing method early enough, to guarantee quality of design. After giving a short overview of software tools available, she presented a couple of case studies to highlight design aspects in practice.

The first example was redesigning of a hydraulic block on a tree harvester boom, with goals of decreasing pressure drop, reducing weight, minimizing manufacturing costs and easier assembly. By combining CFD, FEM and other modelling and simulation tools, remarkable benefits were achieved, including pressure drop reduction of 40% and mass reduction of 60%. Two other examples were also given, namely pressing tool assembly for cylinder head valves and component cooling case.

## 2.4 NEW MATERIALS THROUGH ADDITIVE MANUFACTURING

The program continued with a presentation from **Ulrik Beste**, CTO of VBN Components. He focused on material development utilizing Electron Beam Melting (EBM) technology. VBN Components has developed and launched new, wear resistant and high strength carbide containing material group called Vibenite. Compared to other commercially available AM materials, Vibenite offer high hardness in combination with high yield strength and corrosion resistance. Several application examples were given for these materials including one alloy being especially suitable for nuclear application, as it is Co-free, while still having a high hardness. VBN components customer offering includes services from pre-studies to large serial production as customer site. Direct powder selling is not currently in the portfolio.

## 2.5 QUALITY OF AM COMPONENTS

**Alejandro Revuelta**, Senior Scientist from VTT gave the next presentation. The capability of create very complex geometries and one-off components brings some specific challenges for AM quality assurance. Conventional NDT methodologies are not applicable as such for very complex geometrics and on the other hand, usefulness of destructive testing is reduced for component qualification and single part quality control. In line process monitoring is a promising, but currently not yet a mature enough technology for quality control as such. Therefore, *the current best approach is the combination of these three technologies, i.e. destructive and non-destructive testing and process monitoring.*

Alejandro gave also an overview for AM standardization activities. *Currently, the AM standardization has many gaps that limit the adoption of the technologies.* However, *the standardization organizations are actively developing new standards to address many of the gaps*. Applications specific standards are being developed mainly for the medical and aerospace sectors and nuclear industry specific standards do not exist yet.

## 2.6 EXPERIENCES, NEEDS AND EXPECTATIONS - THE UTILITY PERSPECTIVE

The NPP utility perspective for AM utilization was given by **Dino Nerweyi**, Lifetime Management Engineer from TVO Teollisuuden Voima Oyj. Their main interest towards AM is related to obsolescence part management, better economics and already adequate material availability. TVO has started their AM adoption from polymer-based parts, as there lies some low hanging fruits, so to say. Experiences has been positive so far.

At metals side, the main interest technology wise is related to Laser Powder Bed Fusion (L-PBF) and various Directed Energy Deposition (DED) technologies. The latter one is especially interesting for repairing old or worn components. Related to Powder Bed Fusion, there are several activities on going, including a master theses study and close following of existing code case studies, like EPRI and Westinghouse Code Case (Record no 20-254). TVO is also in the process of having a valve body (316L) printed and to install it to the power plant. One of the valves will be operational (non-critical application) while the other will be sacrificed for testing.

Some general challenges they have faced are related to standardization, quality expectations and control and post processing. Some nuclear specific challenges are related to e.g. irradiation damages and stress corrosion cracking. *In general, understanding what is the required quality level needed to fulfil the performance requirement is a key issue.* He hoped the data needed on AM materials can be gained in joint undertakings.

## 2.7 REGULATORY POINT OF VIEW FOR ADDITIVE MANUFACTURING

**Pekka Välikangas**, Section Head of Radiation and Nuclear Safety Authority, STUK gave a regulatory point of view for AM. He started his presentation by explaining the general framework for Finnish nuclear legislation and safety requirements, which can be divided for mandatory requirements and guidance. YVL Guides deals with quite detailed technical requirements, acceptable practices and guidance. The regulator oversight of additive manufacturing has the goals to 1) oversee the reliability of AM processing and quality of parts, 2) to follow the development of codes and standards for AM, 3) to follow research and international development of AM and 4) gradually implement AM to nuclear facilities. He also presented a comparison between conventional standards and AM standards and highlighted some issues, which should be taken into account in AM standards, such as design margins, quality assurance and testing methodology.

## 2.8 JOURNEY TO QUALIFIED AM MANUFACTURER

The next presentation was given by **Steve Nardone**, Lab Manager Metal AM, from ENGIE Laborelec. ENGIE Facility and Powder Lab have certification by Lloyd's Register and Steve explained their R&D activities, which has led to this certification. Basically, this includes 1) certification of stainless steel 316L powder feedstock and Laborelec Powder Lab 2) validation of SLM500 equipment at ENGIE facility and 3) certification of produced stainless steel (mechanical performance). Lot of activities has been taken *to formulation of acceptance criteria and quality indicators for powder feedstock*. Key is to *ensure process stability, quality and reproducibility* over the long term for large production runs. Factors needed to be taken into account are e.g. powder batch, powder storage and recycling, build position and height. The effect of these factors was explained with illustrative examples and a case study of short lead time component manufacturing was given.

## 2.9 POST-PROCESSING OF AM COMPONENTS FOR CRITICAL APPLICATIONS

Hot isostatic pressing (HIP) as a tool for processing of AM components was highlighted by **Hans Södervall**, Business Development Manager from Quintus Technologies AB. *HIP has applications in nuclear sector as such (i.e. consolidation technology) and as post-processing (densification) technology for AM*. Examples of HIP as densification technology was given, and shown how it can affect for instance in fatigue life of components. In addition, examples of lead time reduction achieved by utilization of HIP as versatile heat treatment process were shown. Special feature of Quintus HIP is Uniform Rapid Cooling and Quenching, which enables high pressure heat treatments directly in the HIP. As an alternative route, approach of porous printing in combination with HIP was presented.

## 2.10 OVERVIEW OF US REGULATORY ACTIVITIES IN ADVANCED MANUFACTURING

The second keynote presentation was given by **Margaret Audrain**, Materials Engineer from US Nuclear Regulatory Commission, NRC. In general, various stakeholders at US are actively working towards more widespread utilization of advanced manufacturing technologies in nuclear applications, including vendors and licensees, Nuclear Energy Institute, Electric Power Research Institute (EPRI) and US Department of Energy. Key activities include addressing standardization gaps and developing Code Cases. For instance, ASME Special Working Group is developing guidelines for NRC on AM "Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing". 316L L-PBF data package and Code Case under development. ASME HIP specific Code Case was approved for use by US NRC in October 2019. A thimble plugging device, made of 316L by L-PBF was installed in NPP in March 2020.

An overview of NRC action plan related to advanced manufacturing technologies was given. NRC activities aims to ensure use of advanced manufacturing technologies with the US nuclear fleet and future advance reactors. Action plan includes task 1 - technical preparedness, task 2 - regulatory preparedness and task 3 - communications and knowledge management. Each task is further divided in sub-tasks. As a part of communication and knowledge managements, a public workshop on AMTs for nuclear applications will be organized Dec. 7-10, 2020.

### 2.11 CLOSING REMARKS

Closing remarks was given by **Pål Efsing**, Senior specialist and materials expert, Vattenfall AB. He summarized the outcome of the webinar by reflecting the Vattenfall activities to main findings from the webinar. Some key drivers for Vattenfall to look at additive manufacturing are related to economic crunch i.e. costs to produce energy for the grid, ageing the plants causing obsolescent issues and strategic choices related to in spare part supply chain. Many of these aspects were highlighted also on webinar presentations. These challenges are approached with virtual warehouse concept with the goal to create a fully digitized tool for the plant staff allowing for automated component status including component trending and spare part ordering. He explained a AM strategy, i.e. process for taking AM into use in nuclear applications. Several aspects, highlighted also by other webinar speakers, were identified, including general AM awareness and knowledge, material and process qualification and quality control, demonstrator to verify the capabilities of technology etc. He also listed several requirements which are and should be followed. He also highlighted the role of Code Cases as vital path towards AM qualification. Also, *the gaps in standardization was highlighted as one specific issue slowing down the AM utilization.*


# Keywords

Additive manufacturing, 3d printing, hot isostatic pressing, nuclear energy, design, quality control, quality assurance, materials, regulations, qualification

# METAL ADDITIVE MANUFACTURING IN NUCLEAR APPLICATIONS

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