

Development and commercialization of innovative manufacturing technologies for SMR applications

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1. Introduction

Small Modular Reactors (SMRs) are gaining global attention as next-generation nuclear technologies capable of supporting the energy transition and achieving carbon neutrality goals. Their modular and compact design enhances safety while enabling factory fabrication of modules followed by on-site assembly and installation, thereby reducing construction schedules and upfront capital investment.

However, conventional fabrication processes for large nuclear power plants relying primarily on large forgings and multi-pass arc welding often require several years to complete and involve extensive post-weld heat treatment and machining. These factors have historically contributed to quality variability and cost overruns. Therefore, to realize a scalable and economically competitive mass-production system for SMR, it is essential to develop and deploy innovative manufacturing technologies that can overcome the limitations of traditional fabrication approaches.

Among the emerging solutions, three technologies have attracted significant international interest: Powder Metallurgy–Hot Isostatic Pressing (PM-HIP), which enables the fabrication of monolithic structures with reduced reliance on welding; Electron Beam Welding (EBW), which provides deep single-pass welds with minimized heat input and distortion; and Diode Laser Cladding (DLC), which produces thin and uniform corrosion- and wear-resistant layers without requiring post-cladding heat treatment. Even when applied individually, these technologies can significantly reduce manufacturing time and cost; when integrated, they are expected to further shorten Reactor Pressure Vessel (RPV) fabrication by approximately 18 months and reduce costs by about 40%.

Accordingly, the objective of this study is to comprehensively review development trends in PM-HIP, EBW and DLC, evaluate their applicability to SMR fabrication processes, and derive strategies for commercialization. Ultimately, this work aims to provide a practical technical basis for securing core enabling technologies, strengthening domestic manufacturing competitiveness, and supporting leadership in the global SMR market.

2. Scope and Contents

This study systematically evaluates the technical feasibility and regulatory acceptability of innovative manufacturing technologies required to support SMR commercialization. Although SMRs pursue a factory-based production model grounded in modular and integral design concepts, conventional fabrication methods primarily based on large-scale forging, casting, and multi-pass arc welding still present limitations in lead time, cost, and quality consistency. In this context, the present work investigates advanced manufacturing technologies aligned with SMR design philosophy and capable of mitigating the constraints inherent in construction-oriented fabrication.

The scope of analysis is confined to safety-significant components within the SMR fabrication lifecycle, specifically the RPV and major pressure-boundary structural components. Non-structural systems, including instrumentation and control and fuel-related systems, are excluded to focus on manufacturing technologies that directly influence structural integrity, quality assurance, and regulatory compliance.

Three representative technologies (PM-HIP, EBW and DLC) are examined within a consistent evaluation framework covering process principles, technical characteristics, applicable materials, equipment and infrastructure requirements, and global R&D and demonstration trends. This structured approach enables a comparative assessment of technological maturity, commercialization potential, and the relative advantages and limitations of each technology against conventional fabrication methods.

PM-HIP is a manufacturing process in which metal powders are consolidated under high-temperature and high-pressure isostatic conditions to produce near full-density solid components. The process consists of multiple precise stages (Fig. 1). In this study, PM-HIP is assessed in terms of its ability to produce monolithic components, thereby reducing internal defects and enabling uniform microstructures with isotropic mechanical properties. Particular attention is given to applications involving complex geometries, such as RPV heads with multiple penetrations, where enhanced design flexibility and reduced fabrication lead time are critical. Regulatory considerations are also addressed, including the need for long-term material property data,

code qualification, and demonstration of structural integrity for key materials such as SA508 low-alloy steel.



Fig. 1. PM-HIP processing and benefits.

EBW is an advanced welding technology that precisely directs a high-energy electron beam onto a joint in a vacuum environment, producing instantaneous fusion. A defining feature of EBW is the “keyhole” welding mode: when the beam strikes the metal, localized vaporization forms a deep vapor cavity, and continued beam penetration into this cavity melts the material through its thickness, enabling deep and full-penetration fusion (Fig. 2). The analysis focuses on EBW’s single-pass deep-penetration capability for thick-section pressure-boundary components and its ability to reduce distortion and residual stresses due to low heat input. Regulatory acceptance pathways are reviewed through relevant ASME Code Cases, welding procedure qualification (WPS/PQR), mock-up testing, and nondestructive examination (NDE) requirements. In parallel, key commercialization challenges such as the need for large-scale vacuum systems and limitations associated with repair welding are identified and discussed.

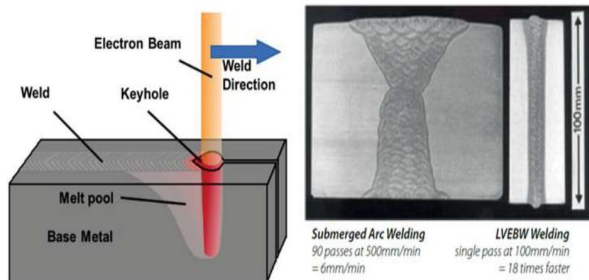


Fig. 2. EBW keyhole weld and weld cross-section (compared to Submerged Arc Welding)

DLC is evaluated as a low-heat-input, low-dilution surface modification technology that can enhance the corrosion resistance, wear resistance, and thermal durability of critical components. Notably, diode lasers can generate a “top-hat” beam profile, which exhibits smaller energy variation between the center and periphery than conventional Gaussian-profile lasers. This facilitates a more uniform molten pool and can

achieve a dilution rate of 5% or less, thereby minimizing base-metal influence on the cladding layer (Fig. 3). The assessment also considers the use of cobalt-free alloys for radiation dose reduction and the compatibility of DLC with automated, factory-based manufacturing environments. Technical and regulatory challenges including process stability, real-time monitoring, inspection reliability, and the lack of explicit recognition in major nuclear codes are comprehensively examined.

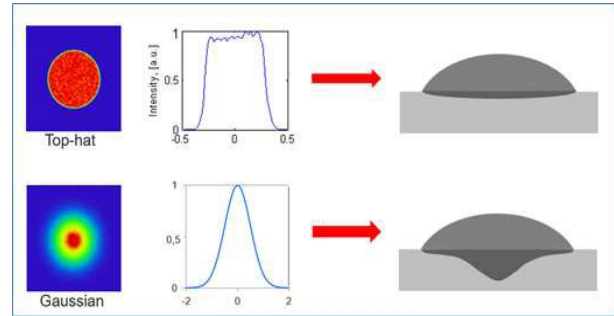


Fig. 3. Comparison of top-hat and Gaussian beams and beads

Beyond the assessment of individual technologies, this study further explores their integration into a unified manufacturing sequence consisting of PM-HIP, EBW and DLC. Such an integrated approach has the potential to shift RPV fabrication from a field-intensive construction paradigm toward a factory-based manufacturing paradigm, enabling reductions in fabrication time and cost while improving quality and reliability. Finally, a phased commercialization strategy is proposed, addressing technology validation, regulatory approval and standardization, industrial infrastructure development, and supply-chain readiness, thereby providing a foundation for future research, policy formulation, and regulatory preparedness for innovative SMR manufacturing technologies.

3. Conclusions

PM-HIP, EBW and DLC are core innovative technologies capable of shortening SMR manufacturing schedules, reducing costs, and improving quality. Their integrated application can facilitate a transition from conventional on-site construction to factory-based manufacturing, thereby supporting mass production and enhancing the economic viability of SMR.

Nevertheless, successful deployment requires the validation of material reliability data particularly for SA508 steel, along with the establishment of rapid qualification frameworks including applicable codes registration and regulatory approval. In addition, large-scale investment in manufacturing infrastructure, strengthened collaboration among industry, academia, and research institutions, localization and strengthening of supply chains, and expanded international joint demonstrations and standardization efforts must be pursued in parallel.

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