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TOPICAL REVIEW

Advanced manufacturing applied to nuclear fusion—challenges and solutions

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Keywords: additive manufacturing, electron beam welding (EBW), plasma facing components, powder metallurgy–hot isostatic pressing (PM-HIP), HIP-bonding, spark plasma sintering (SPS), transient liquid phase bonding (TLPB)

Abstract

Materials needed to achieve designed performance will require formulations and processing methods capable of delivering a compendium of metallic, ceramic and cermet chemistries, which must be finely tuned at source, and tolerant to down-stream thermomechanical adjustment. Structural steels and cermets are continuously being developed by researchers using computational thermodynamics modelling and modified thermomechanical treatments, with oxide dispersion strengthened steel (ODS)-reduced activated ferritic-martensitic steel (RAFM) steels based on 8%–16% wt.% Cr now being assessed. The combination of SiC_f and CuCrZr as a metal matrix composite containing an active coolant would be seen as a major opportunity, furthermore, composite ceramic materials consisting of SiC fibres reinforcing a SiC matrix capable of being joined to metallic structures offer great potential in the development of advanced heat exchangers. Continuing the theme of advanced manufacturing, the use of solid-state processing technologies involving powder metallurgy–hot isostatic pressing and spark plasma sintering to produce near-net shaped products in metallics, ceramics and cermets are critical manufacturing research themes. Additive manufacturing (AM) to produce metallic and ceramic components is now becoming a feasible manufacturing route, and through the combination of AM and subtractive machining, capability exists to produce efficient fluid carrying structures that could not be manufactured by any other process. Extending this to using electron beam welding and advanced heat treatments to improve homogeneity and provide modularity, a two-pronged solution is now available to improve capability and integrity, whilst concurrently offering increased degrees of freedom for designers.

1. Introduction

Energy created from nuclear fusion cannot be delivered at any cost and the research and manufacturing community will need to step up to the challenges faced in developing appropriate materials, manufacturing methods and construction sequences in a cost-effective manner. It is commonly heard that we must ‘design for manufacture’ or ‘design for inspection’ to name but a few, but there seems to be a blind spot in appreciating the challenges designers face in meeting the targeted performance, none will be more so than the requirements to achieve a commercial nuclear fusion reactor by the 2040s. Therefore, a suitable equilibrium between these two approaches must be achieved and underpinned by an ALARP—‘as low as reasonably practicable’ philosophy.

It is the author’s view that a balance between the ‘design for manufacturing’ aspect with a ‘design for performance’ commensurate with acceptable cost, balanced against the return on investment (ROI) will be one of the key metrics of commercialisation. Polymorphic adjustment of a material during processing and fabrication to promote and sustain key properties to function appropriately is emphatically needed. The choice of manufacturing process can therefore play a significant part in a material’s ability to perform, and at the same time be compliant with achieving environmental sustainability targets. This can be achieved through using energy efficient processes, improved material utilisation and new fabrication philosophies.

Manufacturers will therefore be required to challenge the status quo and surmount current engineering limitations through accelerating and adopting advanced technologies and innovative methods through an integrated readiness level approach. This integrated approach pertains to the application of combining industry recognised capability practice involving Technology Readiness Levels, Manufacturing Readiness Levels and Supply Chain Readiness Levels to identify capability in confidently deploying new or innovative methods and practices that not only identify technology as being capable, but it also determines whether the business case is financially viable and that those workforce capabilities exist to deploy this new methodology. Typical acceptance of such systems requires these levels to be moving towards or have achieved a level 6 status, where a system/subsystem model or prototype demonstration has been demonstrated in relevant environment; processing controls and statistical correlation have met the agreed target, and cycle times and all cost drivers, including business case, are achievable with no significant risks remaining.

Step changes in raw material manufacturing and component fabrication, involving additive and hybrid manufacturing, quantum heat source processing, e.g., laser and electron beam systems, and solid-state joining, combined with new construction philosophies will enhance manufacturing capability. The term hybrid manufacturing used in this context refers to two areas:

1. The combination of different conditions of supply of a material, e.g., the deposition of appurtenances or support features onto a forged structure that are beyond the original forging envelope, saving significant time, energy and cost.
2. The combination of additive and subtractive manufacturing (SM) techniques working in tandem on a single platform.

For this manufacturing research to be realised, investment in ancillary services fundamental to performance assessment leading to the creation of appropriate design and construction codes, standards and specifications must be achieved and supported by investment in equipment qualification and verification hardware and practices. The use of surrogate data and processing methods will only take us part of the way. Such testing and performance assessment capacity will need to be ideally at full-scale, or at a very minimum of 66% full scale, to increase our statistical confidence and improve our analytical techniques through the adoption of more machine and deep learning methods. The ability to run both physical and digital models in parallel will accelerate high-definition models to support a 'design by analysis' approach and remove arduous testing for future developments. These potential vehicles will increase our confidence, not only in product performance, but in the improvement of those respective duty cycles associated with new manufacturing processes and the fidelity of the whole manufacturing cycle.

2. Material challenges for fusion reactors

There are several major hurdles to overcome if energy is to be generated on a commercial scale from nuclear fusion. Severe demands being placed on materials capable of functioning within the most extreme environments whilst concurrently acting as functional connectors within and across such zones will stretch the limits of our present knowledge and capabilities in the field of materials science and manufacturing. The author therefore believes that such requirements cannot solely rest on the shoulders of our eminent researchers in this field but will also require a paradigm shift in our current manufacturing, construction and servicing methods.

Components that will rely heavily on material development are:

1. Plasma facing components (PFCs) that include divertors
2. Breeder blankets
3. Structures and ports
4. Radiation shields
5. Thermal shields
6. Vacuum vessels
7. Magnets

These components have been identified by the UK Atomic Energy Authority's materials team as constituting the most difficult material challenges and have been front and centre in defining the UK's fusion material roadmap [1]. However, additional considerations associated with the thermal management systems e.g. heat exchangers (HXs) and Cryostats operating at temperatures above 500 °C (773 K) and down as low as −269 °C (4 K) respectively, will demand severe attention to achieve dimensional stability with tolerant thermal and radiation properties.

This paper provides an overview of those manufacturing challenges and provides potential solutions associated with key material candidates related to some of those critical components.

2.1. PFCs and critical support structures

Components of this type have identified the following material candidates as being potentially suitable for PFCs, divertors, neutron multiplier systems (tritium breeding), heat sink and armour systems:

- Tungsten and some of its alloys [$W/W_{(X,\,Y,\,Z)^*}$]
- Beryllium—Be
- Molybdenum—Mo
- Lithium—Li
- Boron carbide—B_4C
- Carbon fibre composites—CFC thermally modified to form a graphite
- Graphite—C
- Silicon Carbide—SiC

Note $^*x$, y and z represent the stoichiometric composition.

It is expected that not all these materials will be cost effective contenders for an economic fusion reactor due to either the economy of scale or lack of manufacturing capability. Such a situation would result in one-off expensive throwaway items, which cannot be tolerated. Furthermore, plasma-facing component materials associated with the divertor will need to be attached to structurally suitable highly efficient thermal conductivity heat sinks capable of removing very high stationary heat fluxes, expected to be in the region of 20 MW m^{-2} [1]. This thermal gradient will require composite forms of refractory, structural and conductive materials, to overcome significant thermophysical property differences whilst targeted to be isotopically favourable.

2.2. Structural, thermal, and electrical materials

Examples of current materials providing these properties include reduced activated ferritic-martensitic steels (RAFMs), Cu-alloy metal matrix composites (Glidcop™), creep strength enhanced ferritic steels, oxide dispersion strengthened steels (ODS), and composite nanostructured alloys.

For these materials to achieve designed performance the formulation and processing of a compendium of chemistries to process metallics, ceramics and cermets must be finely tuned. This must be done at source and be tolerant to thermomechanical adjustment to allow material and systems designers to achieve a desired functionality. Polymorphic adjustment of the material to encourage phases that promote thermal and structural stability, whilst tolerant to irradiation degradation with high resistance to material loss when subjected to physical and chemical sputtering, are just some key attributes needed. The strategic tailoring of properties in the raw material offering improvements in neutron management may not be realised after subjecting the material to forming and fabricating processes, hence the need to ensure an interdisciplinary approach is adopted that manages and challenges the equilibrium between 'designing for performance', and 'designing for manufacture', at a project's onset.

ODS steels are continuously being developed mainly through using computational thermodynamics modelling and modified thermomechanical treatments. ODS-RAFM steels based on 8%–16% wt.% Cr are now being assessed [2]. Researchers are stating that early indications from these models offer potentially higher payoff through using powder metallurgy techniques, however their chemistry promotes a higher level of risk to achieve this performance after manufacturing. This technique is reputed to be capable of producing very high strength ODS steels tolerant of operating at very high temperatures [3–12]. Their proposed solutions to this issue may be through the development of high concentrations of uniformly distributed inert nanoscale particles that could offer the prospect for very high mechanical strength and nanocluster stability under extreme operating conditions. Figure 1 depicts a processing route for such steels using Y_2O_3 and Ti particles [13].

Whilst this would seem promising, the successful development and use of such material could fail in its adoption because of post-process manufacturing operations, which take it from its condition of supply (COS) to a functional component. This is a significant manufacturing hurdle to overcome and requires a new strand of fabrication techniques.

Non-oxide ceramics of the silicon carbide (SiC) type not only seem to have positive attributes for nuclear fusion applications but also for the Generation IV reactor systems. Composite ceramic materials consisting of SiC fibres reinforcing a SiC matrix offer great potential due to their very low radioactivity and very high operating temperature stability that are commensurate with delivering a high degree of efficiency. These materials could be fundamental in the realisation of PFC and divertor performance for a commercial reactor,

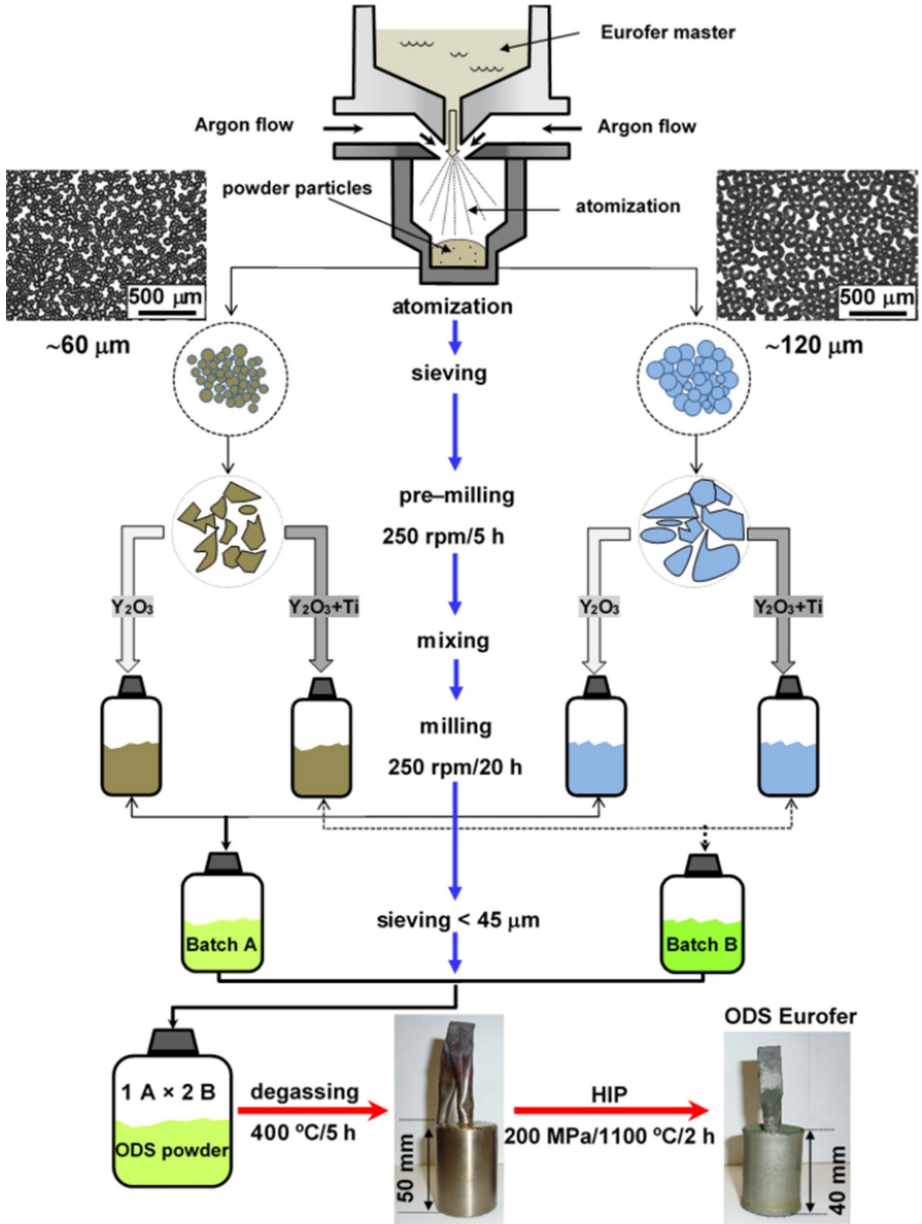

Figure 1. Processing, penetration, and dispersion of Y_2O_3 and Ti into Eurofer powder reprinted with kind permission from [13]. Reprinted from [13], Copyright (2021), with permission from Elsevier.

and could offer additional benefits in other areas, e.g., secondary thermal management systems such as liquid lithium heat exchangers.

Other ceramics of the oxide form such as Lithium orthosilicate (Li_4SiO_4) and Lithium titanate (Li_2TiO_3) continue to be studied as breeder blanket materials in the form of 'pebbles' because of their tritium breeding efficiency [14, 15]; the fabrication of which must be resilient and reliable.

The application of refractory metals such as tungsten, vanadium, and molybdenum for structural applications, whilst extremely promising will challenge the current production routes from a capability and cost-effective perspective. Vanadium alloys based on the V–Cr–Ti system are proposed to offer significant potential for high-temperature applications in combination with a liquid lithium breeder system [16]. The development and use of such new materials should also assess their effectiveness in supporting a more convenient life-cycle analysis strategy to include recycling, secondary reuse, and disposal via lower cost and suitably relaxed conditions.

Since no single material will have all the attributes to withstand continuous exposure at these extreme temperatures, provide suitable neutron transparency, maintain structural performance whilst simultaneously being a highly effective thermal conductor with the capacity to handle the thermal transfer rate, a blend of materials will be required. Work involving the use of CuCrZr alloys, whilst initially promising, restrict their use to 350 °C. This is primarily due to degradation in mechanical strength, which is accentuated further by intense radiation, so are deemed unsuitable to handle the high coolant temperatures. Therefore the combination of SiC_f and CuCrZr as a metal matrix composite containing an active coolant would be seen as a major opportunity, however, once again the manufacturability methods will need to be suitably available and cost effective, so exploitation of this capability using the experience from within the aerospace and space sectors would seem appropriate to explore.

Copper is an indispensable material in the creation of superconducting cable to generate the desired current levels to induce ultra-high magnetic field strengths. The development of very high purity copper capable of handling high current transfer with the lowest achievable resistance is beyond the purity of commercial grades such as the oxygen free electronic C10100 grade, which has a purity classification of 99.99% Cu.

The need to achieve significantly greater purity to the designated residual resistivity ratio (RRR) must have a minimum RRR value of 250 or even higher [17]. The RRR is defined as the ratio of resistivity at 273 K to the resistivity at 4 K. It gives a measure of the purity of the material and the extent of lattice imperfections from cold work. This level of Cu purity must be characterised by the RRR and measured in the soft annealed condition. Here, the use of hot zone refining could be assessed as a production method to evaluate if it is possible to achieve this minimum RRR value, with expected Cu purity values to lie between 99.999% and 99.999 99% Cu.

2.3. Vacuum vessel and cryostat

For inner wall shielding of the vacuum vessel borated steels and ferritic steels have been proposed for the International Thermonuclear Experimental Reactor (ITER), with the base materials being a noted ITER-grade of 316L(N)-IG [18]. The borated and ferritic steels have been used to reduce neutron heating in magnets and reduce magnetic ripples. The 316L(N) steel grades are well established and have relatively favourable fabrication responses, due to their being easily cast, forged, extruded, and welded. However, the complexity of this structure still promotes considerable manufacturing challenges for a future cost-effective reactor construction. Such challenges include, but are not limited to weld joint design, welding metallurgy, dimensional stability, material utilisation and supply-chain capability.

The major material for the ITER cryostat is noted as being fabricated from dual marked Type 304/304L SS plates and manufactured to the ASME Section-VIII Division-2 code [18]. One major manufacturing challenge here will be to ensure that all welds, and their respective heat-affected zones (HAZs) surpass the required minimum Charpy impact toughness values when tested at −268.95 °C (4.2 K).

3. Manufacturing challenges and potential solutions

For nuclear fusion to reach commercial realisation several influential engineering and manufacturing barriers need to be surmounted. The choice of manufacturing process can play a significant part in the materials performance and production time whilst contributing to environmental sustainability. Energy reductions and improved material utilisation through using quantum heat source technology and near-net shaped forming that improves 'product-to-point-of-use' ratios respectively, reduce processing and remove the need for excessive profile envelopes. Their deployment will provide a balance of the 'design for manufacturing' aspect with a 'design for performance' that is commensurate to the acceptable cost versus the ROI of the system.

3.1. Solid-state near-net shaped processing

Near-net shaped products produced by solid-state processing applied to metallics, ceramics and cermets is now a key manufacturing theme. The capability this technology offers should not be looked at in isolation. The strategic planning of a complex component should also consider modularisation to exploit specific benefits, which a hybrid structure could offer. The use of powder metallurgy processing provides a route to create components in materials with specific properties that conventional methods such as casting, and forging cannot achieve. Material combinations that provide pseudoelastic and shape memory properties through functionally graded forms of refractory metals and ceramics, offer interesting opportunities, but the joining of these in composite forms will provide a challenge in maintaining those key properties [19]. The need to provide an engineering ontological toolbox offering a viable strategy for the alignment, reconciliation, and integration of diverse and disparate methods of manufacturing now needs to be researched in parallel with new material developments.

There are many forms of solid-state near-net shape processes being researched, but in this paper the author focuses on those that are exhibiting near-term promise capable of being exploited by design and manufacturing communities creating prototypical components for fusion and advanced modular reactors.

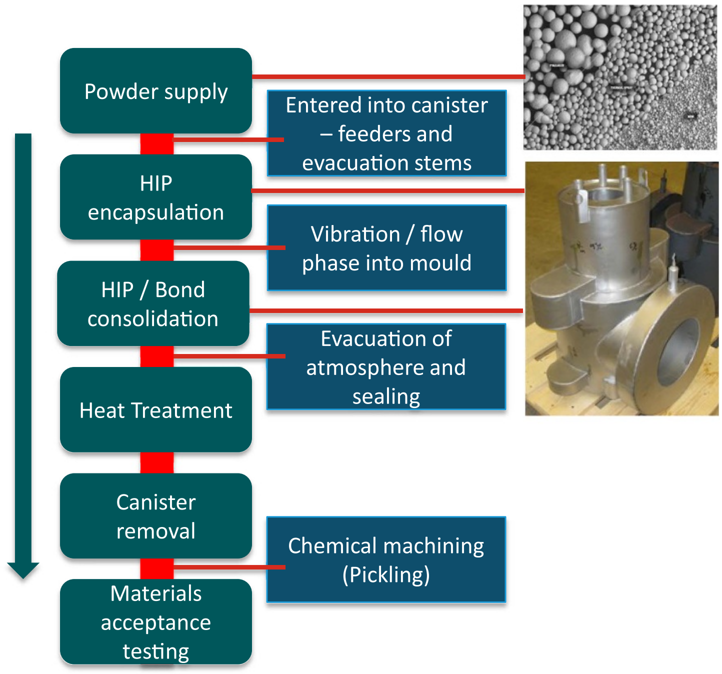

Figure 2. Showing a typical sequence of PM-HIP operations.

3.2. *Powder metallurgy–hot isostatic pressing (PM-HIP)*

Research and development involving PM-HIP for near-net shaped forming and bonding, provides one of the most opportunistic and favourable manufacturing routes to supporting the development and joining of those noted materials. Work in assessing the feasibility of producing nuclear grade components for small modular reactors is now being undertaken by the Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC), the Electric Power Research Institute (EPRI) and Synertech Powder Metallurgy Inc. This research using an SA508 Grade 3 class 1 steel powder (table 1), providing pressure vessel grade mechanical properties, is now being realised as a game-changing practice for future manufacturing improvements offering a myriad of benefits that include:

- Improved material utilisation
- Reduced machining costs
- Improved design freedom through modularised architecture and connector repositioning
- Improved accessibility to attach connectors and appurtenances
- Homogeneous isotropic equiaxed microstructure to improve Z-properties and inspection
- Minimising the number of welds in certain applications
- Reduced residual stress in critical joint regions
- Offering capability to create dissimilar material bonds
- Functionally graded materials—improved management of stress and corrosion aspects
- Providing alternative supply-chain options

Such technology is independent of end users and readily transferrable into the nuclear fusion sector. A typical PM-HIP procedure generally follows the sequence of events shown in figure 2.

Consideration of feedstock in terms of chemistry, particle size distribution (PSD) and morphology are just some of the critical parameters that need to be controlled. The use of vacuum induction melted (VIM) atomised powders, due to their chemistry cleanliness has provided the capability to achieve the required toughness values; this is one of the major mechanical property issues associated with pressure vessel design. Optimisation of the time-temperature pressure cycle for various PM-HIP material conditions is also a critical parameter, not only for delivering high-quality bonds between dissimilar materials, but also highly densified structures (figure 3) and the creation of controlled porosity as an aid for augmenting thermal characteristics.

Further work in the development of air melted powders is required to achieve certain mechanical properties and drive down cost. One potential cost-effective avenue is the use of powders that have been vacuum annealed, which can produce pristine powders with very low oxygen contents. Gas atomised (GA)

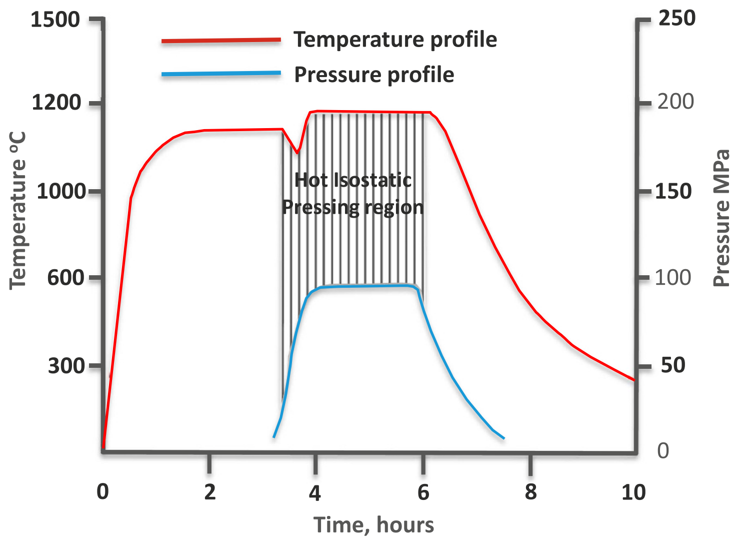

Figure 3. Showing a typical time–temperature–pressure cycle.

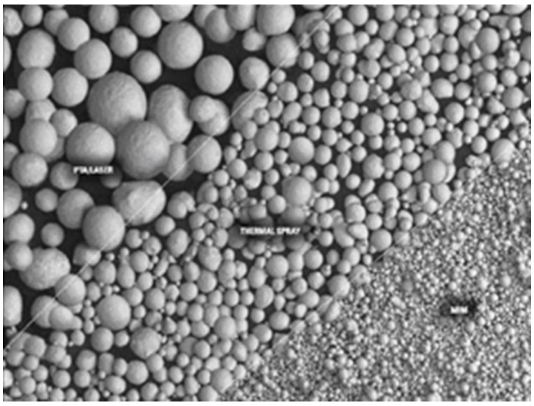

Figure 4. GA powders <1 μm to 500 μm. Figure used with permission from the DOE and EPRI.

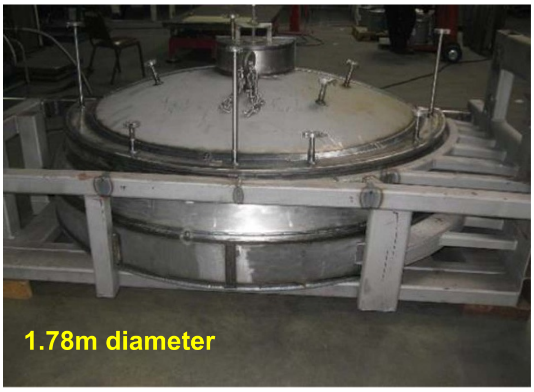

Figure 5. Canister system and frame courtesy of the DOE, Synertech PM Inc. and EPRI. Figure used with permission from the DOE and EPRI.

powders produce fine spherical morphologies ranging in effective diameters from 50 μm to 500 μm (figure 4). Canisters fabricated in mild steel or stainless steels to receive and position the powder in the desired shape, offer varying benefits depending on the post processing requirements. Mild steel canisters were used for this programme (figure 5). Vibration and flow into the canister followed by evacuation and sealing, positions the structure in its most compact form at ambient STP conditions.

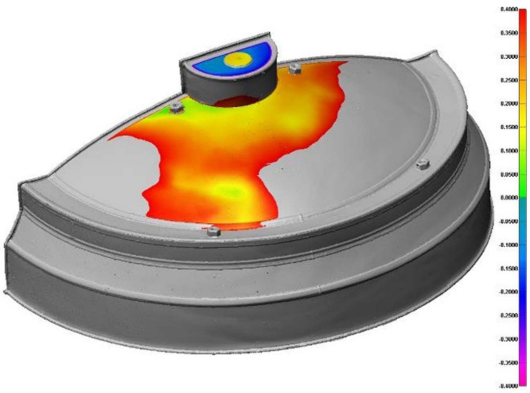

Figure 6. Shrinkage profile—top surface courtesy of the DOE, Synertech PM Inc. and EPRI. Figure used with permission from the DOE and EPRI.

Figure 7. Completed form (1.78 m ⌀) courtesy of the DOE, Synertech PM Inc. and EPRI. Figure used with permission from the DOE and EPRI.

Fabrication of support frames and lifting systems must also be considered within the design, although the key area for further research involves the physical determination of volumetric shrinkage during the consolidation phase that can be digitally modelled to predict consistent integrity and improved repeatability (figures 6 and 7).

As further complexity is needed, sheet forms will be shaped and welded to represent multiple protrusions and changing surface topographies, this results in a corresponding impact on dimensional stability. Therefore, an elevated level of importance attached to advancing the physical and digital process modelling within this manufacturing stage is revealed as being fundamentally important to its success. Studies have shown a promising method capable of predicting the shape of parts produced using PM-HIP through linking the generalised von-Mises criteria applied to the plasticity condition, and assigning the material as a compressible rigid plastic solid that undergoes strengthening via a volumetric straining condition [20]. Examples where this form of modelling will be extremely important relate to the geometry of pressure vessel heads and the integration of penetration nozzles as part of the preform mould (figures 8 and 9).

The canister section depicted here shows the integral nozzle regions that would require several through-thickness welds if processed through the conventional route, i.e., when separately attaching nozzles to the forged head. However, with the PM-HIP method this has now eliminated the use of such highly stressed 'single J' bevel weld joints required to achieve through-thickness fusion (figures 10 and 11). Such joints produce high residual stress, become more difficult to inspect, and require global post-weld heat treatments of the component.

Rearranging the configuration through integrated protrusions will allow designers to reposition these connections and weld in the horizontal position (PC/2G) using bore welding methods. An example of such capability is depicted in figure 12.

Results from research completed by the Nuclear AMRC, EPRI and Synertech Powder Metallurgy Inc. involving the development of a low-alloy pressure vessel steel SA-508 Grade 3 powder, and the generation of a PM-HIP cycle, has shown significant progress towards achieving and potentially surpassing that of conventional wrought alloys in certain properties (table 2 and figure 15). The target toughness is significantly

Figure 8. CAD model of PV head courtesy of EPRI and the DOE. Figure used with permission from the DOE and EPRI.

Figure 9. Canister of PV head (1650 kg) courtesy of Synertech Powder Metallurgy Inc., EPRI and DOE. Figure used with permission from the DOE and EPRI.

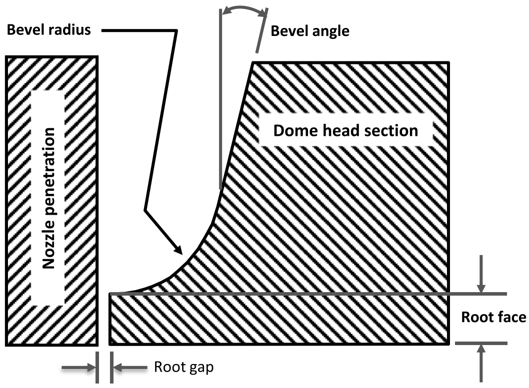

Figure 10. Typical single J bevel weld joint for nozzle to head connection.

higher than the minimum specification average value but still short of the actual wrought SA-508 Grade 3. Significant improvement has been achieved through a combination of using powder processed via the VIM atomisation method, careful chemistry adjustment and vacuum annealing prior to sealing the canister. This work could significantly contribute to the development of cost-effective high integrity structures for critical fusion reactor architecture. Further benefits noted with this technology include the bonding of dissimilar materials (figures 13 and 14).

The results from tensile testing (table 2) show that the PM-HIP material satisfies the required minimum and range of properties as specified within ASME II Part A, but as the oxygen content increases the toughness decreases. Vacuum annealing conducted at 800 °C prior to cannister sealing shows a marked improvement in the average CVN toughness associated with the improved removal of interstitial elements—mainly the oxygen content.

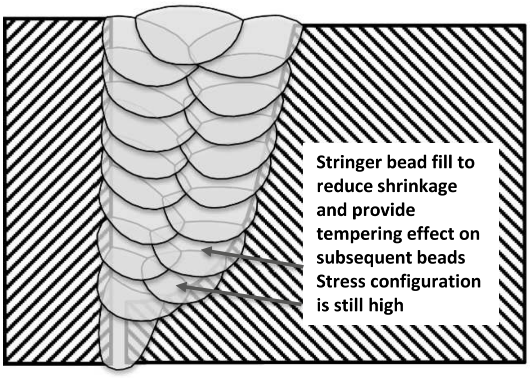

Figure 11. Single J bevel weld joint fusion profile.

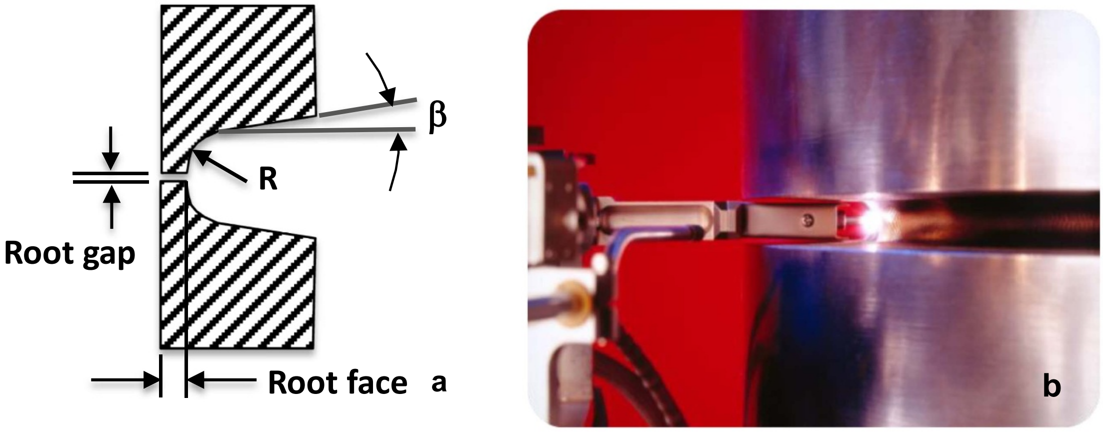

Figure 12. (a). Showing a schematic of a narrow groove U butt weld joint and (b). Showing a narrow groove weld completed in the horizontal position (PC/2G). Reproduced with permission from NAMRC.

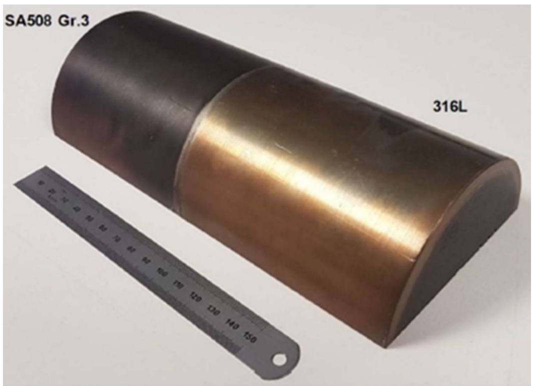

Image courtesy of Wood (now Jacobs)

Figure 13. HIP bond between a 316L and SA508 Gr3 Cl1 steel. Reproduced with permission from NAMRC.

3.3. Spark plasma sintering (SPS)

This technique is characterised by a thermal cycle that utilises a rapid temperature rise, short sintering time and uniform heating for sintered bodies. The process has been applied in the preparation of nanocomposites, functional materials, ceramics, cermets and intermetallic compounds [21]. However, challenges can still exist in the creation of composite structures involving metallic and non-metallic forms, and the author provides a brief description that can be represented by the process of Joule heating in nanowires used by these

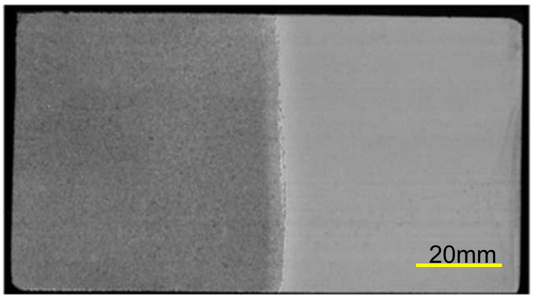

Figure 14. Macrostructure of 316L to SA508 bond. Reproduced with permission from NAMRC.

Table 1. Condition of SA508 Grade 3 class 1 steel powder and wrought alloy chemistry.

	CoS	Particle size distribution (μm)	Elements (wt.%) unless specified by parts per million (ppm)										
ID	Route	PSD	C	Si	Mn	P	S	Cr	Mo	Ni	Al	N	O (ppm)
SA508 Gr.3 min.		—			1.2				0.45	0.4		—	—
SA508 Gr.3 max.		—	0.25	0.4	1.5	0.025	0.025	0.25	0.6	1	0.025	—	—
Wrought	AM-cast	n/a	0.16	0.25	1.27	0.004	0.002	0.17	0.48	0.67	0.02	**0.004**	**20**
PM-HIP 1	Lab. VIM-IGA	0–500	0.15	0.34	1.15	0.01	0.007	0.1	0.51	0.81	0.003	0.03	100
PM-HIP 2	AM-IGA	0–500	0.15	0.30	1.20	0.013	0.005	0.18	0.52	0.85	0.001	0.04	90
PM-HIP 3	AM-IGA	0–500	0.170	0.31	1.19	0.012	0.004	0.11	0.52	0.84	0.000	0.03	90
PM-HIP 4	VIM-IGA	50–500	0.18	0.01	1.18	0.004	0.004	0.13	0.52	0.78	$<$0.030	0.030	**79**
PM-HIP 5	VIM-IGA	50–500	0.15	0.01	1.23	0.006	0.005	0.15	0.53	**1.04**	$<$0.030	0.0304	**50**

Table 2. Mechanical property comparison for SA508 Grade 3 class 1 steel powder and wrought alloy chemistry.

	Rp0.2 (MPa)	Rm (MPa)	A (%)	Z (%)	Ave. (*J*) [21 °C] (700 °C) Anneal	Ave. (*J*) [21 °C] (800 °C) Anneal
ASME	450 min.	620–795	16 min.	35 min.	48 min.	48 min.
Wrought	520	650	27.6	75	262	—
PM-HIP1	515	640	27.5	68	103	**150**
PM-HIP3	620	715	26.0	67	80	**155**
PM-HIP5	620	715	22.0	75	150	**170**

researchers. Here, the process of sintering conductive materials observes that current mainly flows through the die and the green body.

The current density $j\,(r,\,t)$ can be related to the change of temperature T of a material as a function of position r, and time t, using:

$$\frac{\delta T}{\delta t} = \frac{k}{pC}\nabla^2 T + \frac{Q}{pC} = \frac{1}{pC}\left(k\nabla^2 T + Q\right). \tag{1}$$

Here:
k is the thermal conductivity (W (K m)$^{-1}$)
ρ is the density (kgm^{-3})
C is the specific heat capacity (J (kg K) $^{-1}$)
∇^2 is the Laplace operator $\frac{\delta^2}{\delta x^2} + \frac{\delta^2}{\delta y^2} + \frac{\delta^2}{\delta z^2}$
T is the temperature (K)
Q is a heating term (Wm^{-3}).

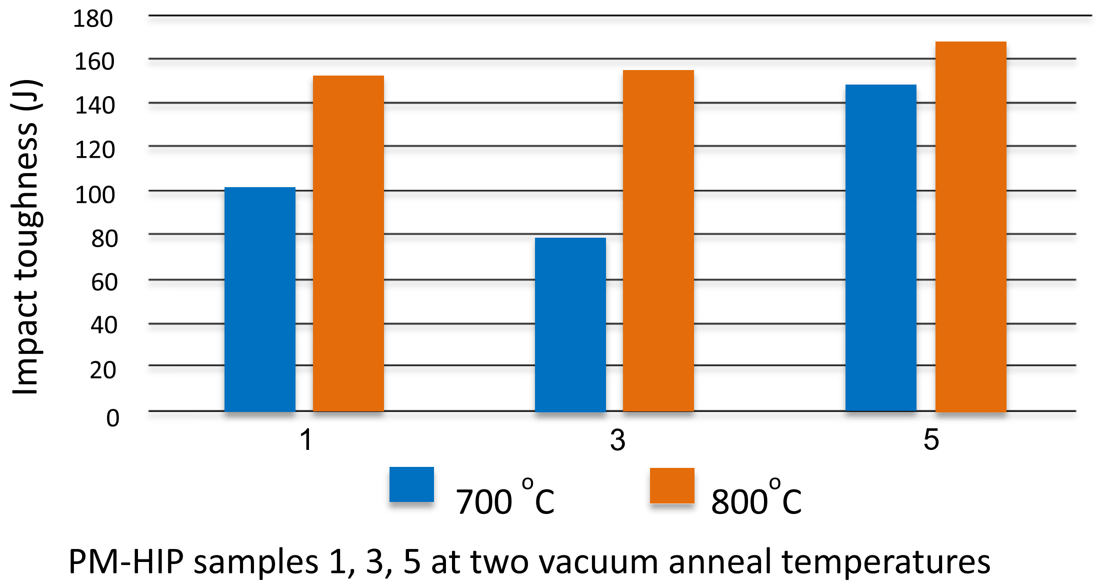

Figure 15. CVN Impact toughness values (J) at 700 °C and 800 °C. Figure used with permission from the DOE and EPRI.

From this, the Joule heating resulting from a current density j in an electrical field E can be expressed as:

$$Q = j \cdot E = \frac{1}{\sigma} j^2 \tag{2}$$

where:

$\sigma =$ the electrical conductivity (S/m $= 1\ \Omega\mathrm{m}^{-1}$)

$j = \sigma \cdot E$

$$j = j_S \mathrm{e}^{-(1+j)\frac{d}{d_s}} = j_S \mathrm{e}^{-\left(\frac{d}{d_s}\right)} \tag{3}$$

where:

$j =$ current density

$j_S =$ the current density on the surface of the conductor

$d =$ exponential decay value of current density at a known depth

$d_S =$ the skin depth arising from an alternating current and provides the extent at which the current penetrates the surface to a depth of 37%. This later variable can be determined by

$$d_s = \frac{503}{\sqrt{\nu \mu_r \sigma}} \tag{4}$$

where:

$\nu =$ the current frequency

$\sigma =$ the electrical conductivity

$\mu_r =$ the relative permeability of the conductivity.

So, for a conducting material, a current skin effect is produced when a high frequency alternating current passes through it. More heat will be created in this case than in that if no skin effect is produced. However, when considering the fabrication of non-primitive structures (asymmetrical) containing re-entry type profiles required for fusion reactor components, there exists the potential to produce heating effects from eddy currents within each grain, resulting in a magnetic flux being induced across such zones that change with time. With such scenarios, it is feasible to consider each grain as a small heat source offering the benefit of forming an *in-situ* sintering condition, thereby locally accelerating the sintering of the green body, which due to its micro inhomogeneity and varying grain shapes, results in a complexity that is difficult to ascertain accurately the heat distribution needed to uphold component confidence associated with integrity and fusion performance. The temperature rise occurring as part of this heating effect will naturally be influenced by the conductivity of the material, therefore, the process will need to consider other thermophysical properties, most notably the coefficient of thermal expansion (CTE) inducing internal stress across

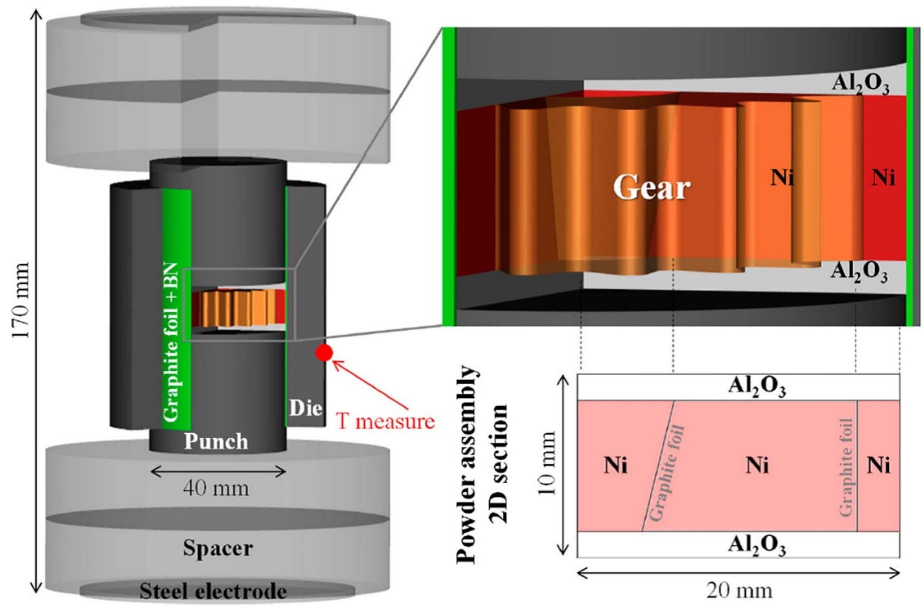

Figure 16. Energy efficient spark plasma sintering configuration of the 'controllable interface method' for creating the nickel gear shape with graphite foil and alumina interfaces [22]. Reproduced from [22]. CC BY 4.0.

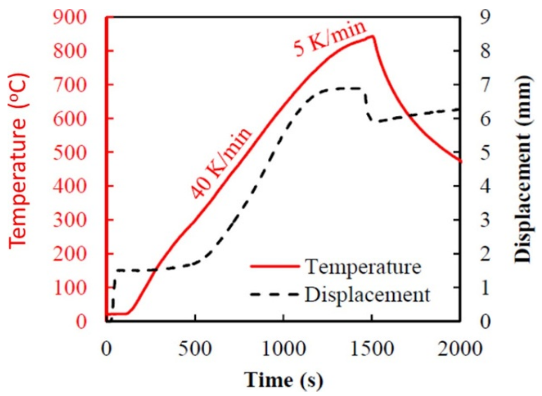

Figure 17. Temperature/time/displacement profile [22]. Reproduced from [22]. CC BY 4.0.

heterogeneous structures. However, according to these researchers, the rapid heating rates and shorter dwell times could reduce undesired reactions and deleterious decomposition of such microstructures [21].

It has been reported that to overcome some of these complex challenges a more general and all-shape-inclusive method called the 'deformed interface approach' should be considered [22]. This method is based on an assembly of powders containing a deformable interface, which allows the post-sintering separation of complex shape parts and those matching sacrificial shapes. Figures 16–18 show the controllable interface approach operated by these researchers using a 99.9 wt.% nickel powder to fabricate gears by means of simultaneous sintering, and subsequently bonded to a 99.2 wt.% Al_2O_3, along with their respective temperature–time–displacement and current–time–pressure profiles.

Reviewing this research the author notes that a certain level of distortion was reported on some gear teeth, which the researchers attributed to a slight movement of the graphite separation foil. To potentially avoid this feature an improvement in support tooling combined with refined powder distribution into the region could be considered. Furthermore, it was noted that a residual level of porosity remained within the structure, believed to be linked to the highly agglomerated powder that can generate a poor packing efficiency. This too could be optimised by an improved PSD control. Whilst this research highlights the barriers that remain with deploying the SPS process for more complex parts, the opportunity to tailor microstructures with the need for a quantifiable level of porosity is arguably a positive attribute that this technology can offer, but it needs to be modelled further. Consideration of post-processing dissimilar materials with significant differences in relative densities between metal–ceramic composites, might require a

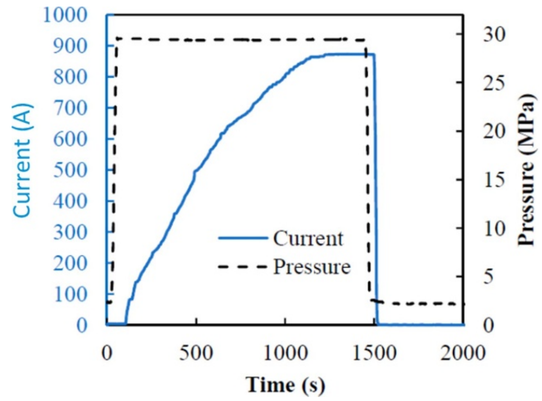

Figure 18. Temperature/time/displacement profile [22]. Reproduced from [22]. CC BY 4.0.

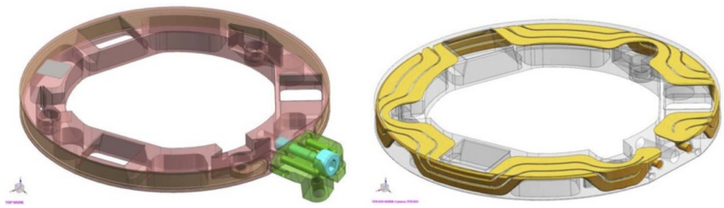

Figure 19. Thermal conditioning ring with milled cooling channels enclosed by a welded cover (left) and with additively manufactured conformal cooling channels (right). Courtesy of ASML extracted from [23]. Adapted from [23], Copyright (2016), with permission from Elsevier.

clear balance between temperature and soaking times, which may only slightly improve densification but could lead to other issues, e.g. intensifying decomposition of the metal alloy matrix. Research in this area needs to continue, but to accelerate its applicability into mainstream manufacturing, the opportunity to modularise architecture through the adoption of a multifarious technology portfolio to remove those barriers is another reason why technology applications should not be considered in isolation.

3.4. Additive manufacturing (AM of metallic structures)

The past few decades have seen substantial growth in AM technologies. However, according to many researchers this growth has mainly been process-driven [23]. Incorporating the material and geometric freedoms of AM into macro scale parts, can provide a variety of benefits that include aesthetic, functional, economic, emotional, and ergonomic. These opportunities should not be blinkered in solely providing components for nuclear reactors but should also be considered as a necessary technology to improve the functionality of specialised tooling to support areas such as inspection and maintenance. Examples of this include the creation of integrated air ducts, and wiring conduits for industrial robots, 3D flexures for integrated actuators and universal grippers [24], complex internal pathways for acoustic damping devices [25], and optimised fluid channels and internal micro vanes for ocular surgical devices [26]. However, one of the most widely studied applications that could be exploited by the nuclear fusion sector is conformal cooling. Conformal cooling channels will be a critical feature to exploit in the development of heat exchangers due to their geometry providing more effective and consistent heat transfer solutions.

Conformal cooling is not limited to tooling. Figure 19 shows two versions of a thermal conditioning ring from the semiconductor industry. The original design has circular cooling channels milled into the outer circumference of the ring and enclosed by a welded cover plate. The redesigned version by advanced semiconductor materials lithography (ASML) was optimised for performance by incorporating additively-manufactured conformal cooling channels on the top and side surfaces of the ring. The subsequent thermal behaviour of the two rings is shown in figure 20.

The cooling efficiency increase predicted for the additively manufactured version by the model within the 10 o'clock and 1 o'clock regions approximate to 8.8% based on the data presented.

This technology offers several optimisation methods to exploit the design of periodic meso-scale cellular structures that could be exploited in the nuclear sector. AM technology can produce structures containing an array of different materials or material properties within strategic regions. This is accomplished by using

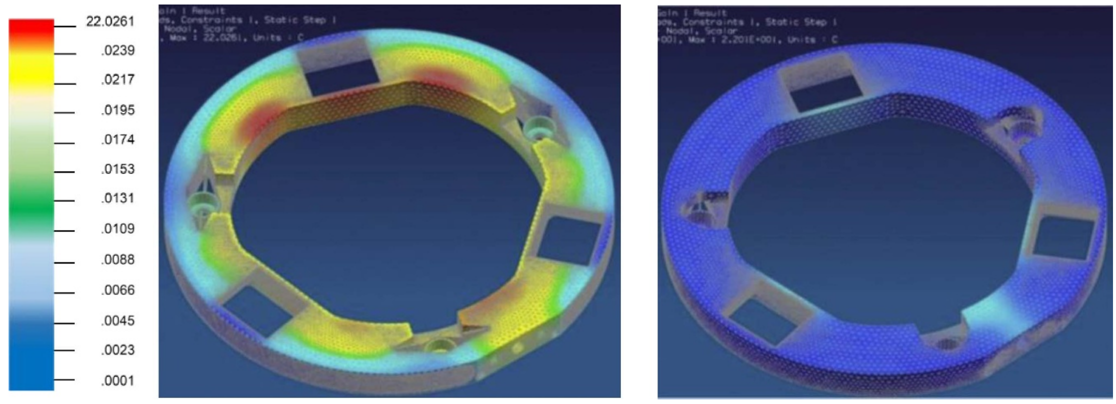

Figure 20. Temperature ratio plots from finite element models of the milled conditioning ring (left) and the additively manufactured conditioning ring (right). Shown with the same temperature scale. Courtesy of ASML [23]. Adapted from [23], Copyright (2016), with permission from Elsevier.

different feedstock or binders for different parts of the model. What is key to note here is that the use of sacrificial third-party materials such as binders requires secondary processing. These binders need to be suitably 'cleaned' of elements that can contribute to the production of dangerous nuclides under favourable radiation conditions, and as such, their impurity levels will need to be extremely well controlled. The development of specific feedstock binders that deliver innocuous effects must be considered within the AM procedure if products are to be used within highly active neutronic zones. Nonetheless, this technology may find sufficient practical use in regions where there is low neutron activity. Its potential application to produce internal cooling channels could be considered in parallel with other performance criteria such as fluid flow efficiency and heat transfer characteristics, because powder-based additive manufactured processes do not produce favourable internal surface topographies in the as-deposited form, and therefore consideration should be given to the integration of additive and SM processes.

Work completed by the Korean Atomic Energy Research Institute (KAERI) [27] using a synchronised hybrid AM and SM technique, combined laser powder direct energy deposition (LASER-DED) and CNC machining to produce a complex safety valve that could not be achieved by any other conventional method.

Combining 3D printing, using the laser metal deposition process, and strategic CNC multi-axis mill-turn machining at timely points within the build sequence, the KAERI team were able to successfully fabricate the 30 kg nuclear safety class 1 valve containing a set of complex internal cooling channels that permitted the dimensional accuracy of all surfaces required to meet performance requirements, and subsequently meet ASME III class 1 code requirements. This chemical and volume control valve system (75 mm bore diameter) is reported have achieved the following performance criteria to meet the demanding class 1 level of safety for commercial spare parts. The safety valve, manufactured from 316L powder was targeted to have a design pressure of 3025 psig (20.857 MPa), and an operating temperature capability of up to 650 °C.

The AM of refractory metals will also be a key technology to develop and adapt for critical fusion reactor components. AM of metals using the DED process is a technology that continues to be researched to produce components in exotic metals for aeronautical, space and nuclear applications.

Adoption of AM in the nuclear sector could strategically address worldwide bottlenecks concerning the fabrication of large-scale forgings containing large asymmetrical appurtenances as necessary features. These features such as lifting lugs, ports, nozzles, and location points currently use oversize forgings and SM to achieve these features. In some instances, a combination of expensive near-net shaped forgings or welding methods are used; the latter commonly incorporating fillet weld joints that inherently contain built-in flaws.

Using AM combined with advanced heat treatments manufacturers could effectively provide hybrid capability, thereby reducing material mass and processing energy. With smaller forgings and the adoption of AM, those economies of scale delivered via such processes could be significantly realised, whilst simultaneously offering benefits through increased design freedom. Because of these advantages, and due to the requirement for purer refractory metals, electron beam AM (EBAM) may surpass other AM technologies in quality and deposition rate, which utilises a very efficient high-power density heat source contained within a clean vacuum environment operating at 5×10^{-3} mbar pressure.

EBAM predominantly uses solid metal wire as the feedstock that is directed into a molten pool, created, and sustained through using a focused stream of electrons in a high vacuum environment (figure 21). The Nuclear AMRC's use of CNC sequencing offering a singular or combined integration of component and gun movement, beam and/or wire feeder oscillation, promotes the benefit of forming high integrity complex

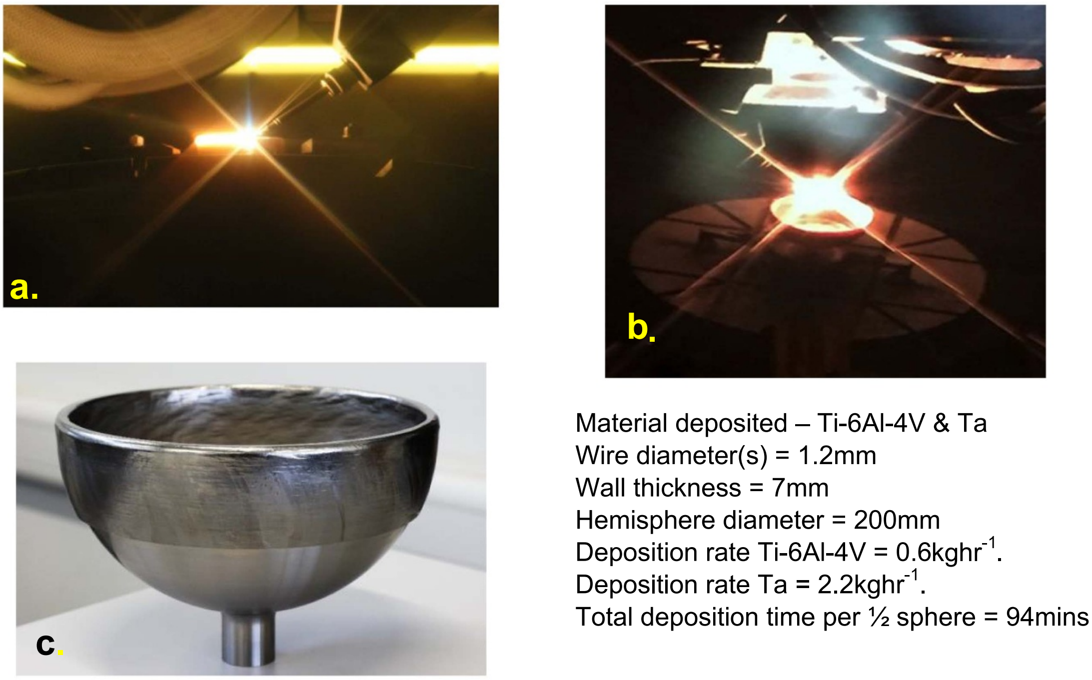

Figure 21. The Nuclear AMRC's EBAM processing of Ti-6Al-4V and tantalum materials using the EBAM process, (a) and (b) depict deposition views in real-time from two positions, Reproduced with permission from NAMRC. (c) shows the finished hemisphere.

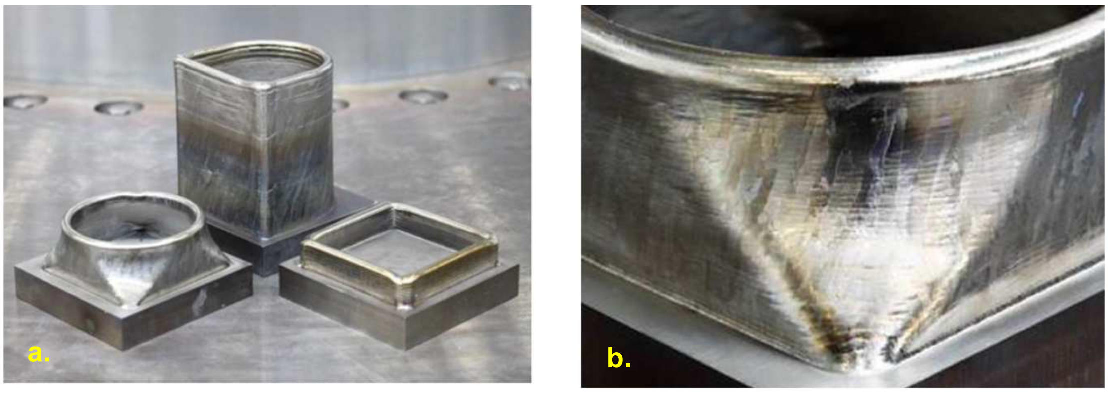

Figure 22. Different Ti-6Al-4V ducts (from left to right): (a) square to circle, D-shape, square. (b) View exhibiting smooth surface: base plates: 150 mm × 150 mm × 30 mm).

structures. The advantages of EBAM compared to other DED technologies is the higher purity of builds, since bulk and surface oxidation is prevented by the high vacuum environment. Other benefits include superior and faster beam control through electro-magnetic beam management, and providing higher deposition rates in electrically conductive materials, including highly reflective alloys such as aluminium and copper. Figure 22 depicts additional shapes produced by the Nuclear AMRC.

The creation of such products under vacuum conditions also allows internal vacuums to be created in deposited structures, which could be used to house specialised sensor systems. Research into the deposition of additional refractory metals should now be given to maximise the opportunities offered by this process in combination with other joining techniques.

3.5. Additive manufacturing (AM of non-metallic structures)

Ceramic AM processes can be categorised according to whether they are 'single-step' or 'multi-step' processes [28]. Single-step techniques are predominantly associated with powder bed and free-flight systems such as direct laser sintering (DLS) and DED respectively. Using slurry and dry powder feedstocks they are still considered immature, but a viable processing method if design requirements can be strategically accommodated. Their potential to reduce production times and negate the use of third-party materials 'binders' that require consolidating or burnout of the build structure are key factors for researchers to convince designers and manufacturers that desired mechanical, chemical, and thermal properties can be reliably repeated.

Single-step AM (SS-AM) research has highlighted the potential use of low-melting point binders. These are capable of being sintered or melted by a laser heat source or by induced chemical reactions from a non-ceramic feedstock to produce a workable ceramic structure. Nonetheless, issues remain in designing appropriate chemistries that are acceptably tolerant to isotropic neutron activation and transmutation. Those ceramic materials that have been produced by the DLS SS-AM process include Al_2O_3, SiO_2, reaction-bonded silicon carbide (RBSiC), Al_2O_3-SiO_2, and lithium aluminosilicate (LAS) glass to name but a few [29]. The creation of SiC and RBSiC considered as a single-step, is debatable due to such parts requiring infiltration, that is, a post-processing step is needed to increase density.

Further research consideration that must be addressed involves the short laser-powder interaction times that occur during the DLS process, which produce extreme temperature gradients resulting in poor ceramic sintering, incomplete densification, microcracking and very poor surface finish. Therefore, scalability will be a major challenge, because as structures increase in dimension the propensity for increased microcracking translating into macro cracks is significantly increased, hence the need to consider the use of appropriate third-party sacrificial compounds. Furthermore, it is expected that surface textures will also be poor and will thereby require additional support features to counter surface finishing forces.

The DED process such as the laser engineering net-shape (LENS™) consolidates ceramic powder particles that are fed from a nozzle into the focal point of a laser beam to create a solidified structure. It has been reported to provide significant advantages over most other ceramic AM processes due to this single-step, providing the final geometry of the part and its final physicochemical properties directly during the AM process, removing the need for post-processing heat-treatment. However [30], reported that a 5 h heat treatment at 1600 °C led to an increase in density from 94% to 98% with slightly improved mechanical properties and strength anisotropy.

Multi-step AM processes result in the formation of a green body that requires subsequent de-binding and sintering thermal treatments to obtain the final ceramic part. Alternatively, another ceramic AM route, which is usually referred to as *negative ceramic AM*, consists in using AM to first shape sacrificial polymer moulds, that are then impregnated with a ceramic slurry by investment casting or gel-casting [31].

Oxide ceramics that have mostly been researched for AM are Al_2O_3. This is due to its versatility, low price, and relatively low sintering temperature. ZrO_2 due to its high toughness, relatively low sintering temperature, and widespread industrial applications is also showing promise. However, because of their brittleness, composite materials incorporating a ceramic matrix reinforced with continuous fibres, whiskers or nanoparticles provide a partial solution to their properties being manoeuvered to developing components for critical applications [32]. The term 'critical application' used in this text refers to a feature or structure that is either exposed to intense radiation, carries extensive loads in elevated temperature regions or a combination of both. Examples of such components are armour strike areas within the PFC and/or divertor system, or radiation shields that could be enhanced using both ceramic and metal–ceramic composites. These structures require a combination of ceramic particles amalgamated with small quantities of a ductile metallic alloy to improve the mechanical properties, control heat transport, and improve manufacturability.

The 'ceramic on-demand extrusion' (CODE) process is a technology developed by [33]. Here the researchers used an aqueous ceramic paste (50–60 vol%) extruded via an auger valve onto a substrate located in a fluid vessel. The CODE fabrication method used by these researchers consisted of a Cartesian gantry system and an extrusion device capable of dispensing viscous ceramic pastes at controlled flowrates. After each layer is deposited, they pump a mineral oil into the tank at a controlled-flow rate to a level just below the top surface of the layer. Infrared heating is then applied to partially dry the layer, with the oil precluding undesirable non-uniform water evaporation from the sides, thus preventing warpage and crack formation. The researchers' use of the CODE device has also been reported to be successfully used to create ceramic functionally graded materials involving Al_2O_3 and ZrO_2 pastes. Other components such as impellers, gears and spheres have been reported to be manufactured from Al_2O_3 with uniform microstructures and sintered densities $>98\%$ [34]. Such a technique is a potential enabler for introducing embedded sensor technologies for nuclear fusion components, but consideration must be given to some of the issues that remain, which include highly anisotropic properties and surface roughness. The CODE device does, nonetheless, offer improvements in its sensitivity index and the quotient ratio of the final product to initial COS. If an increase in the deposition rate is needed without violating these improvements, then a combination of finer nozzles, or the successful development of a hybrid additive- SM process may provide such solutions.

Figure 23. Factors to consider and their interconnectivity when designing for a joining method [35].

4. Advanced joining

Homogeneous and heterogeneous joining is a critical discipline within the manufacturing theme and classified as a special process within the UK's national regulatory framework because of the effect key outputs have on the structural integrity and performance of a component or system. The international standard ISO 4063 is the established nomenclature for welding and allied processes (brazing, soldering and solid-state bonding) and identifies 126 specific processing techniques in the 2010 edition, many of these, including new subsets will be needed to join and construct advanced materials instigating the need to consider their effects on an interdisciplinary level. Henceforth, the choice of joining process must consider appropriate technologies and techniques based on its interdependency with many other factors. An example of this interdependence from a weldability perspective is provided within figure 23.

The effective choice of a joining process is therefore far more complex than simply choosing a method based on its processing economics (productivity and equipment costs). It is arguably affected by many ancillary factors that involve business influence, associated with material security, supply-chain capacity, skills development, decommissioning costs etc, and are beyond the scope of this review. Material suitability is arguably the most fundamental challenge to overcome. Joining is classified as a 'special process' due to its resulting effect on material performance and structural integrity, therefore the ability to translate laboratory

Table 3. List of constitutional formulae development and elemental effect on various chromium and nickel equivalency formula.

Researcher	Year	Chromium equivalent (Cr_{eq}) wt.%	Nickel equivalent (Ni_{eq}) wt.%
Schaeffler	1949 [36]	Cr + Mo + 1.5Si + 0.5Nb	Ni + 0.5Mn + 30C
Kaltenhauser	1971 [38]	Cr + 6Si + 8Ti + 4Mo + 2Al	40[C + N] + 2Mn + 4Ni
Hull	1973 [39]	Cr + 1.21Mo + 0.48Si + 0.14Nb + 2.27V + 0.72W + 2.20Ti + 0.21Ta + 2.48Al	Ni + (0.11Mn–0.0086Mn^2) + 4.5C + 14.2N + 0.41Co + 0.44Cu
DeLong	1974 [40]	Cr + Mo + 1.5Si + 0.5Nb	Ni + 0.5Mn + 30C + 30N
Pickering	1978 [41]	Cr + 1.5Mo + 0.75W + 2Si + 5V + 1.75Nb + 5.5Al + 1.5Ti	Ni + Co + 0.5Mn + 25N + 20C + 0.3Cu
Hammar & Svennson	1979 [42]	Cr + 1.37Mo + 1.5Si + 2Nb + 3Ti	Ni + 0.31Mn + 22C + 14.2N + Cu
Cheng *et al*	1986 [43]	Cr + Mo + 0.75W + 1.5Si + 1.3V 0.5Nb	Ni + 0.5Mn + 30C
Sasmal	1987 [44]	Cr + 1.76Mo + 0.97W + 1.58Si + 2.02V + 1.7Nb + 2.44Ti + 1.22Ta − 0.177Co	Ni + 0.5Mn + 30C
Kotecki & Siewert	1992 [45]	Cr + Mo + 0.7Nb	Ni + 35C + 20N + 0.25Cu
Tchizhik *et al*	1998 [46]	Cr + Mo + 0.5W + 1.5Si + 2.5V + 1.5Nb + 2.8Al + 2Ti	Ni + 0.5Co + 0.5Mn + 30N + 40C + 0.3Cu
Beres	1998 [47]	Cr + Mo + 1.5Si	Ni + 0.5Mn + [10 + 0.2/C]
Uggowitzer *et al*	1999 [48]	Cr + 1.5Mo + 1.5W + 0.48Si + 2.3V + 1.75Nb + 2.5Al	Ni + Co + 0.1–0.01^2Mn + 18N + 30C
Balmforth and Lippold	2000 [49]	Cr + 2Mo + 10[Al + Ti]	Ni + 35C + 20N

results into manufactured products needs to be proven at scale. This will naturally incur outlay that needs to be assessed in terms of an organisation's ROI. If only one technology is available, it is highly likely it will require significant investment. If there are alternative technologies then an assessment of the ROI, considering processing efficiency, skills, and integrity benefits should be considered, in addition to potential spin off applications that could utilise this investment.

The most appropriate process therefore depends on many factors, but the key input aspects mainly concern the substrate material chemistry, thickness, shape factor and size/mass, dimensional stability and inspectability to name but a few. Furthermore, the use of such technologies must also consider sustainability and the level of energy to produce components and systems; this is where the Nuclear AMRC and its stakeholders are exerting significant effort for the future.

Optioneering a component's functionality requires the design and manufacturing community to work closely together to appreciate and understand the compendium of interacting factors. The interaction of several conditions that connect physical and 'condition of supply' properties into the design, allows engineers greater insight to down-selecting the appropriate processing techniques, and necessary qualification programme. Furthermore, it provides an insight into where further research is needed to increase a designer's freedom to improve performance.

4.1. Joining of large-scale steels

Production of a vacuum vessel and cryostat will require extensive testing to reassure that the joining process meets the manufacturing code, and that all input parameters meet the required properties, which for such structures operating at −268.95 °C (4.2 K) will go beyond the accepted testing temperature of −196 °C (77.15 K) specified in ISO 21028—subsection part 1, section 4.2.3 clause (b). Therefore, to ensure impact toughness values are achieved, careful consideration must be given to the welding process, the filler material (if used), the heat input, and technique to achieve the desired mechanical and microstructural properties. Several constitutional equations based on the chromium and nickel equivalents (Cr_{eq} and Ni_{eq}) have been developed to improve microstructural prediction, which date back to 1949 [36]. Research interests continued for several decades within this area [37] and table 3 provides a list of constitutional formulae developed over the past 51 years to accommodate the change in the steel's chemistry to improve performance.

It is the author's strong opinion that these developments will continue for those advanced materials needed for future fusion architecture adopting such steels.

The author would like to inform the reader to approach the use of these constitutional maps with caution, because many are only applicable to arc welding energy densities; the use of high power density methods, e.g. laser and electron beam welding (EBW) (ISO 4063-51 and ISO 4063-52) respectively cannot be accurately modelled against these equations if autogeneously used. This is due to the extremely high heating and cooling rates being sufficiently energetic to shift the kinetics of transformation, promoting a skewed response for ferrite and martensite to retain austenite within some alloys. Further caution should also be taken because these maps do not consider the substrate grain size, weld shape factors and level of restraint on crack susceptability.

Furthermore, the use of these formulae approximates the weld metal microstructure based on substrate chemistry and filler metal chemistry (if used) and will only be applicable to stainless steel alloys using conventional arc welding processes. They do however, provide a good approximation of the solidified structure between dissimilar grades of stainless steels and the joining of these to other steels. In instances of microcracking and hot shortness/solidification cracking, a more accurate relationship has been proposed by [50] relating this the Cr_{eq}/Ni_{eq} ratio with the combined level of P and S. Experiments reveal Cr_{eq}/Ni_{eq} ratios $\leqslant 1.5$ and P + S levels <0.01 wt.% tend to be tolerant to hot shortness/solidification cracking.

The author therefore, expects these models to become more complex as alloys and processes develop, and should incorporate more dynamic artificial intelligence systems that build upon and extend those Bayesian neural network algorithms that have been previously developed [51].

Considering now the welding of carbon–manganese and low alloy—high strength steels used for pressure vessel applications, the assessment of a steel's susceptibility to hydrogen-induced cold cracking is a critical parameter to manage. These material genres use formulae that determine a steel's typical thermal hardening/hardenability response via its carbon equivalency (CEv) or (CET), for carbon–manganese and low alloy high strength steels respectively, denoted within the EN1011-2 standard

$$\mathrm{CE} = \mathrm{C} + (\mathrm{Mn})/6 + (\mathrm{Cr} + \mathrm{Mo} + \mathrm{V})/5 + (\mathrm{Ni} + \mathrm{Cu})/15.\ \text{Method A} \tag{5}$$

$$\mathrm{CET} = \mathrm{C} + (\mathrm{Mn} + \mathrm{Mo})/10 + (\mathrm{Cr} + \mathrm{Cu})/20 + (\mathrm{Ni})/40.\ \text{Method B} \tag{6}$$

Note that these two formulae have a stated elemental wt.% range of values associated with non-alloyed, fine grained and low alloy steels, containing carbon in the range of 0.05 wt.% to 0.25 wt.% for method A, and 0.05 wt.% to 0.32 wt.% for method B. Method A is the version that replicates the formula recognised by the International Institute of Welding. However, this is one of many CEv formulae that have been researched over several years, and caution too should be noted in its application, in defining a confidence level of fusion weldability applied to joining those structural and creep resistant steels under investigation for nuclear fusion architecture.

New generation steels that provide increased creep strength and higher tolerance to neutron radiation are being developed with significantly lower carbon contents, which when overlayed onto constitutional maps reveal that they are readily weldable; one such steel is HiPerFer. This steel has a carbon content below 0.003 wt.% but contains nominal 17 wt.% Cr and 4.2 wt.% W contents, which shifts its classification into those identified as a ferritic stainless steel. Strengthening of this ferritic steel is not accomplished by a martensitic transformation or grain boundary pinning from MCs, hence the argument for this material being defined as readily weldable. Strengthening therefore, is accomplished via alternative mechanisms, which in HiperFer [52] is through a combination of solid solution and intermetallic A_2B Laves phase $(Fe,Cr,Si)_2(Nb,W)$ strengthening.

Strengthening by such processes means there is an imperative need to specifically control heating and cooling rates to allow for microstructural changes. Such microstructural changes, i.e., recovery of excess dislocations or partial recrystallization, along with a drop in dislocation strengthening within the heat affected zone, would be inevitable and must be considered in the design. Further work on developing amenable welding and post-processing parameters to optimise base metal heat treatment prior to welding, welding parameters, consumables and post-weld heat treatments continue to be developed. Hence the view that their level of difficulty be shifted from 'readily' to 'cautiously' weldable.

A more appropriate and generalised formula for determining the weldability of structural and creep resistant steels, has been proposed by [53] to encompass a range of bainitic and martensitic steels with carbon contents $\leqslant 0.3$ wt.%,

$$\mathrm{CEN} = \mathrm{C} + f(\mathrm{C}) \times (\mathrm{Si})/30 + (\mathrm{Mn})/6 + (\mathrm{Cu})/15 + (\mathrm{Ni})/20 + (\mathrm{Cr} + \mathrm{Mo} + \mathrm{V})/5 \tag{7}$$

where $f\,(\mathrm{C}) = 0.75 + 0.25\tanh[20(\mathrm{C} - 0.12)]$.

Whilst these formulae provide engineers with guidance on thermal management, e.g., preheating levels, arc energy and control of residual hydrogen content of consumables to prevent hydrogen cracking, other contributory factors must be considered when developing welding procedures for thick-section steels. These include grain size and morphology consistency, welding (heat) source orientation, joint geometry, component size, form, and restraint, and weld bead deposit strategy.

Taking this information and applying it to typical vessel steel and thicknesses, e.g., ferritic structures in the thickness range of 50–150 mm, those arc welding process can provide some significant challenges to achieve a right first time result.

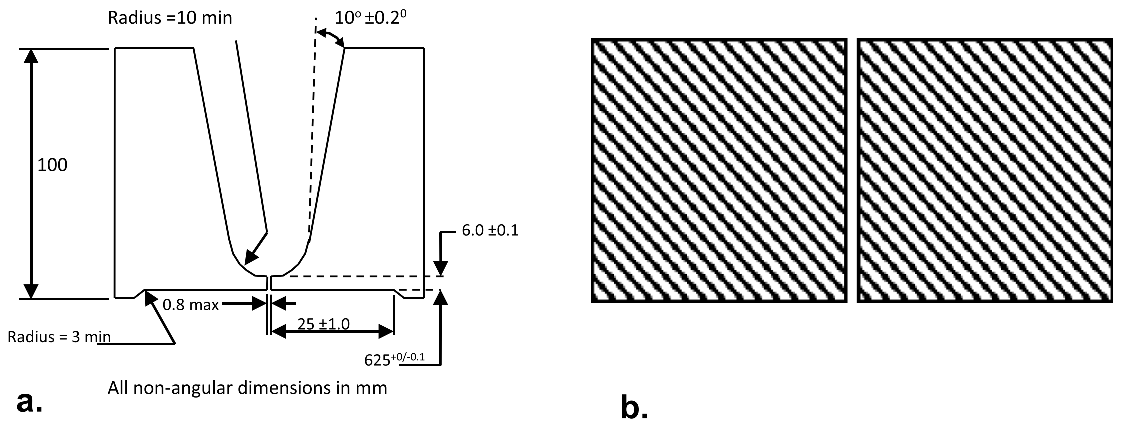

Figure 24. (a). Single U groove butt weld for the SAW process, (b). Square-edge butt weld configuration applied to an SA508 Gr3 class 1 pressure vessel steel.

Table 4. Processing comparison between Submerged Arc Welding and Electron Beam Welding using their respective joint configurations (Single U groove and Square-edge butt weld) respectively.

		Submerged arc welding (ISO 4063-121)			
Joint volume	Deposition rate	Total weld time[a]	Total processing time[b]	Total energy	Energy
(m3)	(kghr^{-1})	(h)	(h)	(GJ)	(kWh)
0.03	6	39.3	79.1	1.45	403
Note, a preheat of 160 °C was applied prior to any welding commencing and an H_2 bakeout of 230 °C for 3h					
		Electron beam welding (ISO 4063-511)			
Joint volume	Speed	Total weld time[a]	Total processing time[b]	Total energy	Energy
(m3)	mms^{-1}	(h)	(h)	(GJ)	(kWh)
0	1.5	2.4	10.4	0.17	47
Note, no pre-heat or bake out process was required					

[a] Indicates only weld time.

[b] Indicates the complete processing cycle (pre-heat, welding, hydrogen bake-out and inspection).

The Nuclear AMRC has undertaken significant work in removing these complexities through adopting the EBW process, and this paper provides a comparison of benefits that are sometimes overlooked when manufacturing components of this form and size. In this example, a single fully penetrating weld has been completed to join two SA508 grade 3 class 1 pressure vessel strakes (0.1 m × 2 m × 1 m) thickness, diameter, and length respectively. One set of vessels is welded using the conventional submerged arc welding (SAW) process, the other using EBW.

The SAW process uses a joint design from BS EN ISO 9692-2 reference no. 1.7, a derivative 'single U' butt weld configuration—figure 24(a); the EBW process uses a 'square-edge' butt weld—figure 24(b).

Table 4 shows the extensive saving in processing time, inspection and energy used when using the EBW process. Figure 25, images (a) and (b) show this cylindrical configuration outside the Nuclear AMRC's 208 m^3 vacuum chamber, and the actual process working respectively.

Extending this capability further to include a normalising heat treatment, it is possible to homogenise the resultant EB weld microstructure, which on a macroscale is difficult to distinguish the weld from the HAZ and base material—figure 26.

The outlay of EBW equipment capable of processing large components within large vacuum chambers is substantial, with costs being approximately 10–15 times more expensive than that of a SAW system. Therefore, such financial outlay needs to be balanced with component size and design requirements involving component thickness, joint geometry, number of weld-passes and weld joint configuration, dimensional stability (shrinkage and buckling) and product performance, which in turn define the number of in-process pre-heat and post-heat treatment activities and inspection cycles. The values given in table 4 relate to one weld. Many welds of varying orientation are needed in a nuclear reactor system, e.g., circumferential, linear, planetary ports and saddles, and fillet welds to name but a few. To drive down the cost of large chambers, the Nuclear AMRC has investigated the use of reduced pressure electron beam methods combined with strategic

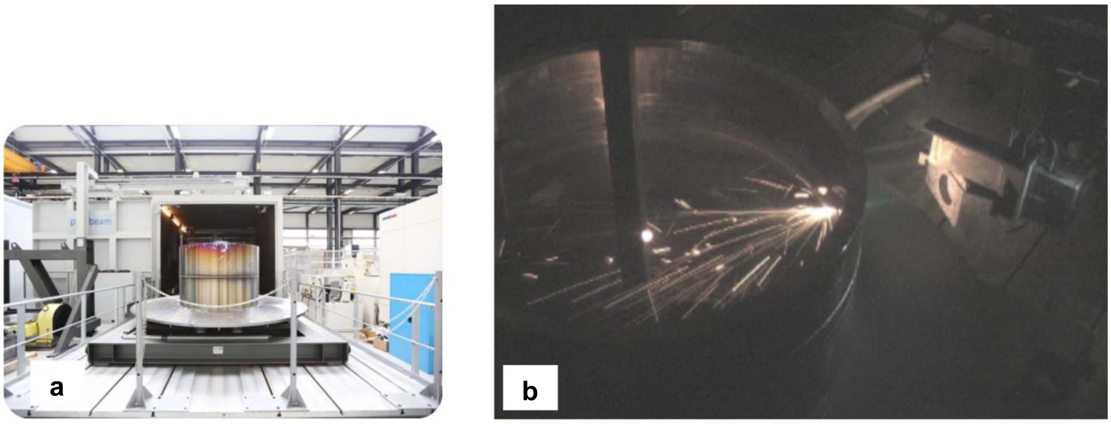

Figure 25. (a) Weld completed using the Nuclear AMRC's 208 m^3 vacuum chamber. Reproduced with permission from NAMRC. (b) EB weld process in real time. Reproduced with permission from NAMRC.

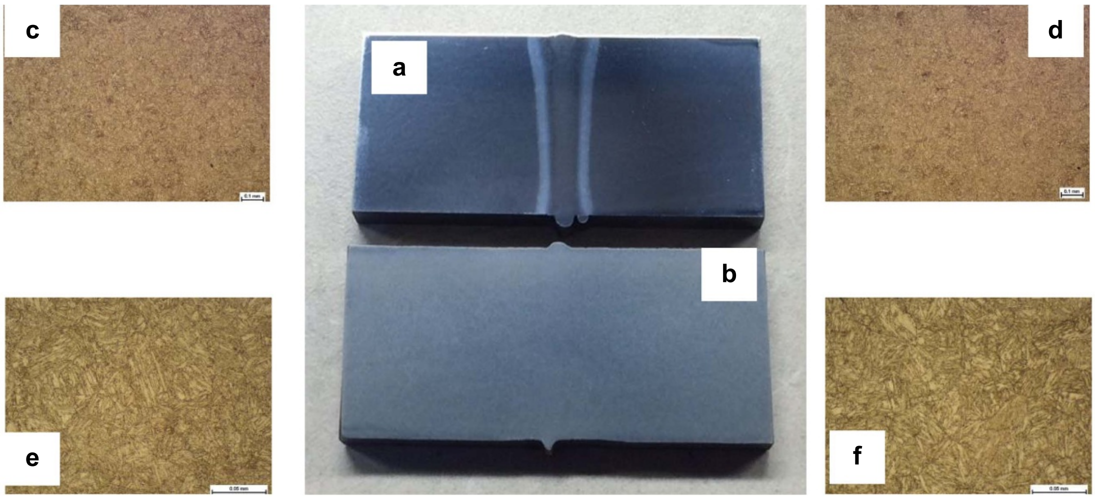

Figure 26. Showing fully penetrated EB weld macro and micro photos, (a) as-welded, (b) with a normalising heat treatment (QHT), (c) ×100 mag at the weld center line (WCL), (d) ×100 mag 5 mm away from WCL, (e) ×500 mag at WCL and (f) ×500 mag 5 mm away from WCL. Reproduced with permission from NAMRC.

modularisation to reduce vacuum chamber sizes. This method uses a localised reduced pressure system operating between 2 to 3 × 10^{-1} mbar. It requires a reduced gun-to-work-distance between 160 mm and 200 mm to achieve the desired penetration, which is generally much lower than conventional chamber systems that typically operate between 300 mm and 700 mm. Increasing the work-distance will reduce the penetration depth at these reduced pressures so this method has certain processing limitations. Furthermore, there is a need for specific or bespoke tooling to match the component's geometry, which presently severely limits its application to component shapes of a symmetrical form. Therefore, the Nuclear AMRC and its partner Probeam GmbH are now investigating the use of integrated component chamber systems capable of achieving conventional low pressures (3 × 10^{-3} mbar) with standard accelerated voltages (150–175 kV) to weld thick sections (>90 mm thickness). The weld will be made using a mobile electron beam gun, rather than the conventional fixed gun system, and is capable of telescopic manipulation to maintain a constant gun-to-work-distance to cater for asymmetrical geometries. This provides far more flexibility and expands opportunities for manufacturers to produce more complex weldments and has been assessed at being capable of reducing capital outlay costs by 50% or more. However, until the cost differential can be reduced and proven to achieve an integrated readiness level of 6, the use of established arc welding equipment will still be favourable if the productivity and performance benefits can be met.

Whilst these innovative methods could provide significant benefits, it must be noted that there exists a solid reason why large chambers are needed to produce special features in large structures and in complex forms figures 27 and 28 depict one such configuration that is needed for the ITER programme.

This is one such benefit from using advanced systems; the real benefits are realised through the combination of these technologies, where the whole is greater than the sum of their individual parts. The use

Figure 27. Shows an EB welded toroidal section. Images courtesy of Probeam GmbH.

Figure 28. Toroid segments. Images courtesy of Probeam GmbH.

of PM-HIP to create modularised structures capable of being joined with the minimum number of thermal cycles can offer new degrees of design freedom. Furthermore, the use of autogenous EBW, currently completed within vacuum chambers removes alloying effects that promote heterogeneous microstructures, which not only significantly reduces processing times, energy usage and CO_2, but negates the need for complex machining of joints, costly filler metal and filler metal control. In parallel, the need to develop fabrication-friendly materials that fall within an acceptable performance window will be paramount. Figure 29 shows the progress being made in achieving impact toughness—a critical parameter for products required for the nuclear fission sector.

The development of 'clean steels' utilising improved casting methods and forging processes would favour low-cost joining techniques to reduce the need for expensive hardware. However, this will also require parallel developments in welding and brazing consumables targeted to address improvements in fusing, bonding and microstructural strengthening, whilst enhancing thermomechanical responses and irradiation-tolerant properties. The use of autogenous processes negates the need for additional control of filler materials, and thus once again, a balance needs to be struck when considering the type of processing methods to use.

Redesigning ports and nozzle connections using a PM-HIP process will allow the repositioning of such features to a more cost-effective and conducive welding and inspection orientation (figure 30). Moving from manually welding nozzle joints currently adopting highly stressed configurations (ISO 9692:2003—ref 1.11), predominately associated with pressure vessels, to more manageable single-U configurations (ISO 9692:2003—ref 1.8) that allow orbital mechanised welds in the PC/2G orientation, will see significant improvements in quality control and human factors. This change in joint design and heat source attitude can reduce filler metal usage by 70% and processing energy and CO_2 emissions per joint by up to 73%, whilst simultaneously improving inspection capability. This overall reduction eliminates the use of flux-based welding processes, which would require additional thermal management to ensure the release of hydrogen

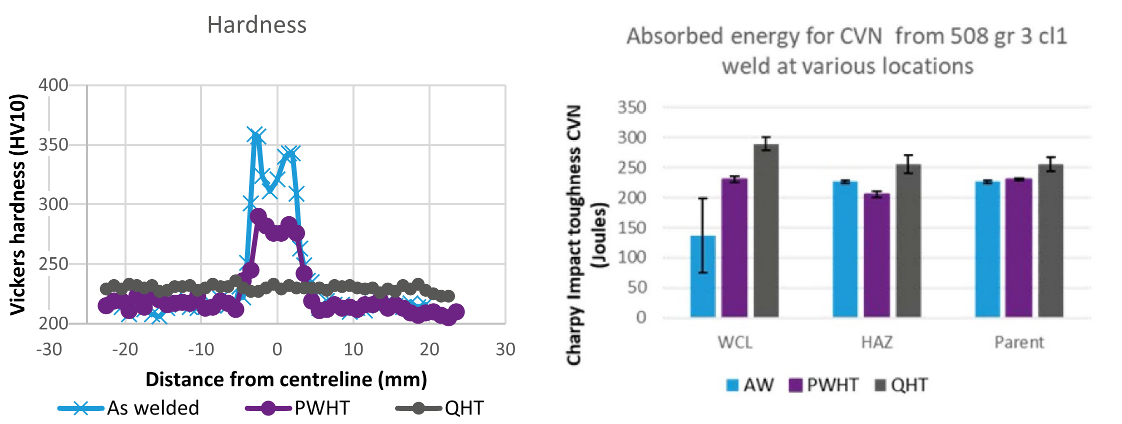

Figure 29. Showing hardness value plots for those as-welded, post-weld heat treated (PWHT) and normalized heat treated (QHT) samples within the base metal (parent), heat-affected zone (HAZ) and weld centre line (WCL) and their respective Charpy Vee-notch toughness values at various locations across these three zones.

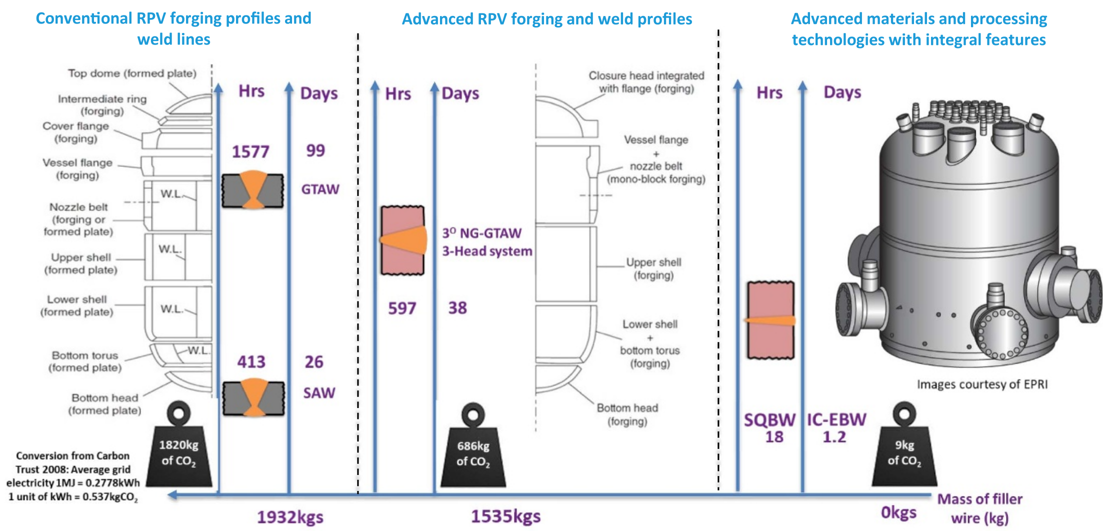

Figure 30. Comparison of benefits when using a combination of PM-HIP and electron beam welding technologies in the advancement of pressure vessel manufacture. Reproduced with permission from NAMRC.

(H_2) in susceptible steels, and the need to maintain a global thermal input throughout the welding cycle. Furthermore, this change in technique subsequently reduces the level of energy required to complete each joint, summarised by the net energy relationship:

$$\text{Net energy per joint} = \frac{mC_P\Delta T_{\text{preheat}}}{H_{\text{eff}}} + \left[\left(\frac{IV}{S}k\right)\left(\rho_{\text{fm}}.\nu_J\left(\frac{m_{\text{ww}}}{t}\right)^{-1}\right)\right] + \frac{mC_P\Delta T_{\text{bakeout}}}{H_{\text{eff}}}\,(J) \tag{8}$$

where:

M = the mass of the structure/region (kg)
C_p = average specific heat capacity of steel across temperature regions ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)
ΔT = the difference between room temperature and targeted welding start temperature (K)
H_{eff} = heating efficiency allowing for heat loss
I = the current values (amperage)
V = voltage (arc potential)
S = speed of heat source (mms^{-1})
k = efficiency of welding process used—EN1011-1
ρ_{fm} = density of filler metal (kgm^{-3})
ν_{J} = volume of weld joint (m^3)
M_{ww}/t = filler metal deposition rate: m_{ww}: mass (kg), t: time (s) (kgs^{-1})

The exploitation of PM-HIP technology does not exhaust itself in simply improving the design freedom and manufacturability associated with fusion weldments, it also offers the potential insertion of chemistry graded transition sections to manage differences in CTE. Furthermore, modularising such structures would provide strategic replacement of architecture and improved decommissioning practices.

4.2. Joining of non-metallics

The author believes that the use of ceramics and cermets will become ever more important in the delivery of a commercial fusion reactor, so their development and the ability to fabricate them as part of a manufacturing supply-chain is paramount. However, history has shown that whilst the production of these materials for general usage could be considered as being 'well established', the joining of ceramics to themselves and to metallics is currently limited to using adhesives or through soldering or brazing.

This application of ceramics and cermets has been highlighted within the UK-Fusion Materials 2021–2040 roadmap, which recognises the need to consider such materials for blanket walls, breeders and amplifiers to increase plant efficiency. This has prompted investigations into the use of optimised SiC–SiC composites, e.g. nanostructured SiC fibre for enhanced irradiation resilience; pyrolysis-free interphases; and transmutation gas routine architecture. To achieve target temperatures for tolerant structural capability at or above 700 °C the potential to use lower cost ODS/HiP'd powder metallurgy variants should be investigated at scale. Furthermore, increasing breeding ratios to yield values >1 will require new breeder materials beyond orthosilicates and titanates, which are currently being targeted through the potential use of AM. Once again, this should be considered at scale.

Although a patent submitted by researchers [54] states that a non-oxide ceramic of the type zirconium diboride (ZrB_2) could be welded using an electric arc process, it is this author's belief that acceptability of such a method should be considered under caution, as the term 'weldability' used within these researchers' [54] work is without extensive weldability testing and validation.

Silicon carbide (SiC) is a key ceramic material identified as offering game-changing properties in the construction of critical fusion reactor components, this has been identified once again within the UK-Fusion Materials 2021–2040 roadmap. All attempts to carry out fusion welding of this material to itself have failed due to it decomposing on heating to temperatures circa 2500 °C, although new techniques known as electric current-assisted sintering (ECAS) and rapid electric current assisted joining (ECAJ) have been identified as a practical and appropriate method for joining SiC-based materials and its composites [55]. This is apparently achieved through lowering the resistivity of the SiC via nitrogen doping. This approach has been reported to allow joining at temperatures as nominally low as 1750 °C, thereby avoiding decomposition. These technologies need to be scaled up to assess their viability and true benefit. Results of their work nonetheless do seem promising.

Joining between ceramics will undoubtably be needed, and furthermore, the practicable capability to bond dissimilar materials (metallics to ceramics and cermets) will provide a step-change towards enhancing component performance and resilience. The use of ECAS and ECAJ as direct joining methods is likely to be ineffective due to the differences in CTE between several ceramic and structural steels. Consequently, the use of pure and heterogeneous composite filler materials to join such combinations presently seems to be the only viable route [55]. It is therefore imperative that attention is drawn to assessing the joining and the performance of these composite structures to achieve a manageable compliance at the bond interface to account for any extreme deltas in CTE, electrical resistivity, thermal shock and elevated strength compliance.

Due to ceramics having special physical and chemical properties, they can be somewhat incompatible with brazing fillers, and the next generation of such materials may create even greater challenges. Whilst it has been proven that joining of ceramics involving glass to metal, and Si_3N_4 fibre-reinforced cordierite glass ceramic brazed to titanium and stainless steel parts, they generally involve simple joint configurations. The challenge, however, is to expand the scalability of joining ceramics and cermets to themselves, and to metallics, and develop models to predict integrity and flow indexes to achieve desired properties to meet standard joint testing methods for varying arrangements. The manufacturing community is limited to using a common failure criteria in predicting failure of brazed joints, and so an alternative approach based on high-fidelity failure assessment diagrams is needed. Furthermore, the reliance on small scale test specimens to assess static and dynamic strength without fully appreciating a combined failure mode at scale is thwarted with problems. The most frequent methods involve modelling the thermomechanical and thermal behaviour of brazed assemblies as well as the hot zone (including the assembly), during ramp-up and cool-down phases of the brazing cycle. These remain a major challenge. Moreover, micro-scale processes, involving complex transport and phase change phenomena associated with more complex alloys, are more difficult to model, and in this domain the challenges for further advances will persist.

The use of cellular metal foams can offer significant benefits through designing a cell network that can offer compliance to accommodate this strain [56]. Furthermore, and somewhat tangential to this benefit is the potential to use such devices to promote internal crossflow cooling to manage the level of heat and strain. Such devices could be developed and applied as compliant composite structures for heat exchanger systems.

Alternative methods that show promise in joining dissimilar ceramics, dissimilar metals and a combination of these at scale, is the use of transient liquid phase bonding (TLPB), also known as diffusion brazing (ISO 4063–919). This technology could provide a solution for both highly alloyed metallics with poor weldability that have been developed for specific performance, in addition to providing a potential ceramic to metallic bonding solution.

TLPB is a relatively new bonding process that was developed to overcome deficiencies in joining nickel based superalloys using an interlayer [57]. On heating, the interlayer melts and the interlayer element (or a constituent of an alloy interlayer) diffuses into the substrate materials, causing isothermal solidification, which results in bonds that have a higher melting point than the bonding temperature. This is especially important for temperature-sensitive materials whose microstructures can be damaged by too much thermal energy and therefore need to be joined at lower temperatures. This improves the design freedom not only for combining materials but potentially offering alternative methods of manufacturing that require staged thermal processing. This allows operations to be done in manageable sequences of decreasing thermal severity. The critical variables to note with this process involve defining the critical interlayer thickness and optimum bonding temperature, and overcoming these hurdles can provide the following benefits noted by [57].

The TLPB process offers several advantages over other bonding methods, which include:

- Operating at a higher temperature than the original bonding temperature
- Reducing thermal severity in materials whose microstructure can be damaged by too high a thermal energy input
- Providing joints with microstructures and mechanical properties similar to or above the substrate material
- Highly tolerant conditions facing the presence of faying surfaces
- Elimination of fluxing agents
- Fixturing pressures being much lower than other joining processes e.g. diffusion bonding
- Reduced melting of the substrate surface when compared with fusion welding processes
- Multiple joints can be fabricated and simultaneously processed in one thermal cycle
- The filling of voids on uneven mating surfaces
- The avoidance of over-aging of temperature-sensitive materials

Naturally, with all technologies, there are drawbacks, and with the TLPB technique the following factors need to be considered:

- For some material systems, bond properties and performance capabilities are difficult or impractical to achieve
- It is a specialised bonding technique that can be time-consuming and expensive compared to other joining methods
- Significant melt-back of a material with a specifically designed microstructure could degrade the targeted performance
- Some materials can form a thick layer of intermetallic compounds in the bond that tend to lower its strength and ductility
- The process can generate particle segregation in metal matrix composites at the joint centreline, leaving a distinct weakened band in the joint microstructure.

The thermophysical attributes of TLPB therefore allow designers and manufacturers to exploit an opportunity for a staged sequence of processing near to the original liquidus of the interlayer material, thereby widening the material scope, properties and operational performance.

5. Conclusions

A myopic approach to manufacturing research cannot be tolerated in developing capability for the production of fusion reactors. Consideration, whilst given to accelerating new technologies or being more innovative with established technologies, must work in synchronicity across a multitude of disciplines. Those manufacturing methods currently being researched to create and join components at both small and large-scale in advanced and difficult-to-process materials, need to be scaled to improve their status as suitable methods that designers can utilise. However, it is strongly advised that an interdisciplinary approach should be adopted to prevent 'silo manufacturing' risks. Silo manufacturing in this context is a term used to identify a lack of integration between manufacturing methods or systems. It leads to failure in recognising issues that could be identified earlier through an integrated manufacturing practice. An example here is using standard arc welding equipment to join a material, followed by a standard integrity inspection operation, and then a standard dimensional inspection operation. They are effectively separate processes requiring significant logistics and can be referred to as defined manufacturing activities operated in silos. Manufacturing research involving the use of combined or integrated processing systems on a single platform involving welding, non-destructive examination and non-contact dimensional inspection, are actively underway and showing promising results. This methodology aims to remove this 20th Century practice that effectively retards the transition from concept to market deployment.

Research into PM-HIP provides substantial design and performance improvements with benefits in material utilisation, improved Z-properties, greater inspection fidelity, and increased processing flexibility. Process flexibility is realised via strategic positioning of critical architecture in a modular format to improve productivity and integrity, whilst simultaneously providing a pathway to accommodate increased throughput and dimensional capacity to scale-up component size. Designs that can adjust connectivity points to a position of reduced stress are a precious characteristic; also, the integration of appurtenances that reduces or removes highly stressed weldments, including those ancillary processes required to qualify them, maintains both integrity and safety with no increased cost.

Combining this technology with autogenous EB welding provides the prospect of modularised fabrication; moreover, research into modularised chambers, and localised (out of chamber) EB welding will offer the prospect of cost effectively joining large components.

Research into manufacturing components must not ignore the need to use such technology in the efficient creation of those ancillary services. One such area is the use of intelligent tooling offering multifarious capability, which not only locates and manipulates parts but has built-in sensor systems that monitor processing loads and dimensional stability. If a component is held too rigidly then the level of residual stress translated to the structure could be enormous, potentially leading to premature failure in service or significant distortion during post-processing. Similarly, if a fixture is too compliant then parts will not be able to maintain dimensional stability resulting in costly rework, leading to potential lowering of optimised structural integrity.

Whilst the successful manufacturing of components capable of meeting their initial target performance may be seen as a success, strategic consideration must be given to plant performance and shutdowns; unplanned or otherwise, these are expensive in terms of energy production. The development of safety-case strategies for components exposed for sufficiently long times under extreme conditions, e.g., high temperature, high stress, irradiation flux and dose, and chemically hostile environments, will also require appropriate testing rigs and facilities scalable to secure further confidence by removing any secondary or tertiary influences from a system's situation.

Large-scale components are expensive and not too numerous, and therefore an alternative method to provide a cost-effective process capability index (CPk) is needed. It is imperative that research and development be conducted under mock-up configurations or facilities on component size scale, or at least 66% scale to generate statistically reliable product information in preference to extrapolating from surrogate data. The approach developed and proven by the Nuclear AMRC over the past 10 years of experimentation exploits a metric based on a volumetric parameter of fused metal rather than welding several individual components completed at full size. For large scale components >1.8 m in diameter and thicknesses in the range of 75–150 mm, this method has been successful in improving our understanding in defining the process parameter window, determining if the process is stable, proving equipment duty-cycle conditioning, and establishing component fit-up tolerances. The minimum fusion volumes for arc welds and electron beam/laser welds equate to 0.1 m^3 and 0.05 m^3 respectively. This approach will reduce the over-engineering of products that can significantly increase cost. Furthermore, modularisation and modelling that supports decommissioning, repair and maintenance needs to be a future research theme. It will be a paramount characteristic that will need to be built into any cost models that drives towards achieving successful commercialisation of energy from nuclear fusion.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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