Rolls-Royce's Introduction of HIP Nuclear Components

US NRC Workshop on Advanced Manufacturing December 2020

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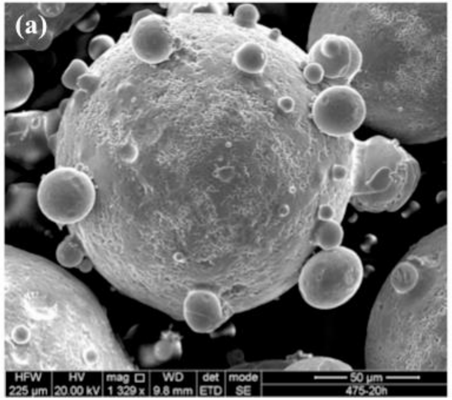
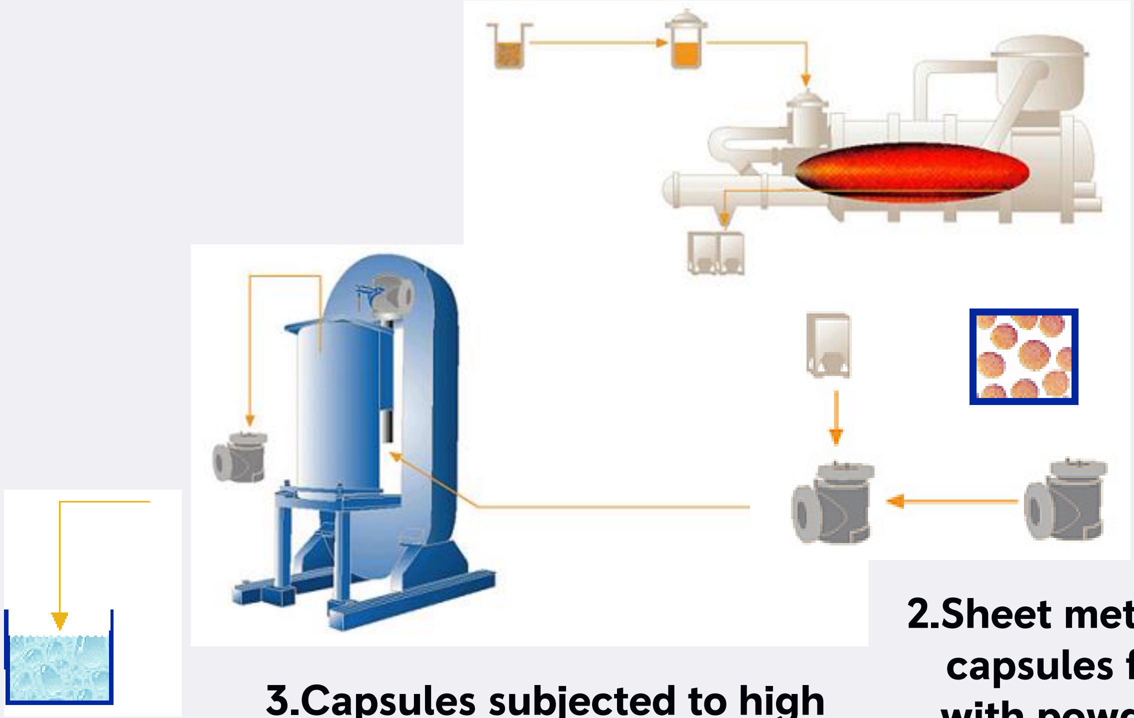
Agenda

HIP Process Overview





1. Inert gas atomisation to produce powder.
2. Sheet metal capsules filled with powder.
3. Capsules subjected to high isostatic pressure and high temperature to obtain full density.
4. Can pickled or machined off.

Why HIP?

- **Project:**

  - Lead-Time Reduction
    - No tooling development required, thin-can encapsulation - welding of mild steel

  - Cost Reduction
    - Scrap/re-work elimination
    - Material quantity - closer to final shape
    - Machining reduction - closer to final shape

- **Product:**

  - Material Quality Improvements
    - Cleaner material, no aligned inclusions
    - Homogeneous
    - Isotropic
    - Improved properties can be achieved due to smaller grain size
    - Smaller defect sizes (sieving size)

  - Non-Destructive Examination Improvement – Sensitivity increase due to:
    - Homogeneous material structure
    - Finer grain size

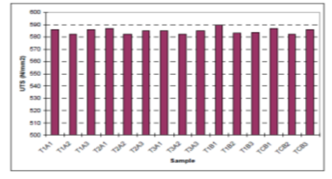
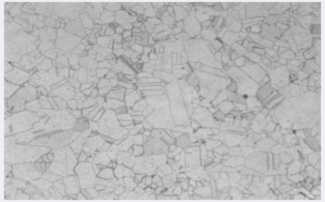


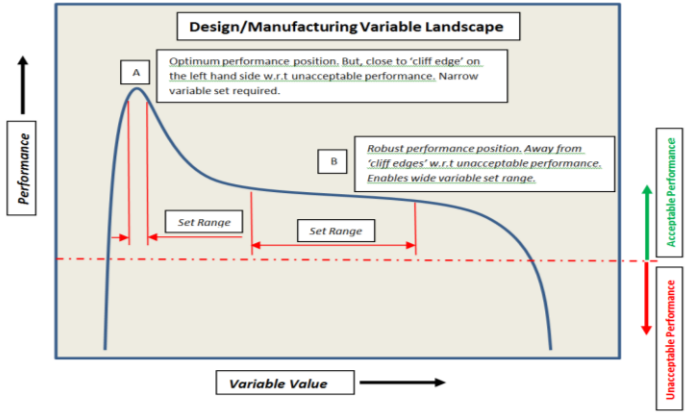
Fig. 4 Tensile Test Results (UTS).



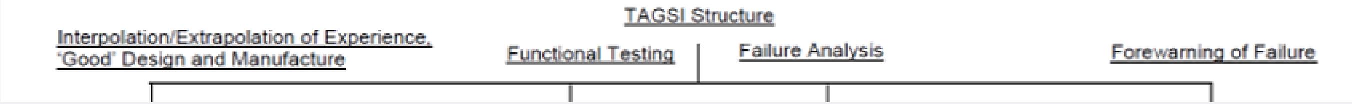
Approach

Enable a Project to adopt the technology by:

- Establishing a **robust** Method of Manufacture (MoM) – understanding of variability. Ensuring risks are appropriately mitigated.



- To provide data in order to produce a generic/base level justification – UK TAGSI four-legged structure. Additional, specific application data may still be required.



Approach

- Demonstrator units produced for each application.
- Dimensionally inspected to show geometry can be achieved.
- NDE examination and destructive examination. Units cut up for material microstructural assessment and property testing.
- Near Nett Shape? Some benefits, but design for inspectability was key consideration.

Approach

- Independent industry survey

- Incremental approach

  - Non-Pressure Boundary
  - Pressure Boundary – Leak Limited
  - Pressure Boundary – Isolable
  - Pressure Boundary - Unisolable

- Material equivalence striven for.

		Material Specification	HIP 304LE Cylinder	HIP 304LE Body	Wrought Casts
0.2% Proof Stress		207 MPa	274 MPa	300 MPa	267 MPa
Ultimate Tensile Strength		517 MPa	625 MPa	628 MPa	589 MPa
Elongation %	Longitudinal	40	73	68	65
	Transverse	30			

CASES OF ASME BOILER AND PRESSURE VESSEL CODE

CASE
N-834

Approval Date: October 22, 2013

Code Cases will remain available for use until annulled by the applicable Standards Committee

Case N-834
ASTM A988/A988M-11 UNS S31603, Subsection NB, Class 1 Components
Section III, Division 1

Inquiry: May ASTM A988/A988M-11 UNS S31603 be used for Section III, Division 1, Subsection NB, Class 1 Components construction?

Reply: It is the opinion of the Committee that, ASTM A988/A988M-11 UNS S31603 may be used for Section III, Division 1, Subsection NB, Class 1 Components in construction provided the following additional requirements are met:

(a) For purposes of welding procedure and performance qualification, this material shall be considered P-No. 8.

(b) The design stress intensity values and the maximum allowable stress values, fatigue design curves, tensile strength and yield strength values, thermal expansion and other properties shall be the same as for SA-240 UNS S31603.

(c) The maximum allowable powder particle size shall be 0.020 in. (0.5 mm) or less.

(d) Following atomization, powders shall be stored under a positive nitrogen or argon atmosphere.

(e) An 8 in. (200 mm) or longer protrusion (extension) shall be added to one end of each item that equals or exceeds the thickest section of that item. The protrusion shall be removed upon completion of isostatic pressing and heat treatment of the item and shall be used for micro structural characterization, density measurements, chemical testing, mechanical testing, and intergranular corrosion testing as required below:

(1) Density measurements and microstructural examination shall be performed at the midsection of coupons removed from the protrusion in accordance with ASTM A988/A988M-11 paras. 8.1.1 and 8.1.2.

(2) In addition to a chemical composition analysis of the final blend powder, an analysis of a sample from each component shall be required.

(3) Intergranular corrosion tests shall be performed using test coupons removed from the protrusion in accordance with ASTM A262 Practice E.

(4) Mechanical property tests, including tension tests and hardness tests, shall be performed using test coupons removed from the protrusion in accordance with ASTM A988/A988M-11, Section 9, Mechanical Properties.

(f) The material shall be examined using the ultrasonic examination method in accordance with NB-2540 over 100% of its entire volume using both straight and angle beam methods. Items that are produced in the form of tubular products shall be examined in accordance with NB-2550.

(g) The material shall not be used for components where the neutron irradiation fluence levels will exceed 1×10^{17} n/cm^2 (E > 1 Mev) within the design life of the component.

(h) Following final hot isostatic-pressing, all surfaces exposed to the process fluid shall be removed by machining or grinding to a depth of 0.008 in. (0.2 mm) or greater. Final accessible surfaces shall be examined by the liquid penetrant method in accordance with NB-2576.

(i) All other requirements of NB-2000 for austenitic materials shall apply.

(j) This Case number shall be marked on the material and listed on the Certified Material Test Report and on the Component Data Report.

- ASME code case – N-834

ASTM INTERNATIONAL

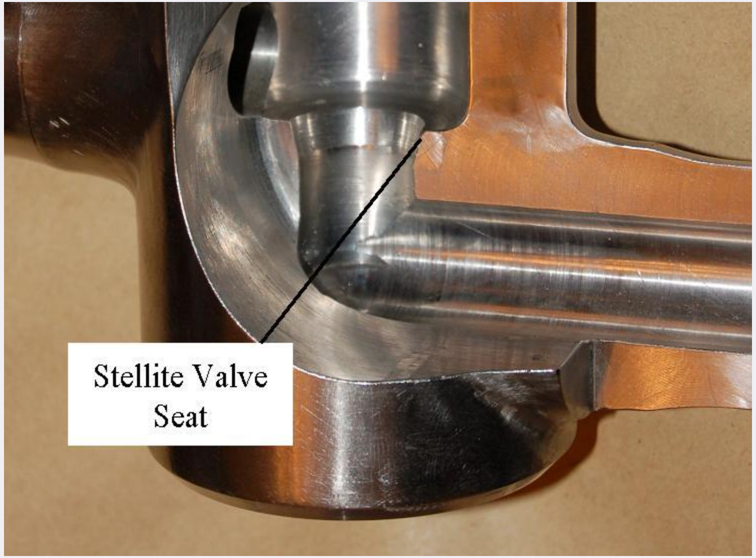
Designation: A988/A988M – 11

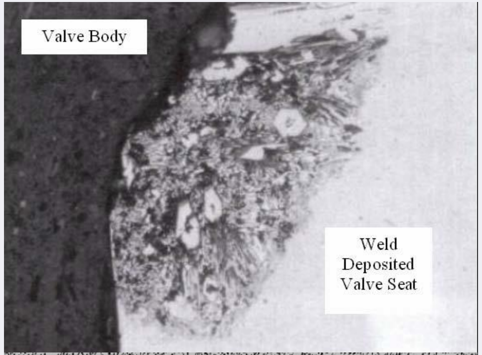
Standard Specification for Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves, and Parts for High Temperature Service[1]

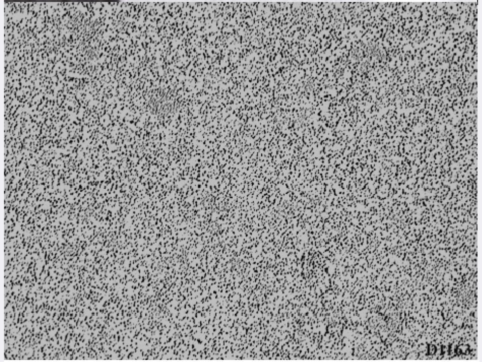
This standard is issued under the fixed designation A988/A988M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

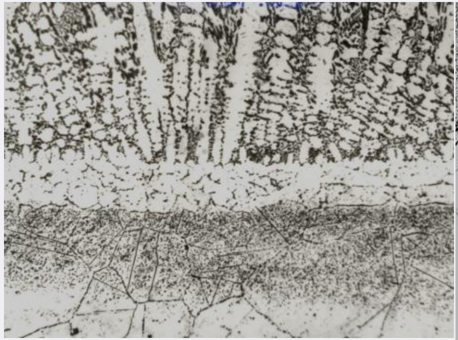
Applications -

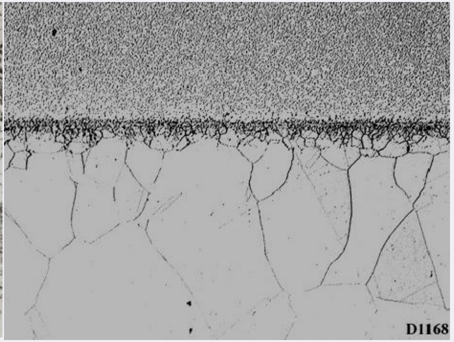
Valve Hard-Faced Seats











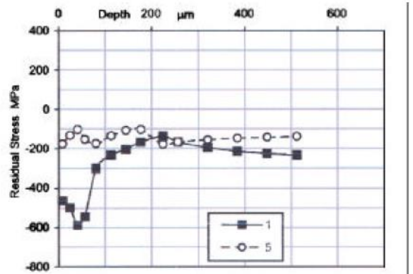


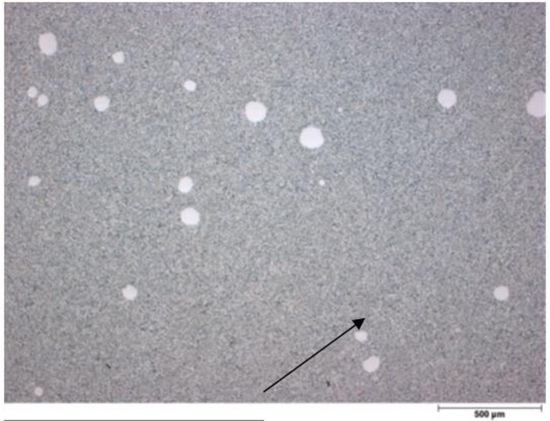
Fig. 9. Residual stress distribution for positions 1 and 5 – Radial/Axial Stresses v Depth.

References:

ICAPP 08-8110, 2008 [1]

ICONE24-61106, 2016 [2]

Applications - Valve Hard-Faced Seats



Cobalt Particle Contamination

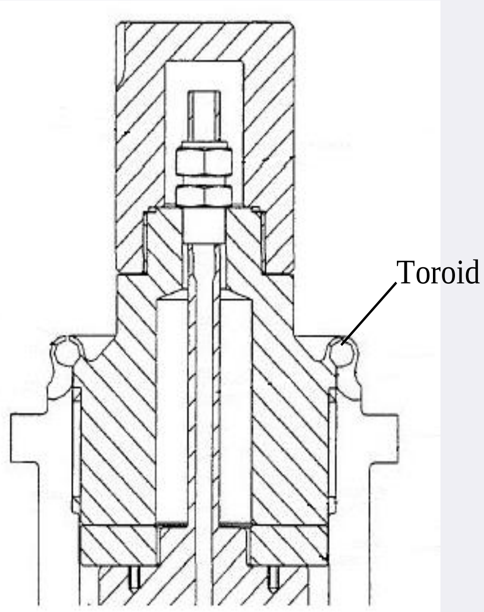
Contaminated Microstructure

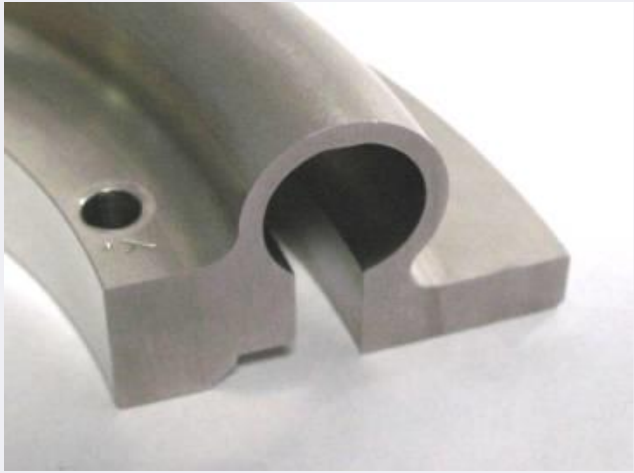
Type of Defect/Issue	Mitigation Control Measure	Rationale
Metallic Inclusions	Exclude elemental cleansing 'washes', e.g. 'cobalt' wash w.r.t the cobalt family of materials, 'Iron' wash w.r.t iron based materials such as Tristelle 5183.	If an elemental wash is conducted, any remnant powder may be drawn through in the subsequent material atomisation run. The elements will be consolidated into the facing matrix as is, i.e. they will not go into solution as is the case for weld deposited facings. If an elemental wash is conducted the equipment clean down prior to the material run needs to be robust.
	Schedule the material production run to follow the exact same material or material family of another order.	Any remnant material from a previous production run will not be adversely different to the material run.
	Sacrificial run conducted of the actual material prior to the production run proper, i.e. a quantity of material is scrapped. The sacrificial material to be taken through all of the powder production processes.	Any remnant material from previous production runs/washes is most likely to be drawn through in the first quantity of material. If this is scrapped it minimises the likelihood of remnant material being contained in the production powder.
	The whole, or specific operations (e.g. sieving), of the production process to be dedicated to a specific material family type.	Any remnant material from a previous production run will not be adversely different to the material run.
	Robust clean down of all the equipment that can come into contact with powder in the production process prior to the production run. Sign-off sheets for demonstrable evidence.	To remove any remnant material from previous production runs.
	The design of the atomiser and sieve to be such that it eliminates/reduces areas where powder can accumulate, and allows ease of access for cleaning, e.g. equipment easily broken down.	To reduce the risk of remnant material from previous production runs becoming dragged through with the production material.
	Examination of a HIPed specimen looking for metallic inclusions. Provision of acceptable and unacceptable micrographs in the acceptance criteria. This conducted on a sample of powder for acceptance of the powder batch, and also for each product form.	This is the key mitigating control measure to ensure unacceptable powder is not applied to product. A HIPed sample is required, rather than relying upon chemical analysis of the powder, as this is the only way to determine if any metallic particles have been HIPed, as is, into the microstructure.

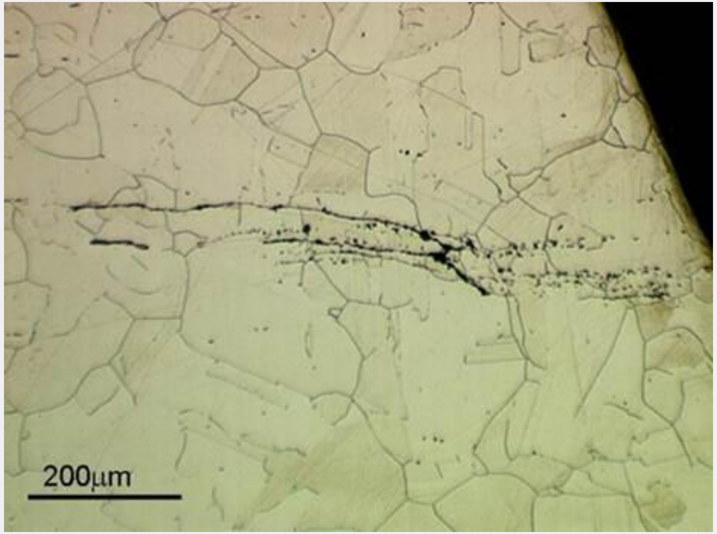
Reference:

ICONE24-61106, 2016 [2]

Applications - Thin-Walled Toroidal Seals



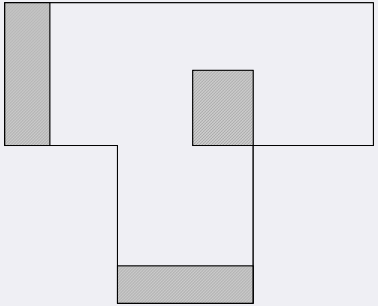


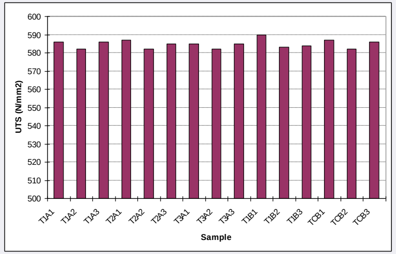


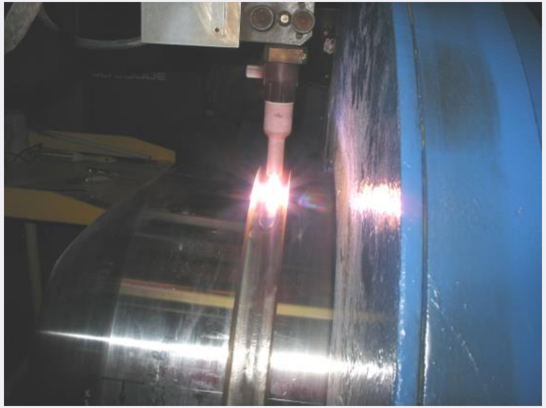
Reference:

ICAPP 08-8110, 2008 [1]

Applications - Thick-Walled Pressure Vessel Section





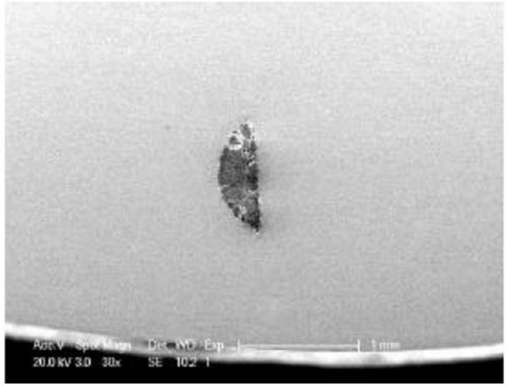


Locations of material used for testing

Reference:

ICAPP 09-9389, 2009 [3]

Applications -
Large Bore Valves

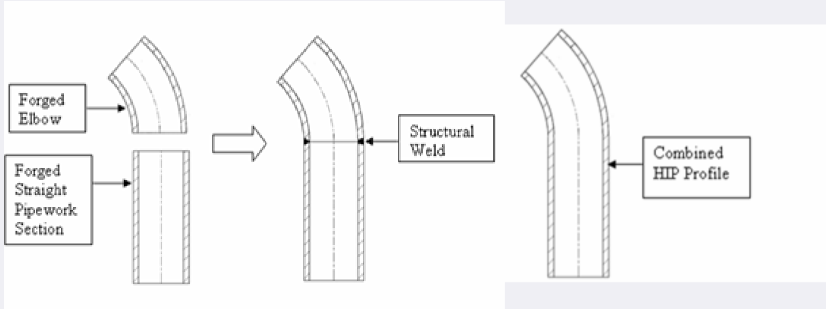


Process Step	Quality Operation	Rationale
Powder Production		
Steel Formulation.	Chemical analysis. Melt – virgin raw stock – produced by induction furnace.	Ensure melt will meet the specification requirements.
Inert Gas Atomized Powder Manufacture.	Atomization machine cleaning & inspection. Cleansing batch of raw material.	Ensure cross contamination of the powder does not occur. Inert gas used to ensure powder quality and hence final material quality, e.g. to prevent powder oxidation.
Sieve Powder.	All powder sieved using a maximum 0.5mm mesh size.	To promote improved packing density and to minimize the possibility of non-metallic inclusions.
Blending.	Blending is only allowed to achieve the required quantity of powder for large components that cannot be accommodated from a single heat. Each heat to be blended together must comply with the powder specification prior to blending. Blending of heats is not allowed to enable [illegible]	To ensure good, overall powder quality and section properties throughout the component.

Reference:

PVP2012-78115, 2012 [4]

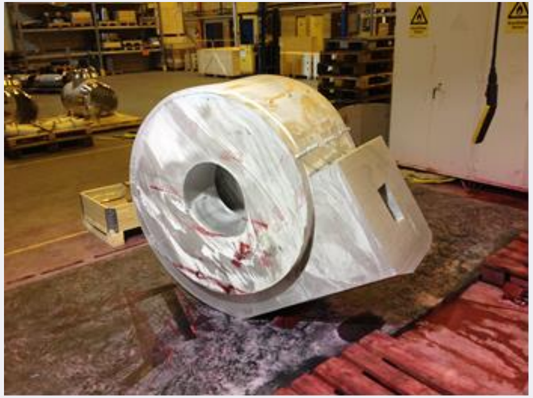
Applications - Pipework

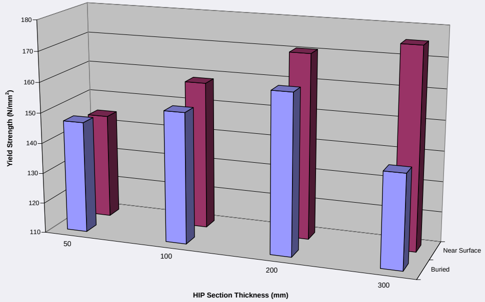


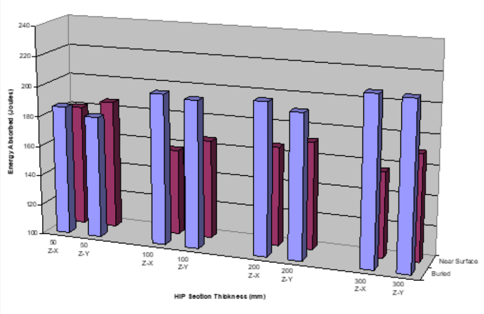
Reference:

AMEE2012, Jan18-19, 2012 [5]

Applications - Pump Bowls







Reference:

PVP2012-78115, 2012 [6]

Acknowledgments

- Our customer for funding the work conducted on Stainless Steel HIP products presented on the previous slides.

Rolls-Royce's New HIP Development Work

Future Advanced Structural Integrity (F.A.S.T)

Low Alloy Steel (LAS) Pressure Vessels with Thick-Section Electron Beam Welding (TSEBW)

Supported by:
Department for Business, Energy & Industrial Strategy

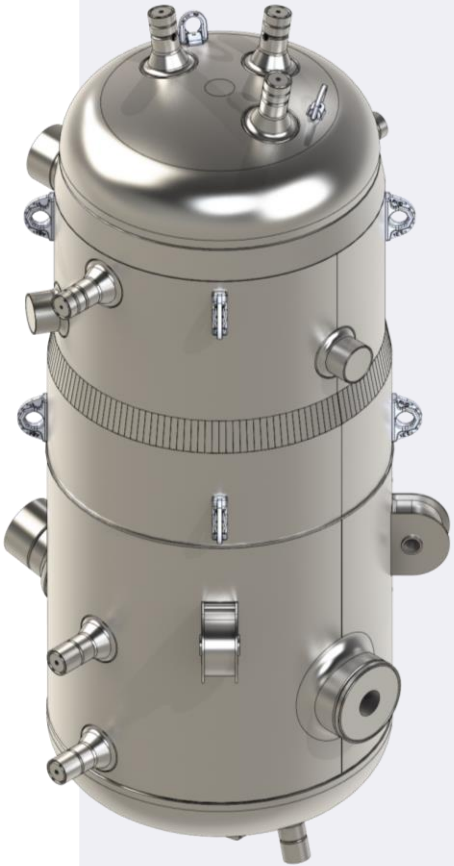
Rolls-Royce's New Development – LAS Vessels

Project FAST

Applying HIP and TSEBW

Net Shape Manufacturing Research Group	Research and Technology	Electron Beam Processes Joining Technologies Group
National Centre for Netshape (HIP) powder analysis, modelling, canning and filling facilities	Nuclear plant design, manufacture, safety justification, programme management expertise	Thick section electron beam welding expertise

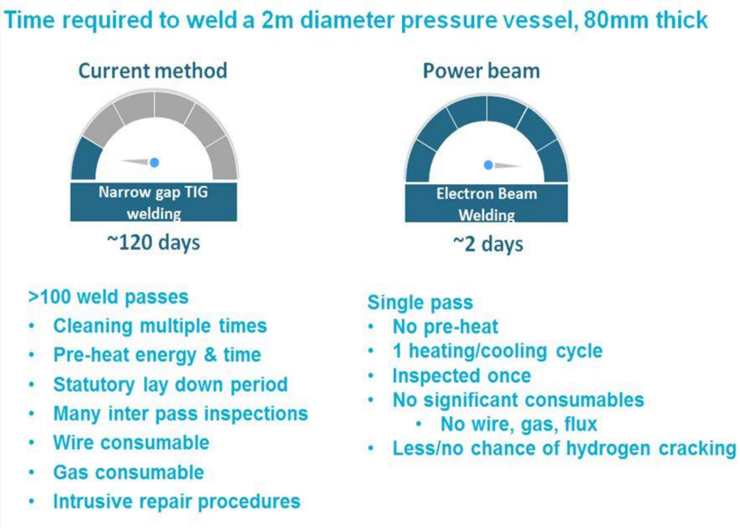
Project Objectives



- Move to additive rather than subtractive processes for nuclear quality vessel manufacture.
- Reduce vessel manufacturing cost & lead-time
- Alternative supply chain to mitigate fragility
- Improve material quality
- Possibility to reduce in-service inspections

TSEBW

Process Overview & Structural Advantages



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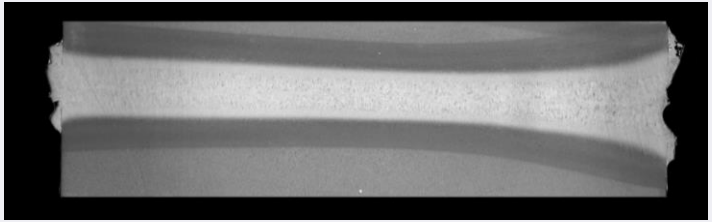


Reference:

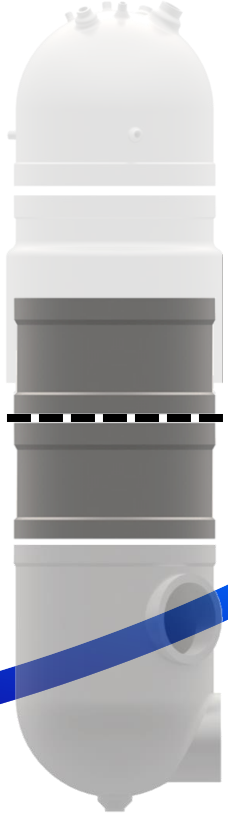
ICONE28-POWER2020-16035, 2020 [7]

Previous work

- Proof of concept
- HIPed test pieces
- Powder filling process

PROJECT FAST (2019-2021)

- TSEBW for HIPed SA508
- Manufacture of a Small Vessel Demonstrator (SVD) and hydrostatic testing
- Manufacture of two Large Vessel Demonstrator (LVD) sections
- Manufacture of a Ring Section Demonstrator (RSD) and thermal cyclic testing



2021+

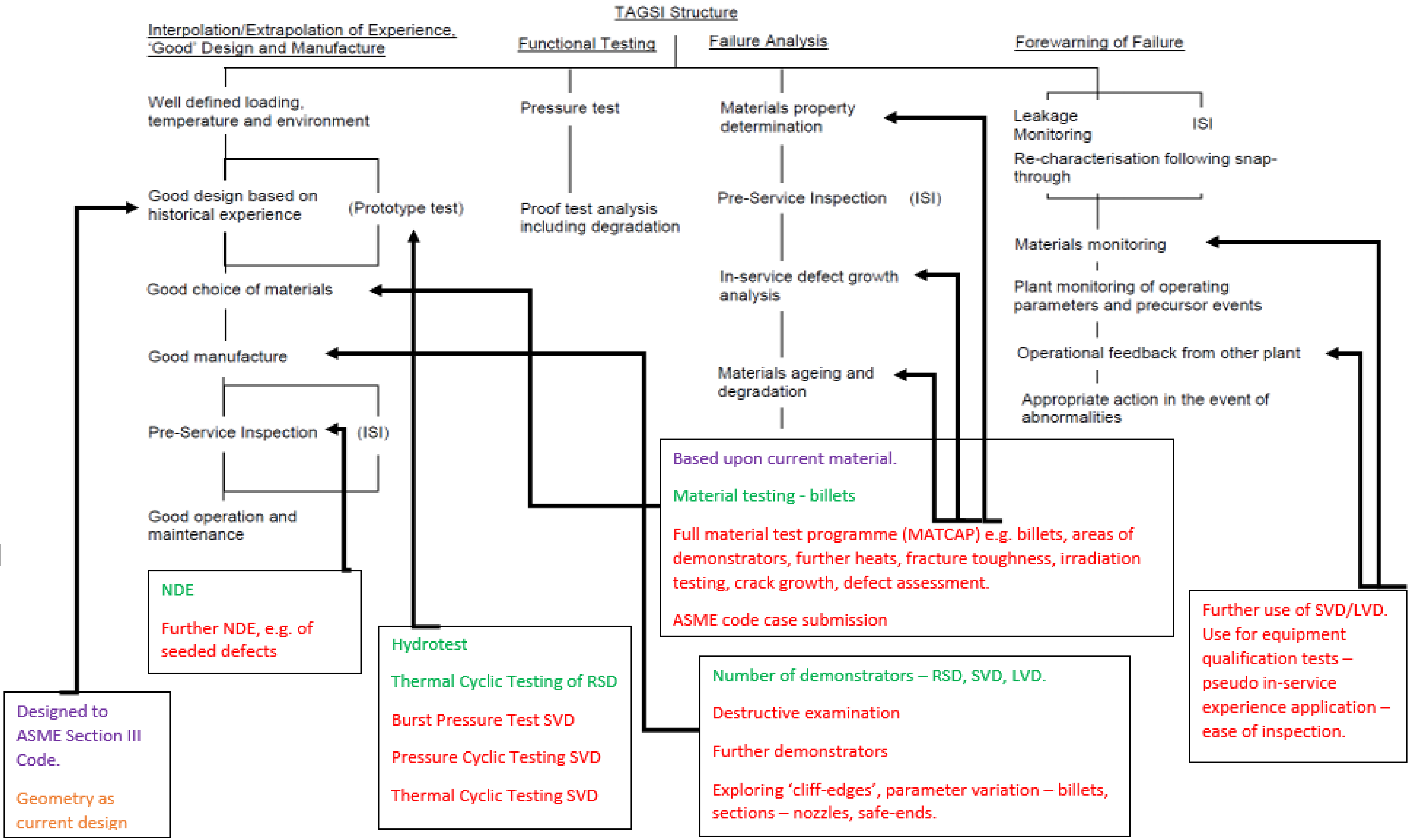
- Pressure & thermal cyclic testing
- Completed LVD for UK component qualification testing

- Full material property testing programme
- ASME code case submission

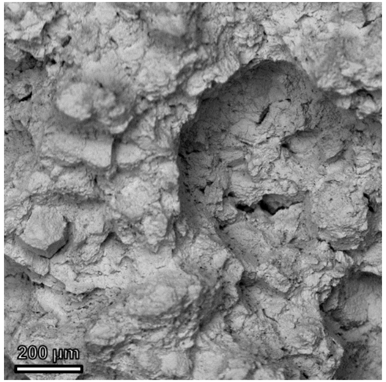
Reference:

ICONE28-POWER2020-16035, 2020 [7]

Justification Approach



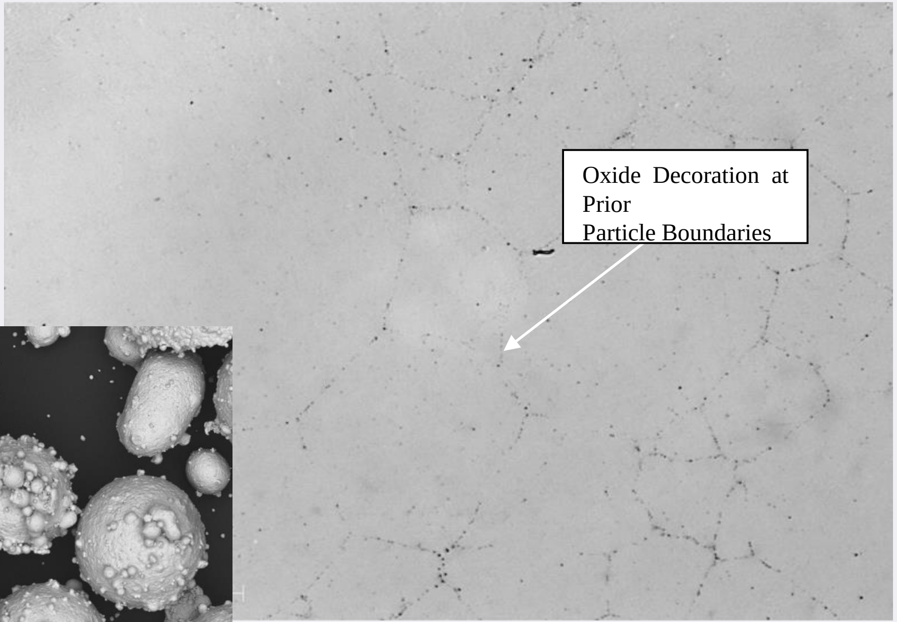
Key Technical Risks

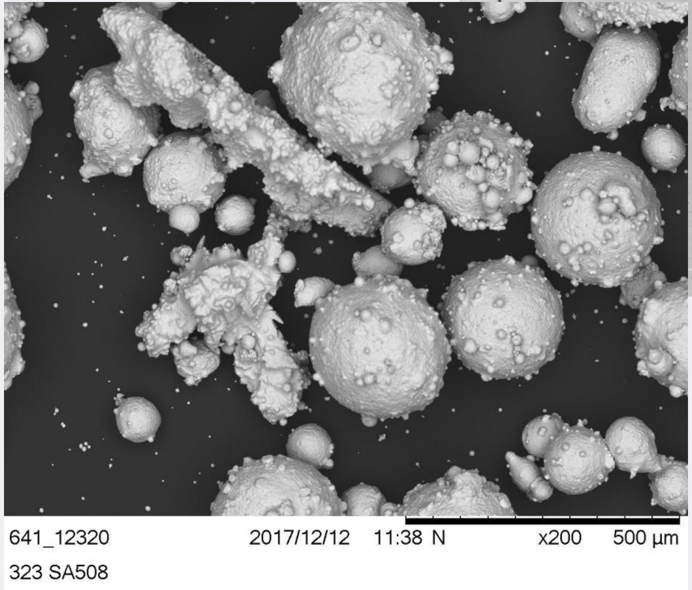


Reference:

ICONE28-POWER2020-16035, 2020 [7]

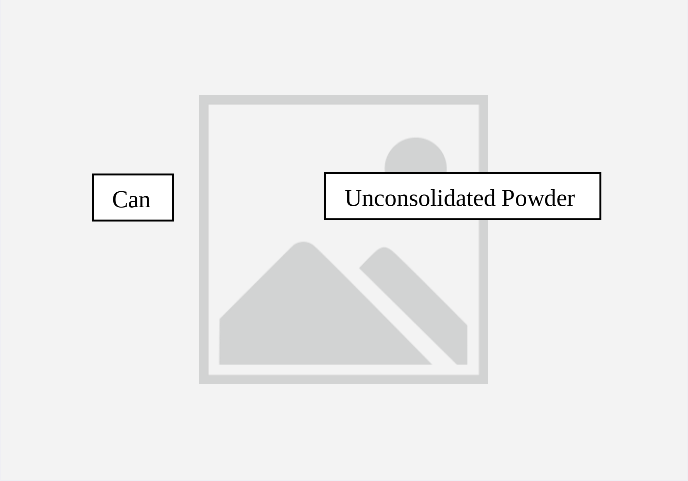
- Poor toughness, oxidisation of powder, poor quality powder

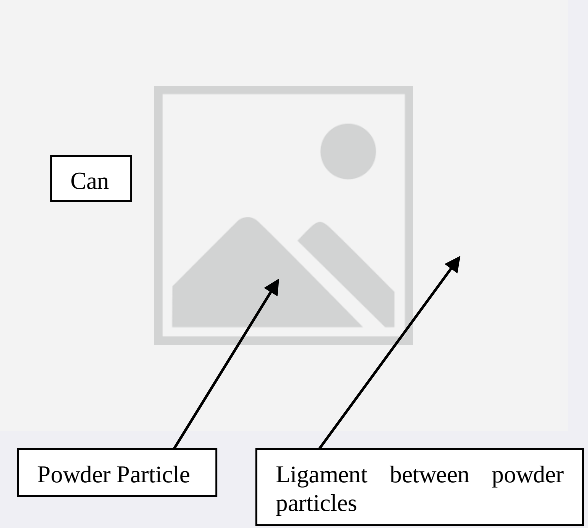




Key Technical Risks

- Can failure during HIP cycle





Reference:

ICONE28-POWER2020-16035, 2020 [7]

Key Technical Risks

- Cracking during quench –hydrogen/poor toughness

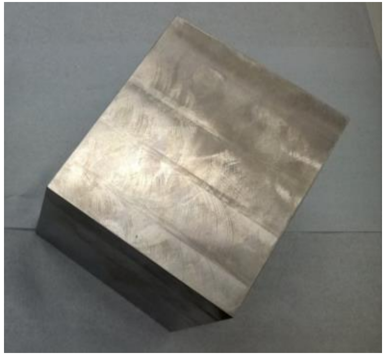
- Achieving geometry – reducing amount of machining

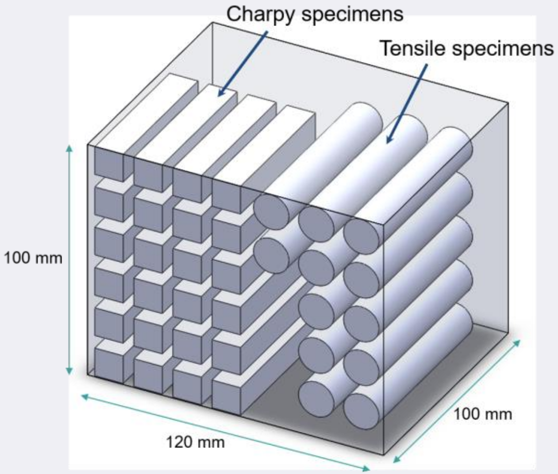
Reference:

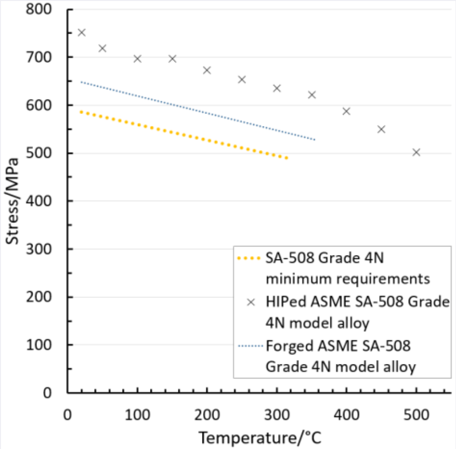
ICONE28-POWER2020-16035, 2020 [7]

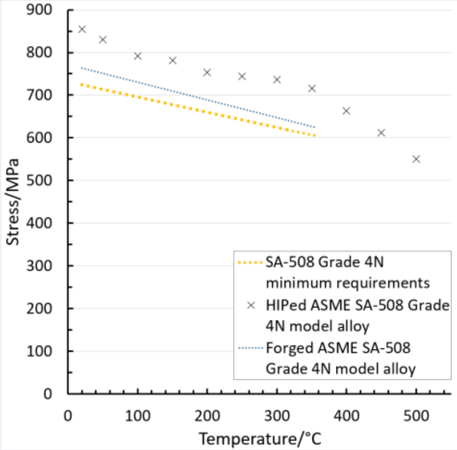
Progress

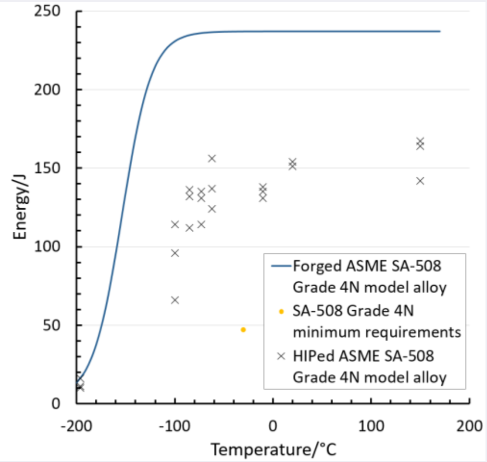
Billets & Basic Material Testing











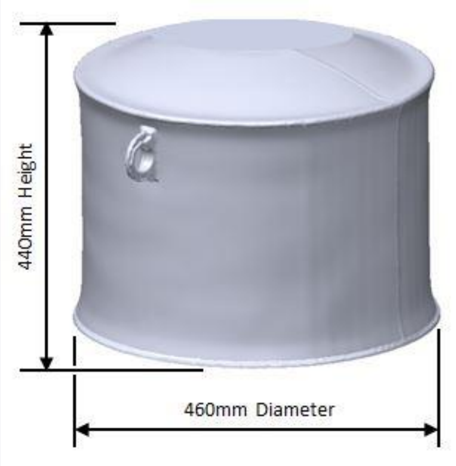
References:

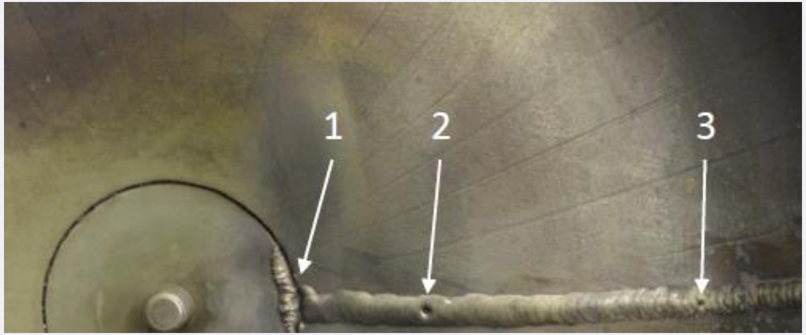
ICONE28-POWER2020-16035, 2020 [7]

ICONE27-1021, 2019 [8]

Progress

RSD Manufacture





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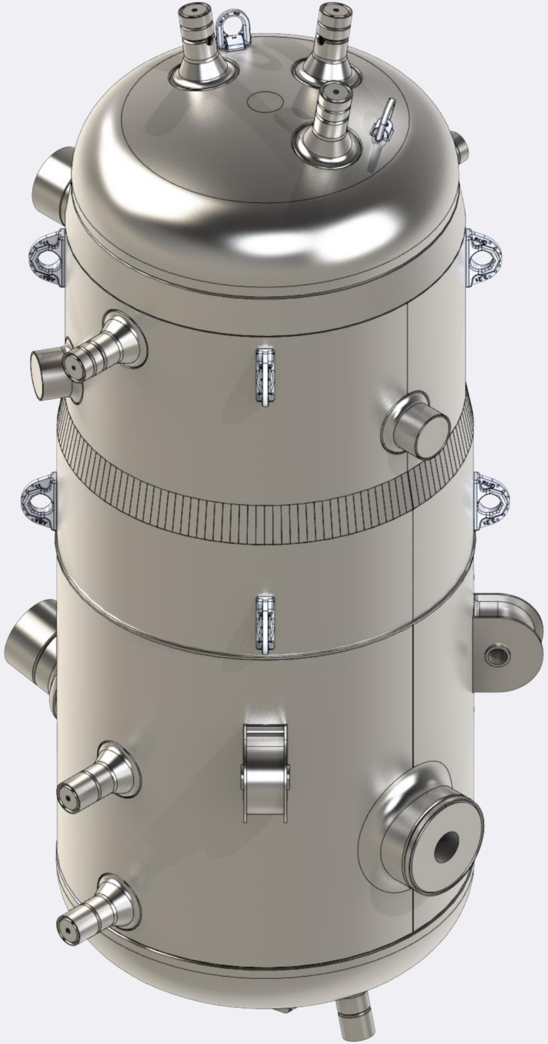
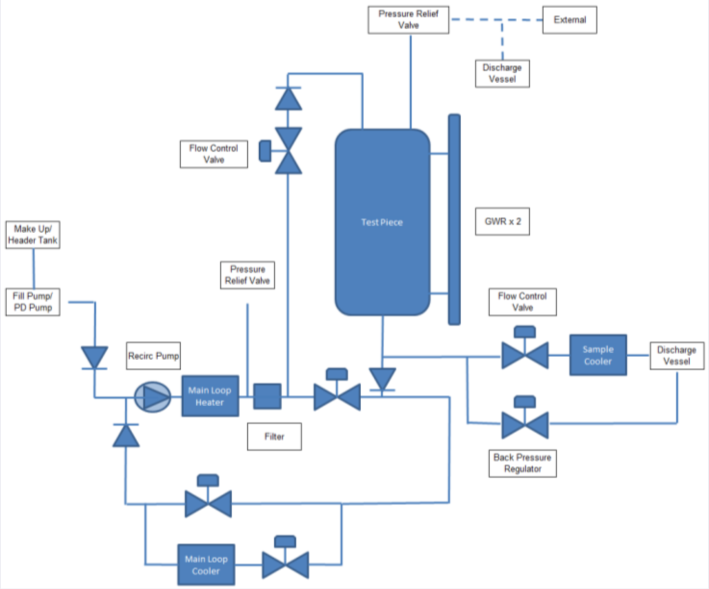
Progress

SVD Design & Manufacture





Reference:

ICONE28-POWER2020-16035, 2020 [7]

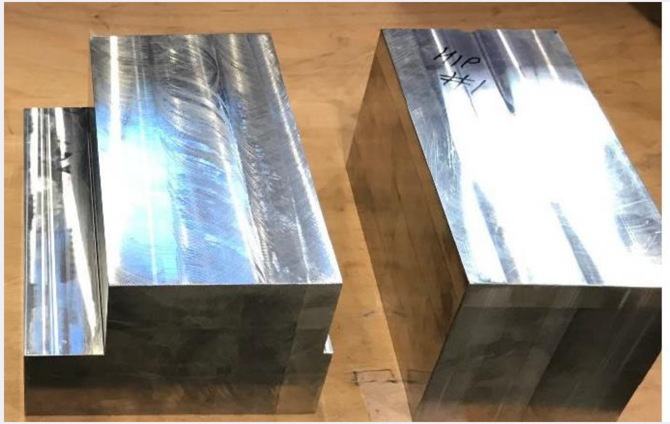
Progress

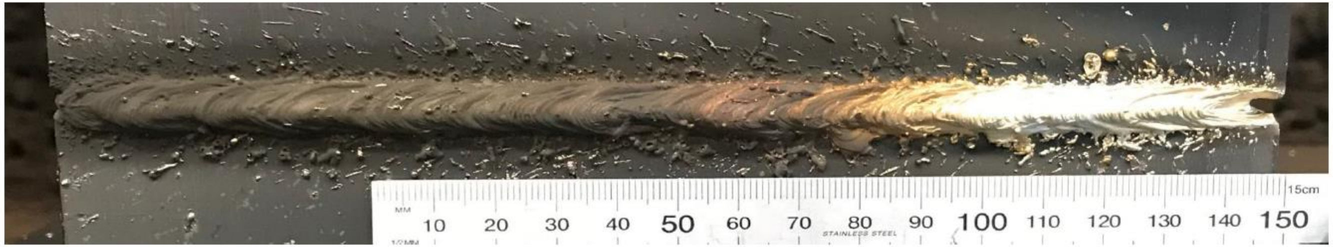
SVD Manufacture

Upper and Lower Sections After HIPing Awaiting EBW

Progress

EBW





Capability Requirements for Deployment

- Large-scale HIP vessel – max dia in Europe = 1.6m
- Large-scale EB chamber
- Improving toughness level –ideally equivalent to forged, oxygen control
- High quality can manufacture – prevention of can failure
- Good quality powder manufacture, low oxygen level, morphology, but at a competitive price, and with reliable, short delivery time – need to ensure competitiveness to forging.
- ASME Code Case – Completion of future full material test programme

Reference:

ICONE28-POWER2020-16035 [7]

Acknowledgments

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References

[1] J L Sulley and I D Hookham, "Justification and Manufacturing Quality Assurance for the Use of Hot Isostatically Pressed, Reactor Coolant System Components in PWR Plant," Proceedings of ICAPP' 08, Anaheim, 2008, CA USA, Paper 8110, p18-20, June 8-12, 2008.

[2] J L Sulley and D Stewart, 'HIPed Hard Facings for Nuclear Applications – Materials, Key Potential Defects and Mitigating Quality Control Measures', Proceedings of the 2016 24th International Conference on Nuclear Engineering ICONE24, June 26 – 30, 2016, Charlotte, North Carolina, ICONE24-61106.

[3] I Hookham, B Burdett, K Bridger, J L Sulley, 'Hot Isostatically Pressed (HIPed) Thick Walled Component for a Pressurised Water Reactor (PWR) Application, Proceedings of ICAPP' 09, Tokyo, Japan, May 10-14, 2009, Paper 9389, p7.

[4] J L Sulley, M Bohan, 'Hot Isostatically Pressed (HIPed) Large Bore Valves for a Pressurised Water Reactor (PWR) Application', Proceedings of PVP-2012: ASME Pressure Vessels and Piping Division, ASME, Toronto, 2012, PVP 2012-78115.

[5] J L Sulley, B Bull, A Wood, 'Hot Isostatic Pressing of Large Bore, Stainless Steel Pipework for a Safety Critical Application,' Proceedings of the International Conference on Applied Materials and Electronics Engineering, AMEE 2012, Jan 18-19, 2012, Hong Kong.

[6] J Sulley, P Mitchell, D Mills, 'Hot Isostatic Pressing of a Varying Thickness, Thick-walled Vessel (Reactor Circulating Pump Bowl) for a Pressurised Water Reactor (PWR) Application', Proceedings of PVP-2014, ASME Pressure Vessels and Piping Division, 20th- 24th July 2014, Anaheim, California, PVP 2014-28013.

[7] J Sulley, P Wallace, T Warner, G Jones, 'Nuclear Pressure Vessel Manufacture Using the Hot Isostatic Pressing (HIP) Process', Proceedings of the 28th International Conference on Nuclear Engineering Joint with the ASME 2020 Power Conference, Anaheim, USA, August 2 – 6, 2020, ICONE 28-POWER2020-16035.

[8] A Morrison, J Sulley, C Carpenter, B Borradaile, G Jones, T Warner, 'HIPed Low Alloy Steel for Nuclear Pressure Vessel Applications – Material Property and Microstructural Assessment', Proceedings of the 27th International Conference on Nuclear Engineering, ICONE 27, Ibaraki, Japan, May 19 – 24, 2019, ICONE 27-1021.

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Thank you

Any Questions?