Rolls-Royce's Introduction of HIP Nuclear Components

US NRC Workshop on Advanced Manufacturing
October 2023

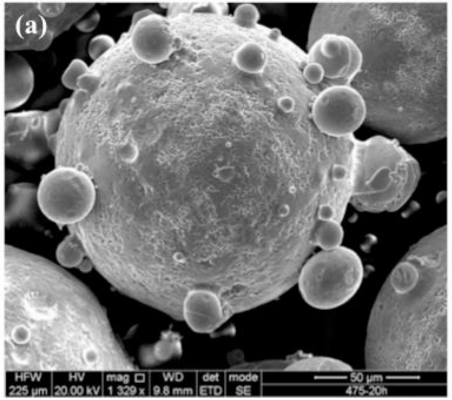
Presenter – John Sulley - Rolls-Royce Fellow

Rolls-Royce PLC

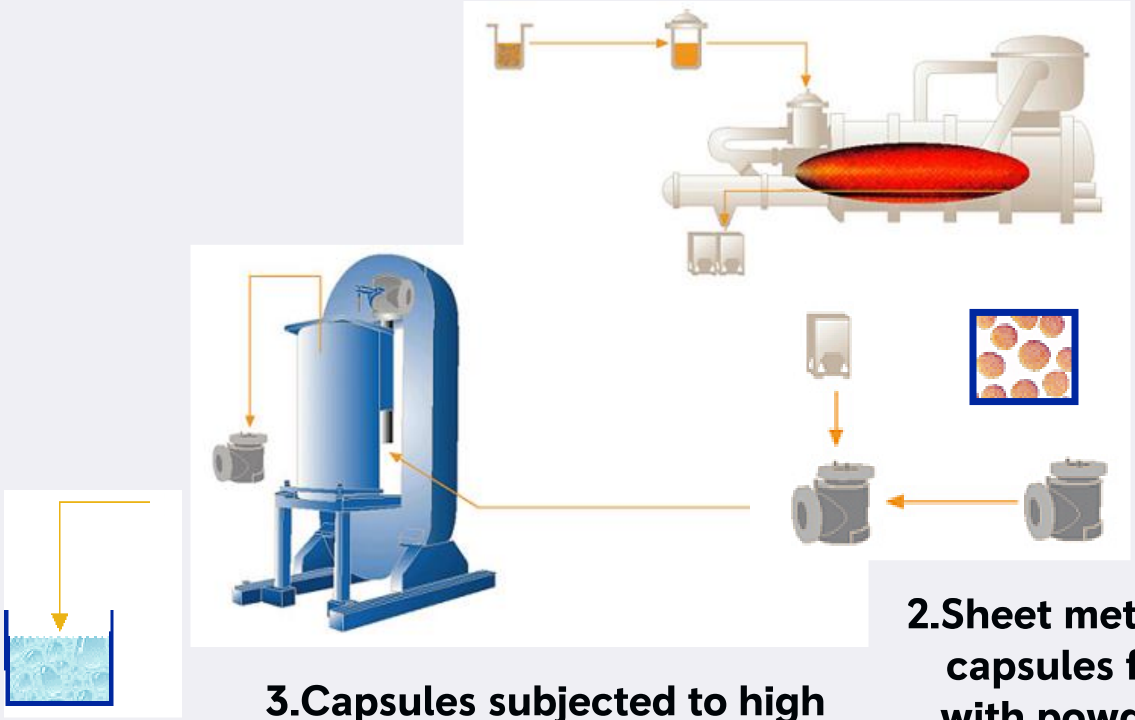
PO BOX 2000, Derby 21 7XX, United Kingdom

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

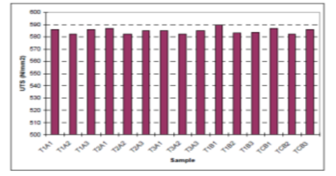
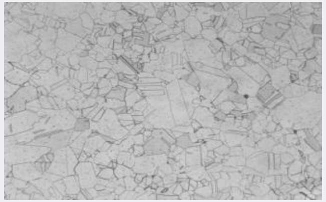


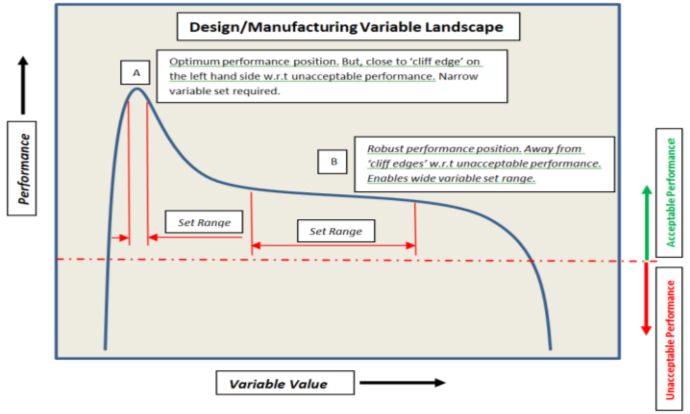
Fig. 4 Tensile Test Results (UTS).



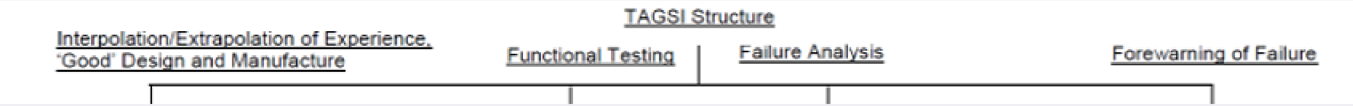
Approach

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 microstructural 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.

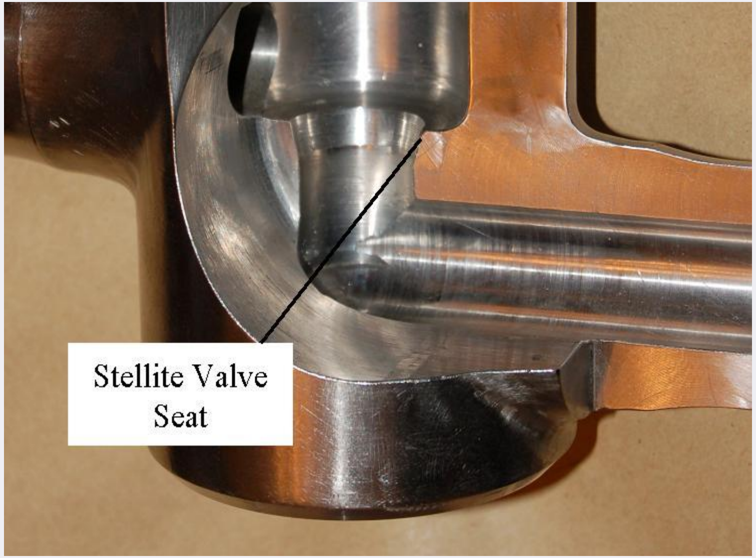
- ASME code case – N-834

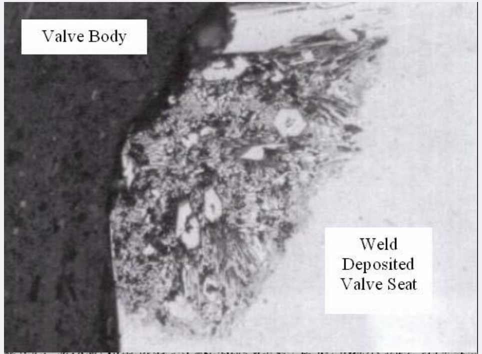
Designation: A988/A988M – 11

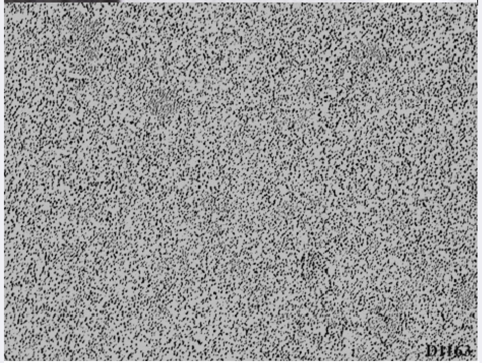
Standard Specification for
Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves, and Parts for High Temperature Service[1]

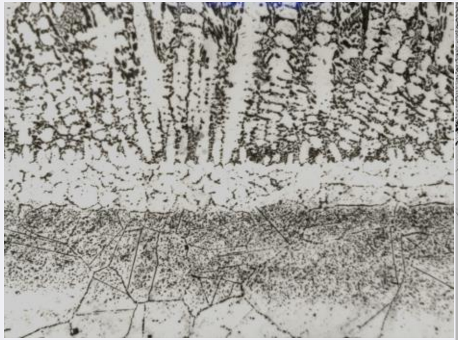
This standard is issued under the fixed designation A988/A988M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates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

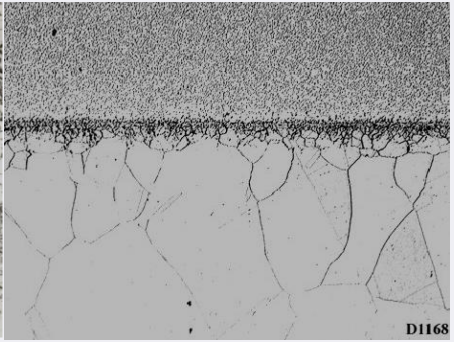
Applications - Valve Hard-Faced Seats











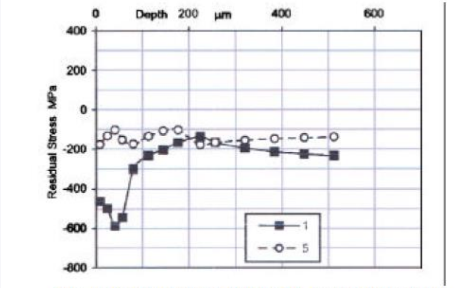


Fig. 9. Residual stress distribution for positions 1 and 5 – Radial/Axial Stresses v Depth.

References:

ICAPP 08-8110, 2008 [1]

ICONE24-61106, 2016 [2]

Applications -

Valve Hard-Faced Seats

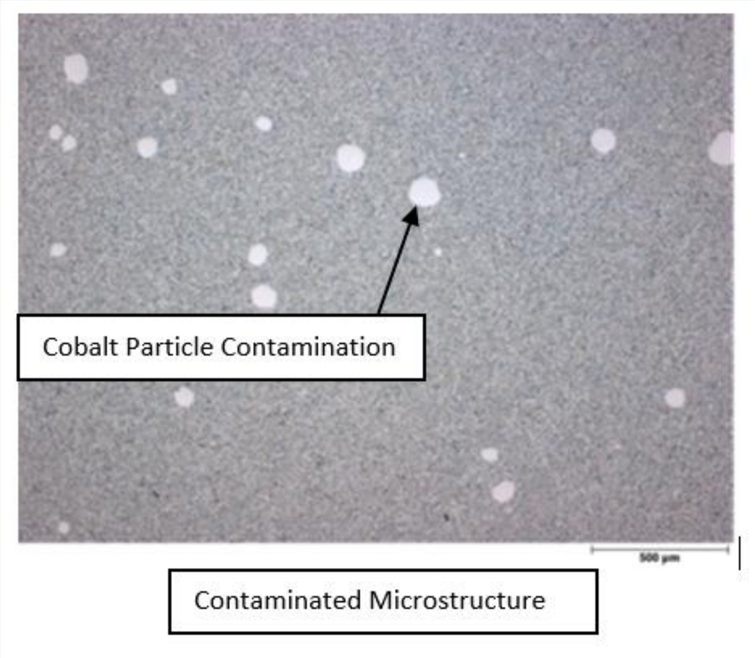

Rolls-Royce

ICONE24-61106
HIPED HARD FACINGS FOR NUCLEAR APPLICATIONS – MATERIALS, KEY POTENTIAL DEFECTS AND MITIGATING QUALITY CONTROL MEASURES

Presented by
Eur Ing J Sulley - *Chief of Engineering Capability*
Co-Author
Dr D Stewart – Technical Specialist

Reference:

ICONE24-61106, 2016 [2]



- **Potential Defects and Mitigating Quality Controls:**
  - **Metallic Inclusions**
  - **Non-Metallic Inclusions – Refractory Materials**
  - **Non-Metallic Inclusions – Melt Oxides**
  - **Porosity**
  - **Grain Growth**
  - **Oxide Formation**
  - **Contamination from Chemical Species**

ICONE24, Paper 61106

All Applications -
Powder Quality

Internet Search – Powder Contamination Aerospace Industry

‘The problem which the company first disclosed in July, stems from defects with powder metal used to make some popular geared turbofan engines, a flaw that can cause cracks.’

‘$3 billion charge!’

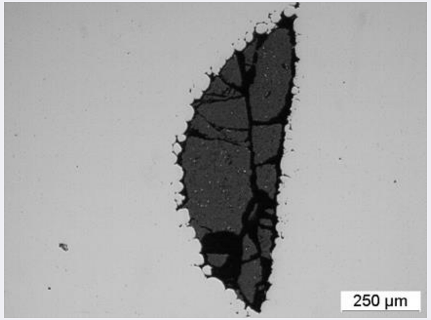
‘Discovered an issue with contaminated powder metal that could cause cracking in stage 1 and stage 2 discs in the high pressure turbine. These obviously must be inspected at certain intervals to ensure there is no actual problem.’

All Applications - Powder Quality

Ensure you have specifications covering powder quality, also other process steps, e.g. HIPing – furnace control.

Reference:

ICONE24-61106, 2016 [2]



Metallic Inclusions Cause and Mitigation

39

Exclude elemental cleansing 'washes', e.g. 'cobalt' wash.	If an elemental wash is conducted, any remnant powder may be drawn through in the subsequent material atomisation run.
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.	Any remnant material from previous production runs/washes is most likely to be drawn through in the first quantity of material..
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.	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.	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.	This is the key mitigating control measure to ensure unacceptable powder is not applied to product.

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POWDER MANUFACTURE BY GAS ATOMISATION 2.0

Rolls-Royce

CONSOLIDATION BY HOT ISOSTATIC PRESSING 4.0

Rolls-Royce MATERIAL SPECIFICATION	RRMS Version 3.0 Date 05 AUG 2021
Acceptance Test Requirements for Metallic Powder and Powder Based Product	

All Applications - Powder Quality

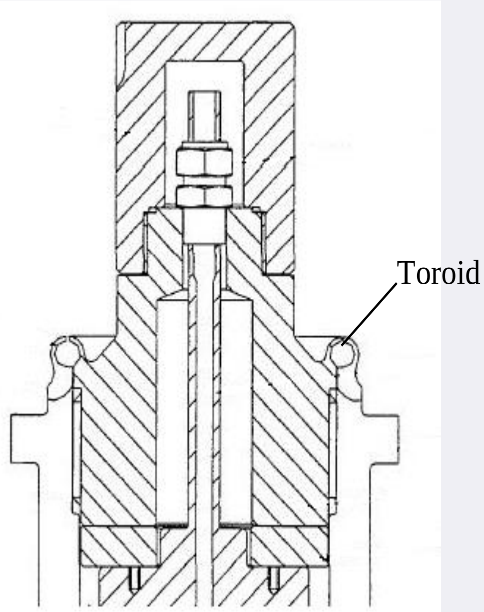
Don't be hands-off with the supply chain!

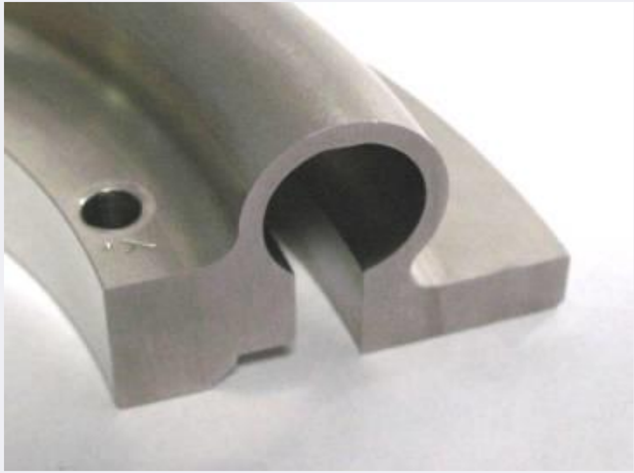
Walk the process, witness key operations, particularly clean-down.

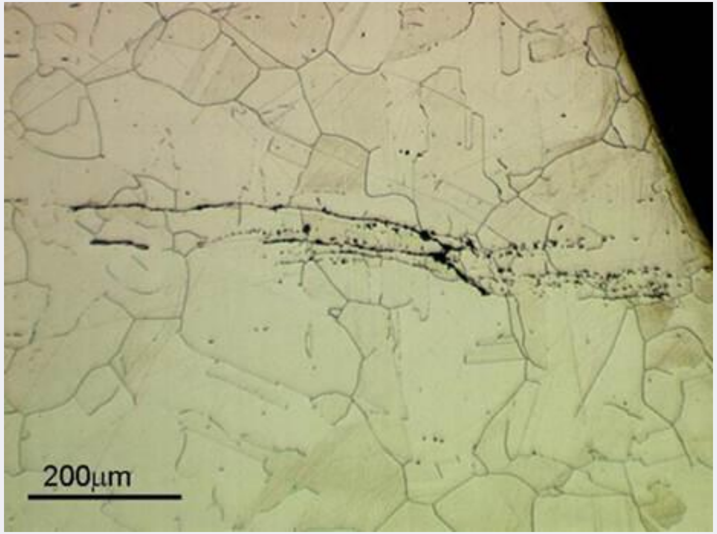
Reference:

ICONE24-61106, 2016 [2]

Applications - Thin-Walled Toroidal Seals





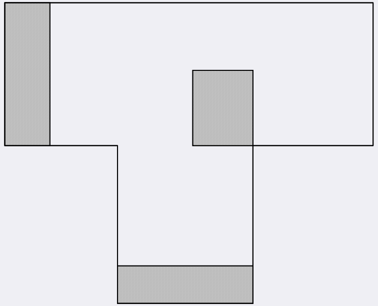


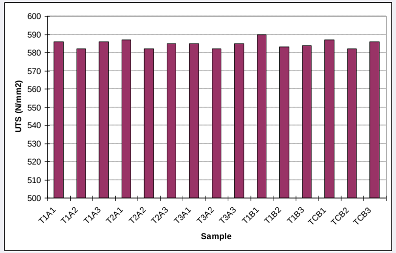
Reference:

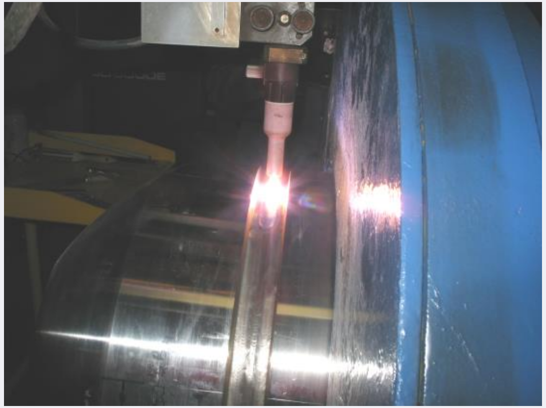
ICAPP 08-8110, 2008 [1]

Applications -

Thick-Walled Pressure Vessel Section







Locations of material used for testing

Reference:

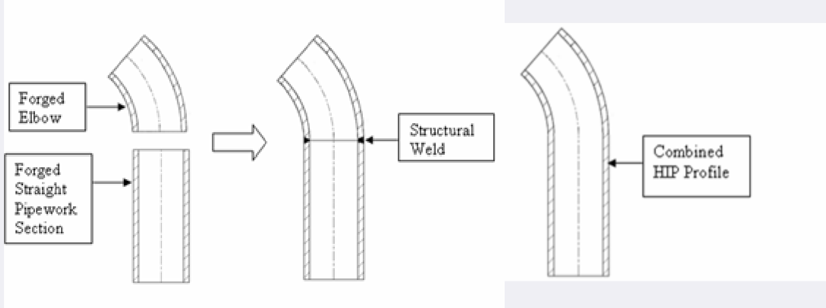
ICAPP 09-9389, 2009 [3]

Applications - Large Bore Valves

Reference:

PVP2012-78115, 2012 [4]

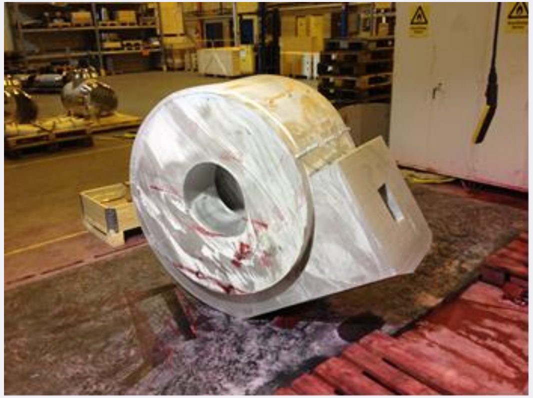
Applications - Pipework

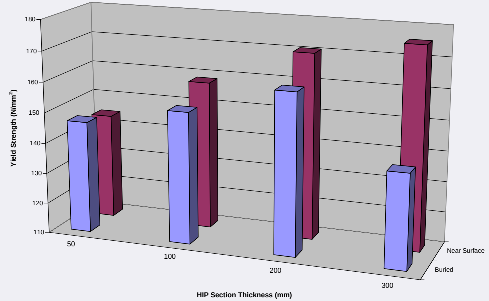


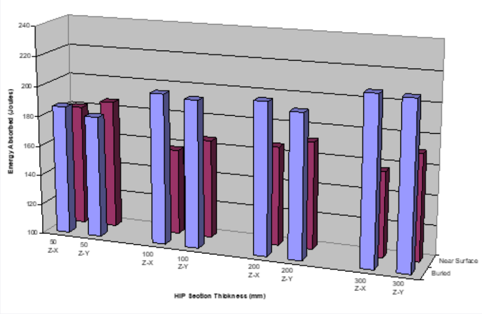
Reference:

AMEE2012, Jan18-19, 2012 [5]

Applications - Pump Bowls







Reference:

PVP2012-78115, 2012 [6]

Acknowledgments

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

Rolls-Royce's New HIP Development Work

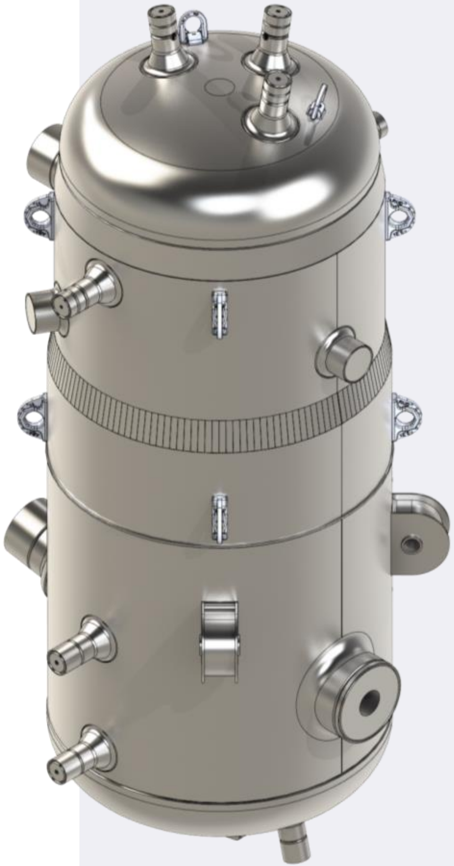
Future Advanced Structural Integrity (F.A.S.T)

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

ROLLS ROYCE

Supported by:
Department for Business, Energy & Industrial Strategy

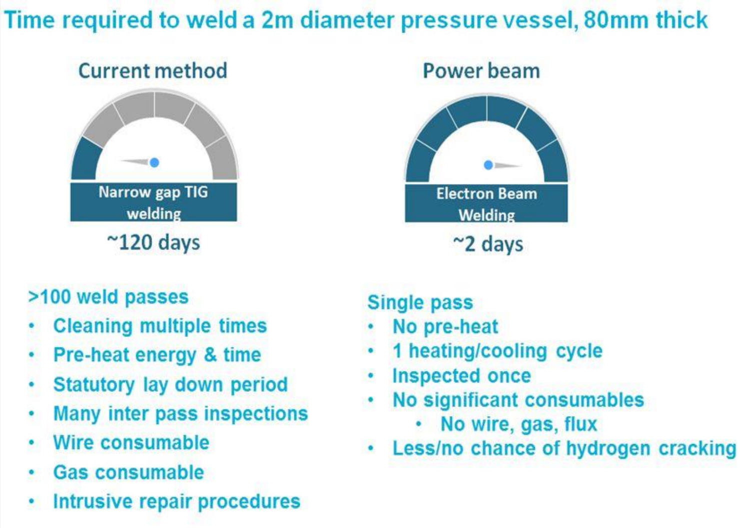
Project Objectives

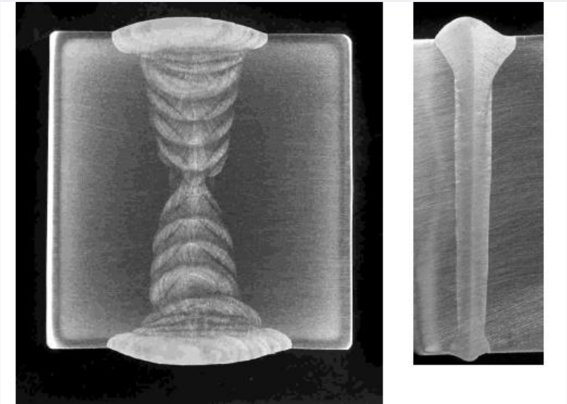


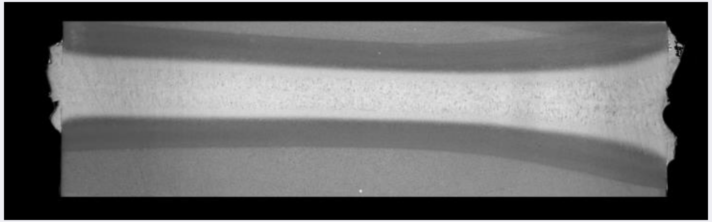
- Move to additive rather than subtractive processes for nuclear quality vessel manufacture.
- Reduce vessel manufacturing cost & lead-time
- Alternative supply chain to mitigate fragility
- Improve material quality
- Possibility to reduce in-service inspections

TSEBW

Process Overview & Structural Advantages







Reference:

ICONE28-POWER2020-16035, 2020 [7]

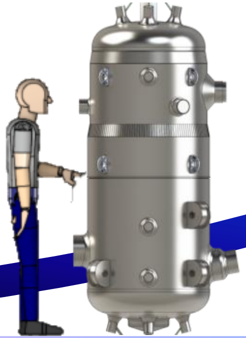
Previous work

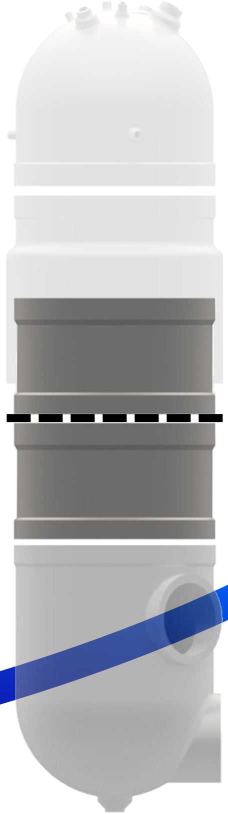
- Proof of concept
- HIPed test pieces
- Powder filling process

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

Department for Business, Energy & Industrial Strategy





2021+

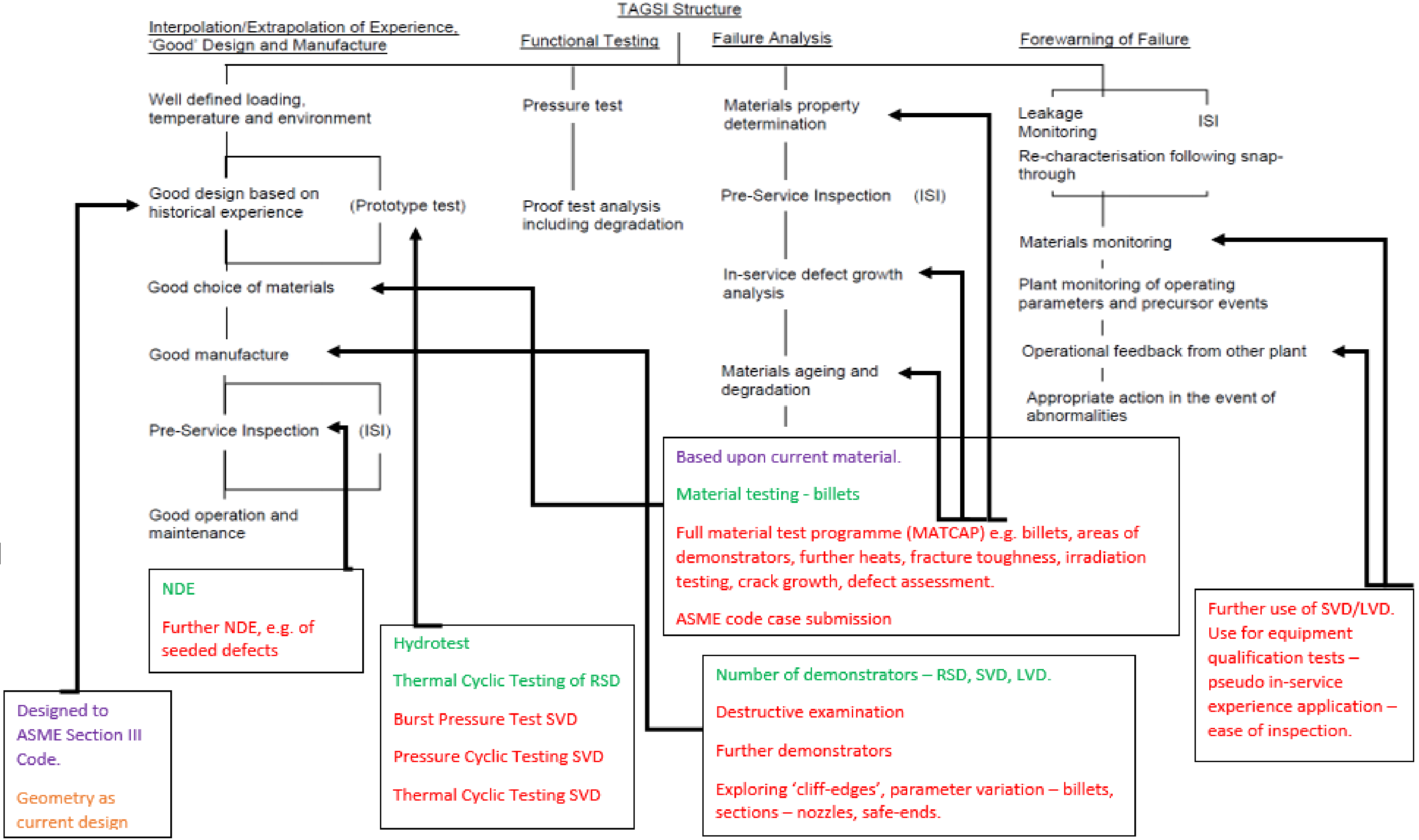
- Pressure & thermal cyclic testing
- Completed LVD for UK component qualification testing
- Full material property testing programme
- ASME code case submission

2018 2019 2020 2021

Reference:

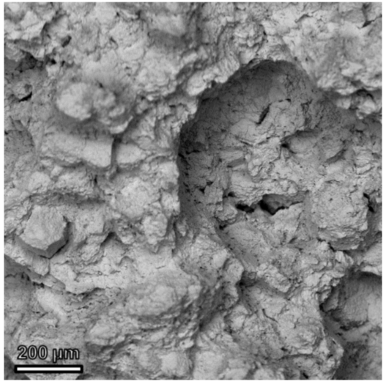
ICONE28-POWER2020-16035, 2020 [7]

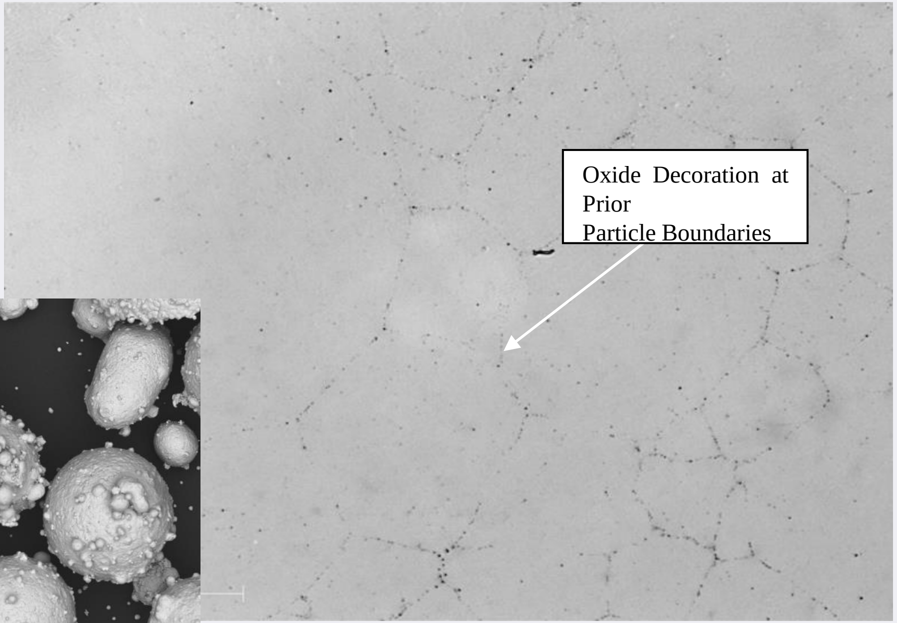
Justification Approach

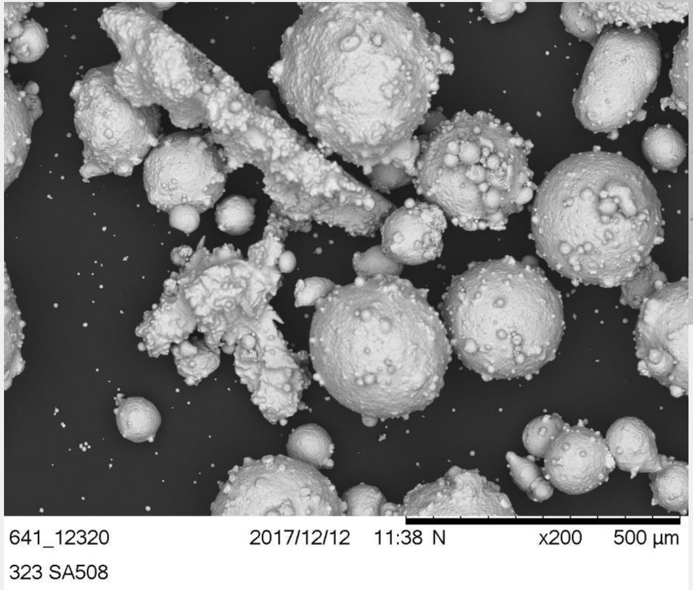


- Poor toughness, oxidisation of powder – need low oxygen powder
- Poor quality powder – morphology – need good supplier

Key Technical Risks





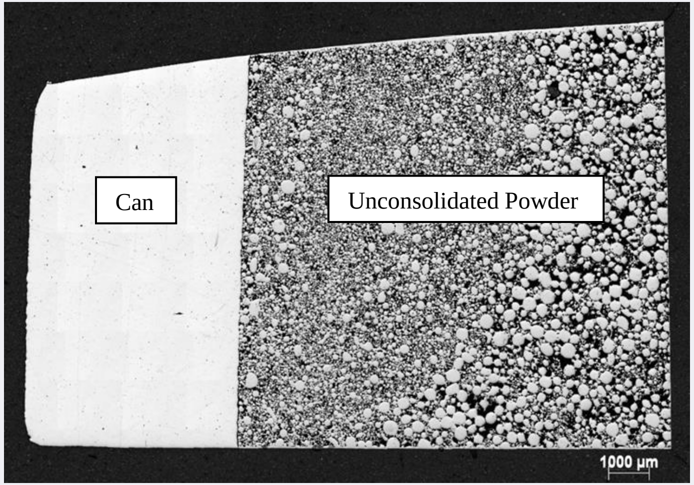


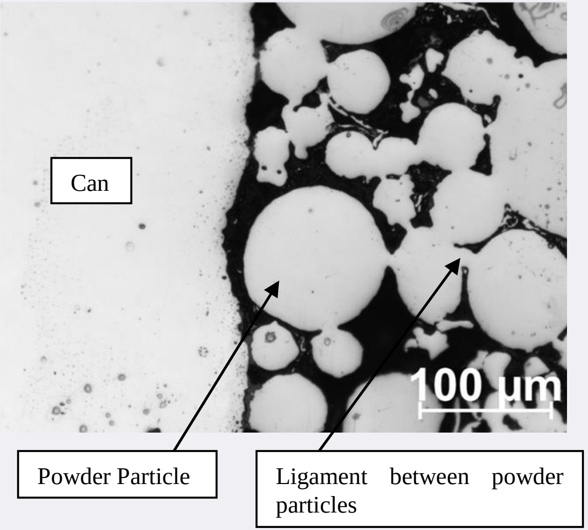
Reference:

ICONE28-POWER2020-16035, 2020 [7]

Key Technical Risks

- Can failure during HIP cycle – need high quality can manufacture – watch the welds!



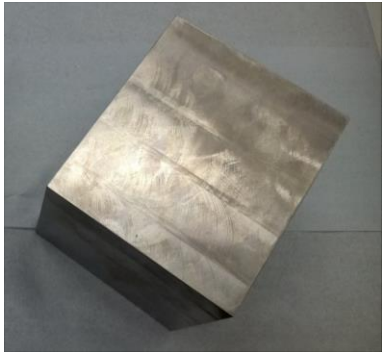


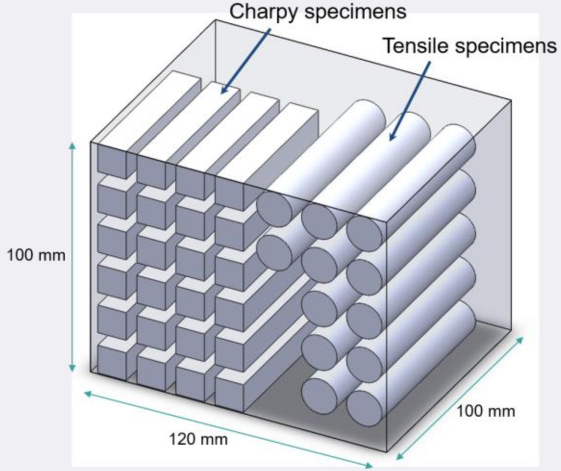
Reference:

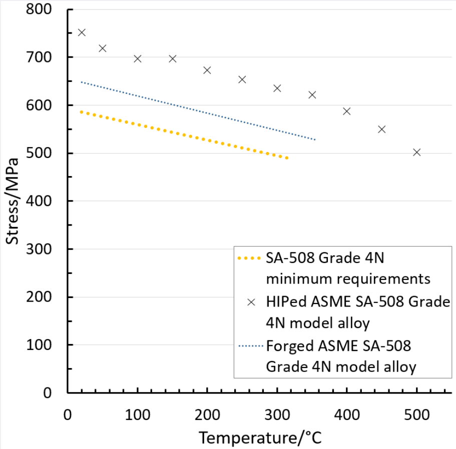
ICONE28-POWER2020-16035, 2020 [7]

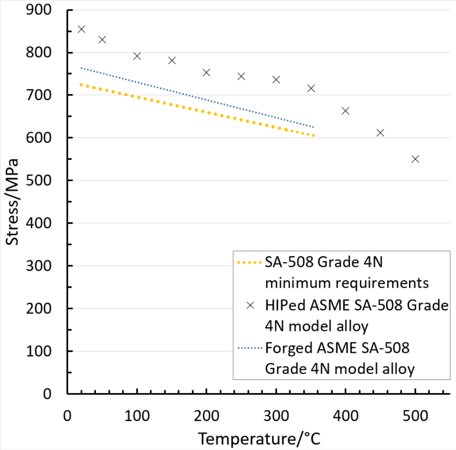
Progress

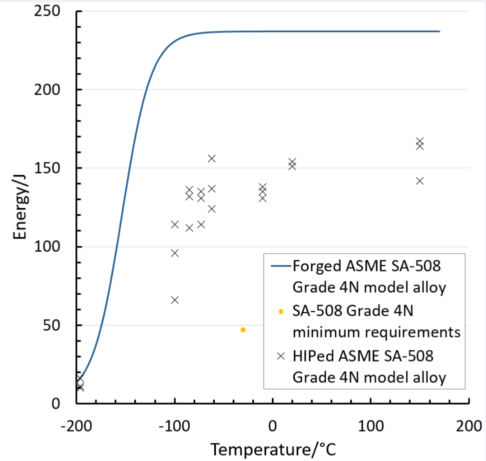
Billets & Basic Material Testing











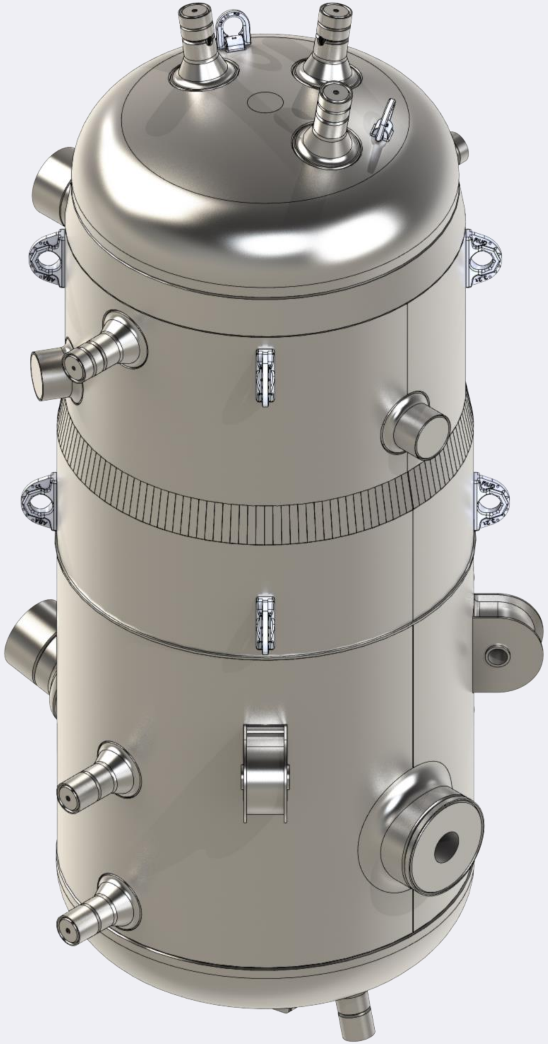
References:

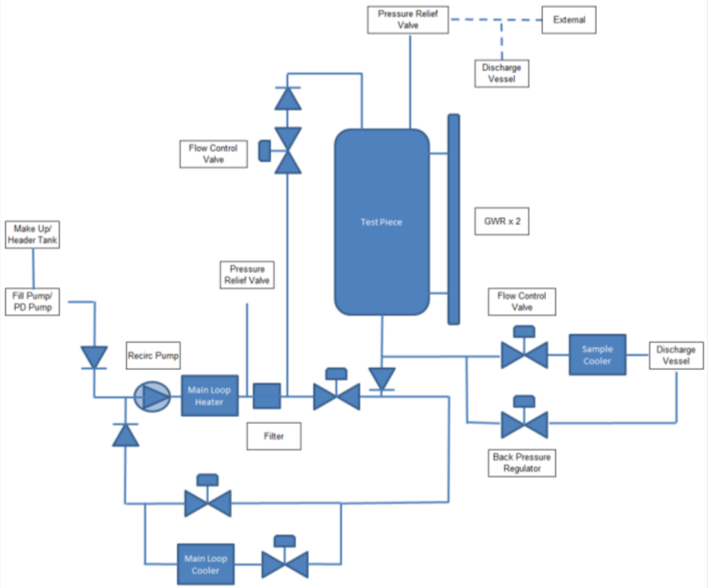
ICONE28-POWER2020-16035, 2020 [7]

ICONE27-1021, 2019 [8]

Progress

SVD Design & Manufacture





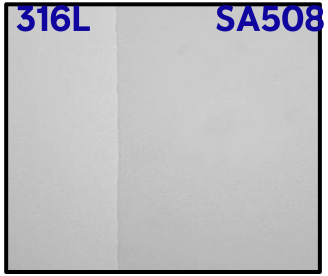
Reference:

ICONE28-POWER2020-16035, 2020 [7]

Progress

SVD Manufacture

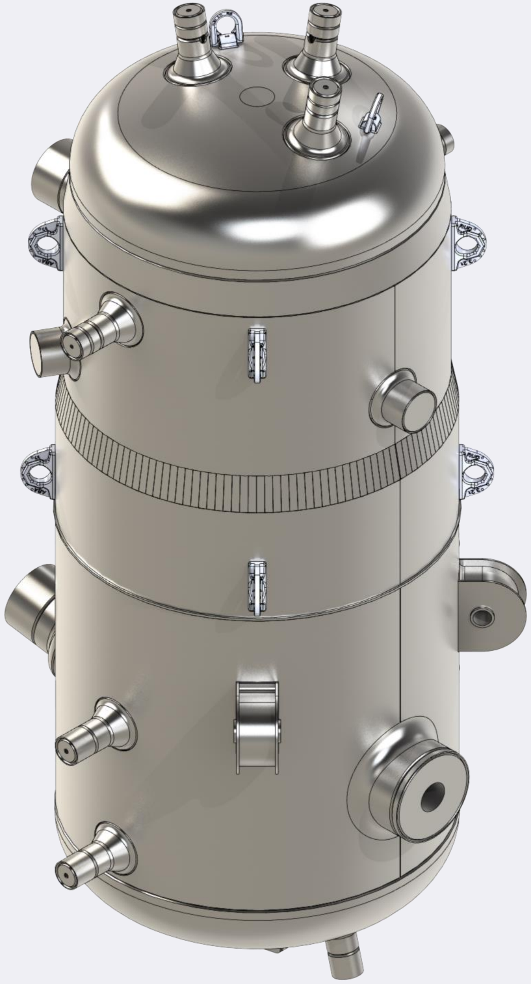
Upper and Lower Sections After HIPing Awaiting EBW



Progress

World's First Complete HIPed LAS 508 Gr 4N, EB Welded Pressure Vessel

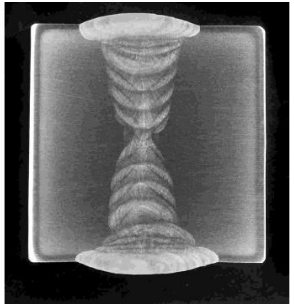
Shape Improvements for Next Vessel – Poor Packing – Poor Vibration, Filling System Changed

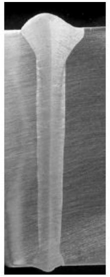


Reference: Proceedings of the ASME 2022 Pressure Vessels & Piping Conference PVP2022, *July* 17-22, 2022, Las Vegas, Nevada, USA, PVP2022-79403.

Progress

Large Vessel Demonstrator





Reference: Proceedings of the ASME 2022 Pressure Vessels & Piping Conference PVP2022, July 17-22, 2022, Las Vegas, Nevada, USA, PVP2022-79403.

Achieving Toughness

Tensile Properties always exceeding forged material, max 22% increase.

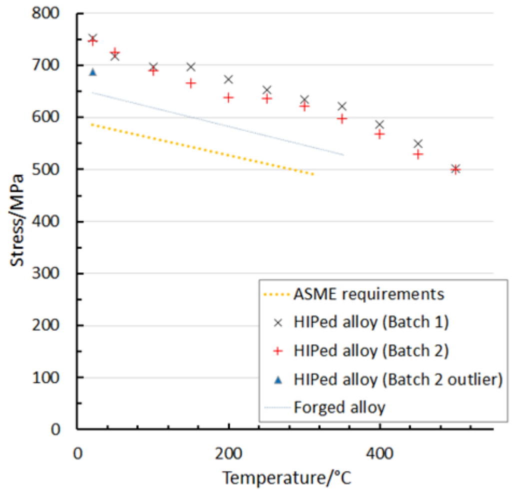


FIGURE 2: HIPED TEST SPECIMEN MEAN 0.2% PROOF STRESS VALUES VERSUS FORGED MATERIAL

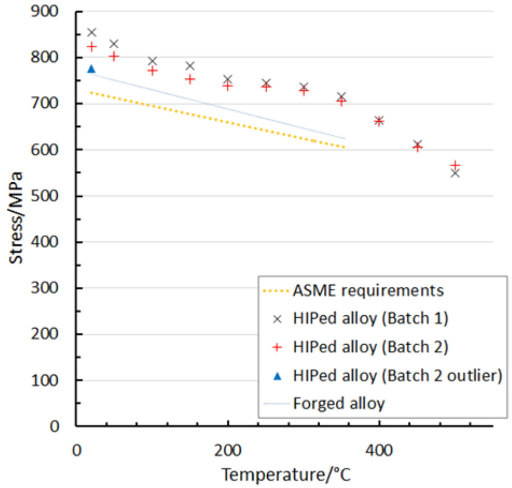


FIGURE 3: HIPED TEST SPECIMEN MEAN ULTIMATE TENSILE STRENGTH VERSUS FORGED MATERIAL

Reference: Proceedings of the ASME 2022 Pressure Vessels & Piping Conference PVP2022, July 17-22, 2022, Las Vegas, Nevada, USA, PVP2022-85077.

- Three batches of powder manufactured from different suppliers:
  Best toughness 66% of forged material.
  Worst toughness 21% of forged material.

Achieving Toughness

Issue is toughness! Only Charpy impact testing conducted.

Equivalence to forged material finally achieved with oxide stripping process applied.

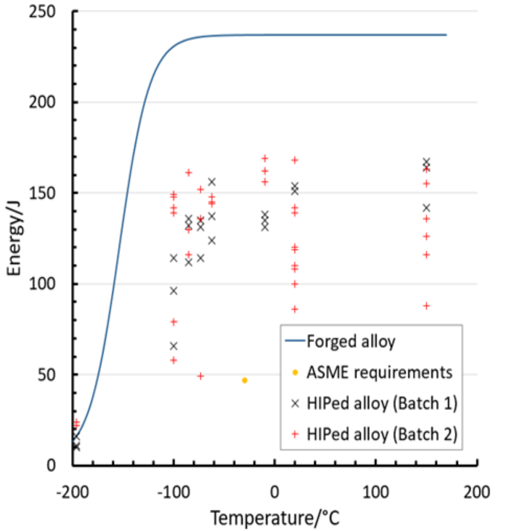


FIGURE 5: HIPED TEST SPECIMEN INDIVIDUAL CHARPY IMPACT TOUGHNESS VERSUS FORGED MATERIAL

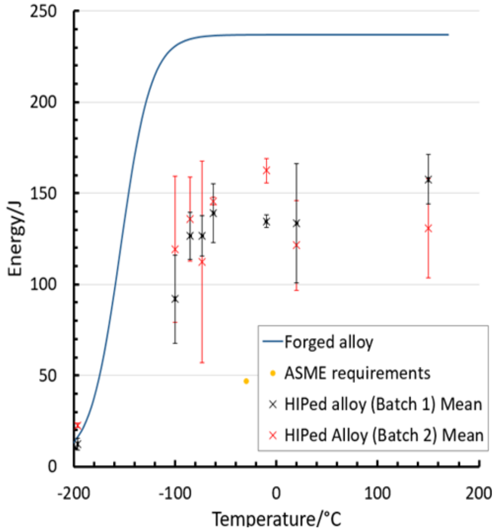


FIGURE 6: HIPED TEST SPECIMEN MEAN CHARPY IMPACT TOUGHNESS VERSUS FORGED MATERIAL

- Oxide stripping process applied – equivalent toughness to forged material achieved for first time! 250J

Reference: Proceedings of the ASME 2022 Pressure Vessels & Piping Conference PVP2022, July 17-22, 2022, Las Vegas, Nevada, USA, PVP2022-85077.

Capability Requirements for Deployment

- Large-scale HIP vessel – max dia in Europe = 1.6m – Project TITAN, circa 4m x 4M
- Large-scale EB chambers
- Improving toughness level –ideally equivalent to forged, oxygen control
- Full material test programme, e.g. fracture toughness, irradiation testing. ASME Code Case.
- 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.

Acknowledgments

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Department for Business, Energy & Industrial Strategy

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Thank you