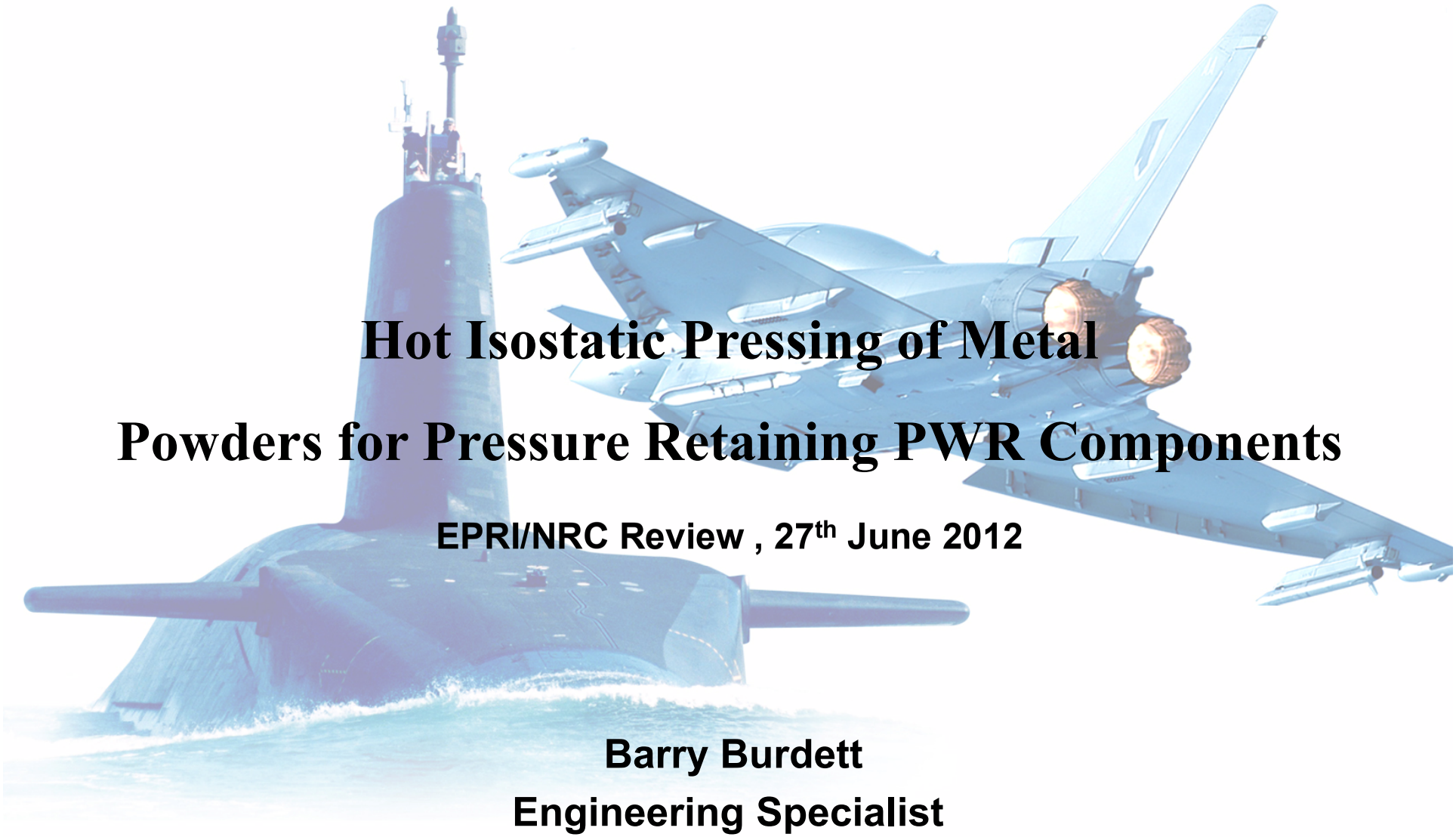


Hot Isostatic Pressing of Metal Powders for Pressure Retaining PWR Components

EPRI/NRC Review , 27th June 2012

Barry Burdett
Engineering Specialist
Rolls-Royce

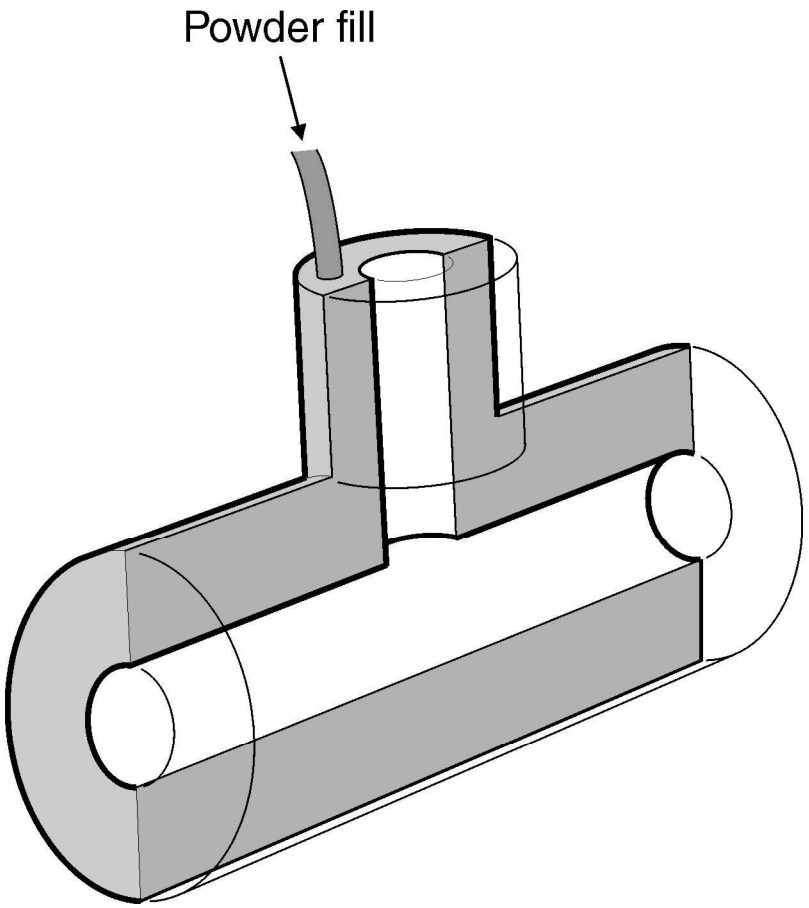
Prototype Testing 1998 - 2010

Type 316L ~ 1 - 2 tons

Type 304L ~ 1 ton

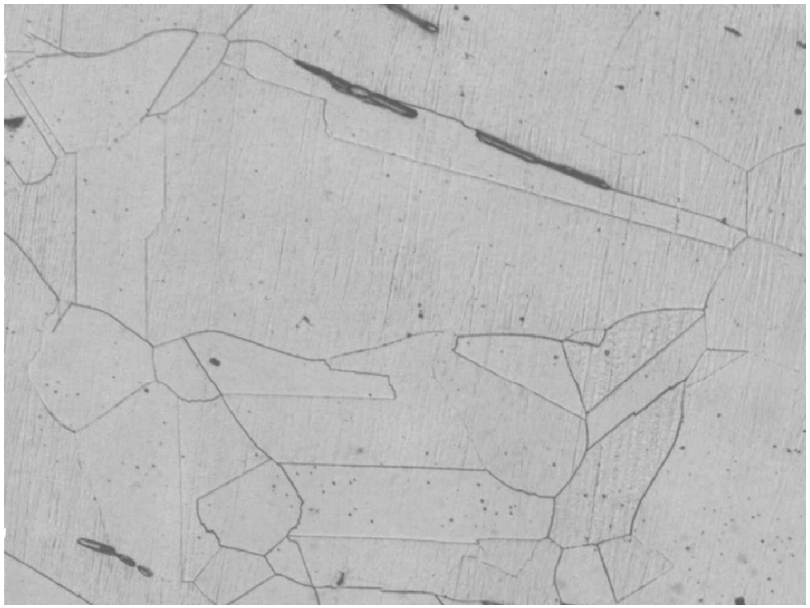
Hydrotested & destructively tested

Isotropic mechanical properties confirmed

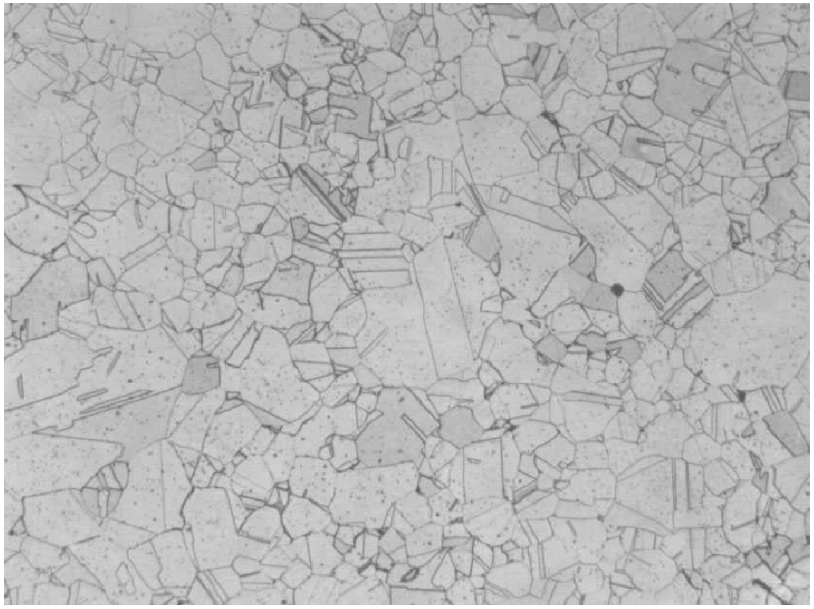


Metallurgical aspects

Type 316L structures (x100)

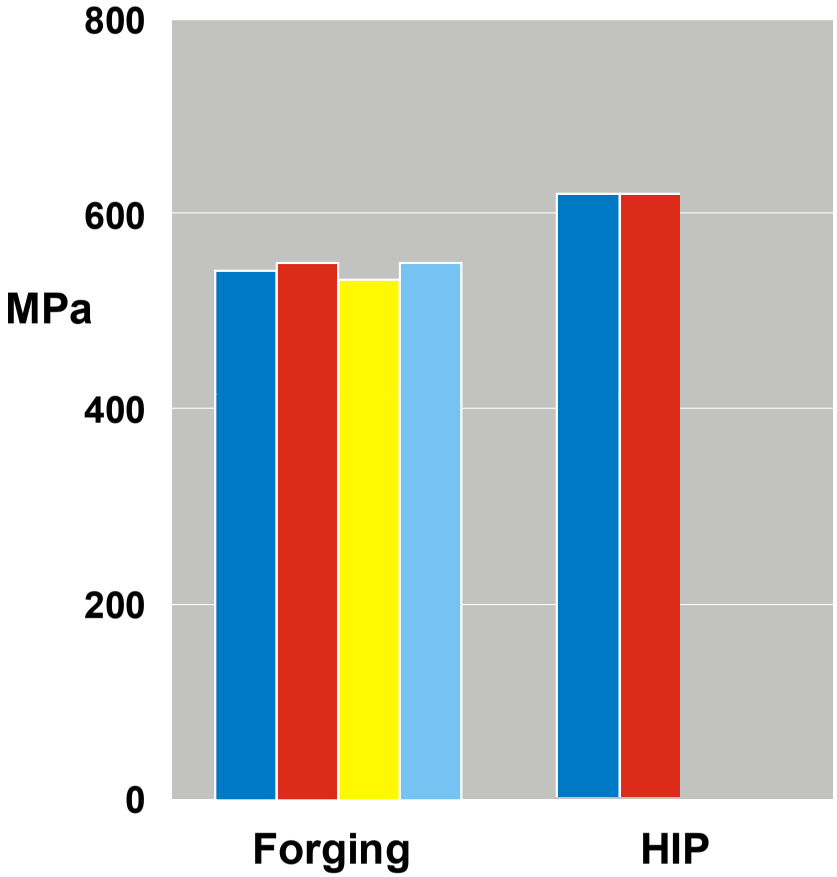


Forging (ASTM No. 2)

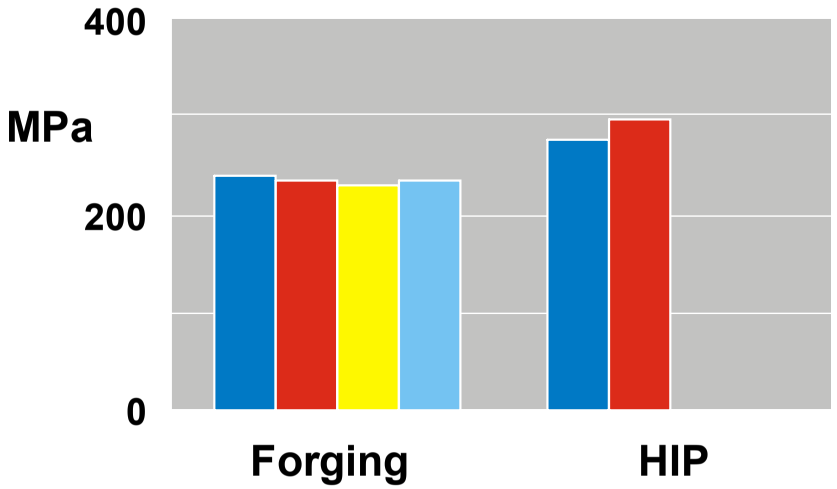


HIPped powder (ASTM No. 5)

Previous forging experience



Ultimate Tensile Strength (RT)



Mechanical Properties
0.2 Proof Stress

Corrosion testing ML6846 June 1999

- ASTM G36-94 ($MgCl_2$)
  - Transgranular Stress Corrosion Cracking

- ASTM G35-88 (Wackenroder's Solution U Bend)
  - Intergranular Stress Corrosion Cracking

- ASTM G78-95 (Boiler Water Chemistry)
  - Crevice Corrosion testing

- ASTM G48-97 ($FeCl_3$ Solution)
  - Chloride Pitting Resistance Test

- ASTM A262-93 (Oxalic Acid (A), Acidified Cu_2SO_4 (E))
  - Detection of Susceptibility to Intergranular Attack

Corrosion testing

- ASTM G36-94 ($MgCl_2$)

- Transgranular Stress Corrosion Cracking

Material 316L	Average time to Failure (hours)	Number of Tests
HIP	20	3
HIP (Sensitised)	20	3
Wrought	15	3
Wrought (Sensitised)	15	3

Sensitisation Treatment- 680°C for 4 hours

Corrosion testing

- ASTM G35-88 (Wackenroder's Solution U Bend)

 - Intergranular Stress Corrosion Cracking

No cracking observed in HIP or wrought product after 25 hours exposure under binocular inspection or metallographic sectioning

Corrosion testing

- ASTM G78-95 (Boiler Water Chemistry)

- Crevice Corrosion testing

No sign of brown staining or corrosion after three months exposure

Corrosion testing

- ASTM G48-97 ($FeCl_3$ Solution)

- Chloride Pitting Resistance Test

Material 316L	Average pit depth (μm)	Weight loss (%)	Number of Tests
HIP	513	0.1	3
HIP (Sensitised)	1983	4.1	3
Wrought	524	1	3
Wrought (Sensitised)	958	18.3	3

Sensitisation Treatment- 680°C for 4 hours

Corrosion testing

- ASTM A262-93 Practice A (Oxalic Acid)

- Detection of Susceptibility to Intergranular Attack

Discontinuous grain boundary ditching was observed on both wrought and HIP sensitised material

Both wrought and HIP sensitised specimens exhibited enhanced attack on some cut faces. This is considered to be due to residual cold work in these regions that has driven carbide precipitation

Corrosion testing (Recommended by Regulator)

- ASTM A262-93 Practice E (Acidified Cu_2SO_4 for 24 hours)
  - Detection of Susceptibility to Intergranular Attack
- Section from TIG welded wrought to HIP Pipework
- No cracking observed on face bend and microsections (3 off)
- EPRI Testing of Type 316L to Practice A and E successful

EAC testing

- Polarisation testing in primary and secondary water chemistries failed to initiate intergranular stress corrosion cracking in HIP or wrought material

- Slow Strain Rate Testing (SSRT)

  Conducted in 2m NaOH with overpotential:-

  HIP material performed as well or slightly better than wrought- crack growth rates in HIP samples were typically 50- 75% of those in wrought material

Additional EAC testing

- Supplementary SSRT in phosphate solutions has shown equivalent behaviour in HIP 316L

Elimination of Welded Joints

- **Many service problems directly attributable to the presence of a weld due to any one or combination of :**
  - **Welding Residual Stress**
  - **Change in local microstructure**
  - **Introduction of Weld Defects**
- **HIPped product has potential for fewer welded connections- substantial savings in costs of pipework manufacture**
- **Elimination of welds is beneficial, removes potential problem regions, leading to improved structural integrity of the component**

Regulator position

- UK Safety & Reliability Directorate (SRD) already supportive of powder HIPping following internal review

- SRD have endorsed the mechanical and corrosion testing outputs included in component safety justifications

Corrosion testing summary

- General corrosion and environmentally assisted cracking tests have clearly demonstrated that HIP powder Type 316L material has equivalent or slightly better corrosion resistance than wrought material

- Improvements in corrosion behaviour are considered to be due to the low level of inclusions and uniform microstructure in HIP powder product.