Cost effective fabrication of a fail-safe first wall

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Outline

- Introduction
- Basic Diffusion Weld Studies
  - Surface Processing
  - Surface Contamination
  - HT Creep under Pressure
- Problem Analysis
- Possible Solutions & Recommendations
- Conclusions
First Wall Fabrication: How ...?
Fabrication/Production Criteria

- **Compatibility with industrial environment**
  - Applicability of standard fabrication processes → mass fabrication
  - Robustness against environmental influences (corrosion, rough handling, storage, ...)
  - Tolerant against scattering of process parameters

- **Efficiency**
  - Costs
  - Recourses

- **Safety/Reliability**
  - Dimensional Accuracy
  - Easy Quality Assurance
  - Reproducibility
**General Fabrication Routes**

- **Casting**
  - In principle, the complete U-bended FW could be fabricated.
  - Draw-backs: The impurity levels of the Eurofer alloy would be increased (higher activation!) and voids/bubbles cannot be excluded.

- **Machining**
  - The only possible way would be ECM, EDM, or broaching. But there is a strict limitation of the channel length.
  - Draw-backs: It is difficult to fabricate the required initial holes (further length restrictions!?).

- **Powder Metallurgy**
  - Route: (1) Powder compaction, (2) encapsulation, (3) HIP
  - (A) embedding of U-bended tubes
  - (B) embedding of straight removable rods/tubes followed by bending the FW

- **Solid State Welding**
Assessment of Fabrication Routes

Casting

- NOT tested yet!
- Relatively expensive due to complicated mold and filler fabrication as well as filler removal
- Material degradations are likely

Machining

- No solution available yet → Development of suitable ECM or other process necessary!
- Therefore, EXPENSIVE
- NO mass production

Powder Metallurgy

- Established in industry
- Extensive encapsulation for embedded tubes necessary
- Severe material degradation: EMBRITTLEMENT!
Solid State Welding

Diffusion Welding (1st step: low pressure with closed channels)

- Weld pressure by HIP
- Uniaxial pressing

WITH encapsulation
WITH pressure plates

R&D since 1996
- E. Rigal, DEM, CEA
- G. Reimann, IMF III, KIT
- A. von der Weth, H. Kempe, IMF II, INR, KIT
- M. Rieth, B. Dafferner, IMF II, KIT
- Kawasaki Ind., Japan

Diffusion Welding (2nd step: high pressure with open channels)

Open channels after 1st step
Laser welding stripes on top of channels, then DW 2nd plate
(1) Diffusion Welding: HIP & Plates

**HIP & Plates**

- **TZM Plate**
  - **Uniaxial Pressure Induction**
  - **Cooling Channels**
  - **Degassing Vent**

**Standard Casing Sheet Material** (e.g. SS 304) with vacuum tight TIG welds and vents for evacuation
(2) Diffusion Welding: Self-Encapsulation

closed cooling channels

circumferential EB weld, evacuation automatically by EB welding chamber

pressure from all directions
Basic Studies

1. Standard Surfaces
2. Surface Treatment
3. Fixing
4. EB-Welding (vacuum tight)
Basic Studies: Surface Fabrication

Diffusion Weld Samples and Charpy Specimen Fabrication

Vacuum tight EB weld

44 mm

25 mm

12.5 mm

25 mm

Diffusion Weld Samples

Charpy Specimen Fabrication

25 MPa, 1050 °C, 2 h

7 different surfaces fabricated with different tools
Surfaces 8, 10, and 12 lead to worse properties compared to the base material!

**Why?**

Surface Fabrication: Test Results

![Graph showing surface fabrication test results](image-url)

- **Base Material**
- Surface 4
- Surface 5
- Surface 7
- Surface 8
- Surface 10
- Surface 11
- Surface 12

**Energy, J**

**Temperature, °C**
Fabrication: Surface Roughness

Effect of different milling parameters on surface quality

Surface 5

Surface 8
Surface Fabrication: Microstructure

Metallography of Diffusion Weld Lines

Surface 12

Surface 7

holes in the bond plane
## Basic Studies

### Surface Contamination Study

<table>
<thead>
<tr>
<th>Surface</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface 20:</td>
<td>Reference fabrication (dry milling with optimised parameters and immediate sealing by EB-welding)</td>
</tr>
<tr>
<td>Surface 21-24:</td>
<td>1, 2, 3, 14 days at 70% relative humidity before sealing</td>
</tr>
<tr>
<td>Surface 25:</td>
<td>Surface protection with oil, 14 days at 70% relative humidity, cleaning with isopropanol before sealing</td>
</tr>
<tr>
<td>Surface 26:</td>
<td>Surface protection with oil, 14 days at 70% relative humidity, cleaning with soap before sealing</td>
</tr>
<tr>
<td>Surface 28:</td>
<td>Surface fabrication with optimised parameters, but milling with industrial standard coolant, just dried before sealing</td>
</tr>
<tr>
<td>Surface 29:</td>
<td>Same as Surface 28, but cleaning with isopropanol before sealing</td>
</tr>
</tbody>
</table>
Basic Studies: Surface Contamination

Diffusion Welding
1150 °C / 2 h, 25 MPa

Oxidation at 70 % rel. Hum.

Charpy Energy, J
-150 -100 -50 0 50
Test Temperature, °C

Surface 20 ➔ Standard Surface
Surface 21 ➔ 1 day oxidation
Surface 22 ➔ 2 days oxidation
Surface 23 ➔ 3 days oxidation
Surface 24 ➔ 14 days oxidation
Base Material
Basic Studies: Surface Contamination

Diffusion Welding
1150 °C / 2 h, 25 MPa

Contamination & Cleaning

- 14 days oxidation
- WD40, 14 d oxid., isopropanol
- WD40, 14 d oxid., soap
- cooling fluid, no cleaning
- cooling fluid, isopropanol

Charpy Energy, J

-150 -100 -50 0 50

Test Temperature, °C

Base Material
The micrographs of all weld interfaces show no weld line. That is, from a micro-structural point of view, the diffusion welds (performed at 1150 °C, under 25 MPa, for 2 hours) are all perfect, regardless of the fabrication history. (The Charpy test results, however, demonstrate that there are small differences, anyway.)
Basic Studies: High Temperature Creep

Creep tests under pressure at 1000 °C

Diffusion Welding
1050 °C / 2 h, 25 MPa

Compression, %

Time, h

5 MPa
10 MPa
15 MPa
20 MPa
Know-how transfer to mock-up fabrication: Theory

7 MPa HIP, bilinear material model
Know-how transfer to mock-up fabrication: Reality

1. Long periods between surface fabrication (dry milling) and EB welding (vacuum sealing) → **7 days**
2. Minimum available HIP pressure to high → **10 MPa** instead of **7 MPa**
Effects of High Temperature Creep: Dimensional Inaccuracies

Cross Direction Profile

Depth, mm

Distance, mm

Longitudinal Profile

Depth, mm

Distance, mm
Effects of High Temperature Creep: Material Flow

14 MPa

19 MPa
Better Results with Lower Aspect Ratio

14 MPa

19 MPa

27 MPa

32 MPa
Problem Analysis

- Increase tolerance of surface conditions
- Improvement of weld properties (esp.: fracture toughness)
  → HIGH TEMPERATURE + HIGH PRESSURE

- Better shape stability, dimensional accuracy
  → LOW TEMPERATURE + LOW PRESSURE
State of the Art FW Fabrication Methods

1. Fabrication of flat FW plates with internal cooling channels by different methods:
   • CEA: closing of channels by EB, then HIP
   • CEA: rectangular tubes between two plates
   • CEA: tubes forming and HIP between two grooved plates
   • KIT: variable temperature and pressure by HIP or UP

2. Bending of the plates

   Pros and cons are well known

   Two additional methods with high accuracy and tolerance against process variations
Stabilization of Cooling Channels with Inlets of Stainless Steel

Standard fabrication of the channel structure

Dry milling of the diffusion weld surfaces
Cooling Channels with Stainless Steel Inlets

Stainless steel inlets to stabilize channels

$\text{Y}_2\text{O}_3$ as separating agent

EB welds
High Pressure HIP with Stabilized Channels

Before and after High Temperature – High Pressure HIP
Stabilization of Cooling Channels

High Accuracy of the cooling channel cross-section (after removal of stabilizers)

No Creep Deformation
Fail-safe First Wall Fabrication

**Fabrication Processes:**

1. Bending of 2 plates
2. Milling of grooves into the plates
3. Fabrication and bending of pipes
4. Assembling plates and pipes
5. Sealing with EB welds
6. High temperature - high pressure HIP
Step 1: Bending of two plates

industrial standard cold bending process of softened Eurofer plates (after perlitzation)
Step 2: Milling of grooves

standard industrial milling tools and environment
Step 3: Fabrication and bending of pipes

Commercial fabrication processes available:

• Pipe production by TIG or Laser welding.
• Bending with given dimensions
• Necessary half-finished product: steel stripes (e.g. 1mm x 40mm x 100m)

Edelstahlrohre auf höchstem Niveau

Wuppermann fertigt auf modernen, leistungsfähigen Anlagen Edelstahlrohre mit besten Oberflächen als Basis für hochwertige Komponenten.
Step 4: Assembling plates and pipes

After storage of several days without special cleaning treatment
Step 5: Sealing with EB welds
Step 6: HIP (1050°C, 100MPa, 2h)
Microstructure near the weld surfaces
Conclusions: Which criteria are fulfilled?

- **Compatibility with industrial environment**
  - Applicability of standard fabrication processes
  - Robustness against environmental influences (corrosion, rough handling, storage, ...)
  - Tolerant against scattering of process parameters

- **Efficiency**
  - Costs
  - Resources

- **Safety/Reliability**
  - Dimensional Accuracy
  - Easy Quality Assurance
  - Reproducibility
  - Inherent Fail-safe Design
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