Diffusion bonding Tests

Anastasia Xydou

Many thanks for their valuable contribution to: S. Lebet, A. Perez Fontenla, D. Glaude.
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The aim of the experimental testing program on the diffusion bonding process is to study the influence of the applied pressure on:

- The **quality** of the final bonded joint
- The **residual deformations** at the end of the heating process

In parallel it is important to develop a theoretical model to predict the thermo-mechanical deformations.
**Pads material:** graphite;  
**Pads diameter:** Ø48 mm and Ø52 mm,  
**Quantity for each pressure:** 8 copper disks  
4 stacks

**SIMPLE DISKS:** Ø = 48 mm

**RF DISKS:** Ø = 80 mm

**Pads material:** graphite;  
**Pads diameter:** Ø85 mm,  
**Quantity for each pressure:** 4 copper disks  
2 stacks

**Graphite 2191**  
$T_m = 3650 \, ^\circ C$  
$CTE = 0.42 \times 10^{-5}/^\circ C$
Workflow

**Degreasing**

**Etching (SLAC)**

**Dimensional control** ($\Phi$, flatness, thickness)

**Diffusion bonding** (pressure, $H_2$, 1040 °C)

**Degreasing**

**Dimensional control** ($\Phi$, flatness, thickness)

**Ultrasound test**

**Cutting**

**Crossing grain analysis**

**Etching**

CMM (accuracy 0.3 μm; repeatability 0.1 μm)

Disks transferred to the furnace for the bonding cycle.

**Ultrasound testing**
Heating cycle

- **Vacuum at 10^{-5} mbar**
- **H₂ at 20-35 mbar**
- **Heating up to 1298 K**
- **Bonding:**
  - T = 1298 K
  - t = 5400 sec
- **Insertion of N₂ and fast cooling for 3600 sec**
- **Slow cooling starts at 750 °C up to room temperature**
## Pictures of the assemblies

### Simple disks

<table>
<thead>
<tr>
<th>Pressure [MPa]</th>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28</td>
<td>51.6</td>
</tr>
<tr>
<td>0.1</td>
<td>18.4</td>
</tr>
<tr>
<td>0.06</td>
<td>11.1</td>
</tr>
<tr>
<td>0.04</td>
<td>7.4</td>
</tr>
</tbody>
</table>

### RF disks

<table>
<thead>
<tr>
<th>Pressure [MPa]</th>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28</td>
<td>114.2</td>
</tr>
<tr>
<td>0.1</td>
<td>40.8</td>
</tr>
<tr>
<td>0.06</td>
<td>24.5</td>
</tr>
<tr>
<td>0.04</td>
<td>16.3</td>
</tr>
</tbody>
</table>
Theoretical background: Diffusion Creep

At high temperature and low stresses, deformation of fine-grained materials proceeds by:
✓ accommodating grain-boundary sliding
✓ transport of matter, diffusion creep.

Transport of matter occurs by lattice diffusion: **Nabarro-Herring creep**

Transport of matter occurs by grain-boundary diffusion: **Coble creep**
Theoretical background: Diffusion Creep

Grain boundary diffusion (Coble creep)

\[ \dot{\varepsilon}_{Co} = A_{Co} \frac{\delta D_{gb} \Omega \sigma}{d^3 kT} \]

Coble creep (\( T < 0.7 \cdot T_m \))

Vacancies flow along the grain boundaries

Nabarro-Herring creep (\( T > 0.7 \cdot T_m \))

\[ \dot{\varepsilon}_{NH} = A_{NH} \frac{D_1 \Omega \sigma}{d^2 kT} \]

Lattice diffusion (Nabarro-Herring creep)

Vacancies flow through the grains

Parameter | Value | Units | Description
--- | --- | --- | ---
\( A_{Co} \) | 150/\( \pi \) | - | Coble's constant
\( \delta D_{gb} \) | \( D_b \cdot e^{-\left(\frac{Q_b}{R \cdot T}\right)} \) | m\(^3\)/s | Coefficient for grain boundary diffusion
\( D_b \) | 5e-15 | m\(^3\)/s | Pre-exponential
\( Q_b \) | 104e3 | J/mol | Activation energy
\( R \) | 8.314 | J/(K·mol) | Gas constant
\( \Omega \) | 1.182e-29 | m\(^3\) | Atomic volume
\( d \) | ... | m | Grain size
\( k \) | 1.3806505e-23 | J/K | Boltzmann's constant
\( T \) | ... | K | Absolute temperature

Parameter | Value | Units | Description
--- | --- | --- | ---
\( A_{NH} \) | [12-40] | - | Nabarro-Herring's constant
\( D_1 \) | \( D_0 \cdot e^{-\left(\frac{Q}{R \cdot T}\right)} \) | m\(^2\)/s | Coefficient for lattice diffusion
\( D_0 \) | 20e-6 | m\(^2\)/s | Pre-exponential
\( Q \) | 197e3 | J/mol | Activation energy
\( R \) | 8.314 | J/(K·mol) | Gas constant
\( \Omega \) | 1.182e-29 | m\(^3\) | Atomic volume
\( d \) | ... | m | Grain size
\( k \) | 1.3806505e-23 | J/K | Boltzmann's constant
\( T \) | ... | K | Absolute temperature

* Values taken from the Deformation-Mechanism Maps, The Plasticity and Creep of Metals and Ceramics, by Harold J Frost, Dartmouth College, USA, and Michael F Ashby, Cambridge University, UK.
Comparison Between experimental and theoretical results

Simple disks

Analytical solution

Considering the uniaxial compression at the Generalised Hooke’s law…

\[ \varepsilon_y = \frac{\sigma_y}{E} \]
\[ \varepsilon_X = -\nu \varepsilon_y \]

Deformation of external diameter

\[ \Delta \phi = \phi \cdot \nu \cdot (\sum_0^{0.7 \cdot T_m} \varepsilon_{Co} \cdot T \cdot \Delta t + \sum_{0.7 \cdot T_m}^{T_{max}} \varepsilon_{NH} \cdot T \cdot \Delta t) \]

Deformation of thickness

\[ \Delta h = (\sum_0^{0.7 \cdot T_m} \varepsilon_{Co} \cdot T \cdot \Delta t + \sum_{0.7 \cdot T_m}^{T_{max}} \varepsilon_{NH} \cdot T \cdot \Delta t) \cdot h \]

Where:
- \( T_{max} \) = bonding temperature
- \( T_m \) = melting temperature of copper (1356 K)
- \( \Delta \phi \) and \( \Delta h \) is the variation of the diameter and of the thickness respectively
- \( \nu \) is the Poisson ratio
- \( \varepsilon_{Co} \) and \( \varepsilon_{NH} \) are the strain rate predicted by Coble and Nabarro-Herring respectively.
- \( \Delta t \) is the time step used for the discretization of the curve.
Comparison Between experimental and theoretical results

**RF disks**

**Finite Element Analysis**

Using both formulas from Coble and Nabarro-Herring the *creep constant for the full Heating cycle* is calculated:

\[ C_{\text{creep}} = \frac{A \cdot D \cdot \Omega}{d^n \cdot k \cdot T} \]

*where n = 2 or 3*
**Aim:** the aim of the development of the FEA model is to compare the outcome of the simulations with the experiments.

- **Nonlinear material model**
- **Material properties as function of the temperature** (20 - 1040 °C): Density, Isotropic Elasticity (Young’s Modulus), Isotropic Thermal Conductivity, Specific Heat, Thermal expansion
- **Symmetry:** Symmetric to both lateral faces
- **Contacts:** Frictional contacts in the interface of the disks
- **Boundary conditions:** Simply supported on the lower face
- **Loads:** Pressure value on the upper face
- **Thermal condition:** thermal cycle

---

A: applied pressure, B: zero displacement on the z axis.

Element size 0.8 mm
Nodes: 249,247, Elements :64979

Displacement result of the x axis
Ultra-sound results: Simple disks

Difference of the interface flatness - Applied pressure

100% successful bonded joint in all pressure cases
Ultra-sound results: RF disks

Difference of the interface flatness - Applied pressure

Difference of the interface flatness - Percentage of the bonded joint
Conclusions

• The theoretical with the experimental results are in good agreement especially for the RF disks.

• “Ideal” pressure:
  i. At the pressure values 0.04 and 0.06 MPa; the permanent deformations are low and are comparable with the case were no pressure has been applied. Where, at 0.1 MPa pressure the final deformations start to be considerable. This drives to the conclusion that at low pressure the temperature effect dominates when at higher pressure values the pressure sum up with the temperature.

  ii. The bonded joint is not only affected by the pressure; the difference in the flatness of the faying surfaces seems to be the major suspect for an efficient bonded joint.

• The theoretical model created with ANSYS describe the phenomenon of diffusion creep and is able to predict the deformations in longer Accelerating Structures.
EXTRA
Simple disk drawing

NOTES:
1. Dimensions in this drawing are at 20°C in free state.
2. Lubricant based on Chlorine or Sulfur should be avoided.
3. No polishing is allowed.
4. No deformations admissible due to stress release or shocks during and after machining.
5. Each disk must be marked as showed below
   S(No. 00, 01...06)
   ex. First disk - S00, second disk - S01 etc.
6. The product must be individually packed inside a main delivery box.

<table>
<thead>
<tr>
<th>ROUND BARS</th>
<th>1</th>
<th>44.09.47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-C6</td>
<td></td>
<td>558.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>POS.</th>
<th>MAT.</th>
<th>OBSERVATIONS</th>
<th>REF.</th>
<th>CERN</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 2768-fH</td>
<td>sqrt</td>
<td>Ra 1.6</td>
<td>✓</td>
<td>ISO 13715</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

CLIC Test (Lab.) - Accelerating Structure

BONDING TESTS
SAMPLE DISK

SCALE: 2:1

DES/ENG: A SOLOMON
CONTROLLED: F. ROSSI
MADE/ENG: G. RODONE
APPROVED: 2012-07-17

CAD Document Number: ST0435356_02
REPLACES

PROJECT ENGINEER INFORMATION

CLIATLAS0186
RF disk drawing

Diamond stylus reference line
the depth of 0.005mm
tolerance ±0.001 mm

Front view
Scale: 2:1

NOTES:
1. Dimensions in this drawing are at 20°C in free state.
2. Lubricant based on Chlorine or Sulfur should be avoided.
3. No polishing is allowed.
4. No deformations admissible due to stress release or shears during and after machining.
5. To be protected against scratches and marks of any nature.
6. The product must be marked with present drawing number, column N of the table, example CLIAAS1201081.
7. The product must be individually packed inside a main delivery box.
8. * * Evaluation length is equal to ±0.5μm.
9. Roughness is according to ISO 1302.
10. The turning of the iris is extended until the beginning of the damping waveguide (specified by —— shown in Detail C).

CLIAAS120108 2 A 18 25-Nov-14
Material properties as function of temperature: OFE copper

**DENSITY**

\[ \rho \text{ [ton/mm}^3\text{]} \]

**YOUNG'S MODULUS**

\[ E \text{ [MPa]} \]

**THERMAL EXPANSION**

\[ \alpha \text{ [10}^{-6} / ^\circ\text{C]} \]

**THERMAL CONDUCTIVITY**

\[ \lambda \text{ [W/(m*K)]} \]

**SPECIFIC HEAT**

\[ C \text{ [mJ/(ton*K)]} \]

**ASM HandBook - Vol 02** - Properties and Selection Nonferrous Alloys and Special-Purpose Materials
Calculations

\[ \varepsilon_x = \Delta L/L = \Delta \phi/\phi \]
Where

\[ \varepsilon_y = \dot{\varepsilon}_y/\Delta t \]
Where

\[ \dot{\varepsilon}_{y,co} = A_{co} \frac{\delta D_{gb} \Omega \sigma_L}{d^3 kT} \]

\[ \dot{\varepsilon}_{y,NH} = A_{NH} \frac{D_1 \Omega \sigma_L}{d^2 kT} \]

\[ \Delta \phi = \phi \cdot v \cdot \left( \sum_{T<0.7 \cdot T_m} \dot{\varepsilon}_{co}(T) \cdot \Delta t + \sum_{T>0.7 \cdot T_m} \dot{\varepsilon}_{NH}(T) \cdot \Delta t \right) \]
Tooling for alignment
Dimensional Control

Before Bonding

After Bonding
<table>
<thead>
<tr>
<th>N</th>
<th>FLATNESS top (plane A)</th>
<th>FLATNESS bottom (plane B)</th>
<th>FLATNESS top (plane A)</th>
<th>FLATNESS bottom (plane B)</th>
<th>dif(mm)</th>
<th>dif(um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04 Mpa</td>
<td>0.0129</td>
<td>0.0149</td>
<td>12.9000</td>
<td>14.9000</td>
<td>0.01410</td>
<td>14.10</td>
</tr>
<tr>
<td>0.04 Mpa</td>
<td>0.0008</td>
<td>0.0006</td>
<td>0.8000</td>
<td>0.6000</td>
<td>0.00790</td>
<td>7.90</td>
</tr>
<tr>
<td>0.06 Mpa</td>
<td>0.0128</td>
<td>0.0138</td>
<td>12.8000</td>
<td>13.8000</td>
<td>0.00570</td>
<td>5.70</td>
</tr>
<tr>
<td>0.06 Mpa</td>
<td>0.0059</td>
<td>0.0066</td>
<td>5.9000</td>
<td>6.6000</td>
<td>0.00360</td>
<td>3.60</td>
</tr>
<tr>
<td>0.1 Mpa</td>
<td>0.0015</td>
<td>0.0013</td>
<td>1.5000</td>
<td>1.3000</td>
<td>0.00160</td>
<td>1.60</td>
</tr>
<tr>
<td>0.1 Mpa</td>
<td>0.007</td>
<td>0.0071</td>
<td>7.0000</td>
<td>7.1000</td>
<td>0.00810</td>
<td>8.10</td>
</tr>
<tr>
<td>0.28 Mpa</td>
<td>0.0129</td>
<td>0.0135</td>
<td>12.9000</td>
<td>13.5000</td>
<td>0.01200</td>
<td>12.00</td>
</tr>
<tr>
<td>0.28 Mpa</td>
<td>0.0015</td>
<td>0.0012</td>
<td>1.5000</td>
<td>1.2000</td>
<td>0.00340</td>
<td>3.40</td>
</tr>
<tr>
<td>no pressure</td>
<td>0.0069</td>
<td>0.0068</td>
<td>6.9000</td>
<td>6.8000</td>
<td>0.00190</td>
<td>1.90</td>
</tr>
</tbody>
</table>
MD simulations

Count_ATOMS

Timesteps

addatoms

0 1000 2000 3000 4000 5000

0 5000

0 10000 15000

0 16000

countadd40
countadd10