ANALYSIS OF THIN METAL FILMS & CERAMIC SURFACE COATINGS TO ENHANCE ADHESION FOR AEROSPACE MATERIALS

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Importance of work

*Adhesion between alumina ceramic and metal structure is not better. Delamination occurs.

*Nuclear reactor and furnaces have ceramic layer inside and outside is metal plates
*Better bonding is necessary for metal plate and ceramic to work in high temperature

*Aerospace or aircrafts engine blades layers of ceramic material is used to make the blades metal high temperature resistant
*Better bonding between these two are necessary.
Research Objectives

* Bonding strength between metal and ceramic coatings

* Structural Integrity of coated surface loading: tensile, cyclic fatigue, flexure and torsional

* Increased understanding in the coating and bonding phenomena
How this work is important for NASA project?

*Better Adhesion will be necessary between materials sandwich structure.*
*Aerospace or aircrafts engine a leading research part of NASA and more research involvement is needed*
*Manufacturing and sintering of metal components related to NASA project*
Test fixture for pull test

ASTM C 633–01
ASTM C 633-79
Substrate fixture
Adhesive bonding agents

**Metallic and metallic matrix coating (55MPa):**
CONAP 1222,
CONAP Inc.

**Ceramic or metallic (28MPa):**
Bondmaster M666, Bondmaster M777
Pittsburgh Plate Glass Co.,
Adhesive Products Div., 225 Belleville Ave., Bloomfield, NJ 07003

Epon 911F,
Shell Chemical Co.,
Adhesives Dept., P.O. Box 831, Pittsburgh, CA 94565.

Armstrong A-12,
Armstrong Products Co.,
Argonne Rd., Warsaw, IN 46580.

Hysol XA7-H368 Grey
Hysol Inc.,
Olean, NY 14760
Features

Dogbone sample

Substrate metal

Features
(square, cylindrical, triangle etc.)

APS (Atmospheric Plasma Spray)
ceramic coating
Grooved features

APS ceramic coating
Ideas

*Different features will show different adhesion/bonding capability with ceramic in mechanical testing (tensile, compressive, fatigue, 3-point bend test etc.)*
*Curves will be found from mechanical testing for different metals adhesion with ceramic*
*Best material bonding with ceramic will be ideal for the purpose*
Drawing

1 inch = 2540000 microns

1000 microns x 1000 microns

AutoCAD drawing
Works involve

- Mask fabrication
- Substrate preparation
- Resist application and removal
Thin metal film manufacturing processes

- Metal sputter deposition
- Atmospheric Plasma spray (APS)
- High Temperature Vacuum Tube Furnace (HTVTF)
Applications of HTVTF

• very useful furnace for sintering operation and heating up thin as well as thick engineering materials.
• widely used for processing materials (such as ceramics), developing new materials and sintering various types of material under vacuum or gaseous condition.
• Using a vacuum technique Y123 metal films were obtained on CeO$_2$-buffered sapphire substrates by Yamaguchi et al. (2006).
• The production of sodium carbonate via flash calcination of Turkish trona ore is described by Demirbas, 2002.
• Method has been developed by Zhang et al. (1997) for the determination of antimony, arsenic, bismuth, selenium, tellurium and tin under subatmospheric pressure in an electrically heated quartz tube furnace.
• Several biomaterials have been pyrolyzed by DeLuca et al. (1993) who used a resistively heated tube furnace.
• Strumpf et al. (1988) summarizes the use of ceramic heat pipe recuperators for high-temperature heat recovery from industrial furnaces.
• Determinations of gases in metals is described in detail by Lounamaa et al. (1963).
• The metallurgical processing of zircaloy for reactor fuel pin cladding (each consisting of an array of tubes) in a high-vacuum furnace is described by Pissanetzky, 1980.
HTVTF showing different parts

- Model number GSL1600X, manufactured by MTI Corporation, USA
- Precision bench-top furnace
- MoSi$_2$ as heating element
- Can be heated up to 1600$^\circ$C (1872$^\circ$K, 2912$^\circ$F)
Operation of the furnace

• The ceramic vacuum tube is inserted into the furnace from back side and then the screw is tightened to fix the tube’s position with the holder of the furnace.
• The material that requires heating is placed at the middle of the tube. Porous cylindrical alumina ‘Blocks’ are placed inside the tube at both ends.
• The tube ends are closed with vacuum cover and the heater is turned on.
• The air within the furnace and the tube, eventually heats up due to convection by the electric heater.
• The major portion of the heat will dissipate by natural convection to the air within the heater and the tube, while its minor portion conducts through the furnace to the lab temperature.
• The heat then conducts through the cylindrical inner wall of the tube and will dissipate to the air inside the tube.
## Design parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace length</td>
<td>550</td>
</tr>
<tr>
<td>Furnace width</td>
<td>270</td>
</tr>
<tr>
<td>Block length</td>
<td>130</td>
</tr>
<tr>
<td>Block radius</td>
<td>35</td>
</tr>
<tr>
<td>Air region length</td>
<td>270</td>
</tr>
<tr>
<td>Air region (inside furnace) width</td>
<td>35</td>
</tr>
<tr>
<td>Tube thickness</td>
<td>5</td>
</tr>
<tr>
<td>Tube inside radius</td>
<td>35</td>
</tr>
</tbody>
</table>
Previous works by researchers

• To develop the method for analyzing transient characteristics of the combined radiative and conductive heat transfer in the industrial furnaces, heat transfer in vacuum furnaces is numerically analyzed by Mochida et al. (1995). Fracture phenomena is neglected.
• Post-mortem failure analysis of a silicon-carbide tube that failed after cyclic operation in a vacuum furnace is analyzed by A.E. Segall, 2006. Results of the fractographic analysis and service history indicated - thermomechanically induced severe defects on the internal (heated) surface.
• High vacuum cylindrical furnace is described by Pissanetzky et al. (1981). Their results allow designing a high vacuum industrial furnace and optimization of its loads.
• Mathematical model was presented by Pissanetzky, 1980 and work is shown for the numerical simulation of heat transfer by radiation and conduction, however important phenomena involving natural convection have been neglected.
Actual & Fractured pipe
Modeling Concepts

The main objectives of simulations are to:

(i) study in detail all the physical phenomena that govern the operation of a HTVTF,
(ii) address the complex phenomena of fracture in HTVTF
(iii) pass air with different flow rates to find out critical thermal stress,
(iv) to study relaxation of the heat affected zone (HAZ) of the tube by inserting a small diameter copper pipe inside cylindrical block to redistribute the heat inside the furnace.
Symmetric model for Furnace

- symmetric model is chosen to save computation time
- symmetry existing for geometry, loads, and boundary conditions.
Meshing
## Constants and parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{Alumina}}$</td>
<td>Modulus of Elasticity of alumina</td>
<td>$3.5 \times 10^{11}$ Pa</td>
</tr>
<tr>
<td>$\rho_{\text{Alumina}}$</td>
<td>Density of alumina</td>
<td>$3900$ kg/m$^3$</td>
</tr>
<tr>
<td>$C_{p,\text{Alumina}}$</td>
<td>Heat capacity of alumina</td>
<td>$1050$ J/kg·°K</td>
</tr>
<tr>
<td>$\kappa_{\text{Alumina, furnace}}$</td>
<td>Thermal conductivity of alumina in furnace</td>
<td>$39$ W/m·°K</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Thermal expansion coefficient of alumina tube</td>
<td>$9.6 \times 10^{-6}$°K$^{-1}$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Poisson’s ratio of alumina</td>
<td>$0.33$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic Viscosity of air</td>
<td>$4.96 \times 10^{-5}$ Pa·s</td>
</tr>
<tr>
<td>$\rho_\infty$</td>
<td>Density of air at ambient temperature</td>
<td>$0.2679$ kg/m$^3$</td>
</tr>
<tr>
<td>$C_{p,\text{air}}$</td>
<td>Heat capacity of air</td>
<td>$1189$ J/kg·°K</td>
</tr>
<tr>
<td>$\kappa_{\text{air}}$</td>
<td>Thermal conductivity of air</td>
<td>$0.082$ W/m·°K</td>
</tr>
<tr>
<td>$T_{\text{heater}}$</td>
<td>Temperature of heater</td>
<td>$1872$ °K</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational acceleration</td>
<td>$9.8$ m/s$^2$</td>
</tr>
</tbody>
</table>
## Major Equations

\[
u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = g \beta (T - T_\infty) + v \frac{\partial^2 u}{\partial y^2}
\]

Natural convection equation  \hspace{1cm} Eq. (1)

\[\vec{\nabla} \cdot (\rho \vec{u}) = 0\]

Mass conservation equation  \hspace{1cm} Eq. (2)

\[\vec{\nabla} \cdot (-\kappa \vec{\nabla}T) + \rho c_p \vec{u} \cdot \vec{\nabla}T = 0\]

General heat transfer equation  \hspace{1cm} Eq. (3)

\[\sigma = E \alpha \Delta T\]

Thermal stress due to thermal expansion equation  \hspace{1cm} Eq. (4)
Results and Discussion

Temperature profile due to natural convection inside furnace without porous cylindrical alumina blocks
Temperature profile with cylindrical blocks and no inlet gas flow condition
Experimental and simulation result of inside temperature of tube between HAZs.
Temperature profile with inlet air flow rate condition of 5 ml/min
Temperature profile for the furnace while a small copper pipe is inserted inside the block.
Temperature profile with small dia copper pipe inside block
Thermal stress versus flow rate

![Graph showing thermal stress versus air flow rate with two lines representing 'without small dia pipe' and 'with small dia pipe'. The graph includes a dashed line indicating the maximum stress of alumina (55 MPa).]
Conclusion

• Mathematical models are developed to understand stress concentration of tube wall and HAZs of a HTVTF.
• Combination of thermal stress with temperature difference determine fracture region.
• Different air flow rates have been considered to find out critical thermal stress region inside vacuum tube and found 20 ml/min critical air flow rate without inserting small diameter pipe inside blocks.
• 1 mm small diameter copper pipe may be inserted inside first cylindrical block from left hand end of vacuum tube inlet to blow hot air of maximum 35 ml/min on HAZ-2 may protect from thermal stress inside the vacuum tube.
On Going Work:

*Ordered epoxies and metal rods needed for pull test
*More numerical analysis for adhesion issue
*CAMD: Micro-fabrication
References


MTI Corporation Inc. user manual, 2006, Richmond, CA-94804, USA.


Yamaguchi, I., Sohma, M., Tsukada, K., Kondo, W., Kamiya, K., Mizuta, S., Kumagai, T., Manabe, T., 2006, Preparation of high-Jc Y123 films on CeO2-buffered sapphire substrates by MOD using a low-cost vacuum technique, Physica C: Superconductivity, Volumes 445-448, 1, Pages 603-607.

Thank you !!!

Comments, Questions & Suggestions!