Low Thermal Diffusivity Investment Casting Molds using Cenospheres

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ABSTRACT

Control of the thermal properties of investment casting molds can be used to improve mold filing and control directional casting solidification. Experiments were performed to design a low thermal diffusivity investment casting mold through the use of hollow spherical refractory particles (cenospheres). The number of stucco layers in which the cenospheres were substituted for silica grain was an experimental variable in this study. The resulting shells were sintered and tests were performed to measure thermal and mechanical properties. Thermal diffusivity of cenosphere-stuccoed shell was determined by the inverse method mold to be 70% lower than silica-based shell molds. Decreases in thermal properties were achieved without sacrifice of strength in fired condition. Design applications of molds made using this material are discussed.

KEYWORDS: Low thermal diffusivity, investment casting, cenospheres.

INTRODUCTION

Investment shell molds have been widely used to produce near-net shape castings, especially with complex geometry and thin sections. Liquid metal filling and solidification during casting in a ceramic shell mold is strongly dependent on the thermal properties of the ceramic molds. Melt superheat and latent heat from solidification of thin-walled investment castings are mainly accumulated within the shell. In this unsteady state condition, heat transfer from casting into the mold is mainly controlled by the value of thermal diffusivity ($\alpha$) of ceramic mold:

$$\alpha = k/\rho C_p$$

Eqn. 1

where: $k$ is thermal conductivity ($W/(m\cdot K)$), $\rho$ is density ($kg/m^3$), and $C_p$ is specific heat capacity ($J/(kg\cdot K)$).

For example, riser efficiency could be improved by designing a shell mold with local areas of different properties, incorporating an adjustment of thermal diffusivity. Thermal diffusivity can be controlled by: (i) bulk thermal properties of ceramic materials used to build mold and (ii) by controlling porosity. In industrial practices, introducing porosity in the molds is an effective way to lower the thermal diffusivity. Many researchers have studied the influence of porosity on ceramic thermal conductivity. The commonly used model for the effect of porosity on thermal conductivity is Eqn. 2, which is satisfactory from zero to up to 74% porosity in the temperature range where emissivity effect is negligible:

$$K/K_0 = (1-P)/(1+nP^2)$$

Eqn. 2

where: $K$ is the thermal conductivity of a porous ceramic body, $K_0$ is that of the dense ceramic body, $P$ is the volume fraction of pores, and $n$ is a constant depending on pore structure and morphology.

As an example, it can be estimated that introducing 40% porosity will decrease thermal conductivity of ceramic shell molds by 40%. However, such an increase in porosity will lower the strength of the shell molds. Recently published experimental strength and porosity data of various porous ceramics were reviewed and these data were compared with values calculated from both the minimum contact solid area and the pore stress concentration effect models. According to the minimum contact solid area model, the mechanical strength of fully dense ceramic decreases exponentially with increase in volume fraction porosity ($P$):

$$\sigma = \sigma_0 \exp(-bP)$$

Eqn. 3

where: $b$ is an empirical parameter related to the minimum solid area and dependent on the pore structure.

According to the pore stress concentration effect model, the resulting fracture strength-porosity relationship for all ceramic materials can be given by a power equation of the form:

$$\sigma = \sigma_0(1 - P)^\eta$$

Eqn. 4

where: $\eta$ is related directly to the pore structure (shape and orientation of the pores with respect to the stress axis) and the Poisson's ratio of the material. Kline et al. found that increasing the open porosity in a shell mold from 19% to 27% reduced the modulus of rupture from 11 MPa to 6 MPa. The adverse effect of porosity on strength of the multilayer ceramic shell mold limits the opportunity for controlling thermal properties by adjusting porosity.
In this study, the authors used hollow cenosphere particles as the stucco in back-up coats of multilayer shell molds. This paper will focus on the determination of thermal and mechanical properties of this type of shell mold. Some other advantages will be discussed as well.

**DESIGN OF EXPERIMENTS**

**MATERIALS AND EXPERIMENTAL STUCOS**

*Material Selection*

The ceramic slurry used to produce the test samples constituted -200 mesh fused silica flour suspended in colloidal silica binder. The silica stuccos applied to the test samples following each dip coating are 149-300\(\mu m\) (0.006-0.011in) in the prime coat and 300-600\(\mu m\) (0.006-0.023in) in the back-up coats. The chemical and physical properties of cenospheres particles are provided (Table 1 & 2). The size distribution of cenospheres particles is plotted in Fig.1.

*Experimental Test Matrix*

For this experiment, the number of back-up layers stuccoed with cenospheres particles or silica stucco was varied (Table 3). The extremes, represented by shells identified as “ceno” and “silica” were stuccoed individually by cenospheres and silica in all of their back-up coats.

*Table 1. Chemical Composition of Cenospheres as Provided by the Supplier*

<table>
<thead>
<tr>
<th>(\text{SiO}_2)</th>
<th>(\text{Al}_2\text{O}_3)</th>
<th>(\text{Fe}_2\text{O}_3)</th>
<th>(\text{CaO})</th>
<th>(\text{MgO})</th>
<th>(\text{K}_2\text{O})</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.00-65.00</td>
<td>28.00</td>
<td>0.50-5.00</td>
<td>0.50-3.50</td>
<td>0.80-2.00</td>
<td>1.00-4.00</td>
</tr>
</tbody>
</table>

*Figure 1. Scanning electron microscope image (a) and size distribution of cenospheres (b).*

*Table 2. Physical Properties of Cenospheres*

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density, g/cm(^3)</td>
<td>0.42</td>
</tr>
<tr>
<td>Sintering Temperature, °C (F)</td>
<td>1300-1350 (2372-2462)</td>
</tr>
<tr>
<td>Melting Temperature, °C (F)</td>
<td>1400-1425 (2552-2597)</td>
</tr>
<tr>
<td>Thermal conductivity, W/mK</td>
<td>0.07</td>
</tr>
</tbody>
</table>

*Table 3. Shell Components*

<table>
<thead>
<tr>
<th>Stucco</th>
<th>Binder</th>
<th>Flour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prime coat</td>
<td>Silica</td>
<td></td>
</tr>
<tr>
<td>Shell “Ceno”</td>
<td>silica</td>
<td>silica</td>
</tr>
<tr>
<td>Shell “1s+4c”</td>
<td>silica</td>
<td>silica</td>
</tr>
<tr>
<td>Shell “2s+3c”</td>
<td>silica</td>
<td>silica</td>
</tr>
<tr>
<td>Shell “3s+2c”</td>
<td>silica</td>
<td>silica</td>
</tr>
<tr>
<td>Shell “4s+1c”</td>
<td>silica</td>
<td>silica</td>
</tr>
<tr>
<td>Shell “Silica”</td>
<td>silica</td>
<td>silica</td>
</tr>
<tr>
<td>Back up</td>
<td>Colloidal silica</td>
<td>+325 mesh flour</td>
</tr>
<tr>
<td>Cenospheres</td>
<td>Silica</td>
<td>silica</td>
</tr>
<tr>
<td>Cenospheres</td>
<td>Silica</td>
<td>silica</td>
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<tr>
<td>Cenospheres</td>
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<tr>
<td>Cenospheres</td>
<td>Silica</td>
<td>silica</td>
</tr>
<tr>
<td>Cenospheres</td>
<td>Silica</td>
<td>silica</td>
</tr>
<tr>
<td>Seal</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

*Sample Shell Building*

The viscosity of the slurry was tested using a Brookfield DV-II+ Pro viscometer equipped with a LV3 spindle operating at 30rpm. The dynamic slurry viscosity was maintained at 1100±100cP for the prime coat and 800±50cP for the back-up and seal coats. All of the test samples were built on 25.4×76.2×152.4mm (1×3×6in) foam patterns. The foam patterns were lightly abraded using 1200-grit sandpaper to remove surface texture differences between cut and uncut surfaces.

The patterns were submerged in the slurry for twenty seconds. Then the patterns were removed and excess slurry was allowed to naturally drip off for one minute.
During drip removal, patterns were rotating around the vertical axis at a speed of 10rpm with the dipped end facing down and oriented at a 45° angle from the vertical axis. Stucco was then applied onto the slurry coat in a rainfall sander. A uniform distribution of stucco was achieved by turning the samples at a constant speed until no additional stucco would adhere to the wet surface. The samples were allowed to air dry for at least four hours before the next layer was applied. For each sample, one prime, five back-up and one seal coats were built.

After being dried for minimum one additional day, the samples were fired at 850°C (1562°F) for an hour and then allowed to cool down in the chamber overnight.

PROPERTIES TESTS METHODS

**Bulk Density and Total Porosity**
The bulk density of specimen was determined in the fired condition according to ASTM c 20-00. Total porosity was calculated based on true density of a silica-stuccoed shell mold by He-pycnometer. Density differences among other components in cenospheres and silica were neglected due to such small weight percent (5%) of those components being present in the shell.

**Modulus of Rupture Testing**
Flexural testing was performed using a 3-point bend fixture shown in Fig 2. Both the lower support radii and the upper loading radius were 6.35mm (0.25in). The separation between the lower supports was 80mm (3.15in). Samples were loading in compression at a rate of 2mm (0.08in) displacement per minute.

<table>
<thead>
<tr>
<th>Sample Shell</th>
<th>Bulk Density, g/cm³</th>
<th>Total Porosity, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>ceno</td>
<td>1.50±0.01</td>
<td>60.0±2.1</td>
</tr>
<tr>
<td>1s4c</td>
<td>1.65±0.01</td>
<td>45.2±1.8</td>
</tr>
<tr>
<td>2s3c</td>
<td>1.68±0.02</td>
<td>42.4±0.7</td>
</tr>
<tr>
<td>3s2c</td>
<td>1.76±0.03</td>
<td>36.7±1.3</td>
</tr>
<tr>
<td>4s1c</td>
<td>1.80±0.02</td>
<td>33.7±1.1</td>
</tr>
<tr>
<td>silica</td>
<td>1.83±0.02</td>
<td>30.1±0.9</td>
</tr>
</tbody>
</table>

**RESULTS**

**BULK DENSITY AND TOTAL POROSITY**
The bulk density and calculated total porosity values for experimental samples are given in Table 4. The presence of more cenosphere-stuccoed coats decreases the bulk density and increases the total porosity significantly by introducing more closed porosity.

**THERMAL PROPERTIES**
Experimental castings were produced in the shell molds (Table 3). The castings poured in all of the shell molds, except the shell mold “ceno”, produced good surface finish and dimensional replication of the pattern. Only the shell mold “ceno” had inadequate strength and consequently partially collapsed during Ni pouring, resulting in a bulge on the casting surface (Fig. 3).
Solidification curves collected during experiments are shown in Fig. 4. In the shell molds consisting of more layers of cenosphere-stuccoed coats, the solidification time of nickel was longer which indicated a lower thermal diffusivity of the shell mold. The shells with more cenosphere-stuccoed layers were much thinner and had less mass, so the maximum temperature that the shell molds reached was higher.

Modulus of Rupture (MoR) was measured at room temperature and was plotted in Fig. 6 for all samples at green and fired conditions. In fired condition, up to 2-3 layers of cenosphere-stucco coats had negligible effects on strength of multi-layered ceramic shell. However, shells with larger portion of cenospheres layers or are fully built with cenospheres had significantly less strength. It was observed during experimental trials, that the “ceno” shell with only cenospheres in the stucco layers had only half of the strength of the “silica” shell and did exhibit bulging during casting. When using cenospheres as stucco coats after at least one layer of silica stuccoed back-up coat, the MoR of the entire shell mold is 20% more than the all cenosphere-stucco shell in both green and fired conditions, and no dimension changes or bulge was found in these shells during pattern removal and casting.
DISCUSSIONS

ENGINEER LOW THERMAL DIFFUSIVITY SHELL MOLDS

Use of cenospheres as stucco layers of investment shell molds produces shell molds which have low thermal diffusivity. This provides a new method to fabricate the investment shell molds to achieve low thermal diffusivity without sacrificing mechanical strength.

The measured thermal and mechanical properties of those samples were compared with the projected model (Eqn. 2&4) values for a pure silica shell mold at the same density (Fig. 7).

With respect to thermal conductivity, the use of cenospheres introduced more pores mainly as closed porosity inside individual cenospheres particles. The results showed (Fig. 7a) that the thermal conductivity decreases dramatically with increasing porosity and the decrease level did not depend on the type of introduced pores. The thermal conductivity depended on the number of introduced layers with cenospheres stucco and followed trend predicted by the model in Eqn. 2 for porous silica shell molds.

Comparison of the mechanical properties as measured by the MoR shows that the samples with cenospheres stucco layers had strength exceeding the strength predicted by the porosity effect model shown as Eqn. 4. One explanation may be that the degradation of strength with increasing porosity in the model represented by Eqn.4 is due to shortened distance between pores as the fracture path passes through connecting the pores. However, in cenosphere-stuccoed coats, the fracture propagation path is along the interfaces between the cenospheres and the bond phase rather than through the pores, as shown in Fig 8. This strength result suggests that ceramic molds with different number of layers built with cenospheres as stucco have a more favorable strength/thermal conductivity ratio.

Fig. 7. Relative thermal conductivity (a) and MoR (b) of silica or cenospheres stuccoed shell molds at a variety of porosity.

Fig. 8. Scanning electron microscope image of the fracture surface of cenosphere-stuccoed coats showing fracture propagates along the interface between cenospheres and bond phase, not through the cenospheres.
OTHER APPLICATIONS

Several cases were simulated when the same casting was solidified in traditional silica-based ceramic mold and mold with several cenospheres stucco layers. Overall larger values of Niyama and the less volume under the critical number were achieved in the cenosphere-stuccoed shell molds, indicating less micro porosity (Fig. 9).

![Fig. 9. Niyama of steel solidification in the cylindrical shell molds built with silica-stuccoed coats (a) and cenosphere-stuccoed coats (b).](image)

The cenosphere-stuccoed shell mold may retain preheat temperature better when there is variation in the time out of the preheating furnace and time actual pouring takes place.

Cenosphere-stuccoed shell can be up to 20% lighter than silica-stuccoed shell, so it could be beneficial in hand dipping for large castings. Also, as it was observed in experiments, that shells build with cenospheres were easily detached from castings, which could be beneficial for production of fragile thin-walled castings.

Use of cenospheres as molding material is also economically favorable because cenospheres are a coproduct of coal fired power plants and need less energy for production when compared to traditional sintered stucco materials used in foundry practices.

CONCLUSIONS

Hollow cenospheres were used as a porosity development additive in the production of investment casting molds. Cenospheres were applied as the stucco material in the back-up coats. At least one layer of fully silica back-up coat including silica stucco was required before the cenospheres stuccoed coats are applied to provide adequate strength. Thermal properties of mold shells containing cenospheres stucco coats were determined by the inverse method. Lower thermal diffusivity compared to fully silica stuccoed shell mold was achieved without sacrificing mechanical strength. Cenospheres stuccoed shells provide a potentially effective method to engineer the shell molds to obtain desired thermal properties for directional solidification and robustness of preheating and pouring processes.

REFERENCES


18. “Standard test methods for apparent porosity, water absorption, apparent specific gravity and bulk density of burned refractory brick and shapes by boiling water”, ASTM C 20-00.