Gas flow through a multilayer ceramic mould in lost wax foundry process

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Received 26.02.2009; accepted in revised form: 30.03.2009

Abstract

The paper deals with the issues of permeability testing of ceramic moulds used in lost wax foundry process. The main issue in the testing is to provide proper specimens of ceramic moulds (CM). The moulds have to be repeatable and must be free of internal defects of microcrack type that are formed mainly during the removal of patterns from CM in the course of heat treatment.

Moreover, the process of forming ceramic moulds must be similar to the general industrial process of CM moulds making regarding their anisotropic structure. The permeability parameter reflecting gas flow through multilayer ceramic moulds was also examined with attention to the investment casting shape accuracy.

Keywords: Ceramic mould, Permeability, Investment casting

1. Introduction

Gas flow through a multilayer ceramic mould (CM) depends primarily on the parameter called mould permeability PCM which is used in foundry engineering. Also, the arrangement of CM mould kit influences the gas flow through the mould and controls to a large extent the shape accuracy of precision castings. It is estimated that at least 70% of shape accuracy is determined by the PCM value – this is illustrated in Fig.1, where the 2 upper castings are the ones manufactured in a CM of low permeability. The arrangement of CM kit (Fig. 2) makes the intersection of casting walls – and particularly that of the upper part – predominantly dependent on CM permeability, because the melted metal pouring into the CM traps the air inside the mould, and subsequent gas flow through the mould walls depends primarily on the $P_{CM}$ parameter.

Fig. 1. AlSi castings made at different ceramic mould permeability
Generally, the value of permeability parameter denoted as \( P_{CM} \) equals to:

\[
P_{CM} = \frac{V_0 \cdot g}{\tau_0 \cdot F \cdot p} \cdot M_t \cdot A_t
\]

(1)

where:
- \( V_0 \) – volume of air (gas) that flows through CM walls,
- \( g \) – thickness of the mould wall,
- \( \tau_0 \) – time the \( V_0 \) flows through the mould walls,
- \( F \) – area of the CM surface the gas flows through,
- \( p \) – pressure of the gas flowing through the \( F \) area,
- \( M_t \) – a coefficient being the ratio of dynamic air viscosity at 20°C to the air viscosity measured in higher temperature
- \( A_t \) – a coefficient related to CM microcracks that are formed during the removal of the pattern from the CM and in the course of CM annealing.

An exemplary coefficient \( M_t = \frac{\mu_{20}}{\mu_t} \)

where \( \mu \) – dynamic air (gas) viscosity. \( M_t \) is 0.41 at the temperature of 800°C. Generally, if the temperature rises, the viscosity \( \mu \) increases significantly [1].

As one can see from examining the \( P_{CM} \) formula, the permeability decreases with the rise of temperature, if \( A_t \) is assumed as constant. The works of Doelman [2] and Dietrich [3] confirm the thesis.

In order to test the permeability, CM specimens of various shape and size are being used, superimposed on lost patterns. The type of pattern mixture and the method of removing the pattern from the CM decisively influence the possibility of mould microcracks formation (and the value \( A_t \)). If \( A_t = 1 \), there are no microcracks in the mould. If microcracks appear, the values of \( A_t \) and \( P_{CM} \) increase.

The paper [4] gives CM permeability testing results and shows that \( P_{CM} \) permeability significantly increases with temperature rise – which is in contradiction to former theses.

The CM specimens were based on sphere-shaped patterns having outside diameter of 50mm; the surface being superimposed on CM patterns of approx. 75cm².

As the heating velocity was less than 2°C/min, one should conclude that microcracks formed in the specimens under test at the stage of pattern removing, and that \( A_t \) greatly exceeded 1 and reached the value of > 10 at 900°C.

2. Authors’ own tests

In order to protect a multilayer ceramic mould (CM) from developing microcracks during testing it is necessary to maintain \( A_t \) at the value of 1 despite the temperature increase.

2.1. Methodology of testing

To prevent microcracks from forming in CM samples, in Zakład Odlewnictwa [Foundry Institute] – ITM PW a CM sample has been created having the form of a cube with heavily rounded (R>6mm) walls joints; the CM sample’s inner surface being of approx. 80 to 100cm².

The CM sample was based (Fig.4) on a pattern made of foamed polystyrene (Fig.3). Making use of patterns fabricated from foamed polystyrene ensures that microcracks will not be formed when removing patterns from CM, because no force is exerted by the patterns on CM walls.
A Ø14 pipe from melted quartz is sunk into the middle portion of the sample (Fig. 4). The pipe combined with a rubber pipe connects to the nozzle socket of a standard apparatus for permeability testing - Fig. 5.

Fig. 5. Standard test bed in Instytut Odlewnictwa [Foundry Institute] used for permeability tests.

To fabricate the CM specimens mainly water-based silicate binder with Remasol Ultra polymers and aluminium silicate materials – Molochite and Remasil – were used. Also, for comparison purposes, Ekosil – a domestic water-based binder with polymers and latexes – was used. Types of specimens intended for testing are listed in Table 1.

Table 1. Methods for making test specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dusting material</th>
<th>Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Remasil new</td>
<td>Remasol Ultra</td>
</tr>
<tr>
<td>A2</td>
<td>Remasil recovered</td>
<td>Remasol Ultra</td>
</tr>
<tr>
<td>B1</td>
<td>Molochite new</td>
<td>Remasol Ultra</td>
</tr>
<tr>
<td>B2</td>
<td>Molochite recovered</td>
<td>Remasol Ultra</td>
</tr>
<tr>
<td>C1</td>
<td>Remasil new</td>
<td>Ekasil</td>
</tr>
<tr>
<td>C2</td>
<td>Remasil recovered</td>
<td>Ekasil</td>
</tr>
<tr>
<td>D1</td>
<td>Molochite new</td>
<td>Ekasil</td>
</tr>
<tr>
<td>D2</td>
<td>Molochite recovered</td>
<td>Ekasil</td>
</tr>
<tr>
<td>E1</td>
<td>Remasil new</td>
<td>Ludox/KE</td>
</tr>
<tr>
<td>E2</td>
<td>Remasil recovered</td>
<td>Ludox/KE</td>
</tr>
</tbody>
</table>

Ludox – colloidal silica
KE – ethyl silicate after hydrolysis

2.2. Test results

The ceramic moulds permeability test results are listed in Tables 2, 3, 4, 5, showing the results for numerous specimens tested at 20°C, 600°C and 900°C. There are also shown the CM permeability values determined for moulds fabricated from new materials and the ones made of materials recycled from used moulds.

From the results presented it may be seen that temperature rise results in decrease of $P_{CM}$ parameter. At the same time the shape of aluminosilicate grains used as a dusting material was determined. The shape is described with $W_k$ index i.e. the ratio of a grain circumference to the circumference of a circle inscribed within the outline of the grain. If the $W_k$ is greater than 1.34 and less than 1.74, then the shape may be considered as angular. Arrangement of angular grains allows for obtaining proper CM porosity and thus proper CM permeability.

Table 2. Permeability tests results at 20°C after previous annealing at 900°C (*)

<table>
<thead>
<tr>
<th>No</th>
<th>Specimen type</th>
<th>Capacity [m³]</th>
<th>Pressure [Pa]</th>
<th>Average time [s]</th>
<th>Average surface area [m²]</th>
<th>$P$ [m²/Pa s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A1</td>
<td>0.001</td>
<td>840</td>
<td>90.3</td>
<td>0.01908</td>
<td>0.595</td>
</tr>
<tr>
<td>2</td>
<td>A2</td>
<td>0.001</td>
<td>860</td>
<td>101.4</td>
<td>0.01928</td>
<td>0.512</td>
</tr>
<tr>
<td>3</td>
<td>B1</td>
<td>0.001</td>
<td>850</td>
<td>95.9</td>
<td>0.02109</td>
<td>0.501</td>
</tr>
<tr>
<td>4</td>
<td>A2</td>
<td>0.001</td>
<td>870</td>
<td>106.1</td>
<td>0.01861</td>
<td>0.501</td>
</tr>
<tr>
<td>5</td>
<td>B1</td>
<td>0.001</td>
<td>850</td>
<td>100.4</td>
<td>0.01901</td>
<td>0.513</td>
</tr>
<tr>
<td>6</td>
<td>A1</td>
<td>0.001</td>
<td>840</td>
<td>101.6</td>
<td>0.01908</td>
<td>0.529</td>
</tr>
<tr>
<td>7</td>
<td>A2</td>
<td>0.001</td>
<td>870</td>
<td>99.9</td>
<td>0.02067</td>
<td>0.479</td>
</tr>
<tr>
<td>8</td>
<td>B2</td>
<td>0.001</td>
<td>840</td>
<td>91.4</td>
<td>0.02138</td>
<td>0.524</td>
</tr>
<tr>
<td>9</td>
<td>B2</td>
<td>0.001</td>
<td>870</td>
<td>96.3</td>
<td>0.01928</td>
<td>0.533</td>
</tr>
</tbody>
</table>

(*) The tests were conducted in Instytut Odlewnictwa [Foundry Institute] in Cracow.
Table 5. Results of CM specimens permeability tests conducted at the temperature of 600°C in Instytut Odlewnictwa [Foundry Institute] in Cracow

<table>
<thead>
<tr>
<th>No</th>
<th>Specimen type</th>
<th>Capacity [m³]</th>
<th>Pressure [Pa]</th>
<th>Average time [s]</th>
<th>Average surface area [m²]</th>
<th>P [m²/Pa·s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E1</td>
<td>0.001</td>
<td>950</td>
<td>137.6</td>
<td>0.023211</td>
<td>0.385</td>
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<tr>
<td>2</td>
<td>E1</td>
<td>0.002</td>
<td>940</td>
<td>298.5</td>
<td>0.023211</td>
<td>0.359</td>
</tr>
<tr>
<td>3</td>
<td>E2</td>
<td>0.001</td>
<td>950</td>
<td>126</td>
<td>0.022923</td>
<td>0.397</td>
</tr>
<tr>
<td>4</td>
<td>E2</td>
<td>0.002</td>
<td>940</td>
<td>274.6</td>
<td>0.022923</td>
<td>0.368</td>
</tr>
<tr>
<td>5</td>
<td>E2</td>
<td>0.001</td>
<td>970</td>
<td>125.4</td>
<td>0.022923</td>
<td>0.391</td>
</tr>
<tr>
<td>6</td>
<td>E2</td>
<td>0.002</td>
<td>960</td>
<td>276.9</td>
<td>0.022923</td>
<td>0.357</td>
</tr>
</tbody>
</table>

The thickness of tested CM was between 0.009 m and 0.01 m.

3. Test results analysis

According to the tests, heating of CM from the temperature of 20°C to 900°C results in P_CM parameter decrease, in average by approx. 30%, despite the fact that the M_t coefficient value in the temperature range should cause a considerably larger decrease of P_CM. However, simultaneous thermal expansion of ceramic moulds in the 20°C–900°C range causes a certain increase of the CM porosity and determines the resultant P_CM.

It is particularly easy to observe the shape accuracy of castings by examining intersection between flat or spherical walls of Al alloys castings.

According to [6] and [7] the precision of walls intersection is influenced by capillary action [5]; this, in effect, allows to estimate the radius r, (Fig.6) responsible for the precision. According to the following formula:

\[ r = \frac{2\sigma \cos \theta}{h \rho g} \]

where:
- \( h \) – height of melted metal column in the CM,
- \( \rho \) – density of melted metal,
- \( g \) – gravity acceleration,
- \( \sigma \) – surface tension of melted metal,
- \( \cos \Theta \) – cosine of CM surface – melted metal contact angle.

Fig. 6. Cross section of the CM for which r has been calculated (R= 0,015m, h= 0,25m) h – height of melted metal column in the mould

The precision of AlSi castings walls intersection determined by radius r (Fig. 6) theoretically equals approx. 0.23mm, according to formula (2).

The checked r value – for CM having permeability P_CM of about 0.5m²/Pa·s at conditions as per Fig.6 – was 0.46 mm, and is an evidence of strong influence of permeability P_CM on the shape accuracy of castings.

If for AlSi9 alloy casting the P_CM measured at 20°C is below 0.2m²/Pa·s, an air (gas) bag forms between liquid AlSi that fills the mould chamber and the mould wall; this leads to severe misruns (the two castings at the top of Fig. 1).

4. Conclusions

1. CM permeability determined with P_CM parameter strongly influences the shape accuracy of castings.
2. Heating CM from 20 to 900°C largely decreases its permeability.
3. More reliable results are ensured when in order to determine the P_CM parameter patterns of foamed polystyrene are used.

Acknowledgements

The present study was financed from MNiSzW resources as part of the R15 019 03 project.

References