Foam Pattern Aging and its Effect on Crack Formation in Investment Casting Ceramic Shells

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ABSTRACT

The application of rigid plastic foam for large investment casting patterns with complex geometries can improve the dimensional tolerances and the surface quality of the casting. However, these pattern materials promote crack formation in investment casting shells during pattern removal using standard firing procedures. In typical investment casting shell processing, drying stages provide an aging period which can change the compatibility strains of the shell/foam assembly. In order to accurately predict shell cracking occurrence during pattern removal, the aging strain of the pattern must be considered. ASTM standard tests and independently developed experimental methods were combined with finite element modeling to predict stress development in the shell. The model takes into consideration the thermal properties of the pattern and the shell materials to determine the heat transfer to establish a thermal gradient within the materials. This is combined with mechanical properties to determine the thermal expansion stresses developed in the shell during firing. An experimentally measured delay of the thermal expansion of the aged pattern was incorporated in a three-dimensional nonlinear finite element model and used to predict possible crack formation in the shells during pattern removal. The effect of pattern aging on crack formation in the shell was experimentally validated. Recommendations for pattern removal parameters to decrease stress and eliminate crack formation in the shell were formulated.

Keywords: ceramic shell, investment casting, crack, stress modeling, molding

INTRODUCTION

The investment casting process is generally used to produce small, thin walled castings with high detail. The process begins with the manufacture of a pattern from an easily shaped, inexpensive material. The most common material for patterns is wax but different types of polymeric foam are also used.1 2 The pattern is dipped in slurry made of inorganic binder and oxide flour usually containing some combination of fused silica, zircon, alumina or other ceramic material. Refractory granules referred to as stucco (usually fused silica, zircon or alumina) are then applied to the wet slurry coating. The combination of slurry and stucco makes a single coat which is allowed to dry before subsequent coats are applied. The shell building process generally consists of three different types of layers. Prime coats are designed to provide a better surface finish for the casting and are applied first, usually in one or two coats. Backup coats are designed to add strength to the shell and are applied after any prime coats; four to ten backup coats are applied. The seal coat is designed to seal the stucco of the final backup coat and is applied last.3 7 The pattern is then removed from the unfired or green shell by melting or decomposition in an autoclave or furnace. Whether done as a part of pattern removal, or as an additional firing process, the ceramic is sintered to increase the strength of the shell such that the pressure of liquid metal will not cause cracks. Liquid metal is then poured into the shell, which is usually preheated, to produce the casting.

Large patterns made from wax often do not have sufficient strength to hold their shape due to their higher weight, especially in situations where the pattern has unsupported extensions, leading to creep.6 Polymeric foams were considered as pattern materials in investment casting in an attempt to overcome some of the wax deficiencies. Some of the first foams used were expanded polystyrene (EPS).9 This material has much lower density than wax and, despite its lower strength, it doesn’t suffer from the self loading creep that is common with wax patterns, especially in larger patterns. This becomes especially important to the dimensional stability of the pattern during storage. However, EPS foams are also very buoyant which causes problems when the pattern is initially dipped in the slurry. The forces on the pattern when submerged can be high enough to distort or even break the pattern. EPS foam and wax patterns also show some dimensional change when they are cooled after production. Because of these issues, stronger, higher density polymeric foams are needed. Polyurethane foams fit these requirements well and can be made in complicated shapes with high surface quality and dimensional accuracy.10 However, polyurethane foams have high coefficients of thermal expansion and high decomposition temperatures, which can cause the pattern to expand and break the shell during the pattern removal process.9

Preliminary aging of EPS patterns to control pattern dimensions has been successfully implemented in lost foam casting.11 The use of aging to prevent shell cracking is based on the change in pattern dimensions over time,
especially at elevated temperatures. The polymeric foam aging mechanism relates to the development of crystallinity. An aged crystalline polymer has two phases: the crystalline phase and the amorphous phase. Preliminary aging of the polymeric foam pattern inside the green shell may increase the ordered domain and crystallinity of the polyurethane pattern during firing leading to volume reduction. Because of this, the effect of the thermal expansion of the polyurethane could be reduced.

The objective of this research was to develop a model to predict the effect of pattern aging on shell cracking. To achieve this goal, the aging properties of the polyurethane foam were experimentally determined along with glass transition temperatures and the Young’s modulus of aged foam. Additionally, samples were tested for shell cracking by firing stucco patterns in various conditions. These data were used in a finite element model to predict crack formation during pattern removal.

PROCEDURES

EXPERIMENTAL Foam Pattern Properties

Polyurethane foam with density of 170 kg/m³ was tested. Samples were cut from the center of foam blocks with a cross-section of 7000 mm.Compression testing of the foam was used to determine the elastic modulus after aging at 100°C (212°F) for 24 h. Samples had a cross-section of 2580 mm² and a thickness of 25.4 mm (1 in.) or 50.8 mm (2 in.) (ASTM D1621). Thermal dilation during foam aging was measured using a laser assisted dilatometer. Foam samples were cut into 50 mm (1.97 in.) long, 18 mm (0.71 in.) diameter cylinders. Two thin aluminum disks were placed on both ends of the foam and inserted into a quartz glass tube (19 mm [0.75 in.] diameter) submerged in an oil bath. A small hole was present in the end of the tube to allow oil flow inside for improved heating of the sample. Another quartz tube was placed on the upper aluminum disk. The expansion of the foam sample was monitored through the linear movement of the upper tube using a laser proximity probe with 1 µm precision. The average temperature of the foam samples was collected by averaging the reading of two thermocouples inserted in the oil bath, one of which was inserted in a spare foam sample and the other thermocouple was left exposed to the oil. The heating rate of the foam was approximately 1°C (3.3°F)/min.

Samples were held at various aging temperatures and times, cooled back to room temperature and heated aging until softening. Additionally one sample was heated and held at different temperatures in a stepped fashion. Differential scanning calorimetry (DSC) was done on the foam in both the aged and un-aged condition. The samples were stabilized by first heating from room temperature to 180°C (356°F) in the instrument, then immediately quenched in liquid nitrogen and held for 1 min. The 2mg quenched sample was then tested using DSC (TA instrument DSC Q2000) from -38°C (36.4°F) to 210°C (410°F) at a heating rate of 20°C (68°F)/min in a nitrogen gas atmosphere.

Shell Construction and Properties

A simple pattern (50.8 x 63.5 x 63.5 mm [2 x 2.5 x 2.5 in.]) was prepared to test shell cracking during burnout (Fig. 1). The slurry consisted of colloidal silica binder (Megasol B1) and fused silica flour (-200 mesh). Slurry viscosity was measured by Brookfield DVII+ Pro Viscometer. All coatings were applied at 800±100 cP viscosity which is equivalent to 19-22 sec on a no.5 Zahn cup. The patterns were submerged in the slurry until completely covered and then removed and suspended over the slurry for approximately 50 sec. During this time, the pattern was rotated and allowed to drain from different points to promote an even coating. A uniform distribution of stucco was then applied using the rainfall method. This was done by continuously rotating the pattern so that all surfaces were directly impacted by the falling stucco until no more stucco would adhere to the surface. The stucco for the prime coat was granular zircon (-100+200 mesh) and the stucco for the back-up coats was fused silica (-30+50 mesh). The seal coat used no stucco. The samples were dried for at least 24 h. Shells were fabricated with one prime coat, either three or five backup and one seal coat. The samples with three backup coats had five total layers (3.8 mm [0.15 in.] average thickness) and the samples with five backup coats had seven total layers (6.4 mm [0.25 in.] average thickness). After the seal coat was applied the samples dried for another 24 h. Half of the patterns were then aged. After sample preparation, the shells were fired in electrical resistance box furnace using flash firing in a furnace preheated to 600°C (1112°F).

Fig. 1. This shell was built around a foam pattern: 50.8 x 63.5 x 63.5 mm.

The maximum stress at rupture and elastic modulus of the five and seven layer shells were determined using three point bend testing of green shells performed at room temperature according to ASTM C1161. The tip of the testing fixture had a radius of 3 mm (0.12 in.). The bulk density of the shells was measured using Archimedes method in distilled water, according to ASTM C20 using approximately 10 g (0.35 oz) samples.
MODELING

A nonlinear coupled finite element model was developed to study the crack formation in the shell during pattern removal. The model accounts for both mechanical and thermal loadings and assumes a fixed interface between the pattern and shell. It is capable of simulating the complete detail of pattern and shell behavior during the firing process. To reduce computational time, one quarter of the pattern surrounded by shell has been modeled and symmetric boundary conditions are applied at the cut planes. An eight-node brick element is used to mesh the model. To mesh the pattern, all edges are initially seeded by numbers. In order to obtain higher result accuracy and save computational cost, additional seeds and biased seeds are used in critical regions and fewer seeds in regions that are of less interest. Hex mesh shape and structured mesh technique are used. The mesh of the finite element model for both the shell and foam pattern is shown in Fig. 2. Finer mesh is used near the corner of ceramic shell; 19,683 brick elements were used for the model. The contact properties between the pattern and shell are defined as fixed in order to simulate the actual experimental process.

The formulation for the transient mechanical analysis can be written as:

\[
[M^e] \{\dot{U}^e\} + [K^e]\{U^e\} = \{F^e\} + \{F^\varphi\}
\]

Equation 1

where:

\[
[M^e] = \int_V \rho [N]^T [N] dV
\]

\[
[K^e] = \int_V [B]^T [C] [B] dV
\]

\[
\{U^e\} = \{u, v, w\}^T
\]

\[\{F^e\}\] is the mass matrix, \([K^e]\) is the stiffness matrix, \([F^\varphi]\) and \([F^\varphi]\) are mechanical and thermal loadings, \(N\) is shape function, \(B\) is strain-displacement function, \(C\) is elasticity matrix, \(\rho\) is the density, and \(\{u, v, w\}^T\) are displacement components in a rectangular Cartesian coordinate system.

The formulation for heat transfer can be expressed as:

\[
[C^\varphi]\{\dot{\theta}^e\} + [K^\varphi]\{\theta^e\} = \{Q^e\}
\]

Equation 2

where:

\[
[C^\varphi] = \int_V \rho c_p N^T N dV
\]

\[
[K^\varphi] = \int_V N^T k N dV
\]

\[
\{Q^e\} = \int_S N^T q dS + \int_V N^T r dV
\]

\([C^\varphi]\) is the heat capacitance matrix, \([K^\varphi]\) is the conductivity matrix, and \([Q^e]\) is the external flux vector. \(c_p\) is the specific heat of the material, \(k\) is the thermal conductivity, \(q\) is the surface heat flux and \(r\) is the body heat flux generated by plastic deformation.

A smeared crack model was used to describe the response of the ceramic material when a crack initiates. The crack model does not track individual “macro” cracks. Cracking is assumed to occur when the stress reaches a crack detection criterion surface. This failure surface is mathematical construction which is a linear relationship between the equivalent pressure stress and the von Mises equivalent deviatoric stress. When a crack has been detected its orientation is stored for subsequent calculations. Subsequent cracking at the same point is restricted to being orthogonal to this direction since stress components associated with an open crack are not included in the definition of the failure surface used for detecting additional cracks.

RESULTS

EFFECT OF AGING ON FOAM PROPERTIES

The effect of time and temperature on foam aging is important when this behavior benefits the process by reducing shell cracking. Appropriate aging times and temperatures can be vital when applying this method to industry. A preliminary study on the effect of aging was done with a sample that was heated and held at various temperatures in a stepping fashion (Fig. 3). This test shows that the aging rate significantly increases at temperatures above approximately 80°C (176°F).

![Fig. 3. Thermal expansion of the stepped aging sample shows increased shrinkage above 80°C.](image-url)
Temperatures above 100°C (212°F) were not tested because these temperatures are high enough to cause shell cracking from pattern expansion. Samples were also aged for various amounts of time at 100°C (212°F) to determine the effect of aging time on the amount of shrinkage (Fig. 4). The results show that after 24 hr the amount of shrinkage does not significantly increase until the aging time is longer than 48 hr.

The coefficient of thermal expansion (CTE) of an un-aged sample of polyurethane foam at temperatures below 90°C (194°F) is approximately 80 x10^{-6} °C^{-1} while above that temperature the CTE increases to 400 x10^{-6} °C^{-1}. At approximately 155°C (311°F), the foam stops expanding and begins to soften. At this point the CTE becomes slightly negative. Aged samples showed similar CTE behavior and foam softening temperature, but because the sample had contracted during aging and did not return to its original size until it had been heated to approximately 80°C (176°F), the net expansion of the aged foam relative to a shell mold of fixed dimension was less (Fig. 5).

To study the physico-chemical nature of polyurethane foam aging, DSC testing of the foam was performed. Results showed two endothermic peaks, indicated by changes in slope, one at approximately 60°C (140°F) and another at approximately 140°C (284°F) (Fig. 6). The 60°C peak is a glass transition temperature and matches well with the transition in CTE. The 140°C (284°F) peak matches the foam softening temperature and is associated with the break down of the crystalline structure.

The elastic modulus is an important property of foam patterns used for investment casting because of its impact on shell cracking. The effect of aging on the elastic modulus of the foam was determined by comparing the results of compression testing of aged and un-aged samples at room temperature. The average elastic modulus of un-aged samples was 53 MPa and the average modulus of samples that were aged at 100°C (212°F) for 24 was 52 MPa. This implies that aging has no significant effect on the room temperature mechanical properties of foam pattern. Temperature dependent values of the elastic modulus of the foam are required to...
accurately simulate stress in the shell during pattern removal. These values were determined using the known\textsuperscript{18, 19} tendency of the elastic modulus to degrade above the glass transition temperature. In the model the elastic modulus begins to degrade at 80°C (176°F) until it is near zero at the foam softening temperature.

**CERAMIC SHELL PROPERTIES**
The maximum failure stress and elastic modulus of the shell were experimentally determined for shells with five and seven layers using three-point bend testing performed at room temperature. Five samples for both types of shells were tested and the calculated values are included in Table 1. The failure stress for the five layer shells was lower than the seven layer shells while the five layer shells had a higher elastic modulus. The variation in mechanical properties is likely due to a higher percentage of zircon stucco in the five layer shells.

**Table 1. Strength and Density of Shells**

<table>
<thead>
<tr>
<th>Property</th>
<th>5 Layer Shell</th>
<th>7 Layer Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell thickness, mm</td>
<td>3.8 ± 0.3</td>
<td>6.4 ± 0.5</td>
</tr>
<tr>
<td>Maximum stress, MPa</td>
<td>4.4 ± 0.5</td>
<td>7.2 ± 1.1</td>
</tr>
<tr>
<td>Elastic modulus, MPa</td>
<td>3411 ± 518</td>
<td>1995 ± 314</td>
</tr>
<tr>
<td>Bulk density, kg/m(^3)</td>
<td>1920 ± 220</td>
<td>1800 ± 30</td>
</tr>
</tbody>
</table>

**MODELING RESULTS**
The experimentally verified thermo-mechanical properties for the pattern and the shell were used as input into the model (Table 2). The foam is assumed to decompose when it reaches a temperature of 155°C (311°F). Instead of modeling the actual shrinkage that occurs during aging, the CTE from room temperature to 80°C (176°F) for aged samples is set to zero in the simulation. A zero CTE prevents stress development in the shell by approximating the gap formed by aging and the subsequent free expansion of the pattern until the pattern expands to fill the gap (Fig. 7). In addition to the experimental data in Table 1, thermal conductivity and specific heat capacity data were used.\textsuperscript{9, 20-22} The thermal boundary conditions for flash firing at 600°C (1112°F) used in the simulations are shown in Table 3. Modeling was completed for aged (100°C [212°F] for 24 h) and un-aged samples with pattern dimensions of 50.8 x 63.5 x 63.5 mm 2 x 2.5 x 2.5 in.

**Table 2. Material Properties for Modeling\textsuperscript{9, 20-22}**

<table>
<thead>
<tr>
<th>Property</th>
<th>Polyurethane Foam</th>
<th>5 Layer Shell</th>
<th>7 Layer Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, kg/m(^3)</td>
<td>170</td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>Heat capacity, J/gK</td>
<td>1.3</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>Thermal conductivity, W/mK</td>
<td>0.06</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CTE, K(^{-1})</td>
<td>See Figure 7</td>
<td>2\times10^{-6}</td>
<td>2\times10^{-6}</td>
</tr>
</tbody>
</table>

**Fig. 7. CTEs are used in simulation for aged and un-aged samples. This shows the assumptions made for the aged sample to approximate aging shrinkage in the model.**

**Table 3. Thermal Boundary Conditions**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Flash Fire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oven initial temperature</td>
<td>600°C</td>
</tr>
<tr>
<td>Shell surface convection coefficient</td>
<td>20 W/m(^2)K</td>
</tr>
<tr>
<td>Emissivity of the shell surface</td>
<td>0.3</td>
</tr>
</tbody>
</table>

An example of the modeling results for flash fire at 600°C (1112°F) for aged and un-aged patterns with shell thickness of 6.4 mm (0.25 in.) is included as seen in Fig. 8. The maximum stress in the shell occurs when the boundary temperature between shell and pattern reaches the foam softening temperature. At that temperature, the applied pressure begins to decrease as a result of foam softening. This critical temperature was experimentally defined from the thermal expansion results. The maximum stress for both aged and un-aged samples occurs at the internal edges of the shell (Fig. 8). Compared to aged, an un-aged sample produces a much higher stress concentration in the shell.
DISCUSSION

Crack formation in the shell during rigid foam pattern removal by heat treatment depends on multiple parameters which can be divided into the following groups:

Group 1 - foam properties, most important of which include elastic modulus, thermal expansion, softening temperature and aging
Group 2 - shell properties, most important of which include failure stress, elastic modulus, and shell wall thickness
Group 3 - firing regime, continuous heating versus flash firing in high temperature preheated furnace.

The effect of aging after shell building and before pattern removal on polyurethane foam properties and shell cracking during pattern removal was investigated. Longer aging times were shown to increase the amount of shrinkage, especially for times less than 24 hr. After approximately 20 hr the shrinkage for a pattern aged at 100°C (212°F) subsides due to nearing completion of the transformation from an amorphous structure to a crystalline structure (Fig. 4a).

When aging temperature is above the glass transition temperature indicated by DSC (approximately 60°C [140°F]) the amount of shrinkage increases from zero to 0.5% (Fig. 4b) supporting the idea that the transformation of the polyurethane foam from amorphous to crystalline is the aging mechanism. Activation energy for aging was determined from the shrinkage in Fig. 3. The activation energy was approximately 600 J/mol when aging was below 80°C (176°F) and 1800 J/mol when above 80°C (176°F). Foam aging was not found to increase or decrease the elastic modulus of the polyurethane foam.

During pattern removal, the strain in the pattern consists of aging strain, thermal strain and elastic strain. The strain in the shell consists of thermal strain and elastic strain. The small amount of shrinkage caused by aging induces a negative strain in the pattern. This negative strain reduces the overall strain in the pattern and shell at their interface thus lowering the stress developed in the shell (Fig. 9).

This concept was applied to a shell cracking model to show the effect of aging on the stress developed in the shell during pattern removal. Specific cases were experimentally verified in the laboratory shell cracking test (Fig. 10). The comparison of experimental results and prediction of crack formation in the model are given in Table 4, indicating that modeling is consistent with experimental results. Aging the patterns significantly reduced the stress in the shell during pattern removal. Aging prevented cracking of the 3.8 mm (0.15 in.) thick shells and lowered stress development in the 6.4 mm (0.25 in.) shells (Fig. 9).
Aging reduces the stress in the shell by producing shrinkage which lowers the compatibility strain on heating and its consequent elastic stress development. A model was developed for predicting crack formation in investment casting shells due to pattern expansion. The model accurately predicts the presence of cracking during pattern removal for un-aged patterns with five layer shells. The results of the model and the experiments demonstrate that aging patterns can be an effective way to prevent shell cracking during pattern removal. To effectively prevent shell cracking it is recommended that aging be done above the glass transition temperature (60°C - 100°C [140 - 212°F]) for at least 24 hr.

REFERENCES

CONCLUSIONS
Aging reduces the stress in the shell by producing shrinkage which lowers the compatibility strain on heating and its consequent elastic stress development. A model was developed for predicting crack formation in investment casting shells due to pattern expansion. The model accurately predicts the presence of cracking during pattern removal for un-aged patterns with five layer shells. The results of the model and the experiments demonstrate that aging patterns can be an effective way to prevent shell cracking during pattern removal. To effectively prevent shell cracking it is recommended that aging be done above the glass transition temperature (60°C - 100°C [140 - 212°F]) for at least 24 hr.

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