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Crack prediction using nonlinear finite element analysis during pattern removal in investment casting process

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ABSTRACT

A three-dimensional transient thermo-mechanical coupled nonlinear finite element model was developed to predict the possible crack formation of ceramic shell during rigid polymer pattern removal in the investment casting process. A smeared crack model was used to describe the response of the ceramic shell when crack initiates. A foam degradation model was implemented to account for the loss of mechanical properties of the foam during firing process. The effects of firing method, pattern type and complex geometry were investigated. The simulation results were validated with experimental findings. The developed model not only serves as a useful tool for designing foam patterns but also can be used for optimizing firing process parameters in investment casting process.

1. Introduction

The Investment casting process is used to produce small, thin walled castings with the highest level of detail and quality. The process starts with choosing a pattern material. Traditional use of wax patterns (Foster, 1994) is fast being replaced by the usage of other types of pattern, like expanded polystyrene (EPS) and Polyurethane foam, as well as stereolithography apparatus (SLA) studied by Yao and Leu (1999). Zhao et al. (2011) reported on the characterization of these polymers patterns. The mechanical and thermal properties along with the build parameters of the patterns were investigated experimentally, and trade-off on using these patterns was investigated. Cannell and Sabau (2005) found out that wax is less advantageous because of their inability to hold their own weight due to low strength. Kline et al. (2009) demonstrated that EPS foams, though they possess lower density than wax patterns, can support their own weight much better. But EPS foams are buoyant during slurry dipping process, thereby causing high distortion on the pattern, which tends to break the initial thin prime coat. Polyurethane foams with higher strength and density addressed the above issues, and they are capable of producing patterns with high surface quality and dimensional accuracy.

However, high density rigid polymeric foam (polyurethane foam) has high thermal expansion and a high thermal decomposition temperature, in conjunction with low failure strength of green shell and high pattern volume, could result in cracks during the firing process (Everhart et al., 2013b). Fig. 1 depicts the cracks formed in ceramic shell during the foam pattern removal process. Although, aging of polyurethane foam after shelling can effectively prevent shell cracking as studied by Everhart et al. (2012), aging time of 24 h, or more in some cases is required. The origin of shell cracking during pattern removal is almost always from thermo-mechanical stresses induced during heating, and therefore the ceramic shell is always under tension. Cracks could be initiated at stress concentration regions and may further propagate due to growing thermal stress and composition gradient in shell.

Komaragiri et al. (2013) reported on the multiple factors governing shell cracking like size of the shell and its thickness, elastic modulus, thermal conductivity and thermal expansion coefficient of pattern as well as heating rate. The increased casting complexity requires more detailed study on shell cracking phenomenon in pattern removal process. Finite element analysis (FEA) is well suited to quantifying parametric factors that influence shell cracking. Yao and Leu (2000) developed a two dimensional finite element model of a ceramic shell with an internally webbed stereolithography pattern, under a stepwise heating process to isothermal temperatures, and no interaction in z-direction. Only static heat transfer was considered. Simulation results were validated by experimental strain-gauges mounted on the webbed epoxy

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Fig. 1. Crack formed in shell during firing.

patterns. Ferreira and Mateus (2003) developed a three dimensional cylindrical hoop model with an internal square frame structure, but the transient heat transfer was ignored. Hague and Dickens (2000) devised a three dimensional finite element model of 50 mm stereolithography cube encased in a 5 mm thick investment casting shell to calculate induced stress. However, no failure mechanism of the shell was introduced. Chen et al. (2011) analyzed ceramic shell cracking in stereolithography-based rapid casting of turbine blade. The authors performed transient thermo-mechanical finite element analysis on the turbine blade 2D cross section, and circumferential stress was calculated and dangerous temperature range was identified. Gu et al. (2012) introduced a pattern lattice structure optimization method to reduce stress level in ceramic shell through finite element analysis, and an optimal lattice design was achieved with less maximum stress in shell compared with existing QuickCast 2.0 lattice style. Li et al. (2013) developed two discrete mechanical and thermal models to calculate stress induced by CTE mismatch between ceramic shell and resin pattern. At a predefined severe temperature case, optimal design of the resin pattern was obtained. Although the previous studies on shell cracking analysis using FEA provide good guideline on prevention of shell cracking, the studies have limitations in terms of simplified 2D geometry model, uncoupled and static thermo-mechanical behavior and no presence of failure mechanism of ceramic shell.

This paper primarily focuses on simulation effort on the problem concerning shell cracking during pattern removal process. The research was to predict the possible crack formation, using finite element analysis, in ceramic shell during firing of the foam pattern. A comprehensive 3D thermo-mechanical coupled nonlinear finite element model was developed to represent the 3D detailed geometry configuration, transient thermo-mechanical behavior and failure prediction of ceramic shell during the foam firing process. A smeared crack model was developed for describing the response of ceramic shell during firing. Cracking was assumed to occur when the stress reached crack detection surface. When a crack was detected, its orientation was stored and the stress and material stiffness were affected for subsequent calculations. The nonlinear mechanical and thermal properties of foam and shell were provided by experimental tests. Thermally degraded foam properties were incorporated in the finite element model. Effects of foam type, firing method and foam complex geometry were studied. The simulation results were verified by the experimental results.

2. Methodology

2.1. Foam removal process

As the first step of the foam firing process, both simple and complex shaped foam patterns were produced (see Section 3.1 regarding the dimensions of the foams studied). In the second step, shell building was done both in laboratory and industrial foundries. Specifically, shells with simple shaped foam were built in laboratory, while shells with complex shaped foam were built in industry. Laboratory shells were developed with one prime coat, either three backup coats or five backup coat, and one seal coat (total 3.8 mm or 6.4 mm average thickness). Details regarding the laboratory shell building can be found in Everhart et al. (2013a). Industrial shells were made with two prime coats and either one, three or five backup coats and a seal coat. The industrial shells with one backup coat had four total layers (total 3.8 mm average thickness) and the shells with three and five backup coats had six total layers and eight total layers (total 6.8 mm and 9.9 mm average thickness) respectively. Details regarding the industrial shell building can be found in Komaragiri et al. (2013). Both types of shells were fired in an electric box furnace using two different procedures: flash firing in the furnace preheated to 600 °C and continuous heating from room temperature to 600 °C.

2.2. Finite element formulation

A fully coupled transient thermo-mechanical nonlinear finite element model was developed to predict shell cracking during pattern removal process. The model is capable of performing complete and detailed foam and ceramic shell behavior during the pattern burnout process. Both the mechanical and thermal loadings were accounted for. The formulation for the transient mechanical analysis were written as (Reddy, 2006)

$$[M^e]\{\ddot{\Delta}^e\}+[K^e_{\Delta}]\{\Delta^e\}=\{F^e_M\}+\{F^e_T\} \tag{1}$$

where $[M^e]=\int_V \rho[N]^T[N]dV$, $[K^e]=\int_V [B]^T[C][B]dV$, and $\{\Delta^e\}=\{u,v,w\}^T$. $[M^e]$ is the mass matrix, $[K^e_{\Delta}]$ is the stiffness matrix, $\{F^e_M\}$ and $\{F^e_T\}$ are mechanical and thermal loadings, N is the shape function, B is the strain-displacement function, C is the elasticity matrix, ρ is the density, and $\{u,v,w\}^T$ are displacement components in a rectangular Cartesian coordinate system. The formulation for heat transfer was expressed as

$$[C^e_T]\{\dot{\theta}^e\}+[K^e_T]\{\theta^e\}=\{Q^e\} \tag{2}$$

where $[C^e_T]=\int_V \rho c_p N^T N dV$, $[K^e_T]=\int_V N^T \underline{k} N dV$, and $\{Q^e\}=\int_S N^T q dS+\int_V N^T r dV$. $[C^e_T]$ is the heat capacitance matrix, $[K^e_T]$ is the conductivity matrix, and $\{Q^e\}$ is the external flux vector. c_p is the specific heat of the material, $\underline{k}$ is the thermal conductivity, q is the surface heat flux, and r is the body heat flux generated by plastic deformation. Then the formulation for transient thermo-mechanical coupled analysis was written as:

$$\begin{bmatrix} M & 0 \\ 0 & 0 \end{bmatrix}^e \begin{Bmatrix} \{\ddot{\Delta}\} \\ 0 \end{Bmatrix}^e + \begin{bmatrix} 0 & 0 \\ 0 & C_T \end{bmatrix}^e \begin{Bmatrix} \{\dot{\Delta}\} \\ \{\dot{\theta}\} \end{Bmatrix}^e + \begin{bmatrix} K_{\Delta} & K_{\Delta T} \\ K_{T\Delta} & K_T \end{bmatrix}^e \begin{Bmatrix} \{\Delta\} \\ \{\theta\} \end{Bmatrix}^e = \begin{Bmatrix} \{F\} \\ \{Q\} \end{Bmatrix}^e \tag{3}$$

2.3. Crack model of the ceramic shell

Since the dominating stress-strain relationship of the ceramic shell during pattern removal process is tension, a smeared crack