Simulation of Wax Pattern Dimensions for Accuracy Improvement in Ceramic Shell Investment Castings

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Abstract—*In ceramic shell investment casting process disposable wax patterns are produced by injecting wax into dies having the shape of the finished part and these patterns are used to produce a ceramic shell by the application of a series of ceramic coatings, and the alloy is cast into the dewaxed shell mold. An important consideration in selecting the wax for pattern is that it must have dimensional stability. In this work, three-dimensional numerical simulations of wax in aluminium die, using the finite element technique and the ANSYS software program, was made. Dimensional changes between a pattern die and the wax pattern occur because of thermal expansion-contraction phenomena and elastic-plastic deformation. The viscoelastic model is assumed to simulate the wax solidification and its shrinkage. From the analysis the net contraction is calculated in each dimension of stepped wax pattern. All FEM analyses were performed using a commercial finite element package ANSYS. The results are compared with the data available in the literature, and a close agreement has been found between the two. Numerical simulation of wax solidification was found useful to calculate and control the shrinkage of wax pattern to improve the accuracy of products.*

Keywords: *Ceramic shell investment casting, Wax pattern, Numerical simulation, Finite element modeling, ANSYS*

Introduction

Ceramic shell investment casting is one of the important casting processes. In this process, a wax pattern is first dipped into a ceramic slurry bath for its primary coating. Thereafter, the pattern is withdrawn from the slurry and is manipulated to drain of the excess slurry to produce a uniform coating layer. The wet layer is immediately stuccoed with relatively coarse ceramic particles either by immersing it into a fluidized bed of particles or by sprinkling the particles on it from above [1]. The waxes used by the investment casting industry are complex blended materials. The wax pattern shrinks in the die following solidification. After cooling the patterns are removed from dies and allowed to shrink in an open atmosphere [2]. Shrinkage characteristics of waxes and its influence on the final dimensions of casting are of great fundamental importance in getting high quality castings, minimizing product cost and scrap. [3].There is a lack of accurate data on the shrinkage characteristics of pattern waxes. The 'British Investment Casters' Technical Association has sponsored an R &D programme in concerned with contraction levels of wax pattern materials and fatigue properties of investment castings [4]. Shrinkage characteristics, both linear and volumetric, were selected by the committee for a programme of work. Bonilla et al. [5] proposed a methodology for computer-aided heat transfer simulation and experimentally derived factors for injection parameters, to predict wax pattern shrinkages in the investment casting process. The focus is on developing techniques for the early determination of optimum injection parameters to be used for wax pattern production. Numerical simulation of solidification is useful in getting high quality castings and minimising product cost and scrap. In this work, three-dimensional numerical simulations of wax using the finite element technique and the ANSYS software program were made. Dimensional changes between a pattern die and its wax pattern occur as a result of complex phenomena such as thermal expansion–contraction and hot deformation (elastic, plastic, and creep). The wax pattern dimensions are determined by thermophysical and thermomechanical properties of wax. The viscoelastic model is assumed to simulate the wax solidification and its shrinkage. From three-dimensional numerical simulations analysis the net contraction is calculated in each dimension of stepped wax pattern.

Objective of Work

The present work is an attempt to quantify dimensional changes by using simulation of the concerned stage. The wax pattern dimensions are determined by thermophysical and thermomechanical properties of wax. The viscoelastic model is assumed to simulate the wax solidification and its shrinkage. Determine shrinkage in wax during pattern production with the help of finite element solver (FEM) ANSYS by assuming wax as viscoelastic material. From this analysis the net contraction is calculated in each dimension of stepped wax pattern shown in Fig 2. The shrinkage value found from the analysis is compared with the experimental results.

Viscoelasticy

An elastic material deforms under stress, but regains its original shape and size, when the load is removed. A practical example of elastic material is any spring working within its limits. For completely elastic materials, stress is directly proportional to strain. A viscous material after being subjected to a deforming load, does not recover its original shape and size when the load is removed. An example is a piston in a dashpot containing a viscous fluid. If a load is applied to move the piston in the dashpot, the piston will not return to its original position after the displacing load is removed, unless a returning load is applied opposite to the original load. A viscoelastic material's response to a deforming load combines both viscous (non-recoverable) and elastic (recoverable) qualities. Upon application of a load, the elastic deformation is instantaneous while the viscous part occurs over time.The ideal linear elastic element is the spring and the ideal linear viscous element is the dashpot. Attempts have been made to model viscoelastic materials by the use of a combination of mass less Hookean springs and dashpots filled with Newtonian fluid where the rate of movement of the piston is directly proportional to the viscosity of the oil and the applied stress. The combination of elastic and viscous elements in series is known as Maxwell element and the combination of elastic and viscous elements in parallel is known as Voigt/Kelvin element. Waxes exhibit linear viscoelastic behavior. The shrinkage of the wax pattern depends on the thermophysical and rheological properties of the wax [6].

Pattern Production Stage

Three types of wax (paraffin wax, bees wax and montan wax) with different melting temperatures (58.5°C to 83.5°C) were selected for the present study. Each wax is solid at room temperature. The wax blend (5th blend) was produced using paraffin wax: bees wax: montan wax in the ratios 50: 30: 20 respectively. The exact melting point of wax blend under study was determined from Differential Thermal Analysis as shown in Fig 1. The weight of each wax was measured with electronic balance having a least count of 0.001 gm. The components of a blend were mixed and melted at 120°C in a steel container with constant agitation in order to get homogeneous melt. After solidifying to room temperature the wax blend was stored in an air tight container to avoid them from humidity and moisture. In order to simulate the material behavior energy equation, momentum equation and constitutive equations must be solved in a coupled manner to determine the wax dimensions. To solve the energy equation, density, thermal conductivity, the amount of specific heat and latent heat released during solidification is required. To solve the stress–strain equations, data on thermal expansion and material parameters that describe the appropriate rheological behavior must be used.

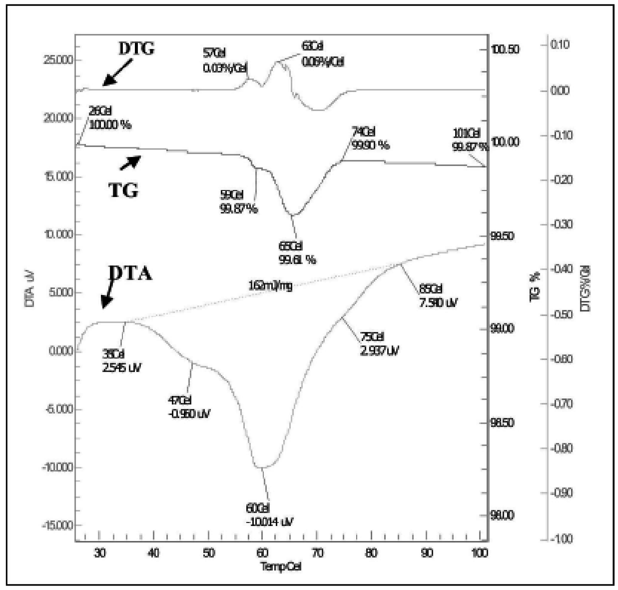

Fig. 1: Thermal Analysis of Wax Blend

Material Properties of Wax for Modelling

The wax is a viscoelastic material and so the material parameters required for the constitutive stress–strain relationships are shear modulus and bulk modulus. Experimental data about thermo-physical and thermo-mechanical properties are available for an unfilled wax, Cerita™ 29–51. Cerita™ 29–51 is a blend of polymers consisting of paraffin wax, microcrystalline wax, a proprietary polymer, and synthetic hydrocarbon resin. The composition of wax used in the experimental work is almost similar. So, properties of Cerita™ 29–51 had been taken form, Sabau *et al.* [3]. Data on density, specific heat, and thermal conductivity are shown in Table 1 [3]. For a generalized Maxwell-material, the shear relaxation modulus as a function of time t is given as:

$$G(t) = g_0 + \sum_{i=1}^{N} g_i \exp\left(\frac{-t}{\lambda_i}\right)$$

Where, g_o is the initial shear modulus, λ_i are the relaxation times and g_i are the relaxation strengths. Sabau *et al.* found these material constants by a non-linear regression of the master curve data and are shown in Table 2. [3].

Table 1: Thermo-physical Properties [3]

Temperature (°C)	Density (kg/m³)	Temperature (°C)	Specific Heat (J/kgK)	Temperature (°C)	Thermal Conductivity (W/mK)
25.0	954	25.0	2292.5	21.0	0.211
30.0	951	30.0	2674.2	56.0	0.211
35.0	947	35.0	3333.7	62.0	0.193
40.0	940	45.0	6033.2	67.0	0.158
45.0	931	47.5	6372.5	97.0	0.154
50.0	921	49.1	6009.6		
55.0	905	53.9	3048.9		
60.0	867	55.5	2738.4		
110.0	846	60.0	2267.7		

Table 2: Relaxation Times, λ_i and Relaxation Strengths, gi at the Reference Temperature 25°C [3]

No.	$g_{i\,(Pa)}$	λ_i (s)
1	9.828E+07	8.429E-03
2	6.720E+07	5.152E-02
3	6.000E+07	2.558E-01
4	4.983E+07	1.250E+00
5	3.855E+07	6.148E+00
6	2.948E+07	3.133E+01
7	2.252E+07	1.608E+02
8	1.817E+07	8.313E+02
9	1.144E+07	4.470E+03
10	8.310E+06	2.228E+04

Viscoelastic Modelling in Ansys

A material is said to be viscoelastic, if the material has an elastic (recoverable) part as well as a viscous (non-recoverable) part. Upon application of a load, the elastic deformation is instantaneous while the viscous part occurs over time. The viscoelastic model usually depicts the deformation behavior of glass or glass-like materials and may simulate cooling and heating sequences of such material. These materials at high temperatures turn into viscous fluids and at low temperatures behave as solids.

The material model is available with the viscoelastic elements VISCO88, VISCO89 for small deformation viscoelasticity and LINK180, SHELL181, PLANE182, PLANE183, SOLID185, SOLID186, SOLID187, BEAM188 and BEAM189 for small as well as large deformation viscoelasticity.

Description of the Element VISCO89

VISCO89 is a quadratic isoparametric element. The element is defined by 20 nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has thermorheologically simple (TRS) viscoelastic and stress stiffening capabilities.

VISCO89 Input Summary

VISCO89 uses a viscoelastic material model that is defined by the TB and TBDATA commands. The constant table is started by using the TB command with Lab = EVISC. Up to 95 constants may be defined with the TBDATA commands.

Viscoelastic Material Constants

Element VISCO89 uses a viscoelastic material model that is defined by entering the following data in the data table with TB commands. Data not input are assumed to be zero. We must enter the data table to perform the viscoelastic computation. A generalized Maxwell model is used to represent the material characteristics. The constant table is to be initialized with TB, EVISC. We can define up to 95 constants (C1 to C95, which are described below) with TBDATA commands.

Problem description

The problem considered for the analysis of wax pattern is a three stepped wax pattern of thickness 33 mm inside a die of size (133.08 mm X 58.5 mm X 43 mm) made of Aluminium. The pattern dimensions are shown in Fig. 2. It was modeled by using the 3-D 20-noded viscoelastic solid element, i.e. 'VISCO89'. 'Cerita 29-51', an industrial unfilled wax is considered as the wax pattern material as the composition of wax used in the experimental work is almost similar to 'Cerita 29–51'. The various constants are supplied as the input to the ANSYS model.

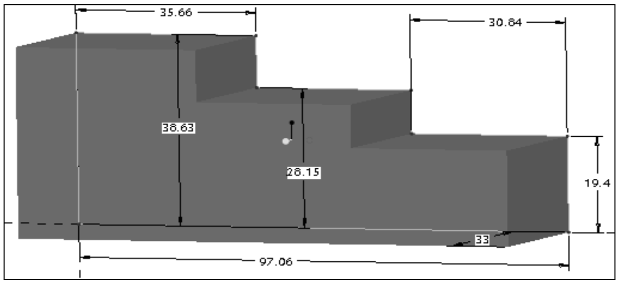

Fig. 2: Pattern Dimensions in mm

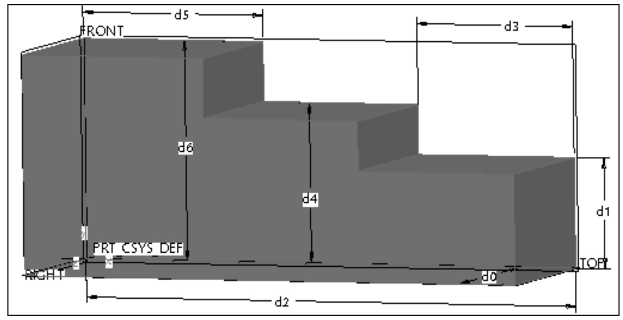

Fig. 3: Pattern Dimensions in the form of Variables

Results and Discussion

The numerical simulation is necessary to reduce the time and cost associated with the pattern production and casting. The simulation result will be accurate, when the same boundary conditions with same material properties variations will be input as in actual experimentation.

The simulation of solidification is performed to get information about the shrinkage in wax pattern. The viscoelastic model was assumed to simulate the wax solidification and its shrinkage. Die is assumed to be elastic and it is made of aluminium. The shrinkage can be calculated by using displacements of nodes in x, y, and z directions found from analysis.

To calculate shrinkage in dimension 'd2' in Fig. 3, nodes at areas 'A12' and 'A13' in, Figure- 4, are considered. The displacements in x-direction of nodes at areas 'A13' and 'A12' are taken under columns 'D21' and 'D22' respectively in Table 3.

To calculate shrinkage in dimension 'd6' in Fig. 3, nodes at areas 'A11' and 'A15' in Fig. 4, are considered. The displacements in y-direction of nodes at areas 'A15' and 'A11' are taken under columns 'H' and 'D61' respectively in Table 3. To calculate shrinkage in dimension 'd4' in Figure 3, nodes at areas 'A1' and 'A15' in Fig. 4 are considered. The displacements in y-direction of nodes at areas 'A15' and 'A1' are taken under columns 'H' and 'D41' respectively in Table 3.To calculate shrinkage in dimension 'd1' in Figure 3, nodes at areas 'A2' and 'A15' in Fig. 4 are considered. The displacements in y-direction of nodes at areas 'A15' and 'A2' are taken under columns 'H' and 'D11' respectively in Table 3.

To calculate shrinkage in dimension 'd0' in Figure 3, nodes at areas 'A5' and 'A6' in Figure 4 are considered. The displacements in y-direction of nodes at areas 'A5' and 'A6' are taken under columns 'D01' and 'D02' respectively in Table 3.

Table 3: Nodal Displacement (in Meter) at Various Steps of Attern

Dimension Variables	D21	D22	H	D61	D41	D11	D01	D02
Nodal Displacement Values At Different Thickeness	2.6E-05	3.11E-05	2.58E-05	3.32E-05	5.76E-05	0.000028	3.39E-05	3.46E-05
	2.4E-05	1.86E-05	2.32E-05	2.95E-05	4.08E-05	4.56E-05	7.28E-05	6.86E-05
	2.6E-05	3.12E-05	2.69E-05	0.000035	5.61E-05	2.78E-05	7.15E-05	7.25E-05
	2.5E-05	1.93E-05	2.32E-05	2.96E-05	3.96E-05	4.61E-05	7.19E-05	7.13E-05
	5.4E-05	4.12E-05	4.04E-05	4.62E-05	6.82E-05	6.15E-05	0.000067	0.000067
	5.7E-05	3.88E-05	4.63E-05	4.06E-05	6.11E-05	0.000061	7.25E-05	7.29E-05
	5.2E-05	8.18E-05	4.88E-05	4.69E-05	6.96E-05	5.97E-05	7.07E-05	7.23E-05
	5.5E-05	8.14E-05	4.11E-05	4.04E-05	6.03E-05	6.27E-05	7.01E-05	7.14E-05
	5.5E-05		4.65E-05	7.39E-05	0.000138	6.42E-05	7.17E-05	7.28E-05
	5.5E-05		0.000041	7.99E-05	0.000136	0.000185	7.21E-05	0.000072
	0.00013		4.59E-05	5.38E-05	0.000132	0.000187	7.18E-05	6.52E-05
	0.00014		4.84E-05	5.42E-05	0.000139	0.000202	6.95E-05	6.83E-05
	0.00014		4.09E-05	0.000101	0.000186	0.000207	6.39E-05	6.23E-05
	0.00013		4.59E-05	0.0001	0.000179	0.000195	6.47E-05	
			5.45E-05	0.000102	0.000159	0.000171	6.87E-05	
			5.37E-05	0.000101	0.000155		6.52E-05	
			3.44E-05	0.000088	0.000149		6.09E-05	
			0.000099	8.63E-05	0.000142			
			0.0001	9.04E-05	0.000153			
			0.000108	8.77E-05				
			0.000101					
Average=	**6.91E-5**	**4.29E-05**	**5.61E-05**	**6.60E-05**	**1.12E-04**	**1.07E-04**	**4.72E-05**	**4.50E-05**

Average of displacements of nodes in each column was taken in Table 3. Then total contraction in each dimension was calculated by adding (Table 4) the average displacements at two ends of that dimension found from Table 3. The same procedure is adopted to calculate shrinkage from the experimental data obtained by measuring the dimensions at number of points (Table 5). The calculated mean percent contraction is 0.429 % (Table 4), which is nearly half of the value for 5th blend (Table 5). For other blends difference vary by large amount. The deformed and undeformed wax pattern is shown in Fig. 5 and Fig. 6.

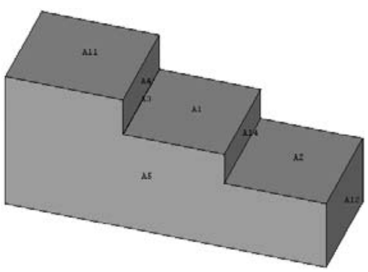

Fig. 4: Wax Pattern with Area Numbers on the Faces

Calculated result for shrinkage is also found to be approximately equal to shrinkage data given in Sabau *et al.* [5], as shown in Fig. 7.

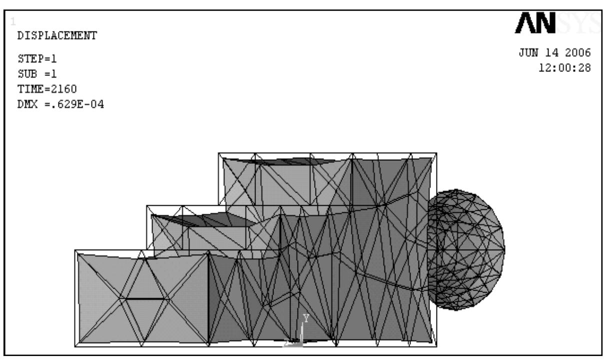

Fig. 5: Deformed Wax Pattern with Undeformed Edges

Table 4: Mean Percent Contraction in Various Dimensions of Pattern

Contraction in Dimension (in mm)		Required Dimension (in mm)	% Contraction
D2	0.112	97.06	0.115
D6	0.122	38.63	0.316
D4	0.168	28.15	0.597
D1	0.163	19.40	0.840
D0	0.0922	33.00	0.279
Mean % contraction			0.429

Table 5: Wax Blend Property Values (Experimental Data)

Blend No.	Mean % Contraction	Mean % Volume Contraction
1	2.99	9.89
2	1.64	5.15
3	1.7	5.17
4	1.05	2.93
5	0.89	2.64
6	1.4	4.48
7	1.67	5.26

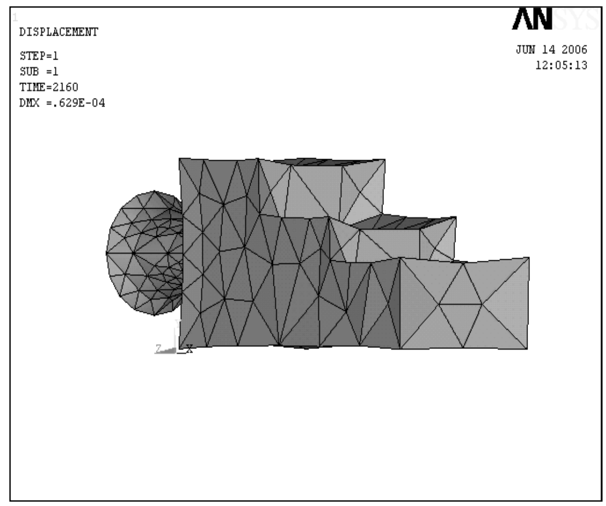

Fig. 6: Deformed Wax Pattern

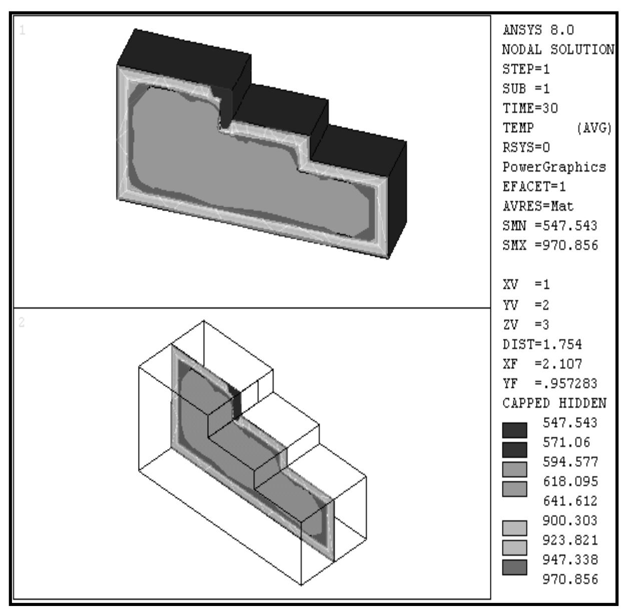

Fig. 7: Temperature Distributions at 30 to 600 Seconds

Conclusion

The following are the conclusions drawn from the discussions:

- Numerical simulation of wax solidification was found useful to calculate and control the shrinkage of wax pattern to improve the accuracy of products.
- The mean percent contraction has been calculated. Result from analysis is compared with experimental work. The experimental data for the 5^{th} blend was near to calculated mean percent contraction value.

Calculated mean percent contraction is verified from the shrinkage data given in Sabau *et al.* [7]. The experimental result of wax shrinkage in the above literature was for 2-dimensional stepped pattern.

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