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Phase Changing Material Used with RP Technology in Quick Wax Molding for Investment Casting

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ABSTRACT

This paper presents a study of replacing, in the domain of wax injection molding process, the traditional metallic mold with a mold made of a RP plastic material combined with a PCM material. The process being studied here uses melted paraffin wax as the injection material. Numerical simulation of transient heat transfer was conducted with COMSOL multi-physics software. The behavior of the melting and heat absorption of PCM was simulated by modifying the specific heat of the material to account for the increased amount of energy in the form of latent heat of fusion over its melting temperature range. ABS plastic mold was made through FDM Rapid Prototyping process and a carefully prepared experiment was successfully conducted. To confirm the validity of the numerical simulation, the data acquired during the experiment was compared with the numerical results and the outcome was satisfactory.

Keywords: wax mold, investment casting, PCM, heat transfer, rapid prototyping.
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1 INTRODUCTION

All around the world, engineers strive hard in order to improve existing tools, produce newer, more creative and most importantly more useful tools, in order to make daily lives easier. Investment casting is one of the processes that were invented for that objective. It is an industrial process based on one of the oldest known metal-forming techniques. It can produce complicated shapes that would be difficult or impossible with die casting yet it requires little surface finishing and only minor machining [7]. Traditional investment casting process uses wax as the expendable material therefore it is sometimes called “lost wax casting”. After the wax patterns are made and attached to a wax tree, they are dipped in ceramic slurry (composed by refractory powder and binder) to create layers that, after air drying, will act as a ceramic shell. A de-waxing process will take place to remove the wax by placing the dried ceramic shell inside an oven at the temperature about 180˚C. The wax will melt and flow outside the ceramic shell. This removed wax can be reused after the de-waxing process lowering material costs. Then the hollow ceramic shell will be exposed to higher temperatures, typically around 1120˚C, for two purposes: further hardening to withstand the stresses and create a vacuum when the molten metal is poured in to form metal parts.

With the development of technologies, Rapid Prototyping (RP) and Rapid Manufacturing (RM) quickly gained popularity due to their flexibility and their competitiveness on the market. RP focuses on small quantities and complex geometries. Its application on investment casting gives designers the freedom to rapidly modify and redesign a product without significant increase of the total development time and cost. RM focuses on fast production, reducing lead-time and labor.

The use of Thermal Energy Storage (TES) can change the world of energy today as it refers to a number of technologies that store energy in a thermal reservoir for later use. They allow an improvement in the use of solar energy therefore connecting day-time and night time which seems to be a very good way of exploiting better the daily sunlight energy. Nowadays, TES has various domestic, industrial and power generation applications while still conquering other technologies such as heating, ventilation and air-conditioning systems due to the fact that it can dramatically help reduce energy cost. TES can be divided into three main types of thermal energy storage: Sensible, Thermo-chemical and Latent. The storage capacity and the possibility of using Latent-Heat Energy Storage Systems (LHESS) are due to the fact that some materials, such as Phase Changing Material or PCM, have a large heat of fusion that can be used to store thermal energy. The modes of heat transfer encountered in the melting and solidification of PCM are mainly conduction, convection and close contact melting. As demonstrated in the following section in this paper, the convection mode can be neglected while the close contact melting plays an important part only during start-up period [1], [11].

In this paper, a simulation has been made to study the transient heat transfer process that occurs after injecting Paraffin wax in an ABS plastic and PCM mold considering mainly the conduction mode. The intention is to use the large latent heat storage capacity of PCM (Rubitherm) to extract the heat contained in the liquid Paraffin wax in order to obtain a solid wax pattern. A successful experiment was conducted, providing satisfactory results and solid wax pieces.

2 SETUPS FOR NUMERICAL SIMULATION

2.1 Geometry

The physical model used for this study is presented in Fig. 1 where main parts can be observed: covers (or containers) which will be the PCM recipient and the cavity where the wax paraffin is injected. These parts are separated by a thin layer of ABS plastic.

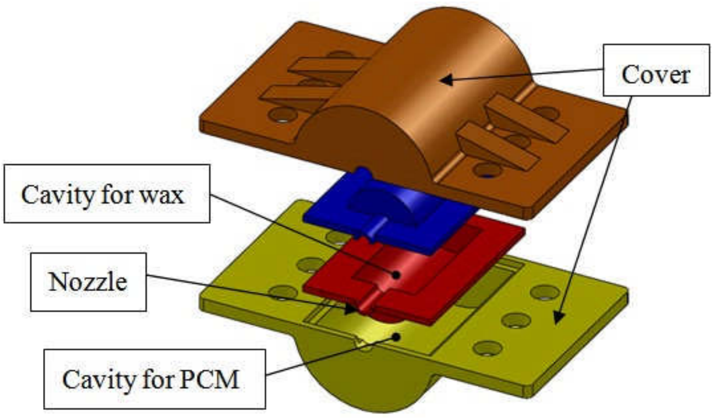

Fig. 1: Real design geometry.

The two cavity parts are made to contain the injected wax through the nozzle as can be seen on the previous picture. The PCM material will be ‘trapped’ between the cover and the wax cavity.

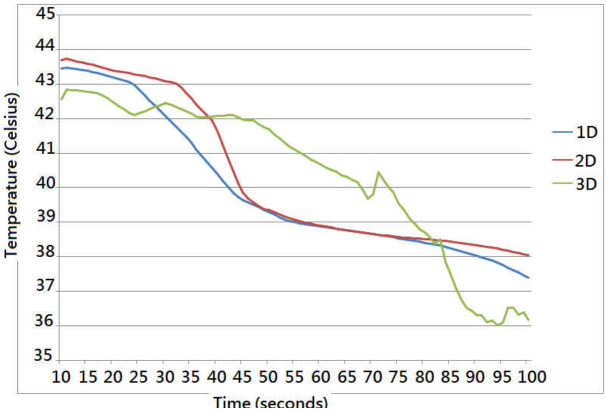

Fig. 2: Temperature vs. time in 1D, 2D and 3D heat transfer simulation [3].

From previous study [11], 1D, 2D and 3D simulations using COMSOL Multi-physics software revealed that these systems all give almost the same trend (Fig 2). For time saving purpose, 2D simulation setting was used in this paper and the setting is illustrated in Figure 3.

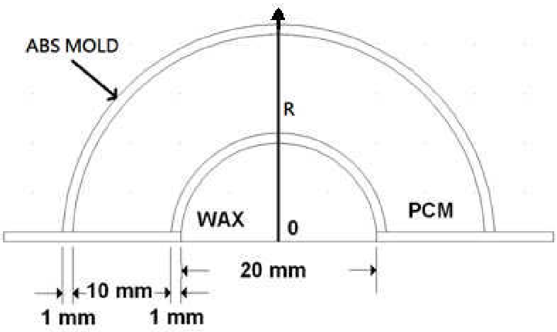

Fig. 3: 2D model for the actual system [6-8].

2.2 Material Properties

The material used in both the simulation and the experiment are described in table 1. Since both wax and PCM behave nonlinearly with phase changing, special treatment should be considered for the simulation. Details are presented in sections 2.5.1 and 2.5.2.

WAX PARAFFIN:	
Thermal conductivity:	0.21 W/m.K
Heat capacity:	2.5 kJ/kg.K
Density:	900 kg/m^3
Enthalpy of fusion:	210 kJ/kg
Melting range:	44^0 C to 46^0 C
PCM Rubitherm SP22 A4 exp:	
Melting point:	24^0 C
Solidification point:	22^0 C
Heat capacity:	165 kJ/kg
Density: (@20^0C)	1.38kg/dm^3
Specific heat capacity:	2.5 kJ/kg.K

	Thermal conductivity:	0.6 W/m.K
ABS:		
	Melting range:	110 to 125⁰C
	Thermal conductivity:	0.188 to 0.334 W/m.K
	Density:	1040 kg/m^3
	Specific capacity:	1.54 kJ/kg.K

Tab. 1: Physical material properties considered in the system.

2.3 Governing Equations

Four physical processes have to be simulated in order to study the entire energy storage processes happening inside the LHESS: fluid flow, heat transfer by conduction and convection, and phase change heat transfer. This section presents a summary of the equations needed to account for all four processes.

2.3.1 Heat Transfer: Convection

The energy equation describing convection heat transfer process is given by:

$$\rho C_p \frac{DT}{Dt} = k\nabla^2 T \quad (1)$$

where C_p is the specific heat of material, k is the thermal conductivity and T is the temperature. The effect of convection on the heat transfer process is taking care of in the material derivative term DT/Dt of Eq. (1).

2.3.2 Heat Transfer: Conduction

It can be assumed that the effect of convection in the melted PCM is negligible [6]. Therefore heat transfer in the rest of the LHESS is by conduction only. In this case, the heat conduction equation as to be solved through:

$$\rho C_p \frac{T}{t} = k\nabla^2 T \quad (2)$$

2.3.3 Heat Transfer in Phase Change Material

In order to account for the phase change processes during PCM and wax melting, the following equation should be solved at the melting interface:

$$k_s \vec{\nabla} T_s - k_l \vec{\nabla} T_l = \rho L \frac{dX}{dt} \qquad (3)$$

where the subscripts *s* and *l* stand for the solid and liquid phase, *L* is the latent heat (enthalpy) of fusion, and *X* is the position of the melting interface. Eq. (3) was not solved using COMSOL, a different equation was used to account for the melting process; A different procedure is used to solve this equation as shown in the numerical resolution. [11][5]

2.4 Boundaries Conditions

Outside boundaries are set to be exposed to room temperature of 298.15 K (25⁰C), as can be seen on figure 4. Due to the symmetric geometry, adiabatic boundary condition was applied on the horizontal center line.

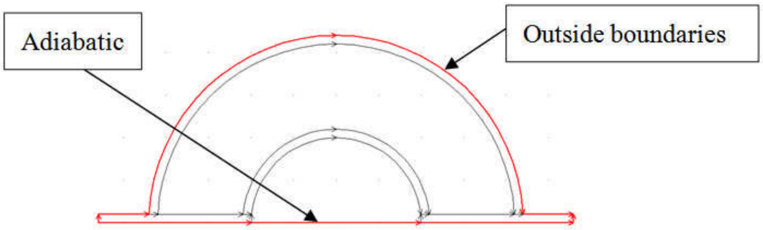

Fig. 4: Setup for the insulated simulation [2].

2.5 Numerical Solution

In order to solve these systems with COMSOL software, taking into account the melting interface and the energy needed to melt the paraffin wax Eq. (5), the non-linear specific heat must be replaced by changing specific heat C_p.

2.5.1 WAX

Using a paraffin wax that has an enthalpy of fusion of 210 kJ/kg and melts over a 2°C temperature range (from 44 °C to 46 °C), the specific heat was modified as the following: [10] Determination of the latent heat of WAX Paraffin for phase change between 44 °C and 46 °C.

- Required theoretical energy for phase change +2 degrees Celsius margin[4-5]:

$$Q = C_p m \Delta T + mL_f = 0.1935 kJ$$

- Equivalent Cp to obtain same result:

$$Q = C_p m \Delta T = 0.1935\ kJ$$
$$C_p = 107.5 \frac{kJ}{kg.K}$$

$$\text{Cp(WAX)}: \begin{cases} 2.5 \text{ kJ/m.K} & \text{for } T<44^0C \\ 107.5 \text{ kJ/m.K} & \text{for } 44^0C < T < 46^0C \\ 2.5 \text{ kJ/m.K} & \text{for } T<46^0C \end{cases}$$

<u>COMSOL formulation (Cp of WAX)</u> looks like:
Cpwax(T) = 2500*(317.15>T)+107500*(317.15<T)-105000*(319.15<T)
The following graph can then be drawn using the command “function” within COMSOL software.

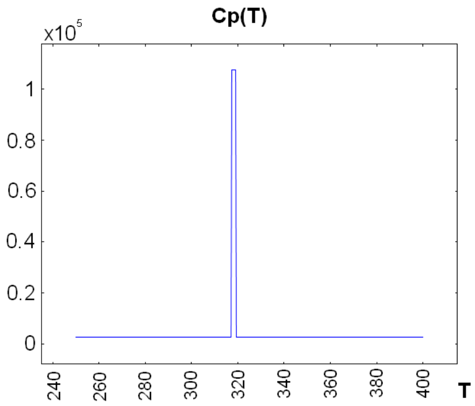

Fig. 5: Relationship between C_p and temperature in COMSOL (WAX) [11]

2.5.2 PCM

Using a PCM that has an enthalpy of fusion of 165 kJ/kg and melts over a 2°C temperature range (from 22 °C to 24 °C), the specific heat was modified as the following: [10] Determination of the latent heat of PCM for phase change between 22 and 24 degrees Celsius.

- Required theoretical energy for phase change +2 degrees Celsius margin:

$$Q = C_p m \Delta T + m L_f = 0.2346\ kJ$$

- Equivalent Cp to obtain same result:

$$Q = C_p m \Delta T = 0.2346\ kJ$$
$$C_p = 85 \frac{kJ}{kg.K}$$

$$Cp(PCM): \begin{cases} 2.5\ \text{kJ/m.K} & \text{for } T<22^0C \\ 85\ \text{kJ/m.K} & \text{for } 22^0C < T < 24^0C \\ 2.5\ \text{kJ/m.K} & \text{for } T<22^0C \end{cases}$$

COMSOL formulation (C_p of PCM) looks like:
$C_{ppcm}(T) = 2500*(295.15>T)+85000*(295.15<T)-82500*(297.15<T)$
The following graph can then be drawn using the command “function” under COMSOL

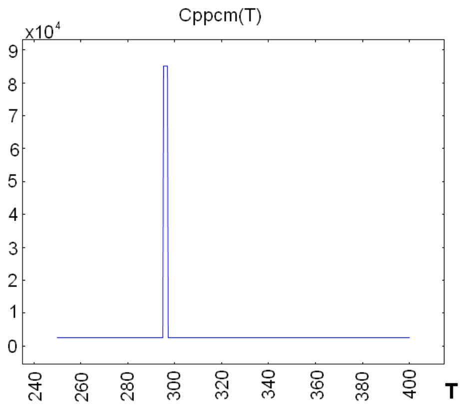

Fig. 6: Relationship between C_p and temperature in COMSOL (PCM).

3 EXPERIMENT AND SETUPS

In order to conduct this experimentation, several steps were taken [7]:
Step 1: Build the mold using a RP machine;
Step 2: Seal the mold;
Step 3: Inject the liquid PCM material in the cavities;
Step 4: Assemble the mold;
Step 5: Place the mold in cold environment (10°C);
Step 6: Take out the mold and inject the liquid wax into cavity;
Step 7: Wait for the wax to solidify;
Step 8: Disassemble the mold and remove the wax pattern [3].

In this experiment, the injection temperature of the wax is approximately 70 °C while the PCM is at 10 °C in the solid state. The wax was heated by an electric stove and a medical needle was used as injection tool. After injecting the PCM into the cavity of the mold and completely sealing, the mold was placed in a refrigerator for several minutes to solidify the PCM and obtain a temperature close to 10°C . The experimentation was done under room temperature (approximately 25°C).

A timer, a thermocouple and a camera were also used during the experiment. The thermocouple was used to record the temperature change at a particular location inside the mold for monitoring purpose but most importantly to verify the predictions made numerically. The timer was jointly used with the camera to keep a visual evidence of the whole experimentation. Graphs were constructed based on the acquired data (Fig.11).

4 RESULTS AND DISCUSION

4.1 Experimental Results

Figure 7 demonstrates the procedure and the outcome of the experiment. The liquid wax was injected at the temperature about 70ºC. This step was then followed by a cooling process and then the mold was opened (figure 7, center) [9]. In this experiment, removing the part took almost no effort, as the part comes out smoothly and little flash is observed (figure 7, right).

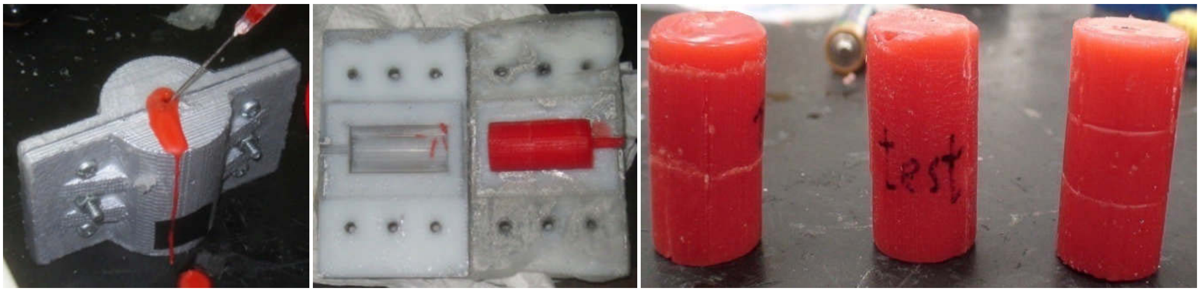

Fig. 7: Wax injection (left), mold open (center), completed pattern (right).

4.2 Numerical Results vs. Experiment

Figure 8 presents the temperature distribution in the wax during cooling process at 20 minutes (1226 seconds). The exact point to be solidified is R=2.5mm from the center of the injected wax [11]. External boundaries are exposed to room temperature in this simulation. It is very obvious that at this moment, wax beyond this point was already solid.

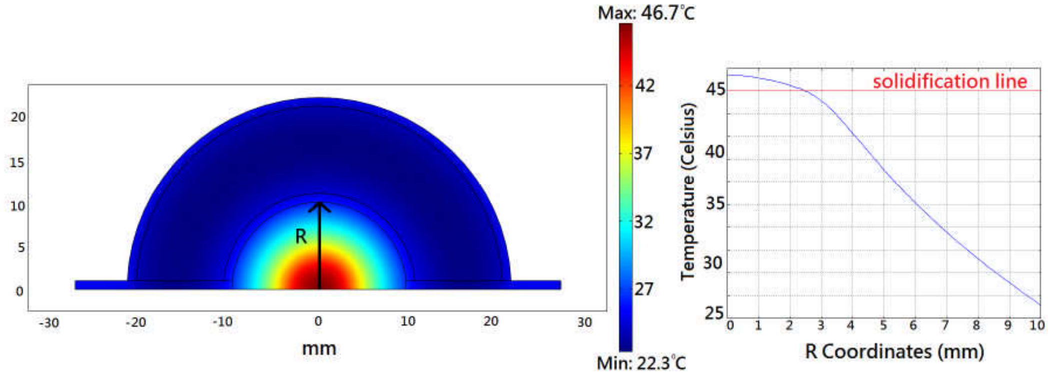

Fig. 8: 2D simulation after 20 minutes (1226 seconds) of cooling.

The cooling target of this experiment and numerical simulation is for 3/4 of the wax to become solid. Then the wax pattern could be removed from the mold without deformation and then be put into cold water for further cooling and hardening. Figure 9 presents the temperature history during cooling at point 2.5mm away from center of wax pattern. The dark horizontal line specifies the solidification temperature at 45ºC. Therefore at 21 minutes, the wax at that point became solid. Therefore the experimentation was a success according to the graph in figure 9.

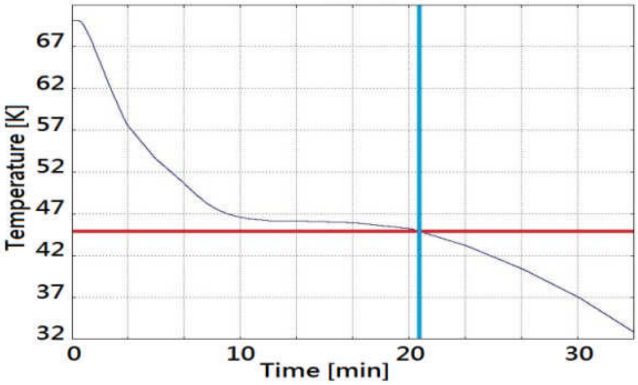

Fig. 9: Temperature varying with time inside wax (R=2.5mm) in Fig. 3.

During the experiment, a camera, a thermocouple and a timer were used to record the data at point R=8.5mm from the center of the injected wax (Fig. 10, 11). The following section exhibits the testing results and compares with the theoretical prediction.

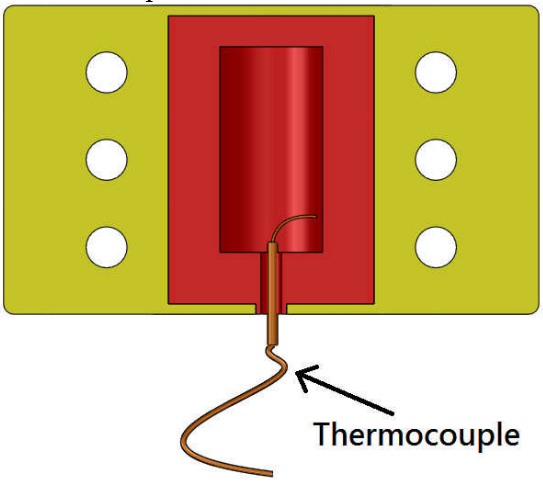

Fig. 10: The position of the thermocouple inside the mold (8.5 mm from the center).

Fig. 11: Temperature measurement during the experiment (solidification point).

At the issue of the experiment, using the acquired data, a graph was built and compared to the predicted graph from numerical analysis as can be seen on the following figure. The predicted curve and the experimental curve exhibit a maximum difference about 3ºC and the trend is consistent.

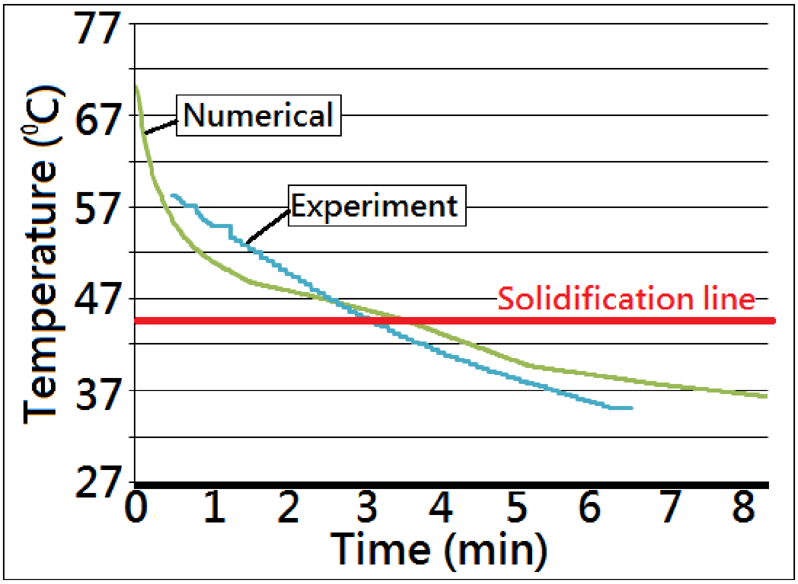

Fig. 12: Experiment graph VS numerical result (8.5 mm from the center).

5 CONCLUSIONS AND OUTLOOK

This paper proposes a new process for quick wax molding using RP technology with PCM material. Numerical simulation was conducted to examine the feasibility of the process.

For the working condition (materials and dimension) considered, about 21 minutes are needed to solidify 3/4 of wax pattern (outter layer).

Carefuly experiment was conducted based on the simulation results, and the outcome was a success.

Comparison was made between numerical predictions and experimental data, the results are satisfactory and the feasibility of the proposed process was confirmed.[11]

Based on the results, it is reasonable to state that, this innovative process provides a new and economical way to produce wax patterns[10].

Further studies are planed to increase the thermal conductivity of the PCM material by adding metal powders with higher thermal conductivity, to reduce the wax solidification time.[6]

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