Temperature Measurements in Wax Patterns and Wax-die Interfacial Heat Transfer Coefficients in Investment Casting

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ABSTRACT

In the investment casting process, wax patterns are formed by injecting hot wax into metal dies. The wax shrinks in the die as it cools down. Estimating the wax shrinkage is very important for dimensioning the pattern tooling. In order to predict the wax pattern dimensions after shrinkage in the die using numerical simulation of wax solidification and deformation, the heat transfer coefficient between the wax and the die must be determined. Temperature measurements were made during wax injection and subsequent cooling in the die. It was found that heat transfer through the thermocouple wires significantly affected the accuracy of the temperature data. Accordingly, the wax-die heat transfer coefficient was determined by numerical simulations of the heat transfer in the thermocouple, wax, and die assembly. The best fit to the measured experimental data was provided by a time-dependent heat transfer coefficient.

INTRODUCTION

The investment casting process consists of making a wax pattern, building a ceramic shell around it, dewaxing the ceramic shell, and casting into the shell mold. The wax patterns are formed by injecting wax into a metal die. Following their injection, the wax shrinks in the die as it cools. Estimating the wax shrinkage is very important for dimensioning the pattern tooling (Okhuysen, 1998; Piwonka and Weist, 1998). In order to predict the wax pattern dimensions using numerical simulation of wax solidification and deformation, the heat transfer coefficient between the wax and die must be determined.

In order to obtain data on heat transfer coefficients, temperature data must be obtained in the wax pattern. If temperatures can be measured accurately close to the die-wax interface, the heat transfer coefficient can be computed using the equation,

$$h\left(T_{DIE} - T_{WAX}\right) = -K_{WAX}\, dT/dx, \qquad \text{(Equation 1)}$$

where h is the interface heat transfer coefficient, T_{DIE} and T_{WAX} are the temperatures of the die and the wax at the die-wax interface, K_{WAX} is the thermal conductivity of the wax, and dT/dx is the thermal gradient at the die-wax interface. This approach is applicable only if the temperature gradient can be estimated accurately using the thermocouple data. Due to size limitations, only two thermocouples are usually used and in most cases, a linear temperature profile is assumed to estimate the thermal gradient.

However, obtaining accurate temperature data using thermocouples placed in the wax pattern is very difficult, since the wax is a polymer with a very low thermal diffusivity and it is injected into the die at high pressures. In addition, the temperature must be measured in regions that are close to the die-wax interface where large temperature gradients are experienced as the wax cools in the die. Another factor is that the ratio between the thermal diffusivity of the thermocouple wire and the wax is very high, and is approximately 50. Accordingly, significant heat is conducted along the thermocouple assembly, creating a large difference between the actual temperature of the wax and the temperature of the thermocouple junction. This effect would be eliminated only if the thermocouple assembly were designed to minimize the heat transfer. Such an assembly must involve the insertion of long and very small gauge thermocouple wires into the wax pattern along isothermal regions. However, the high injection pressures at which the wax is injected into the die preclude the use of small gauge thermocouple wire or the use of long thermocouple wires inside the wax.

In this paper, the heat transfer through the thermocouple assembly, die, and wax was considered in order to account for the error in temperature measurement. An unfilled wax, Cerita^{TM} 29-51 (provided by M. Argueso & Co, Inc) was chosen for this study. The thermophysical and thermomechanical properties of the wax were reported previously (Sabau and Viswanathan, 2002). The response time of several thermocouples were tested by dipping them into the wax. A thermocouple was chosen such that it had a good response time and its sheath diameter was large enough to sustain the high injection pressures. Temperature measurements were made during wax injection and subsequent cooling of the pattern in the die. The time response of the thermocouple was estimated from dipping test data. The wax-die heat transfer coefficient was determined from numerical simulations of the heat transfer in the thermocouple assembly, wax, and the die.

THERMOCOUPLE SELECTION AND RESPONSE TIME

Several thermocouples were tested for use in this study by dipping into molten wax. In addition to having a short response time, thermocouples must endure the applied pressures during the injection phase and dwell time. Five thermocouple types were tested: 0.25 mm (0.01 in.) ungrounded in a stainless steel sheath, 0.51 mm (0.02 in.) ungrounded in an Inconel sheath, 0.81 mm (0.032 in.) grounded in a stainless steel sheath, 0.81 mm ungrounded in a stainless steel sheath, and 0.81 mm ungrounded in an Inconel sheath. The cooling curves for the thermocouples tested are shown in Figure 1. Inconel sheathed, ungrounded, 0.81 mm diameter thermocouples were chosen for this study, since: (a) the 0.25 mm thermocouples had the best response time but they could not likely survive the process conditions, (b) they outperformed the similar stainless steel ungrounded thermocouples, (c) they had a response time similar to that of the 0.51 mm diameter thermocouples, but were mechanically more robust, and (d) grounded thermocouples picked up ground loops from the injection machine and exhibited excessive noise.

The temperature data obtained from the dip test was then used to determine the time constants that characterize the response time of a thermocouple. The response time of a thermocouple to a step change in ambient temperature can be expressed in terms of a Prony series:

$$T(t) = A_0 + \sum_{i=1}^{N} A_i \exp\left(-\frac{t}{\tau_i}\right), \qquad \text{(Equation 2)}$$

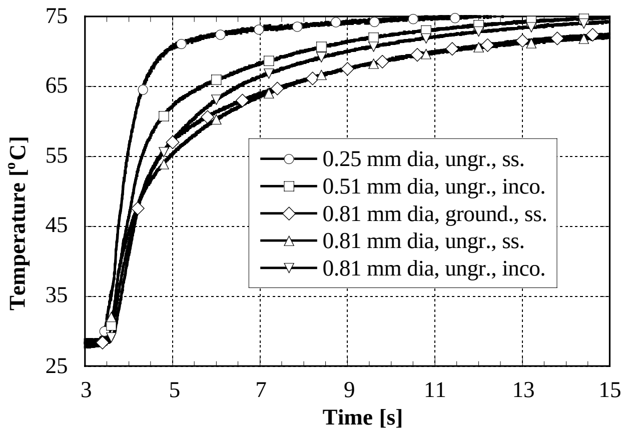

Figure 1. Temperature data obtained during the dip test for various thermocouples.
(ungr. – ungrounded, ground. – grounded, ss. - stainless steel, inco. – Inconel alloy)

From this type of test, only two modal time constants can be usually identified (Hashemian et al., 1992; Tavares et al, 2001). The two modal time constants for the Inconel-sheathed, ungrounded 0.81 mm thermocouple, which were determined by least-square curve fitting of the temperature data, are τ_1= 0.3844 and τ_2= 0.55s.

Following Tavares et al. (2001), the equation for the Laplace transform of the corrected temperature, $T_c(s)$, as a function of Laplace transform of the measured temperature, $T_m(s)$, can be written as

$$T_c(s) = T_m(s)(1+\tau_1 s)(1+\tau_2 s), \qquad \text{(Equation 3)}$$

Without performing Laplace transformations, one can obtain a rough approximation for the corrected temperature, $T_c(t)$, as a function of measured temperature, $T_m(t)$, as:

$$T_c(t) = \tau_1\tau_2\frac{d^2T_m}{dt^2} + (\tau_1+\tau_2)\frac{dT_m}{dt} + T_m(t), \qquad \text{(Equation 4)}$$

where τ_1 and τ_2 are the time constants of the thermocouple. For the sake of simplicity, the Dirac terms that result from the inverse Laplace transform of Equation 3 have been neglected. Corrections of the measured temperature data can be made based on the time response of the thermocouple.

WAX PATTERN DIE INSTRUMENTATION

The geometry of the stepped patterns considered for this study is shown in Figure 2. The 2.54 cm thick step is considered to be Step 1. In order to capture the effects of geometrical restraint on the wax pattern dimensions, cores were placed in the die to provide restraint in the pattern.

The die for the wax pattern had dimensions of 19.5×10.3×9.0 cm. The parting plane of the die almost coincided with the flat surface of the pattern and the centerline of the injection port was in the parting plane of the die (Figure 3). The die was instrumented with thermocouples as shown in Figure 3. The bottom die (Figure 3) had thermocouples in the wax near the die-wax interface in order to obtain data for estimating the heat transfer coefficient at that interface. The thermocouples in the bottom die were inserted into Steps 1 and 2 of the wax pattern. Thermocouples T1 and T3 were inserted 3.2 mm (0.125 in) into the wax, while thermocouples T2 and T4 were inserted 1.6 mm (0.0625 in) into the wax.

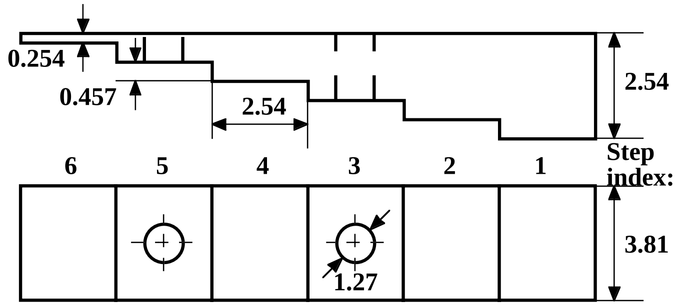

Figure 2: Wax pattern dimensions [cm] and step index.

In order to provide additional stiffness, each thermocouple was placed in an external stainless steel sheath, whose thickness and outside diameter were 0.38 and 1.6mm, respectively. The bare thermocouple was exposed to the wax for a length of approximately 0.75mm from its tip. Thermocouples were held in place by individual fixtures consisting of a ferule and a 1/8 to 1/16 in. pipe thread compression fitting. Thermocouples within each step were placed as close as possible as allowed by their fixtures.

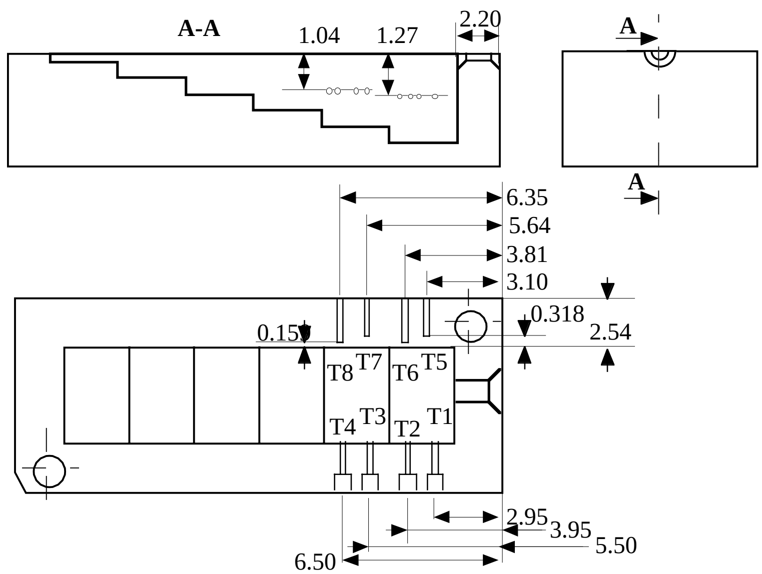

Figure 3. Bottom die showing thermocouple placement (dimensions in cm). Thermocouple index is also shown.

TEMPERATURE AND PRESSURE EVOLUTION DURING WAX INJECTION

For this work, the wax was injected as a paste using an injection machine that was available at the laboratory facilities of M. Argueso & Co. The experimental variables were as follows: injection pressure 2 MPa (300 psi), injection temperature 54°C (130°F), dwell time 30 s, additional dwell time 50 s. The additional dwell time includes the time involved in dismantling the die after wax injection (Sabau and Viswanathan, 2002).

In Figure 4, typical cooling curves in the wax at locations near the wax-die interface are shown for thermocouples T3 and T4, which were placed in Step 2 as shown in Figure 3. The die temperature was 28°C (82ºF) when the data shown in Figure 4 was collected. The data in Figure 4 indicates that the wax injection temperature (54°C) is not recorded by the thermocouples. The maximum recorded temperature, 36ºC, is an unrealistically low temperature, especially since it is measured 4s after injection, and wax has a very low thermal diffusivity and cools very slowly.

The pressure was measured using a pressure transducer (EPX-V01-500P, manufactured by Entran, Inc.) placed in contact with the top surface of the pattern at Step 3. Core pins were not used when pressure was measured, and the pressure transducer was inserted through the die opening for the core pin. The measured evolution of pressure with time, shown in Figure 5, indicates that the pressure drops almost linearly throughout the dwell time. The pressure data suggests that the injection pressure is transmitted into the wax pattern and that contact is maintained between the wax pattern and the die during the application of pressure, i.e., throughout the dwell time.

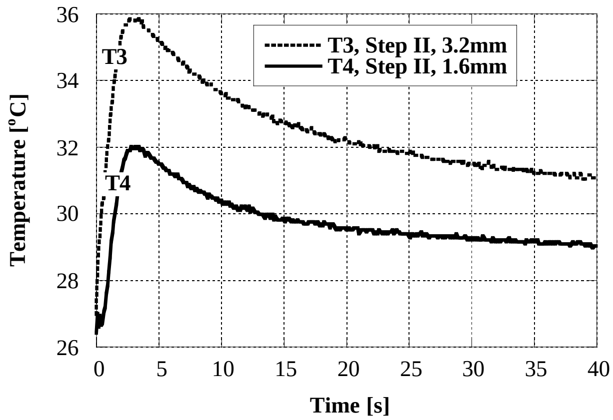

Figure 4: Cooling curves in wax at locations of 3.2 mm (0.125 in.) and 1.6 mm (0.0625 in.) from the wax-die interface for thermocouples T3 and T4 in step 2.

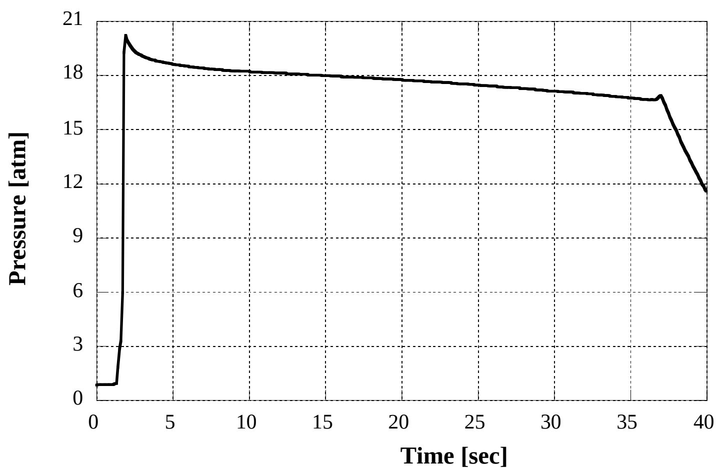

Figure 5: The evolution of pressure in the wax pattern with time.

Temperature Correction for Thermocouple Time Response

The thermocouple data was corrected using Equation 4 and the two modal time constants τ_1= 0.3844 and τ_2= 0.55s for the Inconel-sheathed, ungrounded 0.81 mm thermocouple. The corrected temperature profile is shown in Figure 6. At time = 0, the corrected temperature appears to be close to the wax injection temperature. However, it drops sharply to the measured thermocouple reading of 36°C. Such an abrupt drop in temperature is unrealistic, as noted previously, as wax has a very low thermal diffusivity and cools very slowly. Accordingly, it is likely that the low measured temperatures are due to heat conduction from the wax through the thermocouple assembly.

ANALYSIS OF HEAT CONDUCTION THROUGH THE THERMOCOUPLE ASSEMBLY

The heat conduction through the thermocouple assembly was analyzed by a numerical simulation of the heat transfer through the thermocouple assembly, wax, and die. The thermocouple assembly consisted of Type-K chromel-alumel wires surrounded by a filler (MgO) and an Inconel sheath, as shown in Figure 7. The dimensions of the thermocouple assembly were as follows: diameter of thermocouple wires: 0.13 mm (0.005in.), sheath diameter 0.81 mm, sheath wall thickness 0.13 mm. The thickness and outside diameter of the external support sheath were 0.38 and 1.6mm, respectively, with the thermocouple exposed to the wax for a length of approximately 0.75mm from its tip.

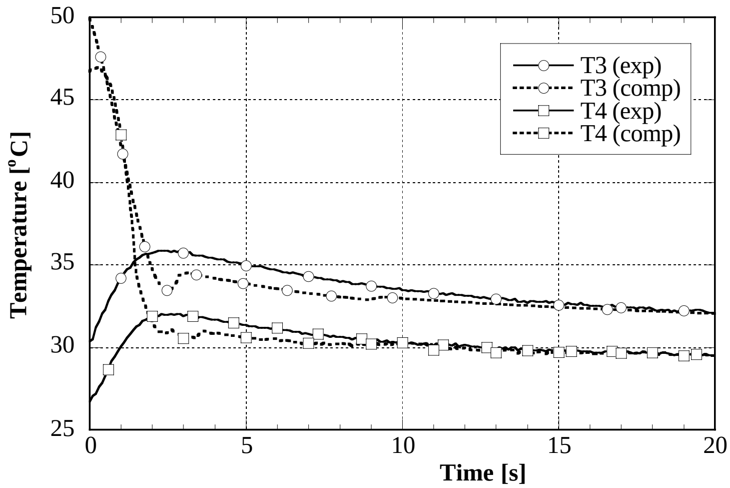

Figure 6: Corrected temperature profile based on thermocouple time response.

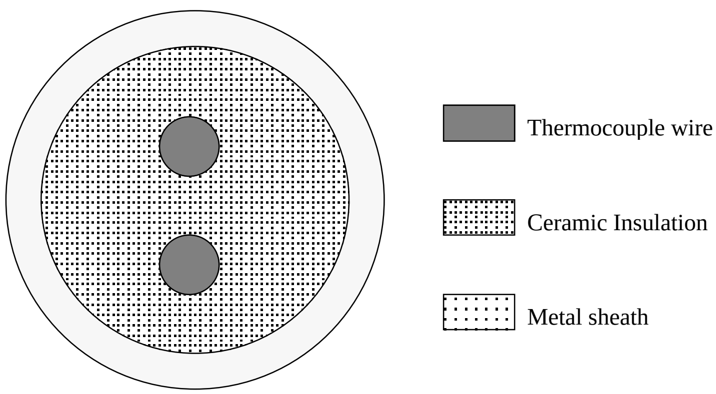

Figure 7: Cross-section of thermocouple wires, filler, and Inconel sheath.

For the sake of simplicity, the numerical analysis was conducted for an axisymmetric configuration as shown in Figure 8. Following Satyamurthy et al. (1979), the chromel and alumel wires were lumped together to form a single wire with an effective diameter of 0.18 mm. The thermophysical properties of the materials used in the analysis are given in Table 1.

Figure 8: Configuration of the thermocouple assembly, external sheath, die, and wax used in the analysis.

Table 1. Thermophysical properties of materials used in the analysis.

Part	Material	Property		
		Density [g/cc]	Thermal conductivity [W/mK]	Specific heat [J/gK]
Thermocouple sheath	Inconel	8.51	15.0	0.46
Thermocouple wires	Chromel-Alumel*	8.49	20.4	0.90
Thermocouple filler	MgO	3.58	40.0	0.88
External sheath	Stainless steel	8.00	16.2	0.50
Mold	Aluminum alloy 6061	2.70	180	0.90
Wax part	Cerita™ 29-51 wax**			

*averaged based on published data for Chromel and Alumel (Satyamurthy, et al., 1979).
**temperature dependent wax properties (Sabau and Viswanathan, 2002).

The values for the heat transfer coefficient used at each interface are shown in Table 2. The contacts between the filler and the thermocouple wire and between the filler and thermocouple sheath were assumed to be very good. The contacts between the external sheath and the die and between the external sheath and the thermocouple sheath were assumed to be reasonably good. Heat transfer coefficients for interfaces with very good contact and reasonably good contact were estimated based on information in the literature and on prior experience. The same time-dependent heat transfer coefficient, h_{wd}, was used at the interfaces between the wax and other materials, i.e., thermocouple sheath, external sheath, and die. h_{wd} was determined by trial and error, as inverse heat transfer analysis provided unrealistic results due to the multiple interfaces involved.

Table 2. Interface heat transfer coefficients used in the analysis.

Material	Material	Heat transfer coefficient [W/m^{2}K]
thermocouple wire	thermocouple filler	5000
thermocouple filler	thermocouple sheath	5000
thermocouple sheath	external sheath	1000
external sheath	die	1000
external sheath	wax	h_{wd}
die mold	wax	h_{wd}
thermocouple sheath	wax	h_{wd}

The trial and error numerical analysis was conducted as follows. Experimental data were available for thermocouples placed 1.6 and 3.2 mm away from the die-wax interface (thermocouples T3 and T4 placed in Step 2 - see Figure 3). The heat transfer coefficient was selected by adjusting its value in order to obtain a good agreement between the measured temperature and computed temperature at thermocouple T3. The temperature reported for each thermocouple was computed at its junction. Constant values for the heat transfer coefficient, as well as values varying with time and temperature were attempted. However, the best fit was obtained when the heat transfer coefficient, h_{wd}, was considered to be time dependent. The final values of h_{wd} were selected to ensure a good agreement with the measured temperatures for thermocouple T3 and checked for consistency with thermocouple T4. The good agreement obtained between the measured and computed temperature values for thermocouple T4 is another evidence that the selected heat transfer coefficients are appropriate for the die-wax interface. The best estimated values for h_{wd} are given in Table 3. A comparison of the measured and computed temperatures at thermocouples T3 and T4 obtained for the best estimate of $h_{wd,}$ is shown in Figure 9.

Table 3. Time dependent heat transfer coefficient at the die-wax interface.

Time [s]	0	2	4	5	10	20	25	40
h_{wd} [W/m^{2}K]	1500	1500	900	700	400	250	200	100

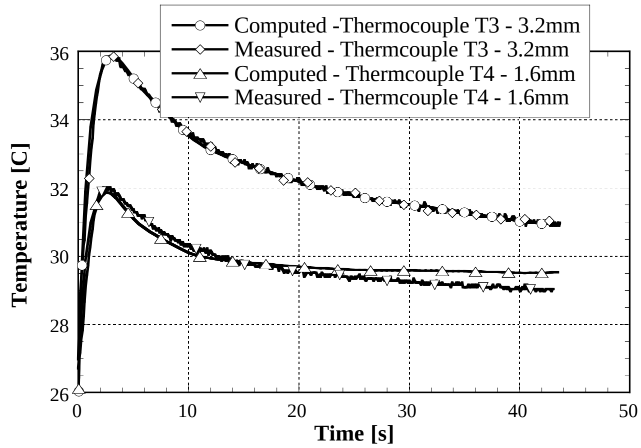

Figure 9: Measured and computed temperatures for thermocouples T3 and T4.

The abrupt decrease in h_{wd} at short times is characteristic of polymer-metal interfaces in general (Pantani et al., 2001). The least square fit to the data shown in Table 3 is given by the following relationship:

$$h_{wd} = \begin{cases} h_0 & t \le 2.5 \\ \dfrac{h_0}{\left(1 + (t - 2.5)/t_c\right)^n} & t > 2.5 \end{cases}, \qquad \text{(Equation 5)}$$

where h_0=1500 W/m^{2}K, t_c=1.41, and n=0.72.

TEMPERATURE PROFILES IN THE WAX

In order to determine the actual temperature profile in the wax, the final numerical simulation was conducted for the wax-die configuration without considering the thermocouple assembly. The calculated temperature distribution in the wax near the die-wax interface is shown in Figure 10. As shown in Figure 10, due to the low thermal diffusivity of wax, thermal gradients near the die-wax interface are extremely steep, especially immediately after wax injection. As a result, temperature measurements at locations 1.6 and 3.2 mm from the wax/die interface will not provide the correct thermal gradient, and the use of Equation 1 to calculate the heat transfer coefficient will provide incorrect results. Accordingly, a combination of temperature measurements and numerical simulation must be used to obtain the correct interfacial heat transfer coefficient.

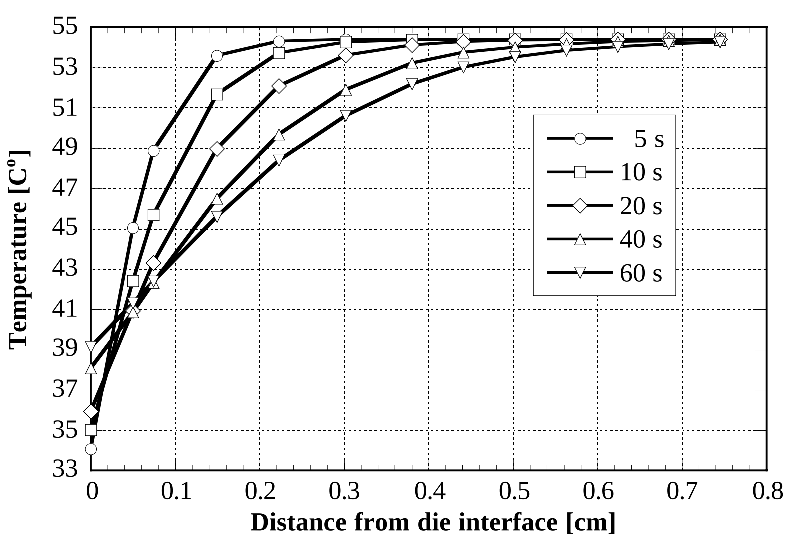

Figure 10: Temperature distribution in the wax near the die-wax interface at various times.

Finally, Figure 11 shows the predicted temperature profiles in the wax at thermocouple locations T3 and T4, based on the results of the numerical simulation. It is apparent that the predicted temperature profiles reflect both the injection temperature and a realistic cooling curve profile that might be expected of a low thermal diffusivity material such as wax. The predicted temperature profile also agrees with experimental observations that wax patterns still had a liquid or pasty core immediately after removal from the die.

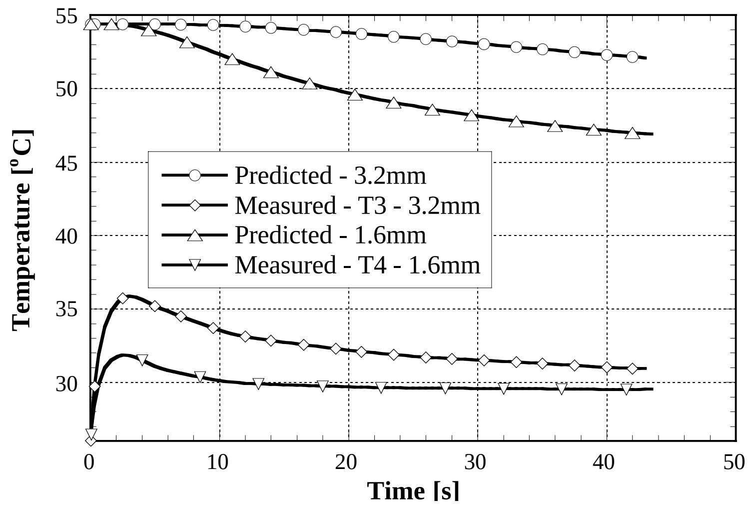

Figure 11: Measured vs. Predicted temperature profiles in the wax pattern for thermocouples T3 and T4.

SUMMARY AND CONCLUSIONS

In order to predict the wax pattern dimensions after shrinkage in the die using numerical simulation of wax solidification and deformation, the heat transfer coefficient between the wax and the die was determined. Several thermocouple types were investigated, and a combination of a sheathed thermocouple and external support sleeve that could withstand the high pressures during wax injection were chosen. The thermocouple assembly performed satisfactorily and temperature measurements were made during wax injection and subsequent cooling in the die. However, the measured temperatures were unrealistically low. Correcting for the time response of the thermocouple did not by itself improve the accuracy of the data, and it was deduced that heat conduction through the thermocouple wires was responsible for the errors in measurement. Accordingly, the wax-die heat transfer coefficient was determined by numerical simulations of the heat transfer in the thermocouple, wax, and die assembly. The best fit to the measured experimental data was provided by a time-dependent heat transfer coefficient. The corrected temperature profiles reflect both the injection temperature and a realistic cooling curve profile that might be expected of a low thermal diffusivity material such as wax.

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