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Mold Temperature Control Effectiveness
Electric Heat vs. Pressurized Water

Background

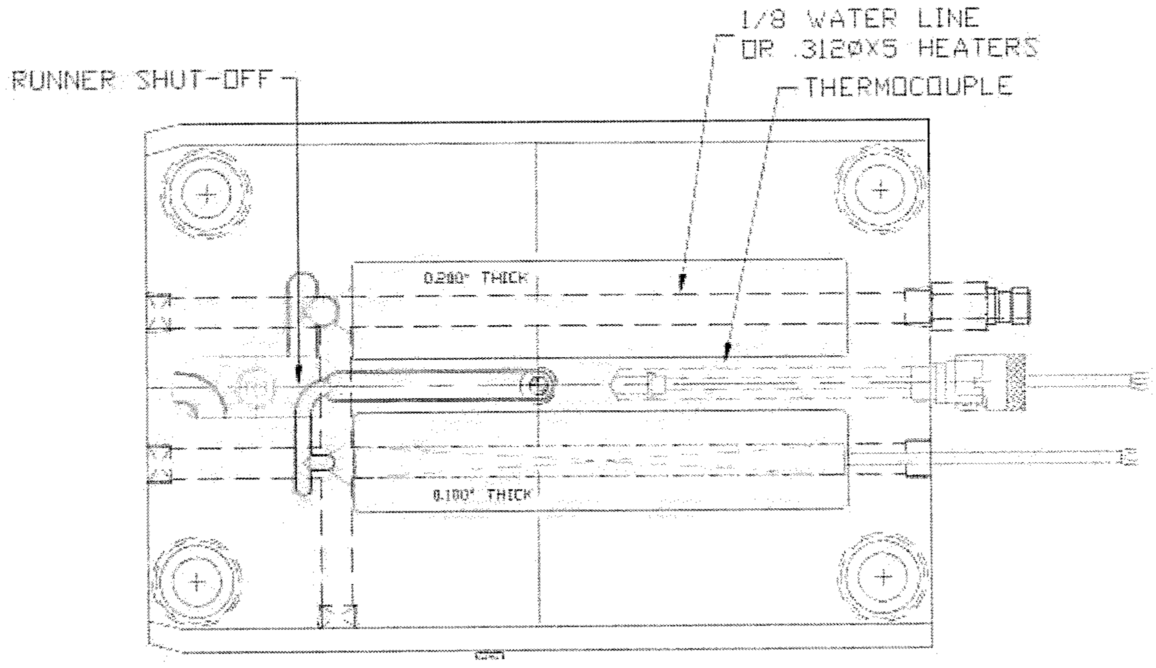
Many materials used for injection molding of medical applications require higher mold temperatures for proper processing than typical water based mold temperature controllers can deliver. Polyetheretherketone (PEEK), polyaryletherketone (PAEK), polysulfone (PSU) and polyphenylsulfone (PPSU) are some of these materials that require mold temperatures in excess of 220 degrees F. Heat transfer oils are typically used for mold temperature control in these high heat applications; however, due to the potential for product contamination, systems that use these oils have traditionally not been used in clean room processing. For this reason, electric cartridge heaters are commonly used to provide mold temperature control in clean room molding for materials requiring these high mold temperatures.

Cartridge heaters have been used for decades in heating many differing molding applications. They do, however, have problems in managing proper mold temperature. The temperature is controlled by applying electric energy to the cartridges based on a comparison of input received from a thermocouple(s) placed in the mold to a temperature set point. This works well for controlling the temperature of the thermocouple location, but not necessarily the mold's cavity surface temperature, which is the most critical for consistency in the quality of the molded parts. Also, cartridge heaters tend to have hot and cold spots along their length which may impact mold surface temperature consistency. Lastly, cartridge heaters have the ability to add heat energy to the mold when the temperature at the thermocouple indicates a value lower than the controller set point. However, they do not have the ability to remove heat energy from the mold if the temperature at the thermocouple is greater than the controller set point. If the heat energy transferred to the mold from the molten plastic is greater than the heat lost by the mold through convection and radiation, the mold temperature will rise until the heat gain and heat loss are equal.

Pressurized water can be heated above the well known boiling point of water, 212 degrees F. There are commercially available systems designed specifically for the temperature control of injection molds that can reach water temperatures of 400 degrees F. In particular, Single Temperature Controls of Charlotte, NC sells these systems. Water systems control mold temperature through the simple principle of temperature equilibrium. The temperature of the water being pumped through the mold is controlled to a set point. The water will transfer heat energy to the mold if the water is at a higher temperature than the mold and the water will remove heat energy from the mold if the mold is at a higher temperature than the water flowing through it.

Experimental Procedure

To determine the effects of electric heat vs. pressurized water on part characteristics, PMC built a mold for a simple plaque to use electric heaters or pressurized water to control the mold temperature. The mold can produce a 1" X 5" X 0.100" plaque or a 1" X 5" X 0.200" with a runner shut-off change. Holes were drilled 0.750" below both parts, centered on the 1" width, on both the stationary and moving halves of the mold. The diameter of these holes was properly sized for a 5" cartridge heater placed directly below the entire part. These same holes could also be used as water channels with the heater cartridges removed. A thermocouple was centered between the two plaques and on the centerline of the 5.0" length on both mold halves for mold temperature monitoring and for control with the electric heat. Please see sketch below.



The material used for all trials was polyetheretherketone. The recommended mold temperature range for this material is from 350 to 400 degrees F. The 2 initial mold trials were using electric heat for each part. The mold temperature controller was set to 380 degrees F and the temperature reading from the thermocouple allowed to stabilize with the mold closed. An optimum molding process was developed using scientific molding principles and methods for both parts. Mold temperature readings were taken on the molding surfaces near the gate, in the part center and opposite the gate after heat soak, after one hour of production and after two hours of production using a surface pyrometer.

After the 2-hour runs for each part were completed, the heater cartridges were removed and the tool was set for pressurized water temperature control using a Single STW200/1-6-25-HO.2 unit. Again, the mold temperature controller was set to 380 degrees F and the temperature reading from the thermocouple allowed to stabilize with the mold closed. The same molding process established for the electric heat was used for the pressurized water. Mold temperature readings were taken just as was performed for the electric heat trials.

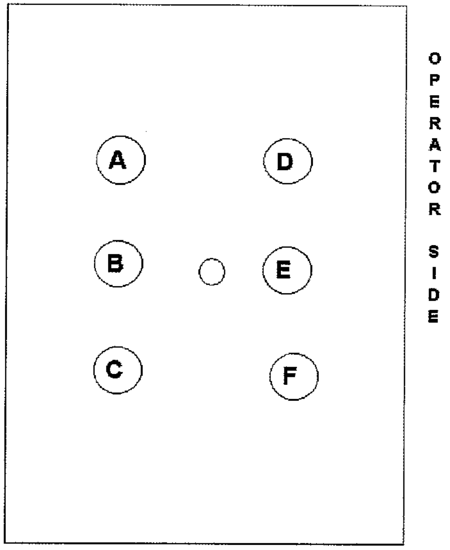
Observations

The time required for the mold temperature to stabilize at the set point of 380 degrees F was noted for both the electrically heated and water heated trials. The electrically heated mold reached equilibrium at the thermocouple within 45 minutes, while the water heated mold reached equilibrium in 135 minutes. This makes sense as the electric cartridge heater can reach temperatures much higher than the set point of 380 in order to shorten the time needed for the thermocouple to read the set point temperature, while the water is flowing through the mold at the set point temperature and will take longer for the thermocouple to reach the set temperature. It is worth repeating that the thermocouple in the mold was used to control the cartridge heaters, while it was used solely for monitoring in the case of the water heated mold, yet both heating methods yielded a steady state mold temperature of 380 as measured at the thermocouple.

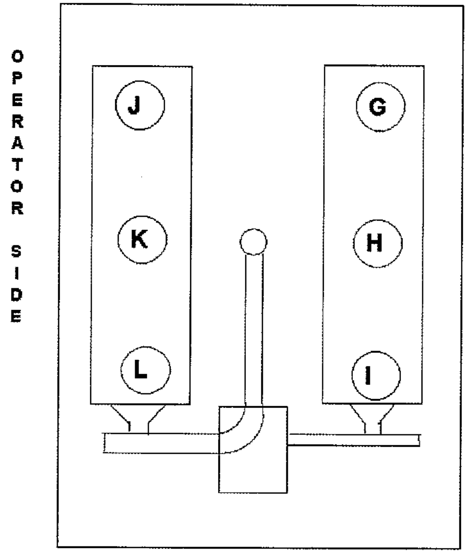
The consistency of the thermocouple reading was also noted during the molding trials. During the electrically heated trials, any changes to the steady state condition yielded large temperature swings in the thermocouple reading. The thermocouple reading changed by as much as +/- 23 degrees F in these trials. After the mold reached steady state during the initial heat soak period, the mold was opened to prepare for the trial. The thermocouple reading dropped significantly at this time, but did recover to reach steady state at the set point within 10 minutes. Once the electrically heated mold trials started, the mold temperature rose quickly. Again, this reading did recover to the set point within 10 minutes. The thermocouple temperature of the water heated molds varied by only +/- 4 degrees and was not greatly influenced by changes in the steady state operating condition.

As described earlier, the mold surface temperature was taken at 12 places in the beginning, middle and end of each two hour run with a surface pyrometer. These sketches depict the locations where the temperatures were taken.

FRONT HALF MOLD TEMP MAP



BACK HALF MOLD TEMP MAP



The measurement results are in the following table.

			Location											
Heat Type	Part	Time	A	B	C	D	E	F	G	H	I	J	K	L
Electric	0.100" Thick	Soak Temp.	326	344	265	317	348	267	315	337	301	321	343	302
		1 Hour	310	329	288	303	329	287	315	344	317	317	341	313
		2 Hours	313	336	289	312	335	289	312	342	321	313	336	316
	0.200" Thick	Soak Temp.	317	337	276	311	338	286	310	346	293	319	351	297
		1 Hour	308	329	286	313	340	290	314	345	318	328	354	323
		2 Hours	311	332	286	317	349	293	311	340	316	327	351	319
Water	0.100" Thick	Soak Temp.	343	347	342	346	349	346	344	346	343	346	348	348
		1 Hour	341	350	342	345	348	342	344	350	346	347	349	350
		2 Hours	342	351	341	343	351	344	343	352	347	348	350	349
	0.200" Thick	Soak Temp.	338	342	342	347	347	346	342	342	341	345	347	346
		1 Hour	343	349	343	347	353	344	341	348	345	350	352	352
		2 Hours	343	349	343	346	354	345	342	347	346	346	349	348

A review of the temperature readings indicates that the water heated runs were more consistent over the 2 hours. The average differential in temperature of the same location over the 2 hours in the water heated runs was 3.5 degrees F, while the average differential in temperature of the same location over the 2 hours in the electrically heated runs was 12.2 degrees F. Although not a major concern, this temperature differential over time for the electrically heated trials could lead to dimensional and physical property changes in the part over the length of the run.

A more concerning point is the difference in temperature over the length of a part. The average temperature differential over the length of one part at the same moment in time is 44.2 degrees F for the electrically heated trials. This average for the water heated trials was only 5.0 degrees F. This large temperature differential over the length of one part in the electrically heated mold would create crystallinity changes within a part. This would create shrinkage differences throughout the part, resulting in a high degree of molded in stress. This stress could cause part warpage, creep and physical property difference within the same part.

Lastly, the overall cycle time between the water heated and electrically heated molds did not change. The rate of heat mass from the molten plastic entering the mold was less than the rate of heat mass being lost from the mold due to convection and radiation. The water and heater cartridges were constantly adding heat energy to the mold to overcome the effects of heat loss, although during the actual runs the energy transferred from the water and heater cartridges was drastically reduced due to the heat energy gained from the molten plastic. As you can imagine, at some critical mass, the rate of heat input from molten plastic will be greater than the rate of heat loss through convection and radiation. Since electrically heated molds can not remove heat energy in any other method, the mold temperature will begin to rise unless this rate difference is compensated by lengthening the cycle time. A water heated mold can remove this heat through transfer into the circulating coolant and lengthening the cycle time is not required.

Results

Five parts were saved after 1 and 2 hours of running and subsequently measured for length, width and weight. They were also analyzed with differential scanning calorimetry (DSC) to determine the % crystallinity in the parts.

The table below indicates the average size and weight values for the 5 parts saved along with the DSC values.

Heating Method	Time	Overall Length (in)	Width (in)			Weight (g)	DSC (Relative Crystallinity %)	
			Opposite Gate	Middle	Gate End		Opposite Gate	Middle
Electric	1 Hour	5.0130	1.0052	1.0034	1.0086	10.63	77	100
	2 Hours	5.0150	1.0047	1.0033	1.0088	10.63	86	100
Water	1 Hour	5.0170	1.0028	1.0040	1.0051	10.67	100	100
	2 Hours	5.0158	1.0029	1.0038	1.0054	10.67	100	100

Reviewing the above data indicates that part size and weight remained stable within 0.05% over the length of the molding trial. The slightly smaller length and weight of the electrically heated mold would indicate less packing of the material. This is confirmed with the colder mold temperatures found at both ends of the cavity, causing the gate and the part itself to freeze slightly quicker in these areas.

The most interesting trend in this data is the difference in width over the same part. The water heated mold produced parts which reduced in width from the gate end to the end opposite the gate. This is typical and is a result of the pressure loss in the material as it flows through the mold. The shrinkage seen in these measurements is considered uniform if effects of pressure loss are taken into account. Parts from the electrically heated mold however were at their thinnest in the center of the part. This indicates a shrinkage differential through the part. Since the direction transverse to flow is the most sensitive to % crystallinity, this would indicate a large % crystallinity change over the length of the part and is also indicated with the large difference mold temperature readings seen across the same cavity. This shrinkage differential across the part results in molded in stress which reduces dimensional stability over time and the part's resultant physical properties.

The DSC results confirm the concerns raised by the mold temperature readings during the molding trials and the part dimensional results. The water heated mold produced parts that had consistent and acceptable DSC results throughout the length of any one part; however, the parts produced from the electrically heated mold had differing crystallinity percentages throughout any single part. The center of the parts made with electric heat had acceptable crystallinity while the end of the same part had less than optimum crystallinity.

Conclusion

In the experiment performed, both the water heated and electrically heated molding trials exhibited consistent mold temperatures, part dimensions and DSC results throughout the 2-hour runs. The main difference between the two mold temperature control methods was the 44.2 degrees F mold temperature difference throughout the mold when using electric cartridge heaters as compared to the 5.0 degrees F mold temperature difference observed when using the pressurized hot water. The effects of this were seen in the dimensional and DSC testing results. The 0.003" increase in part shrinkage difference seen across the same part and an average of 18.5 % reduction in relative crystallinity difference seen in the same parts produced from the electrically heated mold create molded in stress, which reduces a part's dimensional stability over time and also reduces the total applied stresses the molded part can withstand.

The design of the electric heating system can be improved with multiple control zones and better heater designs to drastically change the results and approach the results of the pressurized water; however, this would involve a larger investment in the mold to achieve similar results. Also, small parts would not exhibit as great of a shrinkage and crystallinity difference as these 1" X 5" plaques and thus not have the risk of dimensional instability and physical property reduction.

Lastly, although not seen in this experiment, there would be a point where the critical heat mass gained through constant injection of molten plastic would exceed the convection and radiation heat losses of the mold, requiring a lengthened molding cycle with electric heat. In pressurized water molds, this excess heat mass can easily be removed by the circulating water, eliminating the need for extending the molding cycle.

Heating molds with pressurized water for those jobs that require high heat for proper injection molding should be considered advantageous over the standard electric heating used in clean room applications. The larger the part to be produced, the more advantageous it will be. Pressurized water has proven to be stable over time and more importantly, more consistent throughout the mold, not exhibiting the hot (or cold) spots seen with electric heat.