A Study of the Thermal Characteristics of P20 Steel and S4 Rapid Tooling Material with Conventional and Conformal Cooling Channels

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Abstract

Rapid tooling inserts for plastic injection molding holds the promise of reduced cycle times and improved part quality. In long-run production, the savings of a few seconds could result in huge cost savings over the life of a product. Uniform cooling of a plastic part will help to reduce possible warpage. Rapid tooling has shown value in prototyping plastic parts for many years. Because of process limitations and materials, long-run production was not feasible with rapid tooling. New developments in both process and materials may make this a reality in the next few years.

This project examines the thermal differences between conventional and rapid tooling inserts. It also examines the thermal differences between a commonly used insert material, P20, and a rapid tooling material, S4 by ProMetal. There are three sets of inserts used in this study. The first insert has conventional cooling lines in P20. One rapid tooling insert is an exact copy of the conventional milled insert in S4. The other rapid tooling insert has conformal cooling in S4. The conventional and rapid tooling inserts that have the same cooling layout are used to directly compare thermal properties of the rapid tooling material to P20. The conformal cooling insert is used to show the benefit of conformal cooling.

A cooling time study was performed to study the performance of the inserts as the time in the mold was changed. Several cooling times were selected and all of the inserts were tested under those conditions. Two semi-crystalline polymer materials, High Density Polyethylene and Polypropylene, and an amorphous polymer material, Polycarbonate, were used in this study.

Introduction

For production injection molding tooling, rapid tooling shows the promise of quickly built injection molding inserts, a reduction in cycle time, and an increase in part quality. Every company wants to get their tooling as soon as possible. Traditional insert manufacturing can take several weeks. When looking at reducing time in the injection molding cycle, there is not much time to reduced out of the injection or packing phases. The cooling phase, however, has more time from which to remove valuable seconds. It is the fear of excessive shrinkage or warpage that keeps a company from making a significant reduction in cooling time. A uniform mold temperature can help produce better parts by cooling the part equally.

Once a part is designed in a solids modeling program, it is a natural progression to use that solids model to create core and cavity inserts. Once the inserts are designed with cooling, ejection, and a runner system, these electronic models can be used by some rapid prototyping machines to create actual inserts.

This study examined the thermal characteristics of both conventional and conformal cooling, as well as the characteristics of the P20 and rapid tooling metal. There were three inserts that were be used in this study. The first is a conventional set of inserts made from P20. These inserts used conventional cooling. They were manufactured on a machining center. The second set of inserts was made by the rapid tooling process. *These inserts also had conventional cooling lines. These cooling lines were identical to the conventional cooling P20 inserts. This set of inserts was used to show the thermal differences between the two types of materials. The last set of inserts was also made with the rapid tooling process and used conformal cooling.

The part geometry was selected because it would pose a challenge to conventional cooling channels (Figure 1). It slopes from a higher level in the back down to a lower level in the front. It also slopes down from the left to the right.

A cooling time study was used to compare the different types of mold and material combinations. The cooling time was set for 90 s and incrementally shortened to 4 s by the end of the experiment. The part and mold temperatures were measured at each of the cooling times. Mold-filling analyses were run to find the optimum cooling time.

For this study, High Density Polyethylene (HDPE), Polycarbonate (PC), and Polypropylene (PP) were used. The HDPE and PC were used to show the differences between a semi-crystalline and amorphous material. All of the preliminary work was done with PP and the results are included in this study.

Background and Theory

Rapid tooling can be broken down into two types, indirect and direct tooling [1]. Indirect tooling is constructed from a rapid prototyping part. A mold is cast around a prototype part. While there are several technologies that can be used for this type of tooling, they all are used with low production quantities [2]. In direct tooling, the inserts are constructed in the rapid prototyping machine.

There are additive and subtractive methods to make direct tooling. The subtractive method uses tool-paths from the solids model to run on a CNC machining center. The use of high-speed machining to create aluminum inserts has become the most common method of producing rapid tooling. Parts produced through the additive method are built up over short periods of time using rapid prototyping methods.

The use of rapid tooling for long-run production is an elusive goal for many rapid prototyping companies. Although there is the advantage of fast delivery time for a set of inserts, most materials are not as hard as traditional mold making steels [3]. At this time, most rapid tooling is used for prototyping and short-run production. All rapid prototyping companies that make machines capable of producing rapid tooling are looking to make tooling materials that are capable of long-run production. In the near future this technology may become a viable option for companies as new advances are made [4]. New processes of prototyping and materials are appearing that may make inserts stronger, more wear resistant, and have better thermally conductivity than what are currently available.

The additive process that creates the direct rapid tooling inserts, which are used in this study, is from ProMetal. It is a 3D-Printing process that was originally developed at MIT. A bed of stainless steel powder is leveled and a droplet of binder is deposited onto the powder bed in a process that is similar to an inkjet printer (Figure 2). The droplet penetrates the powder bed (Figure 3) and adheres with the layer below. When the part is finished, it is in a green state and needs to be sintered. The stainless steel is partially sintered and then the free space around the stainless steel is infiltrated with bronze to produce a fully dense product. Because the shrinkage from sintering cannot be accurately predicted, the solids model is scaled to leave about 1.5 mm of material on the final part. The part then needs to be machined to the final size [5].

The S4 material is a composite of about 60% stainless steel and 40% bronze. When the stainless steel powder is partially sintered, there are holes left in the mold insert. It can be compared to a box full of BBs. Because of the shape of the BB, it cannot pack in tight around the other BBs. This leaves voids between the BBs where they do not touch each other. Under the heat of sintering, the areas, that touch other particles, melts and forms a bond with the adjacent particle. There is some shrinkage of the mold inserts as the particles start to bond. The partial sintering reduces, but does not eliminate the voids. Bronze is used to fill these voids and achieve a full density product. Full sintering can be achieved with certain materials that would eliminate the voids, but would increase the amount of shrinkage of the mold inserts. The S4 material has advantages over fully sintered rapid tooling materials. Because it is not fully sintered, there is less shrinkage and warpage of the inserts. Larger sizes can be made because it does not shrink as much as the fully sintered materials. It does, however, wear more than fully sintered materials because the bronze makes it softer.

P20 is a common pre-hardened steel used as a general purpose material to make mold components and inserts. It is a chrome-moly alloy with a carbon content of 0.30% to 0.40% [6]. The properties for S4 and P20 can be seen in Figure 4. The thermal conductivity of S4 is 22.6 W/(m °K) and P20 is 29.0 W/(m °K). Because S4 is stainless steel based and a composite of two materials, heat transfer is much lower than P20. Cooling of injection molded parts while they are still in the mold has an effect on part dimensions and performance outside of the mold. Each polymer material family has a unique mold temperature based on the processing needs of that material. If the mold temperature is too low, the polymer that freezes against the mold walls may become too thick and choke off the flow between the mold walls. It is the rate that the heat is pulled out after the flow has stopped that is important. Based on material properties, P20 should accomplish this better than the S4.

Machining of rapid tooling inserts made using the S4 material system can pose a challenge for machinists. Although the S4 material is not excessively hard, the fine stainless steel and bronze regions within the material react differently to the cutting edge of the machine tool which can cause conventional high speed tooling to wear prematurely. Therefore, carbide tooling is recommended for machining of this class of materials.

Conformal cooling provides the opportunity for quick uniform cooling. This will help to maintain dimensional accuracy of the part. Conformal cooling can follow the shape of the part being molded. CAE analysis is used to optimize the cooling channels for strength and cooling. Conventional cooling lines are limited to what can be drilled into the mold inserts. In order to get good cooling with conventional cooling channels, they may be sized and put in locations where they could cause weakness in the insert. In typical drilled cooling lines, the general rule of thumb is to keep the cooling lines at least 1.5 times the cooling channel diameter from the mold walls [7]. This is important to keep the high pressure from the injection molding process from breaking through to the cooling lines. With cooling lines custom created for each mold insert, shape and placement can be manipulated to maintain structural integrity.

It is possible to have traditional machined inserts with conformal cooling lines (Figure 5). A sub-insert is created with cooling lines. The main insert is bolted or welded to the sub-insert [8]. An O-Ring is needed to keep the insert from leaking. This two-piece insert arrangement is more costly and time consuming to machine than a conventional insert.

Conventional cooling lines are circular in cross-section because they are drilled into the insert. Conformal cooling channels can be any cross-section. Designers are only limited by their ability to use their solids modeling program and their imagination.

Polymer material properties can be seen in Figure 6. HDPE and PP are semi-crystalline materials. Crystals are formed when the temperature drops enough for the polymer chains to start folding on themselves. This happens because the intermolecular forces begin to dominate the forces between the molecules [9]. This occurs around the Melt Temperature (T_m). When the polymer becomes solid, almost all crystal formation stops. Full crystallinity cannot be achieved because of polymer chain entanglement. The speed of cooling determines the amount of crystallinity. When the mold is colder, the polymer is solidified quickly and does not allow the maximum amount of crystal growth. With a warmer mold, the polymer has more time to form crystals.

PC is an amorphous polymer material. There are no crystals formed when the polymer starts to cool. Polymer structure determines if it will be semi-crystalline or amorphous. There is no distinct melt temperature. There is a general softening temperature which is around the Glass Transition Temperature (T_g). Semi-crystalline polymers have a T_g, but it is the point where the behavior changes from glassy and brittle to leathery.

Equipment and Procedure

The part is 57.15 mm long, 38.10 mm wide, and 29.97 mm high. It slopes down from the back to the front and from the left to the right. Due to the small size of the part used in this study, the wall thickness was set at 2.54 mm.

The inserts used in this study were face mounted on the parting line of the mold to allow for quick insert changes (Figure 7). The water inlet and outlet were located in the back of each insert.

There were two sets of rapid tooling inserts created. One set had conventional cooling lines (Figure 8, Figure 9, Figure 10, and Figure 11) and the other had conformal cooling lines (Figure 12, Figure 13, Figure 14, and Figure 15). A conventionally milled set of inserts was machined to match the conventional cooling line set of rapid tooling inserts.

The inserts were put into the Husky Hylectric 90 injection molding machine. The part temperatures were measured with the Professional Equipment T7350 Infrared Thermometer. The mold temperatures were taken with the Infrared Solutions IR Snapshot camera. An adjustable camera base was built to ensure the camera was positioned the same for each picture.

The inserts needed to be treated before being run and the mold was covered during picture taking. This eliminated problems with emissivity from the inserts.

A flow meter was used to measure flow through each insert. The flow rate of the water was entered in the mold-filling analysis software to verify that there was turbulence in all of the inserts.

The three materials were HDPE, PP, and PC. The HDPE is ME9180 produced by LG Chemical. The PP is 9074MED by Exxon Mobile. The PC is Lexan 124R by GE Plastics.

Using the machined set of inserts with conventional cooling lines as the baseline, an optimal process was established (Figure 16). The mold was run for fifteen minutes to stabilize temperatures. There were three parts collected at each temperature. The mold was then run for five minutes before the next set was collected. As each part dropped out of the mold, the T7350 Infrared Thermometer was used to find the temperature at Location A in Figure 1.

After the parts were measured, the mold would be opened to its maximum mold open height. The IR Snapshot was placed in between the molds. A cover was placed over the top tie bars and around the camera. The picture was then taken.

The other two sets of inserts were then run in the same manner. The results were compared to the machined set of inserts.

Presentation of Data

Part Temperature Results

The temperatures of the HDPE parts can be seen in Figure 17. From 50s to 90s there was no difference in the temperature of the parts. However, nobody would set their cooling time at that range. The S4 Conformal insert reached the steady state temperature at 40s. The P20 insert was very close at this time. Mold filling analysis predicted a cooling time of around 15s for this material. The S4 Conventional insert was about 4°C above the P20 insert at 16s. The S4 Conformal was 4°C below the P20 insert. Using part temperature at ejection as the criteria for the end of the cooling phase, the S4 Conformal inserts can shorten cycle time by about 3s to 4s. This is around a 23.3% reduction in cycle time.

The temperatures of the PP parts can be seen in Figure 18. From 45s to 90s there was no difference in the temperature of the parts. The S4 Conformal insert reached the steady state temperature at 35s. The P20 insert was very close at this time. Mold filling analysis predicted a cooling time of around 19s for this material. The S4 Conventional insert was about 5°C above the P20 insert at 18s. The S4 Conformal was 1°C below the P20 insert. Using part temperature at ejection as the criteria for the end of the cooling phase, the S4 Conformal inserts can shorten cycle time by about 1s to 2s. This is around a 7.9% reduction in cycle time.

The temperatures of the PC parts can be seen in Figure 19. From 60s to 90s there was no difference in the temperature of the parts. The S4 Conformal insert reached the steady state temperature at 35s. The P20 and S4 Conventional inserts only came close at 60s. Mold filling analysis predicted a cooling time of around 15s for this material. The S4 Conventional insert was about 5°C above the P20 insert at 16s. The S4 Conformal was 4°C below the P20 insert. Using part temperature at ejection as the criteria for the end of the cooling phase, the S4 Conformal inserts can shorten cycle time by about 4s. This is around a 26.7% reduction in cycle time.

Mold Temperature Results

In Figure 20 through Figure 28, the cavity insert results are on the top row and the core insert results are on the bottom row. The plots are infrared pictures taken towards the face of the insert.

The mold temperatures for the cavity P20 inserts with HDPE can be seen in the top row of Figure 20. At 18s, there was a 5.07°C temperature difference across the face of the cavity insert. The lowest temperature is 25.66°C and is on the lower step (top of picture). The upper step (bottom of picture), had the high temperature of 30.66°C. The maximum difference between 90s and 4s was 3.47°C in the center of the cavity face. Except for a small area of 1.73°C on the right of the lower step, the temperatures are less than 1°C. There is a spot in the center of the upper step that is at 0.73°C. The core insert had a 2.5°C temperature difference across the face at 18s. The lower step has a temperature 29.1°C. At the transition from the lower to the upper step, the temperature drops to 27.6°C in the center. The upper step is 26.1°C with two spots at 26.85°C and 27.16°C. There was a 2.04°C difference on the highest part of the upper step from 90s to 4s. The difference on the lower step was 1.0°C. Most of the upper step had a difference of 0.35°C with a spot at 0.91°C just above the baffle. The 4s and 10s temperatures showed little difference. This may be due to thermolator variations or inconsistent timing of the camera shots.

The mold temperatures for the cavity P20 inserts with PP can be seen in the top row of Figure 21. At 18s, there was a 4.38°C temperature difference across the face of the cavity insert. The lowest temperature is 25.85 and is on the lower step (top of picture). The upper step (bottom of picture), had the high temperature of 30.23°C. The maximum difference between 90s and 4s was 2.97°C in the left center of the cavity face. The temperatures on the lower step are uniform at 2.16°C. The upper step is uniform at 2.35°C. The core insert had a 2.37°C temperature difference across the face at 18s. The lower step has a temperature 28.16°C. There is a spot at 29.85°C beside the baffle on the lower step. At the transition from the lower to the upper step, the temperature drops to 28.48°C in the center. The upper step is 27.48°C with two spots at 28.41°C and 28.29°C. There was a 1.85°C difference on the highest part of the upper step from 90s to 4s. The difference on the lower step was 0.16°C with a spot that ranged from 0.66°C to 0.91°C. Most of the upper step had a difference of 0.16°C with a spot at 0°C just above the baffle. The 4s picture appears to be cooler than the 10s picture. This may be due to thermolator variations or inconsistent timing of the camera shots.

The mold temperatures for the cavity P20 inserts with PC can be seen in the top row of Figure 22. At 18s, there was a 13.37°C temperature difference across the face of the cavity insert. The lowest temperature is 37.1°C and is on the upper step (bottom of picture). The lower step (top of picture), had the high temperature of 46.85°C at the top of the picture. The lower step has a range of 41.22 to 42.35 with two spots of 43.72°C and 43.85°C. The upper step is 38.66°C with two spots of 37.1°C and 40.35°C. The maximum difference between 90s and 4s was 4.54°C just above the left center of the cavity face. The temperatures on the lower step are uniform at 1.1°C. There is a band that circles around the top of the baffle at 1.48°C. The upper step is uniform at 1.23°C. On the left of the bottom baffle, there is a band at 2.91°C. The core insert had a 9.75°C temperature difference across the face at 18s. The lower step has a temperature range of 41.22°C to 42.35°C. There are two spots on the top and bottom of the baffle on the lower step at 43.72°C and 43.85°C. At the transition from the lower to the upper step, the temperature increases to 42.66°C in the center. The upper step is 38.66°C with two spots at 37.1°C and 40.35°C. There was a 6.47°C difference just above the left center of the core face from 90s to 4s. The difference on the lower step was 0.22°C with two spots of 2.16°C and 2.35°C. Most of the upper step had a difference of 1.91°C with a spot at 1.48°C just above the baffle.

The mold temperatures for the cavity S4 Conventional inserts with HDPE can be seen in the top row of Figure 23. At 18s, there was a 10.32°C temperature difference across the face of the cavity insert. The lowest temperature is 27.41°C and is on the lower step (top of picture). The upper step (bottom of picture), had the high temperature of 30.73°C at the sides. The lower step has a temperature of 29.48°C with a partial ring around the baffle with temperatures of 27.41°C to 27.86°C. The upper step is 29.6°C. The maximum difference between 90s and 4s was 2.35°C just below the left center of the cavity face. The temperatures on the lower step are uniform at 0.29°C. There is a band that circles around the top of the baffle at 2.41°C. The upper step is uniform at 0.35°C. On the left of the bottom baffle, there is a spot at 0°C. The core insert had a 3.45°C temperature difference across the face at 18s. The lower step has a temperature of 28.54°C. There are two spots on the top and left of the baffle on the lower step at 30.54°C and 32.16°C. At the transition from the lower to the upper step, the temperature increases to 30.41°C in the center. The upper step is 28.98°C with two spots at 27.48°C and 29.41°C. There was a 6.54°C difference just right of the baffle on the bottom of the core face from 90s to 4s. The difference on the lower step was 2.72°C with a spot of 4.97°C. Most of the upper step had a difference of 3.54°C with a spot at 6.54°C just right of the baffle. The 10s temperatures appeared a little low. This may be due to thermolator variations or inconsistent timing of the camera shots.

The mold temperatures for the cavity S4 Conventional inserts with PP can be seen in the top row of Figure 24. At 18s, there was a 4.38°C temperature difference across the face of the cavity insert. The lowest temperature is 25.41°C and is on the lower step (top of picture). The upper step (bottom of picture), had the high temperature of 29.79°C at the right side. The lower step has a temperature of 27.54°C with a spot of 25.85°C above the baffle. The upper step is 28.85°C with a spot at 28.04°C above the baffle. The maximum difference between 90s and 4s was 3.04°C at the right side of the cavity face. The temperatures on the lower step are uniform at 0.54°C to 1.29°C. There is a band that circles around the top of the baffle at 0°C. The upper step is uniform at 1.66°C. On the left of the bottom baffle, there is a spot at 0°C. Between the upper and lower step, there is a temperate difference of 3.22°C. The core insert had a 4.38°C temperature difference across the face at 18s. The lower step has a temperature of 27.98°C with a ring around the top of the baffle from 29.16°C to 30.16°C. At the transition from the lower to the upper step, the temperature increases to 30.04°C in the center. The upper step is 29.54°C with a spot at 26.66°C above the baffle. There was a 3.85°C difference at the bottom of the core face from 90s to 4s. The difference on the lower step was 0°C with a spot of 2.35°C. Most of the upper step had a difference of 2.04°C with a spot at 0.22°C just above the baffle.

The mold temperatures for the cavity S4 Conventional inserts with PC can be seen in the top row of Figure 25. At 18s, there was an 8.0°C temperature difference across the face of the cavity insert. The lowest temperature is 39.6°C and is on the lower step (top of picture). The upper step (bottom of picture), had the high temperature of 47.6°C at the left side. The lower step has a temperature of 40.04°C with a band around the baffle at 43.79°C. Just above the baffle the temperature was 40.29°C. The upper step is 45.85°C with a spot at 42.29°C above the baffle. The maximum difference between 90s and 4s was 7.79°C at the right side of the lower step on the cavity face. The temperatures on the lower step are 4.54°C. There is a band that circles around the top of the baffle at 0°C to 7.79°C. The upper step is uniform at 1.04°C. On the right of the bottom baffle, there is a spot at 0°C. Between the upper and lower step, there is a temperate difference of 1.79°C in the middle and 4.91°C on the left side. The core insert had an 8.16°C temperature difference across the face at 18s. The lower step has a temperature of 40.91°C with a spot to the left of the baffle of 47.66°C. At the transition from the lower to the upper step, the temperature increases to 47.16°C in the center. The upper step is 41.6°C with a spot at 49.79°C to the right of the baffle. There was a 6.04°C difference at the bottom of the core face from 90s to 4s. The difference on the lower step was 3.29°C with a ring around the top of the baffle from 6.35°C to 8.04°C. Most of the upper step had a difference of 1.16°C with a spot above the baffle of 5.91°C.

The mold temperatures for the cavity S4 Conformal inserts with HDPE can be seen in the top row of Figure 26. At 18s, there was a 3.56°C temperature difference across the face of the cavity insert. The lowest temperature is 26.1°C and is on the lower step (top of picture). The upper step (bottom of picture), had the high temperature of 29.66°C at the left side. The lower step has a temperature of 26.1°C with a band around the right of the top at 27.41°C. The upper step is 28.85°C with a spot at 29.84°C to the left. The maximum difference between 90s and 4s was 2.66°C at the right side of the lower step on the cavity face. The temperatures on the lower step are 0.66°C on the left to 2.66°C on the right. The core insert had an 3.07°C temperature difference across the face at 18s. The lower step has a temperature of 28.16°C with a spot at the top of 27.04°C. At the transition from the lower to the upper step, the temperature increases to 28.54°C in the center. The upper step is 28.98°C with a spot at 25.91°C. There was a 3.72°C difference at the bottom of the core face from 90s to 4s. The difference on the lower step was 0°C. The upper step had a difference of 0°C. The 10s temperatures appeared a little low. This may be due to thermolator variations or inconsistent timing of the camera shots. The core inserts had a 3°C temperature difference at 18s. The 4s and 10s temperatures showed little difference. This may be due to thermolator variations or inconsistent timing of the camera shots.

The mold temperatures for the cavity S4 Conformal inserts with PP can be seen in the top row of Figure 27. At 18s, there was a 4.19°C temperature difference across the face of the cavity insert. The lowest temperature is 25.79°C and is on the lower step (top of picture). The upper step (bottom of picture), had the high temperature of 29.98°C at the left side. The lower step has a temperature range of 25.79°C to 26.41°C. The upper step is 29.1°C with a spot at 28.35°C in the center. There was no temperature difference between the 90s and 4s. The core insert had an 2.75°C temperature difference across the face at 18s. The lower step has a temperature of 28.73°C with two spots of 29.79°C and 30.1°C. At the transition from the lower to the upper step, the temperature increases to 29.66°C in the center. The upper step is 28.41°C with a spot at 30.35°C. There was a 2.48°C difference at the bottom of the core face from 90s to 4s. The difference on the lower step was 0.79°C. The upper step had a difference of 0.66°C.

The mold temperatures for the cavity S4 Conformal inserts with PC can be seen in the top row of Figure 28. At 18s, there was a 8.19°C temperature difference across the face of the cavity insert. The lowest temperature is 37.97°C and is on the lower step (top of picture). The upper step (bottom of picture), had the high temperature of 46.16°C at the left side. The lower step has a temperature of 39.6°C with two spots at 37.97°C and 41.47°C. The upper step is 43.97°C with a spot at 39.85°C. The maximum difference between 90s and 4s was 0.35°C at the right side of the lower step on the cavity face. The temperature difference on the lower step was 0°C. The core insert had a 9.37°C temperature difference across the face at 18s. The lower step has a temperature of 36.1°C with a ring at the top of 42.6°C. At the transition from the lower to the upper step, the temperature increases to 37.79°C in the center. The upper step is 36.72°C with a spot at 41.6°C. There was a 3.72°C difference at the bottom of the core face from 90s to 4s. The difference on the lower step was 0°C. The upper step had a difference of 0°C with a spot of 2.79.

Comparison of Materials

For Figure 29 to Figure 31, A is the S4 Conventional cavity, B is the P20 Conventional cavity, C is the S4 Conformal cavity, D is the S4 Conventional core, E is the P20 Conventional core, and F is the S4 Conformal core.

The results for HDPE can be seen in Figure 29. The S4 Conventional core and cavity inserts are the hottest of the three sets of inserts. The S4 Conventional and P20 core and cavity inserts showed the same patterns. The S4 Conformal cavity had about a 1°C to 2°C lower temperature than the P20 cavity insert. The S4 Conformal cavity insert had a more uniform temperature. The P20 core insert appeared to be about the same temperature range, but the areas of higher heat are different.

The results for PP can be seen in Figure 30. The S4 Conventional core insert are the hottest of the three sets of core inserts. The S4 Conventional cavity insert appeared to be the coolest, but this may be because of thermolator variations or inconsistent timing of the camera shots. The S4 Conformal cavity and core inserts had about a 1°C to 2°C lower temperature than the P20 inserts. The S4 Conformal cavity insert had a slightly better uniform temperature. The results for the core at 18s were not consistent, so the results at 10s were used.

The results for PC can be seen in Figure 31. The S4 Conventional core and cavity inserts were the hottest of the three sets of inserts. The S4 Conventional and P20 core and cavity inserts showed the same patterns. The S4 Conformal cavity had about a 1°C to 2°C lower temperature than the P20 cavity insert except on the lower level which had about a 4°C to 5°C difference. The S4 Conformal cavity insert had a more uniform temperature. The P20 core insert appeared to be about the same temperature range, but the areas of higher heat were different.

Discussion of Results

The part temperatures, at ejection, are determined by how effective the mold is at removing heat while the parts are in the mold. Regardless of which material was used, the S4 Conformal inserts removed the heat quicker. The cooling channels were closer to the part geometry in the mold and spaced to remove the maximum amount of heat. The cavity insert will usually remove heat better than the core insert. There is more volume around the outside of the part to remove heat from the part. The core has a much smaller volume on the inside to absorb and remove the heat. The only restriction to better cooling of the core was to allow for the center ejector pin. Without the ejector pin, another waterline could have been placed across the top of the core.

The cooling time study of part temperature shows that the S4 Conformal inserts remove the heat from the part quicker than either the P20 or S4 Conventional inserts. The reduction of the injection molding cycle can be achieved with the use of conformal cooling. There are two criteria that can be used to determine the reduction in cooling time. One way would be to use the temperature of the part at ejection. Using the temperature of the P20 insert as the standard ejection temperature, the time it takes for the S4 Conformal parts to reach that same temperature can be compared to the time for the P20 insert. The other criteria would be to use part dimension. However, the geometry was small and the wall thickness was relatively thick for this geometry. There was no measurable change between 90s and 4s on any of the materials. This criteria was not used on this study. The mold filling analysis was used to determine the optimum cooling time for each material on the P20 inserts. HDPE at its optimum cooling time would have a reduction of 3s to 4s with the S4 Conformal inserts. PP can have a reduction of 1s to 2s. PC can have a reduction of 4s. Even though the S4 thermal conductivity is lower than P20, the S4 Conformal cooling layout provides quicker cooling. These optimized cooling lines are placed close to the part and follow its geometry better than the conventional cooling lines. Because of the nature of the construction of the conventional cooling lines, they cannot easily be placed uniformly around the part's geometry.

The P20 and S4 Conventional inserts show the same trends. They both have the same cooling line layouts. The S4 inserts have a higher temperature because they have a higher thermal conductivity. Both sets show that the coolest spot is on the lower level of the cavity insert. A cooling line is located just above this area. When looking at this area, the temperature is about the same no matter what the cooling time is set at. The high level on the core was cooler than the lower level. The baffle had less volume to cool than the lower level baffle. The baffle was fairly good at cooling the core. Since the geometry was essentially two linked cylinders, the baffles should do a good job cooling the core.

Because of the poorer thermal conductivity, the S4 Conventional clearly shows a higher temperature on the top surface face. Although the S4 Conformal insert was made of the same material, the conformal cooling lines do a better job of removing heat.

The cooling lines for the S4 Conformal core can be seen in the pictures. Because there is no line over the top of the insert, it is the hottest area. At shorter cooling times, the center ejector pin can be seen. Since it has no cooling in that area, it will retain its heat.

When comparing the inserts by material, the S4 Conformal consistently shows that it is the coldest of the three inserts. Even though it has poorer thermal conductivity than P20, the placement of the cooling lines is more efficient than the P20. It is 1°C to 2°C lower than P20 in both HDPE and PP. It is 3°C to 4°C lower with PC. Although the conventional cooling lines surround the part, they are not always close to the part. The conformal lines are smaller and closer to the part. This allows the conformal cooling lines to overcome the thermal conductivity of the S4 material.

Potential sources of error in the temperature readings are from thermolator temperature cycling and inconsistent timing or infrared picture taking. The thermolator varied by a few degrees for HDPE and PP. When running PC it varied by several degrees.

There was a delay of about 5s from when the mold was fully open and the infrared picture was taken. The camera was inserted manually into the machine. Every effort was made to keep the same timing each time a picture was made. However, a variance of a second or so could have a big effect on temperature. Not only are the inserts cooling in open air when the mold opens, the cooling water is now cooling the inserts without a hot part touching the mold walls. This could result in a temperature reduction of a few degrees.

Future Work

Another study of part and mold temperatures focusing on the temperature distribution on the sides as well as the tops is ongoing at this time. These results will be compared to mold filling simulation.

Thermocouples will be placed on the parting line of both the core and cavity inserts. Putting thermocouples into the mold steel around the cooling lines and the mold walls is being investigated. They will be used to verify the infrared pictures of mold temperature.

A different infrared camera will be used in future studies. It would be desirable to capture the temperature of the mold right as the mold opens.

A larger part has been designed to investigate part warpage. Dimensional information will help to verify the reduction in cooling time for the cooling time study.

Conclusion

The ability to reduce the cycle time without reducing part quality is very important to companies who are interested in cutting production costs. Even a reduction of a second or two over the production life of a product can result in substantial savings. Uniform cooling with traditional machining methods can be very costly and time consuming. Rapid tooling can construct the conformal cooling lines easily, but the materials that are currently available are not yet ready for long-run production.

The P20 inserts represent a common material and machining practice used in the plastics injection molding industry today. Both of the rapid tooling inserts were compared to the P20. The S4 insert with the same conventional cooling lines as the P20 inserts confirmed that the S4 material was a poorer conductor of heat than the P20. The S4 conformal insert has a lower temperature even though it is made with S4. It is the placement of the cooling lines close to the part geometry in the mold that allows it to remove more heat.

Using conformal cooling, the potential reduction in cooling time for HDPE is 3s to 4s (23.3% cycle reduction), PP is 1s to 2s (7.9% cycle reduction), and PC is about 4s (26.7% cycle reduction). This is based on using part temperature at ejection as the criteria. This reduction is due to the placement of the cooling lines closer to the part geometry inside the mold inserts. The S4 material has a poorer thermal conductivity than P20. The placement and diameter of the conformal cooling lines was able to make the S4 perform better than the P20. However, care must be taken when designing the conformal cooling channels. If the cooling lines are not optimized, the heat transfer could be less than the P20.

In the future with new advances in materials, conformal cooling lines mated with rapid tooling inserts that have better thermal conductivity will have more potential for cycle time reduction and superior part quality than is available today.

Acknowledgements

Thanks go to John Arlotti and ExOne for providing the rapid tooling inserts. Many thanks go to my wife, Kim, Lucy Lenhardt and Shelley Readel for their constant revisions.

Special thanks go out to Rick Coon for machining the inserts and helping to plug leaks in the inserts. Thanks also go to Glen Craig and Matt Baker for helping to plug leaks in one of the inserts.

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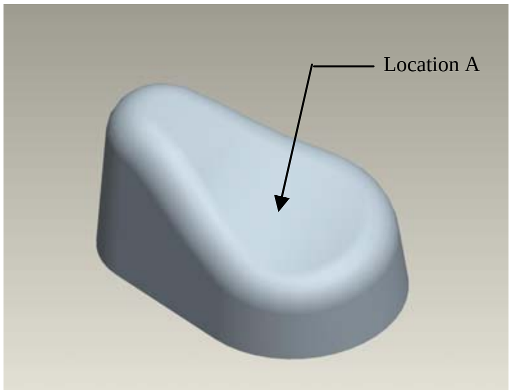

Figure 1 - Part Geometry

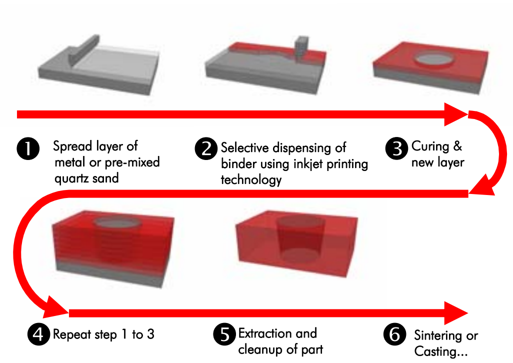

Figure 2 - EXONE Process
(picture provided by ProMetal)

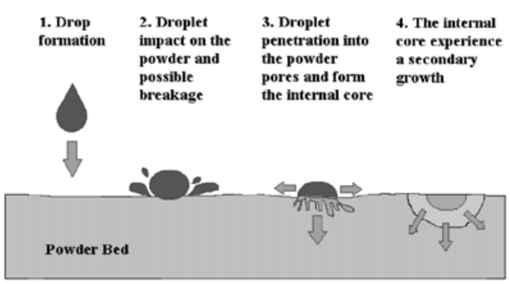

Figure 3 - EXONE Process
(picture provided by ProMetal)

S4 - Material Properties

Material		P20	
Powder	SS		
Infiltrator	Bronze		
Ultimate Tensile Strength	682	971	Mpa
Yield Strength	420	850	Mpa
Modulus	147	205	Gpa
Elongation	2.3	16	%
Hardness	26	32	HRC
Thermal Conductivity	22.6	29	W/m °K
Mean CTE (at 300°C)	1.34E-05	1.28E-05	1/°C
Specific Heat	478	460	J/Kg °K

Figure 4 - S4 Material Properties
(S4 properties courtesy of ProMetal)

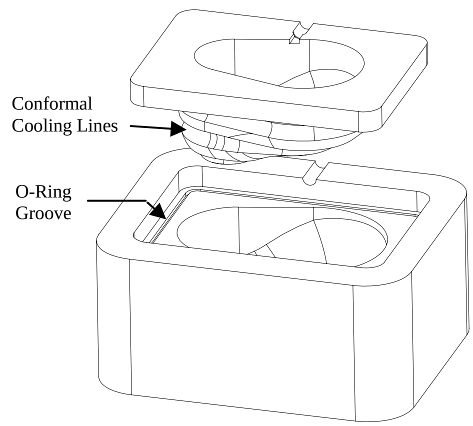

Figure 5 - P20 Conformal Cooling Lines

General Polymer Properties

Material	HDPE	PP	PC	
Density	0.958	0.902	1.19	g/cm^3
Tensile Strength	28.4	34	63	Mpa
Flex Modulus	98.7	1170	2300	Mpa
Thermal Conductivity	0.26	0.16	0.21	W/(m °K)
T_m	133	160		°C
T_g	-125	-10	150	°C

Figure 6 - Polymer Properties

Figure 7 - Insert Mold

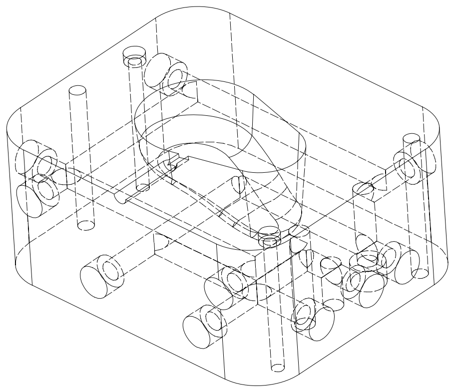

Figure 8 – Conventional Cavity Insert

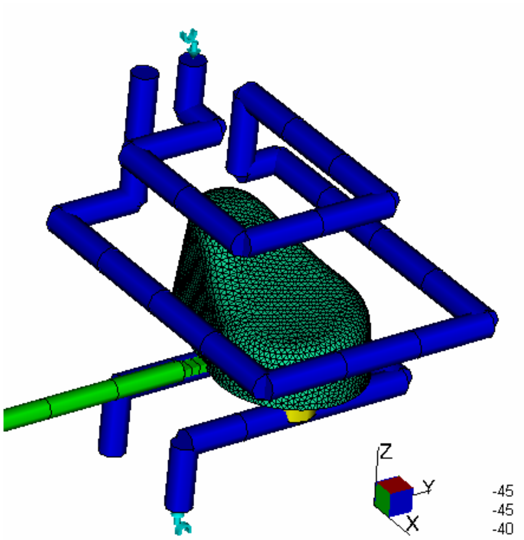

Figure 9 – Conventional Cavity Cooling Lines

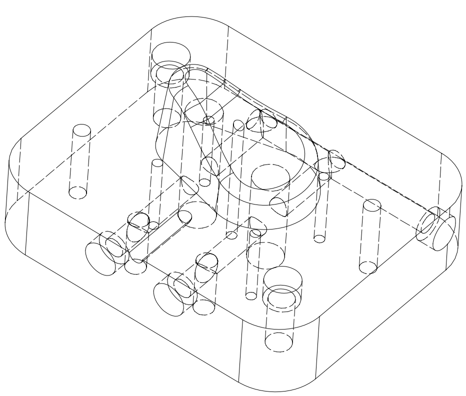

Figure 10 - Conventional Core Insert

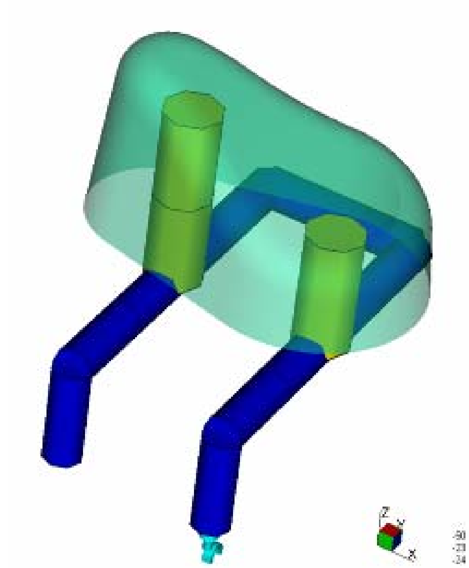

Figure 11 - Conventional Core Cooling Lines

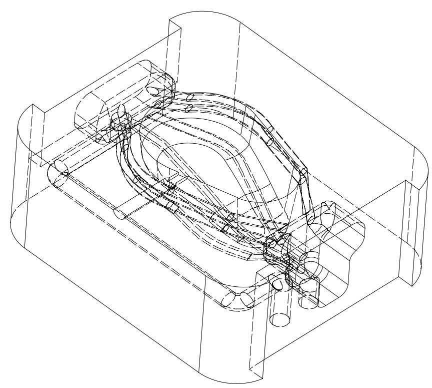

Figure 12 - Conformal Cavity Insert

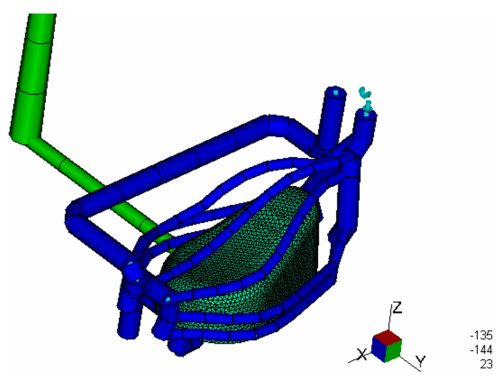

Figure 13 - Conformal Cavity Cooling Lines

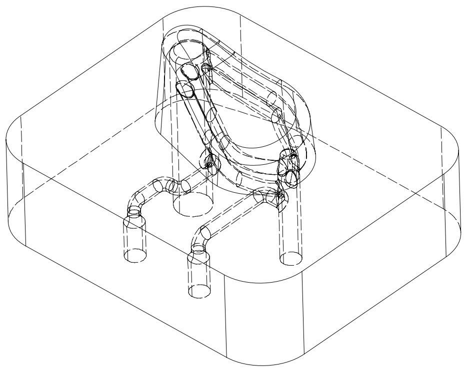

Figure 14 - Conformal Core Insert

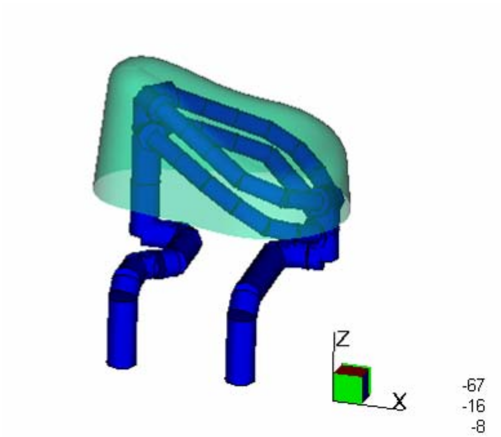

Figure 15 - Conformal Core Cooling Lines

Processing Conditions

Material	HDPE	PP	PC
Melt Temperature	176.67	204.44	304.44 °C
Mold Temperature	32.22	32.22	54.44 °C

Figure 16 - Processing Conditions

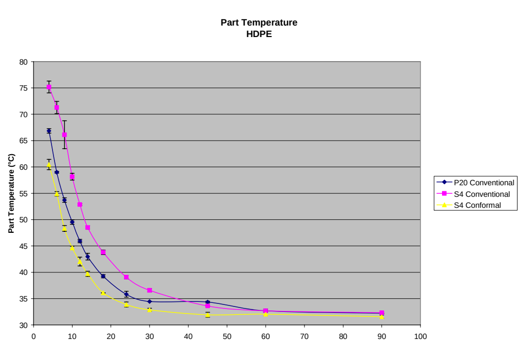

Figure 17 - HDPE Part Temperature Results

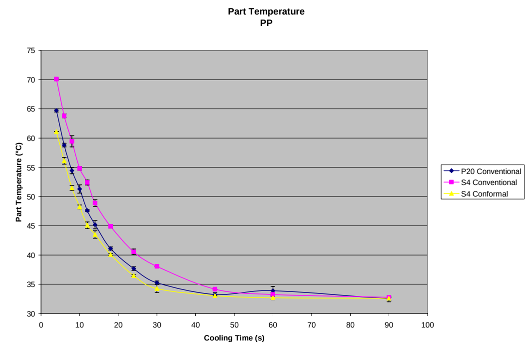

Figure 18 – PP Part Temperature Results

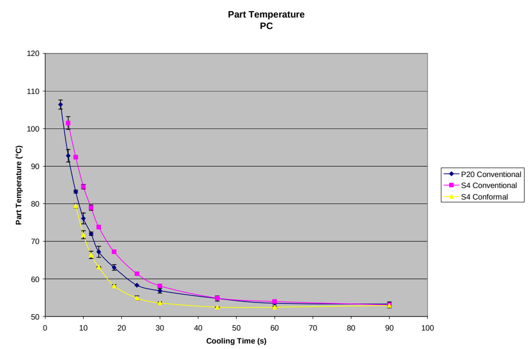

Figure 19 - PC Part Temperature Results

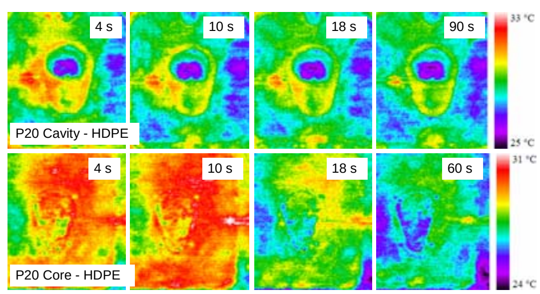

Figure 20 - P20 Conventional HDPE Results

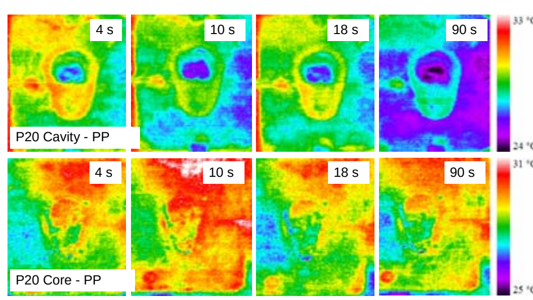

Figure 21 - P20 Conventional PP Results

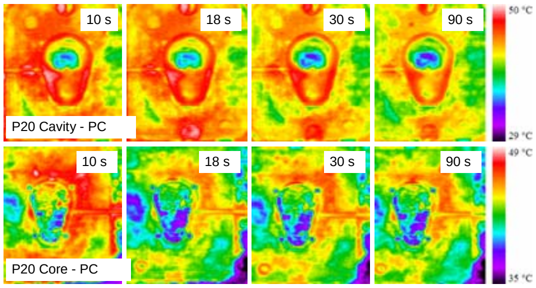

Figure 22 - P20 Conventional PC Results

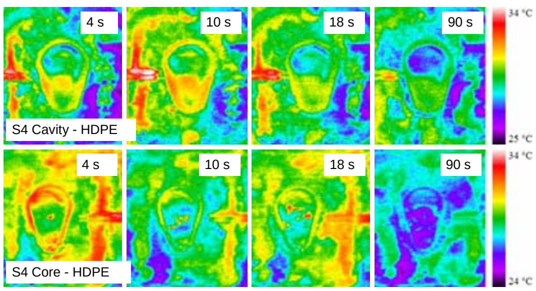

Figure 23 - S4 Conventional HDPE Results

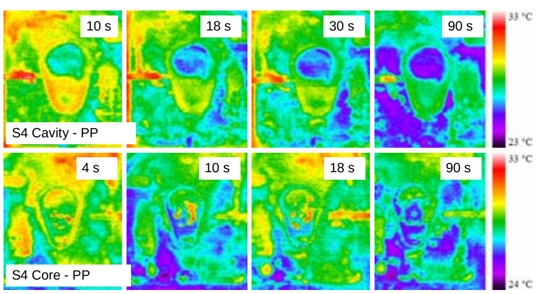

Figure 24 - S4 Conventional PP Results

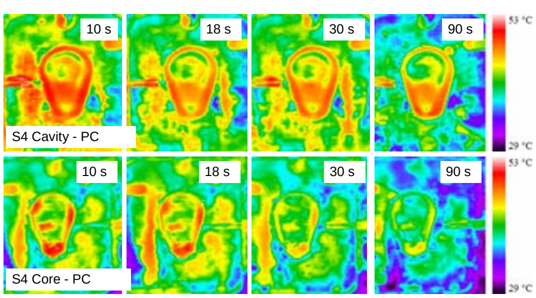

Figure 25 - S4 Conventional PC Results

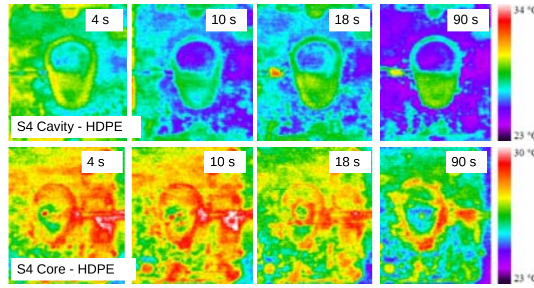

Figure 26 - S4 Conformal HDPE Results

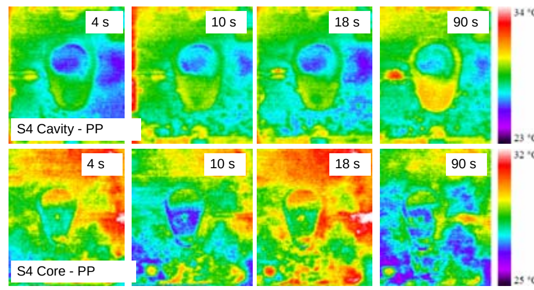

Figure 27 - S4 Conformal PP Results

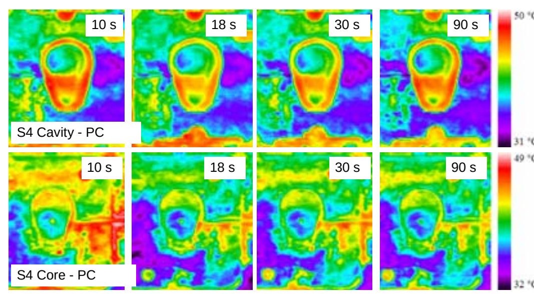

Figure 28 - S4 Conformal PC Results

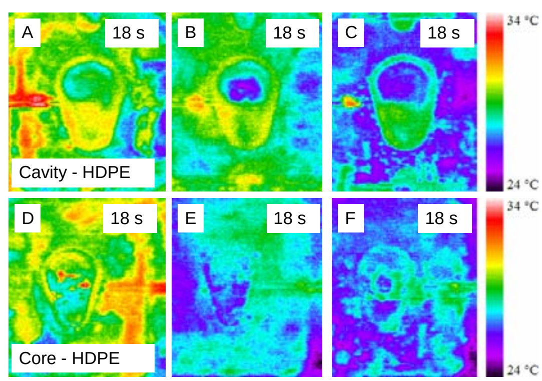

Figure 29 - HDPE Insert Results

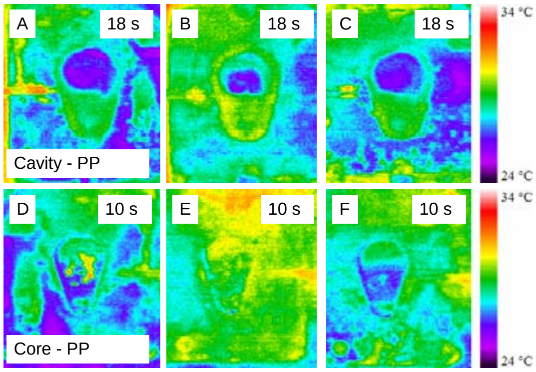

Figure 30 - PP Insert Results

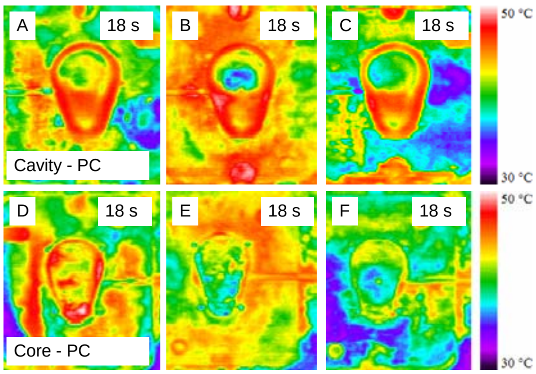

Figure 31 - PC Insert Results