Plunger Tip Evolution in the Diecast Industry
Material, Design, and Lubrication

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Abstract

This paper reviews the evolution of water-cooled plunger tips and discusses available design improvements, optimizations, material selection, and manufacturing methods. Overall performance is evaluated by utilizing computer simulation based on water flow, cooling rate and biscuit formation. Computational Fluid Dynamics (CFD) is used to calculate the cooling performance of plunger tips. Considerations are also made for the often-ignored Leidenfrost effect, as the phenomenon affects plunger tip cooling performance: specifically, when the water flow is low or thermal conductivity of the tip material is high.

Thermomechanical simulation is used to estimate stresses and deformations in the plunger tip, which can evaluate the plunger tip's thermal stability and life span.

Lubrication of plunger tip and proper lubricant selection are also discussed in this paper with presenting measurement of key physical properties of some popular lubricants in the industry.

Introduction

The basics of high-pressure diecasting have not changed since the first high-pressure diecast machine, and neither has the tooling. The plunger tip's external appearance is mostly the same [1], but there has been a gradual evolution in the range of materials, internal design, and manufacturing methods.

The main function of the plunger tip is to push the molten aluminum from the shot sleeve into the die cavity. Secondly, it should have enough cooling capacity to solidify the thick biscuit before the press releases and the die opens. Finally, one of the main design factors is leaving a proper gap between the plunger tip and sleeve to prevent the blow-by or leakage and allow the plunger tip to move freely inside the sleeve without scratching it.

Although the cooling performance of the tip is very important, it is hardly the only factor: cost, thermal stability, scrap, wear, material strength, life span, and safety are necessary considerations when manufacturing a proper plunger tip for any application. Copper alloy tips are popular in North America and Europe; steel tips are popular in Asia [1].

Regarding plunger tip material, some key factors are thermal conductivity and strength. Although copper alloys deliver excellent thermal conductivity, they are not as strong as steel. Castool Tooling Systems has recently used ConDuct [2], a high conductivity alloy steel, in successfully manufacturing plunger tips.

Several factors are usually missed regarding material evaluation and design of plunger tips: the critical softening temperature, the tip face's heat capacity, and the Leidenfrost effect.

Knowing the temperatures and stresses in the plunger tip helps with proper material selection, but measuring these parameters is either too difficult or impossible. Computational simulation is an effective tool to estimate stresses and temperatures in the plunger tip.

In this work, a combination of Finite Element and Computational Fluid Dynamics is used to simulate multi-physic phenomena affecting the plunger tip. The simulation captures the combined effect of water cooling, Leidenfrost effect, heat transfer, biscuit solidification to calculate resultant temperatures of the plunger tip, biscuit, and coolant water. The performance and life of different plunger tips are evaluated based on simulation results, and the rationale behind the evolution of design, materials and manufacturing are also discussed.

Material

A general decision theory for tooling material selection was discussed in a previous publication [3].

In Table 1, important material properties are listed for alloys used in manufacturing plunger tips. Temper resistance is the temperature above which the material loses hardness over time. In terms of strength and temper resistance, hot work tool steels (i.e., H13 and DieVar) are at the top of the spectrum, and copper alloys are at the bottom. Copper benefits from excellent conductivity, but it is much more expensive. The soft copper alloy, i.e. A45, does not have enough strength to be used in the highly-stressed tip face, so it is mostly used in the body of modular plunger tips.

ConDuct [2] has a combination of good strength, temper resistance and thermal conductivity. In addition, it is the toughest with the lowest price among the provided list of materials. For the first time, Castool Tooling Systems used ConDuct for mass production of plunger tips, and the use is continuously increasing in manufacturing plunger tips.

Table 1 – Key material properties for some popular materials used in manufacturing plunger tips.

Material		**Strength [MPa]**	**Temper Resistance [°C] at Specific Hardness**	**Toughness (J)**	**Thermal Conductivity (W/m°C)**	**Cost Factor per Unit Mass**
Steel	**ConDuct**	1000	580°C @32HRC	100	42	75
	H13	1300	580°C @46HRC	25	24	100
	DieVar	1400	555°C @46HRC	30	30	125
Copper Alloy	**A25**	900	460°C @29HRC	40	120	2400
	A45	650	320°C @190HB (<20HRC)	65	220	1300
	A52	750	460°C @26HRC	60	240	1800

The heat capacity of the plunger tip material helps with instant heat removal from the aluminum biscuit. The specific and volumetric heat capacity of steel material is higher than copper, so with the same tip face volume, the heat capacity of the steel is higher, and it provides more strength. On the other hand, the density of copper is about 15% higher than that of iron (Table 2), which adds to the total material cost when using copper.

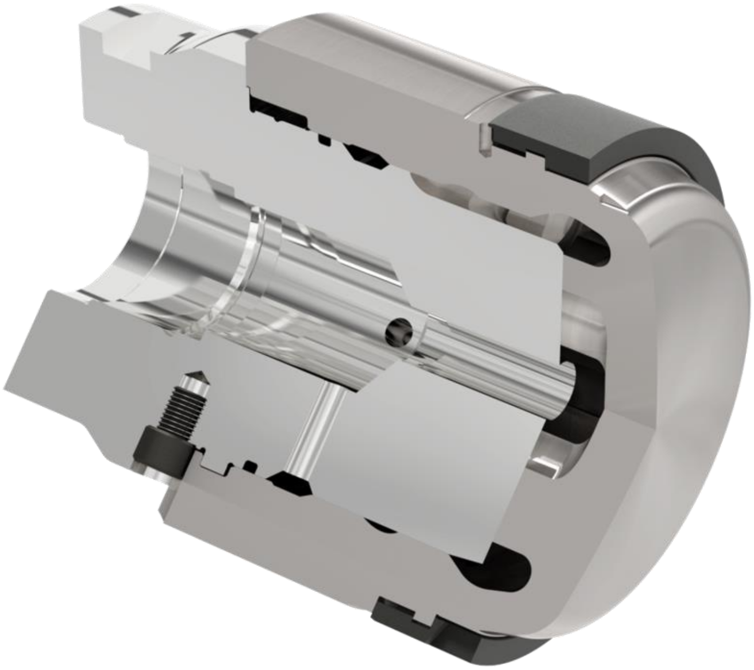
Table 2 –Heat capacity, density and coefficient of thermal expansion for Iron and Copper.

Material	Specific Heat Capacity [J/kg°C]	Density [kg/Lit]	Volumetric Heat Capacity [J/L]	Coefficient of Thermal Expansion [1/°C]
Iron	460	7.85	3611	0.000012
Copper	377	8.94	3370	0.000018

Material selection is affected by process control methods. For example, copper has lower temper resistance than steel, and it can not survive when in contact with molten aluminum without water cooling. While using copper tips, the cooling must be running continuously and consistently. Any interruption in the cooling can cause thermal shock and unwanted expansions. On top of these are the boiling of the water inside the tip and the Leidenfrost effect, which reduces the cooling efficiency and may produce backward pressure in water supply pipes. On the other hand, the thermal expansion rate for copper is about 45% more than iron/steel (Table 2), which magnifies the mechanical effect of thermal shock.

Due to the higher strength of steel, more complex geometries can be achieved to get better cooling while keeping the stiffness within the accepted range. Figure 1 shows a recent plunger tip design with a stainless steel holder, a ConDuct tip and an H13 ring.

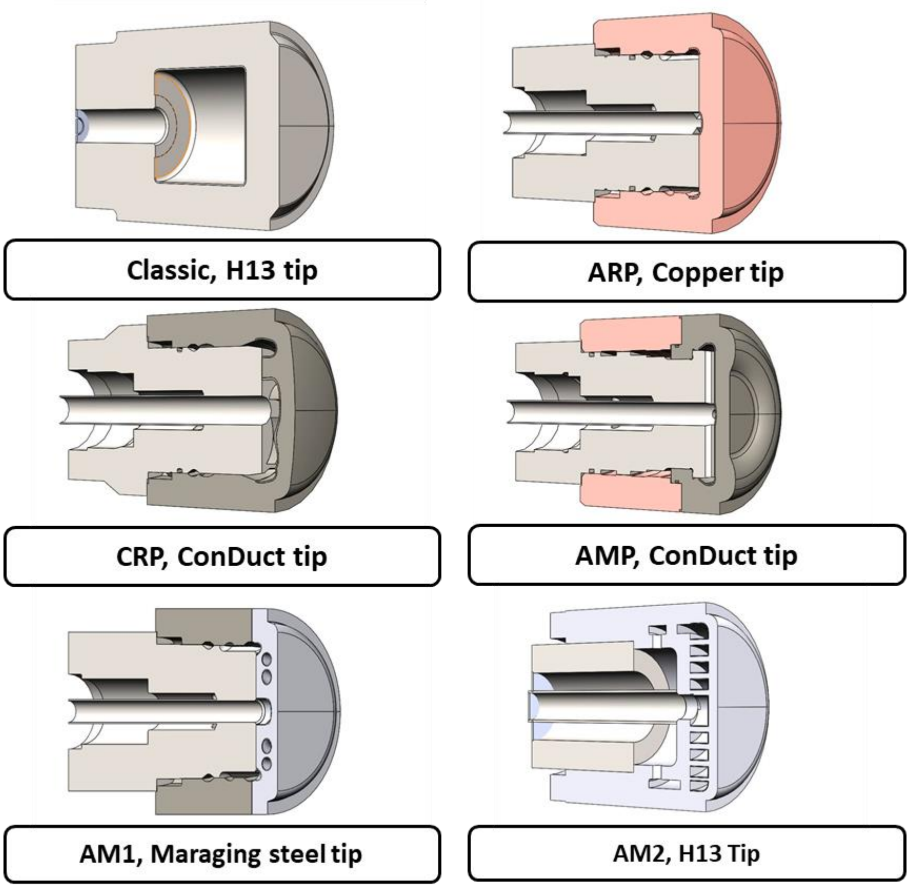
Figure 1 – A Castool Ring Plunger (CRP) with a ConDuct tip.



Design Evolution

The outer shape of the plunger tip has not changed over time. All plungers have water cooling to efficiently cool down the tip face, especially during dwell or solidification. Figure 2 exhibits 6 different plunger designs. Classic solid tips are one piece with a cooling cavity inside them. As there is no holder to support the holder’s inside walls, the material should be strong enough to provide stiffness during the process. An ARP plunger is made of copper tip and steel holder. Copper with high conductivity can efficiently remove heat from molten aluminum and solidify the biscuit. Recently released CRP tips have a similar concept as ARP with a stronger ConDuct tip. In CRP, complex cooling channels are made on the inside of the tip face to make more surface contact between coolant water and the tip, while AMP has a flat tip face on both sides with simple cooling grooves on the holder's front face. A modular AMP design makes it possible to use different materials for the body and face of the tip. In the AMP design shown in Figure 2, the body is made of soft copper alloy, and the tip face is made of ConDuct. AM1 and AM2 are concept designs with complex internal cooling channels to provide maximum surface contact with the coolant water. The internal cooling channels in AM1 and AM2 can not be made by conventional machining methods, which dictates the use of Additive Manufacturing methods. The material selection for AM1 and AM2 is based on required material strength for the specific design and available material for the specific manufacturing method. For example, Laser Powder Bed Fusion (LPBF) is suggested for manufacturing AM1 tip out of Maraging steel and Ultrasonic Additive Manufacturing (UAM) for manufacturing AM2 tip made of H13 steel.

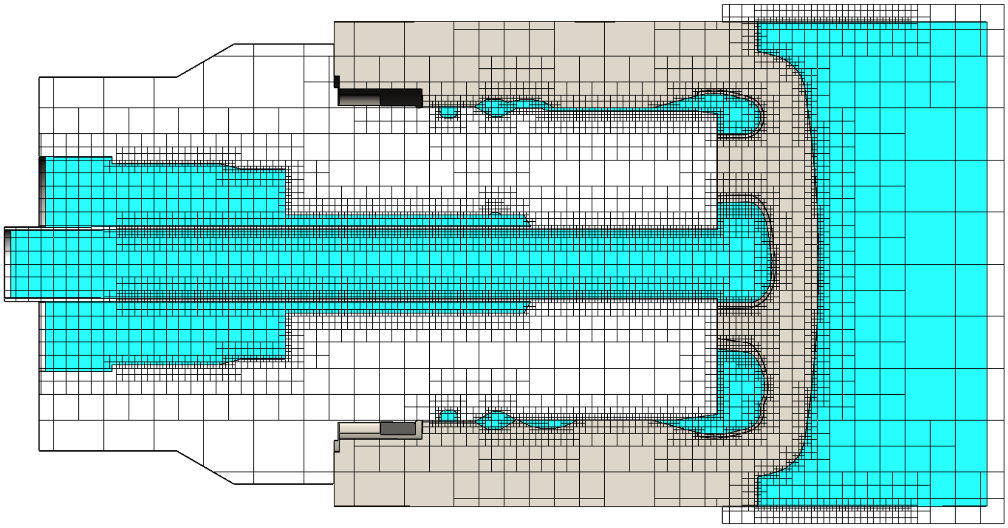
Figure 2 – Different plunger tip designs.



Computational Model

Multi-physical mathematical models were used to predict temperatures and stresses in the tooling and solidification of the biscuit. SolidWorks simulation tools were used to solve the problem. The fluid flow and heat transfer were simulated using the SolidWorks CFD package. The solidification was captured by changing the molten aluminum's viscosity and specific heat capacity at the solidification range, and the Leidenfrost effect was captured by defining the heat transfer as a function of the surface temperature of the tip. Figure 3 shows the mesh distribution in the tip, holder, water and aluminum biscuit.

Figure 3 – Mesh distribution: fluid mesh in blue.



The effect of the sleeve and die is ignored in these simulations so that the results show the pure effect of plunger tip design and material. Simulations were performed for 3 cycles of 65 sec. Each cycle has 5 sec of pouring time, 20 seconds of contact with molten aluminum (delay+plunge+dwell) and 40 seconds not in contact with aluminum before the start of the next cycle. A356 casting aluminum alloy was selected for this study with a pour temperature of 680°C. The OD of the tips is 140 mm, and the biscuit volume is set to 0.85 Liter.

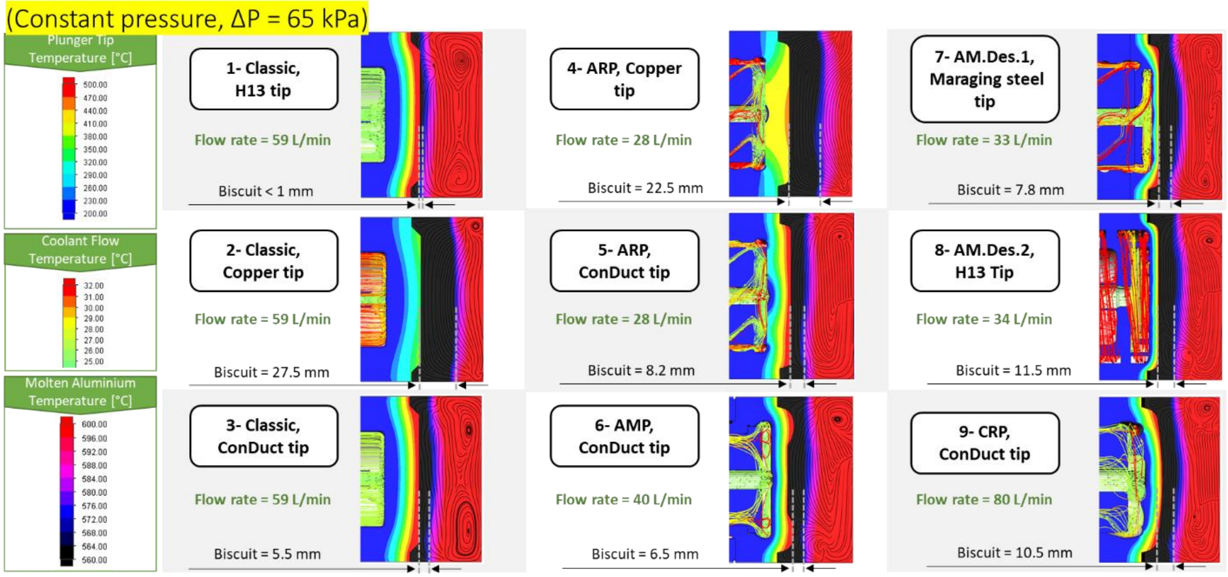
Simulation Results and Discussion

Thermal CFD simulations were performed on different plunger tip designs to evaluate the efficiency and durability of different plunger tip designs presented in this paper. Different tip materials were used for some of the designs to capture the materials effect on tip performance. Figure 4 and Figure 5 compare the effect of design and material on biscuit solidification and tip temperature for 9 different plunger tip designs. The reported solidified thickness is the minimum thickness of a solidified layer at the end of dwell time, which is the weakest part of the solidified layer.

In Figure 4, the water pressure was kept constant for all simulations so that based on the amount of friction and cooling channel design; the flow rate was different for each design. For example, CRP design provides the best water flow (80 L/min) with the same water pressure, and the ARP tip has the lowest water flow. The most influential factor on the biscuit’s solidification rate seems to be the tip material conductivity, as all copper tips have a very high solidification rate and H13 and Maraging tips have meager solidification rates. Instead, steel has a higher strength, allowing for more complex designs such as AM1 and AM2. Cases 1, 2 and 3 are only presented to show the thermal effect of the tip material with the same dimensions; otherwise, the material change would mandate some dimensional changes to compensate for the mechanical and thermophysical property changes. For example, switching from steel to copper (with lower hardness), the thickness of the tip face should increase to provide enough strength.

Expensive additively manufactured tips (7 and 8) did not make considerable improvements in the cooling performance of the tip. AM1 made of Maraging steel has less of a cooling effect than ARP and CRP ConDuct tips. AM2 made of H13 can improve the cooling to some extent, but it provides lower structural strength due to design features.

Figure 4 –Biscuit solidification (black layer), tip and coolant water temperature at the end of dwell time, with constant water pressure of ΔP = 65 kPa at the tip. The water flow rate is reported for each case.



In contrast to Figure 4, in Figure 5, the water flow rate is kept constant for all 9 cases. Beside each case, the required pressure to provide 38 L/min water flow is reported. Compared with Figure 4, the biscuit solidification rate does not increase proportionally to the water flow rate; for example, increasing the water flow rate in a CRP tip from 38 to 80 L/min (more than 100% increase), the solidification rate increases by only 12%. It is worth mentioning that for a highly conductive copper tip, using a thicker tip face can make the tip run colder and increase solidification rate, but for less conductive materials such as steel, using a thicker tip would make the front face hotter lessening the solidification rate. For example, compare a classic ConDuct tip (#3) with an ARP ConDuct tip (#5). The CRP design results in the best biscuit solidification among ConDuct tips (3, 5, 6 and 9).

Figure 5 –Biscuit solidification (black layer), tip and coolant water temperature at the end of dwell time, constant water flow of 38 L/min at the tip. The water flow rate is reported for each case.

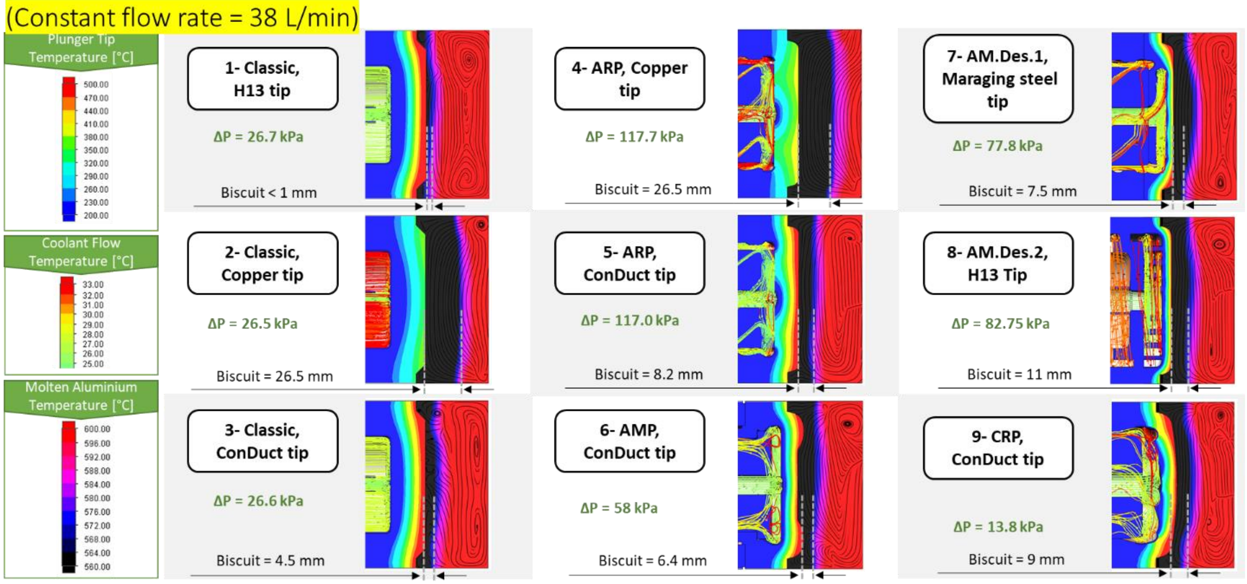


Figure 6 and Figure 7 show the history of the average temperature at the front face of the 9 different plunger tip designs. As observed, copper tips have the lowest tip face temperatures during the dwell time, and CRP ConDuct has the lowest tip face temperature among steel tips. After dwell time, the AM2 tip shows the fastest cooling, and it reaches the lowest temperature at the end of the cycle just before starting the next casting cycle. Although the cooling capability of AM2 is much higher than other designs, this can cause severe thermal shock and extraordinary thermal stresses in the tooling due to high thermal gradients.

Figure 6 – Temperature history during one casting cycle at tip face, with constant water pressure of ΔP = 65 kPa at the tip.

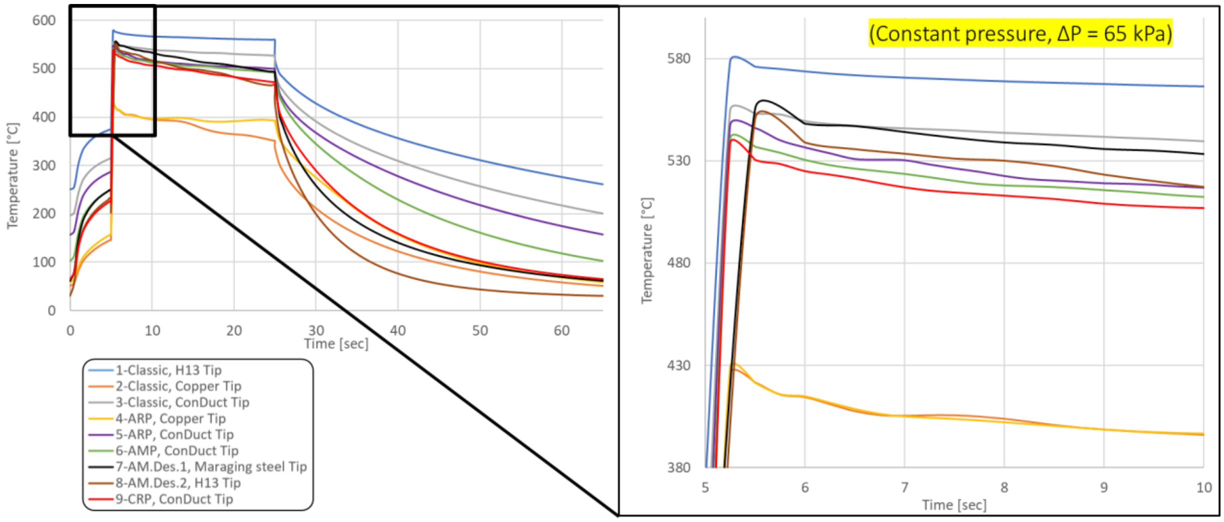
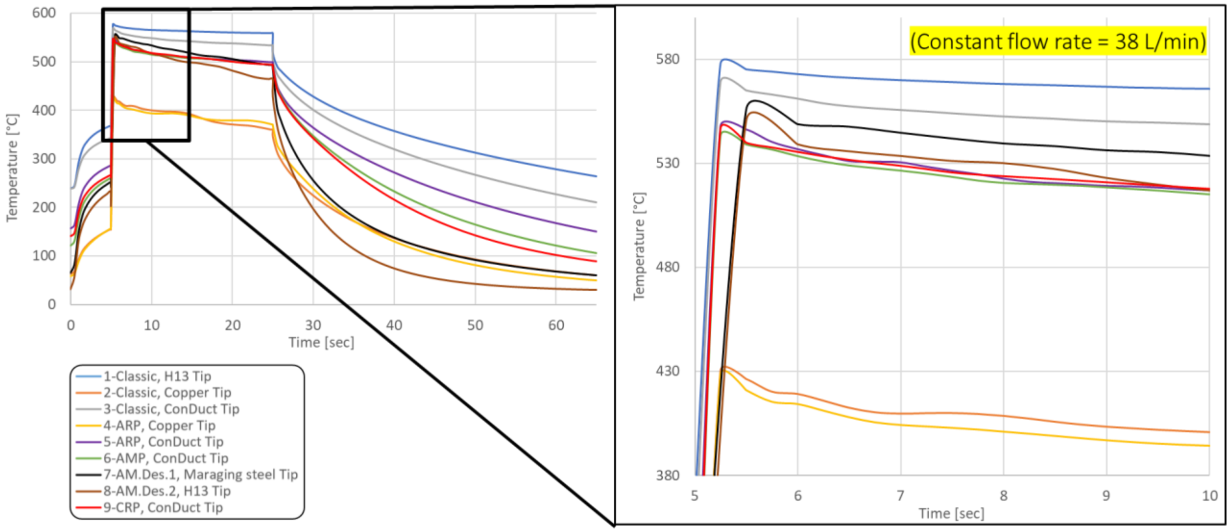


Figure 7 –Temperature history during one casting cycle at tip face, with a constant water flow of 38 L/min at the tip.



Effect of the Leidenfrost Phenomenon on Tip Cooling

To show the effect of Leidenfrost on tip cooling efficiency, tip simulations were performed without considering the Leidenfrost effect and repeated for two different Leidenfrost points of 200°C and 230°C. Results for tip face temperature and biscuit solidification are summarized in Table 3 and Table 4. Although 230°C is a more realistic number, 200°C was also used to show a worst-case scenario and determine the designs that may show low efficiency under poor water flow. It must be noted that this study is done for a constant flow rate of 38 L/min.

The ARP conduct tip is the most affected by Leidenfrost, and the next are AM1, AM2 and CRP. All of them are tips with good cooling and solidification.

Table 3 – Average tip face temperature during dwell time for 9 different designs (constant flow rate 38 L/min).

Design	Average tip face temperature during dwell time [°C]		
	Leidenfrost @ 200 °C	Leidenfrost @ 230 °C	Without Leidenfrost
1-Classic, H13 Tip	562	562	562
2-Classic, Copper Tip	389	385	385
3-Classic, ConDuct Tip	542	541	541
4-ARP, Copper Tip	399	386	380
5-ARP, ConDuct Tip	509	509	509
6-AMP, ConDuct Tip	508	506	506
7-AM.Des.1, Maraging Steel Tip	523	512	512
8-AM.Des.2, H13 Tip	500	492	492
9-CRP, ConDuct Tip	510	504	501

Table 4 – Minimum thickness of solidified biscuit at the end of dwell time for 9 different designs (constant flow rate 38 L/min).

Design	Solidified biscuit thickness at the end of dwell [mm]		
	Leidenfrost @ 200 °C	Leidenfrost @ 230 °C	Without Leidenfrost
1-Classic, H13 Tip	<1	<1	<1
2-Classic, Copper Tip	26	26.5	26.5
3-Classic, ConDuct Tip	4.5	4.5	4.5
4-ARP, Copper Tip	20	26.5	27.5
5-ARP, ConDuct Tip	8.1	8.2	8.3
6-AMP, ConDuct Tip	5.5	6.4	6.5
7-AM.Des.1, Maraging Steel Tip	5.5	7.5	7.5
8-AM.Des.2, H13 Tip	9.8	11	11.5
9-CRP, ConDuct Tip	6.5	9	9.5

It can be concluded that keeping a proper water flow rate is more important for more efficient plunger tips to avoid boiling coolant water inside the tip. It is worth mentioning that the backpressure from boiling water is not considered in the simulation.

Plunger Lubrication

Plunger lubricants help with the smooth running of the die casting system. A good lubricant can improve the castability of the metal, limit porosity and improve injection [4]. On top of these, plunger lubrication prolongs the life of the shot sleeve and plunger by:

1. Reducing the friction between the plunger and the shot sleeve,
2. Producing a thin insulating film between tooling (plunger and sleeve) and molten aluminum [5].

The lubricant layer must be strong enough to avoid its washout from the surface with the flow of the molten aluminum inside the sleeve [5]; otherwise, the molten aluminum is going to contact the surface of the die and make Aluminum-Iron alloys or intermetallic, which cause early failure of the tooling [6]. However, high viscosity is not always a good parameter, especially where the lubricant is sprayed onto the surface.

Plunger lubricants can be dry or wet, but wet lubricants are more popular due to their ease of application. Most used plunger lubricants are oil-based, made from mineral, vegetable, or synthetic oils [4]. They can carry graphite or Boron Nitride and can be very effective for greasing pistons. An ideal lubricant might have the following specifications [6]:

1. It is satisfactory to both surfaces and does not chemically react with them
2. It forms a tight and adherent film on the surface
3. It has good surface coverage with the capability to spread fast and uniformly
4. It does not fume toxic or problematic gases that affect the health of the operator
5. It has a reasonable price because large amounts of lubricants are being used
6. It has a relatively high flash point to avoid excessive vaporization
7. It is environmentally friendly

The most important rule for lubrication is to use just as little lubricant as needed and only where needed. Excessive lubricant will end up deteriorating the quality of casting since the molten aluminum would decompose the oil and produce moisture and gasses that affect the casting soundness [6]. On top of this, excessive lubricant is an unnecessary cost and a workplace pollutant.

Every effort must be made to eliminate the possibility of any non-metallic substance getting into the mould. Graphite-based lubricants, for example, can cause porosity in the casting.

Additives

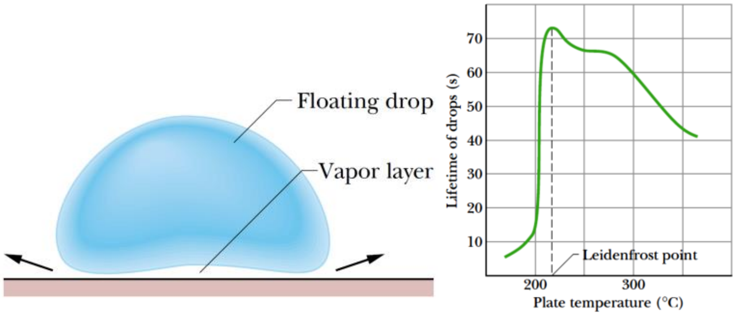
There can be several additives to provide an optimum mixture of properties to the lubricant [5]:

- Cohesion and wetting (animal and vegetable fats)
- High-temperature viscosity control and insulation (pigments like Boron Nitride, graphite, aluminum, mica, and other powdered solids).
- Anti-welding and rust protection (chemical additives).

Wetting Capability

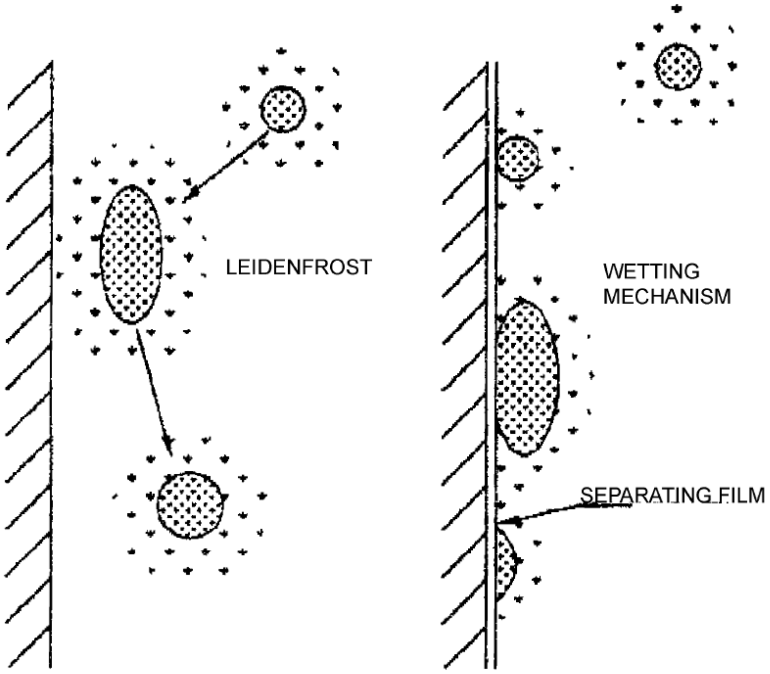
One of a lubricant's most important physical properties is wetting capability, especially when droplets of lubricant are sprayed onto the hot surface. When the surface temperature is much higher than the boiling point of the droplet, a vapour layer will form between the droplet and hot surface that prevents the conductive heat transfer (Figure 8). This phenomenon is called the Leidenfrost effect, a combination of surface tension and vapour pressure [5].

Figure 8. A Leidenfrost drop in cross-section (left) and water drop lifetime on a hot plate (right) [7].



The temperature of the shot sleeve must be controlled to avoid the Leidenfrost phenomenon during applying or spraying the lubricant onto the hot surface. Figure 9 shows two scenarios: on the left side, the Leidenfrost effect prevents the droplet from wetting the surface, whereas on the right, the droplets wet the surface and form a film.

Figure 9. Leidenfrost effect causes the droplet to bounce back from the hot surface (left) versus the wetting phenomenon that forms a separating layer on the surface (right).



Plunger Lubricants

There are several types of lubricants. Among them, two types are more popular: ALS192 (synthetic oil-based with Boron Nitride particles) and CLS200 (vegetable oil-based) [8]. The table below summarizes the physical properties of these lubricants. ALS192 has relatively high viscosity at room temperature, which gives a good strength to lubricant film but makes it difficult to spray at room temperature, so preheating is needed for proper atomization. CLS200 does not have this issue.

Both lubricants are resistant to high temperatures as they have a high flash point and boiling temperature that helps avoid the Leidenfrost effect and excessive fume production. Therefore, it is surprising that the CLS200 with lower viscosity has a higher flash point that puts it in a better position regarding fume production.

Table 5 – Key properties for ALS192 and CLS200 lubricants.

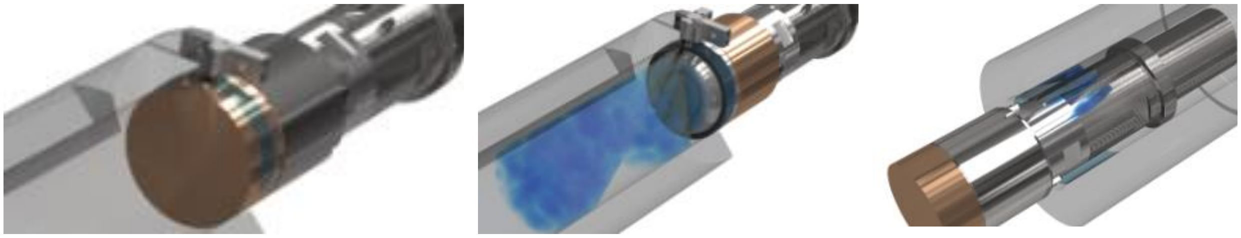
Property	ALS 192	CLS 200
Kinematic Viscosity (at 40°C/104°F)	930 mm^2/s	35 mm^2/s
Flash point	270°C (518°F)	290°C (554°F)
Boiling point	305°C (281°F)	325°C (617°F)

Another benefit of using CLS200 is that it is environmentally friendly as it is vegetable oil-based.

Lubrication Methods

Different methods for applying lubricants are shown in Figure 10. Lube drop is the oldest and easiest method for lubricating plunger tip, but with this method, the lubricant is not carried properly along the shot sleeve, so low viscosity lubricants may not work effectively. Combi Lube and Rod lube methods can apply lubricants to wide areas inside the sleeve so that they are recommended for large tooling (Table 6). These methods can benefit from low viscous, high flash point lubricants. The lubricated location and amount of lubricant are well controlled with these methods. This makes it possible to have more effective lubrication using less lubricant.

Figure 10 – Different lubrication methods [9].



Lube Drop **Combi Lube** **Rod Lube**

Table 6 – Lubrication methods recommended based on shot sleeve size.

Shot sleeve size	Recommended method
Small diameter	Lube Drop
Medium diameter	Combi Lube
Large diameter	Lube Drop + Rod Lube
Large diameter and long	Combi Lube + Rod Lube

Summary and Conclusions

- Computational Fluid Dynamics (CFD) and Heat Transfer models were used to evaluate the plunger tip cooling and biscuit solidification in different plunger tip designs.
- Material selection is an important part of product design—the mechanical and thermo-physical properties of the material affect productivity and tooling durability.
- Although the outer shape of the plunger tip is not changed over time, the inside design and material have evolved significantly.
- The thermal conductivity of the tip's material is the main factor in the biscuit solidification rate.
- A thinner face shows a better solidification rate in steel tips, but for copper, with high thermal conductivity, the thicker tip may show a better solidification rate due to more thermal mass.
- A CRP ConDuct tip with cooling grooves on the tip shows a considerable advantage over the previous generation of tips (ARP and AMP) in solidification rate and tip temperature.
- Additive Manufacturing does not add considerable value to plunger tip performance considering much higher manufacturing costs. On the other hand, the complex design of these tips can cause excessive thermo-mechanical stresses.
- Although the Leidenfrost effect is not considered in the plunger tip designs studied in this paper, simulations show that it may cause issues specifically in high-performance plunger tips in poor water cooling conditions.
- Good lubrication is a combination of proper lubricant and proper lubrication methods.
- For large tooling, low viscosity lubricants with spray application methods are recommended.

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