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Bigger Castings, Bigger Problems

A thermo-mechanical simulation study with a focus on the effect of shot sleeve size

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Abstract

Thanks to ground-breaking innovations, the automotive industry is increasingly interested in manufacturing massive structural parts through cold-chamber diecasting techniques. This introduces new opportunities and challenges to the diecast industry by pushing the limits of tooling and material and decreasing the effective life span of tooling. The more pressing problem becomes managing the critical gaps and tolerances, which remain constant even though parts and tools are getting bigger.

This paper will focus on the shot sleeve as the primary tool for feeding molten aluminum into a mould. Computer simulation methods will analyze thermal and mechanical responses in the shot sleeve and its interaction with other tools, specifically the plunger tip. In addition, thermo-mechanical effects of shot sleeve size will be studied by calculating the temperatures, stresses, and deformations in the shot sleeve during the process.

Introduction

The approach to using giant casting machines, nicknamed Giga Presses, to make car bodies with just a few massive casted parts is catching on in the auto industry. One Giga Press manufacturer says they work with about half a dozen automakers taking the same approach.

Over the last few years, several automakers have invested heavily in casting and alloy development to enable larger casted parts that can significantly simplify manufacturing; in some cases, a single body piece can replace 70 or more parts in the vehicle.

Die casting challenges such as uncontrolled thermal expansions, lubrication, and porosity due to incomplete air evacuation can be easily resolved in smaller machines but seriously magnified when producing large castings.

A few years ago, the largest diecast machines had 3000-4000 ton clamping force and used shot sleeves of 6”-7” diameter. Nowadays, there are diecast machines with more than 6000 tons capacity and shot sleeves of 9” diameter, and in the near future, 12” sleeves with 9000-ton presses are quite predictable.

The clearance between the plunger and the shot sleeve can not exceed 0.004” (0.10 mm) or it will cause excessive wear.[1] The alloy can penetrate as a “flash” or blow-by if the clearance becomes more than this. The clearance between the plunger and shot sleeve never remains constant. At the start of the casting cycle, the sleeve is very hot, while the plunger tip is quite cold at the pour end. As the plunger moves forward, the tip becomes hotter and expands, but the sleeve ID contracts as the heated ID layer cannot expand into the bulk of the shot sleeve. If the initial clearance at the pour end is small enough to prevent penetration of the alloy past the tip of the plunger, the plunger may seize in the sleeve before reaching the end of the stroke. The chance of this happening increases with the length of the shot sleeve.[2]

In long sleeves, keeping a consistent layer of lubricant along the ID of the sleeve is a challenge. Using lots of high viscosity lubricant under the pour and hoping it will reach the end of the sleeve is the wrong solution, and it can introduce many defects in casted parts. The proper method is to use well-designed equipment to put as little lubricant as needed where it is needed.

This paper will present a simulation study to compare different sizes of shot sleeves and their thermal and mechanical states. These findings would help understand the thermomechanical reactions of bigger tooling to the diecast process to overcome challenges associated with casting bigger parts.

Geometry and Mathematical Model

Four sleeves were modelled with different lengths and inner diameters of 3”, 6”, 9” and 12”. Table 1 lists the sizes in diameter and length, and Figure 1 shows the section view of the 3D sleeve models. Sleeve designs were chosen based on existing sleeve designs for different sleeve sizes.

Table 1 *- ID and length of different sleeve sizes used for this study.*

Sleeve Size	Sleeve ID [in]	Sleeve length [in]
Small	3	28
Medium	6	43
Large	9	63.5
Extra large	12	80

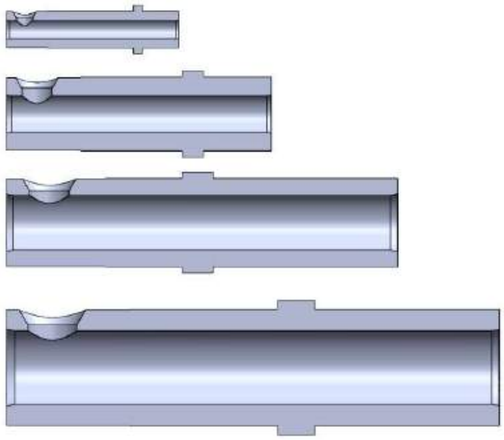

Figure 1 *– Side section view of 4 sleeve models used for this study.*

Transient thermal simulations were performed using Solidworks simulation software. Next, static analyses were performed at selected steps to determine stresses, deformations and deflections. A C++ code was developed in-house to define the complex transient boundary conditions from the interaction of molten aluminum with the sleeve ID.

The computational domain was broken up into a Cartesian mesh (a grid-like mesh made up of box-shaped cells), then a Finite Volume method was used to solve the transient heat transfer equations.

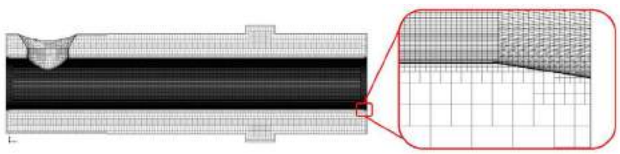

Figure 2 *– Finite volume mesh used to simulate thermal evolutions during the die cast process.*

Five casting cycles were simulated to get a more realistic temperature distribution, and the results for the last cycle were used for discussion. The heat transfer between the atmosphere and the platen is also considered in the simulation.

To properly compare different sleeves, the cycle time and process conditions are kept the same for all simulations. No thermal regulation or cooling system is integrated into the sleeves.

Results and Discussion

Figure 3 shows the model predicted temperature distributions in a 9" sleeve at four different times during a casting cycle. The first snapshot shows the thermal state of the sleeve at the beginning of the pour cycle. Although the molten aluminum has not yet started to contact the sleeve at this point, the spot under the pour is still very hot from previous cycles. The scale of temperature at this region (> 550°C even before the pouring cycle) indicates that a proper cooling or thermal regulation system is needed to balance the thermal. At the end of pouring (with a fill rate of 50%), the bottom half of the sleeve bore gets in contact with super-heated molten aluminum alloy (A380) at a temperature of 650°C. After this point, the plunger tip moves forward slowly until the sleeve is filled with molten material, when the quick plunger shot starts and instantly shoots the molten aluminum out of the sleeve into the die. The third snapshot in Figure 3 shows the temperature distribution at the shot's end and the solidification cycle's start. The last snapshot shows temperatures to the end of solidification, after which the die opens, and the part ejection process starts. After solidification is complete, it takes 74 seconds before the next pouring cycle starts.

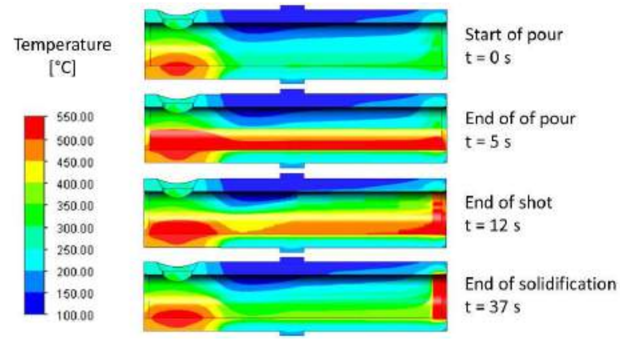

Figure 3 *– Predicted temperature history in a solid 9" shot sleeve during a casting cycle.*

Temperature distribution in the shot sleeve during the process is shown in the figure below for different sleeve sizes. The main difference that catches the eye is the considerably higher temperature under the pour spout for bigger shot sleeves.

Their reasons could be:

- In larger sleeves, the heat needs to travel longer to equilibrate the temperature gradients.
- Typically, in larger sleeves, the ratio of thickness to diameter and the ratio of thickness to length is smaller, making less material available to conduct heat or more resistant to heat conduction.

Table 2 lists the minimum and maximum (extremum) temperatures for different sleeve sizes. The range between minimum and maximum increases with the size of the sleeve. The minimum temperature is generally on the middle top of the sleeve, where molten metal does not get in contact, and the maximum happens under the spout during the pour cycle.

Shot sleeves are often made of H13 hot work tool steel tempered at around 600°C, so any operating temperature close to this is of concern. The 3" sleeve with a maximum temperature of 583°C can last for an acceptable number of cycles, but 6" and higher will experience temperatures at or above the tempering temperature of H13. This indicates the necessity for a cooling or thermal regulation system in larger shot sleeves.

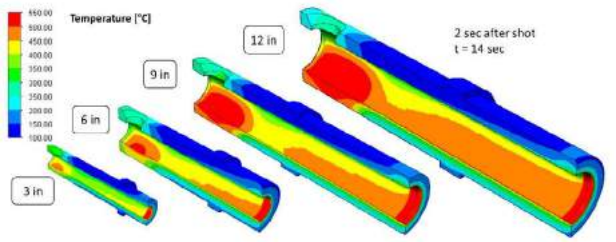

Figure 4 – Temperature distribution in shot sleeves of different sizes during the solidification cycle.

Table 2 – Global temperature extremums and the average temperature of sleeves of different sizes during the extrusion process.

Sleeve	Min Temp. [°C]	Max Temp. [°C]	Average Temp. [°C]
3 inches	111.72	583.48 @ 5 sec	210.56
6 inches	112.06	599.31 @ 5 sec	229.68
9 inches	105.81	618.07 @ 5 sec	244.88
12 inches	105.63	621.84 @ 5 sec	247.64

The material softens when it is exposed to temperatures close to or above the tempering point, provided that the exposure is long enough to make a microstructural change in the material. The figure below shows the temperature history of a point under the pour spout 4 mm below the surface. It shows that the exposure to the maximum temperature is instantaneous and only lasts for a short period of time per cycle.

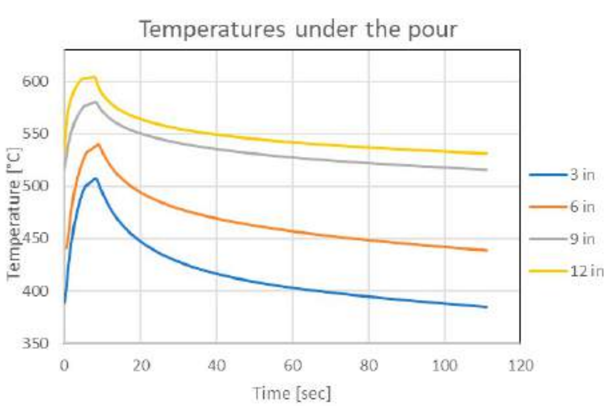

Figure 5 – Temperature history under the pour hole during a casting cycle for sleeves of different sizes.

Stress distribution during the die cast process (for the time at the start of the dwell time) and model predicted deflection of different-sized shot sleeves are shown in Figure 6. When referring to the dimensions of shot sleeves provided in Table 1 and comparing them to the deflection magnitudes in Figure 6 it appears that the deflection magnitude is proportional to the diameter of the sleeve rather than its length.

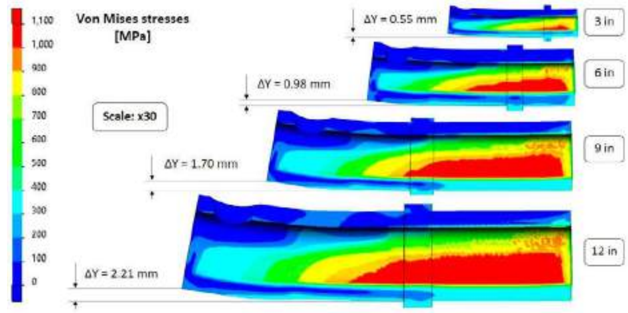

Figure 6 – Deflection of different size sleeves during the process (at the start of solidification/dwell time).

To study the ovality or deformation of the sleeve ID during the process, radial displacements with respect to the centre axis of the sleeve were calculated at 4 different sections shown in Figure 7.

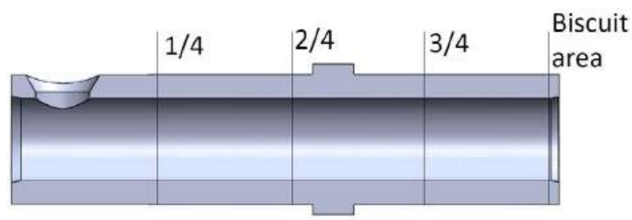

Figure 7 – Four different sections of shot sleeve selected for ID ovality analysis.

The average radial expansion (ΔR) at different sections along the sleeves, shown in Table 3, indicates that the average radial expansion at the pour section of the sleeve (@1/4) is significantly higher than the rest of the sleeve. In other sections (@2/4, @3/4 and @Bisquit), the expansion rates of the sleeve ID are similar. For a 3" sleeve the difference between the average radius at the pour section of the sleeve (@1/4) and the rest of the sleeve is less than 0.03 mm, while for a 6" sleeve this difference is about 0.1 mm and for 9" and 12" sleeves this difference could be even more than 0.1 mm.

A 0.1 mm gap is ideal between the plunger tip and the sleeve; any bigger gap may cause leaking issues during the process.[1] In a 3" sleeve the variation of bore expansion along the sleeve is low so that it can be managed without extra process controls and design optimizations. In a 6" sleeve the variation is in the range of the ideal gap size of 0.1 mm. This means if, at the start of the plunge the gap is 0.1 mm, there will be no gap during the second half of the plunger stroke, restricting the plunger tip movement inside the sleeve. This issue will be even bigger for a 9" or 12" sleeve where the bore expansion variations along the sleeve are bigger than the critical value of 0.1 mm.

In Figure 8, the bore profile of the 9" sleeve is presented at different sections of the sleeve shown in Figure 7. The expansions are magnified by 50 for a better presentation of differences. The plotted radius of each point in Figure 8 and Figure 9 is calculated using the following formula:

$$r = 1 + 50\,(\Delta R/R) \qquad \text{Equation 1}$$

As observed, the expansions at the first quarter of the sleeve are significantly larger than the three other sections

Table 3 – Average radial expansion at different cross sections along the shot sleeve during the die casting process.

Sleeve ID		Radius R[mm]	Average ΔR [mm]				Average ΔR/R [%]			
			@ 1/4	@ 2/4	@ 3/4	@ Biscuit	@ 1/4	@ 2/4	@ 3/4	@ Biscuit
3 inch / 76.2 mm		38.1	0.093	0.070	0.066	0.081	0.24%	0.18%	0.17%	0.21%
6 inch / 152.4 mm		76.2	0.228	0.131	0.130	0.138	0.30%	0.17%	0.17%	0.18%
9 inch / 228.6 mm		114.3	0.309	0.179	0.232	0.225	0.27%	0.16%	0.2%	0.2%
12 inch / 304.8 mm		152.4	0.396	0.268	0.296	0.258	0.26%	0.18%	0.18%	0.17%

along the sleeve. The black solid line in the graph represents the original bore of the sleeve at room temperature. In the 2/4, 3/4 and Biscuit sections, the bore center is on the original sleeve bore but in the 1/4 section the center of the bore is higher than the sleeve axis due to the deflection shown in Figure 5, the so-called "Banada effect". If not controlled with proper design and thermal regulation, this will accelerate the wear and washout under the pour due to interaction with the plunger tip.

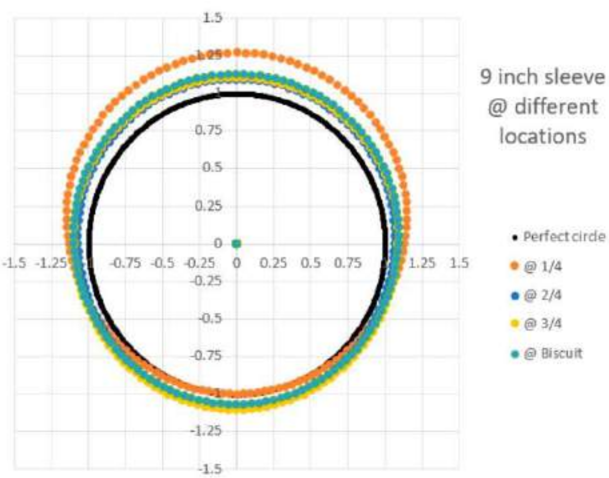

Figure 8 – Predicted ID profile of a 9" shot sleeve at different cross-sections during the process compared to the original ID of the sleeve (perfect circle). The deformations are magnified 50 times.

As shown in Figure 8, the bore deformation of 3", 6" and 12" sleeves also follow a similar trend as the 9" sleeve.

Figure 10 shows the same data as Figure 9, except the radial expansion of each point is not normalized by sleeve bore size. The equation below was used to calculate the radius of plotted points in Figure 10.

Summary and Conclusions

Model predicted thermal history of the shot sleeve indicates that a large sleeve with no thermal regulations can experience temperatures at or above the critical temperatures of the sleeve material.

The sleeve bore expands more at the pour side and is almost constant from half of the sleeve toward the die end of it. For larger sleeves, the variation of bore expansion can get larger than the critical gap between the plunger and sleeve bore, making it difficult to create a consistent gap between the plunger tip and sleeve.

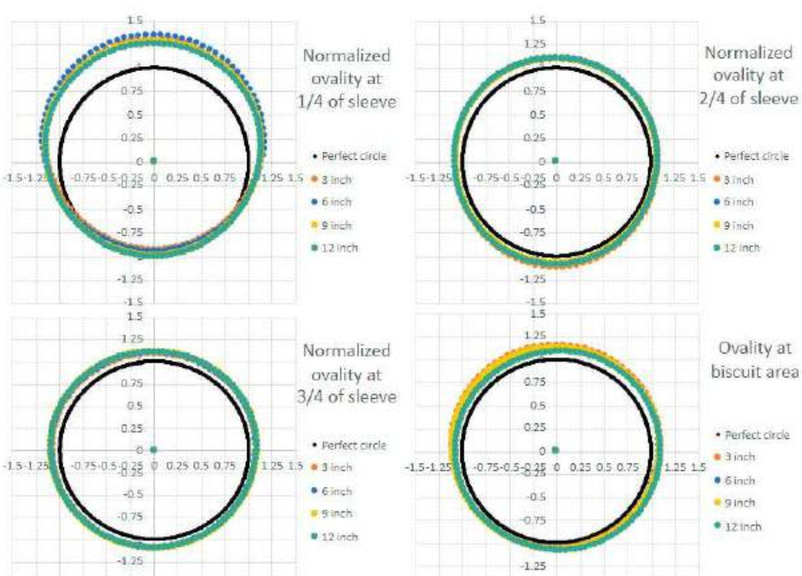

Figure 9 – Sleeve ID profile during the process at the start of solidification or dwell time in different sleeve sections, showing bore deformations relative to bore size (refer to Figure 6 for locations).

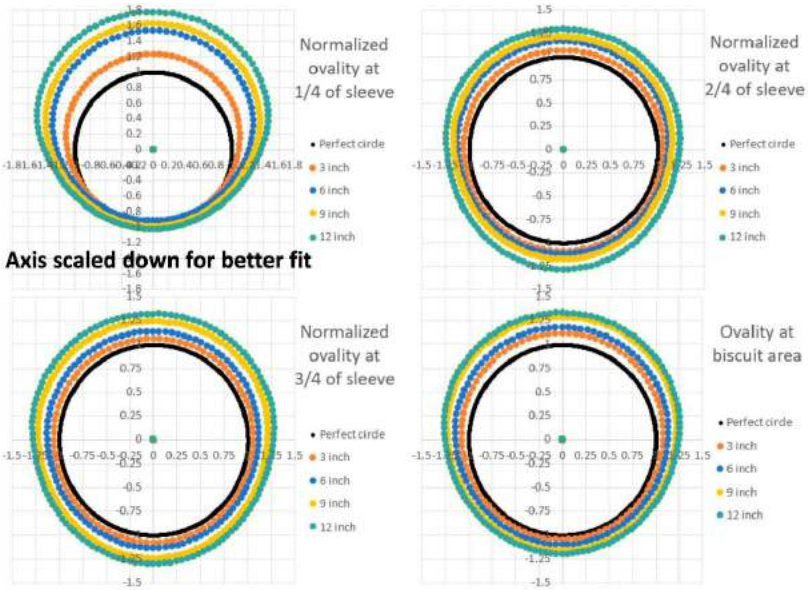

***Figure 10** – Sleeve ID profile during the process at the start of solidification or dwell time in different sections of the sleeve showing absolute bore expansion (refer Figure 6 for locations).*

For a 3-inch sleeve, the temperatures and deformations are in a safe range and can be managed relatively easily. Temperatures and deformations in a 6-inch sleeve are at critical levels and may hardly be managed without thermal regulations. However, for sleeve sizes above 6 inches, such as 9 and 12 inches, it looks impossible to manage a proper gap without thermal regulation and extra design optimizations.

Acknowledgements

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