Better Castings Faster: Tooling Material, Process and Failure Analysis in Diecasting

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Abstract

The purpose of this paper is to discuss the materials available for manufacturing diecast tooling. In addition, this paper will outline a decision theory considering key parameters such as tooling life, cycle time and cost. Tooling failure and the process are discussed as being the main reasons for failure. Case studies using simulation and practical experiments are supplied to validate the theory.

Introduction

The very first aluminum diecast part was made in the early 1900s, which was the starting point for a significant evolution in diecast machine design [1]. Aluminum alloys had a higher melting point than other alloys being cast, such as lead, and zinc. It also corroded steel tooling in hot chamber diecast. This led to the invention of the cold chamber die casting machine in the 1930s, when molten metal was ladled into a relatively cold shot sleeve. Now, aluminum parts made by cold chamber die cast make up more than 70% of the total diecast parts in the world [1], and this number is growing continuously.

While diecast tooling suffers from wear and fatigue, erosion or washout is the main failure mode of tooling in aluminum diecasting. Aluminum has relatively high chemical reactivity and solubility in iron [2]. While in contact with iron, molten aluminum atoms diffuse into the iron matrix and form intermetallic compounds, such as Fe_2Al_5 [3]. These intermetallic phases melt at above 1000°C. This is in contrast to molten aluminum, which is 700°C at most when poured onto steel tooling. Pasche et al. [3] believe that the main mechanism causing shot sleeve washout is when the plunger tip gets in contact with the sleeve surface, and the brittle phases formed at the surface break apart. Once the intermetallic particles are removed from the tool surface and go into the melt, they may not get enough time to dissolve into molten aluminum before solidification. The result is that they end up in the part and degrade mechanical properties.

Material upgrades and proper coatings can often delay erosion at the tool surface with the same success as a design change, but both these methods impose extra costs to tool manufacturing.

Hot work tool steel (specifically H13) is often the material of choice for diecast tooling due to its ideal combination of erosion resistance, hot strength, and wear resistance. It has been found that implementing nitriding and other coating techniques helps to improve the mechanical and chemical properties of tooling surfaces in direct contact with molten aluminum.

While other materials and surface treatment processes might cause better tooling life, nitrided H13 is still the most economical solution for dies and shot sleeves. When it comes to thermal conductivity and toughness, high conductive alloy steel and copper-beryllium alloys, as well as other engineering alloys, are undeniably superior to hot work tool steel. However, replacing steel with other engineering alloys is often costly and can cause unscheduled downtime due to unexpected failure. A better solution could be to optimize design with consideration for the capabilities of advanced manufacturing techniques. A good example of this is making conformal cooling channels in die inserts using additive manufacturing. Major diecast tooling manufacturers are constantly looking into material improvements to increase their tooling life.

Pasche et al. [3] tried different coatings on steel tooling and found that a cobalt-based coating is more effective in delaying the erosion by molten aluminum. Their theory is that cobalt makes it difficult for aluminum to diffuse into the iron matrix.

Zhu et al. [4] evaluated washout and thermal fatigue resistance of different materials, including H13, a cast iron, a copper base, a nickel superalloy, a titanium base, a tungsten base, and a molybdenum based alloy during diecasting of A356 aluminum alloy. They got the best results with tungsten-based alloy. Surprisingly, H13 performed better than nickel superalloy. The copper alloy showed the worst washout resistance.

Schwam et al. [5] applied different coatings on H13 to investigate their effect on die soldering resistance. They found that increasing the carbonitrided layer thickness from 50µm to 165µm will increase the washout resistance of H13. They got their best results using the CrC applied by PVD method.

With all the research performed on different materials and coatings, nitrided H13 is still the most economically effective material for shot sleeves and dies. Numerous studies have been performed to fine-tune the composition and optimize the heat treatment and nitriding of H13 [6]–[8]. Castool Tooling Systems and DEW have developed a new hot work tool steel, TuffTemper, to improve erosion resistance and hot strength, as well as to increase softening temperature beyond that of H13 [9].

Shot sleeves and die components are tools that are designed to withstand many numbers of cycles without failure, and as a result suffer the most from washout. The plunger tip is another tool that is in direct contact with the molten aluminum. New plunger tips are water-cooled to increase the biscuit solidification so that the tool surface temperature does not get as hot as that of the die. The thermal conductivity of the tip is a key factor in keeping the tip temperature low and increasing the biscuit solidification rate. As a result, in water-cooled plunger tips, the hot work tool steel material is replaced with copper alloys and high conductive alloy steels, i.e. ConDuct [10].

Material Selection: Decision Theory

Several aspects must be considered to select the proper material for tooling:

- Cost
- Longevity
- Cycle time
- Recovery
- Energy
- Safety and environmental impact

Cost and longevity are the most important factors. Longevity is affected by the process, design, and material properties. The main material properties affecting the longevity of diecast tooling are listed in Table 1, including hardness, strength, toughness, thermal conductivity, and softening temperature. Factors like wear resistance and thermal shock resistance are functions of these properties. For example, wear resistance is related to hardness and thermal shock resistance is a function of toughness and thermal conductivity.

Although longevity is important for tooling, overspending should be avoided to improve profitability. H13 and DieVar have the same hot strength and softening temperature. DieVar is slightly tougher but double the price of H13. Therefore, using DieVar for applications with wear being the main mode of failure is overspending. More expensive materials do not necessarily improve longevity, and in some applications, it might have an inverse effect. For instance, expensive copper bushing with low wear properties can fail faster than steel bushings.

Diecasting companies like to shorten the cycle time as much as possible to increase productivity. A more conductive material in the plunger tip solidifies the biscuit faster and can shorten the dwell time. Also, partially failed tools do increase scrap rate and decrease recovery. This factor must be kept in mind.

Table 1: Key properties for materials used in diecast tooling

		Working Hardness (HRC)	**Cost Factor**	**Hot Strength**	**Toughness**	**Thermal Conductivity**	**Softening Temperature**
Steel	**ConDuct**	34-38	75	●●	●●●●●●	●●	●●●●●
	H13	42-52	100	●●●	●●○	●	●●●●●●
	DieVar	44-50	200	●●●	●●●	●○	●●●●●●
	1.2367	42-52	200	●●●	●●●	●○	●●●●●●
	TuffTemper	42-52	200	●●●●	●●	●○	●●●●●●○
CuBe	**A25**	28-32	2400	●○	●●●●	●●●●●	●●●
	A52	26-28	1800	●	●●●●●	●●●●●●●●●●	●●●●

Failure Analysis

All tooling fails at some point. When this happens, the questions to consider are:

- How long the tooling performs before failing
- The cause of the tooling failure

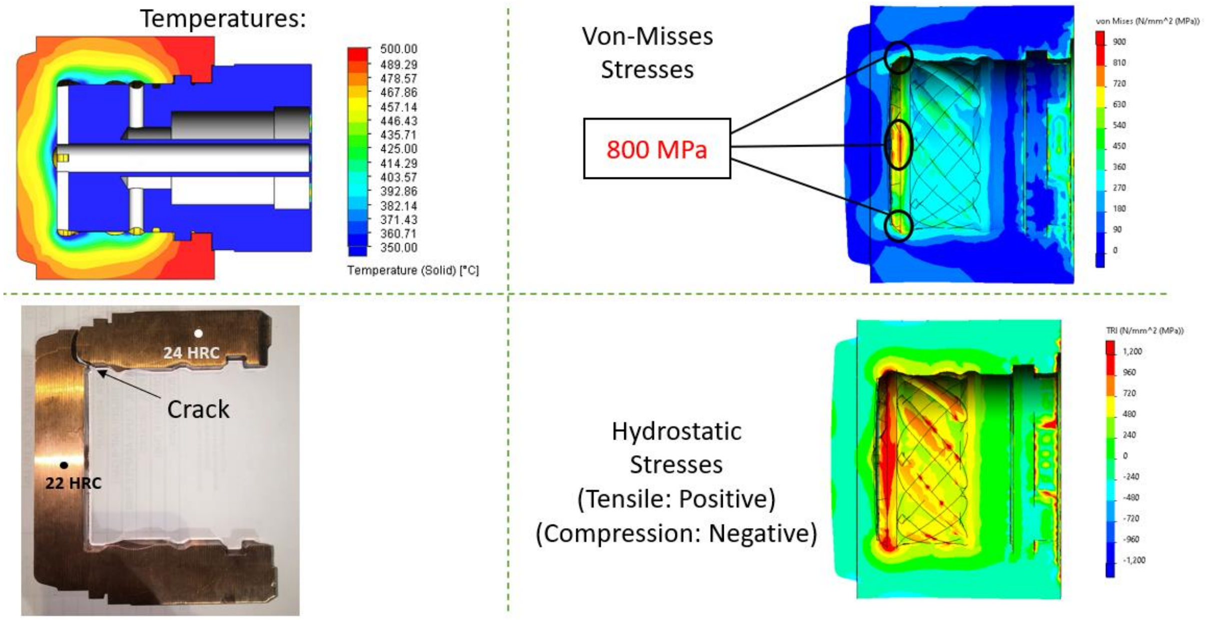
Processes that cause overheating or overloading are often to blame for premature failures. Next comes the design, which can be modified with minimal or no additional cost. Finally, there may be materials that can extend the useful life of the tooling, but they are often associated with a significant cost increase.

Three main modes of failures in diecasting tools are:

- Soldering and washout
- Wear
- Thermal fatigue

Most of the time, the process is to be blamed for premature failures. For example, poor water cooling can cause overheating of a plunger tip made of copper-beryllium alloy with a low softening temperature. Figure 1 shows the summary of failure analysis for a cracked copper-beryllium plunger tip. The main reason for failure was the softening of the tip due to an interruption in water flow during the casting process. The original tip was supplied at a hardness of 27-28 HRC, but the measurement on the failed part shows 22-23 HRC all over the tip. This is an indication of a major softening of the material. Simulations have been performed for the case that the water flow starts after the plunger tip is saturated in heat. The cracked location is exactly the stress concentration point with high tensile stresses. The magnitude of stress (800 MPa) is enough to yield the material with 22 HRC hardness, while the original material was supplied at a hardness of 27 HRC and had a tensile strength of 900 MPa.

Figure 1: Failure analysis of a cracked copper-beryllium plunger tip



Process

Considering the process as the main cause of failure in diecast tooling consists of various factors, including the following:

1) Alloy: chemical composition of molten aluminum is a key factor that affects other process parameters. Alloys with a higher amount of iron and manganese cause less soldering and washout on tooling [1], [11], but iron decreases the ductility of the diecast part [12]. Therefore, the level of iron is usually kept lower in diecast alloys (Table 2) than alloys used for other casting methods (Table 3). The pouring temperature is a function of the melting point of the alloy (Table 4), and the melting range of the alloy indicates how fast the molten metal would solidify in relation to the cycle time. Silicon is the main alloying element in casting aluminum alloys.
2) Pourpuire rate: a standard pour rate in diecast is 30-40%. Increasing the pour rate will make it more difficult to manage the shot sleeve temperature and control the gaps between tooling. The rate at which the molten aluminum is being poured into the sleeve is also important in terms of erosion and washout of the shot sleeve under the pour hole.
3) Size of tooling: the critical gap between tooling (i.e. between the shot sleeve and plunger tip) is a constant [13], but deflections and thermal expansions increase with tooling size, making it much harder to manage the gap.
4) Figure 2 shows simulation results for radial expansion of the plunger tip and shot sleeve during the process.
5) Cycle time: cycle time consists of pouring, plunging, dwell/solidification, ejection, and cooling. Changing the length of each step affects the tooling. For example, reducing cooling time is possible with improving the cooling power; otherwise, it jeopardizes tooling life.
6) Internal cooling and thermal regulation: to avoid a thermal shock at the surface of the tooling, the tooling can be preheated to temperatures higher than room temperature. On the other hand, overheating tools should be avoided so that water cooling or oil cooling channels can be effective in cooling down the tool.

7) Lubrication is one of the main tools to delay wear-related failures, but over-lubrication can degrade the quality of the casting.

Table 2: Alloys for Squeeze casting and Semi-Solid casting [12]

ALLOY	**SI**	**MG**	**FE**	**MN**
A319	5.5-6.5	0.10	1.0	0.50
A355	4.5-5.5	0.4-0.6	0.60	0.50
A380	7.5-9.5	0.10	2.0	0.50
A390	16-18	0.45-0.65	0.5	0.1

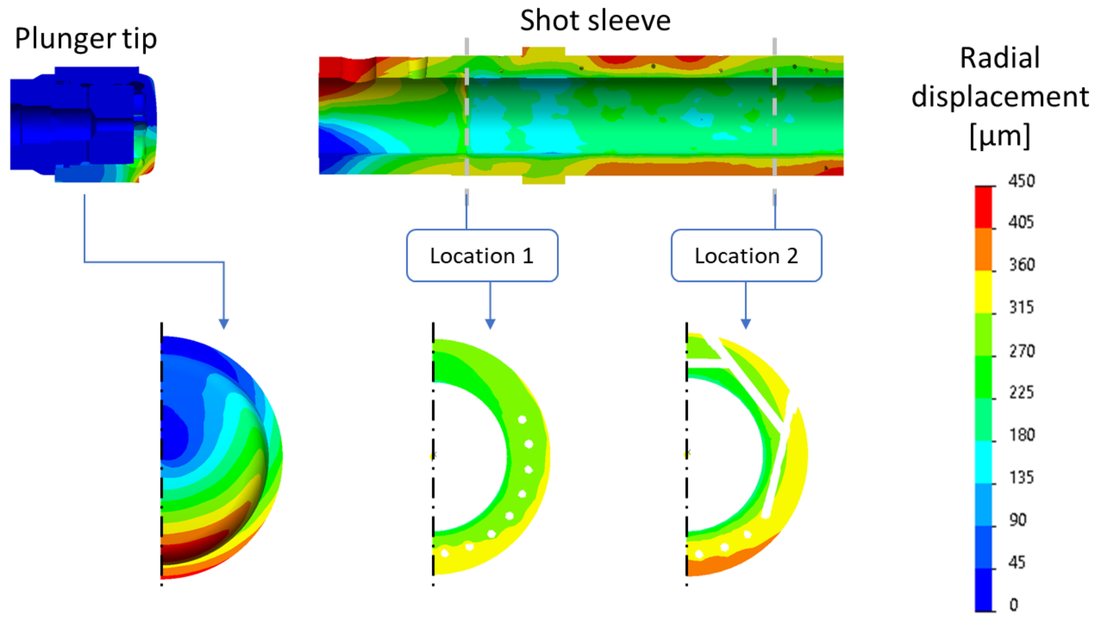
Table 3: Alloys for High Vacuum Die Casting (HVDC) [12]

ALLOY	**SI**	**MG**	**FE**	**MN**
Aural 2	9.5-11.5	0.1-0.4	0.16-0.22	0.4-0.6
Aural 3	9.5-11.5	0.4-0.6	0.16-0.22	0.4-0.6
Castasil 37	8.5-10.5	0.06	0.15	0.35-0.6
Magsimal 59	1.8-2.6	5.0-6.0	0.2	0.5-0.8
Mercalloy 367	8.5-9.5	0.3-0.5	0.25	0.25-0.35
Mercalloy 368	8.5-9.5	0.1-0.3	0.25	0.25-0.35
Silafont 36	9.5-11.5	0.1-0.5	0.15	0.8

Table 4: Melting range of alloys [12], [14]

Alloy	**A319**	**A355**	**A356**	**A357**	**A380**	**A390**	**Silafont 36**
Melting Point [°C] (Liquidus)	605	620	615	615	595	650	590
Melting Range [°C] (Solidus-Liquidus)	515-605	545-620	555-615	555-615	540-595	505-650	550-590

Figure 2: Simulation results showing the radial displacement/deformation in shot sleeve and plunger rod during the process.



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