Material Selection for Diecast Tooling: Decision Theory and Practice

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Abstract

A wide range of engineering materials is available to manufacture diecast tooling. However, only a handful of them get used due to many parameters. This paper outlines a decision theory for material selection that considers key parameters such as tooling life, cycle time and cost. It notes the main reasons for tooling failure, which are the harsh conditions of the diecast process, and how tooling life is improved by using proper materials and designs. Simulation is an effective tool to evaluate new materials and designs, and examples of practical simulation results are supplied to support the decision theory.

Introduction

Over 70% of the world's diecast parts are made of aluminum with a cold chamber die casting technique [1], and this number is continuously growing.

A challenge with molten aluminum atoms is that they can diffuse into the iron matrix, forming intermetallic compounds such as Fe_2Al_5 [2]. These intermetallic phases are formed when aluminum comes in contact with iron, and they melt at temperatures above 1000°C. (This contrasts with molten aluminum, which is (at most) 700°C when poured onto steel tooling.) When the plunger tip contacts the sleeve surface, the brittle phases formed break apart. Once the intermetallic particles are removed from the tool surface, they go into the melt and may not get enough time to dissolve into molten aluminum before solidifying. The result is that they end up in the product, degrading its mechanical properties.

Due to its ideal combination of erosion resistance, hot strength, and wear resistance, hot work tool steel (specifically H13) is often the material of choice for diecast tooling. Additionally, it has been found that implementing nitriding and other coating techniques helps to improve the mechanical and chemical properties of the tooling surfaces in direct contact with molten aluminum. Bringing the same success as a design change, material upgrades, and proper coatings can also delay erosion at the tool surface. However, both options impose extra costs to tool manufacturing.

Shot sleeves come in direct contact with molten aluminum immediately after pouring, so they sense the hottest state of the aluminum. Die components and shot sleeves are tools that are designed to withstand many cycles without failure, therefore suffering the most from washout. The plunger tip is another tool in direct contact with the molten aluminum. The thermal conductivity of the tip is a key factor in keeping the tip temperature low and increasing the biscuit solidification rate. New plunger tip designs are water-cooled to accomplish this effect. In these water-cooled plunger tips, the hot work tool steel material is replaced with copper alloys and highly conductive alloy steels, i.e. ConDuct [8].

Nitrided H13 remains the most economical solution for dies and shot sleeves. When it comes to thermal conductivity and toughness (needed for plunger tips), highly conductive alloy steel and copper-beryllium 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 failures.

Zhu et al. [3] evaluated the 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 the diecasting of an A356 aluminum alloy. Surprisingly, H13 performed better than the nickel superalloy, although the precipitation hardening of a superalloy is done at higher temperatures. Their best results were with the tungsten-based alloy. The copper-based alloy showed the worst washout resistance.

Numerous studies have been performed to fine-tune the composition of H13 and optimize its heat treatment and nitriding processes [4]–[6]. Castool Tooling Systems and DEW have developed TuffTemper: a new hot work tool steel designed to improve erosion resistance and hot strength, as well as to increase softening temperature beyond that of H13 [7].

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

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

Diecasting companies like to increase productivity by shortening the cycle time as much as possible. A more conductive material in the plunger tip solidifies the biscuit faster, which can shorten the dwell time. Also, partially failed tools do increase scrap rate and decrease recovery - a longevity-related factor to keep 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	●●●●	●●	●○	●●●●●●○
Copper Alloy	**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

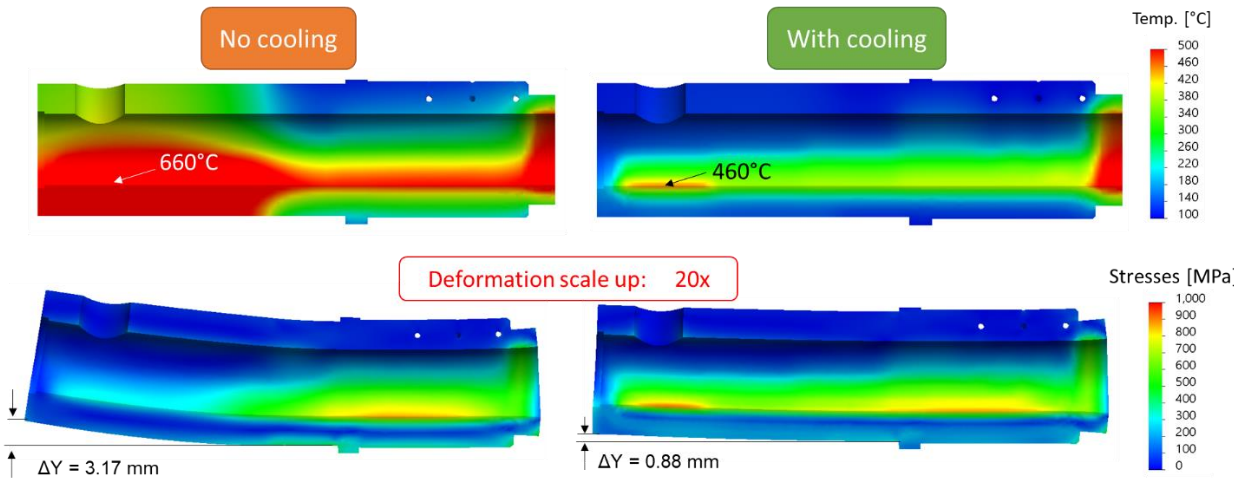
Three main modes of failures in diecasting tools are:

- Soldering and washout
- Wear
- Fatigue

Most of the time, processes that cause overheating or overloading are to be blamed for premature failures. For example, poor water cooling can result in overheating a plunger tip made of a copper-beryllium alloy (with a low softening temperature). The next culprit is often the design, which can be modified with minimal or no additional cost. Figure 1 shows that a shot sleeve with no thermal regulation can overheat to well above 600°C under the pour hole, which is hot enough to soften the hot work tool steel.

Finally, there may be materials that can extend the useful life of the tooling, but they are often associated with a significant cost increase. Using a more heat-resistant nonferrous alloy (such as tungsten-based alloys) could be a solution, but it imposes huge costs, making it economically unreasonable. On the other hand, the thermal bending of the sleeve (banana effect) can also be minimized by thermal regulation (or cooling) of the shot sleeve.

Figure 1: Model predicted effect of thermal regulation (cooling) on temperatures and deformation of the shot sleeve.



Changing the material to improve life is often, but not necessarily, associated with extra cost. For example, using ConDuct steel instead of a copper alloy or a hot work tool steel can significantly increase the longevity of water-cooled plunger tips. Figure 2 shows an example of the life improvement of a plunger tip using less expensive ConDuct material. In this case, ConDuct has better conductivity than the hot work tool steel and better heat resistance and strength than the copper alloy, giving it a good combination of mechanical and physical properties.

Figure 2: Water-cooled plunger tips of the same size made of different materials (hot work tool steel, Copper alloy and ConDuct). Failed tips were sectioned for inspection study.

Process

To consider the process as the main cause of failure in diecast tooling brings up various factors, including the following:

1) **Alloy**: the chemical composition of molten aluminum is a key factor that affects other process parameters. Alloys with higher amounts of iron and manganese cause less soldering and washout on tooling [1], [9], but iron decreases the ductility of a diecast part [10]. Therefore, the level of iron is usually kept lower in diecasting alloys than in alloys used for other casting methods (Table 2). Silicon is the main alloying element in casting aluminum alloys. The Si content in Silafont 36 refers to the eutectic Al-Si binary, and it has a relatively narrow melting range which makes it a

good choice for high vacuum die casting. Hypo-eutectic and hyper-eutectic alloys such as A319 and A390 have a wide melting range and are more suited for squeeze casting and semi-solid casting. The pouring temperature is a function of the melting point of the alloy (Table 2), and the melting range of the alloy indicates how fast the molten metal would solidify in relation to the cycle time.

2) **Fill ratio**: a standard diecast fill ratio is 30-40%. Increasing the pour rate makes it more difficult to manage the shot sleeve's temperature and to control the gaps between tooling.
3) **Pour rate**: the rate at which molten aluminum is being poured into the shot sleeve is also important in terms of erosion and washout under the pour hole. The erosion rate is affected by pouring temperature, velocity, and angle at which the molten aluminum hits the tool surface.
4) **Size of tooling**: the critical gap between tooling (i.e. between the shot sleeve and plunger tip) is a constant [11], but deflections and thermal expansions increase with tooling size, making it much harder to manage the gap.
5) **Cycle time**: the 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 by improving the cooling power; otherwise, tooling life may be jeopardized by a shortening this time.
6) **Internal cooling and thermal regulation**: tooling should be preheated to temperatures higher than room temperature to avoid a thermal shock at the surface of the tooling. On the other hand, overheating tools should be carefully avoided so that water or oil cooling channels can maintain their effectiveness.
7) **Lubrication**: an appropriate lubrication solution is one of the main tools used to delay wear-related failures, but over-lubrication can degrade the quality of the casting.

Table 2: Melting range of alloys [10], [12]

Alloy	**A319**	**A390**	**Silafont 36**
Melting Range [°C] (Solidus-Liquidus)	515-605	505-650	550-590
Si Content	5.5-6.5	16-18	9.5-11.5
Fe Content	1.0	0.5	0.15
Application	Squeeze Casting /Semi-Solid Casting	Squeeze Casting /Semi-Solid Casting	High Vacuum Die Casting

Supplier Effect

A material's response to heat treatment can change due to a slight difference in chemical composition, resulting in a shift in mechanical properties. In order to keep the product quality consistent, it is recommended to source each material from a single supplier plant. Even this does not completely guarantee steady chemical composition: gradual changes may happen over time. This goes to show the necessity of reliable material composition verification.

Although different suppliers may provide the same material type and the composition is within the standard range, the acceptable ranges for alloying elements are often large enough to allow a considerable change in mechanical properties. For example, based on the ASTM standard [13], the acceptable Molybdenum (Mo) content in H13 steel is 1.10% to 1.75%, meaning that any Mo content between these numbers is acceptable based on this standard. This percentile variation in Mo content can result in a 4-5 HRC change in the final hardness of the material [14].

Table 3 shows the chemical composition of H13 steel supplied by two different plants. Both materials' composition is within the standard range, but there are some variations - specifically in C, Mn, Cr and Ni contents. These differences can change the hardenability and temper resistance of the material, so they may not provide the same mechanical properties, even with the same heat treatment procedure.

Table 3: Chemical composition for the H13 material supplied by two different suppliers, compared to the ASTM standard.

	Alloying Elements						**Trace Elements**	
	C%	**Si%**	**Mn%**	**Cr%**	**Mo%**	**V%**	**Ni%**	**Cu%**
Standard Range ASTM A681	0.32-0.45	0.8-1.25	0.2-0.6	4.75-5.5	1.1-1.75	0.8-1.2	N/A	N/A
H13 by Supplier #1	0.40	1.0	0.44	5.1	1.23	0.91	0.12	0.05
H13 by Supplier #2	0.35	1.0	0.32	4.9	1.18	0.92	0.38	0.16

Summary

- The majority of diecast parts are made of aluminum, so the tooling design and material are driven by the aluminum diecast industry.
- H13 tool steel is the most popular and most economical engineering material used for manufacturing major diecast tooling.
- A decision theory for tooling material selection must consider several important factors, including cost, longevity, cycle time, and recovery.
- A material upgrade is often very costly. Alternately, in some situations, less expensive materials have the potential to improve longevity.
- The process is often the main cause of tooling failure, with three main modes of failure: washout, fatigue, and wear.
- The main process parameter is the chemical composition of the alloy being moulded.
- A slight change in the chemical composition of the tooling material can produce considerable changes in its mechanical properties.

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