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TRIBOLOGICAL WEAR MECHANISMS OF MOLDS FOR HIGH PRESSURE DIE CASTING

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The goal of this article is to analyze and define mold wear in relation to: mold material, casting alloy and casting parameters. These are the main elements for design of the experimental laboratory for die casting equipment. Additionally, preliminary tests have been undertaken to ensure there is no adhesion between the mold material sample and molten aluminum during the simulation. Factors that were tested were: geometrical shape of the sample, sample preheating temperature, surface roughness and lubrication.

Key words: casting, Al alloys, mold, wear

INTRODUCTION

High pressure die casting is mostly used for non-iron casting alloys such as zinc, copper, aluminum, magnesium, lead and tin alloys. Castings produced using this technology require very little subsequent machining [1]. “LTH Metal Cast” manufactures aluminum alloy automotive parts using high pressure die casting technology. Die casting technology properties are shown in Table 1. According to data from LTH Service of inspection and maintenance, the Molds prices in “LTH Metal Cast” are in the range of € 30 000 to € 100 000. Every mold has a life span usually around 100 000 to 120 000 casting cycles. After that period it is not possible to achieve the required cast dimensions. The mold has to be repaired or changed with a new one. Premature excessive wear significantly increases the cost of production.

Die casting process

The high melting temperature of aluminum alloy (about 660 °C) in the “LTH Metal Cast” manufacturing plant is the reason that cold chamber die casting is used. The molten metal is introduced into the shot chamber from an external source. This is the reason that the die casting machinery is able to stay cool [2].

The chemical composition of the casting alloy is verified by spectral analysis. At a certain ratio, the alloy is mixed with recycled scrap material. Molten metal is obtained from a separate furnace containing aluminum alloy ingots of Al 226, Al 231 and Al 239 [2]. The temperature of the molten metal is 690 ±20 ˚C. Molds are preheated to 170 ±10 ˚C. Depending on the material and the required casting quality, the hydraulic powered piston forces the molten metal into the mold under pressure of 30 to 100 MPa. The speed of molten aluminum at the mold entrance is in the range of 30 to 50 m/s. It takes from 0,01 to 0,2 seconds to fill up the mold. Filling up the mold is related to the molten metal mass, mold entrance size, pressure and metal density [2].

Table 1 **Comparison of casting technologies [1]**

	Sand casting	Low pressure die casting	High pressure die casting
Cast weight / kg	0,1 … 500	1 … 70	0,01 ... 30
Mold price	Low	Moderate	High
Minimal wall thickness / mm	4 ... 6	3 ... 4	0,8 ... 1,5
Dimension accuracy	Good	Very Good	Excellent
Surface roughness *Ra* / μm	> 6,3 – 12,3	≥ 3,2	≥ 1,6(0,8)
Casting alloys	AlSi10Mg AlSi7Mg AlSi9Cu2 AlSi7Cu2	AlSi12 AlSi10Mg AlSi7Mg	AlSi9Cu3Fe AlSi12 AlSi10Mg AlSi11Cu2 (Fe)

When the molten metal solidifies, the mold is opened and the casting is ejected. After every casting cycle the mold surface is lubricated with a solution of molybdenum disulfide (MoS_2). The force required to keep the mold closed during the injection and solidification process is in the range from 3 400 to 12 000 kN [2].

Mold material

High strength and toughness of mold material is required at temperatures of about 690 ˚C. The mold surfaces, that is in direct contact with the molten metal, are made from tool steel X38CrMoV51. The main properties are: a high resistance to annealing, wear, dynamic loads, thermal fatigue and corrosion [3]. The chemical composition of the tool steel X38CrMoV51 is shown in Table 2 [4].

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Table 2 **Tool steel X38CrMoV51 chemical composition / wt% [4]**

C	Si	Mn	Cr	Mo	V
0,36 - 0,42	0,9 - 1,2	0,3 - 0,5	4,9 - 5,8	1,1 - 1,4	0,24 - 0,5

This material is specifically made for severe operating conditions of tools and molds. It is suitable for quenching by air and is also mostly used for casting light metal alloys [3]. The physical properties of steel X38CrMoV51 are shown in Table 3.

Table 3 **The physical properties of tool steel X38CrMoV51 at certain temperatures [3]**

Temperature	20 °C	500 °C	600 °C
Density / kg/dm^3	7,80	7,64	7,60
Specific heat / J/kgK	460	550	590
Modulus of elasticity / MPa	$215 \cdot 10^3$	$176 \cdot 10^3$	$165 \cdot 10^3$

Wear mechanisms

The mold is heated by the molten metal and cooled by heat conduction into the bulk of the mold. The cooling process is also affected by irradiation and convection when the mold is open. Before every cycle, the surface is sprayed with molybdenum disulfide which causes additional heat loss. Rapid temperature changes cause thermal fatigue of the mold surface layer. Thermal fatigue is the dominant mold failure mechanism in die casting [5].

Dynamic load cycle is represented by expansion and contraction of the material in the mold surface layer. A certain number of cycles generates fatigue in the material surface. Cracks caused by thermal fatigue are usually smaller and are cross linked at the surface. Propagation of cracks causes particle separation. Oxidation can contribute significantly to propagation of cracks caused by thermal fatigue [5]. Figure *1a* shows a mold with significant wear due to thermal fatigue, although Figure *1b* shows the cast produced with the same mold [6].

Erosion is induced by high kinetic energy of molten metal at the mold entrance. It is also enhanced by the presence of solid particles in the molten metal (Al_2O_3). Damage can be observed at the region where the molten metal comes in contact with the mold surface [5]. This is shown in Figure 2 [7].

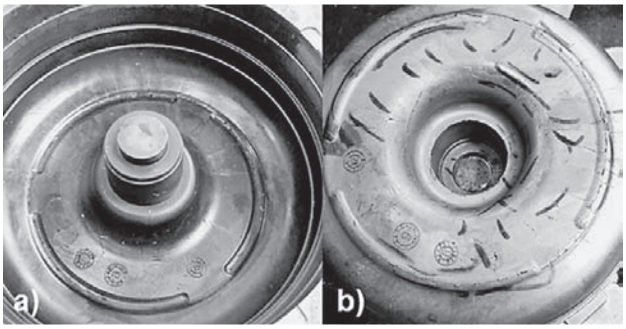

Figure 1 Mold damaged by thermal fatigue and cast produced with the same mold [6]

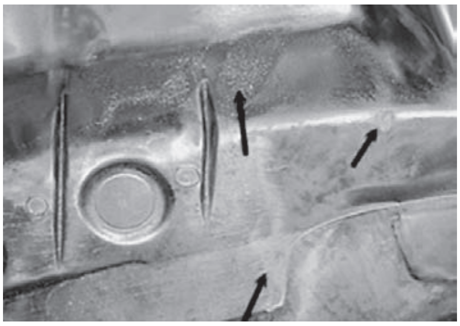

Figure 2 Mold erosion wear [7]

Surface damage is also usually caused by corrosion originating from the dissolution of the mold material in the molten metal and emerging intermetallic compounds [5].

Local adhesion between the mold surface and molten metal during the injection and solidification process may cause some buildup patch on the mold surface. The intensity of wear can be decreased: by achieving lower friction between the mold surface and the molten metal, by increasing the mold hardness and by achieving a lower chemical reactivity between the mold and the molten metal [5, 8].

Casting alloy

The casting material is aluminum-silicon alloy AlSi12Cu1 (Fe). This is a eutectic alloy with excellent casting properties. Silicon provides low viscosity and fluidity in the molten state. This alloy was made for production of castings with complex shapes and narrow cross sections. It is also suitable for machining [9].

A disadvantage of these alloys is poor weld ability. Mechanical properties of the casting alloy are improved by adding manganese and nickel [8]. Chemical composition and properties of the casting alloy are shown in Tables 4, 5 and 6.

Table 4 **Casting alloy chemical composition / wt% [9]**

Si	Fe	Cu	Mn	Mg
10,5 – 13,5	0,6 – 1,1	0,7 – 1,2	0,5	0,4
Cr	Ni	Zn	Pb	Ti
0,1	0,3	0,5	0,2	0,1

Table 5 **Casting properties [9]**

Solidification range / °C	Casting temperature / °C	Shrinkage / %
580 - 530	650 - 700	0,5 – 0,8

Table 6 **Mechanical properties [9]**

Tensile strenght, R_m / Mpa	Proof stress, $R_{p0,2}$ / Mpa	Elongation A_{50} / % (min.)	Brinell Hardness / HB (min.)
240	140	1	70

Controlling parameters

During the heating phase of the first cycle, thermally induced stresses cause accumulation of compressive plastic strains in the surface layer. The presence of stress raising defects may lead to tensile stresses exceeding the mold steel yield strength. The gradual softening of the mold material, which occurs during the thermal cycling, lowers the initial yield strength values of the steel. After a certain number of thermal cycles the surface material will be locally exposed to cyclic stresses that cause accumulation of plastic strains [5]. If the difference between mold preheating temperature and the molten metal temperature is lower the amplitude of the load cycle will be also lower. Therefore, wear can be decreased by optimal adjustment of the mold preheating temperature.

As previously mentioned, due to the high relative speed of the molten metal, erosion wear occurs during the mold filling process with molten metal. It can be expected that wear would decrease with a decrease of molten metal speed. Speed decrease can be obtained by lowering the pressure of the hydraulic cylinder or by a different mold design.

Mold material is also an important parameter. The casting process is conducted at high temperatures. Most of the wear occurs due to material fatigue. The crack length and crack density decreases with higher initial tool steel hardness [5]. Besides high strength and hardness, high toughness is also necessary to withstand as many cycles of load as possible and to extend the mold life.

Laboratory research

As the mold wear research during the production process is very expensive and long-term, the research work has mainly to been done in laboratory conditions.

To correctly obtain the intensity of mold wear during high pressure die casting, it is necessary to reproduce more accurately the manufacturing conditions. The laboratory simulation device will be less complex and more practical if the testing is done by rapid immersion of small samples into the molten metal. This enables simpler wear tests for any die cast material. The samples would be relatively small (about 15 g). Wear intensity can be determined by measuring the specimen mass loss on a precise balance scale.

The main cause for the soldered metal is the tribochemical interaction between the molten aluminum alloy and the die steel surface that results in intermetallic formation and adhesion [10]. Soldering of metal and development of intermetallic compounds can be avoided by using a special lubricant. Graphite and molybdenum disulfide (MoS_2) are the predominant materials used as solid lubricant. Like graphite, MoS_2 has a hexagonal crystal structure with easy shear property. Due to their lamellar structure these materials are effective lubricant additives. The lamellas are oriented parallel to the surface in the direction of motion. Even between highly loaded stationary surfaces the lamellar structure is able to prevent contact. In the motion direction the lamellas easily shear over each other resulting in low friction. Large particles best perform on relative rough surfaces at low speed, while finer particle best perform on relative smooth surface and higher speeds. Other useful components are: solid lubricants including boron nitride, polytetrafluoroethylene (PTFE), talc, calcium fluoride, cerium fluoride and tungsten disulfide [11].

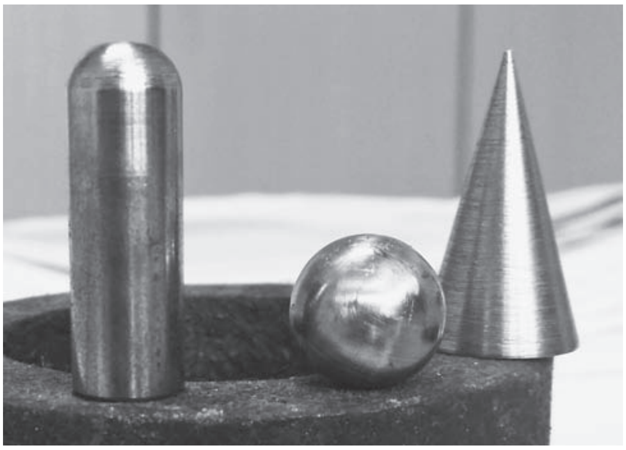

Figure 3 Cylinder with a rounding, sphere and cone sample

Preliminary tests

Adhesion of the aluminum alloy on the sample surface during the simulation of wear would make the test results un-applicable. Preliminary tests were done to find parameters that ensure no adhesion during the simulation. Analyzed parameters were: geometrical shape of the sample, sample preheating temperature, surface roughness and lubrication.

Samples were of similar mass and made in three geometrical shapes as shown in Figure 3.

Initially, without previous lubrication, the samples were immersed into molten aluminum heated at 700 °C. It was obvious that the rough surface from the lathe machining process caused massive mechanical anchoring of the molten aluminum alloy. Therefore all the samples were grinded to a lower surface roughness. When immersing samples without preheating, a large temperature difference between sample and molten aluminum alloy caused mechanical anchoring around the sample. Preheating of the samples reduced mechanical anchoring. Without lubrication, the most optimal shape was the sphere.

The most significant improvement was observed after using the lubricant consisting of molybdenum disulfide. Even without preheating, no aluminum was attached on any of the samples. Results of the tests are shown in Figure 4.

CONCLUSIONS

According to the data in this paper, the most influential parameters are mold preheating temperature, speed of molten metal and mold material. Research data

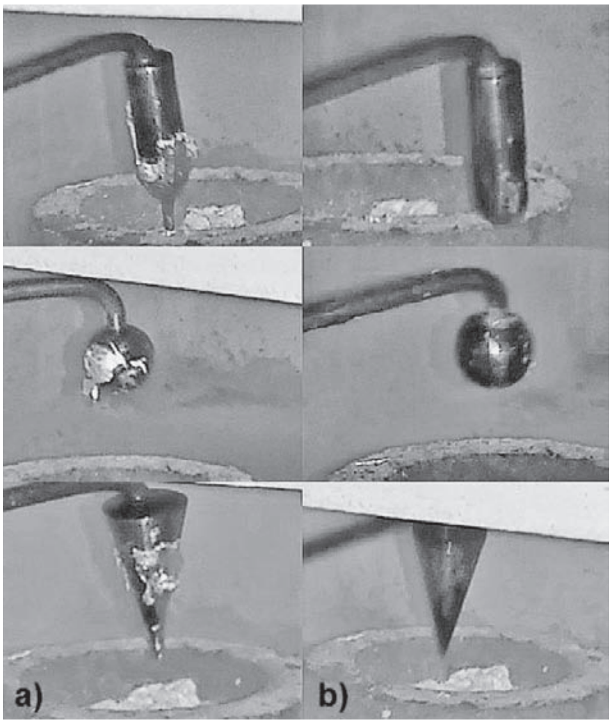

Figure 4 Samples without MoS_2 (a) and with MoS_2 (b)

shows that parameters in “LTH Metal Cast” plant are not optimal which suggests wear intensity can be lowered. According to various sources, wear can be decreased by increasing the mold preheating temperature from the minimum of 180 to 350 ˚C [3, 12, 13]. To effectively reduce wear it is necessary to try out different combinations of parameters and analyze their interactions. The simulation device has to be able to simulate and vary the mold preheating temperature, relative speed of molten metal and different mold materials. As the preliminary tests show, it is necessary to introduce a lubricant in the test process.

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Note: The English language review is done by Ph.D. professor David Kennedy from Dublin Institute of Technology, Ireland