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EFFECT OF FILLING CONDITIONS ON THE QUALITY OF CAST ALUMINUM CYLINDER HEADS

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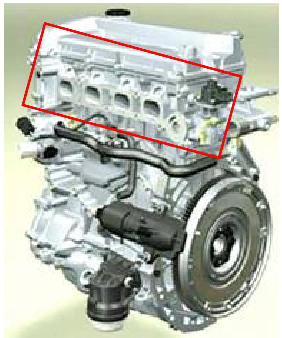
ABSTRACT

By each casting process the filling conditions play a significant role on the casting quality. The family of the aluminum alloys are not exception from that rule. The cylinder head production praxis by gravity casting process shows that the quality of casting is primarily influenced by filling conditions of gating system and mould cavity. This research work focused on the effect of different pouring cup designs, gating dimensions and gating positions, on the filling patterns of the cylinder head produced applying gravity casting process. Various options of pouring cups and gating systems were assessed with a high resolution camera as well as via modelling & simulation. As a result, different filling characteristics were analyzed and a big influence not only on the filling pattern of the mould, but also on the quality of casting products was determined.

INTRODUCTION

The current tendency of new car engines development aims for exhausting gases minimization, weight and consumption reduction and at the same time increase the power and the effectiveness of the engine. The result of this development in the automotive industry is the continuously increasing requirements for higher quality of the castings, the improvement of physical and mechanical properties and last but not least, the reduction of developing time for new products. Therfore, the research and development in the casting industry have to follows these objectives. This is a challenge for development of new or improvement of known producing technologies and materials of casting parts for the engine, which requires extensive experience and the use of tools such as simulation software.

The cylinder head with motor block belongs to the most complex part of the engine. Pictures 1 and 2 illustrated this, showing an engine for passenger car and cross section of cylinder head. On the top of the cylinder head is placed camshaft. The motion of camshaft manage the gas flow exchange through the intake and exhaust valve. Usually in the middle of combustion chamber is placed sparkling plug. They are for passenger cars mostly produced using light metal alloys. The intricate inside shape can be formed only with lost cores.



Picture 1: Example of an engine

Picture 2: Cross section of cylinder head

GRAVITY CASTING

Currently there are many casting technologies which are applied to produce cylinder heads using aluminum alloys. The differences between technologies are established as follow:

(i) by various acting force on the metal flow during filling the mold, (ii) by mold material and (iii) by gating system. This paper is focus only on gravity casting process.

Gravity casting is nowadays very well established in foundry industries for production of cylinder heads using aluminum alloys. Gravity casting occurs without any outside influences, apart from gravity itself using sand mold, permanent mold or lost foam shell. In this work three types of conventional mold processes were considered. The main difference by all of them was recognized in the position of the gating system as it was presented in picture 3.

a) b) c)

Picture 3: Example of cylinder heads with gating system poured by gravity a.)top casting, b.)bottom casting and c.) tilt casting

One of the key factors that has significant influence on the quality of cast products is a design of a gating system. The gating system refers to those channels through which the metal flows from the ladle to the mold cavity. The use of a good gating system is even more important if the casting is produced by a gravity process. If the poor gating techniques are used, lower casting quality is achieved, due to a turbulent flow of the melt through the gating system.

The top casting method allows a better cooling of the combustion chamber area which helps getting better mechanical properties of cast parts due to directional solidification. The probably most complex and at the same time difficult task by gravity top casting, is to avoid surface turbulence. According to Campbell researches summarized in his book „Ten rules of casting“[1], at least 80% of all defects are directly caused by turbulence. It is certainly difficult to influence the free-fall of the melt. To illustrate this, consider that a sessile drop falling down from more than 12,5 mm, can already cause the metal to exceed its critical velocity increasing the risk of having defects on the cast.

The advantage of the bottom casting is laminar flow of the melting metal in the mould. The disadvantage of bottom casting is limited cooling conditions in combustion chamber leading to the reduced mechanical properties. Because of limited directional solidification presence of shrinkage and pores in as cast structure is plausible.

The state of the art tilt casting keeps all advantages present by the top casting but at the same time reduce the turbulent flow of the melt due to the tilting of the whole system during fillling process.

FILLING PROCESS

The filling pattern of gating system plays a significant role for the assessment of the quality of cast products. Particularly the pouring process of light metals is very dynamic and complex.[1,2] The flow velocities in some gating areas are very high. The solidfication of the melt during the mould filling continuously change the properties of liquid and solid phases. In addition the interaction between metal-mould and metal-core have to be continuously monitored. All above mentioned properties have to be taken under consideratin during modeling&simulation of the filling process.

An inappropriate gating system or speeding of the metal stream leads to the turbulent flow of metal that couse creation of oxides in the mould. A strong metal flow can also cause mould erosion. An intensive turbulent flow supports the formation of air and oxide inclusions. On the other side, slow metal flow and fast solidification are reason for cold shots.

Aluminium, silicon and magnesium alloys have a tendency to build insoluble oxide inclusion on the metal surface because of its higher oxygen affinity. Also the higher melt temperature promote the formation of oxide inclusions.

The density of oxide inclusions is similar to the density of the melt. Oxide inclusions will not float on the surface but will stay unevenly in the melt volume. Their presence in the metal structure negatively affects the mechanical and physical properties of casting products.

The production praxis of cylinder heads by gravity casting process showed that the quality of the cast products is related to the filling pattern of the gating system and the filling pattern of the mould. Another important factors that define the quality of cast products are the melt temperature, the mould temperature and filling time.

OXIDE FORMATION

Gibbs free energy of aluminum oxide is very high, due to the high affinity of aluminum to oxygen. This reaction is getting stronger at higher temperature. Depending on the chemical composition of the melt, aluminum forms different type of oxides. In the case when the pure Aluminium is expose to the air, on the surface of liquid aluminum will be form solid Al_2O_3 oxid film. By aluminium alloys which containes magnesium $MgAl_2O_4$ spinells are usually formed.

Typical reactions between melt and oxygen could be summarize as:

$$2\ Al_{liquid} + 3/2\ O_{2\ air} \rightarrow Al_2O_{3\ solid}$$

$$2\ Al_{liquid} + 3\ H_2O_{water\ vapour} \rightarrow Al_2O_{3\ solid} + 6\ H$$

$$2\ Mg + O_{2\ air} \rightarrow 2\ MgO_{solid}$$

By pure aluminum oxidation of the metal surface expose to the oxygen atmosphere starts within milliseconds. [9-16]. The advantage of formed oxide film is that this oxide film has a high impermeability to the diffusion of aluminum and oxygen ions and forms a protective layer over the molten aluminum. Because they are entrained quickly and have little time to grow, amorphous oxide films are referred to as 'young oxides' [11]. They are characterized by extreme thicknness, usually measured in tens of nanometers.

After an incubation time normally around 5 to 10 minutes at 750°C [11]the amorphous oxide layer suffers a discontinuous change of structure. A fast migration of oxygen through the oxide-metal interface occurs at high temperature, resulting in a nucleation and growth of γ-Al_2O_3 crystalline phase under the amorphous layer [12-16]. The incubation time for this transformation is reduced by increased temperature and increased inclusion content in the melt [19]. During this period the film has time to thicken, becoming often micrometres or even millimetres thick. These thicker oxide films, referred to as 'old oxides' [16] are characterised by their crystalline form.

In the available literature there is a lot of proposal how to qualitatively recognized different types of oxides. Just few of them develop the procedure how to quantify them. The reference [3] summarized different methods that has been applied to quantification of oxides such as acoustic resonance, X-ray, thermopictures, ultrasound, rotational current and electrical capability. Among them just X-ray and ultrasound showed good potential for oxides quantification.

Recently the group of autors [4] came with some analytical expression which can be applied to quantify the amount of bifilm using equation (1). This bi-film index is given from the total length of bi-films estimated from a sectioned surface of reduced pressure test samples, using the sum of the maximum length of the pores.

$$Bifilm\ index = \Sigma\, pore\ length = Lb \qquad (1)$$

EXPERIMENTAL PROCEDURE

The modelling & simulation of the filling process is today an integrated part of computer simulation of casting process in each casting plant. Mathematical formulas for calculations of metal flow combined with heat transfer are difficult and need complex numerical solutions, which are affected by various factors. Without experimental trials is difficult to say if the results obtained by simulation of the filling process corespond to reality. However, on the basis of experimental trials it is possible to compare and validate the simulation models with reality and to optimize them.

The filling pattern via direct and indirect pourig basinss were investigated using gravity top casting, bottom casting and tilt casting. The melt preheated to the 725°C was poured from a pouring ladle into the pouring basin. The filling of pouring basin was observed using a high speed camera which can save maximal up to 1000 frames per seconds. In this experiment has been used 250 frames per seconds. The results of the observation of filling process were evaluated with the SpeedCam software program.

Picture 4 shows a smooth filling of pouring basin by tilt casting. In this case the melt falls down from the pouring laddle into the basin from the very short height and flows through the basin wall.

a) b) c)

Picture 4: Tilt casting process

The observation of filling process by direct pouring basin on gravity top casting has shown how important is the design of pouring basin, pouring height and alignment of the flow into the pouring basin for secure of smooth filling. (Picture 5)

a) b) c)

Picture 5: Top casting process

Picture 5a and 5b show that the metal flows from pouring ladle into the pouring basin from a height of about 15-20 cm. The metal flows slightly on the right side of the pouring basin. This causes that the metal on the right side rises on the wall and splashs back on the flowing metal from the pouring basin. The high flow velocity of the melt from pouring ladle into the pouring basin and unappropriate dimension of pouring basin causes a turbulent flow of the melt that splashes from both sides into the middle of the basin causing the creation of oxide inclusions and the air entrapment.

a) b) c)

Picture 6: Bottom casting process

The main advantage of bottom gating system is laminar filling of the mould. Dissavantage is recognize in the turbulent filling of poring basin. In this filling process the metal front hit the opposite wall of the cup and tip over the falling stream. The metal flows through the sprue on both sides of pouring basin next to the mould.

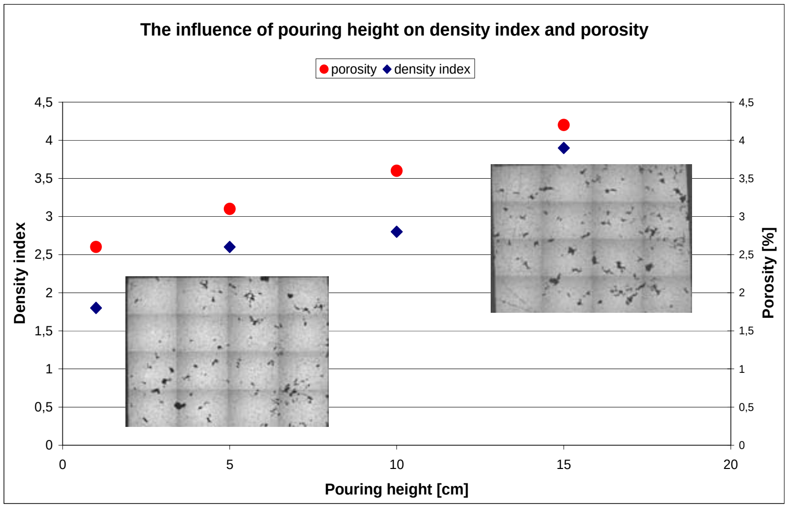
The influence of pouring distance between the basin and the ladle on the melt quality during top casting was separately simulated using simple experimental procedure. The AlSi7MgCu alloy was used for this experiments. The melt has been poured into the cup of reduce pressure test from 4 different heights. The first pouring height was about 1 cm. The other distances were 5cm, 10cm and 15cm respectively. One from two poured samples for each trial was solidified under vacuum while the other sample was solidified under atmosphere pressure. The density index of the casted samples was determined follows the Archimedes law.

The higher pouring distance produced the higher density index, which means that the sample has more pores and oxides inclusions. This is expected results because during the filling the cup from larger distance the stream of melt has more time to react with air and be contaminated with oxides. Also, the stream which is falling down from bigger distance has bigger kinetic energy and will cause larger turbulent movement in compare to the stream that is falling from smaller distance. The metallographic structure analysis confirmed this results. Left picture on the graph 8 represents the structure from sample poured at 1cm while the picture on the right present the structure of sample poured at 15cm. The structure from the sample poured at 15 cm has clearly more and bigger pores vs. the structure from the sample poured at 1cm height. Metallographic evaluation of porosity confirm this trend.

a) b) c)

Picture 7: Simulation of poring distance using reduce pressure test

It is a well known that there is a wide spectrum of oxide films regarding their thickness, size and shape. The Table 1 shows an overview given by Campbell [1]. Based on their growth time oxide films have been related to the various sources where they were potentially formed. It is clear that in the foundry production chain there is a lot of possibility for their formation. Therefore, the foundry engineers need to understan the way of their formation in order to be able to react pro active and eliminate potencial source for oxide film formation.



Picture 8

a) b) c)

Picure 9. Example of a.)surface of leaking intake wall of cylider head, b.)broken leaking section and c.)metallographical analysis of oxide inclusions

The rules how to eliminate the presence of oxide films in the aluminum melt have been already summarized by Cambel [20]. The process engineers have to accept those rules in their everydays praxis in order to be able to reduce potential sources for oxide formation. Unfortunately, in many aluminum casting plants we are still far away that we can produce the cast product without such defect. The Figure 9, shows the cylinder head with detected leaking problem caused by the presence of oxide film. Most likely in this case the turbulent mould filling was a main source for formation of oxide film.

Table 1: Forms of oxide in liquid aluminum alloys

Growth time	**Thickness**	**Type**	**Description**	**Possible source**
0,01s-1s	1nm-1µm	New	Confetti-like fragments	Pour and mould fill
10s-1min	10µm	Old 1	Flexible, extensive films	Transfer ladles
10min-1hr	100µm	Old 2	Thicker films, less flexible	Melting furnaces
10hr-10days	1000µm	Old 3	Rigid lumps and plates	Holding furnaces

CONCLUSION

Three different casting processes have been investigated in order to analyze the effect of the shape of pouring basin, distances between pouring basin and pouring ladle and the position of pouring ladle on the formation of oxide film in cast products. Based on conducted experiments followings conclusions can be drown:

- The main factor for smoothness filling of the mould is the pouring process and the position of ingates
- The shape of the pouring basin has significant influence on the smoothness of the pouring stream and further on the oxide formation.
- Pouring distance is also one of the very important factors that has impact on the formation of oxides consequently increasing porosity in cast structure.
- The point at which the falling stream of Al melt fall down into pouring basin define the smoothness of melt velocity (laminar or turbulent) through the sprue and the mould contributing to the later quality of cast product.

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