Review of Corrosion and Soldering for High Pressure Die Casting

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Abstract. High pressure die casting (HPDC) is a fast-paced manufacturing process that allows the production of high-quality parts. Besides the quality, the cast shows good dimensional precision and a small dependency on post-processing. Many automotive companies are migrating to this process to manufacture high complexity geometry components and avoid assembling several smaller parts. By doing it, these companies are reducing the total weight of the vehicle and, as a consequence, making their products greener. Notwithstanding, the production cost is still a challenge for the broad implementation of this technique. Many are the problems that raise the costs regarding HPDC. One of the price components is die maintenance. These dies are exposed to several kinds of wear, and as the surface is worn the cast quality decreases. This review aims to show the HPDC technology and corrosion/soldering wear.

Keywords. High Pressure Die Casting, Wear, Die Soldering, Corrosion.

1. Introduction

Many efforts have been put into the characterization of die wear for HPDC. According to Bonollo et al. [1] half of the world production of light metal castings is obtained by this technology. There are several reasons why this technique is chosen. However, some requirements are needed to justify the use of this technology. Tool costing is still a problem, and large production quantities are required to justify these costs. In the case of small production, other processes, like sand casting, are recommended [1]. As stated by Dadić et al. [2], HPDC shows an excellent dimensional precision compared to other casting processes. However, the price of the die is high. Many studies attribute thermal fatigue as one of the main mechanisms of die failure [3–5]. Other mechanisms such as corrosion and soldering also play a big role in die wear.

Nitriding and physical vapor deposition are techniques utilized to retard wear [6–8]. Some other techniques are also being used, as welding [9,10] and thermal spray processes [5,11] to recover the surface. These recovery techniques give the surface a survival. However, there is still a lack of studies in this field. This study has the focus of showing the state-of-the-art solutions and problems that engineers still have to overcome.

2. Reviewing

2.1 Technique costs

One of the main disadvantages of HPDC is its relation of price and durability. According to Dadić et al. [2], the lifespan of the die is about 100,000 to 120,000 casting cycles. Due to the harsh environment these dies are exposed to, the tooling costs can contribute to around 10% of the sale prices of castings [12]. An analytical model was proposed by Favi et al. [13]. Many are the components that compose the final price of the castings. The main portion of the cost is the raw material. However, the price is controlled by the economy. Another important variable is dimensional tolerance. For tight tolerances, the price rises due to the increase in failure probability. Die wear causes not only surface defects but also changes the overall geometry of the casting.

2.2 Corrosion

There are several causes by which dies can fail. One of these mechanisms is corrosion. The corrosion occurs due to the contact of the die surface with molten metal, which changes the surface characteristics. Some of the corrosion mechanisms are well described by Sequeira [14]. One of the mechanisms is simple dissolution. Simple dissolution has not been completely understood yet. It consists of the dissolution of the surface by the molten metal. As stated by Zhu [15], the dissolution process is a combination of corrosive, erosive, and chemical reactions. Dissolution may also be diffusion controlled, and it can be described by the equation below [16].

$$\frac{dC}{dt} = D\frac{1}{\delta}\frac{s}{v}(C_s - C) \quad (1)$$

Equation (1) describes the concentration of dissolved metal (C) in the function of time. The limit of diffusion is the saturation concentration (C_s), where the diffusional process is suppressed. The other components of the equation are the thickness of the diffusion boundary layer (δ), the specimen surface area (s), melt volume (v), and the diffusion coefficient of the dissolved metal (D).

Another corrosion mechanism is alloying. According to Sequeira [14], a degree of solubility is demanded in order to alloying to occur. One accessible method to evaluate alloying is by using phase diagrams. According to Hugh Baker [17], phase diagrams give an indication of which phases are thermodynamically stable. Nonetheless, most of the practical problems involve nonequilibrium conditions. Even so, the use of phase diagrams is a powerful tool to have fast answers about the formation of intermetallics from molten metal corrosion.

The driver of the corrosive processes cited before is diffusion. The study of phase transformation has the main concern of the equilibrium arrangement of atoms in an alloy, whereas diffusion is what controls the rate that transformations occur. Diffusional processes occur due to the decrease caused in Gibbs free energy, turning these processes spontaneous [18]. The way diffusion is mathematically described depends on the state of the process. For steady state diffusion, Fick's first law can be used to predict the phenomenon. When diffusion has a concentration gradient, Fick's second law better describes the phenomenon [19].

Diffusion can occur in two forms. The first one is substitutional diffusion. According to Porter [18], substitutional diffusion occurs when atoms oscillate through a certain amplitude and frequency. By increasing the temperature, the energy of the atoms rises, as the frequency remains the same, the oscillation amplitude is increased. As materials have vacancies, an abnormal jump may put the atom into the vacancy. Furthermore, the occurrence of vacancies is strongly influenced by temperature.

Another way diffusion may happen is via interstitial diffusion. In this case, the atom has to be small enough to occupy the interstitial sites. As the solute concentration is usually small, the atoms can jump as much as their thermal energy permits. Moreover, as the atoms are surrounded by interstitials, interstitial diffusion occurs much faster than diffusion via vacancies.

2.3 Die soldering

Die soldering occurs by the bonding forces generated by the casting and the surface of the die. When the molten metal is poured and subsequently injected into the die cavities, the molten material reacts with the die surface. Depending on chemical composition and temperature, this process can play a big role in die wear.

Soldering is derived from corrosion. Usually, corrosion performance is measured by a unit of volume of mass over time. In contrast, die soldering is dependent on the nature of the corrosion products. **Fig. 1** shows the corroded surface by molten aluminum and its residue.

Fig. 1 – Corroded die causing die soldering. The white arrows indicate the most worn regions.

In order to retard both corrosion and soldering, PVD coatings are widely used and studied for uses regarding molten metal wear [20–22]. Song et al. [7] has proposed a mechanism for the soldering process for surfaces coated with CrN by PVD. Other mechanisms of wear, like erosion, cause the wear of the PVD coating. The worn spots and previous defects, commonly found in the literature [23–25], create spots where the molten metal can reach the substrate and initiate the corrosion process. The bonding connection between the molten material and the die surface creates the soldering phenomenon.

Fig. 2 shows scanning electron microscopy (SEM) and electrical discharge spectroscopy (EDS) images of a bonding caused by molten aluminum. After only 10 minutes of immersion corrosion, it is possible to observe a curled surface. Furthermore, the EDS analysis shows a formation of an Al-Fe-Si intermetallic phase.

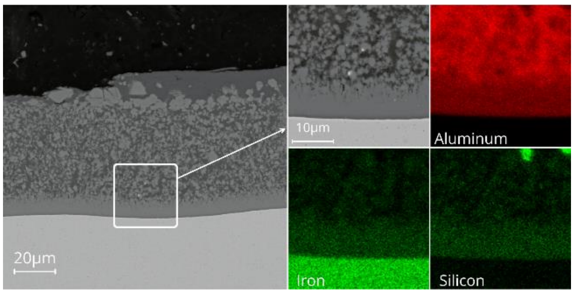

Fig. 2 – SEM and EDS images of soldered aluminum on AISI H13 surface after 10 minutes of corrosion in molten aluminum (A383) at 720 °C.

2.4 Other wear causes

There are several other causes of wear. Erosion occurs on the die surface and can be induced by solid particles or cavitation [26]. A study performed by Ding et al. [27] has analyzed a die after 60,000 shots and came to the conclusion that the main causes for this die to fail were erosion and cracks induced by thermal stresses. Thermal fatigue is also a strong wear phenomenon that occurs on the surface of the die. In order to enhance the surface properties, Peter et al. [5] has analyzed coatings deposited by HVOF on AISI H11 tool steel. After testing the coatings, they have concluded that thermal fatigue was the main wear mechanism.

After several cycles, the surface changes its hardness. The main reasons for hardness drop were described by Markežič et al. [28]. According to them, there are three main drivers for surface softening. The first one is erosion. As the surface of the die usually is nitrided, erosion removes the nitride layer, and the surface hardness drops. The second one is corrosion, which changes the chemical composition of the surface. And the last one is softening, which is caused by microstructural changes in the die material due to temperature changes. By decreasing the surface hardness, the die is more prone to wear.

2.5 Dies materials

High pressure die casting dies are manufactured with high quality forged steels. Cavities are made using electrical discharge machining (EDM) or high-speed milling [29]. AISI H13 is one of the most widely used materials for die manufacturing. The main reason is its high hardenability, strength, toughness, and softening resistance [30]. AISI P20 is also used for dies and molds. However, according to Garcia dos Santos et al. [31], P20 is usually used for polymers molds, as H13 is more mechanically resistant at higher temperatures.

Hot work steels can be classified as either chromium (H10-H19), tungsten (H21-H26), or molybdenum (H42-H43), depending on the main alloying element [32]. Also according to Persson [32], alloying with vanadium improves the high temperature wear, as vanadium carbide is the hardest of all carbides. Furthermore, the oxidation resistance can be improved by silicon addition. Furthermore, the tungsten and molybdenum hot work steels are more resistant to softening and have a higher hardness at high temperatures.

2.6 Lubricant and surface finish

Soldering is unlikely to occur when lubricants are applied to the surface of the die. However, soldering happens when the lubricant coating fails. A detailed model is described by Zhu et al. [33]. When analyzing soldering effects using lubricant, Gobber et al. [34] found a surface finish of about 0.8 R_a, where the probability of soldering is really low. This is due the increase in the surface energy, making the surface more adherent to the lubricant coating [35]. If the surface is over polished, the lubricant does not adhere, and the molten metal can achieve the surface of the die.

2.7 Corrosion and soldering tests

Corrosion tests are usually performed by immersion of the surface in molten metal. Salman [36] has analyzed titanium-based composites deposited by HVOF to create a coating. To evaluate corrosion, immersion tests in molten aluminum at 700 ± 10 °C were performed for different time intervals. After every immersion, the samples were cleaned in a solution of 20% NaOH to remove the adhered aluminum, and then the specimens had their weight measured.

It is also possible to perform corrosion analyses by the use of a rotational system, as the corrosion process is strongly influenced by dynamic agitation. Some of these testing machines are described by Zhang and Chen [37]. Zhu [15] has used a rotational system changing temperature and angular velocity in order to have a complete understanding of the corrosion mechanisms.

Soldering analyses were executed by Terek et al. [38] to understand how some experimental changes could modify the results of soldering for its specimens. Terek has used pins cast inside the aluminum and effectuated the extraction of these pins. A similar process was performed by Fazlalipour et al. [21]. Another methodology was performed by Wang et al. [39] to evaluate soldering. In order to analyze only soldering forces, a pin of aluminum was cast on a flat surface intended to be analyzed.

3. Conclusions

Several are the challenges engineers have to overcome in order to make this technique more affordable. One of the main challenges is the cost attributed to the final cost of the manufactured parts because of tooling wear. By changing materials and making improvements in the die manufacturing technology, it is expected a reduction in casting cost and improvements in surface quality and dimensional precision. Some techniques, such as nitriding and PVD, are broadly used. However, it still needs improvements. As the demands are high, the investment in new technologies is expected. High pressure die casting is a manufacturing process in high demand, mainly due to the automobilist sector. HPDC has the advantage of reducing the assembling process and can make vehicles lighter. Fuel consumption can be reduced by decreasing the weight of the vehicles. To conclude, there are still several topics regarding HPDC which have the opportunity of development.

4. References

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