Research Programs

Investigation of Die Soldering Characteristics of Aluminum Die Casting Alloys

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A major concern in the die casting industry is die soldering: when molten aluminum sticks to the surface of the die material and remains there after the ejection of the part. The challenge in die casting is to minimize the cycle time of the casting operation with the aim of increasing productivity and lowering operational costs. Die soldering is an impediment to this challenge in that it leads to malfunctioning of die inserts that require replacement or repair, thus causing significant decrease in productivity.

Due to the high affinity that aluminum has for iron, a vigorous physio-chemical reaction occurs at the die/molten metal interface when aluminum melt comes in direct contact with the ferrous die. This reaction results in the immediate formation of a series of iron-aluminum-silicon intermetallic compounds over the die surface and eventually the cast metal sticks to this intermetallic layer.

There are several classes of process parameters that influence die soldering. The dominant ones are:

- Temperature of the metal and die.
- Nature and constituents of casting alloy and intermetallic layers.
- Die Lubrication and coating.
- Nature of the die and operating parameters.

In this study, the critical process parameters affecting soldering have been identified and studied. The effect of seven alloying elements in aluminum 300 series alloy, their interactions, cycle time and temperatures of melt and die have been quantified through various experiments. The experiments were performed in a laboratory environment on an apparatus designed to simulate the harsh casting conditions under which soldering occurs. All the results and conclusions have been verified and validated in several production facilities. Recommendations to mitigate soldering have been proposed based on our conclusions.

An overview of the mechanism that leads to die soldering is given below.

Mechanism

Figure 1 shows a schematic of the proposed mechanism of soldering. The various stages leading to die soldering are shown.

The mechanism of soldering occurs in six stages:

STAGE I ==> Erosion of grain boundaries on the die surface
STAGE II ==> Pitting of the die surface
STAGE III ==> Formation of iron-aluminum compounds
STAGE IV ==> Formation of pyramid shaped intermetallic phases

STAGE V ==> Adherence of aluminum onto the pyramids of intermetallic phases
STAGE VI ==> Merging and straightening of erosion pits and intermetallic phases.

The mechanism schematically shown in Figure 1 has been validated through many similar microstructural observations. Each of the six stages is further discussed below.

STAGE I ==> Erosion of the die surface

The aluminum melt repeatedly encounters the die surface at each cast cycle. Tool steels are generally heat treated by double tempering to a hardness of about Rc48-Rc50. In due course of the casting process, the aluminum melt attacks the softer regions of the die surface. The soft regions being the areas in-between the hard martensitic plates and the carbide particles; these are primarily the intergranular regions. When the aluminum erodes these soft areas of the die surface, it results in the formation of a primary solid solution of iron by aluminum dissolution. The solid solution phase is represented by -Fe. This is illustrated in the schematic shown in Figure 1(a). An actual grain boundary attack is shown in Figure 2 (a). In this particular case, Figure 2(a) soldered sample was obtained from Cambridge Tools and Manufacturing, Burlington, MA.

STAGE II ==> Pitting of die surface

Once the grain boundaries and the soft phases on the seel surface have been attacked by aluminum, pits hemispherical in shape form. The typical high drag forces that are experienced by the die surface eject the loosened surface grains from the die, into the melt.

STAGE III ==> Formation of iron-aluminum compounds

The aluminum reacts with the loosened surface grains, and at the surface of the pits more iron-aluminum binary phases are formed such as $FeAl$, $FeAl_2$, Fe_2Al_5 and $FeAl_3$. The formation of these successive layers of binary compounds is due to the reaction of each phase with a continuously renewed molten aluminum and the diffusion of the iron out of the steel surface take place.

STAGE IV ==> Formation of pyramid shaped intermetallic phases

The $FeAl_3$ phase reacts with aluminum and silicon in the alloy melt to form the ternary α-(Al,Fe,Si) phase. The intermetallic layers, formed during this stage, have a pyramid-like morphology. This is due to the radial growth of the intermetallic phases out of the pits on the steel surface. The ternary phase has the highest thickness compared to the other phase layers. As the volume of the aluminum melt is abundant, the reaction between the intermetallic phases and the melt dominates over the diffusion of the iron from the steel surface. However, the overall thickness of the intermetallic layer on the steel surface is controlled by the diffusion of iron from the steel surface. Silicon and other minor elements (Cr, Mn, V, etc.) from the die and the aluminum alloy melt precipitate on the grain boundaries of the Fe_2Al_5 intermetallic phase. Large silicon rich precipitates are also found at the boundary between the binary and the ternary phases. Zinc rich compounds precipitate on the grain boundaries of the ternary -(Al,Fe,Si) phase layer. This stage is shown in Figures 1(c).

STAGE V ==> Adherence of aluminum onto the pyramid-like intermetallic phases

The last reaction product between iron and the aluminum alloy melt is the ternary -(Al,Fe,Si) phase. As soon as the pyramid shaped intermetallic layer forms on the die surface, the excess aluminum sticks to it (see Figures 1(c)). The initial sticking is primarily due to the arrest of the ongoing reaction between the

iron, the aluminum alloy melt, and the surface energy effect of the protruding intermetallic layer into the aluminum melt. Another possible reason for aluminum to stick to these pyramid shaped protrusions is the low thermal conductivity of the intermetallic phase layers compared to the steel surface. Hence, when the rest of the casting is solid and ready to be ejected, the melt around the intermetallic layers is solidifying. This results in the sticking of the melt around the protrusions of intermetallic layers even after the ejection of the cast part. Figure 5 is a micrograph showing the initial pits formed on the die surface, the subsequent intermetallic phase layers that formed and grew out of the erosion pits, and finally the part of the aluminum casting that stuck on to these intermetallic layers and remained on the die steel (after the ejection of the cast part).

STAGE VI ==> Merging and straightening of erosion pitsand intermetallic phases.

In due course, the erosion pits widen and merge with each other, resulting in the straightening of the pits. Once the initial layer of intermetallic layer form inside the pits, the pits stop growing into the steel surface and grow parallel to the die surface. When adjacent pits start to merge with each other, the supply of fresh aluminum melt to the steel surface is restricted to the gaps and cracks in-between the intermetallic layers growing out of the adjacent pits. After a certain period of time these cracks close, resulting in the arrest of the chemical reaction between the aluminum alloy and iron. Figure 5 shows the closure of one such crack in between adjacent pyramid shaped intermetallic phase layers. In this stage, the growth of the $-Fe_2Al_5$ phase is more pronounced than the ternary phase. This is because, the iron/aluminum chemical reaction rate diminishes and the iron diffusion rate is constant. Once the reaction forming the intermetallic layers is arrested, soldering is terminated. This results in a permanent sticking of the aluminum on the intermetallic layers. Re-melting of the soldered aluminum is not probable because the time of contact of the fresh cast melt with the soldered aluminum is very short (4ms). Hence, most of the soldered microstructures exhibit a fixed ratio of 1:5 between the intermetallic layer thickness and the soldered thickness.

Recommendations to Mitigate/alleviate Die Soldering are:

1. Die Condition
  - The die pre-heat temperature must be between 570 F and 625 F. Higher temperatures will result in inadequate application of the lubricant. Lower temperatures might result in the formation of cold solder.
  - The die surface must be polished to a 45 micron (325 grit) sand-blast finish.
  - A mirror polished and a 30 micron (600 grit) polished die surface enhances die soldering.

2. Alloy Temperature
  - The temperature of the melt is a critical factor in creating "hot-spots" on the die surface. Temperature of the holding furnace should be ~ 663 C (1225 F) before pouring the melt into the shot sleeve in a pressure die casting operation.
  - In a permanent mold process, the temperature of the melt must be ~ 643 C (1190 F). This will minimize the occurrence of hot spots in the melt.

3. Alloy Chemistry
  - Iron content should have a limiting range between 0.9 and 1.15 percent by weight.
  - For Low iron alloys, iron content around 0.4 percent by weight, manganese must be raised to around 0.8 percent by weight to compensate for the low iron in the melt.
  - Care should be taken to minimize the nickel and the chromium contents in the melt. Nickel ties down the effectiveness of manganese in the melt, and chromium increases the sludge factor.
  - Reducing silicon content, in a low iron alloy, to about 7 percent by weight will increase the chemical activity of manganese and iron in the melt, and will thus reduce soldering.
  - Titanium additions to the melt of about 0.125 percent by weight is highly recommended to avoid soldering.
  - The nickel content of the alloy must be kept negligible to minimize soldering.
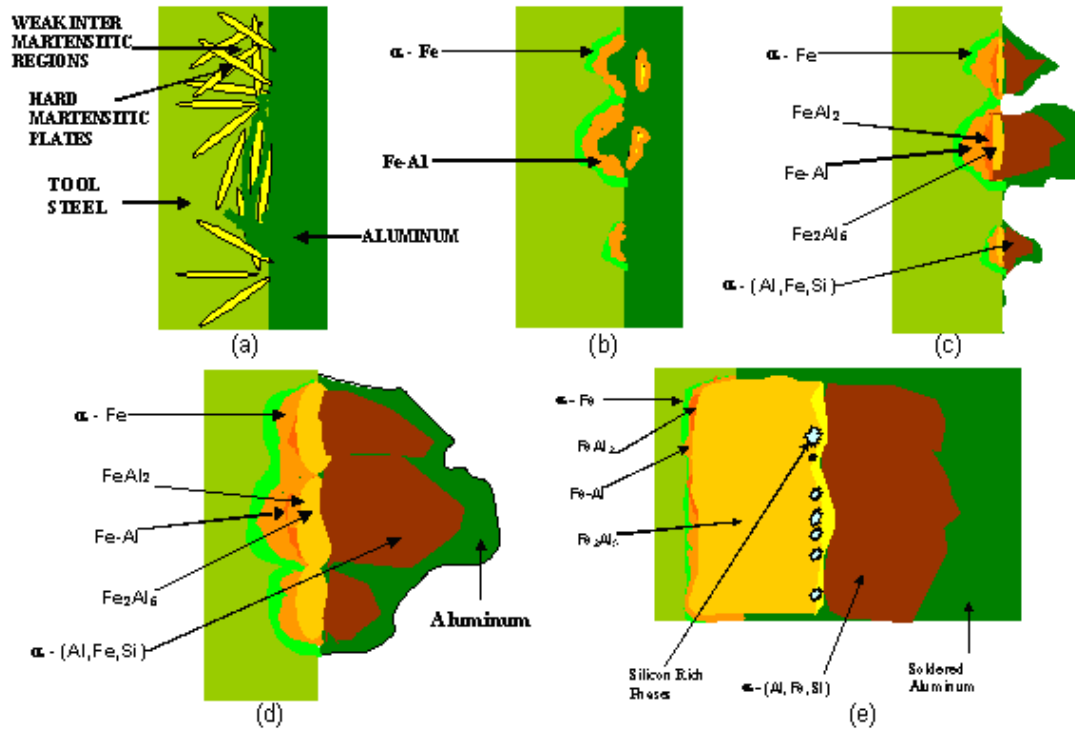
Figure 1: Schematic of the mechanism of die soldering. (a) Initial attack of the grain boundaries by aluminum to loosen up the hard grains and martensitic plates to cause pitting on the die surface. (b) Formation of the iron-aluminum intermetallic phases inside the pits and around the broken grains close the die surface. (c) "Pyramid' growth of the ternary -(Al,Fe,Si) phase on the pits over the -Fe_2Al_5. In addition, the pits expand laterally and in depth. Aluminum begins to stick after this layer structure is formed resulting in the beginning of soldering. (d) Shows the growth of intermetallic layers and merging of neighboring pits. Molten aluminum encounters the die surface only through the cracks and gaps present between adjacent pits. (e) Straightening out of the pits and closing of the gaps between the adjacent pits. The ratio of the intermetallic layer thickness and the soldered aluminum is ~1:5. The reaction mechanism becomes very slow. Silicon is precipitated in the grain boundaries of the -Fe_2Al_5 phase and at the intersection boundaries between the two intermetallic phase layers.

Publications

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