B.1 Die Solder Reduction

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Introduction
Die soldering is a die casting processing problem, which occurs when the cast aluminum joins with the die material, which is typically an iron-based material. Due to the natural affinity for iron and aluminum to react, intermetallic phases form at the interface. Upon ejection of the part, instead of separating at the aluminum-die material interface, the casting instead fractures and a layer of aluminum remains stuck to the surface of the die. Over a series of shots, this layer builds up and reaches a point where the final cast part is no longer satisfactory, whether due to missed dimensional tolerance, a defect from the result of an altered cooling pattern, etc. When this occurs, the casting machine must be shut down and the die face cleaned. Additionally, the reaction at the surface between the cast alloy and the iron in the die causes a reduction in the life of the die. In a study of the negative effects of die soldering at a Contech LLC squeeze casting plant in Pierceton, IN, it was determined that soldering accounts for 1.5% of variable overhead.

A study of the mechanism of die soldering, focusing on the reactions which occur at the cast metal–die steel interface, was completed at ACRC several years ago by Sumanth Shankar [1]. He summarized die soldering as a series of six steps, described here:
1. Erosion of grain boundaries at the die surface
2. Pitting of the die surface
3. Formation of iron-aluminum compounds
4. Formation of “pyramid” shaped structures of intermetallic phases.
5. Adherence of aluminum onto the “pyramids” of intermetallic phases.
6. Flattening of erosion pits and intermetallic phases. The soldered aluminum layer continues to grow at this point. A ratio of 1:5 between the intermetallic layers and the soldered aluminum is typically observed.

Despite the mechanistic understanding developed by Shankar, soldering remains a large problem in aluminum die casting, as illustrated by the results of the study above. The motivation of this project is to bridge the gap between the mechanistic understanding of soldering and practical solutions, and engineer methods for reducing the negative impacts of soldering at the Pierceton, IN plant. One part, the U222 Carrier axle housing is specifically being focused on.
Because of its large size and thick sections, soldering is especially a problem in the casting process for this part.

**Project Overview**

The project work consists of three major phases. Each will be discussed in more detail in subsequent sections

1. **Prediction of die soldering.** In current practice Contech uses MAGMAsoft to model new die designs in order to predict porosity, cavity filling, and other process outcomes. If MAGMAsoft could predict when and where die soldering will occur, and perhaps even its severity, the potential would exist for countermeasures to be engineered into the system that could prevent or mitigate this soldering. Without a method for predicting soldering, solutions for its limitation are reduced, and it is difficult to justify expensive mitigation techniques without an understanding of how soldering will affect the process. Phase one of the project is focused on developing the ability for die soldering to be predicted using MAGMAsoft.

2. **Quantification of Die Soldering.** In order to predict something, it must be able to be quantified or categorized. The study of die soldering on parts in production is currently limited, because many methods of quantifying soldering are not applicable in a case where the die cannot be destructively evaluated. Phase two of the project is focused on developing and evaluating techniques for studying soldering under these conditions. Both quantitative as well as qualitative measures are looked at.

3. **Metallurgical Pathways to Reduction of Die Soldering.** Two methods for reducing soldering are looked at in phase three. The first is the use of strontium modification of the cast alloy. The effect of this modification on the entire casting process is to be studied. Secondly, a novel coating, consisting of aluminizing the surface of the die steel is explored, with several methods of applying the coating evaluated.

**Prediction of Die Soldering**

Much effort has been put into prediction of die casting defects, specifically porosity and hot tearing. Several criteria are suggested for each, as well as efforts to model each of these phenomena from first principles.

Modeling the formation of die soldering from first principles may be possible, but it is a very complex phenomena, and the contribution of the many variables which play a part in promoting it are not entirely understood, or agreed on. Instead, the establishment of a criterion (like Niyama’s criterion which is used to help predict porosity) or some other method for looking at the conditions experienced at a location at the cast part-die material interface and predicting the severity of soldering at that point is being investigated.
A data mining approach is being utilized to attempt to discover the critical variable values that lead to soldering. To do this, 41 points on the surface of a part are selected and assigned a solder rating of 1 (no soldering), 2 (moderate soldering) or 3 (severe soldering). MAGMAsoft is then used to determine the conditions at these locations. The result is a series of curves for temperature, velocity, etc. at each of these points, as shown in Figure 1. These curves are then quantified into a series of variables. Currently, various statistical techniques are being used to evaluate the relationships between the data generated by MAGMA and the solder rating. The end goal is to be able to use the data generated by preliminary simulations of new dies and use them to predict die soldering.

![Time vs. temperature curves at the steel surface colored by solder rating.](image)

**Quantification of Die Soldering**

A variety of methods have been used in past studies to quantify die soldering. These methods can be separated into quantitative and qualitative measurement techniques. Quantitative techniques can be used to assign a numerical value to the extent of soldering, independent of any human observer. Qualitative techniques, on the other hand, rely on the interpretation of a human observer. Clearly, quantitative methods are preferable, so that bias can be avoided, but not every situation can be measured quantitatively.

Unfortunately, in the case of the part being studied at the Pierceton, IN plant, a good quantitative measure was not available. Previous studies, as in Shankar’s
work, use destructive techniques to evaluate any reactions occurring at the surface of the die. The use of destructive techniques is not a possibility in studying a part in production.

Instead, a qualitative method for quantifying soldering at various locations in the cavity relative to the rest of the cavity was designed, through the use of a rating system. To assign such a system to one specific part, the surfaces of the die and the cast part were examined and, at each location on the surface, assigned a rating of:

1- minimal or no soldering
2- moderate soldering
3- severe soldering

A picture showing this rating system on the surface of the casting in question is shown in Figure 2.

Additionally, over the course of a trial, a visual examination of the surface after a set number of shots through visual documentation can also be used to examine how quickly soldering begins and the extent of its spread.

A rough quantitative measure that can be used is the amount of cleaning time required to remove solder that is stuck on the surface of the die. As soldering becomes worse, this time will increase. This is overall a very good measure of soldering because it measures directly the negative effects of soldering on the casting process, rather than a proxy of this. However, to use such a measure requires very long experimental runs to remove variability from the study. It is
also difficult to measure how soldering at specific locations in the die respond to
the treatment, since the cleaning time is an overall value for the entire die.

Due to these limitations discussed above, the majority of the quantification phase
of the project has been to evaluate methods of quantitatively measure soldering,
for eventual use in trials. Specifically, using surface metrology to quantify die
soldering. It was noted that the cue for shutting down the machine and cleaning
down the die surface at the Pierceton, IN plant is a visual inspection of the
surface of the cast part. The part surface is compared to given standards which
show the maximum acceptable soldering. Once the maximum level is reached,
the die is shut down for cleaning. After learning this, it was determined that by
measuring the surface of the cast part, it may be possible to quantify soldering.

To test this, 19 locations were chosen on the surface of a part. The castings
were sectioned so that the surface roughness at each of these locations could be
measured over a series of shots on both the first casting after the die was
cleaned due to soldering all the way to the last casting before the die was
cleaned due to soldering. The surface at each location was analyzed with a
variety of linear parameters such as Ra, as well surface parameters such as area
scale analysis, where the relative area at a given scale is determined, yielding a
plot as shown in Figure 3. It can be seen that the relative area at many scales
increases over the series of castings at location 9.

![Results Plot](image)

Figure 3: Relative Area at a series of scales for location 9. First casting after cleaning plotted in blue;
last casting before cleaning plotted in red.

The results of this analysis are currently being analyzed more completely to
determine the ability of each of the surface parameters to measure soldering.
The deliverables of this section are hoped to be a die soldering quantification
technique, and potentially new insight on the phenomenon of soldering.
Metallurgical Pathways to Reduction of Soldering

The last phase of the project focuses on ways to resolve soldering on the plant floor. The first of these is through modification of the alloy through strontium modification. Strontium increases the viscosity of the molten aluminum alloy, and affects the interfacial energy between the cast alloy and the die. Experimental evidence of this was measured by Shankar and Makhlouf at MPI, plotted in Figure 4[2].

![Figure 4: Change in viscosity of aluminum alloy with the addition of Strontium.][2]

With this change in interfacial energy, die soldering can be significantly reduced, since the alloy does not wet the die material surface as well, and the relative area of interaction is reduced, limiting any of the steps leading to soldering. In pilot studies performed in August, additions of strontium were shown to reduce the amount of time required for die cleaning by over 25%.

However, the addition of strontium also changes the solidification characteristics of the alloy. It is theorized by Shankar and Makhlouf[2] that the change in interfacial energy prevents the eutectic phases from nucleating on the aluminum dendrites and therefore promotes some significant undercooling. This is evidenced by data collected at ACRC with modified ADC12 casting alloy, shown in Figure 5, with varying levels of Strontium. At modified Sr levels, the temperature at which the eutectic phases form is lowered by approximately 8 degrees celsius. This is a kinetic phenomena, as thermodynamic simulations of the system do not predict any change in eutectic temperature.
The effect of this change in solidification was a resulting increase in porosity scrap rate during the August trials. This scrap rate increase negated any gains achieved through modification. Additional trials are currently planned to determine how to minimize the scrap rate while using modified alloy, so that the benefits of modification can be realized.

A second metallurgical pathway to mitigating soldering is through the use of coatings. In this project, a novel coating of aluminum and aluminum oxide is being tested. The coating was first suggested by Sumanth Shankar in his Ph.D. dissertation[1]. The theoretical structure of the coating is shown in Figure 6.

Two methods for applying this coating are being tested. The first is hot-dip aluminizing, the second is a CVD-like microwave aluminizing process.

Figure 5: Effect of Sr level on eutectic nucleation temperature in ADC12 alloy.

Figure 6: Schematic of an aluminum coating for reduction of die soldering.[1]
Currently the pins are being coated, with trials to test their success to be carried out contingent upon the completion of the coating.

References