

# MECHANISM OF DIE SOLDERING DURING ALUMINUM DIE CASTING

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## Abstract

Soldering is a unique casting defect associated with die casting or metal mold casting of aluminum alloys. It occurs when molten aluminum sticks or solders the surface of the die steel and remains there after the ejection of the casting, causing surface defect and dimensional inaccuracy of the castings and increased machine downtime. Soldering occurs easily when a bare die steel mold is used for die casting of aluminum alloys. When molten aluminum comes in contact with the die steel at a temperature higher than a critical temperature, the iron and aluminum atoms diffuse into each other, forming a series of intermetallic phases and a liquid aluminum-rich fcc phase. This liquid phase exists between intermetallic phases. On cooling the liquid fcc phase solidifies on the intermetallic phases and grows into the casting, resulting in soldering. The critical temperature is the eutectic temperature near the aluminum corner of the phase diagram. If the die is protected using a nonreactive ceramic coating, soldering starts at locations where local coating failure occurs. Molten aluminum comes into contact with die steel through the coating failure locations and eats into the steel matrix, forming small pits. As these small pits grow, the coating is gradually removed and soldering becomes more severe. Details of step for die soldering on a bare steel die and on a coated die material are discussed.

**KEY WORDS:** Soldering, die sticking, aluminum alloys, and die casting

## 1. Introduction.

Die casting, or high pressure die casting (HPDC), is a century old process of injecting molten metal into a steel die using high pressure. This cost effective process is capable of producing net-shape products at a rapid production rate and with a high metal yield per mold. No other metal casting processes allow for a greater variety of shapes, fine intricacy of design or closer dimensional tolerance. Today, the die casting process is used to produce over one-third of the all metal castings, most of them are aluminum castings [1].

One major issue limiting the productivity of aluminum die castings is die soldering. Soldering or die sticking is a phenomenon in which molten aluminum “welds” to the die surface. Under severe conditions, die soldering occurs after just a few casting cycles, resulting in increased machine downtime, scrap that is related to surface quality and pressure or leak tightness of a casting, and costs since the dies are generally expensive and downtime results in lost production. Die soldering is also associated with other metal mold casting processes including low pressure permanent mold casting.

Small features on a metal die that are surrounded by molten metal are prone to soldering formation because such features are usually heated to higher temperatures than the bulk of the die during each run of die casting process. Core pins, used for forming small holes in casting, are such features on a metal die that are prone to soldering during the die casting process. The

use of core pins reduces the requirement for drilling the holes on castings, making the casting process more cost effective. A typical die casting machine uses about 10 to 100 pins. The die casting industry uses H-13 steel for making dies and core pins due to the fact that H-13 steel resists to heat checking and wear.

Two types of soldering are claimed by the diecasting industry. One occurs at high temperatures due to a chemical/metallurgical reaction between the molten aluminum alloy and the die [2], the other occurs at low temperatures due to mechanical interaction [3]. Limited systematic study has been carried out to investigate die soldering until in 1990s when the North American diecasting industry faced strong international competition. It became vital for die casters to minimize downtime and to increase their productivity in order to survive but most die casters in North America are small business companies that are lack of resource for research. As a result, research on die soldering has been sponsored by industrial organizations and by governmental agencies. Significant progress has been made in understanding die soldering that occurs due to a chemical reaction. Little is understood on soldering due to mechanical interactions.

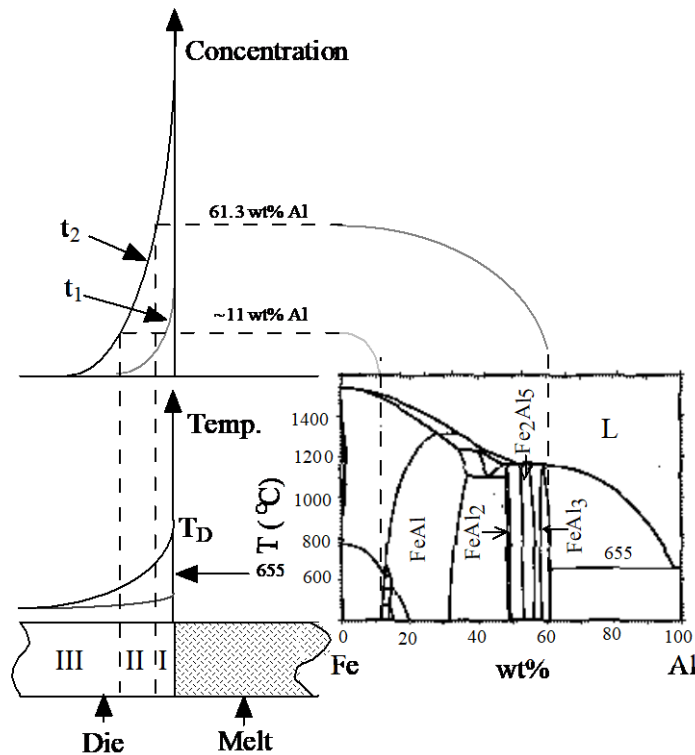
This article discusses die soldering as a result of chemical interaction. It is generally acknowledged that this type of soldering is closely related to the “washout” of a protective film on the die surface [2]. Washout occurs when the molten aluminum alloy destroys the protective film (coating or lubricant) on the die. The molten aluminum then comes into contact with the die surface and react with the die material, usually H-13 steel. Die lubricant can be easily destroyed by the molten metal but a coating, especially a coating made using the physical vapor deposition (PVD) process, can stay on the mold for many casting cycles. When a large portion of the die lubricant is removed, soldering is controlled by a direct chemical reaction between the molten metal and the bare die steel. In case there is a strong PVD coating on a die, soldering is controlled by the local failure of the coating. This article describes soldering on a bare steel mold and on a coated die or core pin.

## **2. Soldering on a Bare Steel Mold/Core Pin**

Interaction between molten aluminum with a bare steel mold/core pin occurs on a mold/core pin where liquid metal impingement is severe or where cavitation occurs. We first consider the simplest case for die soldering which is the casting of pure aluminum in an iron mold. When molten aluminum contacts the surface of the die shown in Figure 1, the die is heated by the melt. At the same time, iron dissolves into the melt and aluminum diffuses into the iron die. Since there is a strong convection in the melt, iron dissolved by the melt will be carried into the bulk melt by fluid flow and entrained in the casting. This means that for each shot, pure aluminum comes in contact with the die surface, and the iron concentration on the aluminum side of the melt-die interface is very low. The rate at which iron dissolves into the melt will be smaller and smaller as intermetallics start to form at the die surface. This indicates that the transport of aluminum into the die material is more important for die soldering.

Now consider the transport of aluminum into the die. Aluminum in contact with the die tends to diffuse into the die and react with iron to form intermetallics. When the Al concentration is high enough, a layer of intermetallics will gradually be formed at the die surface. As more and more Al comes into the die, the intermetallic layer will expand. This is schematically illustrated in the composition plot in Figure 1. At a time  $t_1$ , the aluminum composition profile in the die is illustrated by the  $t_1$  curve. As time increases to  $t_2$ , the concentration of aluminum in the die increases. Combining the composition profile at time  $t_2$  with the aluminum-iron phase diagram,

we can identify three regions at the die surface as shown in Figure 1. Region I is the portion of the die that is in contact with molten aluminum. In this region, the aluminum concentration is higher than 61.3 wt pct and the phases are  $\text{FeAl}_3$  and an aluminum rich phase. An important feature is that the solidus temperature of the phases in this region is  $655^\circ\text{C}$ , which is less than the temperature of the molten aluminum. In Region II, the aluminum concentration varies from 11 to 61.3 wt pct, and the phases are mainly  $\text{FeAl}_3$ ,  $\text{Fe}_2\text{Al}_5$ ,  $\text{FeAl}_2$  and  $\text{FeAl}$ . The solidus temperatures of the phases in region II are higher than  $1100^\circ\text{C}$ , which is much greater than the temperature of the molten aluminum. The iron substrate is in Region III where the aluminum concentration is less than 11 wt pct. It is the phases that are formed in Region I that are responsible for die soldering since they may be liquid at die casting temperatures. The phases in Region II may be present in the die, but they are typically solid at die casting temperatures.

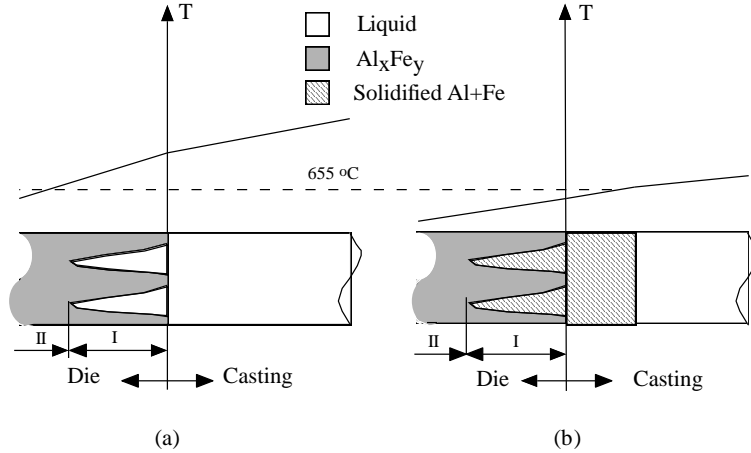


**Figure 1:** Schematic illustration showing possible aluminum composition and temperature profiles at the die surface, and the resulting phases for the case of pure aluminum cast in an iron die. Three regions at the die surface can be identified. Soldering occurs in Region I [4].

The state or consistency of the phases in Region I is dependent on the temperatures in the die. Two possible temperature profiles in the die are also illustrated in Figure 1. If the die temperature is lower than  $655^\circ\text{C}$  everywhere as shown in the lower line in Figure 1, the phases in Region I will be solid. It is difficult to imagine that a casting can stick to a solid die surface in a few seconds since the die surface is largely contaminated by lubricant or by oxidation. When the temperature in Region I is higher than  $655^\circ\text{C}$ , a liquid phase will be present. The amount of liquid that is present depends on the aluminum concentration and the temperature in the region. This liquid is responsible for die soldering.

The mechanism by which the liquid in Region I causes soldering is illustrated in Figure 2. When the die surface temperature,  $T_D$ , is higher than  $655^\circ\text{C}$ , a fraction of aluminum-rich liquid phase

occurs between the  $Al_xFe_y$  phases. On cooling, solidification starts with this liquid phase since the temperature in the die is lower than that in the melt. The solid thus formed will grow into the melt, joining the casting to the die. As a result, die soldering occurs. If the liquid fraction is small, the joint is weak and the casting can be easily ejected. The liquid fraction will gradually increase as the aluminum concentration increases. When the liquid fraction is large enough, the joint will be strong enough after solidification that either the die or the casting surface will tear on ejection of the casting from the die.



**Figure 2.** Schematic illustration of the mechanism of die soldering, indicating (a) the presence of liquid at the die surface when the temperature at the surface is higher than a critical temperature,  $655^{\circ}C$ , and (b) the formation of a joint between the casting and the die on solidification of this liquid phase.

In summary, the process of die soldering in a pure aluminum/steel system can be divided into three stages. In Stage 1, aluminum reacts with iron, forming intermetallics at the die surface. The aluminum concentration near the surface gradually increases. At this stage, since the melting temperatures of the intermetallics are much higher than the temperature of the aluminum melt, die sticking is unlikely to occur. In Stage 2, the aluminum concentration at the die surface increases to a critical value such that some fraction of liquid occurs when the temperature,  $T_D$ , of this intermetallic layer is higher than a critical temperature,  $T_C$ . This critical temperature is determined by the local chemical composition at the die surface. In Stage 3, the liquid fraction becomes larger as more and more aluminum atoms diffuse into the die. Die soldering occurs when the liquid fraction at the die surface is large enough that on solidification, a strong joint is formed between the die and the casting. These three stages of soldering formation are evident from studies on die soldering and steel aluminizing. It is well known that a layer of intermetallic compounds exist on the mold during soldering for die casting [6-7] and on the steel substrate for steel aluminizing [8-9]. When the liquid fraction is too great that leads to severe erosion, undercut or negative draft can be formed on a die or core pin. Under such a condition, soldering will surely occur.

The above discussion shows that liquid formation at the mold surface is the key for die soldering to occur. Thus, the condition under which die soldering gradually takes place can be expressed as

$$T_D > T_C \quad (1)$$

When the condition stated by Eq. (1) is satisfied, liquid starts to form on the mold surface and die soldering gradually occurs. In Eq. (1), the local temperature,  $T_D$ , at the die surface is governed by heat transfer between the casting and the die. Casting parameters such as the pouring temperature and the geometry of the die and the casting greatly affect  $T_D$ .  $T_D$  is also affected by the thermophysical properties of the die and the intermetallics formed on the die surface. Since the thermal conductivities of the intermetallics are lower than that of the steel, the temperature below the intermetallic layer may be much lower than the temperature at the die surface. The soldering critical temperature,  $T_C$ , is determined by the thermodynamics of the chemical reactions between the molten aluminum alloy and the surface material of the mold.

Simple dipping and dipping coating tests were carried out to validate the soldering mechanism [4]. A mild steel cylinder 12 mm in diameter and 25 mm in length was dipped in pure aluminum or a 380 alloy melt held at various temperatures. A thermocouple was welded to the sample surface to monitor the sample surface temperature and the sample was held in the melt for various times. The dipping tests carried out in this study were used to investigate soldering at sample surface temperatures both higher and lower than the liquidus temperature of the alloy being tested, whereas the dipping tests reported in the literature [1,10-12] were carried out at temperatures higher than the liquidus temperature of the alloys.

For tests at a sample surface temperature higher than the liquidus temperature of the alloy, the steel sample was directly dipped into the melt held at a temperature 30°C higher than the desired sample surface temperature. In order to maintain the sample surface temperature close to ( $\pm 3^\circ\text{C}$ ) of the desired test temperature, the sample was dipped in and out of the melt based on readings obtained from the surface thermocouple. Using the above approach, dipping tests were carried out using steel cylinders and pure aluminum at five sample surface temperatures above and just below the melting temperature (660°C) of the pure aluminum – 657, 661, 665, 680, and 740°C. Dipping tests were also carried out for 380 alloy at five sample surface temperatures above and just below the liquidus temperature of 380 alloy – 568, 575, 600, 630, and 680°C.

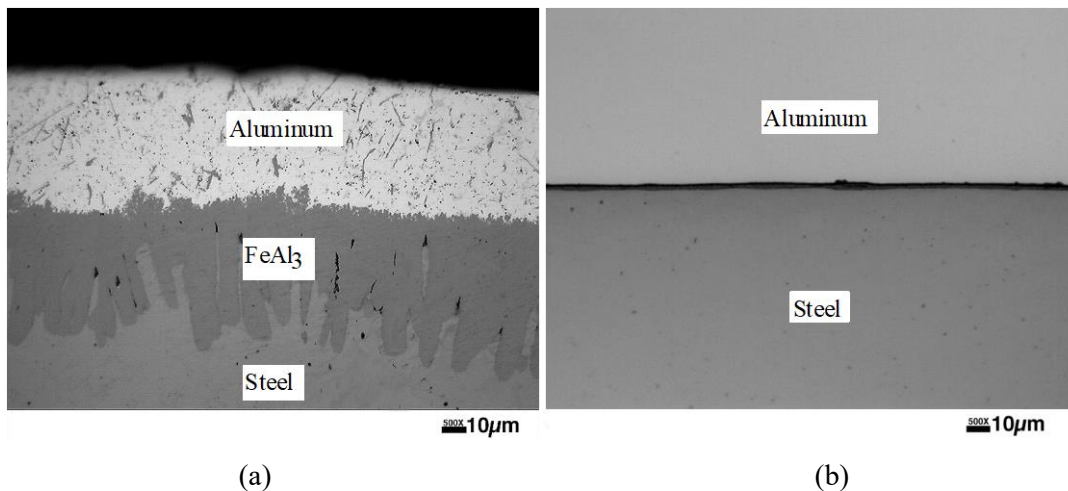
For tests at a sample surface temperature lower than the liquidus temperature of the alloys, the cold steel sample was dipped in the melt held at a temperature 30°C higher than the liquidus temperature of the alloy. As the sample was dipped into the melt, a layer of alloy was “coated” on the cold sample. As soon as the sample surface temperature reached the desired test temperature, it was moved to a furnace set at the desired test temperature and held for various times. Using the dip-coating approach, tests were carried out for steel cylinders and pure aluminum at two sample surface temperatures below the melting point of pure aluminum - 643 and 630°C. Dip-coating tests were also carried out for 380 alloy at three surface temperatures below the liquidus temperature- 550, 510 and 500°C. The experimental conditions for pure aluminum and 380 alloy are summarized in Table 1.

**Table 1.** Experimental conditions.

Alloy	Surface Temp., °C	Dipping time, min.	Remarks
Pure Al	740	1-4	Soldering
	680	1-5	Soldering
	661	4-6.6	Soldering
	665	2	Soldering
	643	6-1200	No soldering
	630	6	No soldering
A380	680	6	Soldering

	630	6	Soldering
	600	6	Soldering
	575	6	Soldering
	550	6	No soldering
	510	6	No soldering
	500	6	No soldering

In pure aluminum, soldering occurred on all samples with a surface temperature higher than 660°C, the melting point of pure aluminum. Also, the soldering area increased with increasing surface temperatures and dipping times. Figure 3(a) illustrates the typical microstructure obtained in the presence of soldering, consisting of iron-aluminum intermetallic phases, mainly FeAl<sub>3</sub> and an aluminum-iron eutectic (aluminum + FeAl<sub>3</sub>) phase. It is consistent with the typical soldering microstructure reported in the literature and indicates the formation of a metallurgical bond between the steel die and the aluminum casting.



**Figure 3.** Typical microstructures observed at the die surface for three cases: (a) metallurgical bond resulting in soldering, and (b) absence of reaction between steel and aluminum.

When the surface temperature of the samples was below 643°C, no soldering was observed. This remained true even though the sample coated at 643°C was held at the test temperature for 20 hours. Figure 3(b) illustrates the typical microstructure observed in the absence of soldering, namely, pure aluminum and steel separated by a gap. In fact, the gap separates the aluminum from the steel substrate. The results indicate that the critical soldering temperature is between 643 and 661°C for iron in contact with pure aluminum. The eutectic temperature at the Al-rich corner of the Al-Fe phase diagram is 655°C. Clearly, soldering is almost certain to occur above 660°C, the melting point of pure aluminum. From the experimental evidence, we can draw the conclusion that soldering occurs for the case of pure aluminum in an iron mold when the die surface temperature,  $T_D$ , satisfies Eq.(1)

For the case of aluminum alloys such as 380 alloy cast in a steel die, an argument similar to the case of pure aluminum in an iron mold would suggest that the critical temperature above which soldering can occur would be the solidus temperature of the reaction product of 380 alloy and iron. The actual temperature would depend on the local composition of the reaction product when 380 alloy reacts with the steel die and must be determined by considering the multicomponent phase equilibria, but a measure of the critical temperature may be obtained by

considering the solidus temperature of 380 alloy, which is approximately 480°C. However, this temperature can be affected significantly by composition and cooling rate.

Another important consideration is that since the liquid fraction in 380 alloy is fairly small (less than 5%) close to the solidus temperature, it is likely that the critical temperature at which soldering is likely to occur is the dendrite coherency temperature. The dendrite coherency temperature is the temperature below which the primary aluminum dendrites form a coherent network and behave more like a solid. In the absence of flow, the oxide layer on the aluminum alloy surface may impede diffusion and prevent a reaction between steel and aluminum. Above the dendrite coherency temperature, the alloy may be expected to flow in the form of a slurry, allowing a fresh aluminum surface to come in contact with the die surface. For 380 alloy, the dendrite coherency temperature [13] is about 560°C.

Dipping and coating tests using steel samples and 380 alloy indicated that while soldering occurred when the sample surface temperature was equal to the liquidus temperature of the alloy (575°C), soldering did not occur when the sample surface temperature was 550°C or lower. This would indicate that the critical temperature for soldering for 380 alloy would either be the liquidus temperature (575°C) or the dendrite coherency temperature (560°C). While these results are consistent with the observations of Chen and Jahedi [14], they must be considered to be inconclusive as the tests used in this study do not duplicate die casting conditions. It would be instructive to repeat the soldering studies for 380 alloy under die casting conditions.

### **3. Soldering on coated die/core pins**

To prevent soldering from formation, the core pins are usually coated with a layer of ceramic coating to separate the steel from the molten metal. The nonreactive ceramic coating provides a mechanical barrier to protect the H-13 steel from contacting the reactive molten aluminum alloy. Die soldering on coated core pins occurs when Eq. (1) satisfies but the rate of soldering formation is controlled by the process of coating failure. The whole process of soldering from its origin, growth, and development could be divided into five steps, namely: (1) local coating failure, (2) pit formation, (3) in-depth growth of a pit, (4) pit connection, and (5) formation of negative draft or undercut on a core pin [15]. Here, pit is a tiny soldered area formed on the surface of the H-13 steel pin. Evidence of these five steps of soldering formation can be found in core pins that have been used in a diecasting machines for various of times.

The first step of die soldering is the local coating failure. The locations where the coating becomes cracked or detached acts as the origin for a soldered area, or a pit, to start. Figure 4 shows the first step of soldering— local coating failure. Two typical coating failure modes were cracking and detaching from the H-13 matrix. Even if the coating is sputtered onto the H-13 matrix with the best technology and application methods, it could still fail because of microvariations in the application and from the thermal cycles of the die casting process. First, the present coating technology could not guarantee 100 pct bonding between the coating and H-13 matrix. Some defects, such as coating nonuniform areas, coating microcracks, and uncombined areas, could not be avoided. Second, the physical properties between the coating and the H-13 matrix are quite different, especially the ductility, thermal conductivity, and coefficient of thermal expansion. These differences in physical properties cause the coating and the H-13 to expand and contract at different rates during the die casting thermal cycle. Finally, the interaction between pins and high temperature melting fluid during die casting cycles could cause existing coating microcracks to expand and detach the coating from the steel matrix. The molten alloy is

injected at a high temperature and high pressure, quickly heating up the die steel. When the die opens, the die quickly cools back down. These cyclical temperature and pressure changes cause alternating and different deformations in coating and matrix, as well as thermal fatigue. In other words, the coating bore great alternate pressure from molten fluid in the die casting processes, and the bonding layer could have failed because of thermal fatigue induced by several thousand die casting cycles. In addition, the detached coating could easily be washed away by the high-speed (70m/s~100m/s) molten alloy. If a local coating failure occurred, either because of cracked coating or detached coating, the failure site would become a solder generating site because the molten alloy could react directly with the H-13 matrix.

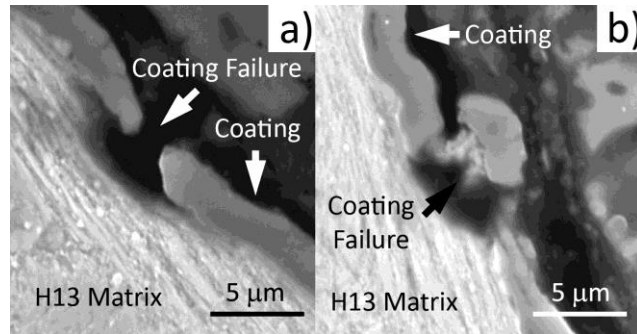


Figure 4: SEM images illustrating coating failure in two ways: (a) cracked and (b) detached.

The second step is the pit formation. Molten aluminum comes through the locations where local coating fails and interacts with the H-13 matrix to form a small pit or reaction region, shown in Figure 5.

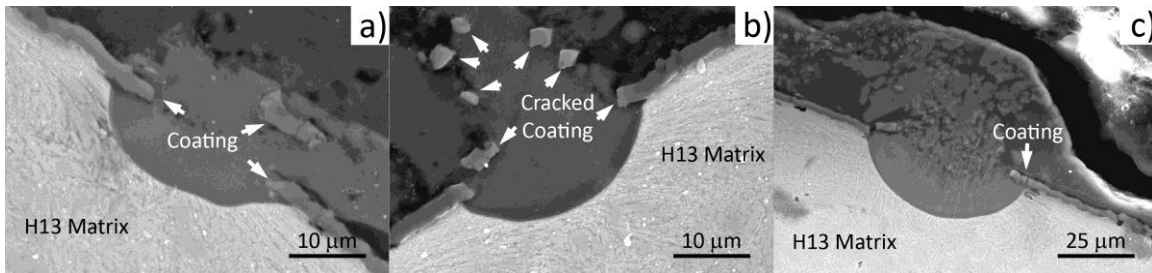


Figure 5 SEM images of the reaction areas: (a) coating broken by lateral growth in soldering area, (b) coating cracked and migrated away, and (c) coating washed out.

In the early stage when a pit, or a soldered area, is formed, the layer between the coating and H-13 matrix adjacent to the pit becomes the channel for the mutual diffusion of aluminum and iron atoms, allowing the pit or solder area, to grow laterally more rapidly shown in Figure 5(a). During this step, phases formed in the pit are iron aluminides (the light phases in the reaction region). These phases grow underneath the ceramic coating, leading to changes in physical properties, like volume, density and thermal expansion coefficient, and decreasing the bonding strength of the coating. As a result, the coating film could detach more easily than before. Thus, further coating failure is inevitable at the end of the second step. Figure 5(b) shows fragments of the coating at the front of the intermetallic phases. These fragments can be washed away during the next cycle of mold filling shown in Figure 5(c).

As the pit grows laterally, the intermetallic phases also grow both into the H-13 matrix and outward from the core pin as a result of the mutual diffusion of aluminum and iron atoms. An Al-



rich fcc phase starts to form between the intermetallic phases at the outside end of the reaction area. This Al-rich fcc phase is the dark phase in the reaction areas shown in Figure 5(c). When high-temperature molten aluminum impinges this region, the Al-rich fcc phase becomes a liquid phase, promoting the disintegration and erosion of the intermetallic phases on the pin surface and a further coating failure. The erosion of intermetallic phases leads to a direct contact of the molten aluminum alloy with the intermetallic phases in the pit. When erosion occurs inward into the coating surface, the in-depth growth of the pit is enhanced. This is the starting point for the third step of die soldering.

In the third step of the soldering process, the in-depth growth of the intermetallic phases is accelerated, leading to the formation of a parabolic/pyramidal shape of the pit shown in Figure 6. Figure 6(a) shows the typical image of a pit or soldered area. The parabolic pit contains an Al-Fe reaction region and Al alloy regions (containing the Al-rich, fcc phase) located in the center of the pit. The magnified area with coating, H-13 matrix, and reaction area is shown as an insert in this image. The coating appears to protect the matrix in the nonsoldered area, yet it disappears in the soldered area. A 45-micron-long line scan located in this image was used to analyze the elemental distribution in the matrix, reaction, and Al alloy regions.

Figure 6(b) shows the weight percentage distribution of five elements along the line. Al and Fe are the main elements in the soldered region, and their compositions change along the line with an inverse trend. Iron concentration is high in the H-13 matrix. The iron concentration decreases sharply with increasing distance from the steel matrix. Both Al and Fe elements change slowly in the reaction area. Towards the center of the pit, iron concentration decreases sharply and Al concentration increases sharply to over 90 pct. The concentrations of the other three elements (Cr, Cu, Si) are much lower compared with that of Al and Fe along the line. In order to give a more detailed analysis of the Al and Fe elements, the atomic percentage, and the Al/Fe ratio were examined. These results are shown in Figure 6(c). The shape of the curves is similar to the weight percentage curves. The atomic percent of Al increases slowly from the H-13 matrix site to the Al alloy site and the Fe percentage decreases in the reaction area. The Al/Fe ratio increases slightly from approximately one to three, and the average ratio is two in the reaction area. The sharp changes are shown at the interface between the H-13 matrix and reaction area, and between the reaction and the Al alloy area. There do not seem to be a transition zone at the interface area. Several compounds formed in the reaction area include  $\text{Al}_{12}\text{Fe}_6\text{Si}_5$ ,  $\text{Al}_{15}\text{Fe}_6\text{Si}_5$  and  $\text{Al}_4\text{FeSi}$  [16].

The accelerated growth of the intermetallic phases into the H-13 steel might be closely related to the formation of the Al-rich fcc phase within the pit. As the hot molten aluminum alloy erodes the intermetallic phases from the outside surface of the pit, more aluminum alloy comes into the pit to replace the intermetallic phases that eroded. During the mold filling process for forming another casting, the impingement of molten alloy melts this Al-rich fcc phase and causes stirring or convection in the pit, which enhances the reaction between molten alloy and the intermetallic phases. As a result, more aluminum atoms diffuse deep inward into the H-13 matrix.

The existence of an Al-rich fcc phase in the pit can be inferred from the composition profiles shown in Figure 6(b) and Al-Fe phase diagram shown in Figure 1. The composition of aluminum in the center portion of the line scan shown in Figure 6 can be as high as 90 pct. According to the phase diagram, alloys with Al content higher than 61.5 wt pct contain an aluminum-rich fcc phase which melts at a temperature higher than 655°C. The volume fraction of this Al-rich fcc phase increases with increasing Al concentration and approaches one when the Al concentration is higher than 90 pct. Indeed, the central portion of the pit on the line scan consists of a uniform dark phase, which is the Al-rich fcc phase. The sharp tip of this dark phase could result from the

“water hammer” effect when this phase is liquid while the molten alloy impinges on the pin surface.

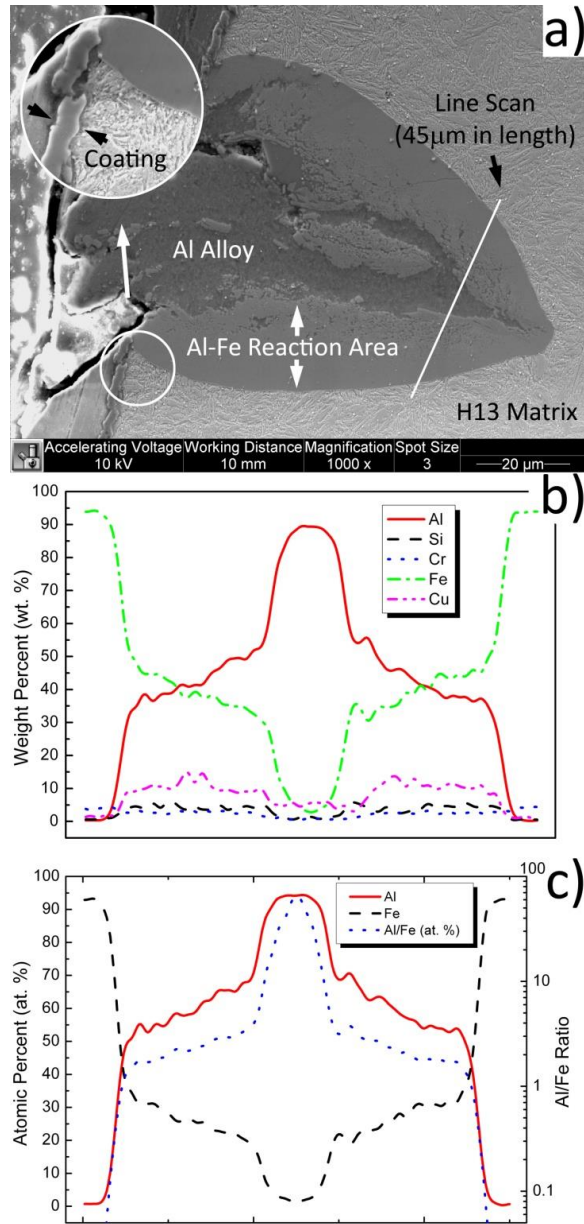


Figure 6: Typical pit or soldering area with parabolic/pyramidal shape: (a) the SEM image and line scan location, (b) weight percentage curves of five elements along the scanned line and (c) atomic percentage curves and the ratio of Al/Fe curve.

As the chemical reaction between the aluminum-rich fcc phase and the intermetallic phases continues, the pit size increases in both the in-depth direction and the lateral direction. Pit connection, the fourth step of soldering, occurs when several or many of the neighboring pits shown in Figure 7(a) are connected as they grow, shown in Figures (b) and (c). As a result, a consecutive zigzag shape of the soldering layer is formed.

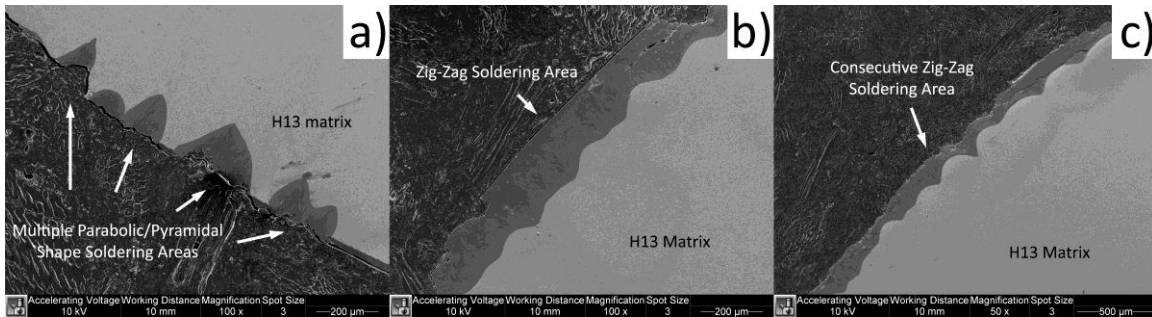


Figure 7: SEM images of soldering area: (a) multiple pits of parabolic/pyramidal shape, (b) and (c) two views of soldering area with a consecutive zigzag shape.

When the neighboring pits are connected, the aluminum-rich fcc phase exists at the outer surface of the reaction region. The phase fraction of the aluminum-rich fcc phase decreases from 100 pct to 0 pct as the distance to the H-13 matrix is reduced. When hot molten metal impinges the surface of this region again, the aluminum-rich fcc phase melts, forming a single liquid phase with the molten aluminum alloy. As the alloy solidifies, the casting solders with the H-13 core pin through this fcc aluminum phase, forming a metallurgical bond between the casting and the H-13 pin. Die soldering or die sticking is likely to form by this mechanism.

If the core pin is used further, erosion of the core pin is accelerated, forming negative draft or undercut in the regions where coating has been totally failed. This is the 5<sup>th</sup> step of the soldering process. In this soldering step, the soldering areas are not protected by a coating so erosion or dissolution of the steel matrix becomes much faster in the soldering regions where molten metal impinges the core pin or where cavitations occurs [17], forming negative draft or undercut locally. Figure 8 shows a severely used core pin with negative draft or undercut its surface. This core pin has certain locations where erosion is worse than other locations, forming undercut. A casting solidified on core pins with such negative draft or undercut would be difficult to eject. Often, the skin of the casting would be damaged or the core pin would be broken during the ejection of the casting from the mold.

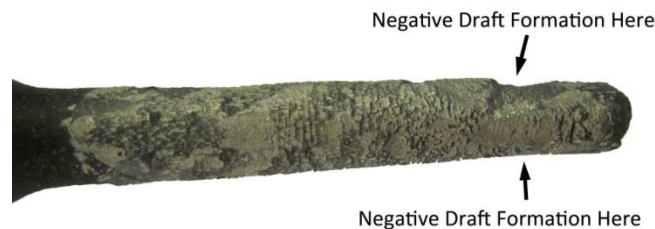


Figure 8: Schematic of negative draft or undercut formation on a core pin (arrow showed).

## 4. Conclusions

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