DIE SOLDERING IN ALUMINUM DIE CASTING

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Abstract

Two types of tests, “dipping” tests and “dip-coating” tests, were carried out on small steel cylinders using pure aluminum and 380 alloy to investigate the mechanism of die soldering during aluminum die casting. Optical and scanning electron microscopy were used to study the morphology and composition of the phases formed during soldering. A soldering mechanism is postulated based on experimental observations. A soldering critical temperature is postulated at which iron begins to react with aluminum to form an aluminum-rich liquid phase and solid intermetallic compounds. When the temperature at the die surface is higher than this critical temperature, the aluminum-rich phase is liquid and joins the die with the casting during the subsequent solidification. The paper discusses the mechanism of soldering for the case of pure aluminum and 380 alloy casting in a steel mold, the factors that promote soldering, and the strength of the bond formed when soldering occurs.

Introduction

Soldering, or die sticking, occurs during die casting when molten aluminum “welds” to the die surface, resulting in damage to the die and in a poor surface quality of the casting. Two types of soldering are identified in the literature: one that occurs at high temperature due to a chemical/metallurgical reaction between the molten aluminum alloy and the die (1), the other that occurs at low temperature due to mechanical interaction (2). This paper addresses soldering that occurs due to a chemical/metallurgical reaction.

For the type of soldering occurring at high temperature, it is generally acknowledged that soldering is closely related to the “washout” of a protective film on the die surface (1). Washout occurs when the molten aluminum alloy enters the die and destroys the protective film (coating or lubricant) on the die. The molten aluminum then comes into contact with the die surface. Iron in the die material dissolves into the melt whereas aluminum and other elements in the melt diffuse into the die. As a result, a layer of intermetallics is formed at the die surface. Under the right conditions, an aluminum-rich soldering layer may also form over the intermetallic layer (1). Although a significant amount of research has been conducted on the nature of these intermetallics, (3-7) little is known about the conditions under which soldering occurs.

In this study, the formation of intermetallics and the occurrence of soldering are differentiated, since it will be shown that the mere presence of intermetallics is not a condition or cause for soldering. In addition, the study will attempt to focus on the initiation of soldering rather than the growth of intermetallics. This study will address the following questions:

1. At what temperatures does soldering occur?
2. Is the formation of intermetallics on the die surface an indication that soldering has already occurred?
3. How does an aluminum alloy casting solder (join) to the die?
4. What determines the strength of a bond?

In this study, simple dipping and dip-coating tests were carried out to investigate the temperatures at which soldering occurs. The

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morphology of the interface between the intermetallic layer and the soldering layer was examined by optical and scanning electron microscopy. A soldering mechanism is postulated based on experimental observations. The type of soldering considered in this study is only that due to chemical reaction between the elements in the die material and the alloy. Soldering occurring at low temperature due to mechanical interaction is not included in this study.

Experimental Procedure

The experimental setup used in this study is illustrated in Figure 1. 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 (1,5,7) were carried out at temperatures higher than the liquidus temperature of the alloys.

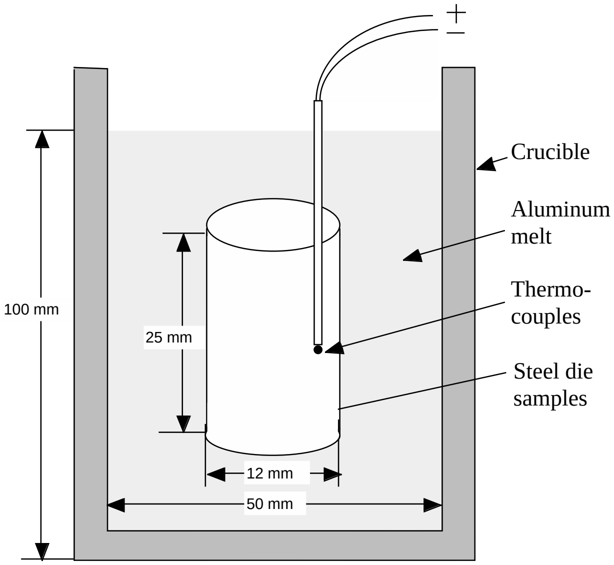


Figure 1: Schematic illustration of the experimental setup for the dipping tests.

For tests at a sample surface temperature at or above 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 (±3°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 four 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 sample surface temperatures above and just below the liquidus temperature (575°C) of A380 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.

After the test, the dipped and dip-coated samples were air cooled to room temperature and sectioned for microstructural characterization. The samples were polished and examined by optical microscopy, and a Phillips XL30/FEG scanning electron microscope was used to determine composition profiles across the intermetallic and the soldered layers. The accuracy of the compositional analysis is approximately 3%. The experimental conditions for pure aluminum and A380 alloy are summarized in Table 1.

Table I Experimental conditions used in the soldering study

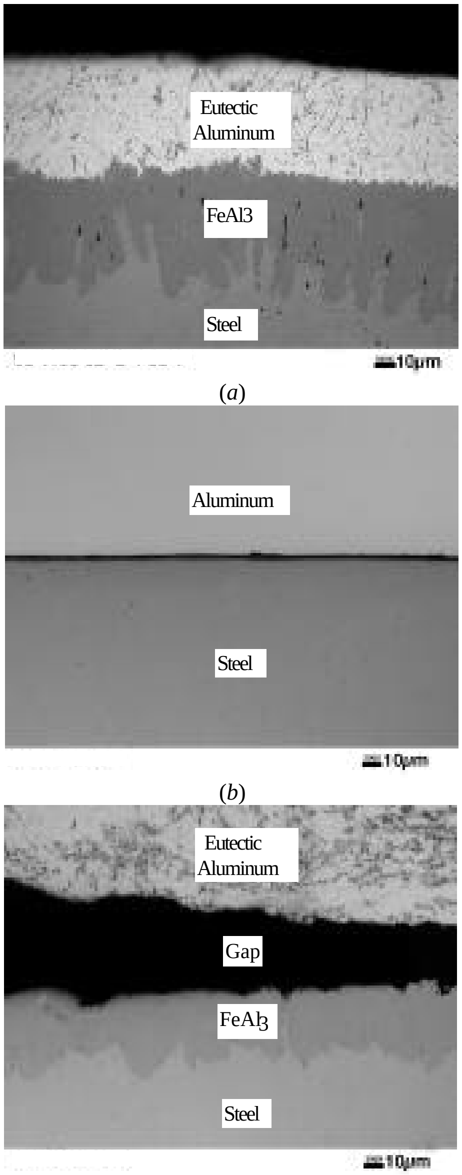
Alloy	Surface Temp. (°C)	Dipping Time (min)	Remarks
Pure Al	740	1-4	Soldering
	680	1-5	Soldering
	665	2	Soldering
	661	4-6.6	Soldering
	657	6	Soldering
	643	6,1200	No soldering
	630	6	No soldering
380	680	6	Soldering
	630	6	Soldering
	600	6	Soldering
	575	6	Soldering
	568	6	Soldering
	550	6	No soldering
	510	6	No soldering
	500	6	No soldering

Results and Discussion

This section will: (1) discuss the results of dipping and dip-coating tests on steel cylinders with pure aluminum and 380 alloy, (2) use the experimental results to postulate a criterion for the onset of soldering, and (3) discuss phases present in die soldering.

Soldering of Steel by Pure Aluminum

Soldering occurred on all samples with a surface temperature at or higher than 657°C. Also, the soldering area increased with increasing surface temperatures and dipping times. Figure 2(*a*) illustrates the typical microstructure obtained in the presence of soldering, consisting of an iron-aluminum intermetallic phase ($FeAl_3$) and an aluminum-iron eutectic (aluminum + $FeAl_3$) 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.



(*a*)

(*b*)

(*c*)

Figure 2: Three typical microstructures observed at the die surface for three different cases: (*a*) soldering resulting in a metallurgical bond, (*b*) absence of reaction between steel and aluminum, and (*c*) intermetallic formation on the die in the absence of soldering.

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 h. Figure 2(*b*) illustrates the typical microstructure observed in the absence of soldering, namely, pure aluminum and steel separated by a gap. In some cases, intermetallics are produced at the die surface even in the absence of soldering [see Figure 2(c)]. This will be discussed later.

The results indicate that soldering is initiated at temperatures between 643 to 657°C for iron in contact with pure aluminum. In order to provide a mechanistic interpretation of the results, it is instructive to compare the experimental results with the reactions indicated in the iron-aluminum binary phase diagram (Figure 3). In the aluminum-rich portion of the iron-aluminum system, the lowest temperature at which a reaction can occur with liquid aluminum is at the eutectic temperature of 655˚C. Below this temperature, any reaction will involve solid-solid diffusion that is unlikely to occur in the short times involved in this test (and almost certainly during die casting). Consequently, it is likely that the critical temperature at or above which soldering can occur for the case of pure aluminum cast in a steel mold is the eutectic temperature of 655˚C, which is the solidus temperature of the alloy produced when pure aluminum reacts with iron. Clearly, soldering is almost certain to occur above 660˚C, the melting point of pure aluminum.

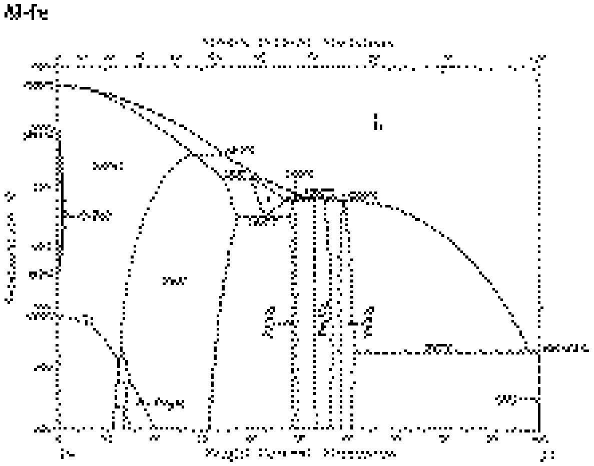


Figure 3: The aluminum-iron phase diagram (8).

When the die surface temperature is lower than the solidus temperature of the aluminum-iron alloy, the aluminum will solidify on the die. It is likely that the oxide layer on the solid aluminum surface or any oxide existing on the steel surface will block the diffusion of iron and aluminum across the steel/aluminum interface. As a result, no chemical/metallurgical reaction is observed at the die surface. In fact, a gap separates the aluminum from the steel substrate [see Figure 2(*b*)]. This is also the desirable condition for die casting.

The results of the experiments involving pure aluminum and steel can be summarized as follows. 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 the condition

$$T_D > T_C \quad , \tag{1}$$

where T_C is a critical temperature equal to the eutectic temperature of 655˚C. T_C is also the solidus temperature of the alloy produced when pure aluminum reacts with iron and results in an aluminum-rich iron-containing alloy.

Soldering of Steel by Aluminum Alloys

For the case of aluminum alloys such as 380 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 slurry, allowing a fresh aluminum surface to come in contact with the die surface. For 380 alloy, the dendrite coherency temperature (9) 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 higher than 568˚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 is certainly below the liquidus temperature (575˚C) and could be the dendrite coherency temperature (560˚C). While these results are consistent with the observations of Chen and Jahedi (10), 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.

Phases Resulting from Die Soldering

The microstructure in the soldered region shown in Figure 2(*a*) is primarily comprised of two phases in the region of interest: an iron-aluminum intermetallic ($FeAl_3$) and the aluminum-iron eutectic (aluminum + $FeAl_3$) phase. The interface between the intermetallic and the eutectic phase exhibits an interlocked structure. This interlocked structure provides a strong metallurgical bond between the aluminum and the substrate. The continuity of phases and the presence of a metallurgical bond indicate that both the intermetallic and eutectic phases result from die soldering.

Experimental observation indicated that the intermetallic and eutectic phases occurred whenever a metallurgical bond was observed [see Figure 2(*a*)]. However, at some locations, the intermetallic and eutectic phase were observed although no metallurgical bond was observed (Figure 2(*c*). Thus, the presence of an intermetallic phase on the steel surface is an indication that a reaction occurred between aluminum and steel. However, the presence of a gap indicates that die soldering or bonding did not occur at this location as the aluminum concentration at the die surface was insufficient to form a liquid phase between the intermetallics..

It must be emphasized that whenever a metallurgical bond is formed, both the intermetallic and the eutectic phase are present as an interlocked structure that exhibits a zigzag interface. Figure 4 is a backscattered electron image showing the interface between the intermetallic and eutectic phases. Note that in Figure 4, the light regions correspond to the intermetallic phase and the dark regions to eutectic aluminum phase. As shown in Figure 4, it is the presence of the eutectic phase together with the intermetallic phase, rather than the formation of the intermetallic phase alone, that is an indication that die soldering has occurred. It is pertinent to further analyze this interlocked structure, as it is provides the microstructural evidence that die soldering has occurred.

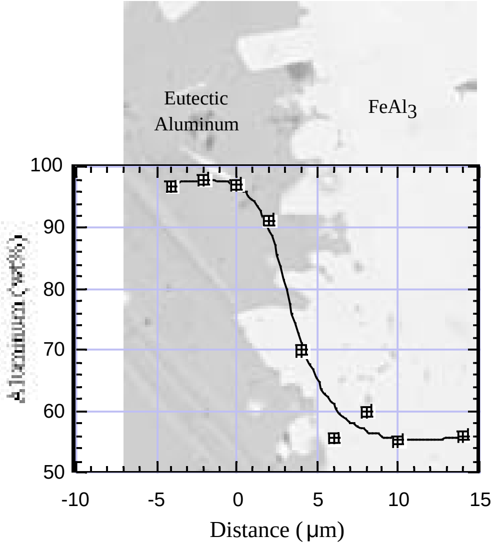


Figure 4: Composition profile across the aluminum/intermetallic interface in the soldered layer superimposed on a backscattered scanning electron image of the interface.

The measured average aluminum concentration across the eutectic/intermetallic interface is also plotted in Figure 4, with the origin placed at the tip of the zigzag intermetallic front. The composition at each location represents the average composition along a line scanned at that location parallel to the interface. Again, note that the light regions correspond to the intermetallic phase and the dark regions to eutectic aluminum phase. The aluminum concentration is approximately 97 wt % at x = 0 and about 60 wt % at x = 6 μm. A comparison of these values with the iron-aluminum phase diagram indicates that they correlate with the composition of the eutectic and $FeAl_3$ phases. The resultant phase fraction profile for each phase should vary from almost 0 at one end to 1 at the other.

Now let us consider the state of each phase in the region of the intermetallic/eutectic interface for samples tested with surface temperatures above 655°C. The phase diagram (see Figure 3) indicates that for locations where the average aluminum concentration is greater than 61.3 wt %, the eutectic phase should be liquid. Clearly, it is this liquid phase that is the basis of the formation of a metallurgical bond (i.e., die soldering). This liquid aluminum phase exists between the solid intermetallic phase that forms on the steel die and links it with the aluminum casting. On cooling, the two phases form an interlocked structure of eutectic and intermetallic phases as shown in Figure 2(*a*).

The existence of the liquid eutectic between the intermetallic phase can also be inferred from Figure 5, which indicates the presence of porosity in both the eutectic and intermetallic phases. The presence of the pores in the intermetallic phase is a strong indication that liquid was present prior to solidification.

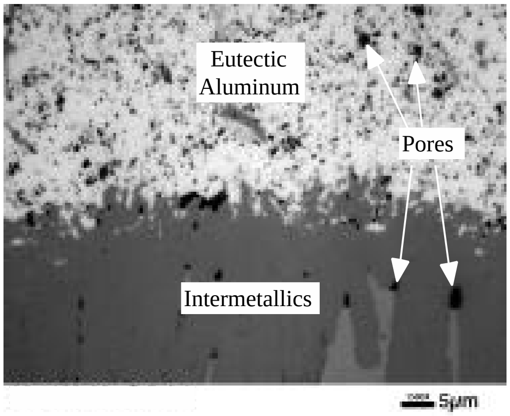


Figure 5: An optical photomicrograph of the aluminum/intermetallic interface indicating the presence of pores in both the aluminum and the intermetallic phases.

In summary, the formation of intermetallics at the sample surface is only an indication of a chemical/metallurgical reaction between aluminum and steel. An aluminum-rich liquid that occurs as a product of this chemical/metallurgical reaction when the aluminum content at the surface reaches a sufficiently high value is responsible for soldering. For the case of pure aluminum solidifying in a steel mold, the soldering reaction occurs when the die surface temperature is higher than the eutectic temperature (655˚C) and the aluminum concentration at die surface is higher than 61.3 wt %.

The Mechanism of Soldering

Based on the experimental observations discussed in the previous section, the mechanism of soldering can be postulated as follows. When molten aluminum contacts the die, the die surface heats up. If the die surface temperature rises to a value greater than the soldering critical temperature (i.e., $T_D > T_C$), iron dissolves in the melt and aluminum diffuses into the die (as long as there is no impediment to diffusion such as a layer of lubricant or an oxide coating). A layer of intermetallics will gradually form at the die surface. If the aluminum concentration at the die surface becomes sufficiently high, a small fraction of a liquid aluminum-rich phase comes into existence in contact with and in between the intermetallic phase. The volume fraction of the liquid phase varies with the aluminum concentration and the local temperature. On cooling, this liquid aluminum phase solidifies, forming an interlocked structure of aluminum-rich phase and intermetallic between the die and the casting, joining the casting to the die. It is the existence of the aluminum-rich liquid phase in conjunction with and in between the intermetallic phase that plays the role of glue, joining the casting with the die.

The results of this study indicate that the soldering critical temperature can be either the solidus temperature of the reaction product between the die steel and the aluminum alloy or the coherency temperature. Further experiments under the conditions of die casting will be needed to ascertain the actual value.

If the die surface does not heat up to a temperature higher than the soldering critical temperature, a layer of aluminum solidifies on the die. The oxide layer at the solid aluminum surface impedes the diffusion of aluminum and iron atoms across the interface. Consequently, soldering does not occur. In this case, even intermetallics are not formed at the die surface (see Figure 2(*c*). This would be the preferred condition in die casting.

The strength of the bond formed during soldering depends on the area over which the bond is formed. For a given area of the bond, the strength of the bond depends on the area fraction of the metallurgical bond. Since the metallurgical bond is formed on solidification of an aluminum-rich liquid phase, the area fraction of the bond will depend on the local liquid fraction prior to solidification. The local liquid fraction will depend on temperature and composition. If a strong bond is formed, the casting is likely to stick. If the bond is weak, it is likely to be sheared during ejection of the casting.

The ideas proposed in this paper are in accordance with industrial observations that die soldering occurs more easily at high casting temperature, as high casting temperatures would result in a high die surface temperature. The identification of a liquid aluminum-rich phase that promotes the soldering reaction and joins the casting with the die explains why soldering can occur in just a few shots. Other factors that increase the heat transfer coefficient at the casting-die interface such as a high gate velocity or high intensification pressure, and thereby lead to higher die surface temperatures, will also result in a higher tendency toward soldering. Alloys with a large latent heat of solidification such as 390 are also likely to promote soldering as they are likely to increase the die surface temperature.

Summary and Conclusions

Two types of tests, “dipping” tests and “dip-coating” tests, were carried out on small steel cylinders using pure aluminum and 380 alloy to investigate the mechanism of die soldering during aluminum die casting. Optical and Scanning Electron Microscopy were used to study the morphology and composition of the phases formed during soldering. A soldering mechanism is postulated based on experimental observations. A soldering critical temperature is postulated at which iron begins to react with aluminum to form an aluminum-rich liquid phase and solid intermetallic compounds. When the temperature at the die surface is higher than this critical temperature, the aluminum-rich phase is liquid and joins the die with the casting during the subsequent solidification.

The study attempted to provide answers to the following questions:

1. At what temperatures does soldering occur? - The results of this study indicate that the soldering critical temperature can be either the solidus temperature of the reaction product between the die steel and the aluminum alloy or the coherency temperature. Further experiments under the conditions of die casting will be needed to ascertain the actual value.

2. Is the formation of intermetallics on the die surface an indication that soldering has already occurred? - The formation of intermetallics at the sample surface is only an indication of a chemical/metallurgical reaction between aluminum and steel and does not constitute soldering.

3. How does an aluminum alloy casting solder (join) to the die? – When molten aluminum contacts the die, the die surface heats up. If the die surface temperature rises to a value greater than the soldering critical temperature, i.e., iron dissolves in the melt and aluminum diffuses into the die (as long as there is no impediment to diffusion such as a layer of lubricant or an oxide coating). If the aluminum concentration at the die surface becomes sufficiently high, a small fraction of a liquid aluminum-rich phase comes into existence in contact with and in between the intermetallic phase. On cooling, this liquid aluminum phase solidifies, forming an interlocked structure of aluminum-rich phase and intermetallic between the die and the casting, joining the casting to the die. For the case of pure aluminum solidifying in a steel mold, the soldering reaction occurs when the die surface temperature is higher than the eutectic temperature (655˚C) and the aluminum concentration at die surface is higher than 61.3 wt.

4. What determines the strength of a bond? - The strength of the bond formed during soldering depends on the area over which the bond is formed. For a given area of the bond, the strength of the bond depends on the area fraction of the metallurgical bond. Since the metallurgical bond is formed on solidification of an aluminum-rich liquid phase, the area fraction of the bond will depend on the local liquid fraction. The local liquid fraction will depend on temperature and composition. If a strong bond is formed, the casting is likely to stick. If the bond is weak, it is likely to be sheared during ejection of the casting.

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References

1. Y. L. Chu, P. S. Cheng, and R. Shivpuri, "Soldering Phenomenon in Aluminum Die Casting: Possible Causes and Cures," Transactions (Rosemont, Illinois: North American Die Casting Association, 1993), 361-371.
2. D. Argo, R. J. Barnhurst, and W. Walkington, "NADCA Sponsored Research: The Causes of Soldering in Zinc Die Casting," Transactions (Rosemont, Illinois: North American Die Casting Association, 1997), 77-82.
3. V. G. Rivlin and G. V. Raynor, "Critical Evaluation of Constitution of Aluminum-Iron-Silicon System," Int. Met. Rev., 26 (1981), 133-152.
4. W. Kajoch and A. Fajkiel, "Testing the Soldering Tendencies of Aluminum Die Casting Alloys," Transactions (Rosemont, Illinois: North American Die Casting Association, 1991), 67-74.
5. R. W. Richards, R. D. Jones, P. D. Clements, and H. Clarke, "Meallurgy of Continuous Hot Dip Aluminizing," Int. Mat. Rev., 39 (1994), 191-212.
6. S. Shankar and D. Apelian, "Die Soldering - A Metallurgical Analysis of the Molten Aluminum/Die Interface Reactions," Transactions (Rosemont, Illinois: North American Die Casting Association, 1997), 243-251.
7. Y. L. Chu, S. Balasubramaniam, R. Rajan, and R. Shivpuri, "A Study of the Cast Alloy - Die Surface Interactions in Aluminum Die Casting," Transactions (Rosemont, Illinois: North American Die Casting Association, 1997), 205-212.
8. H. Baker et al., eds., ASM Handbook, vol. 3, Alloy Phase Diagrams (Materials Park, OH: ASM International), 1992.
9. L. Arnberg, L. Bäckerud, and G. Chai, Solidification Characteristics of Aluminum Alloys, vol.3, Dendrite Coherency (American Foundrymen's Society, Inc., 1996), 115.
10. Z. W. Chen and M. Z. Jahedi, "Formation of Die/Casting Interaction Layer during High-Pressure Die Casting of Aluminum Alloys", Tooling 99, Melbourne, (March 1999), 165-169.