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Dross formation during remelting of aluminum 5182 remelt secondary ingot (RSI)

Q. Han[a,*], W. Simpson[a], J. Zeh[b], E. Hatfield[a], V.K. Sikka[a]

[a] Oak Ridge National Laboratory, Oak Ridge, TN 37831-6083, USA
[b] Logan Aluminum Inc., P.O. Box 3000, Russellville, KY 42276, USA

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Abstract

This article reports, for the first time, a surprising result that in the center part of some commercial aluminum 5182 remelt secondary ingot (RSI), more than 50% of the alloy turns to dross during melting. The solidification microstructure of the RSI was characterized in order to understand where the dross comes from and how it forms. Optical microscopy showed that severe interdendritic porosities and hot tears exist in the RSI. These cavities provide continuous channels that expose the internal interdendritic surfaces to the atmosphere outside of RSI. SEM revealed that the dendrites in the center of RSI are covered by magnesium and aluminum oxides. It is the oxidation of the surfaces of the interdendritic pores that results in a large amount of dross formation during the remelting of aluminum 5182 RSI.

Keywords: Dross formation; Remelt secondary ingot; Aluminum recycling; Aluminum remelting; Solidification defect

1. Introduction

Bulk aluminum alloys intended for remelting are often cast in the form of large shapes, weighing from 320 to 900 kg (700–2000 pounds), known as “sows”. In the aluminum recycling industries, aluminum scrap is recycled and cast into sows. A sow cast with molten aluminum from the aluminum scrap is termed as a remelt secondary ingot (RSI). RSI is produced by pouring molten aluminum into open top molds.

Three types of cavities usually exist in the remelt secondary ingot. There are shrinkage cavities, hot tearing (cracking), and hydrogen porosities. Of these three types of cavities, large shrinkage cavities occur near the center of RSI, cracks form in the top layer of RSI, and small hydrogen pores precipitate throughout RSI. The cracks and hydrogen cavities, although small and almost invisible to the eye, may form passageways into the center shrinkage cavities, allowing water to be collected inside RSI. As the passageways are relatively small, the water in the cavities cannot be evaporated quickly. The existence of water in RSI is a safety issue during the remelting of RSI [1]. As a result, considerable research has been performed to reduce cavities in RSI [2,3]. However, in the public literature, no research has tried to link these cavities to the dross formation during the remelting of RSI.

Recently, the industries have been found that dross formation during the remelting of commercial aluminum 5182 RSI varies significantly from ingot to ingot. This led to a speculation that the dross might be inclusions that existed in the melt and were entrapped in the RSI by the aluminum dendrites. As a result, advanced Non-Destructive Evaluation (NDE) techniques, such as radiography and ultrasound scanning, were used in order to find inclusions [4]. The amounts of the inclusions detected were much less than expected. In our research, melting experiments were carried out to investigate dross formation. The results were surprising. Some of the solid aluminum specimens taken from the center of RSI did not collapse at 850 °C (1562 °F), about 212 °C higher than the liquidus temperature of aluminum 5182 alloy. This represents a huge dross formation during the remelting of aluminum 5182 alloy RSI. This paper reports the melting experimental results and addresses the mechanism of dross formation during remelting of aluminum 5182 alloy RSI.

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[*] Corresponding author.
E-mail address: v6q@ornl.gov (Q. Han).

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Table 1
The chemical composition (wt.%) of aluminum 5182 RSI

Chemical composition	Balance (wt.%)
Si	0.20
Fe	0.35
Cu	0.15
Mn	0.35
Mg	4.50
Cr	0.10
Zn	0.25
Ti	0.10

2. Experimental process

Experiments were carried out using commercial aluminum 5182 RSI. The composition of aluminum 5182 RSI from which the specimens were taken is given in Table 1. The weight of RSI was about 900 kg and the largest dimensions of RSI were 1.16 m (45.5 in.) long, 1.16 m (45.5 in.) wide, and 0.33 m (13 in.) tall. The top surface of the RSI was cooled using water spray.

A specimen weighing approximately 0.6 kg was cut from the center of each RSI. The specimen was then held in a boron nitride coated graphite crucible. A Muffle furnace (resistance heating) was used for the melting experiments. After the furnace had been heated to 850 °C, the crucible with the specimen at room temperature was charged into the furnace for the melting experiments. Since the volume of the crucible was much smaller than that of the chamber of the furnace, the temperature in the furnace was not changed much during the charging of the cool specimens.

To our surprise, the solid specimen could not be melted after it was heated to 850 °C and held at 850 °C for one hour. Note that 850 °C is about 212 °C higher than the liquidus temperature of the alloy (638 °C). In fact, the specimen did not collapse and it looked solid despite the high temperature. We confirmed that the specimen temperature was 850 °C by burying a thermocouple in the specimen. Using a thermocouple to touch the specimen, we noticed that the specimen was mushy. The specimen was then left in the furnace at 850 °C for 26 h but it did not collapse. The specimen was still mushy. Even the shape of the specimen was not changed much.

The melting experiments were repeated using the specimens taken from the center of other aluminum 5182 RSI. The conditions for each experiment are given in Table 2. Specimens were held at 850 °C for either 3 or 26 h. The aluminum liquid collected at the bottom of the crucible was then poured into a metal mold. The rest of the mushy aluminum left in the crucible was considered as dross. The amount of dross formation in each experiment is also given in Table 2. The experimental results indicated that about 50–80% of metal has been turned into dross during the melting experiments. The dross formed during the melting experiments was characterized using optical microscopy and scanning electron microscopy (SEM).

Table 2
The experimental conditions and results of the melting experiments

Specimen no.	Holding time (h)	Specimen weight (g)	Dross weight (g)	Dross ratio (%)
1	3	597	319.2	53.43
2	3	603	485.4	80.50
3	26	572	331.4	57.94
4	26	582	383.8	65.95

3. Results and discussion

Fig. 1(a) shows the microstructure of the dross. It contains aluminum dendrites and cavities identical to interdendritic

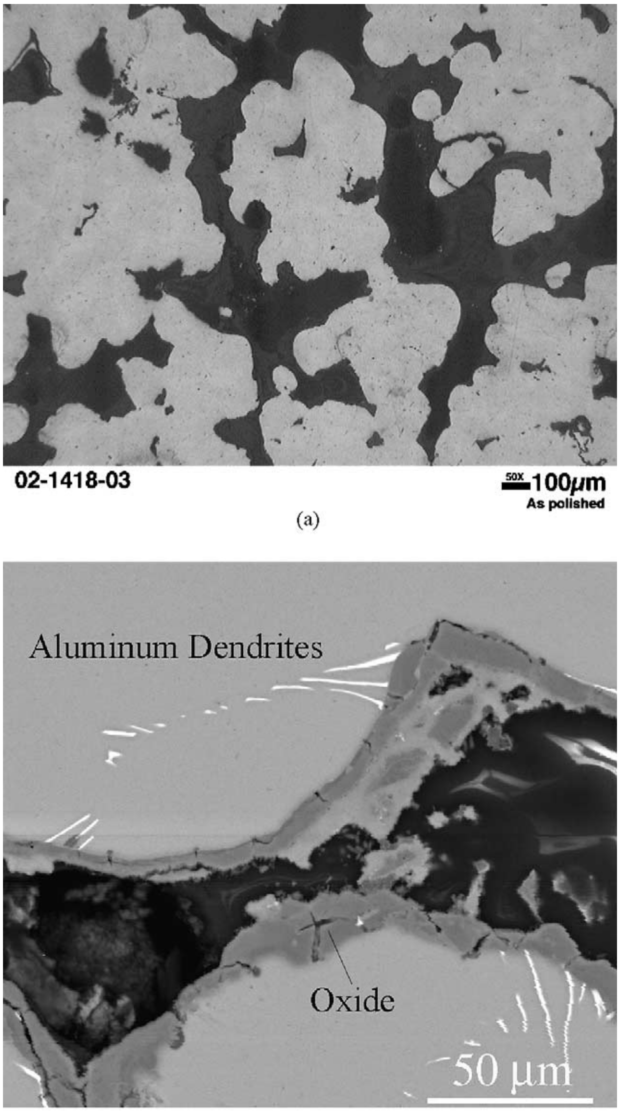
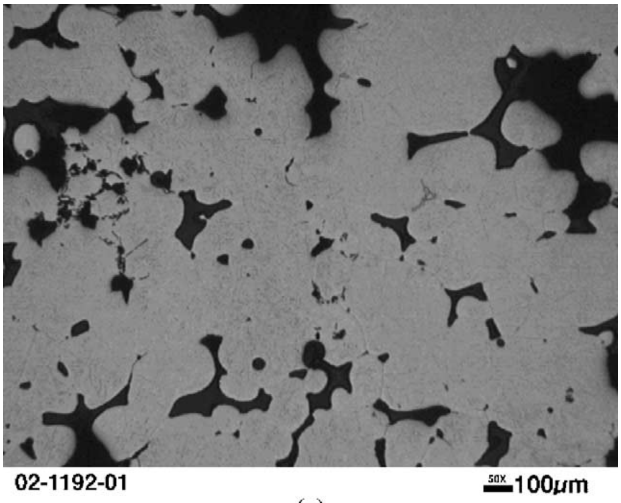


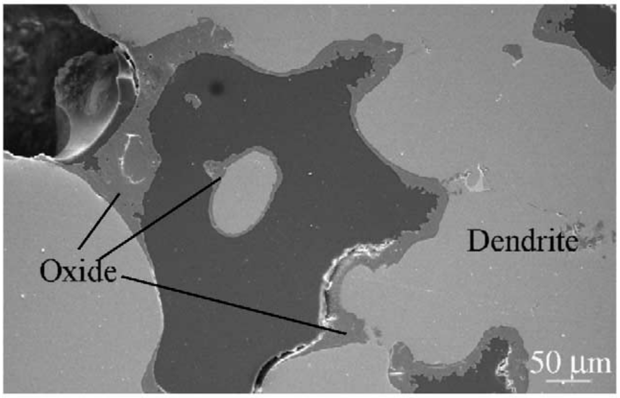
Fig. 1. The microstructure on the as-polished surface of the dross formed during the remelting of a specimen taken from the center of RSI: (a) optical image and (b) SEM image. The white phase is the aluminum dendrites. The black regions contain porosity.

pores that form during solidification due to hydrogen precipitation [5–7]. Fig. 1(b) is an SEM image showing that the aluminum dendrites were covered with a layer of oxides, more than 10 μm thick. This explains the reason why the specimen did not collapse at 850 °C for such extended holding times. The oxides are usually of high melting temperatures. At 850 °C, the aluminum dendrites were melted but the oxides were still solid. As a result, the aluminum liquid was entrained in the oxide shell. It was the oxide-reinforced dendritic structure that prevented the specimen from collapsing at 850 °C.

Fig. 2(a) shows the as-cast microstructure of a specimen taken from the center of a RSI. The microstructure is comprised mainly of aluminum dendrites and interdendritic porosity. The porosity level was so high that the dendritic grains were almost separated by the interdendritic pores. Surprisingly, an oxide layer has already formed on the surfaces of the interdendritic pores, see Fig. 2(b). In fact, oxide layers shown in Fig. 2(b) can be found everywhere on the specimen taken from the center of RSI. The question is how do the oxides form on the surfaces of the pores in the center of RSI. One possibility is that the oxides shown in Fig. 2(b) are oxide films that were formed at the melt surface in the melting furnace, brought into suspension in the melt by fluid flow or during pouring, and entrapped by the growing dendrites during solidification. However the morphology of the entrapped oxide films reported in the literature [8] is very much different to that shown in Fig. 2(b). It is difficult to believe that the entrapped oxide films can cover the zigzag dendritic surfaces so uniformly. Another possibility is that the oxide layer was formed in situ on the porosity surfaces.



(a)



(b)

Fig. 2. The as-cast microstructure of a specimen taken from the center of RSI. (a) On the optical image, only aluminum dendrites and porosity can be seen. (b) The SEM image shows an oxide layer formed on the surfaces of interdendritic pores. Even the small dendrite arm at the center of the image is covered by oxides.

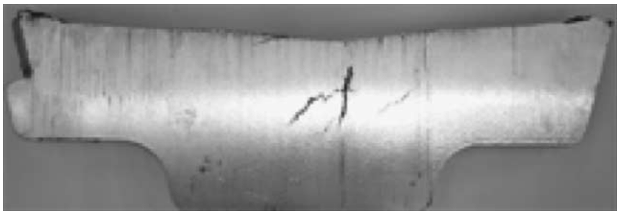


Fig. 3. An image of a slice cut from the center of RSI. Cracks can usually be found in the center of RSI. The dimensions of this slice are 1.16 m (45.5 in.) wide and 0.33 m (13 in.) tall.

In order to investigate the possibility that the oxide layer was formed in situ in the center of RSI, the macro- and microstructure of RSI were characterized. A RSI was cut vertically, using a bench saw, through the center to expose its internal integrity. Cracks, porosity, and the oxides on the surfaces of the pores were characterized.

Cracks are visible to the eye on the as-cut surface as illustrated in Fig. 3 (these cracks are sometimes visible on the top surface of a RSI). The SEM image shown in Fig. 4 reveals that the fracture surface is dendritic. This is a typical fracture morphology of hot tearing that occurs at temperatures higher than the non-equilibrium solidus temperature of the alloy [9–11].

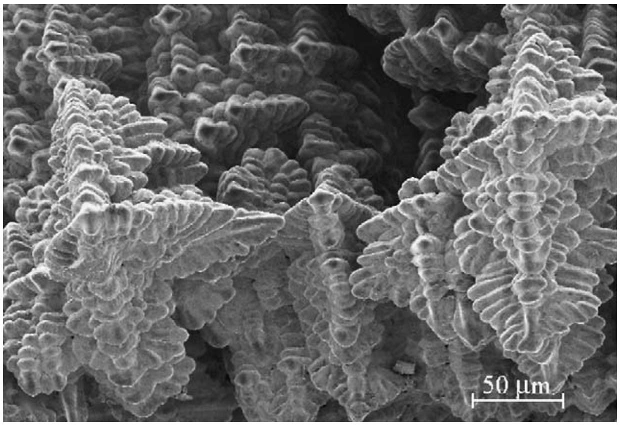


Fig. 4. SEM image of the fracture surface. Dendrites are clearly visible on the fracture surface, indicating the nature of the crack is hot tearing.

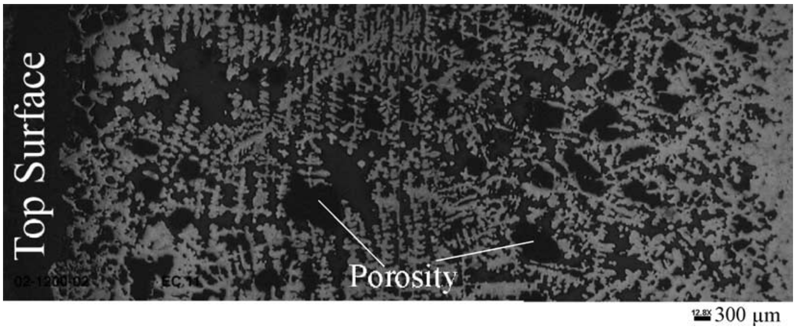


Fig. 5. Optical image of the microstructure of a specimen taken from the top of RSI. A porous layer is identified. The layer is comprised of aluminium dendrites and cavities.

Porosity is almost invisible to the eye on the as-cut surface. Specimens were then taken at various locations and polished. Fig. 5 shows the microstructure of a specimen taken from the top surface of a RSI. It reveals a porous layer on the top surface of the RSI. The thickness of the layer varies from RSI to RSI but typically is about 6–20 mm. Under this porous layer, interdendritic porosity occurs as illustrated in Fig. 2(a). The pore size becomes larger towards the center of a RSI. In fact, interdendritic pores occur throughout a RSI.

The surfaces of the interdendritic pores are covered by oxides. Fig. 6 shows the oxides on the pores in the porous layer of a RSI. The oxide layer is fairly uniform in thickness. Energy dispersive spectrum (EDS) analysis indicated that the oxide layer was comprised of two kinds of oxide. The outmost bright regions shown in Fig. 6 contain aluminum and oxygen and are likely alumina. The majority of the oxide is in the dark region which contains aluminum, magnesium, and oxygen and is likely the mixed oxide $MgO.Al_2O_3$, known as spinel [8]. The oxides on the pore surfaces in the center of RSI, illustrated in Fig. 2(b), are very similar to that shown in Fig. 6 in terms of oxide types and oxide layer thickness. There is no significant difference between the oxide layer formed near the top surface of RSI and that formed in the center of RSI. This suggests that the mechanism of oxide layer formation in these two locations is identical. Since the pores in the porous layer are certainly open to the atmosphere so the oxide layer is most likely formed in situ on the pore surfaces, the oxide layer on the pore surfaces in the center of RSI should also be formed in situ.

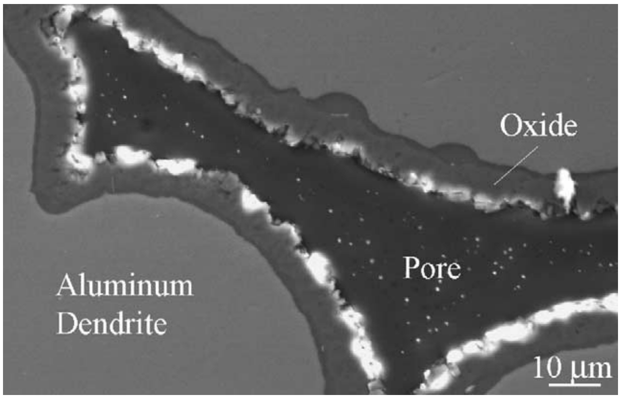


Fig. 6. The SEM image showing the oxides on the surfaces of the pores in the porous layer of RSI. The oxide layer is fairly uniform in thickness. The bright regions on the surface of the oxide layer contain Al_2O_3 and the dark region of the oxide layer contains spinel.

It is clear that the large amount of dross formation during the remelting of aluminum 5182 RSI is due to the presence of an oxide layer on the surfaces of the interdendritic pores. In fact the aluminum dendrites/grains were covered by a continuous layer of oxides. When the specimens were heated to 850 °C, 215 °C higher than the melting temperature of the alloy, the aluminum dendrites/grains were melted but the oxides were still solid. It was the oxide frame-work that prevented the aluminum specimen from collapsing. As a result, aluminum grains were entrained in the oxide shells and contributed to the large amount of dross formation.

The oxides that covered the aluminum dendrites/grains were formed in situ on the pore surfaces. The question is how does oxygen get into the center of a RSI and react with aluminum and magnesium at the surfaces of the interdendritic pores. As long as oxygen is available, spinel can form easily on the surfaces of hot tears and interdendritic pores since the magnesium content in the alloy is about 4.5 wt.%. It is reported in the literature that spinel is the main oxide that forms in aluminum alloys containing more than 2 wt.% of magnesium [8]. SEM analysis of the oxide layer shown in Fig. 6 indicates that majority of the oxide (the dark region in the oxide layer) is spinel. This is in agreement with the literature data [8].

The microstructural characteristics shown in Figs. 2(a), 3 and 5 indicate that hot tears and interdendritic pores may provide the pathways for oxygen to get into the center of RSI. Solidification shrinkage may yield a necessary pressure difference between the center and the surface of RSI that sucks oxygen into the center of a RSI through the pathways comprised of hot tears and interdendritic pores.

Imagine the solidification process of RSI. After molten aluminum alloy has been poured into a metal mold, a solid shell will be gradually formed on the mold surface. The RSI is also cooled at its top surface with water spray, which promotes the formation of a solid shell on the top of the RSI. As solidification continues, the remaining molten aluminum will be enclosed in a solid shell. As the shrinkage due to the solidification of the remaining melt cannot be compensated, this shrinkage tends to reduce the pressure within the solid shell and to pull the top shell down, generating stresses in the top solid shell (sometimes results in the formation of hot tears). The pressure difference between the center and the surfaces of the RSI increases as solidification continues until air is sucked into the center of the RSI. The air contains oxygen that forms oxides easily on the pore surfaces at temperatures higher than the solidus temperature of the alloy. As a result, spinel forms on the surfaces of the interdendritic pores as air passes through these pores.

The oxides on the surfaces of interdendritic pores grow as well during the remelting of the specimen. A number of small cracks can be seen on the oxide layer shown in Fig. 1(a). This is due to the fact that the aluminum has a larger thermal expansion coefficient than that of the oxides. When the specimen was heated, the aluminum expanded more than the oxides. As a result, the oxide layer fractured. A fresh aluminum surface was formed but oxides formed on the fresh surface immediately since oxygen existed in the interdendritic pores. Oxygen could also get into the fresh surface through the pathways comprised of interdendritic pores and hot tears.

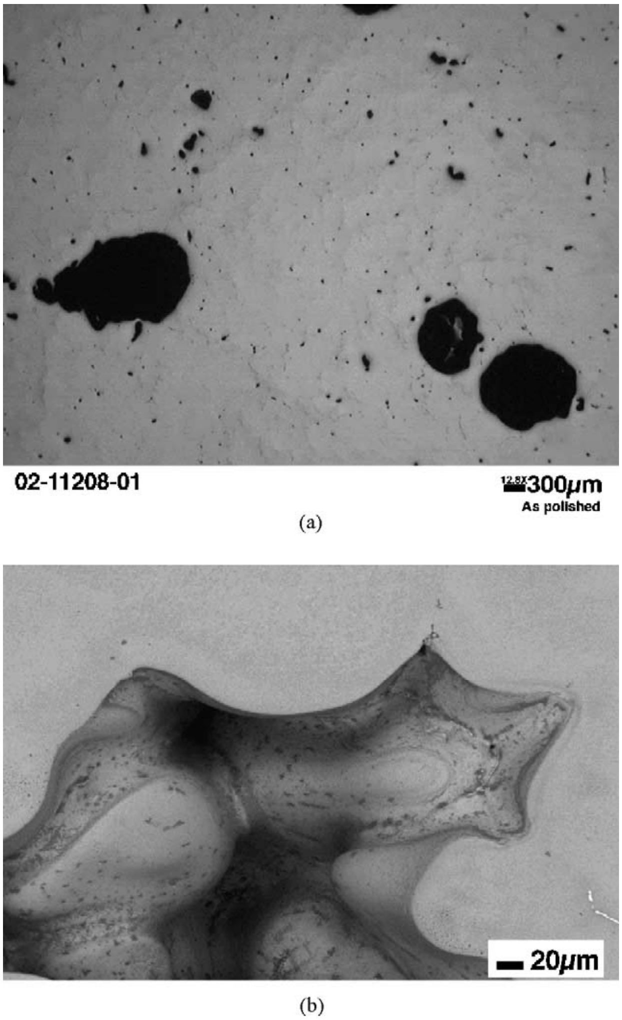


Fig. 7. (a) The optical image and (b) the SEM image of the as-cast microstructure of a specimen containing spherical pores. The pores are isolated. No oxides have been found on the aluminum dendrite surface. The amount of dross formation is much less than that of the specimens containing interdendritic pores.

To validate our argument that the interdendritic pores and hot tears provide pathways for oxygen to get into the center of a RSI, we carried out a melting experiment using specimens taken from RSI that contains spherical and isolated pores. The as-cast microstructure of the specimen is illustrated in Fig. 7(a). The optical image shown in Fig. 7(a) indicates that the pores are isolated and spherical. No oxides can be found on the SEM image shown in Fig. 7(b). Because the pores are spherical and isolated, they cannot form continuous pathways for oxygen to get into the center of RSI. Specimens weighing 0.6 kg were cut from the center of the RSI and charged into the furnace under the same conditions given in Table 2. As we expected, the specimens were melted immediately at the liquidus temperature of the alloys. The amount of dross formation at 850 °C varied from 1.2 to 3.2 wt.%, much lower than that of the specimens containing interdendritic pores.

4. Conclusion

We have observed a surprising phenomenon that some of the specimens taken from the center of aluminum 5182 RSI did not melt and lose shape at 850 °C, 215 °C higher than the liquidus temperature of the alloy. This is due to the fact that the specimens contained a severe interdendritic porosity and the surfaces of the interdendritic pores were covered with oxides. The oxides on the surfaces of the interdendritic pores form a continuous network that entrains the liquid aluminum and prevents the specimen from losing shape. As a result, a large amount of aluminum is entrained in the oxide shells and turned into dross during the melting of aluminum 5182 RSI.

The oxides on the surfaces of the interdendritic pores are formed during the solidification of the RSI. The interdendritic pores and hot tears provide pathways for oxygen to get into the center of a RSI. The solidification shrinkage yields a low pressure in the center of the RSI that sucks air into the center of a RSI through the pathways, leaving behind a layer of oxides on the surfaces of the interdendritic pores.

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