Research Programs

Novel Methods for Grain Refining Aluminum Alloys

Research Team:

Nasim Alem
Anacleto de Figueredo
Diran Apelian

Inoculation is the introduction of a second phase particle into the melt in order to enhance grain refinement or modification. In grain refinement, the role of inoculants is to increase the number of nucleation sites, and for them to be a catalyst during the early stages of solidification. Grain refinement provides an equiaxed grain structure, uniform mechanical properties, and better machinability. It also eliminates shrinkage, increases resistance to hot tearing and improves feeding.

Cibula and subsequent researchers established the effectiveness of grain refinement through the addition of master alloys containing TiC or TiB2 nucleating agents. Such master alloys release insoluble TiC and TiB2 particles in the melt. These particles are potent inoculants for aluminum melt and form very fine grains. However, some undesirable attributes have been noticed in this practice. When grain refining using Ti-B master alloys, TiB2 particles tend to settle down or agglomerate into clusters after they are added into the melt. Although the agglomeration tendency of TiC particles in TiC is much lower, it still presents a problem. In addition, it has been noticed that borides present in the Ti-B master alloy are associated with residual K2TiF6 and KBF6 salt, which comes from the manufacturing process of these master alloys.

In order to obtain grain refinement without these undesirable side effects, this study was directed towards novel methods of aluminum grain refinement. The work was divided into 4 independent phases. Each phase addressed a different approach such as the effect of vapor phases (carbon and boron containing gases); the use of novel master alloys such as, Al-La and Si-1B; as well as obtaining structural refinement via mixing two different alloys.

In Phase I, various vapor phases, containing the nucleating agents boron and carbon, were purged into the melt. This is an in-situ process, in which grain refinement and degassing are performed simultaneously. The concept of vapor phase grain refinement is theoretically viable since mass transfer rates in the vapor phase exceed those in the solid and liquid phases. This attribute enhances equal distribution of the gas all over the melt. Thus one would expect that the grains produced by this method should be uniform in size and structure. However, several procedural issues must be resolved before vapor phase inoculation can be introduced as a robust manufacturing procedure in commercial foundries. Paramount among these issues is the safety regulations associated with the use of potentially hazardous and corrosive gases. Phase I of the project addressed the feasibility of using vapor phase inoculants, such as BCl_3, CH_4 and C_2H_2, in grain refining aluminum alloys.

Phase II of the project examined the effectiveness of rare earth element, lanthanum, on grain refinement and modification of 356 aluminum alloys. Previous work showed that modification, grain refinement and melt cleanliness are enhanced by lanthanum addition. Lanthanum is an expensive element; however, If lanthanum fulfils these three tasks, there may be the potential for total cost decreases. The objective of this phase was to evaluate lanthanum as a means to grain refine, modify, and reduce hydrogen content of aluminum-silicon alloys.

Phase III focused on grain refinement of aluminum-silicon alloys via addition of Si-1B master alloy. According to the literature boron is an effective grain refiner in aluminum-silicon alloys. It has been shown that addition of Si-1B master alloy permanently grain refines aluminum-silicon alloys without fading even after remelting. *Aluminum Elkem* (Norway) produces an aluminum-silicon alloy similar to A356, named SiBloy. SiBloy is a permanently grain refined alloy using Si-1B master alloy. During solidification of this alloy boron, which is already in solution, undergoes a eutectic reaction and forms the eutectic phases AlB_2 and ?-Al just above the liquidus temperature of the alloy. The eutectic phases further nucleate the aluminum melt. The purpose of this investigation (Phase III) was to evaluate the characteristics of modified and unmodified versions of SiBloy, as well as the effectiveness of Si-1B master alloy in grain refinement of A356 aluminum-silicon conventional alloy.

The fourth and the last phase in this study (Phase IV) investigated the possibility of having structural refinement by mixing two different alloys, A356 and SiBloy. Such techniques of mixing two liquids have been applied in semi-solid processing and resulting in a very fine structure. In order to better understand the grain refinement mechanism in aluminum-silicon alloys, SiBloy and A356 were mixed both in the solid state and in the liquid state, respectively. In the former, A356 and SiBloy were remelted together and kept in the furnace to study the effect of mixing on the final grain size during a long holding time. In the latter, SiBloy and A356 were remelted separately. The liquids were then mixed and cooled down, while either one or both of them may contain nuclei prior to mixing.

Conclusions

Grain Refinement and Modification with Lanthanum

- *Al-10wt.%La grain refines A356 alloys at concentration levels above 0.6%. However its grain refining potency fades away quickly after addition. In the case of lanthanum addition, fading could be attributed to the oxidation of lanthanum in the melt.*
- *Lanthanum modification is observed at 0.8%La concentration level. The modifying effect of this element tends to persist and some improvements are observed at increasing holding times.*
- *No grain refinement was observed when pure lanthanum was added to aluminum alloy melts This points out the importance of properly introducing lanthanum into the melt.*

Grain Refinement With Si-1B

- *Si-1B master alloys are effective grain refiners of aluminum silicon alloys. The eutectic phases ?-Al and AlB2 in the Al-B system precipitate at 660 C. and nucleate the aluminum melt. Grain sizes as low as 200 microns are achieved by adding 200 ppm boron to the melt.*
- *There is no fading of the grain refiner Si-1B, both in the first melt and after remelting.*
- *Thermal analysis of SiBloy revealed no undercooling of the melt, confirming the nucleating potency of Si-1B master alloy.*
- *Very small grain size changes were observed over a wide range of cooling rates, from 1 to 200 C/min.*
- *There is no loss in modification with strontium after remelting. However, modification with sodium fades away quickly after remelting. In modification with strontium blocky silicon was observed on the boundary of the interdendritic regions and ?-Al.*
- *In the Sr-modified SiBloy, there might be an interaction between strontium and boron that results in smaller grain size. Larger variations of grain size were observed on Sr-modified SiBloy as well.*
- *Thermal analysis of SiBloy shows that a depression of the eutectic occurs after addition of strontium.*

Structural Refinement by Mixing Two Alloys

Melting SiBloy and A356 Charges

Observations made when melting charges composed of A356 and SiBloy at different titanium contents, showed that

- *The interaction between boron and titanium in the melt formed by remelting a charge composed of SiBloy and A356 alloys, leads to a grain size as small as 100 μm.*
- *The nucleating agent in the alloy mixture seems to be TiB2 with residual titanium.*

Observations made when mixing SiBloy (at various fractions) and A356 (without titanium) are:

- *There is no interaction observed in the alloy mixture, except that the boron content is diluted due to mixing with A356. The final boron content in the alloy mixture (maximum 100 ppm) is too low to nucleate the aluminum melt.*

Mixing SiBloy and A356 Melts at Higher Temperatures

When only Sibloy contained nucleating particles (aluminum borides), the resultant grain size was relatively large, or about 500 μm. The cooling curve for this melt revealed some undercooling. The low cooling rate of 11°C/min also contributed to larger grain sizes.

Mixing SiBloy and A356 at Lower Temperatures

In this case, the solidification microstructure was somewhat non-dendritic and was composed by well-equiaxed, fine grains with sizes ranging from 50 to about 200μm. Higher cooling rates due to the insertion of the stirring and nuclei dispersion are likely to be important factors in the development of the observed microstructure.