Essential Readings in Light Metals: Cast Shop for Aluminum Production.
Edited by John F. Grandfield and Dmitry G. Eskin.
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NOVELIS FUSION^{TM}, A NOVEL PROCESS FOR THE FUTURE

Todd F. Bischoff[1], Lawrence G. Hudson[2], and Robert B. Wagstaff[1]

[1]Novelis, Spokane, Washington US
[2]Novelis, Specialty Products Business Unit, Oswego, New York

Keywords: DC Casting, Novelis Fusion^{TM}, solidus-liquidus range, Al-Clad

Abstract

Production of multilayered products in the aluminum industry has entered a "new birth" period in the flat rolled aluminum sheet industry as a result of the recent introduction of the Novelis Fusion^{TM} process. This paper analyzes the interplay in the liquidus temperature and the freezing ranges of each alloy as well as potential problems and possible solutions encountered when producing some clad products.

Introduction

Francis C. Frary, while trying to avoid surface cracking during rolling found that plates of pure aluminum would bond to some alloys. Without having any direct interest or use in his finding, the concept was shelved until years later when Edgar H. Dix used Frary's technique to attach a corrosion-resistant pure aluminum layer on a high strength alloy ingot in such a way that it could be rolled into sheet while producing a uniform coating to protect the corrosion-sensitive alloy.[1] Today this strategy is used in sheet applications where:

- A lower melting point clad layer is desired on a moderate strength yet highly formable core in brazing applications. e.g. 4045/3003/4045
- A galvanic layer of corrosion resistant clad layer is desired on a medium strength, formable core, e.g. 7072/3004/7072, and
- A corrosion-resistant layer is desired exterior to a high strength core, e.g.1200/2124/1200.

Aluminum clad alloys are commercially produced today by hot roll-bonding where a clad layer is bonded to a core alloy by rolling under significant loads at elevated temperatures. This conventional process has many manufacturing steps with ample opportunities to generate scrap. The clad layer must be produced via a separate route of casting, scalping, pre-heating, rolling and trimming to the necessary clad plate thickness and size. The clad and core surfaces must be clean when mated, possibly requiring a surface preparation step. As well, "tacking" (welding) or strapping the clad plate to the scalped core is required for pre-heating. There are limitations to the alloy combinations that can be roll bonded since some alloys form tenacious oxide films that are difficult to disrupt during the bonding process. This can result in "dirty" interfaces that degrade the useful strength of the sheet. In this latter regard, alloys high in Mg are particularly difficult to bond efficiently.

Conventionally clad materials contain a diffusion bond, originally formed at the hot mill which is passed downstream to final gauge, which leads to inherent material conditions or properties present in all products manufactured from conventionally clad material. Edge, head, and tail "wipe-off" occur in areas of the conventionally-clad sheet where significant mill loading occurs and the resulting stresses are unbalanced.[2]

The commercial production of multi-alloy ingots have intrigued solidification and rolling experts for years as it was recognized that such a process would open doors to new products far beyond the classical selection of monolithic and conventional Al-clad products.

In Binczewski, U.S. patent 4,567,936 issued February 4, 1986, a method is described for producing a composite ingot by DC casting where an outer layer of higher solidus temperature material is cast about an inner layer with a lower solidus temperature.[3]

In Robinson, U.S. Patent 3,353,934 issued November 21, 1967 a casting system is described where an internal partition (baffle) is placed within the mould cavity to substantially separate areas of different alloy compositions. The end of the baffle is designed so that it terminates in the "mushy zone" just above the solidified portion of the ingot. Within the "mushy zone", alloys are free to mix under the end of the baffle to form a bond between the layers.[4]

In Matzner, German patent DE 44 20 697 published December 21, 1995 a casting system is described using a internal partition to Robinson, in which the baffle position is controlled to allow for liquid phase mixing of the interface zone to create a continuous concentration gradient across the interface.[5]

In Robertson et al, British patent GB 1,174,764 published 21 December 1965, a moveable baffle is provided to divide up a common casting sump and allow casting of two dissimilar metals. The baffle is moveable to allow intermixing of the alloys.[6]

In Kilmer et al., U.S. Patent 6,705,384 issued March 16, 2004 a casting system is described using a barrier material in the form of a thin sheet between two different alloy layers. The thin sheet has a sufficiently high melting point that it remains intact during casting, and is incorporated into the final product.[7]

While each of these innovators realized varied levels of success, none of these processes have been realized on a commercial scale. In our investigation, we found that foreign items inserted into the melt produced complex oxides at the clad interface or on top of the molten sump. We also found that technologies with mechanical items terminating in the sump were difficult to optimize for both start and run conditions.

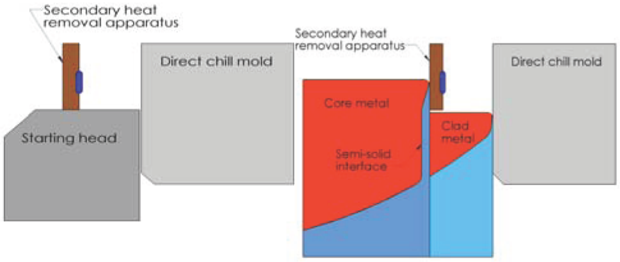
In previous publications, a new process – "Novelis Fusion" – was introduced.[8] This technology produces clad material directly by DC casting. It was reported that this technology produced a clean, high-strength interface with few restrictions for the combination of alloys involved. It was also reported that Fusion sheet is produced by essentially the same hot and cold rolling route used for conventional monolithic alloys.

In subsequent articles, the diffusion of magnesium across the interface in the presence of silicon was discussed.[9] Later, the formation and transformation of some common manganese-silicon intermetallics was examined.[10] Some products employing these concepts have been discussed for both traditional brazing sheet[11] as well as novel Al-Mn cladding on Al-Mg-Si for automotive applications.[12]

Process

Equipment Configuration

As reported in our U.S. Patent application a Direct Chill (DC) mold and starting head, commonly used in the industry, serve as the primary heat removing, geometry-defining apparatus.[13] The molding apparatus also includes a secondary heat removal apparatus (SHRA) internal to the mold opening. Multiple coolant flows and liquid metal streams are controlled by a series of flow control and metal level sensors which maintain the necessary thermal, structural and mechanical boundaries during solidification. See Figure 1a.



(a) (b)

Figure 1. Typical set up for products where the liquidus temperature of the core is higher than the liquidus temperature of the clad.

Solidification commences after liquid metal enters the cavity corresponding to the alloy with the highest liquidus temperature prior to the lowering of the starting head. See Figure 1a. After the starting head is lowered and before it exits the lower end opening of the mold, a second stream of metal enters the mold cavity and is raised in the cavity to contact the semisolid interface of the first alloy immediately below the secondary heat removal apparatus Figure 1b. Critical process parameters are modified to correct for the transient heat removal conditions typical to the start up and end portions of the cast.

Figure 1 represents the apparatus set up and description for the production of brazing sheet products where the core material has the higher liquidus temperature. In our patent application, we also describe a methodology where we vary the geometry of the secondary heat removal apparatus during the cast to compensate for the transient heat removal conditions at the start and end of the cast when compared to the more consistent heat removal conditions common to a steady state process. The same article describes a methodology to solve the transient lateral movement of a clad alloy across the rolling face during longitudinal rolling such that a flat clad layer can be obtained across the entire width of the finished sheet. Data supporting this claim can be found in the article described above.[11] The same technology features are also employed in alloy combinations where the clad alloy has a higher liquidus temperature compared to the core. See Figure 2.

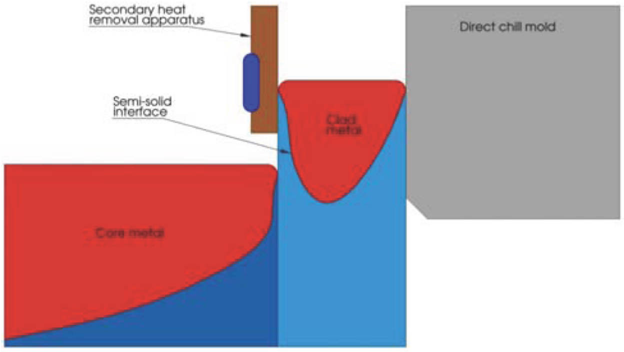


Figure 2 Typical set up for products where the liquidus temperature of the clad is higher than the liquidus temperature of the core.

Liquidus and Freezing Range Effects in the Fusion Process

When engineering the equipment configuration and estimating the initial "first cast" start up and run parameters, it is paramount that exact thermal conditions are known for the liquidus and solidus temperatures of each alloy being solidified. Figure 3 is a graph of the equilibrium liquidus (T_L) contrasted to the equilibrium freezing range for some common Fusion packages. Differences in liquidus temperature can be used also to predict the probability of success. For example, in brazing sheet – where the core alloy has a higher liquidus temperature – we use the configuration common to Figure 1. Whereas the balance of alloy combinations where $T_{Lcore}<T_{Lclad}$ are produced with the configuration as outlined in Figure 2. The total brazing sheet liquidus difference of $T_{LAA3003}-T_{LAA4045}=$ 54˚C indicates that this combination can be easily produced in a commercial environment; combinations AA1200/AA2124 ($T_{LAA1200}-T_{LAA2124}=$ 19˚C) and AA5005/AA5456 ($T_{LAA5005}-T_{LAA5456}=$ 14˚C) with reasonable difficulty; and AA7072/ AA3104 ($T_{LAA7072}-T_{LAA3104}=$ 3˚C) with special attention to alloy superheat on the core alloy.

In casting with the configuration as presented in Figure 2, especially with very thin clad layers, core alloy superheat can help to increase the percent liquid at the Fusion interface and thus enhance the bond between the two alloys. In the case where initial alloy material is melted we found that after contact with the second alloy, diffusion of liquid elements into the initial alloy layer occurs quite rapidly, modifying the composition of not only the clad alloy but the composition of the intermetallic particles as well.[10]

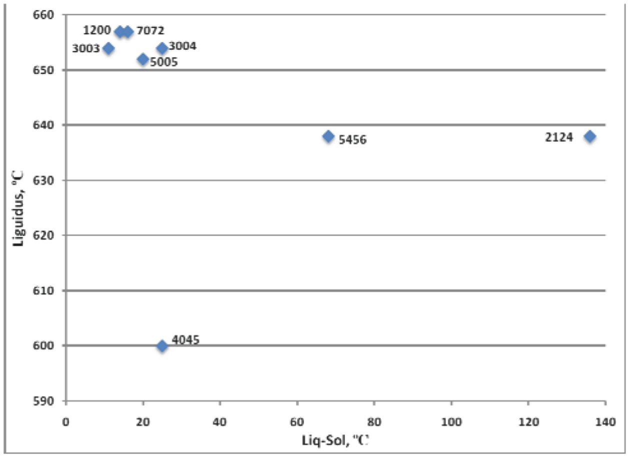


Figure 3. Equilibrium liquidus versus equilibrium freezing range for some common alloys cast with the Fusion technology.

Oxide Management in the Novelis Fusion Process

In the case where brazing sheet ingots are produced (Figure 1), oxides formed on the top of the ingot (in the core) easily roll over the edge of the meniscus against the secondary heat removal apparatus and help to counteract the core alloy splaying forces. Interestingly, this same oxide is consumed and plated out as an inverse image onto the oxide of the clad at the point where the brazing alloy contacts both the oxide and the solidifying layers of the core alloy. This outer "migrated" or combined core/clad oxide is then removed during scalping prior to preheat and rolling.

Other alloy combinations common to Figure 2, are produced with a series of oxide skimmers designed to penetrate each alloy enough to restrain any metal oxides from entering the clad-core interface. Alloying elements commonly used to restrict oxide growth are introduced to either or both clad-core metal streams at the furnace or in the launder.[14]

Sump Geometry and Gradient Effects

Many of the ingot and clad shape e.g. mold bore and SHRA geometrical issues encountered with the development of the Fusion Process have been presented in some of our earlier work.[15] In the equipment set up common to Figure 2, taper along the SHRA was found critical to a safe cast start. In addition, we found that large differential thermal expansion of core-clad alloy combinations presented problems.

In cases where the core alloy has an extremely high coefficient of expansion e.g., magnesium and zinc, the solidifying clad alloy shell can be easily collapsed or wrinkled after it contacts the core alloy and continues to solidify and contract in concert with the sump of the core alloy. In this case, alloy chemistry, cleanliness, and sump depth begin to have a significant effect on ingot recovery. High magnesium in the core can be easily cast by making sure that (1) the clad layer is hot enough to allow interface deformation at the initial contact point and (2) that the shearing action created at the secondary heat removal apparatus is mitigated by increased taper at the outer extremities of the ingot. See Figure 4.

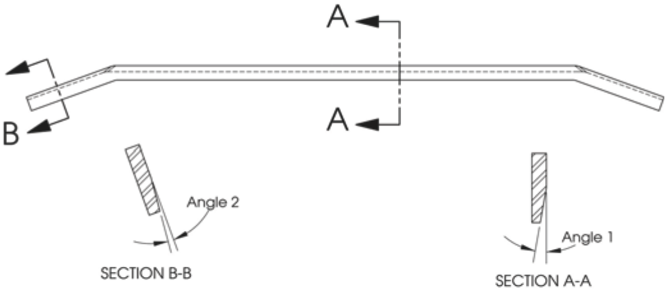


Figure 4. Taper of SHRA necessary for interface deformation during rolling when casting metals with a high thermal coefficient of expansion.

Unique Thermo Mechanical Processes

The need to provide brazing sheet products in the –O temper suggests that Fusion ingots must undergo a homogenization process prior to hot rolling. As with many products a uniform chemical composition is desired across the as-cast grains in order to generate a population of intermetallic precipitates (dispersoids). Without an even particle distribution of mature precipitates, the appropriate texture and formability cannot be obtained. Precipitates provide requisite dislocation pinning and tangles, the predecessors for recrystallized grains and preferred texture development. Homogenization normally takes place at or above the solvus for the particular transformation being considered. In the case of most brazing products, we are concerned about the concentration gradient of copper and silicon across the crystal and the transformation of $MnAl_6$ to α-AlMnSi, the latter of which takes place at temperatures in excess of 600˚C. This temperature is higher than the *liquidus* temperature of most brazing alloys. e.g. AA4045, AA4343.

To meet or exceed these material requirements, modifications to the casting process needed to be introduced, so that equilibrium solidification conditions could be approximated in a non-equilibrium world. In a separate but related patent filing, we describe a process under which common industrial solidification rates are maintained without cooling the bulk of metal such that equilibrium solidification structures can be generated.[16] Once the desired concentration gradient is produced in the grain and the necessary intermetallic composition is formed, the ingot is cooled to room temperature (below the transition or transformation temperature) and removed from the casting pit. During ingot preheat for rolling, a two stage preheat is employed where intermetallic precipitates (dispersoids) are formed prior to hot rolling. See Figure 5 and Figure 6.

We also use the same process to help minimize the formation of and dissolve the β-Mg_5Al_8 with high magnesium core alloys opening new alloy/clad combination opportunities beyond any commercial products currently available in the market place. See Figure 7 and Figure 8.

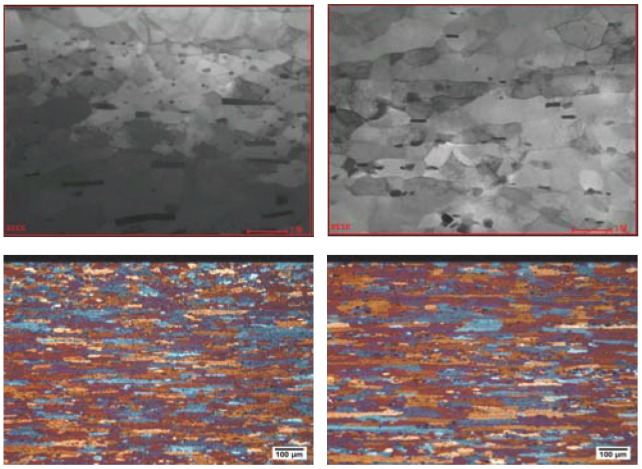


Figure 5. Al-Mn1.5-Cu0.6 (X900) showing a typical precipitate (dispersoid) population and recrystallized grain sectioned from the center (left hand) and surface (right hand) portion of an ingot.[16]

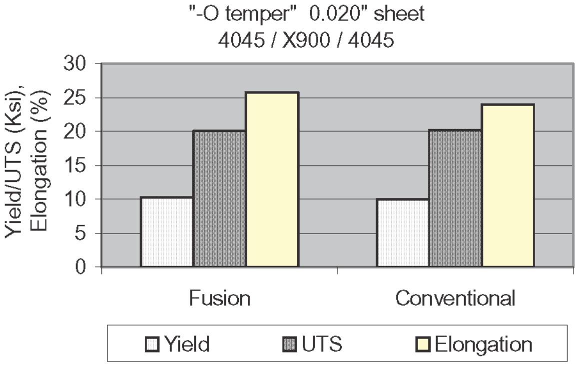


Figure 6. Mechanical properties of Fusion Al-Mn1.5-Cu0.6 (X900) sheet commercially produced in the –O temper.

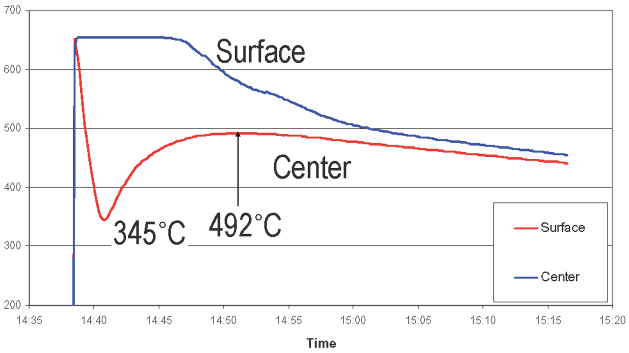


Figure 7. Casting temperature versus time for Al-Mg7.

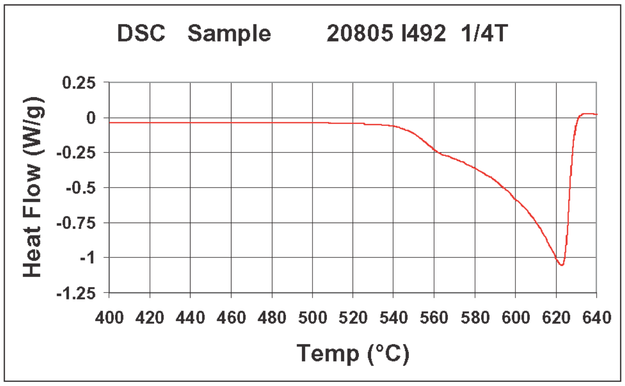


Figure 8. Differential Scanning Calorimeter trace for Al-Mg7 alloy (as-cast) showing the absence of β-Mg_5Al_8 phase normally appearing in the 450-453°C temperature range.

Conclusion

The Novelis Fusion startup and its initial months were not without challenges and difficulties, but as the casting operator's understanding advanced and we integrated the technologies discussed we have successfully advanced our product offering to include the alloy combinations discussed.

The recent installation at the Novelis Ulsan, Korea facility and the new products targeted at the Sierre, Switzerland installation demonstrate the Fusion technology's ability to provide new multi-alloy products in combinations which were not feasible using conventional cladding approaches and showcase the potential of this technology.

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