Upcycling of Aluminium Alloys

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On average every kilogram of primary aluminium produced in 2009 carries a high emissions burden of nearly 10kg CO$_2$e from the energy and carbon used in its mining and processing. Emissions can be much higher from old pot-lines and where electricity production is fossil fuel based: coal being a particularly bad example where an inefficient station can be responsible for 20.8kg CO$_2$e/kg just for electricity production. This means that once primary aluminium has been made alloyed, processed and manufactured into components every effort should be made to recycle the aluminium post consumer scrap at end of life as it is a high value material compared to the other main material components of the scrap stream. Presently, annual primary aluminium production is about 37Mt and the carbon emissions associated with this production are of the order of 360 Mt CO$_2$e that is equivalent to 65% of the total carbon emissions from the UK or about 1% of the world’s industry based emissions. Primary aluminium production uses about 3% of the world’s electricity and about 10% of its hydropower. Although in primary form the carbon burden is high if this is amortised over the first product use then the drive to recover and recycle aluminium rather than make more primary metal should be overwhelming as the embodied energy in recycled metal is dramatically reduced. It is interesting to note that presently the greenest aluminium ingots in Europe are probably made in the UK at the Novelis, Latchford recycling plant provided any sweetening is made from a low carbon source of primary metal or from recycled scrap like lithographic plate. Latchford’s environmental report suggests that each kilogram of recycled aluminium carries the low environmental burden of an additional 0.68kg CO$_2$e from their decoating, melting and casting operations.

For aluminium recycling of post consumer scrap is the major challenge as the recycling of production and process scrap from within an aluminium producer or from within a aluminium fabricator like a beverage can maker or an aluminium intensive car maker like JLR or Audi is relatively straightforward. Recovery of process scrap is important but it is really only recycling of primary alloy or the mix of primary and secondary metal used to formulate the alloy in the first place. Aluminium old scrap may require decoating but does not have the issues associated with de-tinning of steel old scrap from packaging products like food cans or the de-zincing issues associated with old automotive steel scrap. Can to can recycling of post consumer steel cans is either negligible or at a very low level.

For aluminium the classic example of successful recovery and high level recycling of post consumer scrap is the used beverage can or UBC. In the UK 6.7 billion (90kt) of aluminium drinks cans are sold each year. The recovery rate of aluminium UBCs in the UK has improved progressively from 30% in 2001 up to 50% today which unfortunately means that only 45kt of UBCs are returned and most of the remainder are lost to landfill. However, of the of recovered UBCs only about 30kt finds its way back for direct recycling into can body stock at Latchford and most of the remainder
(15kt) is recycled into castings. This is a can to can recycling rate of 33%. For comparison in 2001 the recovery rate of aluminium UBCs in Japan was 83% and the can to can recycling rate was 68% which shows what can be achieved. The can to can recycling rate in North America is also higher than in the UK where it is claimed that 95% of recycled UBCs go back into can sheet although the average can recovery rates are similar to the UK except in states which use a deposit system to encourage recycling. In the UK can to can recycling is carried out at Latchford which also reprocesses a significant proportion of aluminium UBCs generated across Europe. However, the recycling of UBC’s in the EU appears to be limited by the available decoating capacity at Latchford which contrasts with North America where there is significantly more decoater capacity and can to can recycling rates are much higher from recovered UBCs.. For most of the other aluminium wrought products particularly in Europe recovery of post consumer scrap and its recycling back into the same product is not significant except for a relatively low volume of architectural sheet made by continuous casting. Most wrought product scrap is used as a metal source for the casting industry or is exported representing a loss of an import low carbon aluminium feedstock.

A major barrier to the recycling of aluminium is the increase of inclusions and impurity elements in re-melted post consumer scrap. These can result in severe losses in ductility and strength and certain impurity elements are believed to significantly reduce corrosion resistance. The main issue for the successful reprocessing of aluminium alloy post consumer scrap is therefore dealing with the increased inclusion and impurity levels. Conventional wisdom states that the amounts of such inclusions and impurities must be reduced by a chemical refinement approach, a high cost and low efficiency process. In contrast to refining, we are developing melt conditioning technologies to process aluminium alloy scrap using a physical approach to eliminate the detrimental effects of both the inclusions and impurities, so that higher grade products can be produced directly from old scrap. In the limit this would mean the recycling of castings into wrought products.

Melt conditioning by advanced shear technology (MCAST) is a process that can be used to reprocess aluminium scrap into either cast engineering components or feedstock materials, with equivalent or improved properties compared to currently available primary alloys. We have called this “upcycling”, in contrast to the current concept of recycling where post consumer scrap is converted either into a grade of alloy with inferior quality or is used as a more impurity tolerant casting alloy.

Upcycling is achieved by using a twin-screw melt conditioner, which has a pair of co-rotating, fully intermeshing and self-wiping screws rotating inside a barrel. The screws have specially designed profiles to achieve a high shear rate and a high intensity of turbulence. The high shear and turbulence to which the liquid melt is subjected for short times of the order of ten to twenty seconds results in the break up of oxide films and agglomerates and their dispersion throughout the melt as fine nanoscale oxide particles. These dispersed oxides are potent sites for the nucleation of solidification once the processed melt is transferred to a mould or a casting station. Solidification after melt conditioning results in a fine and uniform microstructure, a uniform chemical composition throughout the entire casting (either components, blocks or billets), and a much reduced (or even eliminated) presence of cast defects, resulting in a substantial improvement in mechanical properties. Large inclusions are eliminated and the cast microstructure is much more tolerant to impurities as intermetallics are refined. This melt conditioning process is a development from the rheoforming processes described in and earlier article in Aluminium International Today in November/December 2005. The main difference is that the high shear melt
treatment is carried out on liquid metal rather than on a semi-solid slurry. Figure 1 shows the effect of melt conditioning and superheat on the as cast grain size of an Al10wt%Mg alloy. Melt conditioning of the liquid alloy results in a finer as cast grain size compared to a non-conditioned melt processed at the same level of superheat and the grain size is much less sensitive to the superheat used.

If a MCAST processed melt is filtered through a ceramic filter and the filtrate solidified and sectioned for metallographic examination then it can be seen as shown in Figure 2(a) that aluminium oxide films and agglomerates have been dispersed and the dispersed oxides are responsible for the nucleation of iron-bearing intermetallics. After melt conditioning the iron rich intermetallics are both smaller and more uniformly dispersed. Figure 2(b) shows the dispersion of oxide films by high shear melt processing at higher resolution and Figure 2(c) shows the qualitative analysis of the oxide types by energy dispersive X-ray microanalysis. We have shown that spinel-type oxides oxide can directly nucleate aluminium as there is excellent lattice matching. Recycling aluminium scrap is achieved by turning oxide films from defects into potent nucleating sites by melt conditioning.

The MCAST process is suitable for the direct recycling of aluminium scrap from end-of-life vehicles. The process is especially useful when combined with twin roll casting as strip can be cast with significantly reduced centre line segregation and at low roll force. Continuous casting of aluminium alloy strip by roll, belt and block casting inherently increases tolerance to impurities due to the higher solidification rate and this type of process is already used to make high iron foil alloys and architectural sheet from recycled scrap. However, to date these processes have not produced aluminium automotive sheet that has been used for commercial vehicle production. The combination of melt conditioning and twin roll casting (MC-TRC) offers the possibility of manufacturing aluminium automotive sheet directly from recycled automotive scrap. This has the potential to make aluminium automotive sheet cost competitive for low carbon vehicles for the mass market. Figure 3 shows a section through a high iron MC-TRC AA5754 alloy strip showing the absence of centre line segregation and a fine and uniform grain structure.

It is time to blur the distinction between cast and wrought alloys and to develop melt conditioning and casting processes for the economic production of structural castings, rolling blocks, extrusion billets and continuously cast strip from melts made with high levels of post consumer scrap. Presently about 8.3 Mt of aluminium scrap from used products are available globally and 75% of all the aluminium ever produced since the 1880s (more than 600 Mt) is still in use and a significant amount more is in landfill sites waiting to be reclaimed. Rather than to continue to increase primary production of aluminium each year, especially where this is based on carbon intensive electricity generation and the use of carbon in the reduction process, more and more wrought and high performance cast products should be made from “upcycled” post consumer scrap.

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Figure 1: Effect of melt conditioning on the as-cast grain size in a TP1 mould for and Al10wt%Mg alloy sheared at 800rpm for 60 seconds

Figure 2(a): Images of sections through filter residue from an LM24 alloy (Al-9.4Si-2.3Cu-1Zn-0.8Fe-0.5Mg-0.2Mn) showing the effect of high shear melt conditioning on the oxide film morphology and the intermetallic particle size
Figure 2(b): Images of sections through filter residue from an LM24 alloy (Al-9.4Si-2.3Cu-1Zn-0.8Fe-0.5Mg-0.2Mn) showing break up of oxide films into small spinel-type crystallites in the size range 200-300nm.

Figure 2(c): EDX analysis of the spinel type oxide crystallites after melt conditioning.
Figure 3: Comparison of grain structure and segregation in grain refined AA5754 (0.4 wt% Fe) twin roll cast with and without melt conditioning. (Longitudinal and transverse sections across the strip)