Upcycling of Light Alloys

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Primary metal based aluminium and magnesium alloys both carry a high emissions burden from the energy and carbon required for their mining, processing and manufacture. On average every kilogram of primary aluminium produced is responsible for 10kg of CO_2e and half of this is from power generation although this can be much higher from old pot-lines and where electricity production is coal based. 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. For magnesium it is the direct recycling of process scrap, especially from high pressure diecasting (the main process used to make magnesium alloy castings from alloys like AZ91 and AM60), that is the present challenge. However, annual primary magnesium production is only about 800kt compared to 37Mt of aluminium. Magnesium production is about 78% by the Pidgeon process and 22% by electrolytic reduction. For electrolytic production each kilogram of magnesium can represent as much as 44kg CO_2e embodied although this reduces to 21kg CO_2e if the use of SF_6 as a covering gas is avoided and to 6kg if the electricity for reduction is hydro-generated. For the Pidgeon process the embodied carbon is of the order of 47kg CO_2e/kg for present most Chinese production (660kt/year in 2007) although process improvements, particularly the change from coal to natural gas could reduce this to 13kg CO_2e/kg. Although in primary form their carbon burden is high if this is amortised over their first product use then the drive to recover and recycle these light alloys rather than make more primary metal should be overwhelming as the embodied energy in recycled metal is dramatically reduced.

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. Both aluminium and magnesium have the potential for high level recycling where the old scrap is recovered and recycled into the same high performance product.

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 drinks cans are sold each year. The recovery rate of UBCs in the UK has improved progressively from 30% in 2001 up to 50% today which means that only 45kt of UBCs are returned and most of the remainder are lost to landfill. However, of the of returned UBCs only about 30kt finds its way back for direct recycling into can body stock the remainder (15kt) being recycled into other products. For most 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.

A major barrier to the recycling of light alloys 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 can significantly reduce corrosion resistance. The main issue for the successful for reprocessing light 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 light alloy scrap using a physical approach to eliminate the detrimental effects of both the inclusions and impurities, so that higher grade light alloy products can be produced directly from their scrap. In the limit this would mean the recycling of castings into wrought products.

Melt conditioning by advanced shear (MCAST) processing can be used to reprocess light alloy 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 in both aluminium and magnesium alloys 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 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.

We have recently established that once a melt has been conditioned and cast by the MCAST process it can be re-melted and cast repeatedly without loss of the refined microstructure as is shown in Figure 1 for magnesium alloy AZ91D. The series of micrographs were obtained from the alloy cast and re-cast at 650℃ with and without melt conditioning. We have also shown that melt conditioning enables the AZ91D alloy to be formulated entirely from recycled high pressure diecasting process scrap without any loss of mechanical properties.

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 that magnesium oxide has been dispersed and has been responsible for the nucleation of Al_8Mn_5 intermetalics. After melt conditioning the Al_8Mn_5 intermetallics are both smaller and more uniformly dispersed although these intermetallic particles are probably not responsible for the direct nucleation of magnesium. However, we have shown that magnesium oxide can directly nucleate magnesium as there is excellent lattice matching as shown in the high resolution lattice images shown in Figure 3. Recycling magnesium casting process scrap is achieved by turning oxide films from defects into potent nucleating sites by melt conditioning. In addition to recycling casting scrap the MCAST process should be suitable for the direct recycling of magnesium scrap from end-of-life vehicles although this has not been evaluated to date.

Melt conditioning of aluminium alloys using the MCAST process also disperses oxides and refines primary intermetallic phases and grain structure. 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 4 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.

We believe 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 castings and preforms from melts made from 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 and magnesium 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.

The authors would like to thank both the EPSRC and the UK Technology Strategy Board for their financial and technical support.

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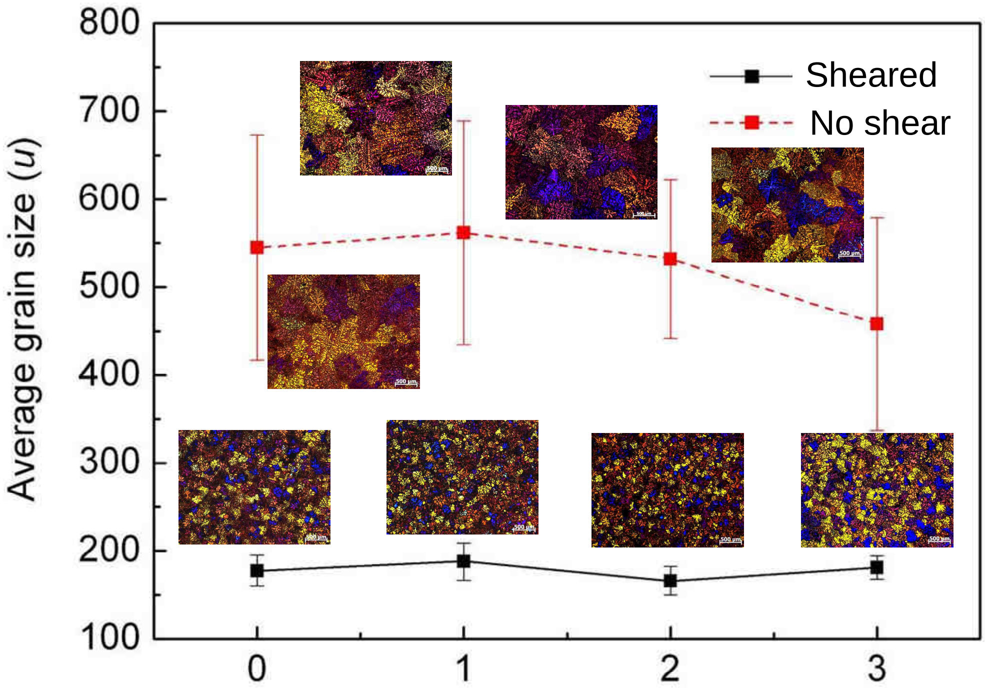


Figure 1: AZ91D cast with and without melt conditioning by the MCAST process at 650℃ and then re-melted and cast three times

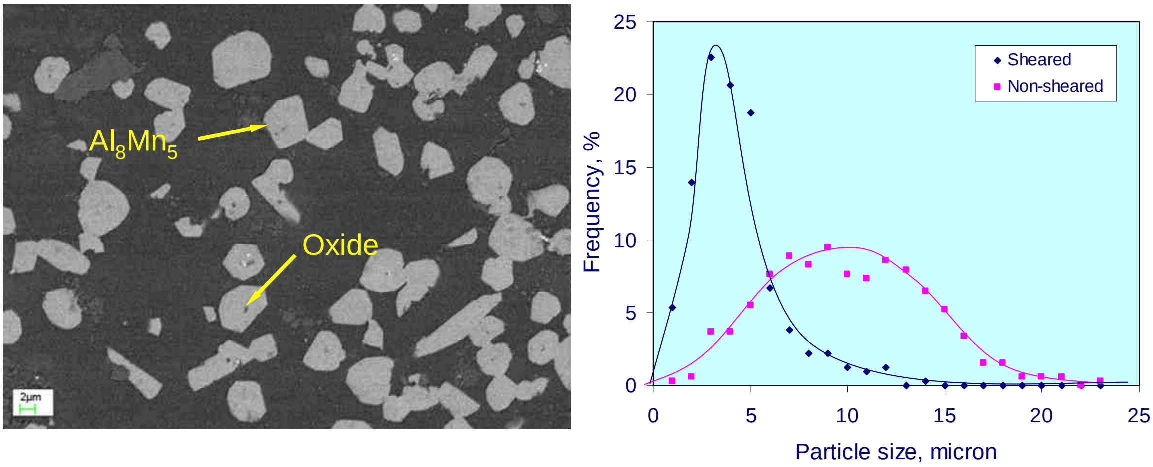


Figure 2: AZ91D filtrate after melt conditioning by the MCAST process showing the Al8Mn5 intermetallics nucleated on dispersed oxide particles and the effect of melt conditioning on particle size distribution

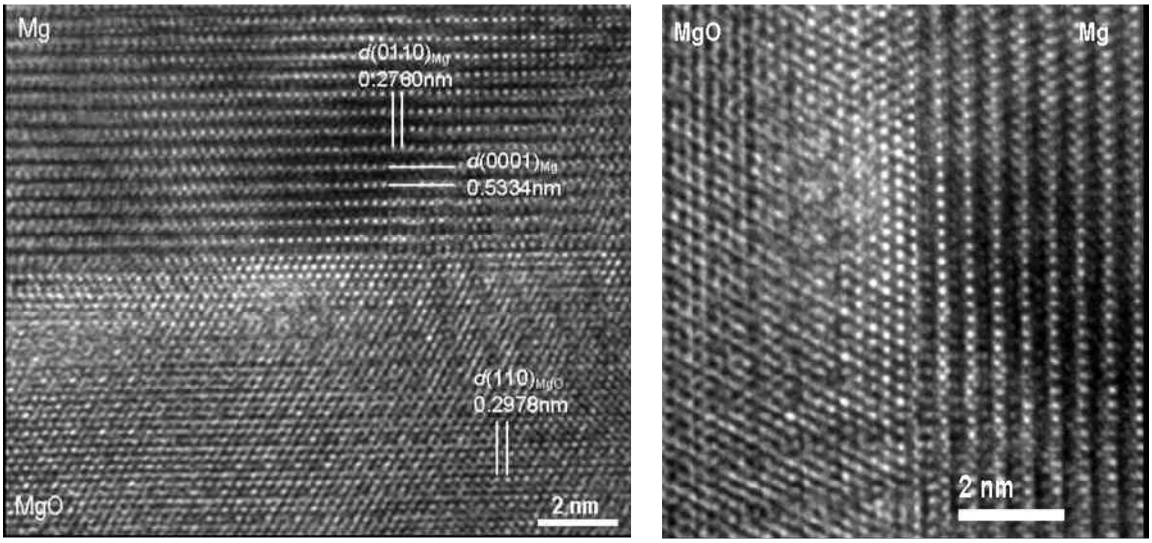
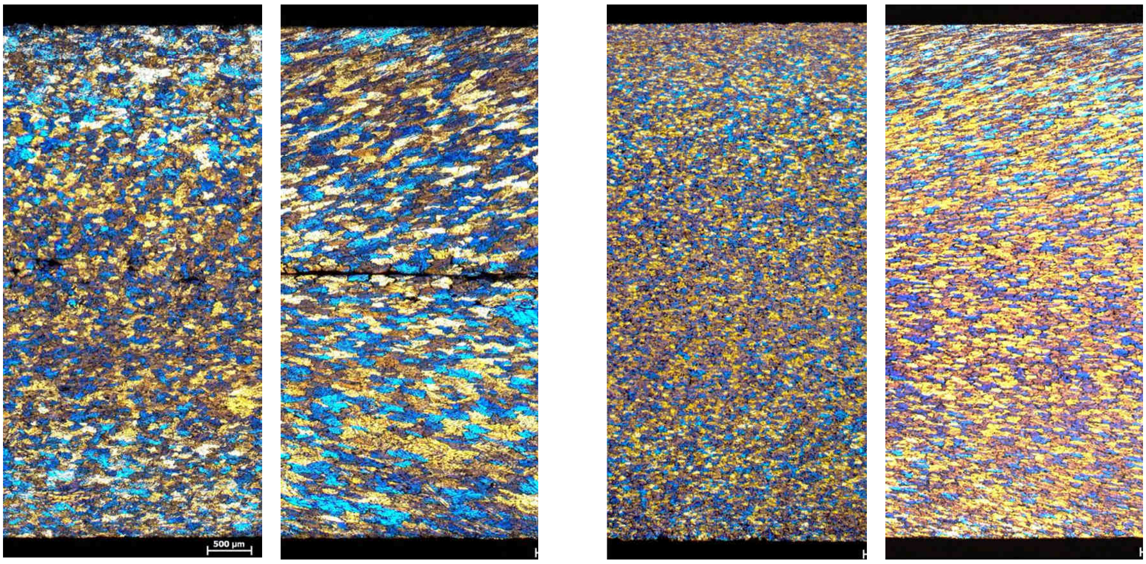


Figure 3: High resolution TEM images showing the close matching between the MgO and magnesium lattices

(micrograph courtesy of Zhou, Thompson and Manchester University)



TRC **MC-TRC**

Figure 4: 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)