



Recycling of Post-Consumer Mg Scrap

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Mg is coming into its own as a structural parent metal. Annually, primary Mg metal production is quickly approaching one million tonnes, new scrap recycling and remelting 300 kt, and the potential availability of old post-consumer scrap is approaching 100 kt ("t" is a metric tonne).

Since the EU waste directive mandates the recycling of end-of-life vehicles (ELVs), the recyclability of materials in the ELV is becoming a significant consideration that affects the penetration of magnesium-based alloys into the vehicular market.

In North America, there is still almost no recycling of Mg-based scrap (Used beverage cans (UBC) consist of Al alloys that contain a significant proportion of magnesium). USGS statistics show a decreasing trend in the recycling of post-consumer Mg scrap with only 730 kt consumed in the US in 2005, as compared to the 9-18 kt of old Mg-alloy diecastings one already expects from shredded ELVs in the US. The majority of the Mg in the portion of the scrap that is sold directly by the shredders to the secondary smelters as Al concentrate product ends up chlorinated out of the Al foundry melt and lost in Al dross.

We explore the true global picture of Mg metal recycling, show where and how it is actually taking place, and highlight areas of current and potential use for Mg-based scrap. We describe technologies that are currently used for separation of old Mg from other scrap and waste and that may help improve Mg recovery the future. Areas where Mg losses occur in the current recycling system are described and strategies for minimization of these losses are proposed.

Global picture of Mg metal recycling

The technical feasibility of using Mg-based alloy castings, extrusions and sheet in automotive and aerospace applications was demonstrated on an industrial/commercial scale in the 1950s. The large price premium over steel and aluminium, however, prevented wide-scale commercial adoption of these products until the 1980s. At that time China made a concerted effort to capture the Mg production market and drove down the price of Mg to near par with Al using a silicothermic reduction process developed in Canada in the 1940s. The return of Mg alloys to the World consumer market was spearheaded by the diecastings that started finding applications such as automotive interior components and housings for portable electronic and electrical equipment (EEE). Until recently there was not a significant amount of Mg alloy in old metal scrap. However, the first Mg-alloy components that made their way into cars in the 1980s and 1990s are now appearing in a small but ever-increasing proportion in ELVs. Until recently

waste electronic and electrical equipment (WEEE) was landfilled with municipal solid waste (MSW). The regulations in EU and some parts of North America now require the manufacturers to take the responsibility for collecting and recycling their WEEE in a system separate from MSW and ELVs. The scrap recycling system is already adjusting to these new opportunities.

The challenge of enabling the recycling of post-consumer Mg alloys involves the need for collection and recycling system plus a financial profit incentive.

Until recently (~2003) there was not sufficient Mg-alloy content in the metal concentrate shredder product to warrant the separation of the Mg as separate scrap product, nor was there market demand for such a product. Any Mg present ended up as a contamination in shredded Al and was sold to secondary Al smelters where it was chlorinated out of the Al foundry alloys to be lost in Al dross residue.



Al secondary smelters now know that it is in their interest to demand that their suppliers (the ~800 shredders and ~50 media plants and metal sorters) remove free Mg from shredded scrap aluminium. (There may not be a need to remove the residual free Al from the Mg byproduct created by such a separation). Enlightened secondary Al smelter operators, in turn, share with the suppliers the benefit of reduced chlorination and improved plant throughput by paying a price premium for the low-Mg Al shred. That price premium must be sufficient to pay for the investment at the shredder for the Al-Mg sorting circuit or to induce the shredder to leave the Al in the metal concentrate sold to a dense media sink-float plant. At the sink-float plant, Mg is separated from Al and recovered in the magnetite-float fraction that contains Mg and hollow Al. This fraction is exported to Asia for handsorting.

In the case of Mg, if the metal stays at a price par with Al for the same functional component, its rate of substitution will be paced simply by the availability of the metal from prime or old scrap and the capacity of part manufacturers to produce the required shapes with the required properties at the right price.

Types of Mg-Alloy Scrap Available and its Sources

New Scrap

Diecasting dominates the fabrication of Mg-alloy components. Typically, the cast component weighs only 50% of the diecasting machine shot weight; the rest is trimmed off and recycled as scrap. In US there were 70 kt or globally ~300 kt of new diecasting scrap recycled in 2006 (1,2,3). Diecasters generally maintain alloy segregation at source. This allows closed-loop recycling back into the same alloy or into a compositionally more tolerant alloy.

Remelting residues: Mg can be remelted up to four times before ending up in a product component: once as primary "crown" Mg, then during alloy remelt ingot casting, then prior to diecasting and lastly as new scrap. Each of these steps generates remelt scrap and losses in the form of dross and sludge. A 3-4% melt loss in each step would be representative of a good melting and casting practice. Our estimate for 2006 in the US gives 7 kt metal, mixed with 15 kt of oxides and intermetallics contaminated with flux. This quantity is included in the global 40 kt of metal with 80 kt of

oxides and intermetallics, a mixture that is sold to Mg granulation plants. There is a potential for upgrading this residue by separating the metal from its oxide by crushing, screening, eddy current separation or conceivably sensor-based sorting.

Post-Consumer Scrap

Primary Shredder Metal Concentrate: Scrap is traded on a World market where in 2006 there were ~40 million ELVs with ~2 kg of Mg diecasting each (mainly AZ91 or AM60), or 80 kt coming back from ELVs in the Al and nonmagnetic metal concentrate (NMMC) shred streams flowing from ~800 separate shredders. In 2030 we will be scrapping the 2015 model year, which is predicted to have 0.6% Mg alloy in a 1.7 t car. There could be 70 million ELVs with 11 kg of Mg per ELV, or 770 kt of old Mg alloy scrap, exiting the system by 2030. This assumes that these Mg components can be produced by 2015.

In total, shredder nonmagnetic metal concentrate currently contains ~100 kt of Mg-alloy particles in ~7 Mt of nonmagnetic metal shred recovered from a mixture of ~40 million ELVs, appliances, bulky consumer durables, mixed metal from demolition residue, and mixed-metal scrap yard categories shredded in 2006.

Consumer Electronics – Mg-alloy housings are penetrating the markets of 300 million cell phones and personal digital assistants (PDAs), 50 million digital cameras and video recorders, and 250 million MP3, CD and DVD players, and 200 million PCs and laptops, plus miscellaneous digital sound recorders, portable radios and TVs (4,5). EEE is already providing a major market for Mg diecastings and in the not-to-distant future, EEE will provide a major source of post-consumer Mg diecasting scrap.

These consumer electronics have a relatively short time to obsolescence (2-5 years) and are mostly non-repairable. A separate system is being set up to collect and recycle WEEE materials. This system will attempt to capture the Mg housings from WEEE. At this point, the penetration of the housing market by Mg diecastings is still limited to high-end products and the collection systems are just beginning to be set up. The majority of the collected scrap is exported to China and Africa in contravention of the Basel convention.

Forty million notebook computer housings with 750g of Mg each can bring back ~30 mt of Mg scrap by 2010. A similar annual amount will be



available soon from cell phone, PDA, and audio player housings. Mg alloys from these products, mostly Mg-AZ91D diecastings, are already in the current post-consumer scrap streams – MSW and WEEE. As Mg-alloy housings continue to penetrate this huge market, this source of old Mg alloy scrap will grow quickly.

Portable Power Tools that can benefit from Mg-AZ alloy housings are drills, saws, screw drivers, weed trimmers and lawn mowers. Plug-in electric and gas-powered tools have long lives (~15-25 years). The lives of battery-powered tools are shorter (~5 years), limited by the evolution and availability of replacement battery packs. The use of Mg housings is just beginning and significant quantities of end-of-life Mg-alloy power tools will not make it to WEEE until 2025-2030.

End-of-life electronic and electrical consumer products are supposed to be collected and processed separately as WEEE. There is battery removal and some dismantling for component and subassembly reuse, but that rarely includes housings. These are shredded for material liberation and segregation. WEEE material needs to be shredded to a finer size than vehicles and appliances to liberate individual materials.

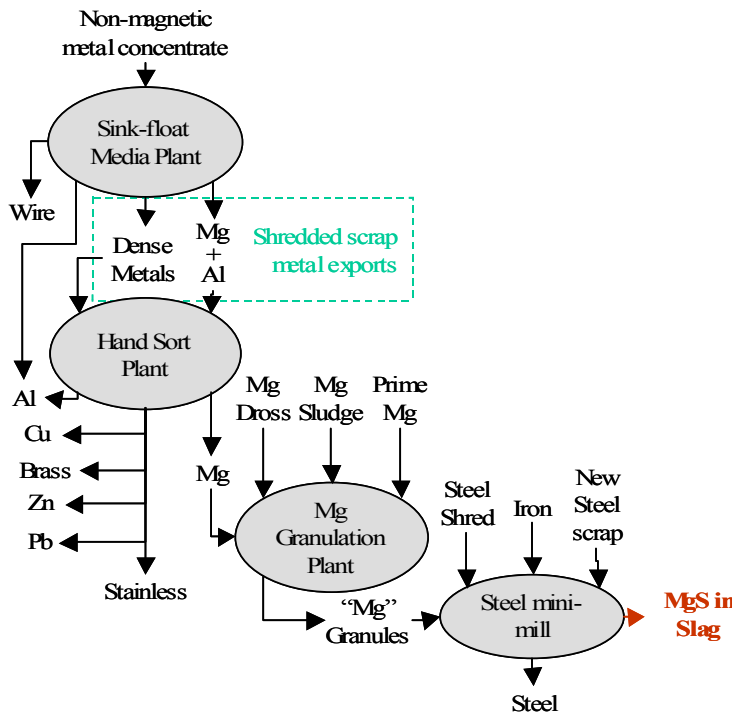
Current Markets for Post-Consumer, Mixed-Alloy, or Contaminated Mg-Alloy Scrap

There are three potential markets for old Mg scrap, either alone or in a mix with Al. These are: additives for steel and nodular iron production, Al can sheet alloys, and Mg diecasting alloys in property non-critical applications (such as housing for portable electronics, or automotive interior components such as instrument panels). These markets are all growing quickly in the developing part of the World. Whoever wants to get this scrap to feed their market will have to pay the full metal value of the scrap, which is set, as is the case with Al scrap, by comparison with the prime price on the LME or Shanghai exchange. As long as expansion in the combination of these three markets outpaces the growth of supply of old, post-consumer Mg-alloy scrap, there will be no Mg metal recycling system need to include old scrap content in property-critical applications in automotive, marine, aerospace and defence applications.

Granulates for steel desulphurisation, thermites and pyrotechnics: In 2006 these applications consumed ~8 kt of Mg in the US, or ~75 kt globally.

Mixed-alloy machining chips, turnings and borings – always contaminated with cutting lubricants – are difficult to melt with high metal recovery. Remelting residues, including melting drosses and refining sludges, are heavily contaminated with oxides, fluxes and intermetallics. In many cases, the Mg remelt facilities are not yet equipped to deal with old, dirty, Mg-alloy scrap. Steel desulphurisation granulates, however, only require a specified Mg content which, depending on the grade, can vary between 75-90% (Fig. 1). This metal content can be supplied by the Mg scrap with no melt losses. These granulates at this time most likely consume the bulk of the post-consumer Mg-alloy scrap as well as remelting residue and mixed alloy machining chips.

Figure 1. Steel desulphurisation





Potential Markets for Post-Consumer Scrap

Al alloying – 3X04 can body sheet needs replacement for Mg in ~800 kt of cans lost to litter and landfill in the US. In 2006 this required ~10 kt of new Mg in US. Globally this amount expands to ~15 kt of Mg, which could grow to ~40 kt of Mg in the future if the rest of the World adopts Al cans to the extent that the US has – ~1 can per person per day. Other Al-Mg alloys could use Mg-alloy scrap for alloying element addition, if it were converted into a specification Mg hardener alloy ingot with tightly controlled composition. Total amount of prime Mg used for Al alloying globally was ~180 kt in 2006.

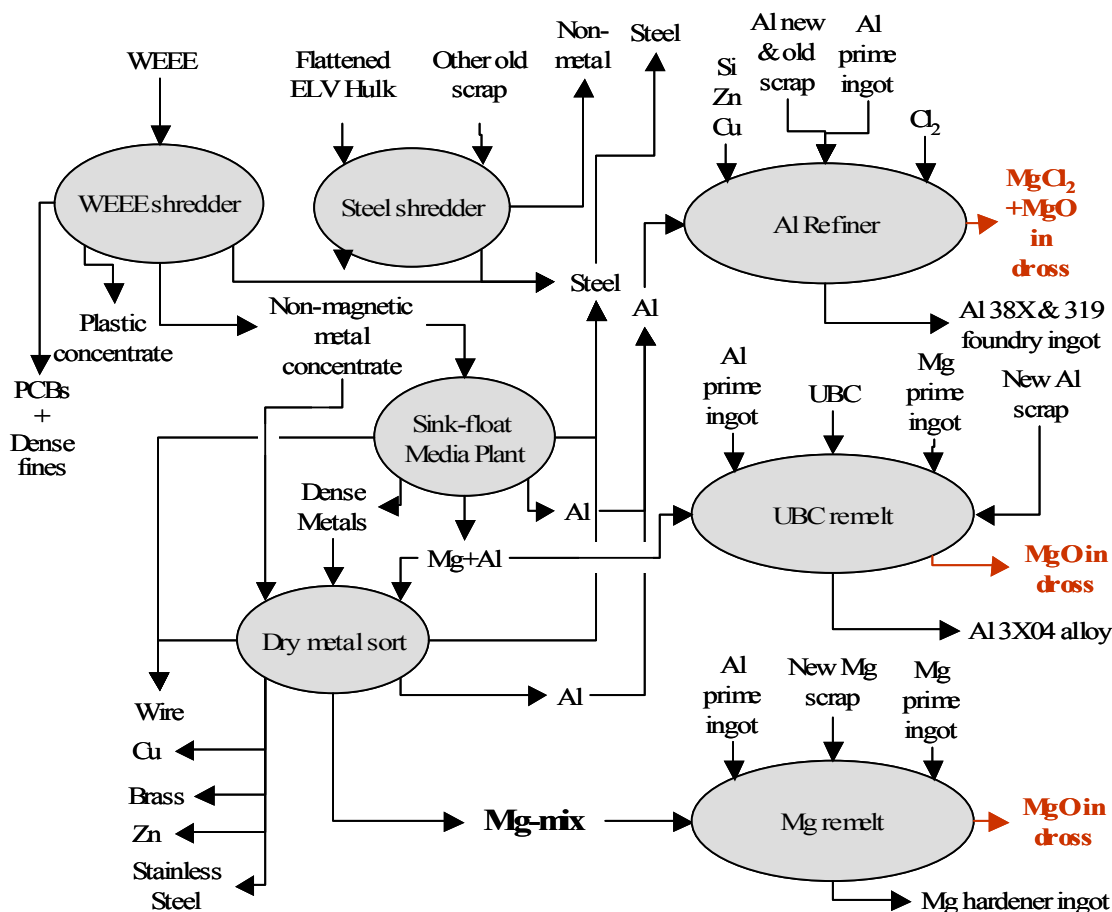
At this point, Mg-alloy scrap is not used in Al alloying, in spite of the fact that UBC remelt plants could easily add Mg-alloy machining scrap or post-consumer shredded Mg-Al mix to the UBC plant feed and allow it to be cleaned and vortex sub-

mergence melted with the UBC shred. In a vortex strong enough to draw Mg particles under the surface of molten Al, one would likely see a high recovery of the Mg in the melt. (Fig. 2)

The procedure in the Al industry is to use prime Mg ingot or a hardener ingot batched from prime Mg to add Mg to the melt after melting and determining the melt batch composition. In order to fit into this procedure while using Mg-alloy scrap, one would need to batch and melt Mg scrap, adjust the composition and cast Mg hardener ingot with tightly controlled composition limits. This would make economic sense only if the secondary smelter could consistently buy Mg-Al magnetite float product at a discount and sell the Mg content of the hardener ingot at the prime Mg price.

Once the Mg-Al mix is exported for handsorting, the sorted products do not return to NA or EU. Rather, the handsorted Mg scrap is used in Asia for steel desulphurisation or for batching common Mg diecasting alloys.

Figure 2. Mg and Al Scrap for Al Alloying





Mg alloy diecasting – Shipments in 2006 of Mg-AZ91 alloys for portable electronic and power tool housings and non-structural automotive components (e.g. instrument panel, interior brackets) were ~50 kt in US, or ~200 kt globally. With the price of prime Mg being at par with prime Al, and with rising oil prices making plastics more expensive, the growth of this market is limited only by the availability of competitively priced Mg.

Mg-AZ91 (Al9% Zn1% Mn0.2% bal Mg) has the three most common alloying elements in the generally used -AM and -AZ alloys that supply most of the diecasting alloy market. A melt of a mixture of the post-consumer diecasting scrap coming from automobiles and consumer durables is likely to end up requiring the addition of Al and Zn to satisfy the AZ91 composition requirement, while the Mn and Fe levels can be controlled by fractional precipitation of the FeMnAl intermetallics.

Auto components diecast out of old-scrap-sourced Mg AZ91-type alloys for property non-critical shapes (such as instrument panels, inner door components, sunroof and tailgate hardware) could contribute significantly to the use of Mg in automobiles. As we reach 2015, there will be about 100 kt coming back in ELVs and another ~100 kt from other sources of Mg diecastings. Even if the recycled metal is not used in automotive applications, each tonne of old Mg beneficially used frees up a tonne of prime Mg that could be directed to an automotive application.

Future Need for Additional Markets

Mg alloys with exotic alloying elements – Mg-AJ62 (Mg Al6% Sr2%) or Mg-AE41 (Mg Al4% RE1%), (RE = Ce, Nb, La) – have been developed for higher temperature structural applications requiring creep, fatigue and corrosion resistance. But these are composition incompatible with either Mg-AZ or -AM series of alloys. Mg-AJ62 is coming in at 20 kg/car in an R6 in-line 6-cylinder engine crankcase (300,000 units in 2006). BMW predicts that up to half of its fleet, or ~600,000 cars, could be equipped with these engines (6,7). That is 12 kt/y that will be coming back in BMW ELVs in about 2025, a number that is likely to grow as other companies follow suit. It is likely, at least initially, that there will be a variety of mutually incompatible high-performance alloy compositions as various manufacturers battle for market share.

Where and How Old Mg Scrap Recycling is Actually Taking Place

Mg Diecastings from Automotive and Durables

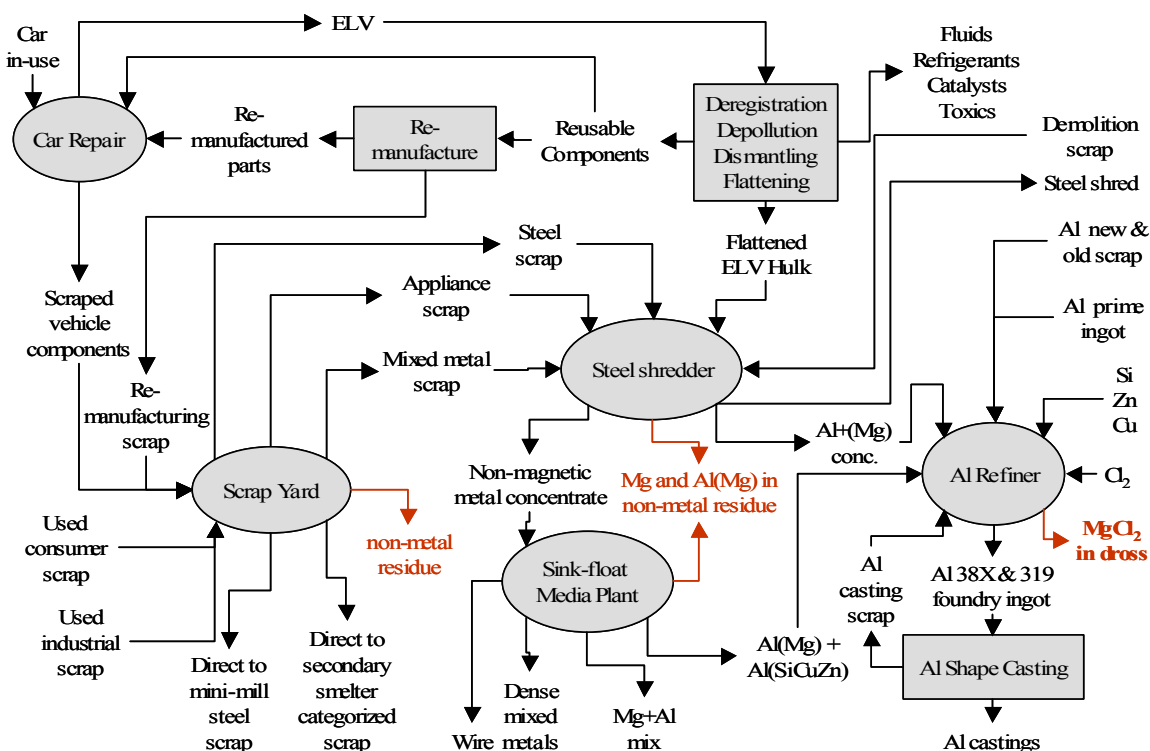
End-of-life automobiles and major appliances are co-shredded with other heavy steel and mixed-metal scrap at the ~800 primary shredding plants around the world (Fig. 3). Steel is removed magnetically, nonmetals by screening, air elutriation and eddy current separation, and the Mg ends up in one of the non-ferrous shredder products. NMMC is sold to dense media sink-float plants; the Al shredder product is sold directly to Al secondary smelters. Mg alloys entering the Al secondary smelter end up in an Al foundry alloy melt, which has a low Mg alloying element specification limit. Mg is then refined out of the melt by chlorination, ending up as Mg chloride salt in the Al dross. Mg content is lost, so is some Al at the cost of productivity. There are also concerns with safety and handling of poisonous chlorine gas. It would be much better and cost effective to separate Mg from Al and recycle it into another product. This happens with the Al in the NMMC, and this is where sensor-based sorters could help at the secondary Al smelter.

Magnetite Slurry Float, Mg + Al Product

NMMC that reaches sink-float plants should contain up to 50-60 kt of Mg alloy, ~90% of it is in the >10 mm size fraction that is floated in the magnetite slurry at a specific gravity of ~2.2 g/cm³. Mg alloys at density of ~1.8 g/cm³ float, but so do hollow aluminium shapes like cans, tubes and crumpled sheet. Mg recovery is highly efficient, but since it is only at ~2% of the Al in the plant feed, the product composition ends up to be a mix of ~75% Al cans and extrusions and 25% Mg diecastings. There should be ~45-50 kt of Mg in this product. Its exports from NA and EU to Asia for handsorting is a loss of raw material to the EU and NA Mg remelters or granulating plants, but is not a loss globally. The Mg recovered by handsorting in Asia finds its way onto the old scrap market and is fully utilized. The most likely current uses for this material in China are granulates for steel desulphurisation and common Mg-AZxy diecasting alloys (8).



Figure 3. Light Metals in the Car Recycling System



Consumer Electronics and Power Tools

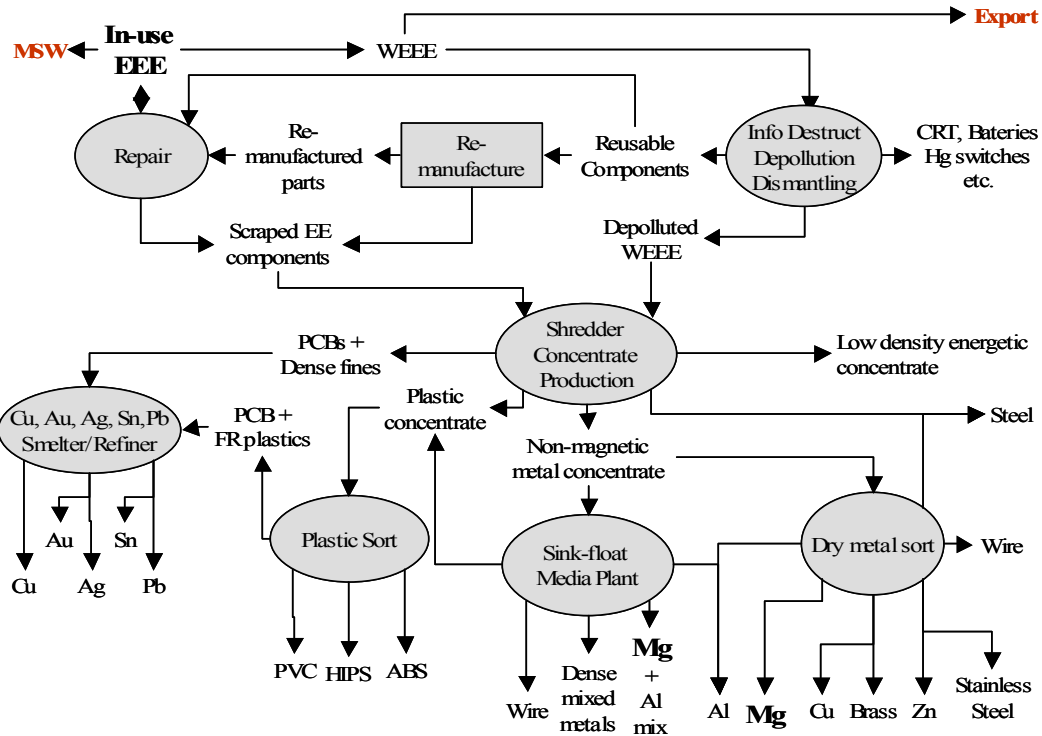
End-of-life electronic and electrical products are either landfilled or are recycled through a separate WEEE system that has been set up to deal with many substances of environmental concern in these functional materials (Fig. 4). There is dismantling of batteries for material recycling and internal subassemblies for re-use, but Mg is mainly found in housings that are shredded for material liberation and segregation. In this case, the material needs to be shredded to a finer size (~1 cm) before adequate material liberation is achieved. The shredded scrap is treated in a similar sequence of bulk mechanical separations as the auto shred, albeit with equipment scaled down in proportion to the particle size. Mg is found with aluminium in the NMMC. The coarser portion of NMMC can be treated by sink-float and jig separation to produce Mg-alloy rich magnetite slurry float product.

Defence and Aerospace Scrap

Mg-alloy missile housings do not tend to survive to be recycled. However, aircraft, helicopter and vehicle and portable weapon components mostly do. These are most often specified with extremely high performance specifications with little regard to economic considerations. This spurred development of Mg alloys with exotic alloying elements, such as Ca, Sr, Li, Y, Zr, Ce, Nb and La. These alloys usually do not tolerate Zn in their make up, and common Mg-AZ alloy specifications treat these exotic elements as unwanted impurities. Hence we have an incompatibility in the Mg- alloy recycling system. As long as defence scrap is left on the battle field or is auctioned off in separate army scrap auctions, it does not affect the bulk of the global Mg-alloy recycling system. However, the civilian transportation market is starting to adopt some of these alloys for demanding power-train applications. In time, these alloys will contaminate the main NMMC scrap stream and will open up opportunities for alloy sorting of the Mg alloys from this source.



Figure 4. Light Metals and Other Materials in WEEE Recycling



Mg Scrap Losses in the Recycling System

Shredder residue – Chunky pieces of shredded Mg diecastings are easily separated from nonmetallic residues. Hence, the Mg scrap losses in shredder plant residues are negligible.

Metal grain is 5-10 mm product of the sink-float plant and/or jig separation. Mg alloys end up in the light metal fraction currently at ~2% particle concentration. The grain output comprises ~5%-10% of the sink-float plant output, and will take with it similar proportion of Mg alloys (~5-6 kt). The light metal grain is either sold to the Al secondary as Al product or exported to Asia for manual handsort clean up.

Mg in shredder Al product: Primary shredders process de-polluted, flattened ELVs, consumer durables, mixed metals from building demolition, and some even shred municipal solid waste to prepare residue derived fuel and recover the metal scrap. The ELVs at this point globally contribute ~5 Mt of Al and 100 kt of Mg. Some of the light metal that is easily dismantled – Al wheels, for example – does not make it to the shredder but

this deficit is more than made-up by the Al from the other scrap sources. Most of Mg scrap is from the ELVs. Some of the shredding plants installed a second splitter on the eddy current separator allowing the low density electrically conductive metals to be concentrated in a separate fraction. Without much more sophisticated procedure it is not possible to recover high proportion of the Al at the high metal grade that can be sold directly to the Secondary Al smelters, or exported to Asia. Typically less than 50% of the Al is recovered in the Al product with >95% metal content. This does not imply that half of the Al is diverted at the shredder from the NMMC bound for the sink-float plants.

Not all the shredding plants are equipped with eddy current separator circuits, and fewer still have second splitters installed. Mg, having a lower density and similar electrical conductivity to Al, follows the Al and splits between the Al product and the NMMC. The Mg-alloy particles that end up in the Al product go to an Al secondary smelter. Currently there can be up to 2% Mg alloy particles in the Al shredder product, and that fraction is set to increase in parallel with the Mg-alloy content of the ELV. Unless there is an additional upgrading step at the Al smelter, Mg particles end up in the



foundry alloy melt from which Mg is refined-out by chlorination to bring the Mg concentration in the Al foundry alloy down to 0.1%-0.3%. Unless something is done, and as more shredders equip themselves with eddy current rotors and second splitters, up to half of the Mg alloy particles from the >10 mm particle fraction could be lost in this way. We estimate that ~20 kt of Mg alloy scrap were lost chlorinated out of the Al foundry alloys in 2006 (1).

The current situation of not recycling the old Mg-alloy scrap contained in Al concentrate purchased by the Al secondary smelters from the shredders is wasteful for both magnesium- and aluminium-alloy producers. This will also fuel arguments against magnesium substitution for aluminium in the automotive market. The solution is technically simple. Magnesium can be easily separated from other scrap, and the markets that could consume this separated Mg-alloy mix are already developed and operational.

Technologies Used for Separation of Old Mg from Other Scrap

Dismantling

Dismantling is justified partly by de-pollution regulations, and partly by the high value of sub-assemblies in the re-use re-manufacture market. Dalmijn and DeJong (11) quote a cost of \$1,300 for each ELV that is dismantled according to Dutch requirements. Clearly this is not justified by the value of 800 kg of steel scrap (~\$150), 150 kg of Al scrap (~\$150) and 2 kg of Mg scrap (~\$2) or the value of the prime metal replacement (\$300+\$450+\$6=~\$750). Even the Dutch are joining the rest of the world in embracing post-shred separation for material value recovery. The parallel WEEE management system in NA or EU also dismantles for de-pollution by removing CRTs, batteries and mercury or PCB-containing components, and sometimes recovers electronic chips and subassemblies for reuse. New WEEE material recovery and recycling plants are based on shredding and mechanized material separation paralleling the unit operations used for material recycling of the ELVs.

Bulk Liberation & Separation at the Shredding Plant

After de-pollution, bulky end-of-life products including ELVs are shredded followed by screening,

elutriation, magnetic and eddy current rotor separation (12,13). In separate plants, de-polluted WEEE is shredded to a finer size, and is separated by smaller-scale machines in a similar sequence of unit operations. Mg alloys are recovered in the nonmagnetic metal products – Al and NMMC. The latter is further processed, usually by wet density separation.

Sensor-Based Sorting

Dry metal scrap sorting circuits are under development. They combine bulk material separation methods and sensor-based particle sorters to separate metal scrap from nonmetals, and then sort the metal scrap into parent metal categories. At this point these circuits do not include the provision for sorting or batching Mg alloys, but in theory a laser-induced breakdown spectroscopy (LIBS) elemental analysis sensor that could achieve this task exists.

Wet Density Sort

Wet density sort is the gold standard in the current material recycling system. It is used (separately) for both metal scrap and plastic scrap separation. For metal scrap, sink-float separation is done at three specific gravity levels: in water at ~1, in magnetite slurry at ~2+ and in ferrosilicon slurry at ~3.5. Magnesium sinks in water but floats in the magnetite slurry, but so do closed or boat shaped Al particles. This product ends up as a mixture of ~25% Mg alloy and 75% sheet and extrusion Al, adding up currently to ~5% of the total light-metal scrap output of the sink-float plant.

Handsort

China and India import large quantities of scrap for handsorting. Both the ferrosilicon sink dense metal mix and the magnetite float light-metal mix outputs of the sink-float plant are handsorted there. The light metal mix is a combination of Mg diecast particles and Al sheet and extruded shapes in 1:3 weight ratio. This is an ideal feed for visual identification by shape and hand separation. It is not practical to handsort small quantities of Mg cast shreds that are difficult to identify in a very large quantity of Al cast shreds in Al concentrate from shredding plants. Visual identification and handsorting of Mg scrap by alloy is not possible. Handsorting is a low productivity process economically enabled by a combination of geopolitical and geo-economic factors. As the stan-



dard of living in Asia improves, the wage demands of the handsorters will drive the Asians to adopt the mechanized sorting methods they drove out of business in Europe and North America.

Need for Mechanized Sorting

Sink-float plants that automatically separate Mg-based alloys from the nonmagnetic shredded metal concentrate were industrially implemented in 1970s. Mg-based alloy particles report nearly exclusively to the magnetite slurry float product. This Al-Mg magnetite float product could be used in AA3X04 Al can sheet without further sorting.

In most cases, separation of metal scrap by parent metal categories is the minimum required for material recycling. Sensor-based particle sorting technology introduced in 1990s first allowed automated separation of pure Mg alloy from Mg/Al magnetite slurry float concentrate (10). Recent improvements in sensors and computing speed now allow dry separation of all common parent metals. Particle-sorting technology based on elemental chemical analysis allows for batching of specific secondary alloys from mixed-alloy post-consumer scrap.

Separation of Mg-alloy particles from shredded Al scrap products purchased directly from the shredder is an issue for the Al foundry alloy producers. Handsorting of this material is not economic by, especially in EU and NA. Colour and DE x-ray sensor-based sorters are well suited for this task. The alternative is to buy a premium (low free Mg) Al scrap product from the sink-float plants.

Currently the global market of ~75,000 T of Mg content of steel desulphurisation granulate could consume most of the post-consumer Mg scrap and Mg-containing byproducts and residues. At present, post-consumer scrap collection is not set up to be efficient, and the majority of the desulphurisation granulate is produced from prime Mg.

Other markets that could consume mixed-alloy Mg scrap include Mg-AZ diecasting alloys. The added value of the Mg-AZ91 or similar common diecasting alloy may justify batching of that alloy composition from post-consumer scrap. Initially, with post-consumer scrap dominated by Mg-AZ and -AM diecasting alloys, this should be possible by melting the Mg-alloy mix, adding Al and Zn, and refining the Mn and Fe to the required concentration levels.

As long as steel desulphurisation, aluminium alloying and common Mg diecasting markets still need

input of prime Mg to satisfy the demand for Mg metal, there is no recycling system need to find other uses for the old Mg alloy scrap or to further upgrade it by sorting.

Sorting will be required when Mg alloys with exotic alloying elements become a significant fraction of post-consumer scrap. At that time, the x-ray fluorescence (XRF) and LIBS sensor particle sorters will be able to both batch the targeted secondary diecasting alloy and group the residue by the exotic alloying element.

For the scrap streams that have a substantial content of Mg alloys with exotic alloying elements, sorting these out and then sorting among them will be justified by both incompatibility with the common AZ alloys or by the economics of recovery and recycling of the exotic alloying element content. These high-performance alloys are already beginning to penetrate auto powertrain applications. The 300,000 BMW R6 engines produced in 2006 alone will bring ~7 kt of old Mg-AJ62 alloy scrap containing ~150 t of strontium. This strontium, diluted by 300 kt old Mg scrap expected from ELVs in ~2020, gives ~0.05% average Sr content. This exceeds the 0.01% impurity limits for "other-each" element specification of AZ91D and AM60B alloys by a factor of 5. The situation will quickly get worse after that as other engine lines adopt high-performance Mg-alloy engine blocks. This means that the need for alloy sorting in the post-consumer scrap recycling system will become acute in about a decade.

Sorting of Mg alloys with exotic elements is not justified by the reduction of the demand for prime Mg, but rather by the recovery of the exotic elements. These are strategic since they are produced at few locations and are reasonably expensive, with prices in \$10-100/kg range compared to \$3-4/kg for Mg. The incentive to sort will be economic, rather than any impact on energy consumption or greenhouse gas emissions. One can expect a well-justified reluctance from engine manufacturers to include the old scrap containing exotic alloying elements in performance-critical engine applications. More likely this material will become a source for a new family of secondary alloys that will provide performance improvement over Mg-AZ91 in non-critical applications.



Recommendations for Actions to Promote and Improve Recycling of Post-Consumer Mg Scrap

The lifecycle and financial benefits of recovery of post-consumer Mg and its use in secondary Mg diecastings, or in controlled alloying of aluminium, or desulphurisation of steel need to be quantified.

The current status of post-consumer Mg-alloy recycling and the waste and negative environmental impact associated with the destruction of Mg content by chlorination should be publicized among magnesium- and aluminium-alloy producers and their suppliers (scrap shredders, sink-float plant operators and metal sorters).

The current free-Mg content of the Al concentrate product of the shredders needs to be quantified and tracked by the secondary aluminium smelters and compared to the low-Mg Al product of the sink-float plants. The price difference between these products must reflect the difference in chlorination needs, melter productivity and metal yield. This price difference economically justifies the separation of Mg from Al scrap and enables its beneficial recycling.

An optimum short-term tactic to promote and improve recycling of post-consumer Mg scrap could be to direct as much mixed-alloy Mg scrap as can be accommodated to a secondary Mg diecasting alloy without sorting and to granulate the rest for steel desulphurisation.

The Mg+Al mix and Mg-alloy mix products need to be cleaned and re-melted, refined and cast into recovered secondary ingots (RSI) to demonstrate the metal yield and its dependence on scrap cleanliness and the average composition of the product melts.

The use of these RSIs as a Mg alloying addition to Al can sheet needs to be demonstrated at aluminium can recycling remelt facilities and compared to the practice of adding Mg+Al mix shred to the UBC feed stream of the secondary can sheet remelt plant.

Granulation of post-consumer Mg and Mg+Al shredded scrap products, and use of these granulates as additives to various consumptive applications, needs to be demonstrated. These applications include steel desulphurisation, production of nodular iron, metallothermic thermite mixtures, flares and other pyrotechnics.

To improve on the current system, separation of Mg-alloy scrap from the Al concentrate shredder product by automated sensor-based particle sorting needs to be demonstrated on an industrial scale. Use of such sensor-based particle sorting should also be demonstrated for separation of Al from Mg in the magnetite slurry float fraction.

Use of post-consumer Mg and Mg+Al shredded scrap products in batching a widely used alloy with high content of common alloying elements needs to be demonstrated. The Mg AZxy alloy family used in common diecastings is a good choice for such a demonstration. The practical amount of control of the concentration for less-common alloying elements such as Ca, Sr, Li, Y, Zr, Nd and Ce needs to be determined.

The need for separation and batching of alloys with these less-common alloying elements needs to be demonstrated and quantified. This need will result from either performance degradation of the alloys that use the old mixed-alloy Mg scrap, or by the loss and non-recycling of the expensive uncommon metals.

Alloy sorting of the Mg-alloy mix designed to separate and batch Mg-RE alloy compositions needs to be demonstrated by either LIBS- or XRF- sensor-based particle sorters.

The applications that could tolerate significant post-consumer recycled content of alloy-sorted Mg-RE scrap will need to be developed in the future, when the recycling of the RE alloying elements will become either required or profitable.

Conclusions

One needs to consider the World scrap market to find where the old Mg scrap is recycled. The Mg in the portion of the old scrap that is treated in the sink-float plants is recovered. At this time metal mix recovered as 2 g/cm³ float fraction captures nearly all free Mg-alloy particles from the shredded metal concentrate treated at the sink-float plant. This float product is exclusively exported to Asia for separation by handsorting. It consists of ~75% Al cans and extrusions and ~25% Mg diecastings. The handsorted Mg is most likely granulated for use in the fast-growing Asian steel industry for desulphurisation.

The current major markets for prime Mg that can use post-consumer scrap include granulate for steel desulphurisation, Al can sheet, or a master alloy for Mg alloying element addition to other Al-based alloys and common Mg diecasting alloys.



Use of the scrap containing old Mg alloys in these applications does free up a supply of prime Mg for production of new Mg alloys.

When the supply of post-consumer Mg-alloy scrap exceeds the demand for steel desulphurisation and of Al(Mg) alloys, there will be a system need to recycle Mg into Mg alloys. Following what is the case in the established Al recycling system, it is most likely that the majority of post-consumer Mg scrap will find a home in a small number of die-casting alloys. Mg-AZ91 is the most likely candidate. Chemical-analysis-based particle sorting will be useful at that time to maximize the recovery of the Mg scrap that can be batched into these target die-casting alloys.

From a global lifecycle point of view, recycling of scrap reduces the demand for the production of prime metal, which has a high cost of resources, energy and emissions. There is a large advantage to the separation of Mg-alloy particles from the Al scrap bound for refining into foundry alloys and directing this Mg scrap into steel desulphurisation, Al alloying and common die-casting applications. There is very little additional lifecycle advantage to further tightening the recycling loop and directing post-consumer Mg scrap back into production of other Mg alloys or sorting these alloys to close alloy or product loops.

The rate of penetration of Mg alloys into the transportation market is likely to be limited by the World capacity to produce prime Mg metal. Even though, as was pointed out above, there is no system need or lifecycle advantage to direct post-consumer Mg-alloy scrap to the production of Mg-alloy components for the transportation market, the importance of post-consumer scrap as a Mg metal source will be increasing with time. Also, the inclusion of old Mg scrap in batching alloys for the common Mg die-castings used in automobiles has the potential to significantly increase the rate of penetration of the Mg-alloy components into the vehicle market.

As there is a concurrent growth in the other Mg-scrap-consuming markets (steel production, and aluminium alloying), Mg scrap will continue for the foreseeable future to remain in short supply and will remain to be priced by reference to prime Mg metal replacement. Consequently, one should not expect material price reductions related to the inclusion of old scrap in the batching of Mg alloys.

Unless western Mg-alloy producers are willing to invest in automated scrap metal sorting plants, recycling of old Mg-alloy scrap will take place in China (8) and India, as they have the existing

scrap hand-sorting plants and quickly growing steel production and Mg die-casting industries to provide ready markets for the hand-sorted products.

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