PARTICLE SORTING OF LIGHT-METAL ALLOYS AND EXPANDED USE OF MANUFACTURING SCRAP IN AUTOMOTIVE, MARINE AND AEROSPACE MARKETS

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Abstract

Composition- and property-critical alloys for aerospace, defence, marine and automotive markets tend to have very tight composition limit ranges and tend to use exotic alloying elements. Two examples are Al-Li alloys and Mg-RE alloys. These are composition incompatible with a majority of the common alloys circulating in the present materials recycling loop.

Aluminum producers and fabricators of semi products already attempt to maximize the re-use of prompt scrap in their own plants in the original alloys. However, there is a reluctance to accept nominally alloy-segregated manufacturing scrap for use for these composition- and property-critical applications for fear of contamination of an entire melt batch.

The result is that the expensive alloying elements are either lost by dilution in non-critical foundry alloys, or are refined out and lost by chlorination or selective precipitation.

In the titanium and super-alloy markets, it is a common practice to manually analyse each piece of purchased scrap using a hand-held spectrometer prior to its use in a re-melt batch. This is not an option for more modestly priced Al and Mg alloys.

We show how an automated particle sorter equipped with an elemental composition analysis sensor could be used to address this problem efficiently and economically, enabling closed-loop recycling of Al and Mg alloy-segregated scrap within the key alloy and product families.

Introduction

New scrap is generated at nearly every step of metal alloy production, casting, semi-product fabrication and component manufacture. In spite of conscientious efforts to reduce scrap generation, the quantities produced of new scrap are often large. The total of new Al alloy scrap generation is actually three times the amount of old post-consumer scrap recovered and recycled globally. Recovery and recycling of post-consumer scrap reduces demand for the prime metal. New scrap is already recycled, and hence new scrap generation does not significantly increase overall demand for prime metal.

The generation of new scrap, however, has immediate financial impact on product component costs. Manufacturers purchase metal for their products – and the resulting scrap – at a high price that includes the cost of all metal fabrication steps, from production of the prime metal to any upstream processing. Manufacturers then sell the new scrap at a discount to prime metal. The size of the discount depends on how clean the scrap is and if it is segregated by alloy or sold as a mixture. In this way scrap generators pay more, while scrap recyclers get the benefit of the discount when they batch secondary alloys from scrap.

Currently some of the scrap generated internally during metal production, ingot casting and semi fabrication is kept segregated and is reused in production of the same alloy. Virtually all new manufacturing scrap is used in a small number of secondary alloys, for example 38X foundry alloys or 3105 painted building sheet alloy.

Automotive powertrain components provide the largest market for 38X foundry alloys, and hence the remelters and refiners supplying engine and transmission manufacturers should be the largest financial beneficiaries of recycling of both new manufacturing and old post-consumer scrap. In many cases scrap brokers act as intermediaries and buy new scrap from manufacturers, combine lots and deliver categorized scrap to secondary smelters. Since both new and old scrap is in short supply, brokers set the price charged to the smelters by reference to the market price of prime metal and pocket the discount at which they bought the scrap. Brokers also have the option to export scrap to countries such as China, India, Turkey or Mexico, which in the past decade paid substantially higher prices for metal scrap than what was paid on North American or European markets.

Secondary smelter operators are well aware of this market reality. They choose not to integrate upstream and invest in technology that would allow them to buy lower-cost mixed scrap and upgrade it to their internal alloy specifications. The combination of rapidly developing automated scrap particle sorting technologies and the quickly rising wages in China will soon tip the economics in favour of automated scrap sorting at shredders or secondary smelters.

Property-Critical Light-Metal Markets

Automotive

In the high-volume automotive market, the following factors are important: light-weighting for reduction of fuel consumption; low and predictable component costs; and strength, ductility, toughness, corrosion resistance and formability. Both aluminum and magnesium light metals are penetrating this market. Al is used in higher volumes and is better entrenched, but Mg components weigh less and, at a similar material cost, are set to explode onto the automotive market, where they will replace not only Al but also plastics and steel. Recent increases in the price Mg relative to that of Al are slowing down Mg-alloy penetration. Prior to these price increases, the rate of penetration of Mg into automotive applications was limited by the availability of the metal on the World markets.

Light-metal automotive components are dominated by aluminum castings, sheet and extrusion semi products manufactured with minimum machining by stamping or hydroforming. Most magnesium components are diecast or thixocast.

Table 1. Use of Al- and Mg-based alloys in automotive components

Parent	**Alloy**	**Application**
Al	38X.0, 319, 356	power train castings
	A356.2	cast wheels
	6016, 6111	closure sheet
	5182, 5754	stiffener sheet
	6061, 6082, 7004, 7008, 7129	extrusions
	1100/4147, 3003/4147	brazed heat exchangers
Mg	AMxy (Mg-Al-Mn)	x<4 sheet and extrusions
	AZxy, AZ91 (Mg-Al-Zn-Mn)	x>4 castings
	AJ62 (Mg-Al-Sr-Ca)	Creep resistant castings
	AE41, AE44 (Mg-Al-RE)	

Marine

Aluminum is used both in small pleasure craft and very large vessels manufactured by shaping and welding of sheet plate and extrusions. Manufacturing scrap is mainly in the form of large clips and cut offs.

Table 2. Al alloys dominant in marine market

Alloy Family	**Alloys**	**Applications**
5XXX	5052, 5X56, 5X83, 5X86	sheet and plate: hulls, superstructures
6XXX	6061, 6063	extrusions: spars, structural stiffeners

Aluminum alloys in marine applications are listed in Table 2. Marine applications require the low density, strength, weldability and corrosion resistance of these alloys. Galvanic corrosion resistance is of prime importance. Limited availability of wrought Mg and its susceptibility to galvanic corrosion has kept Mg out of marine applications.

Aerospace

For aerospace applications – which demand large, precision-, property- and failure-critical parts – lightweighting is essential. As the volumes of material used are much smaller than those for the automotive market, it is often more economic to hog out a thin-wall part out of plate rather than to produce a forging or fabricate it out of sheet components. In this case the weight of scrap is often much larger than the finished product weight. Much of the new scrap is in machining chips. Aircraft manufacturers rarely segregate scrap by alloy in their machining and forming plants, and usually sell it mixed at scrap auctions.

Table 2. Use of Al- and Mg-based alloys in aerospace components

Alloy Family	**Alloy**	**Application**
Al + Cu	2X14, 2X19, 2X24	sheet and plate
	2014, 2X18 2024,2026	extrusions
Al + Zn	7010, 7X50, 7X75	sheet and plate
	7X50, 7055, 7X75	extrusions, sheet
Al + Li	2050, 2X95, 2090, 2X98	sheet and plate
	2X96, 2099	extrusions
Al + Mg	5086	sheet
Al + Mg + Si	6056, 6061	extrusions
	6061	sheet and plate
Mg + Al + RE	AE41, AE44	Creep-resistant castings

New Metal Production and Fabrication Scrap

Scrap is produced at virtually every stage of metal production and fabrication. Fabrication refers to production of semi-finished products that are shape cast, or rolled into plate, sheet or foil, or extruded into rod, or profiles. Metal production and fabrication scrap includes:

- pot-room dross, melt skim and dross
- sludge produced in refining by fractional solidification
- ingot and billet end trim
- ingot scalper chips
- scrap ingots and billets
- shape casting trim
- rolling edge trim and coil end trim
- extrusion profile cut offs
- extrusion billet and profile saw chips

Metal production and fabrication scrap is mostly alloy segregated and internally recycled often, but not always, closed-loop into the same alloy, at semi-fabrication remelt and ingot casting plants.

New Manufacturing Scrap

Semi-finished materials are manufactured into finished components by machining or other forming operations. Manufacturing plants are usually distinct from semi-fabrication plants and often use several metals and several alloys of each metal in one plant.

Manufacturing scrap types include:

- blanking skeletons
- stamping edge trim
- extrusion end trim, punch outs
- sheet and plate clips and cut offs
- sawing, milling, turning and boring chips.
- off-spec or defective parts

Manufacturing plants typically do not have their own scrap remelting facilities and they sell their scrap on the open market or have a deal with their supplier of semi-finished feed to buy back their scrap. Sometimes manufacturers contract with the semi fabricator for take back of manufacturing scrap, but more often it is sold to scrap dealers.

Quantities of new fabrication and manufacturing scrap

A mass balance of global Al flows done around 2005 demonstrated that new scrap represents >50% of prime metal production at ~15,000 kt. This is twice as much metal as is currently recovered from old post-consumer scrap. Mg-based alloys consume currently ~300 kt of prime Mg and result in ~200 kt of die trim and machining chips.

New scrap has a significant advantage over post-consumer scrap in that it is already collected at the fabrication and manufacturing locations, is generally more predictably contaminated, and is not corroded.

Segregation by alloy at source

Part of this new manufacturing scrap is alloy segregated at source, but more often the scrap represents a mixture of alloys processed in a given manufacturing plant. Manufacturing plants are specialized: machine shops mill component shapes out of plate and rod, or mill and bore shape castings; stamping plants form components out of sheet; and hydroforming plants bend extruded tubing. For any given manufacturing plant, the number of alloys is small and their composition is known to a better precision than given by a spot check with a hand-held spectrometer or any on-line sensor.

Segregation of new scrap by alloy at source is always preferable to later sorting. At source, the composition of each alloy is known to a better precision than can be determined by on-line sensors. Alloy segregation is typically practiced at the semi-fabrication plants. Logistically, scrap segregation by alloy is difficult in large machining shops and stamping plants.

When source segregation is attempted, mistakes often happen. Even when the manufacturer segregates the scrap by alloy, a remelt plant buying new manufacturing scrap for recycling has to consider the relatively high probability of mix-up in scrap collection at the manufacturer or at the scrap dealer.

Mixed scrap

Occasionally mixed scrap has an average composition that is compatible with an alloy with a higher alloying element content, and can be used directly in batching this alloy without sorting. This is a case for used beverage cans, where the average can composition can be used for batching the can body alloy. However, these cases are exceptions, and more commonly new mixed metal scrap is sold at a discount to be used later for secondary foundry alloy or painted building sheet applications. To recover full material value and keep this metal in marine and automotive wrought product markets, sorting of mixed scrap would usually be necessary.

Scrap Sorting Tasks

Nominally alloy-segregated scrap

In alloy-segregated scrap, one needs to remove contaminants prior to remelting. These contaminants include cutting fluids and forming lubricants, paint and plastic films, and discrete or attached particles of foreign metals or non metals.

Identification and removal of such contaminants is practical for both large particles and machining chips. It can be done in bulk by magnets, eddy-current separators, washers and dryers, and thermal decoaters. Nonmagnetic contaminant particles are best identified and removed by particle sorters using x-ray transmission sensors. In pre-segregated new scrap, typically there is a small fraction of contaminants that needs to be sorted out. This makes it practical for particle sorting of even small (2-3 mm) particles.

Mixed scrap

New mixed scrap arises mainly in manufacturing plants. It can be a mixture of different parent metals, and/or a mixture of different alloys of the same metal. It consists of large particles trimmed from components and small chips generated by cutting tools. While bulk separation methods usually apply to both small and large particle sizes, particle sorting of mixed-alloy scrap is practical only for larger particles ($r>20$ mm). This is because in a mixture containing similar quantities of various alloys, almost all particles need to be diverted individually, and the number of particles per unit weight scales with $(1/r)^3$. Typical sorting tasks for such mixtures include:

- light-metal/dense-metal sort
- Al/Mg sort
- sorting of a mix of few known alloy compositions

The first two of these tasks can be accomplished by bulk sink float methods. The quantity of scrap available from any one plant, however, is usually too small to be economically separated by existing sink-float techniques. There are only ~10 sink-float plants in North America separating metals from shredder concentrate derived from post-consumer scrap. The alternative is to employ sensor-based particle sorters.

Sensors Suitable for Scrap Sorting Tasks

There are a number of sensors that can remotely inspect and analyse particles distributed on a conveyor belt, sliding down a chute or in free fall.

Vision 2-D and 3-D sensors identify shape and size of individual particles. In new scrap there may be a consistent correlation between the metal/alloy type and the shape/size of scrap pieces. In cases where such a correlation exists, sorting by shape is one of the most cost-effective options.

Colour or grey-scale sensors identify painted particles and contaminants and sort by parent metal (Mg, Al, Zn, Cu, Fe). Sometimes, during a pre-cleaning step, the scrap surface is chemically altered to selectively tint different alloys in the mix.

X-ray transmission sensors are able to look through light-metal particles. This enables the sensors to identify attachments or contaminant particles; sort by wall thickness; separate light metal from dense metal; Al from Mg; and Al alloys with Mg or Si only from Al alloys that contain dense alloying elements such as Cu and/or Zn.

Elemental composition sensors identify the concentration of the major alloying elements in the alloy particle. Elemental composition sensors enable separation of alloy mixtures that are not separable by physical shape or colour. For new scrap mixtures consisting of few known alloys, calculation of the actual elemental concentrations is not necessary. It is adequate to base the sort on the alloy spectral fingerprint. This significantly simplifies the complexity of the sorting task, as compared with trying to batch an alloy from a mixture of scrap particles of many unknown alloy compositions.

There are two types of elemental sensors on the market:

> X-ray fluorescence sensor is used for discrimination based on high (>18) atomic number alloying elements. In air it can remotely sense characteristic x-rays from Ti, Mn, Fe, Cu Zn and denser elements. However, air absorbs low-energy x-rays from light metal elements such as Li, Mg, Al and Si. Hence, XRF sensors have limited usefulness for Al- and Mg-based alloys.
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> Laser-induced plasma spectroscopy (LIBS) is used where discrimination based on light alloying elements (Li, Mg, Al and Si) is necessary. The optical emission from a plasma spark generated by the ablation laser impact is spectroscopically analysed. All alloying elements of interest for the light-metal alloys have optical emission lines in the ultraviolet and visible part of the spectrum used for optical emission spectroscopy.

Particle sorters

The above-described sensors are the basis for particle sorters. These particle sorters tend to come in two varieties:

Chute-type sorters analyse particles while they are sliding down a chute or in free flight after they drop off the chute. These sorters are typically used for small particles or when double-sided inspection is required.

Belt-type sorters analyse particles that are spread out in a single layer and separated from each other on a moving conveyor belt.

Multiple sensors on a single sorter are possible and often necessary to achieve adequate particle identification. Sorting decisions are made based on a combination of information from all the sensors. Diversion of selected particles in both cases is most commonly done by a blast from a line array of high-pressure air jets.

Sorting Circuit

In order to provide sorted products with an acceptable combination of recovery and product purity, sorters are arranged in a circuit with auxiliary unit operations. A typical dry sorting circuit for light-metal scrap might include the following unit operations:

- Particle sizing – size reduction and size separation
- Clean and dry – removing cutting fluids and forming lubricants from new scrap
- Sort out non-Al contaminants from Al-alloy mix
- Sort mix by alloy or batch target alloy(s) from the mix

Sorters have a limited throughput and, in a larger scrap sorting plant, multiple machines operating in parallel may be required to handle the feed flow rate. Often, more than one sorting batching step is necessary to obtain the desired combination of product composition and material recovery from the feed. To achieve this one can add more sorters in series or arrange them in parallel and re-run the material through the same sorters. As long as the same sensors can accomplish the subsequent sorting task, a parallel sorter set up is simpler and more cost efficient.

Alloy Sorting and Alloy Batching with New Scrap

There is a practical limit to the number of diversion blowbars that can be implemented on a single sorter. Sorters with three blowbars are already successfully operating in commercial applications. Such sorters can separate the feed into four output streams: two sorted products, a recycle-to-feed stream, and still-mixed residue. Consequently a mix of two or a maximum of three alloys can be sorted in a single pass through the sorter. When more alloys are present in the sorter feed stream, one has the option of re-running the mixed output stream through the sorter to recover two more sorted alloys, or to batch new alloys (i.e. combine the feed alloys in a right proportion to make two new output alloys). The sorter batches these alloys on line, particle by particle. In this way, the result is a small number of useful product alloys that have a ready market.

New scrap gives the sorter a significant advantage when compared with old post-consumer scrap. A new scrap stream coming from a particular plant consists of mixture of known alloy compositions. Hence, once the sorter is able to identify these alloys, their composition is accurately known, including trace element concentrations that are not tracked by an elemental analysis sensor. This accurate information is very useful in batching new target alloy compositions.

By contrast, old post-consumer scrap contains a large variety of alloys and their particular variants. In the sorting of the old scrap, one needs to be satisfied with less precise estimates of major alloying element concentrations measured by the sensor. Sorting of old scrap by alloy really is not a practical option. It is batching that enables upgrading of complex mixtures of both old and new scrap.

New Opportunities with Alloy Segregation

Recycled new scrap substitutes for, and hence should have a value of, prime Al or Mg and alloying element hardeners replaced in batching an alloy. When manufacturing scrap is sold to a scrap dealer as an alloy mix, only a fraction of that value is realized. Mixed-alloy scrap is used in secondary alloy applications such as engine blocks or painted building sheet.

Segregation of new scrap by alloy enables its use in a variety of composition-compatible alloys. In most cases, it is not necessary to use the scrap closed loop in the same alloy or the same application. To recover the full value, it is sufficient that the scrap replace prime and hardeners without need for removal of alloying elements by refining by, for example, chlorination or fractional precipitation.

For semi fabricators, the ability to buy back and use manufacturing scrap enables them to reduce their raw material costs. Alternatively, they are able to offer their customer the price for returned scrap that they would pay scrap dealers for a similar scrap category.

Sensor-based particle sorting enables the semi fabricator to remove contaminants from nominally source-segregated scrap and sort mixes by alloy so they can use them in compatible alloys of their choice.

In aerospace alloys, scrap sorting would enable expanded use of exotic alloys. Scrap from Al-Li, Mg-Li and Mg-rare-earth alloys segregated and recycled in a way that minimizes loss of the expensive alloying elements would reduce the cost of these alloys. It would also enable expanded use of such high-performance alloys in non-aerospace markets such as automotive and marine. In the aerospace market, material traceability specifications are often interpreted so as to limit the ability of the scrap remelter/alloy producer to use purchased scrap in aerospace alloy formulations. This is ironic as the more common aerospace alloys such as 2024 and 7075 contain a higher concentration and number of alloying elements. For example, 2024 is based on a combination of Cu, Mg and Mn, while 7075 on a combination of Zn, Cu and Mg. Hence, with proper process control, these aerospace alloys should be able to accept metal from a variety of new scrap alloys.

Particle sorters equipped with elemental analysis sensors can enable required composition control in the batching of these more common 2024 and 7075 aerospace or 6111 or 6082 automotive alloys from the mixed manufacturing scrap coming back from aircraft manufacturers or from automotive stamping plants.

In some specific cases, other lower cost sensors could also separate a mixture of few known alloys coming back from a given manufacturing plant. For example, a DE-XRT sensor could differentiate between automotive sheet stamping skeleton scrap based on the gauge difference between outer closures and inner stiffeners separating 6111 alloy from 5754. This combination of alloys cannot be separated by a DE-XRT sensor based on average atomic number difference. Shape and size recognition by a vision sensor could allow separation of trim scrap from machining chips, turnings and borings.

The scrap market buys both fabrication and manufacturing new scrap at a discount, contributing directly and significantly to the cost of the finished product. If alloy producers could buy back new scrap from fabricators and manufacturers, they could cut out the middle man and contribute to a reduction in the cost of alloy production.

Scrap does not need to return to the same alloy or market. It is actually more likely that alloy producers supplying the very cost-sensitive automotive marketplace will be the first to adopt automated scrap sorting technology and would thus benefit by buying up the available new scrap from smaller and less cost-sensitive marine and aerospace markets. Actually, this is already happening to a large extent as virtually all high-copper and high-zinc Al-alloy scrap from aerospace is used for batching Al foundry alloys mainly for automotive powertrain applications. Automated scrap sorting and batching could enable more new scrap to be used in Al wrought alloys such as 6111 closure sheet, 6082 extrusions, or 7XXX bumper stock, or in Al foundry alloys with tighter composition limits (such as 356) that now use a significant proportion of prime metal.

Summary

Automated particle sorters equipped with a suitable sensor can enable efficient and economical closed-loop recycling of Al and Mg alloy-segregated manufacturing scrap within key alloy and product families.

Although sensor-based particle sorters have not been widely applied to sorting of new manufacturing scrap, it is quite feasible to do so. Sensor-based particle sorters are used industrially to sort post-consumer plastic scrap, both bottles and granulated flakes, by polymer type and colour. Such sorters are also used to remove stainless steel from auto shredder residue and have been successfully used to sort old nonferrous metal scrap by parent metal. A LIBS sensor elemental analysis sorter has been used since 2004 to batch 3105 building sheet alloy from Al recovered from shredder nonferrous metal concentrate. Sorting of new scrap is easier than batching secondary alloys from old scrap and-alloy sorting of new scrap waits for an enterprising semi fabricator to figure out how to profit from a technology that promises access to a significant volume of metal available at a discount to prime-based ingot.

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