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Recycling of automotive aluminum

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Abstract: With the global warming of concern, the secondary aluminum stream is becoming an even more important component of aluminum production and is attractive because of its economic and environmental benefits. In this work, recycling of automotive aluminum is reviewed to highlight environmental benefits of aluminum recycling, use of aluminum alloys in automotive applications, automotive recycling process, and new technologies in aluminum scrap process. Literature survey shows that newly developed techniques such as laser induced breakdown spectroscopy (LIBS) and solid state recycling provide promising alternatives in aluminum scrap process. Compared with conventional remelting and subsequent refinement, solid state recycling utilizing compression and extrusion at room or moderate temperature can result in significant energy savings and higher metal yield.

Key words: recycling; automotive aluminum; sorting; mechanical separation; solid state recycling

1 Introduction

The global demand for aluminum and aluminum products is increasing because aluminum alloys can offer excellent corrosion resistance with good strength and low density compared with steel. Aluminum, when being used in mobile applications, saves much more energy and greenhouse gas (GHG) emissions over lifetime of the product. It was reported[1] that 1 kg of aluminum in a car reduces CO_2(eq) emissions by 19 kg during its whole life-cycle. In addition, 5%−7% fuel savings can be realized for every 10% weight reduction by substituting aluminum for heavier steel through appropriate design. The application of aluminum in passenger vehicles and light trucks manufactured in 2006 will lead to potential savings of approximately 140 million tonnes of CO_2(eq) emissions and to energy savings of equivalent to 55 billion liters of crude oil over the lifecycle of these vehicles[2−3].

By 2020, worldwide consumption of aluminum products is expected to double, driven by growth and industrialization/urbanization in China, India, Russia, and Brazil, according to the Alcoa's 2005 Annual Report[4]. Asia is expected to account for 60% of this growth. Meeting this demand would require nearly 80 new smelters with 400 kt production each.

However, the production of primary aluminum is an energy costly process, involving bauxite mining, purification of alumina by a Bayer process, and a molten salt electrolyte based on cryolite (Na_3AlF_6). With the climate change of concern, environmental benefits for recycling of aluminum include the following items.

1) Energy saving. It is widely cited[5−6] that the remelting of recycled aluminum saves almost 95% of the energy required to manufacture pure aluminum from bauxite ore. An integrated assessment of primary and secondary aluminum production, carried out by ROMBACH[7] showed that 113 GJ energy is required to produce one tonne primary metal, and most of the energy use is due to the electrolysis of alumina. Energy use in production of alumina accounts to approximately 20% of the total energy in primary aluminum production. However, including scrap transportation, preparation, remelting, and salt slag treatment, direct energy use in production of aluminum from scrap is approximately 13.6 GJ/t. It is reduced by 88% from that required for primary aluminum production (as shown in Fig.1).

2) Reduced solid waste disposal. Primary aluminum production generates solid wastes such as mine wastes, red mud residue, and spent pot liner at bauxite mining, alumina purification, and electrolysis process, respectively. Investigation carried out by BOIN and BERTRAM[8] showed that more than 5 t of bauxite is

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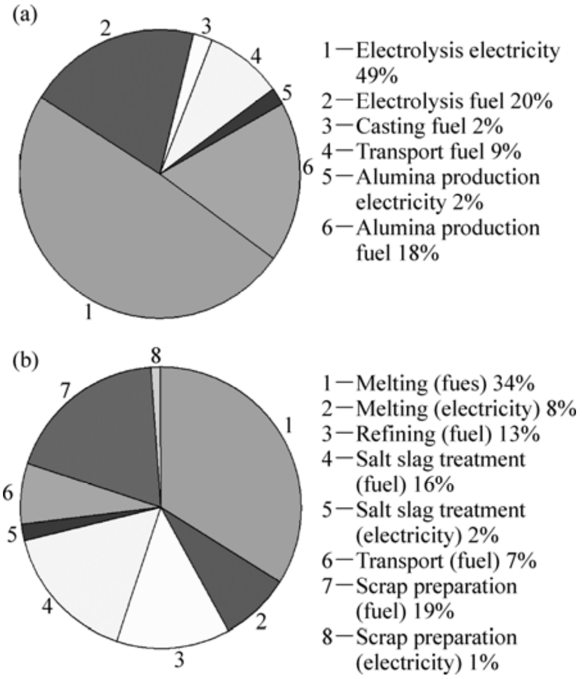

Fig.1 Energy requirements[7] for production of primary aluminum (113 GJ/t) (a) and secondary aluminum (13.6 GJ/t) (b)

consumed to produce 1 t primary aluminum metal. The volumes of the solid wastes, such as dross and salt slag generated from aluminum recycling industry are much smaller. Researches suggested that the mass of solid waste generated per tonne of secondary aluminum is 90% lower than that of primary metal[9].

3) Reduced GHG emissions. Greenhouse gases are emitted at a variety of points in the primary aluminum production, including fossil fuel use in the upgrading and purification of bauxite; electricity consumption in the electrolysis process; and perfluorocarbon (PFC) and CO_2 emissions due to chemical reactions in the electrolysis process. According to the report[10] from the World Resources Institute (WRI), GHG emissions associated with aluminum production account for approximately 0.8% of global GHG emissions, which amounts to about 4% of all manufacturing emissions. The amount of GHG emission is reduced by more than 95% when aluminum is produced by recycling rather than primary processes[5, 10−11].

2 Aluminum alloys in vehicles

Investigation on automotive aluminum applications in Germany was carried out by ZAPP et al[12]. The result showed that automotive aluminum applications cover nearly the whole range of semi-finished products and castings (as shown in Fig.2 and Fig.3). Recently, new research from DUKER[13] reported that the main material for automobile components was casting alloy

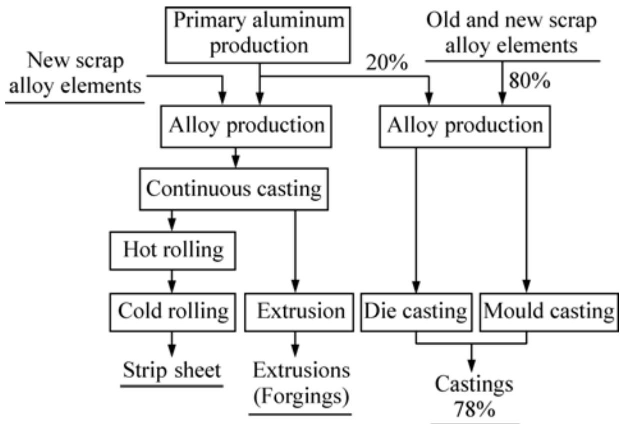

Fig.2 Production scheme for semi-finishes and castings for automotive sector[12]

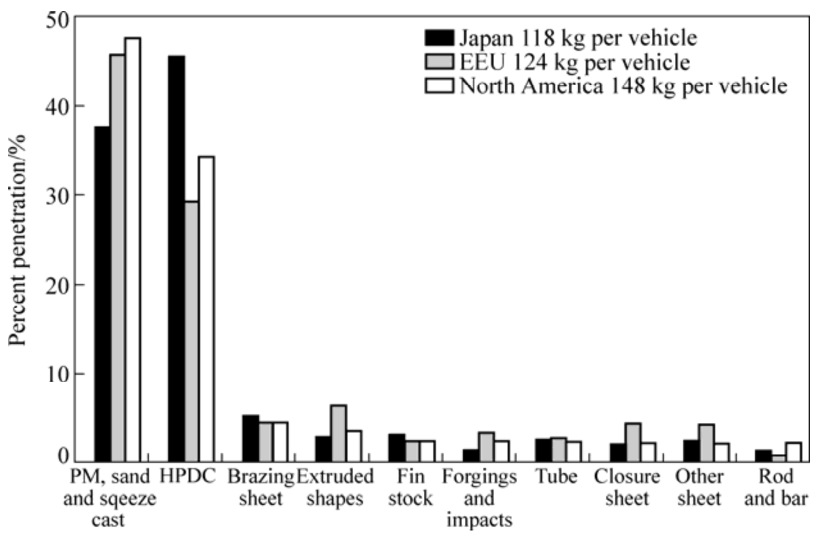

Fig.3 Light vehicle aluminum content comparison in 2009[13] (EEU: European Economic Union (including Russia in research); PM: Powder metallurgy; HPDC: High pressure die cast)

with a share of 73.8% in Europe counties in 2009, down from approximately 78% in 1997[12]. This indicates that the use of wrought alloys is increased in the last decade. Fig.3 gives aluminum products as a percent of total aluminum content in light vehicles in 2009[13]. It can be seen that Japanese market has its highest castings with more than 82% of total aluminum content, compared with approximately 81% for North America and 73.8% for Europe. However, North American light vehicle has its highest total aluminum content with average of 148 kg per vehicle, followed by European vehicle at 124 kg per vehicle and Japanese vehicle at 118 kg per vehicle.

Table 1 shows a typical automotive alloys and their application distributions[12]. It can be seen that the most widely used casting alloy for automotive applications is A359 (AlSi9Cu3) alloy with a share of approximately 48% of all castings. In addition, the casting alloy A356 (AlSi7Mg) used for wheels and brake parts shares about 20%. It should be noticed that the alloys used in automotives may vary with manufacture and age of the vehicles. For instance, nearly all of the early aluminum usage in vehicles was in the form of casting.

Table 1 Alloy composition of automotive aluminum[12]

Alloy type	Code	Notation	Share/%
Casting alloys (78%)	A359	AlSi9Cu3	48
	A356	AlSi7Mg	20
	A361	AlSi10Mg	12
	−	AlSi12Cu	9
	A413	AlSi12	7
	A332	AlSi12CuNiMg	4
Wrought alloys (22%) including extrusions, forgings and rolled products	AA6060	AlMgSi0.5	35
	AA6082	AlMgSi1	11
	AA3003	AlMn1	10
	AA5182	AlMg4.5Mn0.4	9
	AA5754	AlMg3	14
	AA6016	AlSi1.2Mg0.4*	15
	AA7020	AlZn5.4Mg1	6

* It was AlSi1.2Mn0.4 in Ref.[12]

Vehicle design for environment/recycling has been considered by automotive manufactures and researches[3, 14]. Based on the weight reduction concept, some basic ideas should be considered such as[14]: 1) designing key structural components for prime alloys with a maximum property-to-mass ratio; 2) minimizing the number of materials/alloys in any one part; 3) choosing standard alloy families based on the common alloying elements Al, AlCu, AlMn, AlSi, AlMg, AlMgSi, and AlZn; 4) avoiding exotic alloying elements.

The difficulty in recycling wrought aluminum alloys is its low tolerance, the ability of an alloy to absorb impurities, which is not normally present in its composition. Table 2[12] provides an example of wrought aluminum alloy mixture from an automobile. It can be seen that the zinc content of the mixture is higher than the allowed maximum for many common alloys except for the 7××× series. However, the silicon content is higher than that allowed in 7××× alloys. There are two possibilities to recycle this alloy mixture: one is that the wrought aluminum alloy mixture is used to produce a cast aluminum alloy because cast alloys accept higher alloy elements; alternatively, this wrought alloy mixture can be used to produce new wrought alloy if the impurities are diluted by the addition of primary aluminum metal.

Table 2 Wrought aluminum alloy mixture from automobile[12]

Alloy	w/%	Composition, w/%				
		Si	Fe	Mn	Mg	Zn
AA6060	35	0.45	0.2		0.5	
AA6082	11	1.0	0.3	0.7	0.9	
AA3003	10	0.5	0.5	1.3		
AA5182	9	0.1	0.2	0.4	4.5	
AA5754	14	0.3	0.2	0.4	3.2	
AA6016	15	1.25	0.3		0.5	
AA7072	6	0.2	0.3	0.3	1.2	4.5
Total	100	0.57	0.26	0.32	1.27	0.27

3 Automotive recycling process

Modern automotive recyclers use a number of efficient processes to recover valuable materials from end-of-life vehicles (ELVs) (as shown in Fig.4). From

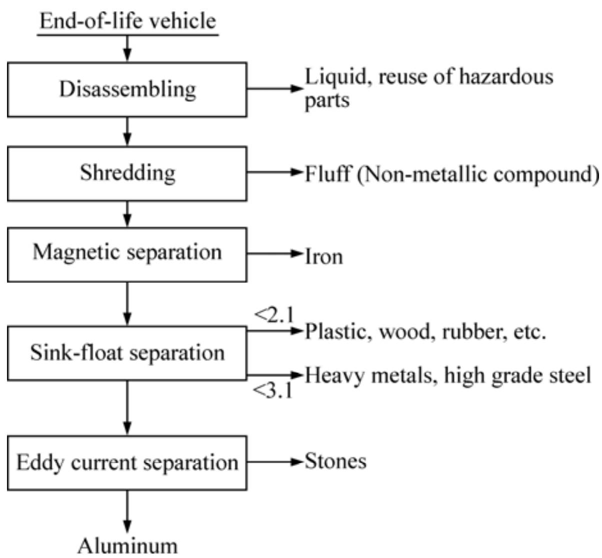

Fig.4 Typical end-of-life vehicle recycling process

the view point of recovery of aluminum metal from wastes, disassembling process and mechanical/physical separation are briefly introduced as follows.

3.1 Disassembly of automotive vehicles

Selective disassembly targeting on singling out hazardous or valuable components is an indispensable process in automotive recycling. It is a systematic approach that allows removal of a component or a part, or a group of parts or a subassembly from a product (i.e. partial disassembly); or separating a product into all of its parts (i.e. complete disassembly) for a given purpose. For instance, dismantler removes subassemblies such as engine, transmission, wheels, radiator, catalytic converter, gasoline, fuel tanks, fluids, tires, batteries and air bags from the vehicle for their value or because the shredder requires their removal[15−16].

The areas of disassembly that are pursued by researchers are focused on disassembly process planning (DPP) and innovation of disassembly facilities. The objective of disassembly process planning is to develop procedures and software tools for forming disassembly strategies and configuring disassembly systems. The following phases for developing a disassembly process plan have been proposed[17−18]:

1) Input and output product analysis: In this phase, reusable, valuable, and hazardous components and materials are defined. After preliminary cost analysis, optimal disassembly is identified.

2) Assembly analysis: In the second phase, joining elements, component hierarchy and former assembly sequences are analyzed.

3) Uncertainty issues analysis: Uncertainty of disassembly comes from defective parts or joints in the incoming product, upgrading/downgrading of the product during consumer use, and disassembly damage.

4) Determination of dismantling strategy: In the final phase, it is decided whether to use non-destructive or destructive disassembly.

3.2 Mechanical/physical recycling of vehicles

3.2.1 Magnetic separation

Magnetic separators, in particular, low-intensity drum separators are widely used for the separation of ferromagnetic metals from non-ferrous metals and other non-magnetic wastes. Over the past decade, there have been many advances in the design and operation of high-intensity magnetic separators, mainly owing to the introduction of rare earth alloy permanent magnets capable of providing very high field strengths and gradients.

3.2.2 Eddy current separation

In the past decades, one of the most significant developments in recycling industry was the introduction of eddy current separators based on the use of rare earth permanent magnets. The principal of eddy current separator is illustrated in Fig.5. Eddy currents can be induced in an electrical conductive particle by a time-dependent magnetic field (magnet rotor in the Fig.5). Further, the eddy currents will in return result in magnetic fields that oppose the inducing fields, giving rise to a so-called Lorentz force, a repulsive force.

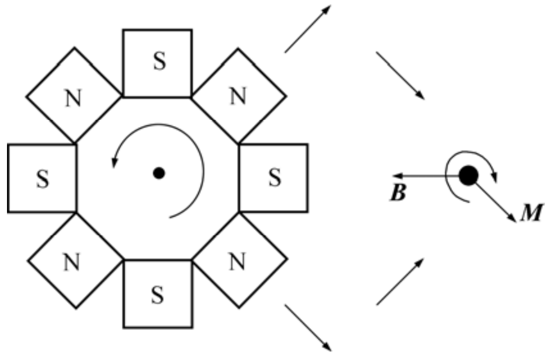

Fig.5 Illustration of eddy current separation

3.2.3 Density-based separation

Gravity concentration separates materials of different specific gravity by their relative movement in response to the force of gravity and one or more other forces, the latter often being the resistance to motion offered by a fluid, such as water or air[19]. The motion of a particle in a fluid is dependent not only on the particle's density, but also on its size and shape, so large particles will be affected more than smaller ones. In practice, close size control of feeds to gravity processes is required in order to reduce the size effect and make the relative motion of the particle specific gravity dependent.

It was reported that[20] each year more than 50 million vehicles reach the end of their life worldwide. About 95% of the ELVs enter the recycling infrastructure that includes auto parts dismantlers, remanufactures, and scrap recyclers in North America[16]. Today, more than 75% of automotive materials are profitably recycled via parts reuse, parts and components remanufacturing and by the scrap processing industry. The 15% of the mass that is not recycled ends up in a landfill in the form of automotive shredder residue (ASR). Table 3 lists a material composition of ASR from Italy[21].

Table 3 Automotive shredder residue (ASR) composition (mass fraction, %) [21]

Rubber	Plastics	Metals	Wood	Other (paper, foam, fabric, dirt)
38	20	6	10	26

4 New technologies in aluminum scrap process

As discussed before, the tolerance of most wrought aluminum alloys is low. Recycled automotive aluminum by mechanical ways involves a mixture of alloys from a fairly wide variety of applications. These mixtures of alloys have too much iron, silicon, or zinc to be directly reused in new automotive wrought alloys. Progress has been and is still being made in addressing this challenge. Some alternatives are: 1) techniques to separate aluminum alloys from each other during the upgrading process, 2) developing cost-effective technologies for removing excess alloying elements from molten aluminum, 3) developing new solid state recycling process, and 4) designing new recycling friendly alloys. Recently, new developed techniques in aluminum alloy separation and solid state recycling provide promising alternatives in aluminum scrap process.

4.1 Aluminum alloy separation

4.1.1 Color sorting

The technological advancement of computers over the last decade has greatly increased the speed of real time image analysis. Consequently, color sorting based on computer image analysis is one of the first automated sorting processes to be used industrially.

In a patented process[22], the aluminum scrap is colored by selective etching in chemical solutions because the color of the scrap after etching depends on the concentration of particular alloying elements. For example, aluminum with a high silicon and manganese contents will turn the scrap gray while zinc and copper combine to turn the scrap dark[23]. However, color sorting cannot be used to separate individual alloys within a family. For example, an alloy with high zinc and low copper concentration has a similar etching response as an alloy with high copper and low zinc contents[24].

4.1.2 Laser induced breakdown spectroscopy (LIBS)

Currently, the laser induced breakdown spectroscopy (LIBS) is the only method to separate both cast and wrought aluminum into their individual alloys[23−24]. In the LIBS process, a sensor first detects the presence of a particle which is then bombarded with a pulse. The pulse laser illuminates the surface of the metal, producing an atomic emission, and the chemical information about the material can be obtained by a spectral detector. Using an optical fiber, a polychromator and a photodiode detector which are all connected to a computer system, the resulting emission can be transferred to a sorting signal. The sorting signal then activates a mechanical device that forces the identified piece to be placed in a particular sorting bin. Thus, complete separation of the scrap particles into specific alloys is achieved.

The major limitation for the LIBS system is that the surface of the aluminum scrap must be free of paints, lubricants or adhesives, since the pulse laser can only penetrate to a depth of 30 Å or less on the surface of the aluminum.

4.2 Solid state recycling

With the global warming of concern, recycling of wrought aluminum alloys by new solid state recycling techniques instead of conventional remelting and subsequent refinement has been taken into account. Solid state recycling process utilizing compression and extrusion at room or moderate temperature can result in significant energy savings. In addition, there is a substantial loss of aluminum metal during the conventional remelting process. LAZZARO and ATZORI[25] analyzed the metal losses in conventional recycling of aluminum turnings (Fig.6 and Fig.7). It can be seen that approximately 45% of the aluminum metal will be either lost or carried into a new scrap phase. New solid state recycling techniques without remelting might result in much higher metal yield than conventional recycling process.

Researches in solid state recycling of aluminum have been focused on recycling of turnings (trimmings)[25−27]. However, recycling of automotive

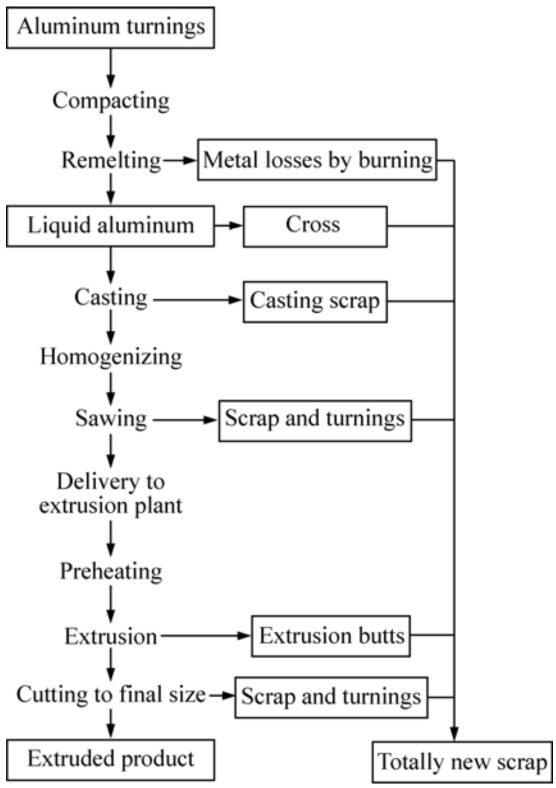

Fig.6 Flow chart of conventional process for recycling of aluminum turnings[25]

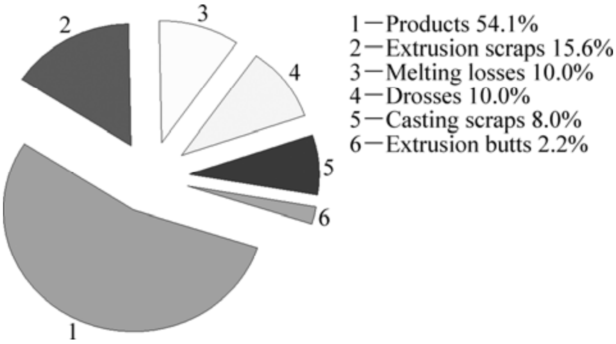

Fig.7 Metal yield in recycling of aluminum turnings by conventional recycling process[25]

aluminum scrap by solid state recycling is just beginning. Challenges in solid state recycling of automotive aluminum scrap involve inhomogeneous property of the scrap, iron contamination, and organic coating[28−29] etc.

Fig.8 illustrates the solid state process for automotive aluminum scrap recycling. In the process, a mature preparation should be performed before the aluminum scrap is fed to the compression and deformation process. The preparation covers scrap purification and decoating (degreasing). Practically, automotive aluminum scrap should be segregated according to their alloy families (i.e. 2×××, 3×××, 6××× etc). Investigation is undergoing to clarify the influence of mechanical properties of extruded product from a mixture of alloys[29]. Decoating (degreasing) of automotive scrap can be performed by chemical method or a thermal way[29]. Utilization of chemical cleaning by acid and/or hydroxide was reported for removing surface oxides after a thermal decoating process[28, 30].

Cold compression at room temperature with a pressure range of 200−600 MPa is used to pre-compact the decoated aluminum scrap. Studies[29, 31] indicated that the cold compaction process did not result in metallic bonding between particles. In the deformation step, extrusion of pre-compacted scrap at approximately 450−550 °C is performed to obtain good diffusion bonding between particles[32]. It should be noted that new development of severe plastic deformation (SPD), such as high ratio extrusion, equal channel angular pressing (ECAP), may provide new approaches for solid state recycling of automotive aluminum scrap.

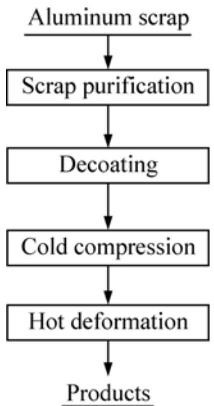

Fig.8 Illustration of solid state recycling

5 Conclusions

1) With the climate change of concern, usage of aluminum in automotive applications with the concept of light weight is predicted to be increased steadily.

2) Using recycled aluminum in place of primary aluminum metal results in significant energy and greenhouse gas emissions savings.

3) The increasing use of wrought alloys in vehicles, especially in European market (with share of 26%) leads to developing new techniques for accurately sorting aluminum scrap into individual alloys.

4) In practice, automotive recycling process includes selective disassembling process, targeting on singling out hazardous or valuable components, shredding process to liberate desired materials, and a number of mechanical separations, such as magnetic separation, eddy current separation, and density-based separation.

5) Newly developed techniques such as aluminum alloy separation by laser induced breakdown spectroscopy (LIBS) and solid state recycling provide promising alternatives in aluminum scrap process. Compared with conventional remelting and subsequent refinement, solid state recycling utilizing compression and extrusion at room or moderate temperature can result in significant energy savings and higher metal yield.

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