December 2021

Roadmap for Automotive Aluminum

DRIVING INDUSTRY **INNOVATION** AND **COLLABORATION**

DRIVEALUMINUM

The Aluminum Association

ACKNOWLEDGMENTS

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INTRODUCTION

Aluminum is a foundational element in today's vehicles. The aluminum industry is realizing steady global growth—driven by technological advances in manufacturing processes, increased aluminum use in building and construction, and growing electrification and mass reduction in transport. Reports indicate the global aluminum market could reach 242 billion USD by 2027, with annual growth rates from 3.2 to 5.7%.[1,2] The large projected increase in the production of battery electric vehicles (BEVs) over the next two decades is a strong catalyst for automotive aluminum; predictions show that BEVS could represent as much as 12% of vehicles on the road globally by 2030.

The rising use of aluminum in place of steel is a strong driver in the internal combustion engine (ICE) vehicle sector; aluminum is already the leading material in BEVs to achieve better driving range and mass reduction. Lightweight aluminum has helped boost fuel efficiency in vehicles since the early 1970s, and it is now facilitating the transition to electrification and other clean propulsion technologies. Global consumption of secondary (recycled) aluminum is also rising due to its high value and low energy footprint.

The aluminum industry is uniting to enhance its competitive position in the coming era of electrification. The inherent properties of aluminum make it an ideal solution to future vehicle challenges—all while improving or maintaining vehicle safety, value, customization, and performance.

This *Roadmap for Automotive Aluminum* lays a foundation for the industry to continue its growth and differentiation in the automotive sector. It contains ambitious goals to substantially increase value and market share across multiple automotive applications. These goals will be achieved through innovations in design, alloys, and manufacturing processes. Collaboration with automakers and end-users will be key to success.

Aluminum: Inherent Value in Vehicle Design

- **Recyclability.** Aluminum is a nonferrous metal that can be easily recycled to save more than 90% of the energy used in the production phase. On a percentage basis, it is one of the most recycled industrial metals.
- **Low Weight, High Strength:** Aluminum offers an excellent strength-to-weight ratio. In BEVs, aluminum can decrease vehicle weight and extend travel range.
- **Thermal Management:** Aluminum's superior thermal properties are beneficial to cut battery draw for heating/cooling the passenger compartment—extending vehicle range.
- **Safety:** Aluminum absorbs twice as much crash energy as steel. Aluminum components can also be designed to fold predictably during a crash, allowing the vehicle to absorb much of the crash energy before it gets to the passenger compartment.
- **Performance:** All else being equal, vehicles made lighter with aluminum accelerate faster, brake in shorter distances, and handle better than their heavier counterparts.
- **Corrosion Resistance:** Aluminum generates a natural oxide coating, which helps maintain a vehicle's structure and extend its service life.

Sources: Drive Aluminum; Aluminum Association.

1 Global Aluminum Market: Opportunities and Forecasts. Allied Market Research (2019-2026). www.alliedmarketresearch.com/aluminium-market

2 Aluminum Market Size, Share & COVID-19 Impact Analysis, by End-Use, Fortune Business Insights. October 2020. www.fortunebusinessinsights.com/industry-reports/aluminium-market-100233

ROADMAP SCOPE AND OBJECTIVES

The aluminum industry and automotive sector have successfully pioneered many innovations in response to market, regulatory, and technology challenges over the last two decades. Notable innovations include advances in material and component designs and the reengineering of fabrication and joining processes.

To meet future challenges and drive growth, the Aluminum Transportation Group (ATG) within the Aluminum Association held a virtual roadmapping workshop in March 2021. The two-day event brought together over 120 stakeholders from the aluminum and automotive industries to discuss ideas for this *Roadmap for Automotive Aluminum*. A subsequent series of interactive meetings with important stakeholders collected further expert feedback.

Collectively, these activities identified future goals and opportunities as well as R&D priorities on which the industry can take concerted action to enhance aluminum value in dynamic markets. Figure 1 shows the set of Roadmap activities identified as most important to undertake. More broadly, this Roadmap provides guidance on R&D priorities and collaborative efforts to transform the industry's products and manufacturing processes—setting the stage for sustainable, long-term growth year-over-year.

Automakers are innovating at a rapid pace, engineering vehicle design solutions that meet or surpass consumer demands and sustainability priorities—and improving their competitive edge. Many pursue a multi-material approach to vehicle construction, selecting parts and materials that meet the individual engineering requirements of each application. In these multi-material systems, aluminum is the fastest growing material in the mix.

In this evolving automotive environment, the aluminum industry is energized to apply recently developed technologies that help predict properties, consolidate parts, improve performance, optimize systems, expand recycling, and increase value. Aluminum suppliers are eager to work with automakers on focused projects to transform manufacturing processes and deliver the vehicle solutions that will drive the development of efficient transportation for years to come.

Aluminum suppliers are ready to collaborate with auto manufacturers on focused projects that deliver high-value solutions.

Aluminum Industry Technology Challenges and Sustainable Pathways

	Challenges	Pathways
Design Engineering	• Ensuring OEMs and Tiers have easy access to detailed, relevant, and updated material data for forming and manufacturing simulation. • Developing more robust joining designs, particularly for dissimilar materials. • Designing components/subsystems for greater strength, formability/ease of fabrication, parts consolidation, and corrosion resistance.	Establish Open Access Resource for Design Data Optimize Joining Designs and Processes, Including Adhesives Improve Aluminum Component Manufacturability & Process Design
New Alloys, Products & Grades	• Developing affordable, ultra-high-strength, corrosion-resistant aluminum alloys exceeding the specific strength of press-hardened steels. • Modernizing/updating simulation/material property cards to cut costs and shorten development time in Computer Aided Engineering (CAE) for safety, durability, and other attributes. • Achieving industry consensus on fit-for-purpose material specs and testing, including joining and bonding durability.	Tailor Alloys for High Performance in OEM-Specific Applications Harness Data Analytics & Predictive Modeling of Alloy Properties Expedite Testing and Qualification of Next-Generation Alloys
Future Vehicles	• Developing robust and cost-effective aluminum solutions to meet all structural and safety requirements of parts, including battery enclosures (crash, underride impact toughness, fire protection). • Improving alloys and processes to enhance battery component functionality and flexibility. • Balancing customer design requirements for stable dimensions/tolerances with material properties and cost of processing.	Reduce Overall Part and Sub-system Costs Create Alloys Specifically for Electric Vehicle Batteries Tailor Designs for Battery Enclosures
Next-Generation Fabrication	• Developing higher-formability aluminum grades that can substitute for mild steels without compromising design. • Putting in place real-time process data collection and sharing across the automotive aluminum value chain to enable use of Industry 4.0, machine learning, and artificial intelligence for process and product optimization. • Overcoming high capital expense for new technology deployments and creating cost-effective solutions.	Develop Advances in Formability Enable Real-Time Process Data Collection at All Manufacturing Steps Develop Innovative, Cost-Effective Next-Generation Fabrication Processes
Recycling & Sustainability	• Developing the next generation of high-speed, alloy-selective, low-cost sorting technology for shredded scrap; making sure state-of-the-art technologies for closed-loop recycling are available to all users. • Developing comprehensive systems for tracking and recording global scrap flow and properties data related to recycled materials. • Efficiently shredding/separating dissimilar metals and alloys that are bonded, welded, or riveted.	Develop High-Speed / High-Volume Sorting and Recycling Enable and Ensure Life Cycle Management Across the Value Chain Recycle Bonded and Riveted Joints

Figure 1. Automotive Aluminum Roadmap Priority Action Pathways

SHIFTING AUTOMOTIVE MARKETS

Automakers are simultaneously responding to evolving trends in consumer preferences and vehicle markets, including electrification; sustainability and decarbonization; advanced communications technology, customization, and infotainment; and shared vehicle mobility options. These trends are often described with acronyms like CASE (connected, autonomous, shared, electric).

Automakers also seek to distinguish their brand and gain a competitive edge by rethinking the design, material, and processes to meet or exceed the needs or expectations of their target customers for each vehicle. This drive is creating significant opportunities for aluminum in diverse applications.

> "All players, especially incumbent OEMs and suppliers, must prepare to navigate an increasingly complex mobility landscape."
>
> McKinsey & Company. March 22, 2021. Defining and seizing the mobility ecosystem opportunity

ELECTRIC

One of the most impactful changes in the automotive industry is the transition from internal combustion engines toward BEVs. The thermal properties[3] and low weight/high strength of aluminum can be a boon to these vehicles, but the pace of deployment will depend on charging infrastructure, grid capacity, and battery and energy storage technologies.

From a global total of 10 million electric cars on the road at the end of 2020, the International Energy Agency (IEA) projects the number of electric vehicles (all modes except two/three wheelers) will grow to 145 million (Stated Policies Scenario) or 230 million (Sustainable Development Scenario) by 2030—accounting for 7% or 12% of the on-road vehicle fleet, respectively.[4] In 2021, automakers supported the current Administration's Executive Order targeting a 50% sales share for electric vehicles in 2030 (including plug-in hybrids and hydrogen fuel-cell vehicles).[5]

Automotive original equipment manufacturers (OEMs) are facing multiple challenges in the transition to BEVs. The investment cost for development and production is relatively high, given the lower volume of vehicles during the early stages of this transition. Batteries take center stage in consumer concerns—particularly the driving

BEVs represent a unique opportunity to demonstrate the sustainability, flexibility, and value of aluminum.

[3] Alex Kamczyc, "Building better practices for automotive sustainability," May 2021, Recycling Today. www.recyclingtoday.com/article/ford-university-of-michigan-sustainability/

[4] IEA, Global EV Outlook. www.iea.org/reports/global-ev-outlook-2021/prospects-for-electric-vehicle-deployment

[5] White House Fact Sheet: President Biden Announces Steps to Drive American Leadership Forward on Clean Cars and Trucks. August 5, 2021. www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/fact-sheet-president-biden-announces-steps-to-drive-american-leadership-forward-on-clean-cars-and-trucks/

range and time required to recharge. As the global BEV market grows, so will the performance of battery technologies and charging systems. Aluminum adoption is an important step toward lowering costs in many of these areas.

SUSTAINABLE

With a growing need for global decarbonization—especially in the transportation sector—OEMs must maintain a focus on the cradle-to-grave energy, carbon, and environmental impacts of vehicles. As BEVs eliminate tailpipe emissions, vehicle materials will represent an increasing share of a vehicle's life cycle carbon footprint. Aluminum offers high recyclability, and its carbon footprint will continue to shrink as the grid moves toward net-zero emissions, effectively decarbonizing electricity-based aluminum manufacturing processes.

Primary materials re-use approaches include closed-loop recycling, wherein recovered materials are used in producing the same part from which they came (e.g., cast to cast). Optimizing end-of-life (EOL) materials recycling requires design for recycling as well as cost-effective protocols for later dismantling or disassembling components.

The Sustainability Characteristics of Aluminum

Highly recyclable—Aluminum can be infinitely recycled, as melting does not change its properties.

Lightweight and strong—Aluminum can lower energy costs and carbon emissions in vehicles.

Low energy and carbon footprint—Using recycled aluminum can save 95% of the energy that is required to produce new aluminum.

The aluminum industry can build on its existing strong credentials in sustainability to make the business case to automakers. A McKinsey analysis suggests that increased recycling, new smelting technology, and green electricity can eliminate 73% of current emissions from aluminum production—while reducing costs.[6]

EOL recycling, closed-loop recycling, and design for recycling are critical to sustainable use and reuse of aluminum.

CONNECTED AND AUTONOMOUS

Vehicle drivers and occupants already benefit from a range of in-car electronic display screens and sound systems to navigate, stay informed, be entertained, or access smart home control systems. Vehicle communications are increasingly connected to phones, other vehicles, infrastructure, and the cloud—enabling enhanced safety, synchronization, access to work functions, vehicle efficiency, and maintenance. Aluminum solutions may offset the weight of new equipment needed in connected and autonomous vehicles. Automakers are already leveraging mass

[6] McKinsey, "The zero-carbon car: Abating material emissions is next on the agenda," September 18, 2020. www.mckinsey.com/business-functions/sustainability/our-insights/the-zero-carbon-car-abating-material-emissions-is-next-on-the-agenda

reduction with aluminum to accommodate the new electronics/interior features that consumers demand.

Fully electric vehicles may now be equipped to receive over-the-air software updates and share insights directly with the OEMs. As vehicles increasingly take over many operator functions, occupants could reconceive in-vehicle time as an opportunity to consume media. Aluminum has three times the thermal conductivity of steel, making it a popular material for use with onboard electronics.[7] While aluminum is less conductive than copper, its lighter weight provides an advantage when replacing a copper wiring harness.

The outlook for self-driving vehicles relies on customer perceptions, Federal and state regulatory approvals, and the presence of an adequate supporting communications infrastructure. Companies in North America's autonomous vehicle market include Waymo, Ford, General Motors, Uber, and Tesla, among others.[8] Work is reportedly focused on the integration of advanced electronics like LiDAR, radar, sensors, and cameras, leading key players to build their expertise in critical fields through mergers and acquisitions.

The self-driving sector is moving toward hybrid vehicles and BEVs to meet projected demand, and the industry is expected to achieve a CAGR of 12% in North America through 2024, assuming costs for electronics, LiDAR, and cybersecurity do not impede growth.[2] According to a McKinsey report, fully autonomous vehicles are not expected before 2030.[9]

Vehicles of the future—electric, sustainable, connected, and autonomous.

[7] A. Kamczyc, "Building better practices for automotive sustainability," Recycling Today, May 5, 2021. www.recyclingtoday.com/article/ford-university-of-michigan-sustainability/

[8] Graphical Research, *North America Autonomous Cars Market*, 2018–2024. www.graphicalresearch.com/industry-insights/1198/north-america-autonomous-cars-market also www.marketwatch.com/press-release/autonomous-cars-market-to-2024-covid-19-impact-competition-and-forecast-2021-06-07?siteid=bigcharts&dist=bigcharts&tesla=y

[9] McKinsey Center for Future Mobility, "Autonomous Driving," 2021. www.mckinsey.com/features/mckinsey-center-for-future-mobility/overview/autonomous-driving

Automotive Aluminum Outlook

CURRENT AND FUTURE STATE

Aluminum content in vehicles has grown as automakers pursue even greater fuel efficiency in both ICE and hybrid vehicles and innovations in BEVs. Today, aluminum is the top choice among metals for a variety of automotive parts, including the chassis, structural components (e.g., shock towers and internal panels), and motor or battery housings.[10]

In North America, average aluminum content grew by 62 pounds per vehicle between 2016 and 2020. By 2020, total aluminum content per vehicle had reached an estimated 459 pounds as manufacturers increasingly incorporated auto-body sheet (ABS), aluminum castings, and extrusions in place of conventional steel.

By 2026, aluminum content is expected to increase to 514 pounds per vehicle. This growth will be driven by greater use of aluminum in all vehicle closures, body in white (BIW), and chassis, and by aluminum used in electric powertrains and platforms (sheet, extrusions, and castings) to extend vehicle range. By 2030, total aluminum content per vehicle is estimated to reach 570 pounds on average, an increase of 24% (see Figure 2).[11]

From bumpers and trunks to closure panels and engine blocks, aluminum use in cars and trucks continues to rise on top of 40 years of consistent growth. Today, advanced aluminum alloys are the second-most-used material in the auto industry and the fastest-growing material in the design of new cars and trucks.

From Drive Aluminum. www.drivealuminum.org/

While estimates of the pace at which BEVs will displace ICE vehicles vary, the likely impacts on aluminum show a *net increase* in demand. BEVs would reduce the number of aluminum engine blocks produced for use in ICE vehicles, ultimately eliminating about 200 pounds of traditional aluminum components (including the transmission and driveline). More than offsetting this loss, BEVs are likely to employ 400 pounds or more of BEV-specific aluminum components to help extend vehicle range prior to recharge. Key applications include battery and motor housings as well as body structural components to improve crash management systems.[12]

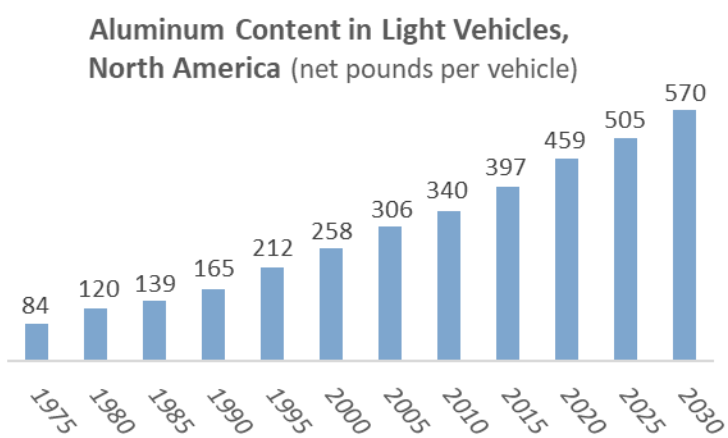

Figure 2. Projections to 2030 for Aluminum in Vehicles

[10] Desai, Pratima, "Auto parts makers shine spotlight on aluminum's role in electric vehicles," July 27, 2020, Reuters. Accessed June 8, 2021.

[11] DuckerFrontier, "North American Light Vehicle Aluminum Content and Outlook" report, 2020.

[12] DuckerFrontier, "North American Light Vehicle Aluminum Content and Outlook" report, 2020.

TECHNOLOGY TRENDS

ALUMINUM SHEET

Aluminum sheet, usually 0.008 inches to 0.25 inches thick, is one of the fastest growing product segments in vehicles today. The use of aluminum panels for automobile bodies and tractor trailers is driving this growth. Aluminum hoods, for example, went from 50% market penetration in 2016 to above 60% in 2020.

Use of aluminum sheet is expected to increase in vehicle doors, hoods, and fenders (closures). Doors are the largest projected growth area for aluminum through 2026. Sheet use per vehicle grew from 77 pounds in 2016 to 133 lbs. in 2026.[13] Figure 3 illustrates the trends in aluminum sheet as well as other forms.

Technology advances have been helping to move sheet into growing product markets. The continued development and improvement of forming techniques over the last decade have helped elevate capabilities to manufacture high-strength aluminum components in more complex shapes, such as panels. Applications for aluminum sheet in automotive and other sectors are expanding rapidly with the advent of advanced forming technologies like sheet micro-forming (e.g., micro-hydromechanical deep drawing, laser shock micro-forming, etc.), warm/hot forming, advanced incremental forming, electromagnetic sheet forming, and others.[14]

New systems have been emerging to weld consecutive billets together, enabling an endless rolling process. The process reduces both energy consumption and material losses while improving the quality and reliability of the components.[15]

CASTINGS

Castings are widely used in vehicle powertrains to help automakers meet the standards set by the National Highway Traffic Safety Administration and the Environmental Protection Agency to boost fuel efficiency and reduce carbon and other emissions. Castings represent the largest share of aluminum parts per vehicle today.

Die-cast aluminum is often used to make thin-walled enclosures with interior ribs and bosses to integrate parts and maximize strength. This type of casting can produce precisely formed aluminum parts requiring a minimum of machining or finishing.

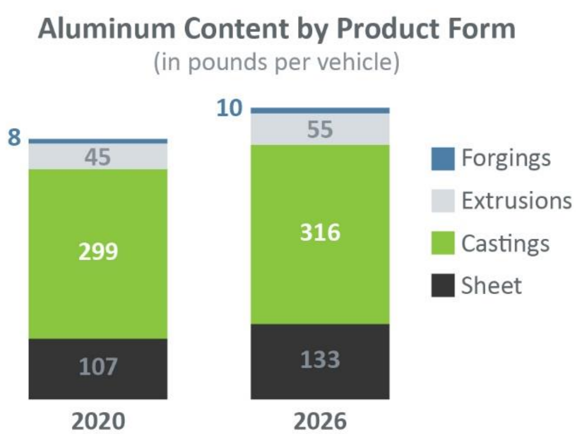

Figure 3. Projected Increases in All Forms of Aluminum

[13] DuckerFrontier 2020.

[14] Tomasz Trzepieciński, "Recent Developments and Trends in Sheet Metal Forming," Metals 2020, 10(6), 779; https://doi.org/10.3390/met10060779 and www.mdpi.com/2075-4701/10/6/779/htm

[15] ERT-EBROS Billet Welding Technology for Long Products. May 2018. 10th China International Steel Congress, Beijing, China. www.researchgate.net/publication/327689953_ERT-EBROS_Billet_Welding_Technology_for_Long_Products

The global die casting market is investing in R&D to improve production processes and alloys.[16] Lightweight castings show great promise for use as structural components and housings for electric motors in BEVs. Similarly, aluminum castings are a good fit for complex battery trays, as they can easily form intricate passages for cooling the battery packs.[17]

ICE and BEV applications for very large die castings have been emerging since 2015.[18] Tesla is planning to replace large numbers of robots with giant aluminum casting machines that can produce less complex vehicle chassis components. A single large casting will replace 70 components that are currently glued and riveted into the vehicle underbody.[19]

EXTRUSIONS

Extrusion is a highly flexible and low-cost aluminum forming process for custom parts and signature style. Extrusion enables highly complex cross-sectional shapes and often allows for integration of several different components into one extrusion shape, reducing joining and overall costs. Growing demand for electric vehicles is expected to boost the market for extrusions in lightweighting vehicle substructures, chassis, motor and battery housings, closures, BIW parts, and body reinforcement beams.[20] Innovations in extrusion equipment, rapid prototyping, and further R&D are addressing challenges sometimes associated with welding of frames and body parts or other downstream fabrication steps.

Extrusions in Automotive Aluminum Markets

- Sub-structures
- Door Beam
- Bumpers
- Pillars
- Sub Frames
- Seat Back Bar
- Front Side Rail
- Space Frames
- Body Panels
- Others

Technology trends for extrusions include significantly more complex shapes and larger circular extrusions for battery tray and BEV designs, requiring larger extrusion presses and equipment. The need to improve crashworthiness is also necessitating greater use of high-strength alloys. In addition, long components used in battery tray side rails and cross members are reducing tolerances over the length of the extrusions.

TECHNOLOGY AND SUSTAINABILITY

For decades, aluminum parts producers have been striving to increase the energy efficiency of their manufacturing processes and shrink their life cycle energy and carbon footprints. A 2013 report noted that the energy needed to produce new (primary) aluminum had declined nearly 25% in the preceding 15 years, and the

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[16] ReportLinker, April 15, 2021. Intrado Global Newswire. www.globenewswire.com/news-release/2021/04/15/2210708/0/en/The-global-aluminum-parts-gravity-die-casting-market-was-valued-at-USD-5-351-in-2020-million-and-is-projected-to-reach-USD-7-413-million-by-2026-registering-a-CAGR-of-about-4-82-du.html

[17] Pratima Desai, “Auto parts makers shine spotlight on aluminium's role in electric vehicles.” July 27, 2020. www.reuters.com/article/us-aluminium-electric-autos-analysis/auto-parts-makers-shine-spotlight-on-aluminiums-role-in-electric-vehicles-idUSKCN24S1QM

[18] Robert Brooks, “Pushing for Larger-Dimension Diecastings,” Foundry Management & Technology, November 16, 2015. www.foundrymag.com/molds-cores/article/21928689/pushing-for-largerdimension-diecastings

[19] Tesla bets on aluminum casting for German plant. Reuters. September 08, 2020, Automotive News Europe. https://europe.autonews.com/automakers/tesla-bets-aluminum-casting-german-plant

[20] DuckerFrontier 2020.

industry's carbon footprint had been reduced by nearly 40%.[21] Aluminum recycling also mitigates over 90% of the greenhouse gas emissions associated with primary aluminum production while requiring just 8% of the energy.

The increased use of automotive body sheet in multiple vehicles represents an opportunity for recyclers to recover and reuse this high-value scrap stream. Aluminum ABS scrap from these vehicles is estimated to rise globally to 125 kt in 2035 and 246 kt in 2050, with most available in the United States for processing.[22]

While recycling of aluminum is strong and growing, research is underway to modernize the recycling technology to accommodate increased volumes and mixed material scrap. For example, researchers at the University of Michigan are developing easier and more cost-effective ways to make recyclable, lightweight automotive sheet metals. They are developing new design tools and best practices to assist material producers and automakers with closed-loop recycling.[23]

Next-generation manufacturing processes offer opportunities to lower cost, improve quality, and enhance the sustainability of aluminum applications.

[21] The Environmental Footprint of SemiFinished Aluminum Products in North America A Life Cycle Assessment Report. www.aluminum.org/major-sustainability-gains-north-american-aluminum-industry

[22] Yongxian Zhu, Laurent B. Chappuis, Robert De Kleine, Hyung Chul Kim, Timothy J. Wallington, George Luckey, and Daniel R. Cooper, "The coming wave of aluminum sheet scrap from vehicle recycling in the United States," Resources, Conservation and Recycling, Volume 164, January 2021, 105208. www.sciencedirect.com/science/article/abs/pii/S0921344920305255

[23] U-M launches $2M effort to make recyclable lightweight automotive sheet metals," April 21, 2021. Green Car Congress. www.greencarcongress.com/2021/04/20210421-cleansheet.html

GOALS FOR AUTOMOTIVE ALUMINUM

High-level goals have been established for automotive aluminum (Al) in the areas that are key to future growth and competitiveness. As illustrated in Figure 4, these goals address innovative products and engineering design, new and existing market opportunities, and aggressive recycling and sustainability requirements as an integral part of all future operations. Close collaboration and strong partnerships with OEMs will support high-value engineering of products and are critical to achieving goals.

PRODUCTS & ENGINEERING

Develop high-performance alloys/products to expand automotive Al.

- New generation of aluminum automotive alloys with higher tolerance for scrap content without compromise of properties.
- Ultra-high-strength alloys with more than 500 MPa in service strength.
- High-strength non-heat treatable die casting alloys.

Innovate and improve processes that are critical to key markets.

- Next generation of multi-material joining technologies allowing any grade of aluminum to be joined.
- Optimized designs for end-of-life recycling by 2025, jointly developed with OEMs.
- Protocols for real-time data sharing between aluminum fabricators and OEMs to enable process improvements with machine learning

MARKET PENETRATION

Grow North American automotive aluminum gross shipments from 8.7 Blbs in 2019 to 10.2 Blbs in 2025 and 13.8 Blbs in 2030, including both ICEs and battery electric vehicles (BEVs).

Maintain preferred material position and support massive growth, sustaining preference for Al content in BEVs and staying above Al content in conventional ICEs:

- Average Al content to remain above 630 pound per vehicle (ppv) through 2030, continue to be preferred material for battery enclosures, closures, cable management systems, and significant share of body in white (BIW).

Continue to replace steel in multi-material designs.

- Al content to grow from 450 ppv in 2020 to 510 ppv in 2025, and 570 ppv by 2030. Aluminum remains material of choice in powertrain castings and continues to substitute steel in closures and BIW.

RECYCLING & SUSTAINABILITY

Increase focus on sustainable, low-carbon products and processes.

- Improve the cradle-to-gate automotive aluminum carbon footprint to below 5 kg CO_2/kg Al by 2025 and around 3.5 kg CO_2/kg Al by 2030.
- Increase ultra-low carbon (inert anode) primary aluminum to 25% of current production by 2030.
- Support U.S. goals to achieve carbon-free power sector by 2035 and net-zero carbon economy by 2050 via renewables, carbon capture, and sequestration.

Develop technologies/methods to optimize recycling and scrap use.

- Establish closed-loop recycling for 100% of pre-consumer OEM manufacturing scrap by 2030.
- By 2025, establish collection, sorting, and return infrastructure for coming wave of end-of-life vehicle aluminum scrap.
- By 2030, develop advanced sorting technologies with volume capacity to separate shredded end-of-life scrap by alloy family.

Figure 4. High-Level Goals for Automotive Aluminum

DESIGN ENGINEERING

OVERVIEW

Design engineering refers to devising a material, system, component, or process to meet desired requirements. Design is an iterative decision-making process typically supported by fundamental sciences, process design tools, computational models, and a wide spectrum of physical and chemical properties data.

Lightweight aluminum body on Jaguar XF.

Alloy design engineers develop and test different formulations to understand the most cost-effective blends of elemental additives and the resulting properties of the final material. Component design engineers need to integrate materials that are adaptable, functional, and meet performance specifications, including requirements for recycling and waste reduction. Computational design methods are evolving rapidly along with digital technology and data science. Design engineers must be able to keep up with advances in design methods as well as OEM requirements to remain competitive, relevant, and successful.

The predicted explosive growth of the BEV market is highlighting design issues as well as opportunities in aluminum formability, joining, cost, and recyclability as compared to steel. Designers working to advance the use of aluminum in BEVs and other vehicle components have demonstrated the potential safety and lightweighting advantages of aluminum designs compared to steel. For example, aluminum can deform predictably and absorbs up to twice as much crash energy as steel.[24]

Designers of aluminum alloy components face challenges in the areas of joining and sustainability. Joining of aluminum and steel is a particular challenge for multi-material, lightweight design strategies. Challenges include galvanic corrosion potential in addition to joint strength and stiffness. Factors that impact joint properties must be fully understood and resolved to enable effective metallurgical bonding between aluminum and steels for automotive applications.[25]

Designing for sustainability (e.g., recycling, disassembly, waste reduction) presents additional challenges. Aluminum joined with dissimilar metals could be difficult to disassemble and separate for cost-effective recycling.

[24] ATG's 2019 Aluminum Design Workshop demonstrates safety and environmental benefits of automotive aluminum. *ALCIRCLE*, May 5, 2019. www.alcircle.com/news/atg-s-2019-aluminum-design-workshop-demonstrates-safety-and-environmental-benefits-of-automotive-aluminium-45819

[25] Majid Pouranvari (2017) Critical assessment 27: dissimilar resistance spot welding of aluminium/steel: challenges and opportunities, *Materials Science and Technology*, 33:15, 1705-1712, DOI: 10.1080/02670836.2017.1334310. Accessed 6/9/2021. https://doi.org/10.1080/02670836.2017.1334310

GOALS

Goals for design engineering focus on designing components that offer superior performance and longer life; raising awareness of the advantages of aluminum components in the automotive sector; and collaborating with OEMs to resolve key design issues. Specific goals identified for design are shown in Table 1.

Table 1. Goals for Design Engineering	
Near Term (1-5 years)	• Improved post-processing characteristics: shelf life, resolution of aluminum aging, joining and hemming issues. • Greater dissemination of aluminum design material models, practices, and comparative case studies (aluminum vs. other materials) within the OEM community. • Design of products with improved recyclability.
Mid Term (5-10 years)	• Improved models and materials data to support vehicle crash simulation. • Progress toward 4th- generation door designs. • Greater availability of high-strength, high-elongation materials that are easier to weld, form, extrude, and stamp.
Long Term (10+ years)	• Common customer specifications and design requirements.

FUTURE OPPORTUNITIES

Advances in design engineering can potentially open up enormous opportunities in automotive aluminum (Figure 5). For example, developing innovative ways to combine aluminum extrusions or incorporate other materials like steel into the components of assemblies could optimize both mass and performance. Design engineering can explore questions of how to join materials more effectively, and the effects of different design approaches on processing.

Collaboration between OEMs and aluminum manufacturers can increase the effectiveness of the design engineering process. Clear direction on defined automotive targets will produce the best possible products for each application. Specific areas in which close collaborations can improve designs include:

- *Structural design*—collaborating on composite materials to enhance crash performance; designing body structures and reinforcements that consolidate components (such as welded blanks with different gauges) to reduce weight.
- *Streamlined requirements*—combining requirements across design groups (e.g., battery and crash readiness), and creating common specifications across different programs for greater flexibility and reduced lead times.
- *Forming*—collaborating with OEMs to implement highly formable and high-strength aluminum to substitute for hot-forming steel components; applications for roll-forming of aluminum sheet.

Figure 5. Future Opportunities for Design Engineering

TECHNOLOGICAL/OTHER CHALLENGES

Several challenges have been identified related to design engineering (Figure 6). Major challenges for design center around improving the attributes of aluminum components to enhance its ability to compete with steel in the same or similar applications. Improved formability combined with higher strength would place aluminum in a more competitive position for structural components.

Joining and the recyclability of joined aluminum components are both key challenges for designers. The performance of innovative alloys and component designs must be balanced with the ability to recycle and disassemble the part at end of life (EOL). Joints and bonds that prevent the materials from being recycled are problematic and need to be addressed with new designs or innovations.

Many OEM design engineers and metallurgists have worked primarily with steel and remain unaware of the advantages of modern aluminum alloys or the performance gains and weight reductions that new aluminum designs can achieve. Training new engineers and designers in aluminum solutions is one way to reduce misconceptions about aluminum usage and capabilities.

Design Data and Testing

- Ensuring OEMs and Tiers have easy access to detailed, relevant, and updated material data for forming and manufacturing simulation.
- Developing models to inform design codes for component design.

Joining

- Developing more robust joining designs, particularly for dissimilar materials.
- Developing industry accepted standards and testing for bond durability (adhesive bonding) and pretreatment of bonded joints; correlating adhesive bond durability lab testing to field data.
- Improving resistance spot welding reliability to enable replacement of rivets; robustness of robotic spot welding (RSW) in aluminum sheet.
- Understanding the impact of joining and bonding on EOL recycling.

Plant and Component Design

- Designing components and subsystems for higher strength, improved formability/ease of fabrication, and increased corrosion resistance.
- Optimizing process and component design, while incorporating scrap utilization.
- Designing processes around modern digital tools such as AI/ML.

Figure 6. Technology Challenges for Design Engineering

R&D NEEDS

MAJOR RESEARCH TOPICS

Priorities for research revolve around design improvements for formability as well as joining and bonding (both to aluminum and multi-materials). Formability is of major importance for increasing the use of aluminum in structural components relative to steel.

Joining and bonding are integral to virtually all automotive component designs. New methods of joining and bonding are needed to make aluminum an attractive alternative to other materials, as well as for situations in which aluminum must be bonded to dissimilar materials. Using non-aluminum rivets and bonding materials may impact the capability to disassemble and recycle parts, making aluminum less attractive from a sustainability perspective. Research is needed in all of these areas to maximize the benefits of aluminum for end-users. The identified research needs are shown in Table 2.

Table 2. R&D Needs and Other Activities Identified for Design Engineering			
Category	**Priority** Low	Med	High
Design Data			
Generation of design data for advanced alloys and components; open-source databases to inform design and reduce design cycles; ability for sharing with OEMs for forming and manufacturing simulations.			◊
Understanding of mechanical and other property relationships to forming and processing, from material and component design perspectives.			◊
Integration of emerging specifications for new vehicle designs, based on OEM requirements.			◊
Material models for use in design codes, including fracture and spring back.		◊	
Joining and Bonding			
Evaluation of joining methods including welding, bolting, and potential innovations (electromagnetic pulse joining, laser welding).		◊	
Innovative joining processes that minimize flange lengths, allowing for designs that maximize the benefits of aluminum (e.g., specific stiffness).			◊
Methods to reduce the cost of joining aluminum; joining techniques to optimize results from the standpoint of cost, performance, and recyclability.		◊	
Plant and Component Design			
Vision for the design of an all-aluminum vehicle plant, as opposed to a formerly steel vehicle plant (processes to eliminate, such as paint).	◊		
Design process optimization/scrap reduction to lower cost relative to steel.	◊		

ACTION PLANS

Action plans for potential research efforts have been developed to address some of the most critical challenges in design engineering for aluminum alloys and components. The action plans describe the path forward, a detailed research approach, desired outcomes, and benefits to the industry. Specific projects include:

- *Establish Open Access Resource for Design Data (Figure 7)*—Properties and other data to inform design of materials and components; includes material cards, tolerances, mechanical, composition, and other information.
- *Optimize Joining Designs and Processes, including Adhesives (Figure 8)*—Advances in joining that minimize flange lengths and designs that maximize joint-specific stiffness and reduce overall cost.
- *Improve Aluminum Component Manufacturability and Process Design (Figure 9)*—Designing for process digitization and optimization, scrap reduction, and the future all-aluminum vehicle plant.

Establish Open Access Resource for Design Data

A comprehensive and accurate set of data is an important foundation for the design process. In developing new alloys as well as components, data can be used in design simulations to predict and compare the performance characteristics of different alloys and how they will behave as a formed component under practical operating conditions.

Table 3. Establish Open Access Resource for Design Data: R&D Benefits

Rank	Impacts
●●●●●	**Design Optimization**: Comprehensive, accurate data enables better material selection and shortens design cycles.
●●●●●	**Reduced Cost:** Data enables OEMs to identify desired performance characteristics of available alloys and optimize material/cost for specific components.
●●●●●	**Vehicle Performance:** More accurate prediction of part performance is possible.

Research is needed to develop detailed, relevant, and updated material data for forming and manufacturing simulations. Data should be able to support OEM requirements in conducting material selection, enabling comparisons to common parameters with other materials. Open access to enable sharing of this data with OEMs will be critical to encouraging greater use of aluminum in automotive.

Information for input to material cards and provide understanding on tolerances, mechanical properties, or other relevant data should be included. The potential impacts of research are shown in Table 3.

Good design data enables developers to work toward a performance goal and compare different types of material options, rather than developing an alloy and testing the outcomes. It allows designers to change properties, see the impacts, and then expand or change targets for new alloys that better meet customer requirements. Good predictive models and data can also support design processes for parts, informing OEMs on potential issues. Automakers will always look for lighter, stronger doors, and other ways to improve safety and performance. To push beyond low range BEVs, OEMs need to see the predicted impact of aluminum and decide if it makes sense for specific components.

Research should include collaboration OEMs to identify important properties data needed to optimize selection of aluminum for key components. Figure 7 illustrates the roadmap and action plan for developing improved data for design.

Figure 7: Establish Open Access Resource for Design Data

Barrier/Problem Statement: Open source, consistent properties data are lacking to enable comparative design simulations and expedite product development. Data accessibility is an important challenge; OEMs need better access to a wider range of data to enable selection of aluminum as a premier material of choice.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Determine type of data needed for company-specific alloys and identify common properties suitable for pre-competitive research. • Conduct research to fill gaps in materials and component data needed for predictive designs. • Develop data for best design practices for aluminum in extruded, rolled, or cast parts; included specific impacts on performance characteristics (e.g., higher R or N values, elongations, etc.) • Work with OEMs to determine data gaps and needs. • Develop wide range of data related to joining and adhesive processes. • Develop methods and platforms for safe and secure sharing of properties and process data.	• Open-source databases of properties and characteristics related to casting, rolling, and extrusion, by component. • Protocols for design best practices for all forming types.
5-10 years	• Develop process for periodic update of open-source data. • Work with OEMs to understand new data requirements as future component designs emerge.	• Periodically updated open-source databases.

Stakeholders and Potential Roles

Product manufacturers: Contribute to database with material and product data.

End-users/OEMs: Provide future requirements and input on data gaps; test and use databases.

National laboratories: Collaborate on projects, conduct applied research.

Government: Provide resources for pre-competitive research.

Academia: Develop data; conduct fundamental research to develop new data sources and measurements.

Aluminum Association: Provide central ownership of databases to ensure open access.

Optimize Joining Designs and Processes, Including Adhesives

Joining, bonding, and adhesive processes are critical factors for the design and deployment of aluminum automotive components. Types of joining technologies include mechanical fasteners (bolts, nuts, rivets), welding (fusion welding, resistance spot welding, laser welding, friction stir welding), adhesive bonding, brazing/coating, and soldering. A technique is applied based on factors such as the cost and strength required for a given joint. Combinations of techniques can be used for assemblies or parts that are difficult to join.

Table 4. Optimize Joining Designs and Processes, Including Adhesives: R&D Impacts

Rank	Impacts
●●●●	**Cost Reduction:** Innovative joining/bonding processes are expected to reduce costs and wastes.
●●●●	**Weight Reduction Potential:** Improved joining can reduce bonding surface and material overlaps, reducing material needs; enables use of higher strength and lower ductility materials.
●●●●●	**Vehicle Safety:** Better joint durability will lead to improved component and vehicle life.
●●●●●	**Multi-Material Aspects:** Innovations in joining will enhance marketability of aluminum in new applications.

Designs often call for joining of aluminum and other materials (e.g., steel), which can be challenging. Aluminum has three times the thermal conductivity and four times the electrical conductivity of steel, requiring higher welding currents. Aluminum joints can melt before the steel joint has melted. Intermetallic compounds can form, which are brittle and difficult to prevent or control. Galvanic corrosion is a challenge with materials that have different electrode potentials. Welding can have advantages over other joining methods, including less weight, less material waste, and stronger bonds. Innovations in welding techniques are emerging, such as refill friction stir spot weld technology and a spinning process based on rotational friction welding that can join aluminum, steel, and other lightweight materials.[26]

Designs need to be flexible and adaptable for different types of joining technologies, with a focus on cost as well as joint strength and longevity. Research is needed to explore joining techniques that can provide the best results from the standpoint of cost, performance, material/waste reduction, and recyclability. Table 4 illustrates some of the potential impacts and considerations of proposed research.

Applied research is needed to map the best methods for a given joint. This research involves finding ways to extrapolate joint effectiveness for material combinations that have not yet been physically tested using material models and properties. Joining designs that minimize flange lengths are needed to maximize the benefits of aluminum (e.g., specific stiffness). An understanding of failure modes is needed, such as the effects of heat-affected zone (HAZ) softening on joint strength.

Figure 8 illustrates the roadmap action plan for improving the design of joining and adhesive processes, including joining of dissimilar materials. Successful research could lead to new types of joining that use less material and are more cost-effective, easier to recycle, and enable greater use of aluminum in automotive applications.

[26] New Techniques for Joining Steel and Aluminum. Assembly e-Magazine. April 11, 2017. www.assemblymag.com/articles/93777-new-techniques-for-joining-steel-and-aluminum

Figure 8: Optimize Joining Designs and Processes, Including Adhesives

Barrier/Problem Statement: Limitations in joining are dependent on the method and material(s). Welding can be problematic when joining aluminum with steel due to formation of intermetallic phases, while mechanical joining has limitations for high-strength, low-ductility materials. All joining technologies are limited by differential thermal expansion rates during vehicle paint baking. Most joining technologies are irreversible, making it difficult to separate different materials later for recycling. Industry standards are lacking for bond durability and for consistent testing/requirements across OEMs.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Conduct research to understand which joining techniques provide the best results from a standpoint of cost, performance, and recyclability. • Compile available details of processing parameters for joining technologies for different material/thickness combinations; identify important commercial joint combinations for optimizing and generalize requirements to enable prediction of best practice joining. • Establish adhesive bond durability SAE testing standards, procedures, and requirements for aluminum; establish deep understanding of factors contributing to test performance. • Understand limits/opportunities of Al welding by studying coated high-strength steel. • Collect existing data and examples and generate additional joining data and joint test results for a wider range of joining technologies and material combinations. • Explore innovations in joining and bonding to reduce cost and improve durability. – Multi-material and multi-product (castings, extrusions, sheet) joining. – Techniques such as laser welding (issues with reflectivity), electromagnetic pulse joining, rapid friction stir welding for welded blanks. – Spot welding of aluminum as an alternative to using rivets. – Joining processes that minimize flange lengths and maximize design. – Joint designs to prevent hot cracking.	• Stronger, more durable joining and bonding methods. • Standardized, open database of best practice joining methods for material combinations. • Standards for joint and bond testing and validation. • Improved welding methods to enable a wide variety of material combinations. • Joining and bonding innovations to support new markets.
5-10 years	• Develop clear understanding of root-cause failure mechanisms, especially for welding technologies (e.g., HAZ softening, brittle phases, hot cracking); develop mitigation strategies for failure modes. • Test and validate new joining concepts on automotive components. • Continue to explore innovations in joining as vehicle component markets emerge.	• Cost-effective joining and bonding innovations to meet OEM needs.
>10 years	• Research new adhesive bonding technologies for reversible joints that can be deactivated at end of life, such as UV-cured adhesives that set very fast and mechanical joints that eliminate fastening elements for each joint configuration.	• Components with improved joints and disassembly potential.

Stakeholders and Potential Roles

Product manufacturers, product designers, design engineering groups: Design and specify innovative joints and bonds for performance, recyclability, and test designs; provide supplier process and physical data and joining expertise.

End-users/OEMs: Specify vehicle performance, cost, and recycling requirements; provide data, specifications, and test joints for integrity and durability; ensure capability for after-market maintenance/repair of new material combinations.

Scrap suppliers, automotive shredders/sorters: Provide data on recyclability and impact of joining technology.

National laboratories: Scale validation; interface with manufacturers/producers on research projects.

Government: Support advanced manufacturing research.

Academia: Build models and conduct research toward understanding the mechanisms of failure modes and root causes.

Improve Aluminum Component Manufacturability and Process Design

Improved data and methodologies are needed to enhance design codes and enable better understanding of performance and other factors in the early stages of design. Materials data, including fracture and spring back data, is key to understanding how new designs will perform under practical conditions. Materials data is particularly important for the design of aluminum components to be used in totally new applications or those in which the components will be exposed to unusual external stresses or environments (e.g., crash, fire, etc.).

Table 5. Improve Aluminum Component Manufacturability and Process Design: R&D Impacts

Rank	Impacts
●●●●	**Cost Reduction:** Innovative designs can reduce material waste and consolidate parts, reducing both raw material and processing costs.
●●●●	**Weight Reduction Potential:** Comprehensive design codes can help to predict performance in new applications, enable parts consolidation, and support other strategies for lightweighting.
●●●	**Vehicle Safety:** Better understanding and prediction of component crash protection, wear, and durability will lead to fewer failures and improved vehicle safety.

Research is needed to collect, validate, and incorporate material and other types of data in design codes. The need includes mechanical properties data as well as any other data that helps to evaluate the durability and wear (e.g., aging) of components during practical use.

Secondary aluminum is a large and growing market segment with many opportunities for use in future vehicles. The industry needs design models that incorporate factors pertaining to the recycling and reuse of components. Such models will require data on the compatibility of different types of aluminum alloys used in parts, as well as feasible means for disassembling those parts. Table 5 shows potential impacts of the proposed research.

Research is needed to support development of innovative designs for the vehicle factory of the future—where use of aluminum is maximized, processing requirements are optimized, processes are flexible and efficient, and closed-loop recycling is routine. In the future, automakers could also be producing a next generation of vehicle body designs with totally restructured interior and exterior styles, creating a need for new component designs.

Figure 9 shows the roadmap action plan for improved design of both aluminum components and manufacturability. Successful research will lead to design codes that give designers greater flexibility and empower them to produce innovative designs for high-performing vehicle components.

Figure 9: Improve Aluminum Component Manufacturability and Process Design

Barrier/Problem Statement: Automotive designers currently have insufficient access to robust materials property and process data for optimizing or performing comparative analysis of designs. Limited collaboration with OEMs on key design requirements, especially for vehicles in the early design stage, creates challenges to effectively designing to key performance attributes and results in multiple iterations, adding time and cost to design.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Develop material models for use in design codes. – Fracture and spring back – Materials data to support crash simulations – Post-processing characteristics, such as shelf life, aging, etc. – Data to enable materials comparisons (between Al alloys and other materials) • Disseminate aluminum design material models and practices within the OEM community; work closely with OEMs on understanding new design requirements; formalize and build relationships. • Initialize new design activities with a big-picture focus. – Vision of an all-aluminum vehicle factory – Parts consolidation, huge castings, etc. – Vehicle body redesign/restructure – Processes that could be eliminated, such as paint – Next-generation design of body structures (e.g., doors) and innovative vehicle components • Design alloys and components for process optimization and scrap reduction relative to steel and other materials. – Models that incorporate data on compatibility of alloys for recycling – Scrap material cleaning and sorting technology progress integrated into the alloy development process; universal alloy development	• Enhanced material design models. • New, flexible design approaches to meet changing requirements for future vehicles. • Reduction in number of parts and processing steps to reduce cost.
5-10 years	• Incorporate changes in requirements into models and designs as they emerge. • Continue building partnerships with OEMs to stay on top of changing requirements.	• Cost reductions through improved designs.

Stakeholders and Potential Roles

Product manufacturers, product designers, design engineering groups: Participate and contribute to material models and design codes.

End-users/OEMs: Specify vehicle performance, cost, and recycling requirements; test and validate new designs in practice; provide insights on the future vehicle plant and ideal processing characteristics.

Government: Support advanced manufacturing research.

Academia: Interface with manufacturers and producers on research projects.

NEW ALLOYS, GRADES, AND PRODUCTS

OVERVIEW

BMW X5 Structural casting (shock tower).

Aluminum is a versatile metal with many advantages in terms of recyclability, weight reduction, and carbon footprint. To compete with steel more effectively in automotive markets, new aluminum alloys and grades need even better performance characteristics than today.

In general, aluminum alloys are identified by four-digit composition classes, which fall into two main classifications: heat treatable (2xxx, 6xxx, 7xxx) and non-heat treatable (1xxx, 3xxx, 4xxx, 5xxx).[27] Aluminum alloys used in automotive are cast, extruded, or rolled depending on their vehicle application. Automotive alloys fall into numerical series (e.g., mostly 6xxx, 5xxx) based on chemical composition; each alloy within the series has tempers[28] defining properties, formability, and other characteristics. 6xxx series alloys are generally higher strength than 5xxx alloys.

Aluminum alloys are composed of various alloying elements that provide strength, corrosion resistance, formability, or other attractive properties. Silicon, copper, magnesium, manganese, and zinc are some of the elements commonly combined with aluminum to form alloys. In addition to composition, post-processing techniques and strengthening mechanisms can impart unique performance characteristics. For example, work-hardening, precipitation-hardening, annealing, aging and other processes can affect properties of strength or formability.[29]

Series 7xxx offers ultra-high strength and has been used primarily in the aerospace industry. Alloys in this series balance strength, corrosion, and fracture toughness and may potentially gain acceptance and use in structural automotive applications requiring impact resistance. Specific chemical compositions or innovative processing techniques further enhance performance characteristics.

New generations of 6xxx and 7xxx series alloys are in development to provide additional strength at lower cost to meet automaker needs and expectations. Additives such as scandium, zirconium, and lithium can be added to improve performance. Challenges to be resolved include resistance to corrosion and stress, strength retention, ease of welding, ability to easily join different aluminum alloys and other materials; and crack/impact resistance.

Recyclability of aluminum alloys is critical to sustainability. Alloys that can accommodate increased amounts of iron, copper, and other elements will facilitate production from closed-loop recycling, which is on the rise to meet the growing demand for sustainable vehicles.

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[27] Aluminum Alloys 101. Aluminum Association. www.aluminum.org/resources/industry-standards/aluminum-alloys-101

[28] Common temper designations for aluminum alloys include -F (as fabricated); -0 (annealed); -H (strain hardened); -T (thermally treated); and -W (specific as-quenched condition).

[29] Aluminium Alloys in the Automotive Industry: a Handy Guide. Aluminum Insider. 2/28/2019. Accessed 5/20/2021.https://aluminiuminsider.com/aluminium-alloys-automotive-industry-handy-guide/

GOALS

Goals for alloys focus on improved performance characteristics, form-specific grades, and increased recycling capabilities. Specific goals identified for new alloys, grades, and products are shown in Table 6.

Table 6. Goals for New Alloys, Grades, and Products	
Near Term (1-5 years)	• Non-heat treatable casting alloys. • Aluminum laminated sheets (e.g., Quiet Aluminum®) with noise, vibration and harshness dampening performance. • Tighter, more consistent properties, and increased performance, including 6xxx series alloys. • Extrusion alloys combining high strength and extrudability, variable extrusion thicknesses.
Mid Term (5-10 years)	• Standardized formability tests for new alloys and mapping of alloy solutions. • Recycling of inner layer of aluminum laminated sheet. • High ductility casting alloy and structural die castings that eliminate the need for heat treatment. • Semi-solid alloys for giant castings allowing components rationalization for less costly architecture.
Long Term (10+ years)	• New alloys that meet or exceed selected properties of high-strength steel, e.g., formability. • Recycling-compatible alloys/alloy blends—fully recyclable at vehicle end of life (EOL).

FUTURE OPPORTUNITIES

The growing demand for high-performance automotive materials is creating a wealth of prospects for new aluminum alloys, grades, and products. Opportunities range from high-performance grades to more sustainable and recyclable alloys. Figure 10 illustrates the spectrum of opportunities identified.

Cost is an over-arching consideration for product opportunities. Automakers want alloys with higher strength, formability/ductility, fracture toughness, and extrudability—at lower cost. For example, non-heat-treatable alloys provide cost advantages for some components, producing less-expensive wrought products and mitigating the need for heat-treating equipment. Innovative processes could enable intricate forming of aluminum shapes (beyond die casting) with improved properties and better finishes. Large castings or castings that consolidate multiple assemblies can also provide cost savings as well as weight reduction.

Alloys with higher strength and good formability to enable continued downgauging, and other important characteristics can find applications in many different types of structural automotive components. Opportunities for structural components are expected to grow rapidly with the expansion of BEVs in the marketplace.

Figure 10. Future Opportunities for New Alloys, Grades, and Products

Collaboration between OEMs and aluminum manufacturers can streamline and accelerate the alloy and grade development process. Clear direction on automotive industry targets and specific properties wanted for new alloys will expedite delivery of the best possible alloys and products for a given application. Specific areas in which close collaborations are most critical include:

- Alloy design—working together to redesign alloys—high-strength 6xxx and potentially 7000 series alloys, when possible.
- Crashworthiness—characterizing alloys for design/crash simulation and improving impact resistance.
- Semi-solid casting—developing suitable alloys with short cycle times and low-cost casting processes.
- Recyclability—understanding levels of acceptable alloy recyclability versus performance; requirements for levels of recycling content; “green” drivers, i.e., overall life cycle.

TECHNOLOGICAL/OTHER CHALLENGES

Diverse technological challenges for developing new alloys, grades, and products have been identified, ranging from reducing development cycle times to harmonizing testing of alloy performance. Figure 11 summarizes some of the key challenges.

Long development cycles make it difficult to effectively formulate and produce new alloys to meet the needs of emerging, fast-paced markets. Simulation tools such as integrated computational materials engineering (ICME), artificial intelligence (AI), and machine learning (ML) hold great promise to reduce development times but have not yet been adapted to aluminum alloy application. More information on materials properties and data will help to move these tools forward for aluminum alloys. The steel industry has an advantage in that data is more standardized in its high-strength grade structure.

Standardization across alloys across producers is a challenge. Ideally, an OEM would be able to source the same alloys from multiple manufacturers (similar to steel) and know that the properties would be uniform.

High-Performing Alloys

- Developing affordable, ultra-high-strength, corrosion-resistant aluminum grades exceeding the specific strength of press-hardened steels.
- Understanding complexity in developing more independence between tensile properties and formability (i.e., improving properties without a decrease in formability).
- Ensuring all new alloys are fully compatible with closed-loop and end-of-life recycling.

Simulation and Data

- Updating simulation/material property cards for Computer Aided Engineering (CAE) for safety, durability, and other attributes to cut costs and speed up development time.
- Expanding use of simulation tools that could shorten alloy development cycles.
- Developing statistically significant databases, with accurate data for each alloy.

Testing and Qualification

- Achieving industry-wide consensus on fit-for-purpose material specs and testing, including joining and bonding durability.
- Ensuring ability to accurately test across multiple facilities (e.g., correlate mechanical properties between tensile test equipment, labs, etc.).
- Lowering the cost of component performance testing.

Figure 11. Major Challenges for New Alloys, Grades, and Products

R&D NEEDS

MAJOR RESEARCH TOPICS

Priorities for research focus on the development of new alloys for casting and extrusion; advanced or innovative process designs to accommodate new alloys and products; the use of computational design methods for alloy development; and the establishment of consistent testing and validation protocols. Table 7 summarizes some of these research needs.

The aluminum industry is highly motivated to continue developing new and/or enhancing existing alloys with properties that are comparable to steel but can be manufactured and delivered at a competitive cost. Improvements to existing 6xxx series alloys, for example, could enhance mechanical properties and improve extrudability and formability. Alloys are developed in tandem with the process for which they are designed; process innovations can impart improved functionality and performance to the final component or material.

Table 7. R&D Needs and Other Activities Identified for Alloys, Grades, and Products

Category	Priority		
	Low	Med	High
Alloys for Casting and Extrusion			
High-strength 6xxx extrusion alloys with excellent extrudability and high formability.			◊
Castable aluminum alloys with improved strength and ductility.			◊
Addition of exotic elements to base alloys to improve properties.		◊	
Evaluation of alloy composition compatibilities based on EOL recycling.		◊	
Data and Computational Design			
Generation of data for existing alloys and new alloys; expansion of property database expansion to meet needs of designers.			◊
Deeper understanding of the process-property relationship.			◊
Wider training/knowledge in advanced computational techniques for materials R&D.			◊
Exploration of materials properties in various axes (X,Y,Z), especially in extrusion, that result in non-isotropic mechanical properties.			◊
Testing and Validation			
Common testing protocols for next-generation alloys to establish consistency.			◊
Accessible casting pit facilities for making small volumes of billets/ingots.			◊
Component-level testing beyond the coupon level (i.e., fatigue testing).			◊
Column crush and 3-point bend test availability for sheet and profiles.		◊	

Effective computational tools are the foundation for successful materials design. Research is needed to fill gaps in fundamental materials data and to use that data more effectively. A better understanding of how the manufacturing process impacts material properties will help guide designers in developing process innovations as well as new material blends.

An industry-wide challenge is the consistent testing and validation of alloys and components. Many producers utilize their own testing protocol following industry standards; OEMs and end-users also have unique testing and validation requirements. This variability highlights the need for standardized and consistent methods, which may require additional research.

ACTION PLANS

Action plans for potential research efforts were developed to address some of the most critical challenges in the development of new alloys, grades, and products. The action plans describe the path forward, a detailed research approach, desired outcomes, and benefits to the industry. Specific projects include:

- *Tailor Alloys for High Performance in OEM-Specific Applications (Figure 12)*—Methods and technologies to develop innovative alloys with enhanced performance properties to meet automotive requirements.
- *Harness Data Analytics and Predictive Modeling of Alloy Properties (Figure 13)*—Fundamental data and models to expedite and improve design and production of new alloys.
- *Expedite Testing and Qualification of Next-Generation Alloys (Figure 14)*—Standardized methods for testing, validating performance, and qualifying new materials and components.

Targeted research will support development of higher-performance aluminum alloys to meet emerging automotive needs.

Tailor Alloys for High Performance in OEM-Specific Applications

New alloys are needed to meet the demand for higher-strength, lightweight, durable, and recycle-friendly aluminum components. Research will focus on developing new alloys, including a 6xxx series alloy for extrusion with high mechanical properties, excellent extrudability, and high formability; and wrought and castable aluminum alloys with higher performance and strength. Projects will consider strength, ductility, fatigue, and toughness properties at room and elevated temperatures. Collaboration will improve understanding of OEM expectations and uniform testing and data reporting across the industry. Table 8 illustrates some of the impacts and considerations for research to develop advanced alloys.

Table 8. Tailor Alloys for High Performance in OEM-Specific Applications: R&D Impacts

Rank	Impacts
●●●●●	**Reduced Cost:** OEMs are highly sensitive to $/kg saved and cost of raw materials and processing.
●●●●	**Weight Reduction Potential:** Improved, more readily recycled alloys support greater use of aluminum for weight reduction.
●●●●	**Vehicle Performance:** New alloys provide more lightweighting, parts consolidation, and enhanced driver compartment comfort.
●●●●●	**Sustainability:** Improves carbon footprint with greater recycling, more lightweight vehicles; could be impacted by carbon tax.
●●●●●	**Joining/Multi-Material (MM) Aspects:** Increases market potential for MM joining solutions.

New alloys will also need to be more recycle-friendly. Any new alloys that are developed must have more tolerance for recycled content. Recyclable sheet alloys should be tolerant of one another. Carbon tax could impact cost metrics; environment, social and governance (ESG) funding availability may increase OEM ability to gain low-cost capital.

The impact of impurities (i.e., in recycled materials) on alloy performance needs further exploration. While data exists, credible publicly available information needs significant augmentation to examine the effects of impurity elements on a broader range of aluminum alloys. The use of casting alloys could potentially increase, though in a different format than used today (e.g., Tesla has proposed an entire system formed via aluminum die casting). Several million tons of castings with relatively low purity are in vehicles now on the road; future castings are being developed with a focus on high quality.

Innovations are needed so that secondary aluminum can be deployed at full value in automotive components or parts, with some compromises on purity as long as performance is attained. Aluminum inputs today are mostly 100% secondary aluminum (scrap) or 100% primary aluminum. The industry needs to be able to efficiently mix scrap and primary aluminum, similar to what is done with steel. Steel has an advantage in that any useless steel scrap can be used for construction; similar approaches are needed for aluminum (over and above engine blocks).

Figure 12 illustrates the roadmap and action plan for advancing joining technologies, particularly for multi-material component designs.

Figure 12: Tailor Alloys for High Performance in OEM-Specific Applications

Barrier/Problem Statement: Alloys are needed to meet automotive requirements for strength, ductility, toughness, formability, and other key performance properties. Barriers to be addressed include the lack of testing uniformity and data reporting across the industry and limited situational awareness of OEM requirements for materials and cost.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Refine baseline cost and mass ($/kg) for primary parts; baseline properties and benchmarks versus forming processes; define improvement goals for properties of interest using baseline research and "outside the box" properties. • Pursue R&D to develop sheet and extrusion alloys that are recycle-friendly. – Consider strength, ductility, fatigue, and toughness properties at room and elevated temperature – Demonstrate impact of elements on 6000 series and related alloys – Develop closures and BIW more tolerant of recycled content • Conduct collaborative project to develop an alloy that is extrudable with extremely thin wall thickness (1 mm). • Research additions of exotic elements to base aluminum alloy to yield better properties; evaluate alloy composition compatibilities based on EOL recycling. – Fundamental research on low-cost alloying elements/interactions, structure/ crystal formation; correlate to multi-physics engines that predict alloy behavior • Develop ICME tools for alloy development to speed up development cycle; include key data, properties, and materials testing; apply to extrusion, sheet, and casting.	• Design allowables for standardized material properties (database) • Established values and targets associated with critical properties. • Down-gauged size of current parts through increased strength (30-50%) • Alloys that are recycle-friendly and compatible with EOL recycling (e.g., flat rolled, extruded, cast).
5-10 years	• Evaluate new manufacturing processes (e.g., rheo-casting) for structural components (semi-solid) in future vehicle markets. • Study end-to-end parts consolidation impacts (i.e., vehicle doors); evaluate value of reducing number of individual components into a single casting. • Demonstrate recycle-friendly alloys developed based on studies in year 1-5.	• Target 40% minimum weight reduction via strength increase. • 20% reduction in parts per vehicle. • Faster cycle time and smaller plant footprint.

Stakeholders and Potential Roles

Product manufacturers: Realize improvement benefits, develop design allowables.[30]

End-users/OEMs: Provide input on design criteria and driving properties.

Scrap suppliers, automotive shredders/sorters: Research technology, support future of EOL recycling in terms of supply chain.

National laboratories: Model using ICME; studies on advanced characterization; collaborative projects on new alloys.

Government: Provide program support and SAFE standards.

Aluminum Association: Serve in a coordination role, conduct workshops and stakeholder engagements.

[30] Design allowables - statistically determined materials property values derived from test data.

Harness Data Analytics and Predictive Modeling of Alloy Properties

Property data is vital for developing new alloys, understanding potential physical characteristics, and predicting or simulating how material will perform in various environments.

Research is needed to develop properties data and create accessible databases that contain information useful for alloy selection for automotive applications. Connecting data to processing is critical as processing methods can impart different performance characteristics. The objective is to create databases for aluminum that are similar to those used for steel, making it easier to select aluminum as a material of choice. The potential impacts of research are shown in Table 9.

Table 9. Harness Data Analytics and Predictive Modeling of Alloy Properties: R&D Impacts

Rank	Impacts
●●●●●	**Design Optimization**: Materials data makes it easier for customer to decide when to use/select aluminum; and standardizes data.
●●●●	**Design Tools:** Accessible, comprehensive data enables focused application of ICME and avoids IP issues; allows metallurgical data to drive property evolution.
●●●●●	**Reduced Cost:** Data speeds identification of desired goals for new alloys, by predicting which property needs to change; interpolation between conditions helps uncover structure-property correlations.
●●●●●	**Vehicle Performance:** More accurate prediction of part performance is possible.
●●●	**Sustainability:** Assures compatibility with low carbon, high recyclability themes.

Predicting alloy performance characteristics and changes with different chemistries is possible through simulation software. Predictive capability is dependent on the type and quality of data available for input. Software requires some basic properties data to be effective; part of this research will include collaborating with software suppliers and OEMs to identify and develop key properties data for aluminum and associated processes. Materials come from around the world, and information for materials requirements should be gathered from both domestic and global automotive manufacturers. There is the potential to collaborate with European companies and universities doing research and partner or find ways to share pre-competitive data.

A deeper, more fundamental understanding of the process-structure-property relationship in aluminum is needed to better direct future product development. ICME could be utilized on the front end to define property evolution. Data card definition on the back end will provide OEMs with requisite data needed. Figure 13 illustrates the roadmap and action plan for developing properties data and supporting the effectiveness of good predictive models.

Figure 13: Harness Data Analytics and Predictive Modeling of Alloy Properties

Barrier/Problem Statement: Good properties and other data is lacking, particularly for new alloys, for predictive modeling and directing further product development. More comprehensive and accessible data as well as better understanding of property relationships is needed, particularly for ICME.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Explore steel databases used by OEMS and develop similar databases for aluminum (casting, corrosion, joining, etc.); work with OEMS to identify simulation software, required data/format, and material requirements (e.g., alloy, structure, representative properties of high-grade steel). • Explore best software to enhance/improve design process for new alloys, such as AutoForm for stamping; Magma for casting; flowability simulation, etc. • Understand current state of ICME for aluminum and chemistry/microstructure characterization; identify needed data and improvements.	• Database of properties matrixed to software for forming processes. • Clear definition of data/alloy states for data cards. • “How to Design with Aluminum” best practice document. • Broadly accessible, software packages for ICME and processing.
5-10 years	• Develop ICME approach to alloy development and practical deployment. • Develop standard process for periodic updates to property databases; update as new alloys are developed; refine with emerging OEM requirements. • Work continuously with OEMs to determine new requirements for emerging vehicles; expand to global OEMs and manufacturing.	• Computationally planned improvements for alloys. • Training tool for utilizing ICME approach. • Periodically updated data/database.
>10 years	• Deployment of specifically designed alloys and processes into production and vehicle application. • Develop virtual handbook with mechanical properties for selected alloys to support design of aluminum; includes major processes and supports curricula in engineering schools; enables engineers who work with steel to understand advantages of aluminum and aid in material selection.	• ICME-elucidated alloys meeting OEMs’ cost and performance needs. • Handbook integrated with curricula.

Stakeholders and Potential Roles

Product manufacturers: *Software suppliers*—provide formability simulation software, casting software, etc. *Product manufacturers*—implement, apply ICME tools; generate data for data cards.

End-users/OEMs: Provide future material requirements, desirable properties, data formats, IP restrictions; benefit from data.

Scrap suppliers, automotive shredders/sorters: Economically segregate new alloys; input on recycling stream impacts.

National laboratories: Conduct fundamental work on metallurgical structures; large-scale data generation/collection.

Government: Direction/coordination of resources for pre-competitive research; incentives for sharing data.

Academia: Develop data; fundamental research on constructing/linking ICME tools across length scales; provide students with project and real-world options for material selection.

Aluminum Association: Take ownership of database; work with simulation suppliers; and assist with handbook (similar to aluminum design manual).

Expedite Testing and Qualification of Next-Generation Alloys

The testing and qualification of new materials go hand in hand with materials design and production. Testing standards require research to collect data and better understand the physical and chemical properties of new materials and their impacts on performance and functionality. Tests cover a wide range and could include mechanical testing, failure analysis, corrosion testing, chemical and metallographic analysis, environmental testing, melt quality analysis, leak testing, welding tests (e.g., voids, lack of fusion), and many others depending on the application or purpose (new material or part).

Table 10. Expedite Testing and Qualification of Next-Generation Alloys: R&D Impacts

Rank	Impacts
●●●●	**Design Optimization**: Standardized testing and protocols support the ability to predict and test part performance across industry and OEMs.
●●●●	**Reduced Cost:** More accurate early-stage testing of an alloy or component reduces the time and cost of development and deployment cycles.
●●●●	**Vehicle Performance:** More accurate testing provides greater assurance of part suitability for the intended application.

Qualification testing verifies the part design and production process, ensures requirements are met, and provides a baseline for acceptance. A part qualification test that ensures the material, component, and or part quality is integral to a robust, continuing supplier relationship. Qualification testing may be conducted by third parties or by the OEM.

Research is needed to develop and standardize testing methods that can be used across the industry, and to establish shared facilities where samples can be produced and tested in a uniform manner. The potential impacts of research are shown in Table 10. Current testing methods for aluminum need to be more consistent and standardized across OEMs and the industry. Many OEMs have their own unique testing and qualification methods based on specific requirements; aluminum producers may also conduct tests unique to an alloy or component. Testing methods are sometimes proprietary and used only by the individual supplier to protect intellectual property.

Suppliers need better capabilities to test whole components rather than coupons. Coupons are small samples that are typically removed from the existing structure or material batch and used for subsequent analysis and testing, such as tensile and chemical tests. Due to their small size, coupons might not accurately reflect how a material will perform in the final component application. While many OEMs operate their own testing laboratories, the aluminum industry needs a shared or individual test facility to enable larger-size sample testing for strength, forming, joining, part qualification, and other properties.

Automated testing of cast, clean billets, or ingots could be useful. Melting processes need to be controlled and tested early. In other cases, tests are available but not readily accessible (e.g., three-point bend testing). Figure 14 illustrates the roadmap and action plan for developing standardized testing and qualification techniques for next-generation alloys and components.

Figure 14: Expedite Testing and Qualification of Next-Generation Alloys

Barrier/Problem Statement: Testing and qualification methods are currently not standardized or consistent across aluminum producers and OEMs or end-users. Testing is often conducted on sample sizes that are too small to give accurate measures of the performance of the produced part or component.

	Roadmap Action Plan	Overarching Goals

1-5 years	• Develop common testing protocols for next-generation alloys to enable consistency across OEMs and industry.
	  – Work with OEMs and end-users to determine common requirements for protocols
	• Design methods for component-level testing that will improve upon the usual coupon level.
	• Develop a practical, standard column crush and three-point bend test that will be made available for aluminum sheet and profiles.
	• Research processes for dedicated lab-scale rolling and annealing/heat treatment lines to enable rapid production and qualification of prototypes.
	• Establish methods for producing the most appropriate sample sizes.
	  – Facilities able to cast a small volume of ingots or billets
	  – Standard protocols and methods for producing a meaningful starting product size (not just very small samples)
	• Conduct fundamental research to properly understand the metallurgy in casting wrought products.
	• Collect data on pilot testing and use of aluminum powders to advance and expand design techniques.
		• Standardized tests applicable across OEMs and aluminum industry.
		• Protocols and methods for producing appropriately sized samples for measuring performance.

Stakeholders and Potential Roles

Product manufacturers: Provide and develop testing formats; qualify alloys and components; establish testing and sample production facilities.

End-users/OEMs: Provide future requirements and specifications; provide input to testing formats and apply.

National laboratories: Conduct fundamental work on metallurgy and testing facilities.

Government: Direct/coordinate resources for pre-competitive research.

Aluminum Association: Provide forum for discussion and establishment of protocols and test methods.

FUTURE VEHICLES

OVERVIEW

Extruded aluminum crash can for bumper (crash management system).

Technology has been disrupting the automotive sector for over a decade (i.e., digitalization and electrification). Digital advances have led to a reinvention of both hardware and software in vehicles, leading to connectivity and autonomy. Engineers are moving toward the next generation of automated intelligent vehicles (AIVs) by replacing human eyes with cameras, sensors, and lasers to enable navigation. Future vehicles will provide connections to people, objects, and the surrounding infrastructure. Electrification is pushing vehicles toward clean electric propulsion systems and a new paradigm for automobiles and trucks.

While ICEs will continue to dominate the highways for many years, the car of the future will be electric, autonomous, and connected—as well as safer, less polluting, and equipped with new services.

Where does aluminum fit in? A survey released by the Aluminum Association shows that aluminum content in vehicles could grow 12% by 2026—continuing a strong growth trend.[31] This increase will be driven by growing use of aluminum in vehicle closures, BIW, chassis applications in conventional vehicles, electrified powertrains, and battery electric vehicle (BEV) platforms. Aluminum can also enhance supply chain sustainability with lower CO_2 emissions and enhanced recyclability.

Electrification is affecting desired vehicle attributes and the use of automotive aluminum. BEVs may initially be heavier than their internal combustion equivalents, making weight a significant factor in materials selection. Use of aluminum will also continue to increase in batteries and in lighter-weight, larger vehicles.

As OEMs repurpose and design platforms for BEVs, unexpected changes to vehicle performance may occur (e.g., weight distribution, crash performance). The unique properties of aluminum can be applied to address some of these challenges while improving overall vehicle performance.

New vehicle designs represent many opportunities for aluminum. Integration of the battery enclosure into structures, for example, could reduce the cost of AIVs (e.g., using the battery cover to serve as the floor pan).

[31] DuckerFrontier, *North American Light Vehicle Aluminum Content and Outlook*. August 2020. www.drivealuminum.org/research-resources/duckerfrontier-rth-american-light-vehicle-aluminum-content-and-outlook-august-2020/

GOALS

Goals for future vehicles address the automotive components and markets that offer the greatest potential for aluminum. Table 11 shows the specific goals identified for future vehicles. While the automotive sector represents some of the greatest market potential for BEVs, commercial and heavy-duty vehicles, including military transport, are also a growing opportunity. Trucks with either ICE or battery-electric propulsion systems are beginning to incorporate more and more aluminum.

Last-mile urban delivery markets[32] are a particularly great opportunity for aluminum-intensive delivery vehicles; the lighter the vehicle, the more cargo can be carried at least cost. An alloy that competes with mild steel is needed to narrow the competitive gap with steel (5xxx or 6xxx series) in this market. Special alloys are also needed to compete with press-hardened steel. Market opportunities exist for both high-end and lower-end vehicles.

Table 11. Goals for Aluminum in Future Vehicles	
Near Term (1-5 years)	• Capture of majority of market share for automotive hoods (70%). • Solid knowledge of cost goals to maximize competitiveness. • Major focus on passenger vehicles with move to larger vehicles based on markets (commercial and heavy-duty vehicles, military vehicles). • Capture of significant share of BEV markets; preparedness for vehicles designed in 2025, with a focus on weight-range balance. • Competitive with steel in terms of cost, performance, and ease of recycling. • Education of OEMs on benefits of aluminum versus other materials (crash resistance and durability, longevity, recyclability, lightweight, rust resistance, etc.). • Maximum weight savings relative to steel (minimum 40%). • Aluminum doors for all vehicle segments at less than $3/kg weight.
Mid Term (5-10 years)	• Capture of 100% of market for automotive hoods and 50% of automotive doors. • Capture of more of the economy battery enclosure market segment. • Move into larger vehicle markets (commercial/heavy-duty vehicles, military vehicles).
Long Term (10+ years)	• Capture of large share of autonomous vehicle market (20 million vehicle potential).

FUTURE OPPORTUNITIES

Aluminum can be used in a variety of components in future vehicles, including battery enclosures, chassis, hoods, doors, and crumple zones. The unique properties of aluminum can help meet many future design requirements, such as lightweighting for range, thermal conductivity for cooling batteries, high corrosion resistance, and longer fatigue life.[33]

[32] Last-mile delivery refers to the last leg of a journey in the movement of goods from a warehouse or hub to the final destination, often the customer.

[33] Number of loading (stress) cycles a material can sustain before failure of a specified nature occurs.

Product opportunities in the exploding BEV market are wide-ranging, along with applications in new model ICE vehicles (see Figure 15). Manufacturers will need to produce components cost-effectively for low volume BEV start-ups while staying competitive with steel. In Europe, aluminum is the material of choice for battery enclosures in premium vehicles. Steel is used in economy vehicles and aluminum can seize opportunities to capture more of this market.

Electric trucks and last-mile delivery vans show promise for new products, with wider application on smaller vans. Breaking into these markets will require a significant reduction in the cost of aluminum. Producers will need to demonstrate the performance of aluminum versus other materials.

BEV Batteries

Battery enclosures (prismatic battery housing, closures).

High growth of BEV SUV and pickup segments, where batteries are larger; target more of the economy BEV battery market (where steel is most common).

Cooling solutions for batteries (e.g., high thermal conductivity for cell cooling in battery enclosures) and new battery approaches such as aluminum ion batteries.

Lightweight Structural and Other Components

High Pressure Die Casting (HPDC) aluminum and extrusions for battery enclosures and structural chassis components.

Low-cost casting or extrusion applications for a variety of components, such as subframes, security features, cosmetic applications, etc.

Structural part replacement, integration, or enhancement to enable larger batteries size without losing crash performance or lightweighting; BIW, motor frames/subframes, hoods, and doors.

Lightweight crash management systems with enhanced crash worthiness; energy absorption systems (crush cans/tubes).

Passenger cells in autonomous vehicles where stiffness may be of greater importance; seat structures.

Braking systems (regenerative material to reduce weight and decrease brake dust).

Pure aluminum wiring harnesses.

Greater corrosion resistance and fatigue life (i.e., for high-mileage autonomous or other vehicles).

Finished parts with improved cosmetic surface qualities.

Vehicle Classes

Top opportunities—BEVs, autonomous vehicles, and high-performance ICEs, with increased performance and longevity.

Automotive and truck BEVs with the largest weight challenges.

Last-mile delivery vans and wider application on smaller vans such as C- and B-class segments.

Figure 15. Product Opportunities for Future Vehicles

TECHNOLOGICAL/OTHER CHALLENGES

A number of the identified technological challenges are related to emerging vehicle markets, particularly electric vehicles of all sizes. Figure 16 summarizes some of the major challenges. Challenges broadly focus on addressing performance requirements, structural and other limitations for batteries, and sustainability and recycling needs.

Highly integrated parts are needed for some vehicles, requiring different functionalities and performance characteristics within the same component. A part might need additional strength but also have requirements for ductility. Parts that have higher strength, better recyclability, better energy absorption, and higher crash readiness will be needed. Battery materials must meet requirements for strength, crash readiness, fire protection, and complicated joining solutions. Second-generation battery technologies are needed to resolve some of these issues, particularly in joining, weight reduction, and part consolidation.

Cost-Effective Battery Applications

- Developing robust and cost-effective aluminum solutions to meet all structural and safety requirements of battery enclosures.
  - Impact toughness for lower protection plates of batteries; crash side and under-ride impact toughness.
  - Cost-effective fire protection solutions; materials can be applied to lengthen heat transfer but are costly.
- Achieving complex design geometries and tight tolerances required.
- Overcoming cost and construction challenges of first-generation BEV batteries (e.g., single sided joining technology).

Alloy Performance

- Improving alloys and processes to enhance component functionality and flexibility (e.g., high strength in one area of a component, formability in another).
- Balancing customer design requirements for stable dimensions/ tolerances with material properties and cost of processing.
- Expanding capability for flexible assembly processes with different alloys in different components (castings, stampings, extrusions, etc.).

Sustainability

- Ensuring aluminum designs maintain competitiveness in full life cycle analysis, developing low-carbon-content aluminum solutions utilizing EOL vehicle scrap.
- Expanding credits for zero emissions vehicles, which ultimately reduces the need to downweight ICE vehicles.

Figure 16. Technological Challenges for Aluminum in Future Vehicles

Alloys in use today have been around for 20-30 years, whereas the steel industry has continued to evolve grades for higher strength and formability. Aluminum alloys must follow suit in a tighter timeframe, using processes to greater advantage (e.g., hot forming). Wrought and cast alloys also need to be more compatible in the manufacture and recycling stages to maximize utilization.

Cost continues to remain a challenge for aluminum competitiveness with steel. Designers are always looking for stronger alloys (e.g., 7xxx)—but volume-based manufacturers will look for cheaper alternatives. To gain market share, aluminum producers must strive to meet all challenges with more cost-effective solutions.

R&D NEEDS

MAJOR RESEARCH TOPICS

Research needs were identified in diverse areas, as shown in Table 12. Priorities for research tend to focus on more sustainable components and improved alloys, designs, and processes to support growth in markets for electric vehicle batteries.

Battery enclosures are a key market and will require both alloys with high formability and strategies for fire protection. Advances in processing technologies are needed to reduce costs, reduce manufacturing complexity, and enable higher-performing parts.

Data is a fundamental to many improvements. Methods are needed to effectively connect processing methods with material properties and structure. This foundational understanding will allow for better material and component designs and more accurate predictions of performance.

Recycling and sustainability are important aspects for all future vehicles. Technologies that reduce the carbon footprint of parts and strategies for EOL recycling and reuse will become increasingly important factors in the competitiveness of automotive components.

Manufacturers are focusing on advanced processing technologies that will produce high-performing, high-value vehicle parts.

Table 12. R&D Needs and Other Activities Identified for Future Vehicles			
Category	**Priority** Low	Med	High
Materials			
High formability alloys for single shell battery enclosures; deep draw with tight radii.			◊
Targeted development of alloys for battery components.			◊
New cost-effective fire protection materials to be combined with aluminum component.			◊
High conductivity alloys for bus bars.		◊	
New alloys with high strength that don't require expensive extra manufacturing processes (e.g., hot forming).		◊	
Processing and Design			
Production methods and processes to reduce the cost of alloys and processing for battery components.			◊
Improved tolerance in extruded components to mirror stamped products.		◊	
Ability to design/model future vehicle components with intentionally variable properties; modeling reconfigurable vehicle designs that extend vehicle life (e.g., interior/exterior changes and structure/configurations).		◊	

ACTION PLANS

Action plans for research have been developed to address some of the most critical challenges in the development of alloys to meet requirements for future vehicles. The action plans describe the path forward, a detailed research approach, desired outcomes, and benefits to the industry. Specific projects include:

- *Reduce Overall Part and Sub-System Costs (Figure 17)*—Reducing part costs via cost-effective processing, recycling/reuse, standardization of OEM product shapes or materials of choice, and less costly multi-material joining.
- *Create Alloys Specifically for Electric Vehicle Batteries (Figure 18)*—Developing alloys for battery components to improve intrusion protection, fluid containment, joining, corrosion resistance, and structural characteristics.
- *Tailor Designs and Processes for Battery Enclosures (Figure 19)*—Targeted research on highly formable alloys, new coatings/lubricants, joining processes, design geometries, innovative processes, fire protection, and other methods to improve battery enclosures and related components.

Reduce Overall Part and Sub-System Cost

Reducing the cost of aluminum parts is a key differentiator when competing with steel in current and future vehicles. The strategy is to reduce both the cost of aluminum and the cost of manufacturing and assembling the component into the vehicle. A three-phase approach to reducing overall installed aluminum part cost includes: 1) reducing the cost of manufacturing aluminum (e.g., find/address cost drivers in producing extrusions, sheets, castings, etc.); 2) reducing the amount of aluminum needed via alloys with better properties and improving component design to reduce mass; and 3) reducing the cost of making and assembling the part by developing lower cost, more efficient manufacturing and assembly processes. In extrusions, for example, is it more cost-effective to use induction pre-heating versus gas heating? Equipment and methods that slow process throughput (e.g., roll passes, coils, furnace restrictions) are cost drivers in rolling; these can affect hours to process and amount of metal pushed or rolled.

Table 13. Reduce Overall Part and Sub-System Costs: R&D Impacts

Rank	Impacts
●●●●●	**Cost Reduction**: Lower cost parts create a strong differentiator from steel and composites.
●●●	**Weight Reduction Potential:** Lower cost improves competitive position compared to other lightweight materials and steel.
●●	**Vehicle Performance:** Standardized product mix could improve quality and performance of parts.
●●●●	**Sustainability:** Secondary aluminum with comparable quality to primary aluminum shrinks the carbon and energy footprint.
●●	**Joining/Multi-Material Aspects:** Lower-cost joining methods can improve the competitiveness of aluminum parts.

On the raw material side, the potential cost reductions possible through increasing recycling content need to be explored. Primary aluminum is still preferred for some of the more critical safety applications. On the process side, identifying a common product mix (standardized shapes) from OEMs could reduce complexity of manufacturing, with costs rippling down to processors through better planning and productivity. Table 13 illustrates some of the potential impacts and considerations of proposed research to reduce overall part costs.

To compete with steel in cost and functionality, research is needed to increase body applications and alloy strength in the near to long term. Aluminum alloy composition limits vary widely; different companies may have different “flavors” of the same alloy, which makes consistency more challenging. Historic design and “old knowledge” are important and prevalent but may not lead to advanced alloys. A long-term stretch goal is for recycled materials to deliver the same quality as primary material—with no discernable difference between primary and secondary aluminum.

Design is a key aspect in cost reduction. Collaboration and close relationships with customers and the OEM design team can lay the groundwork for future product development, leveraging Aluminum Association networks where possible. Early discussions on design can steer development of products toward cost-effective decisions that will help OEMs meet targets.

Figure 17 shows the action plan for improvements to help lower the cost of parts.

Figure 17: Reduce Overall Part Cost and Sub-System Costs

Barrier/Problem Statement: Many continuous, favorable processes are available for steel when compared with aluminum. Challenges must be addressed to go a similar route with Al. For example, there are complex aluminum alloys that require longer aging, special quench or other unique processing. Continuous processes may help alleviate some of these roadblocks. Different processors also have different equipment with different capabilities, i.e., processing is not consistent across products.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Investigate cost benefits of closed-loop recycling with customers; research/model new alloys with less stringent processing requirements. • Investigate inexpensive ways to join dissimilar materials. • Identify possible common product mix or standardized shapes to meet OEM needs. • Research factors affecting extrudability and improving press productivity (overall equipment decisions). • Address inconsistent formability testing at OEMs.	• Increased strength of aluminum alloys to compete with steel while increasing body applications. • Standard method of testing materials across suppliers. • Better relationships with customer/OEM design team to set basis for future products. • Generic specification for standardized application of alloys with recycled content.
5-10 years	• Research mixed material joining methods (e.g., self-piercing riveting [SPR], adhesives, 1- and 2-side axes). • Align alloy standards to a one industry approach (like steel). • Establish active partnership with design engineers; create and share “Design Guide” for design engineers. • Implement closed-loop recycling; pursue qualification with OEMs. • Conduct alloy modeling (LS-Dyna) with closed-loop recycling for predictable design/simulations and comparison against other alloys.	• Standardization of mixed material joining methodologies across OEMs. • Aluminum Design Manual to assist designers and OEMs in alloy selection/shape design. • Differentiation of aluminum use between BEV offerings across OEMs (enabling sharp styling as a differentiator; aggressive forming, sharp feature lines, sharp geometry, etc.). • Better understanding of cost relationships with OEM/customer re: closed-loop recycling. • Higher scrap value, closing gap between primary/ secondary aluminum (lower net part cost).
>10 years	• Develop better design criteria, including accurate predictive failure models for use during design phase and to create linkages between tooling and part design. • Reduce number of die re-cuts and spring back compensation (in steel vs. aluminum) for stampings. • Standardize lubricants (e.g., rollers, mitigate differences among OEMs) for surface of sheet, to help with spring back and streamlining the supply chain.	• Aluminum design criteria matured and built into designer tools (Catia, Solidworks, etc.). • Standardization/reduction of component design time to OEM (e.g., joining, sheet lubricants, die recuts, spring back, etc.) • Expanded property database of alloys that use recycled or secondary content for critical applications.

Stakeholders and Potential Roles

Product manufacturers: Develop alloys and material test data.
End-users/OEMs: Develop product designs and implement parts.
Scrap suppliers, automotive shredders/sorters: Provide recycling and scrap management processes.
National laboratories: Conduct research and serve as potential testing partners.
Government: Provide regulations and potential support for research.
Academia: Conduct research and develop white papers.

Create Alloys Specifically for Electric Vehicle Batteries

Research is needed to improve alloy performance in BEV batteries. Specifically, the industry needs aluminum alloys that improve intrusion protection, fluid containment, joining, corrosion resistance, and structural characteristics. Research will focus on casting, extrusion, and rolling alloys, individually and in combination. For example, research could focus on alloys for large, single castings as well as alloys for battery enclosures that combine extrusions and sheet. Table 14 shows the potential benefits from battery alloy development.

Table 14. Improved Alloys Specifically for Electric Vehicle Batteries: R&D Impacts

Rank	Impacts
●●●●●	**Design Optimization**: Reducing profile and sheet thicknesses enables a wider selection of more cost-competitive alloys.
●●●●	**Vehicle Performance:** Improved intrusion performance optimizes battery protection and provides more choices for alloy selection/ development.
●●●●●	**Weight Reduction Potential:** Lighter battery materials and shapes with increased intrusion protection and corrosion resistance are a winning combination for future BEVs.
●●	**Sustainability:** Recycling-friendly alloys have broad importance but trade-offs in performance might arise.

Alloys need to adequately contain battery fluids and protect against environmental fluids. When using extrusions plus sheet materials, the design is more complex with many joints and seals. High-strength steel alloys are commonly used, and issues of corrosion could arise with multi-material (MM) joining. Fluid containment and corrosion within the battery compartment, electrical isolation, and galvanic corrosion accelerants all require further research.

Intrusion protection is an important area of research. Materials are needed that impart “armor” qualities. A challenge is to design around the battery weight—and optimize the design and material choices with heavy batteries but thin structures. Studies are needed to better understand the intrusion protection requirements for batteries. New approaches (e.g., coatings) are needed to handle the electro-magnetic waves that penetrate aluminum faster than steel and understanding of vehicle-to-vehicle (V2V) electromagnetic interactions.

Aluminum alloys developed for increased recyclability could also improve some of the performance characteristics needed for batteries, such as corrosion and sealing/adhesive performance; toughness against intrusion; and weldability. Trade-offs in performance and recyclability will need to be considered and tested.

Figure 18 shows the roadmap and action plan for developing new alloys for batteries. Through this research, new alloys that perform well in existing and future vehicles will be developed along with best practices to inform advanced designs and testing protocols (Figure 19).

Figure 18: Create Alloys Specifically for Electric Vehicle Batteries

Barrier/Problem Statement: The lightweight aspects of aluminum make it the most popular choice today for BEV battery enclosures. Next-generation, durable, high formability alloys will be needed to cost-competitively meet future requirements for single shell, advanced battery enclosure designs. Deep draw processes with tight radii, for example, might increase durability and quality to meet growing market demand. Research and testing are needed to improve corrosion and fluid containment, joining, intrusion protection, and structural characteristics to meet requirements for future BEVs.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Research EV battery materials for key intrusion protection and crash performance characteristics; conduct studies based on designs/applications. • Examine impacts of recycling of alloys on performance characteristics and trade-offs. • Develop alloys suitable for deep draw processing; develop/test new high formability alloys in battery enclosure (BE) prototypes. • Apply existing sheet pre-treatments to extrusions/castings, specifically for adhesive bonding and sealants for fluid containment and corrosion protection.	• Alloys for extrusions/castings that can join with sheet (aluminum or steel) and pass corrosion and fluid containment requirements. • Deep draw alloy up to 150mm for single stack; 300mm for double stack BEs. • Material selection parameters connected to important properties and characteristics; recycling characteristics tied to BE alloy selection.
5-10 years	• Create new (or improve existing) pretreatments/coatings optimized for battery castings, sheet, and extrusions, and by alloy. • Design and test prototype of advanced aluminum alloy BE that incorporates best practices and design criteria optimized for specific applications.	• Pretreatments that work with battery tray adhesives and improve performance (longer corrosion lifetime, higher pressures/time maintaining water tightness). • Joint performance characteristics/behavior (material card) that can be used in LS-DYNA[34] or other software for crash simulations.
>10 years	• Develop roadmap for impact of future battery technologies on BEV design/material choices.	• Roadmap addressing changes in future battery technologies and BE materials.

Stakeholders and Potential Roles

Product manufacturers: *Chemical suppliers*—Share information on requirements (i.e., specific needs for BE or Al alloys/products utilized for BE) and learn from chemical suppliers about pretreatments that might be available.
Aluminum suppliers—Share information on new alloys in development and knowledge transfer from other industries into automotive; collaborate on prototyping projects.

End-users/OEMs: Write specifications for suppliers with performance requirements (e.g., water tightness, corrosion, thermal management, electromagnetic interaction).

Scrap suppliers, automotive shredders/sorters: Assist with recycling methods for batteries; scrap suppliers need to prepare for how to handle incoming BEs (of various designs) and recover/recycle the structural components.

National laboratories: Operate prototype/testing facilities.

Government: Work with industry to generate standards for intrusion protection of battery cells.

Academia: Study corrosion interaction between aluminum parts and sealants/adhesives; electromagnetic interaction from V2V; and EMF interference.

Aluminum Association: Maintain a coordinating role, conduct workshops.

[34] Finite element program that simulates complex real world problems, used by automotive, aerospace, construction, military, manufacturing, and bioengineering industries. Developed by Lawrence Livermore National Laboratory. www.lstc.com/products/ls-dyna

Tailor Designs and Processes for Battery Enclosures

While aluminum is a more costly choice of material, its use is justified in today's BEVs due to the mass and cost savings resulting from downsizing of the battery and powertrain. Over the last decade, the cost of batteries has dropped significantly while energy density has almost tripled, significantly reducing the weight of batteries. At today's prices, aluminum is still the logical choice, especially for larger vehicles. As costs continue to drop, aluminum will become less viable, especially for smaller vehicles, and will face competition from fiber-reinforced plastics and other materials. Table 15 illustrates some of the impacts and considerations for research.

Table 15. Tailor Designs and Processes for Battery Enclosures: R&D Impacts

Rank	Impacts
●●●●●	**Cost Reduction**: Lower costs are possible through advances in technology and processing and simpler designs.
●●	**Vehicle Performance:** Innovations in battery placement enhance comfort and aerodynamics.
●●●●	**Weight Reduction Potential:** Greater lightweight potential with simpler battery designs and locations.
●●●●	**Sustainability:** Reduced vehicle life cycle carbon footprint is possible through greater potential for recycling.

Research is needed to develop next-generation battery enclosures with greater durability, lower cost, and further potential for lightweighting. As batteries become increasingly inert, safety requirements may become less restrictive. In future, more organic shapes will also be needed for battery packs.

Research will explore new geometries, processes, and technologies for next-generation battery enclosures. Deep draw aluminum forming offers some advantages over stretching processes. Deep drawing is a cold working process resulting in hardening of the aluminum into a tougher and more durable material. Changes in grain structure that occur during the process also improve strength.[35]

Figure 19 shows the action plan for developing new designs for batteries. This research will lay the groundwork for the next generation of aluminum battery enclosures. In addition, the industry is expected to develop and share best practices for material selection parameters, property targets, and methods to develop, test, and utilize prototypes for best results.

[35] The Advantages and Process of Forming Deep-Drawn Aluminum Parts. Hudson Technologies, June 19, 2019. www.hudson-technologies.com/blog/the-advantages-and-process-of-forming-deep-drawn-aluminum-parts/#:~:text=Deep%20drawing%20offers%20many%20advantages,a%20stamping%20machine's%20die%20cavity.

Figure 19: Tailor Designs and Processes for Battery Enclosures

Barrier/Problem Statement: While aluminum is a primary choice for battery enclosures in BEVs today, it will face greater competition in future as batteries become lighter and costs drop. Current battery enclosure designs are complex, and some require additional processing steps. New designs and processing techniques are needed to help overcome current limitations in design and processing and create the next generation of BEV battery enclosures.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Define strategies to overcome limitations of current materials and processes for developing second generation battery enclosure, and research alternatives. – Simple geometries (pencil box design) – Heating blank (warm, hot, or super form) versus new deep draw alloys – Compatibility with proposed joining technologies – Packaging industry solutions (e.g., deep draw square boxes) – Minimum wall angle (draft), minimum radius at corners (and optimal tightness of radii), and associated thinning impact from both – Higher performance lubricants versus battery modules that tolerate lubricant left on the tub, or better lubricants across entire process • Make available material cards and specifications with friction values for new lubricants; ensure up-to-date computer-aided engineering (CAE) models for cold, warm, hot, and super form processes are available to OEMs and Tier 1 suppliers.	• Reduced complexity to lower costs by 25-50%. • Maximized packing density; minimum bottom radius and draft angle, and plan view radius, dependent on design. • No post-forming heat treatment required (only paint shop). • Matrix of best practices for design of BEs (structural/ non-structural); application-based material selection parameters.
5-10 years	• Review second generation battery enclosures solutions for lessons learned and future challenges.	• Updates to second generation technology
Beyond 10 Years	• Develop third generation solid state (or similar) battery enclosure that is smaller, lightweight, safe, requires less packaging, or is package-compatible. • Explore innovations made possible by new battery cell technology. – Battery enclosure becomes the floor panel of the BIW and the undertray, for better aerodynamics – Complex battery shapes that consider occupant comfort, i.e., foot garage or other space – Battery cells relocated in the body structure (e.g., A/B pillar and rockers, in center spine of vehicle [transmission tunnel] in low roof cars, etc.)	• Third generation battery enclosure technology to meet requirements for solid state (or similar) battery cells.

Stakeholders and Potential Roles in Project

Product manufacturers: *Aluminum producers*—Develop material solutions. *Tier 1 and Technology Suppliers*—produce and test.

Academia: *Metallurgy-based institutes*—Conduct research on, model, and test materials.

End-users/OEMs: *BEV OEMs and Tier 1 manufacturers of BEs*—Develop, manufacture and test prototypes.

National laboratories: Address major forming and material development challenges; how to develop processes for numerous applications to ensure little or no "down cycling" of future deep draw BEs.

Government: Set appropriate safety and performance standards relative to cell chemistry.

Scrap suppliers, automotive shredders/sorters: Recycling second use BEs for domestic and commercial use; at the end of battery storage life in domestic/commercial applications, processes to dismantle and recycle batteries. Vehicle junk/scrap yards adopt capability to remove battery at end of vehicle life for safety and maximized use.

NEXT-GENERATION ALUMINUM FABRICATION TECHNOLOGIES

OVERVIEW

Fabrication of aluminum into automotive components is accomplished using castings (65% of 2020 North American automotive aluminum volume), rolled sheet stampings (23%), extrusions (10%) and forgings (2%).[36] The type of fabrication process used depends on the size and shape of the part, the volume of parts to be produced and the desired performance and finished part characteristics

Castings are most cost-effective in high volume production lines where complex 3D shapes are required. The near-net shape parts created by mold / die casting ensures a high metal recovery rate and enables significant parts consolidation/reduction when used instead of stamped-sheet assemblies.

Rolled sheet is typically stamped into shaped parts in high-productivity stamping presses. Sheet stampings have relatively high initial tooling costs but are good for high throughput with moderate operating costs, so they are used widely in high-volume vehicles for closure panels and the main body structure.

Extruded profiles allow large freedom in design of 2D cross sections, enabling the consolidation or incorporation of assembly features. Extrusions lend to fast product development cycles due to low-costs and flexible tooling. Prototype and testing phases can be performed in a relatively short amount of time by rapidly creating and evaluating different profile designs.

Forged parts allow an excellent combination of strength and toughness for structural parts in the body structure or chassis, including knuckles or ball joint yokes.

Aluminum Fabrication Processes for Automotive Components

Casting—includes permanent mold casting, where molten aluminum is gravity-fed, and die casting, where pressure is used to force aluminum into the die cavity. Structural, vacuum die castings are increasingly used in vehicle body and chassis. Permanent mold castings are more common for larger powertrain parts such as transmission casings, wheels, engine blocks, and cylinder heads.

Extrusion—heated aluminum billet is forced through a custom-designed die press to create an elongated profile of specified size/shape and used to make auto space frames, bumpers, crash boxes, battery housing frames, etc.

Rolling—aluminum ingots are passed between rolls under pressure first at high temperature (hot rolling) and then at ambient temperature (cold rolling), becoming thinner and longer in the direction of movement. The flat auto body sheet is then stamped into shape and used in closures and autobody structures.

Forging—metal is pressed, pounded, or squeezed under great pressure to produce high-strength parts; used in parts such as control arms, knuckles, or forged aluminum wheels.

Powders—aluminum powders for additive manufacturing of parts (emerging technology for automotive).

During vehicle assembly, the different semi-fabricated aluminum parts are finally joined with each other and other materials to form the final vehicle structure. Key processes in assembly and finishing lines are welding, mechanical joining, adhesive bonding, surface treatment, and painting.

[36] DuckerFrontier, “North American Light Vehicle Aluminum Content and Outlook” report, 2020.

In addition to these traditional manufacturing processes, aluminum can be used in a powder form for the additive manufacturing (AM) of automotive parts. While powder AM is currently too expensive for large-volume automotive production, the technology is finding use for production of prototypes and in niche part markets. Used for many years in batch aerospace and medical equipment applications, recent developments in mass AM production suggest progress toward feasibility for the production of aluminum automotive parts.

GOALS

Goals for next-generation fabrication focus on improving manufacturing methods to enhance the competitive position of aluminum in both existing and future vehicles. As shown in Table 16, goals center on enabling closed-loop recycling of process scrap as well as end-of-life (EOL) vehicle scrap; reducing energy consumption and processing steps; utilizing available through-process data for machine learning; developing innovative forming and joining methods; and combining processes and alloy characteristics to enable higher strength and higher-performing aluminum components. The overarching goal is to offer aluminum solutions with the same freedom of design as steel or other materials.

A long-term goal envisions future plants that use next-generation, cost-effective fabrication processes for casting, extruding, and rolling. Next-generation mills would be optimized to deliver components quickly. Successful new joining technologies would be available for all amenable material combinations (i.e., less material-dependent). Plants and fabrication processes will also be sustainable—becoming CO_2 emissions-free by 2050, assuming access to clean, low-carbon energy sources.

Table 16. Goals for Aluminum in Next-Generation Fabrication	
Near Term (1-5 years)	• Closures—aluminum-forming technologies with the same freedom of design for doors as allowed by the forming technologies for alternative materials. • Reduce processing steps and associated costs (e.g., eliminating or minimizing need for surface finishing or heat treating) • Giant castings to rationalize the number of components (e.g., one vs. 70), reducing joining, assembly costs, number of robots, and overall plant footprint.
Mid Term (5-10 years)	• Fabrication manufacturing processes that can be applied in a heterogenous fashion—improving localized sheet properties or increasing sheet ductility (e.g., sheet metal components formed from blanks). • Redesigned/developed surface-finishing processes for closures. • Continuous casting to reduce cost (plate or sheet continuously cast instead of slab).
Long Term (10+ years)	• Next-generation castings, extrusions, and rolling processes operating in optimized mills (reduced days/inventory required between mill production and OEM/testing). • Manufacturing methods to create alloys for semi-finished products without the need for primary aluminum. • Elimination of painting/surface-finishing processes altogether. • CO_2 emissions-free fabrication on the plant floor by 2050.

FUTURE OPPORTUNITIES

Next-generation fabrication technologies offer many opportunities to help meet OEM objectives, reduce cost, and increase value (see Figure 20). These opportunities range from innovations in processing technologies and manufacturing configurations to the transformative use of digital technologies.

Reducing batch processing and replacing it with continuous processing technologies will enable cost, material, and energy savings—leading to more competitive products. Using alternative designs (e.g., consolidating multiple parts into a single extrusion) or alternative processes (e.g., castings instead of extrusions or sheet parts) can lead to part reduction, lower costs, and better material utilization.

Next-Generation Processing

Structural fabrication for electric auto, truck, and SUV bodies for lightweighting, rust resistance, and cost advantages.

Technologies to reduce batch and interrupted aluminum manufacturing processes (e.g., continuous casting).

Large, structural, high-performance die castings to replace sheet or extrusion parts with better utilization.

Flexible aluminum rolling processes for greater choice of width.

Improved tribology and lubrication for sheet stamping and other forms to lower costs and improve quality (e.g., hot melts, waxy lubes, etc.).

Broader, faster, higher-volume additive manufacturing of aluminum alloys; low-cost aluminum powder atomization for yield improvements.

Hands-free mill-applied lubricants especially designed for forming.

Universal sheet surface inspection technology and standards for OEMs.

Tailored blanks for better material utilization and nesting of aluminum coil.

Reduced material usage through better edge stretchability, less cracking, and minimized transition scrap from furnaces.

Digital Technologies for Fabrication Processes

Smart manufacturing integrated with supply chain for economic, quality, and yield benefits.

Digital twins of systems to better understand performance.

Rationalized material properties to enable application of multiple processes to the same material; capability to tailor properties to maximize design and performance.

Accurate models of mechanical properties of any alloy with ability to feed-forward mechanical property data and optimize processing; continuous feedback of downstream manufacturing data for upstream adjustments.

Machine learning/artificial intelligence to create new alloys with balanced strength and elongation.

Digital tools to eliminate non-value-added manufacturing steps (sampling, final inspection).

Figure 20. Future Opportunities for Next-Generation Fabrication Technologies

TECHNOLOGICAL/OTHER CHALLENGES

Several technological challenges must be met to advance the state of fabrication technologies. As shown in Figure 21, challenges center on two key areas—using advanced computational technologies to improve manufacturing and eliminating the limitations of current forming and processing techniques. The high cost of new technology development and scale-up are key issues affecting adoption.

The ability to use digital technologies is a critical challenge for today's modern production facilities. Good digital models require accurate data on the process as well as on the mechanical and physical properties of materials. Some data is difficult or impossible to measure; real-time data from a process can help to confirm the validity of theoretical simulations. In many cases, data is proprietary and must be scrubbed and managed securely (with sufficient permissions and governance) to enable broader access across the industry—suggesting the need for an acceptable and secure data management infrastructure. As producers move toward Industry 4.0, the digital convergence of industry, business, and related processes, suppliers, and customers will need access to detailed process data.

Process and Material Simulation

- Putting in place real-time process data collection and sharing across the automotive aluminum value chain to enable effective use of Industry 4.0 and artificial intelligence for process and product optimization.
- Addressing limits of existing high-fidelity models and enable capability to use these effectively for design and manufacturing/process control.
- Fully understanding key material requirements before designing the manufacturing process.
- Securing the data management infrastructure and data accessibility.
- Developing generic models that work for all suppliers, even with proprietary alloy compositions and processes.

Processing

- Overcoming high capital expense of new technology deployments and creating cost-effective solutions via digital twins and extensive prototyping.
- Ensuring availability of less expensive, smaller-profile equipment for newer alloys (e.g., extrusion presses and dies).
- Developing cost-effective standardized methods for component qualification.

Figure 21. Technology Challenges for Next-Generation Fabrication Technologies

R&D NEEDS

MAJOR RESEARCH TOPICS

Research needs were identified in various areas of next-generation fabrication, as shown in Table 17. Priorities for research focus on simulations and data needs, advances in joining and bonding, and next-generation casting processes.

The ability to use real-time process data to improve production efficiency and part quality is a priority need. This capability contains many facets, including the need for real time, *in-situ* process sensors for data collection; control data management techniques; and methods for managing the large volumes of data to be secured, stored, analyzed, and acted upon.

Table 17. R&D Needs and Other Activities Identified for Next-Generation Fabrication

Category	Priority		
	Low	Med	High
Formability			
Improvements to formability and related manufacturing processes (rolling, heat treating, blanking, lubricants, stamping, assembly, etc.).			◊
Designs for universal alloy material for inner and outer body structures.		◊	
Development of standardized tests and specifications to describe the crush quality performance of a component or material.	◊		
Process and Material Simulation			
Capture of real time process data to support models; low-cost sensors for accurately collecting relevant process data from fabrication processes.			◊
Model to predict final material properties based on alloy composition and process parameters.			◊
Technical solutions for safely sharing huge quantities of detailed process data among companies.		◊	
Next-Generation Forming Processes			
New forming technologies (e.g., cryogenic forming, hot and warm forming, super plastic, etc.) and innovative heat treatments for high-ductility alloys.			◊
Smart extrusion, sheet, and cast aluminum manufacturing processes for higher quality and lower cost; combined extrusion and sheet, co-extrusion.			◊
Pretreatment for extruded products to improve adhesive bond durability.			◊
Extrusion dies to reduce wall thickness of extruded parts; decreased billet skin depth in high-strength 6xxx alloys.		◊	
Casting technologies that can accommodate high levels of impurities without negatively impacting final product properties.		◊	
Validation methods for large-scale castings for chassis and structures.	◊		

Good data leads to more effective models and process simulators. Incorporating validated natural-aging models into OEM material requirements planning and quality control systems, for example, would improve part acceptance. Accurate data would enable more effective designs for topology and part consolidation and improve performance prediction to help optimize materials for innovative technologies, such as additive manufacturing.

Process data can also help identify the limitations of production processes and ways to improve them. A database of past experiences on what worked or did not work in aluminum part production would complement a database of real-time process data.

ACTION PLANS

Action plans for research have been developed to address some of the most critical challenges facing development of next-generation fabrication processes. The action plans describe the path forward, research approach, desired outcomes, and benefits to the industry. Specific projects include:

- *Pursue Innovations to Improve Formability (Figure 22)*—Alloy and mill process design and development to improve formability—increasing aluminum applicability as steel replacement.
- *Enable Real-Time Process Data Collection at all Manufacturing Steps (Figure 23)*—Data collection methods and improved models for predicting final material properties based on the input alloy composition and real-time process parameters.
- *Develop Innovative Next-Generation Fabrication Processes (Figure 24)*—Research to develop smart extrusion, sheet, and cast aluminum manufacturing processes with enhanced product capabilities and higher quality at lower cost.

Next-generation processing offers opportunities to lower costs, improve quality, and enhance the sustainability of aluminum parts.

Pursue Innovations to Improve Formability

Alloy and mill process development is needed to improve formability and specifically the forming limit diagram (FLD) or curve (FLC).[37] The formability of any sheet material depends on the material properties, process parameters, and strain bounding criteria. The objective is to increase the maximum allowable stretch as defined by the alloy's FLC. Table 18 illustrates some of the potential impacts and considerations of proposed research.

Possible approaches include application of warm or cryogenic forming processes. Forming of certain aluminum alloys at elevated temperatures can improve the ductility and formability of the sheet or increase the strength of the final part. Cryogenic forming can potentially lower residual stresses and boost wear and corrosion resistance.

Table 18. Pursue Innovations to Improve Formability: R&D Impacts

Rank	Impacts
●●●●●	**Cost Reduction:** Improved formability enables part consolidation (e.g., one-piece inners) and greater platform compatibility.
●●●●●	**Weight Reduction Potential:** Highly formable aluminum can allow design of more complex shapes and reduce implementation barriers.
●●●	**Vehicle Performance:** Improved formability allows for lower-gauge / lower-weight closures.
●●	**Sustainability:** More formable 6xxx series alloys can reduce sorting requirements and enable/improve recyclability.
●●●	**Improved Quality:** One-piece stamped inner construction exhibits less dimensional variation.

Development of new lubrication approaches (e.g., dry lubes) along with different types of finishes and coatings can also improve aluminum formability. Using alternative surface finishes on material such as electric discharged texturing (EDT) can improve both friction and formability. The application of die finishes and coatings can also enhance formability and increase part life.

Research is needed on advanced press controls and servo/speed control to manage binder pressure variations. Prior research in quality and process monitoring of metal stamping processes has demonstrated that repeatability (i.e., in interactions between tool and workpiece) can significantly impact the geometric consistency of the stamped product. Variations in tool-workpiece interactions also influence the kinematics of the sheet metal motion in-process. Increases or uncontrolled variations can lead to failure in the forming process or poor sheet quality. Pressure and draw-in (PDI) maps based on coupled sensing and modeling techniques have been shown to be an effective tool for quantifying process variations in sheet metal stamping and enabling new insight into the process physics.[38] Figure 22 illustrates the roadmap and action plan for improvements and advances in formability.

[37] The forming limit diagram or forming limit curve, is used to predict the forming behavior of sheet metal.

[38] Sripati Sah, Persimmon Technologies Corp.; Numpon Mahayotsanun, Khon Kaen University; Michael Peshkin and Jian Cao, Northwestern University. "Pressure and Draw-In Maps for Stamping Process Monitoring." *Journal of Manufacturing Science and Engineering*, September 2016, Vol. 138/091005-1 https://peshkin.mech.northwestern.edu/publications/2016_Sah_Pressure_DrawIn_Stamping.pdf

Figure 22: Pursue Innovations to Improve Formability

Barrier/Problem Statement: Aluminum does not draw as well as steel, making it difficult or costly to match steel's depths of draw and characteristics of edge cracking and wrinkles. When compared to steel, portions of an aluminum stamping with low strain values will have the advantage of increased stretchability. However, during forming and due to strain, this stretchability declines to become equal to or even less than that of steel.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Explore processes to improve the forming limit diagram (FLD) of aluminum alloys, such as warm or cryogenic forming. • Research applications and identify optimal die coatings for formability improvements, including physical vapor deposition (PVD), hard carbon, etc. • Develop better material formability data to support tooling and process simulation. • Conduct dry lube studies to develop new lubricants compatible with paint systems. • Explore use of press line control simulators to improve formability. • Conduct surface finish study to identify improved metal finishes.	• Improvements in forming by 20% over current 5xxx aluminum alloys. • Experiments on press control for formability. • Improved finish and lubrication to reduce cost of finishing by 20%; compatibility with existing paint systems. • Cost neutral or little added cost.
5-10 years	• Implement, commercialize, and industrialize the results of prior research.	• Application/serial production using improved FLD, better lubricants, etc.
>10 years	• Continue developing improvements to attain higher formability than steel.	• Match FLD of appropriate alloys to CR5 and other steel.

Stakeholders and Potential Roles

Product manufacturers: Contribute and research alloy and lubricant improvements.

End-users/OEMs: Sponsor research, test and utilize advance press line controls simulation.

National laboratories: Collaborate on projects, conduct applied research.

Government: Resources for pre-competitive research on energy efficiency.

Academia: Run specific research projects.

Enable Real-Time Process Data Collection at All Manufacturing Steps

A deeper understanding of what happens in real time during the processing of aluminum can help pinpoint problems that lead to rework or rejects and identify process-related structural or performance issues in components. This understanding will require data collection, data analytics, and models based on real-time process data. Table 19 lists potential benefits from predictive modeling based on real-time process data.

Table 19. Enable Real-Time Process Data Collection at All Manufacturing Steps: R&D Impacts

Rank	Impacts
●●●●	**Reduced Cost:** Standardized information will lower development and optimization costs; reducing inventory will reduce cost; less rework will reduce costs and support improvements to OEM processes.
●●●●●	**Weight Reduction Potential:** Better material selection and design will be possible via a tool that predicts data based on specific supplier process information; tool allows OEMs to use the material more efficiently.
●●●●●	**Vehicle Performance:** Improved design and use of material may improve vehicle performance.
●●●●	**Sustainability:** Shared data and analysis enables operation of more efficient processes and less material waste. Digital technology (e.g., tracking or visual systems) of scrap and optimization will enable more scrap utilization.
●●●●	**Material Properties:** When OEMs are working with consistent, accurate and predictable material properties, it can reduce differences in material performance in manufacturing and vehicle use.

Research is needed to develop models that predict final material properties based on the input alloy composition and real-time process parameters. Data collected *in situ* provides the most comprehensive insight into what really occurs during processing. Processes vary among aluminum producers, which can create challenges; techniques will be needed to standardize or normalize data to enable common predictions.

Sharing of data, which is often proprietary, is another challenge. Data collection methods that protect or anonymize real-time data will be useful to ensure protection of intellectual property (IP) and encourage data sharing among manufacturers. Technical solutions will be needed for safely sharing huge quantities of detailed process data among different companies. Machine learning or AI can be particularly effective as tools to process and utilize the potentially enormous amounts of data and could potentially extend applicability to all product forms.

Key stakeholders will need to align on the value of the model and its advantages, such as lower inventory and faster material flows. Automotive OEMs will gain the greatest benefit, including a reliable understanding of material properties. This insight will enable more effective material selection and lead to greater uniformity in the performance of final parts.

Government could play a role in supporting the development of a pre-competitive database; the Aluminum Association could take a role in creating a repository and serving as a coordinator of data.

Figure 23 shows the roadmap action plan for collecting and using real-time process data to develop predictive models.

Figure 23: Enable Real-Time Process Data Collection at All Manufacturing Steps

Barrier/Problem Statement: While a large amount of real-time process data is available, no infrastructure is currently available for safely sharing this data among companies/entities. Cost-effective standard data sharing platforms are currently not available. Process routes vary across suppliers; many processing variations make data consistency/standardization more challenging. OEMs may not accept process data versus physical testing results.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Gain acceptance by OEMs in early stages of development; demonstrate the value of a real-time process data tool and database. • Conduct data collection and statistical analysis of data; determine relevant process window and processes in control. • Validate correlation between physical testing data and process data; understand process changes and impact on final properties. • Set up task group to determine database structure and rules: type of data, sharing protocols, etc. • Develop workable database and models.	• Alignment with OEMs on the value proposition. • Databases completed within 5 years; includes specific modules for casting, corrosion, joining, and other processes. • Identification of key process parameters. • Model that predicts the mechanical properties of alloys.
5-10 years	• Develop design guidelines based on modeling results. • Implement the model for one vehicle program from design through production cycle. • Apply process models in test studies of auto body panels. – Test and validate results to ascertain whether the predicted mechanical properties can be used for product design	• Model and design guidelines for OEMs. • Single model for all product forms. • Process-specific validation of model results.
>10 years	• Continue refining and expanding process models; use same approach for other products with different process steps. • Apply modern data analytics to support smart manufacturing and seamless data flow. • Use process information along the length of the coil to create useful guide for OEM manufacturing processes.	• Product enhancement via process improvements based on the model. • Simplified or improved processes. • Shortened time to qualification.

Stakeholders and Potential Roles

Product manufacturers: Provide supplier process data, physical data, and rolling process expertise.

End-users/OEMs: Collaborate and support the effort to own benefit; apply the model in design and manufacturing of the vehicle and verify the model; address IP challenges.

National laboratories: Confirm the model results and provide artificial intelligence (AI) tools.

Government: Provide incentives or a central repository for data storage and curation; support research programs to lead AI/ML and digital transformation of manufacturing companies involved in processes, e.g., aluminum rolling.

Academia: Develop models; accommodate IP challenges for software or model development.

Develop Innovative, Cost-Effective, Next-Generation Fabrication Processes

As noted, casting, rolling, and extrusion are the major processes used to produce aluminum components. Next-generation fabrication processes and new technologies covering all forms are needed for aluminum to effectively compete in future automotive markets.

Research in this area will focus on the development of smart fabrication processes for higher-quality, lower-cost products. R&D could include, for example, processes that combine extrusion and rolling, or co-extrusion processes, such as those that combine steel with aluminum. Large castings to consolidate multiple parts is another example. Producing rolled products with increased recycled content could enhance sustainability. Table 20 shows some of the impacts and considerations for research in next-generation fabrication processes.

Table 20. Develop Innovative, Cost-Effective, Next-Generation Fabrication Processes: R&D Impacts

Rank	Impacts
●●●●	**Weight Reduction Potential:** Thinner wall thickness combined with strength could reduce overall weight of components.
●●●●	**Cost:** Reduced processing steps, processing requirements and thinner parts could all lead to more cost-effectiveness of fabrication.
●●●	**Sustainability:** The ability to use a variety of fabrication processes for parts with recycled aluminum provides an advantage for companies seeking more sustainable suppliers.

Eliminating process steps is one way to lower costs. Replacing batch processing with continuous methods is one way to save material, cost, and energy. Substituting processes, such as casting in place of extrusion, is another strategy to optimize both materials and process energy. Obviating surface finishing can cut steps and reduce process complexity, lowering overall costs.

In extrusions, improvements are possible by optimizing die design and the extrusion recipe (including temperature, ram speed, and lubrication). Temperature is a key parameter, as it imparts characteristics such as hardness, strength, and finish.

For the next generation of fabrication technologies, research will need to reach beyond common process parameters to look at innovations, such as super-thin or super-strong parts made possible by digital technologies. Decreasing the volume of raw material required for castings or rolled products can directly impact cost. Research activities should include developing capabilities to move into Industry 4.0 and using advanced digitization methods like AI and machine learning to optimize processing and support manufacturing innovation.

Areas in which improvements are possible include innovations in casting (e.g., salt cores, vacuum die casting), form-specific alloy development, heat treatment, and minimal lubrication, among others. In rolling, innovations are needed to improve surface quality, reduce defects (e.g., wavy or cracked edges, etc.), and avoid unwanted deformation.

Figure 24 shows the action plan for innovating and advancing next-generation fabrication processes for more cost-competitive and sustainable components.

Figure 24: Develop Innovative, Cost-Effective, Next-Generation Fabrication Processes

Barrier/Problem Statement: Current fabrication processes are widely used but require innovations to improve part performance and significantly lower costs relative to steel and other materials. Batch-style operations and high costs for process set-up raise the cost of extrusions. The continuous-production extrusion process is relatively slow and more difficult to adapt. Defects and deformation can occur in rolled products, leading to material waste and additional processing. Casting often requires surface finishing or other treatments.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Develop smart, innovative, next-generation fabrication processes. – Apply advanced simulations and smart technologies, such as artificial intelligence and machine learning – Explore extensive use of digital twins and relevant scale prototyping – Combine processes for extrusion and rolling; co-extrusion to combine steel in the extrusion – Develop fabrication processing technologies for secondary material arising from recycling – Develop extrusion dies or extrusion processes to reduce wall thickness of extruded part without compromising strength or other properties • Achieve lower costs by reducing processing steps via new technologies or approaches. – Replace batch processing with continuous processing technologies – Explore casting technologies to accommodate high levels of impurities without a negative impact on final product properties – Eliminate the need for surface finishing through advances in the use of lubricants or other approaches	• Smart fabrication processes that enable higher-quality and lower-cost products. • Thin-walled, strong extrusions (1 mm). • Reduction in process steps and lower overall processing costs.
5-10 years	• Understand and take advantage of extrusions with inherently non-isotropic mechanical properties (based on axes). • Continue research and build on innovations to improve the cost-effectiveness and sustainability of fabrication processes.	• Improved fabrication techniques based on materials properties data. • Cost-effective, sustainable, and high-quality product forms.

Stakeholders and Potential Roles

Product manufacturers: Provide supplier process data, physical data, and process expertise; design and test new manufacturing processes.

End-users/OEMs: Define specifications; test new components.

National laboratories: Participate in collaborative projects; conduct material and lab-scale research; provide data and testing/verification facilities.

Government: Support research programs.

Academia: Develop models, provide materials, data, and process research and validation at the lab scale.

RECYCLING AND SUSTAINABILITY

OVERVIEW

Recovered aluminum pressed together for recycling.

The use of recovered aluminum is a vital part of the industry and has been practiced since the early 1900s. The practice became mainstream with beverage can recycling in the 1960s, bolstered by growing public awareness of the environmental advantages. Recycling aluminum scrap into aluminum for reuse is referred to as secondary production. In comparison to primary aluminum production, this process is 92% more energy efficient, providing significant economic and environmental benefits for both industry and consumers. Secondary production is responsible for about 40% of North American aluminum supply today.

Aluminum reuse has been growing for decades, with recent gains attributed to the strong demand for automotive aluminum. Aluminum recovery from scrap totaled 263,000 tons in April 2021, up 8% from April 2020. The average price of some types of aluminum scrap more than doubled from April 2020 to April 2021 (old sheet and castings).[39]

A 2016 study on the end-of-life (EOL) recycling of automotive aluminum found the overall recycling rate (best case) to be as high as 90%, with specific values ranging from 80 to 98%.[40] The effectiveness of recovery can be variable, depending on separation processes, types and combinations of alloys, and other factors. Today, over 90% of a vehicle's aluminum is recovered and recycled. While this is less than 10% of the average vehicle by weight, it represents almost 50% of the scrap value.[41]

The use of secondary aluminum in products can vary considerably. For example, aluminum sheet for use in the North America automotive sector contains about 25% recovered aluminum, mostly from pre-consumer scrap.[42] Roughly 95% of aluminum die castings are produced using only recycled material.[43] The growth of aluminum content in vehicles is expected to continue, largely in the form of wrought products. The demand for some casting applications (engines and transmissions) that currently consume much of the recycled aluminum may decline, providing a compelling and urgent need to direct more wrought alloy scrap back into wrought products. As automakers strive to produce more fuel-efficient, battery electric, and sustainable

[39] Aluminum: Mineral Industry Surveys. April 2021. U.S. Geological Survey. https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/atoms/files/mis-202104-alumi.pdf

[40] Sean Kelly and Diran Apelian. Automotive aluminum recycling at end of life: a grave-to-gate analysis. Center for Resource Recovery and Recycling. Worcester Polytechnic Institute. 2016. www.drivealuminum.org/wp-content/uploads/2016/06/Final-Report-Automotive-Aluminum-Recycling-at-End-of-Life-A-Grave-to-Gate-Analysis.pdf

[41] 20 Auto Recycling Facts and Figures. August 2019. The Balance Small Business. www.thebalancesmb.com/auto-recycling-facts-and-figures-2877933

[42] Per ISO14021:2016, pre-consumer material is diverted during manufacturing process and excludes rework, regrind, or scrap generated and capable of being reclaimed within the same process.

[43] Benefits of Recycling in the Die Casting Industry. October 23, 2017. Premier Engineered Products. https://diecasting.com/blog/benefits-of-recycling-in-die-casting/

vehicles, aluminum use will continue to grow. This growth will require more efficient ways to separate, recover, and reuse aluminum scrap in automotive components.

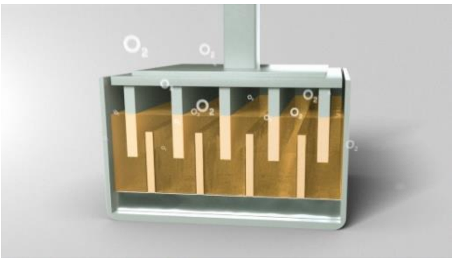
GOALS

Goals for aluminum recycling and sustainability range from an improved, more efficient infrastructure for aluminum scrap recovery to increased utilization of scrap and the wide promotion of automotive aluminum as a sustainable solution. As shown in Table 21, near-term goals focus on building and deploying the improved infrastructure needed to collect, sort, and reuse scrap. Key factors will be the expanded abilities to return scrap to the mill; create applications for both pre- and post-consumer[44] recycled materials; and identify, segregate, and reuse different types of alloys effectively.

Table 21. Goals for Aluminum Recycling and Sustainability	
Near Term (1-5 years)	• Infrastructure to collect, sort, and recycle scrap generated in the supply path from mill to end user by 2025; ability to sort by family and by alloy; improve the efficiency of current systems beyond one-ton per hour on a throughput and cost/ton basis. – Standards and guidelines that promote pre- and post-consumer recycling. – Segregation of wrought alloy from cast alloy at EOL recycling, with improved cost-effectiveness of sorting cast from wrought. • Recycled aluminum from pre-consumer scrap: increase to 40-50%; from post-consumer scrap: increase wrought application 1% year after year. • Improved energy efficiency and reduced life cycle emissions (air, waste) related to aluminum manufacture. • Open standards for fabrication (extrusions, casting, sheet) to allow scrap absorption (achieved via OEM collaboration) to support closed-loop recycling. • Industry consensus on the methodology for calculating carbon footprints of primary and secondary production.
Mid Term (5-10 years)	• Increase in recycled content of aluminum in automotive products via sustainable, closed-loop processes, EOL recycling, and reduction in pre-consumer scrap.[44] • Ability for EOL shredders to separate wrought from cast aluminum and recover post-consumer scrap to meet increasing demand in the automotive sector. • Reduced environmental footprint of the manufacturing and recycling processes by improving efficiency and selecting lower-footprint raw materials in supply chains.
Long Term (10+ years)	• Support of U.S. goals for a carbon-pollution-free power sector by 2035 and net zero economy by 2050 by reducing process carbon emissions (e.g., inert anode smelting technology), using renewable electricity or low-carbon energy sources, utilizing clean hydrogen fuel and/or clean electricity-based technology to melt and process metals, and implementing carbon sequestration or carbon capture strategies. • Aluminum positioned as an environmentally sustainable solution, helping OEMs meet internal and regulatory objectives for carbon neutrality and emissions reductions. • Full transparency and traceability of the aluminum carbon footprint, from mining to EOL.

[44] Per ISO14021:2016, pre-consumer material is diverted from the waste stream during a manufacturing process. Excluded is reutilization of materials such as rework, regrind, or scrap generated in a process and capable of being reclaimed within the same process that generated it.

An important consideration in setting and achieving these goals is the ability to make well-sorted scrap available to processors or recyclers. A preponderance of automotive aluminum today is fully recycled, including both manufacturing and EOL scrap. However, most of the scrap ends up being recycled as cast alloys, both domestically and in foreign countries. Future automotive demand for cast alloy is expected to be limited while demand for wrought alloy will grow significantly. To address this imbalance, the industry needs to achieve closed-loop recycling—for both manufacturing and EOL scrap.



Inert anode technology for electrolysis of alumina. The ELYSIS™ technology eliminates direct greenhouse gas (GHG) emissions.

Segregation of materials has been an issue. In some cases, the available technologies are not economically viable. To be cost-effective and increase the value of secondary aluminum, the cost of technology must be less than the value of the recycled stream. Wrought aluminum producers can play a role in helping to increase demand for wrought alloy scrap. Guidelines for segregating and recycling scrap are key—and should be developed in collaboration with supply chain partners.

The separation and sorting of aluminum at EOL continue to pose a challenge. Advances and innovations are needed to improve the speed, selectivity, and efficiency of sorting operations. As the requirements and design of automotive components change with the move toward BEVs, the industry will need to explore new uses for certain types of scrap, such as castings.

Tracking of material flows from cradle to grave would enable the entire value chain to address sustainability issues effectively and efficiently. Big data and data analytics will play a significant role. As companies move toward smart systems and Industry 4.0 manufacturing plants, data collection points will increase along with ability to rapidly translate data into knowledge.

FUTURE OPPORTUNITIES

Automotive aluminum components can offer lower carbon emissions than steel, provide more recycle-friendly alloys and products, and support a cost-effective, sustainable scrap market (see Figure 25). Automotive cast parts, sheet, battery enclosures, and structural components can all benefit from improved recyclability relative to cost and value. Closed-loop recycling, a unique competitive advantage for aluminum alloys, could effectively reduce the life cycle carbon footprint of a vehicle.

Closed-loop recycling requires a stable scrap supply and reliable methods for identifying and separating materials. New paradigms include cradle-to-grave tracing/identification for each part, i.e., a QR or similar code allowing the user to see the complete life cycle of the part. The ability to recover and return aluminum back to its original processing mode is critical (e.g., wrought products back to wrought products, cast back to cast, etc.).[45] The recyclability of aluminum in an ecosystem-based approach; even if the material goes to other sectors, it will increase awareness of aluminum as a sustainable material.

[45] Wrought refers to aluminum that is subjected to mechanical working processes such as rolling, extrusion and forging.

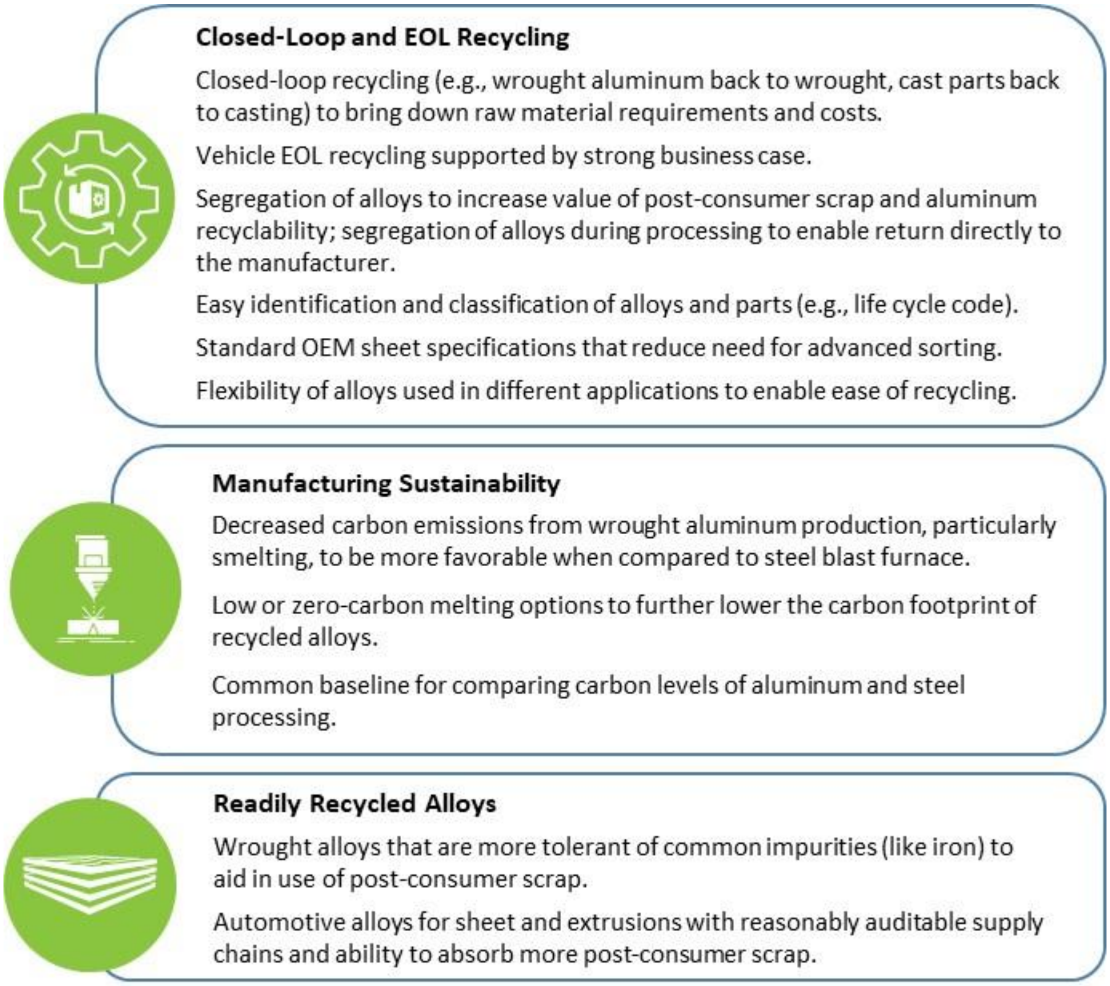


Figure 25. Future Opportunities for Recycling and Sustainability

A key opportunity is to improve vehicle EOL recycling. The business case is currently developing to show how EOL recycling improves overall cost-effectiveness and sustainability for automakers. More accurate predictive models of costs and benefits and better awareness of the value of EOL recycling are needed to catalyze investment in this approach.

As the United States moves toward more stringent carbon and emissions standards, aluminum components hold great potential to help meet regulatory or legislative targets like those in the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule. Aluminum can demonstrate a clear carbon and sustainability benefit over other materials in production, recycling, and use phases. As noted, secondary aluminum represents a substantial reduction in the energy and emissions footprint of aluminum. Lightweight vehicles reduce fuel consumption and emissions. Through lightweighting, aluminum can also increase the driving range of BEVs—making them a more viable and sustainable vehicle option.

While current regulations only address tailpipe emissions, aluminum will become more attractive if regulatory requirements are changed to address the full life cycle energy demand of automobile production and use. Aluminum has a higher scrap value than steel, creating more incentives to responsibly recycle, and aluminum recycling could become even more economically viable if carbon taxes increase the cost of manufacturing vehicle components.

Aluminum is an infinitely recyclable material—presenting many opportunities for more sustainable automotive parts.

TECHNOLOGICAL/OTHER CHALLENGES

A number of identified technological challenges pertain to recycling and sustainability of aluminum. As shown in Figure 26, challenges center on the lack of sufficient sorting and recycling infrastructure, limited capabilities, methods to enable effective EOL component recovery and use, and incorporation of design elements to ensure that parts can be disassembled and recycled.

The infrastructure for recycling is well established in the scrap industry. However, the availability of cost-effective separation and segregation technology for aluminum is limited. Technology is needed to enable true closed-loop recycling. The EOL vehicle recycling infrastructure works but better sorting technology (speed, material specificity, cost, etc.) is needed. Proven and demonstrated alloy identification is needed to effectively separate and segregate aluminum in scrap yards.

OEM collaboration is needed to develop open standards for requirements, enabling more absorption of scrap and closed-loop recycling.

A major challenge is to efficiently shred and separate dissimilar metals and alloys joined together by automotive bonding, welding, or riveting. Innovative joining methods could enable more efficient shredding of metal.

The United States lacks standards for EOL recycling; industry-wide specifications like those of the German Association of the Automotive Industry (VDA) would be beneficial.[46] The VDA has established a high-quality, certified take-back and recycling

[46] German Association of the Automotive Industry, or Verband der Automobilindustrie (VDA) www.vda.de/en/topics/environment-and-climate/environmental-protection-in-production/end-of-life-vehicle-recycling.html

network for EOL vehicles in Germany, where free take-back is guaranteed. Ineffective dismantling of parts at EOL is a major challenge that can be addressed through design and alloy specifications that are more flexible for recycled materials.

Tight markets are limiting the business case for EOL recycling in the short term. The current demand growth rate for recycled aluminum outstrips scrap and is expected to do so for the next 15 years. The challenge is to manage being a net-scrap exporter (aluminum scrap recycled is more than domestically used). A business case is lacking to justify investment in advanced sorting; refining and scrap recyclers are likely waiting for the right cost and market signals before investing.

Design for recycling can improve EOL use of materials but is rarely the least expensive option when designing components to be cost-competitive. Designs must overcome the challenges that prevent all the component materials from being readily identified and cost effectively dismantled and recycled. Designs for recycling must also ensure the performance of materials is maintained as materials recyclability and secondary aluminum content is increased.

Sorting and Recycling Infrastructure

- Developing the next generation of high-speed, alloy-selective, low-cost sorting technology for shredded scrap.
  - Creating effective processes for dismantling component parts before shredding; body structure components that are not easily separated.
  - Effective removal of non-metallic scrap.
  - Efficiently shredding/separating dissimilar metals and alloys that are bonded, welded, or riveted.
- Making sure state-of-the-art technologies for closed-loop and EOL recycling are available to all users.
- Designing recycle-friendly alloys; incorporating design considerations for EOL recycling.

Material and Scrap Life-Cycle Management

- Developing comprehensive systems for tracking and recording global scrap flow and properties data related to recycled materials.
- Establishing open standard OEM aluminum specifications (like VDA in Europe) to support closed-loop recycling and EOL recovery.
- Improving flexibility in sheet and extrusion specifications to enable aluminum suppliers to use more EOL recovered materials.
- Addressing tight alloy control that hinders use of post-consumer scrap and limits compatibility.

Figure 26. Technology Challenges for Recycling and Sustainability

R&D NEEDS

MAJOR RESEARCH TOPICS

Research is needed in multiple areas to improve aluminum recycling capabilities and the overall sustainability footprint of aluminum automotive products. Priorities for research focus on selective, high-speed/volume sorting and shredding technologies; processes and materials to enhance recyclability; and analysis of data related to scrapped or recovered materials (Table 22).

Table 22. R&D Needs and Other Activities Identified for Recycling/Sustainability

Category	Priority Low	Priority Med	Priority High
Material Sorting and Shredding			
High output sorting equipment.			◊
Effective combined use of x-ray transmission (XRT), Laser Induced Breakdown Spectroscopy (LIBS), and AI to achieve alloy segregation.			◊
More reliable and sensitive tools to analyze materials, from scrap sorting to metal cleanliness; artificial intelligence systems to enable sorting/recovery.	◊		
Processes Impacting Recycled Materials			
Separating bonded and riveted joints for recycling, or ways to use the shredded material that has bonded and riveted metal content; elimination of steel rivets that are hard to remove during shredding.			◊
Alternatives to using rivets (e.g., spot welding); increasing the recyclability of joined aluminum components.			◊
Sheet and extrusion alloys and mill processes for closures and BIW; structural die casting alloys that are more tolerant of recycled content.			◊
Structural die casting alloys with high iron limits.		◊	
Design and process optimization to further enable recovery and recycling.		◊	
Recycling Data			
Line-of-sight, auditable data/understanding of supply chain for metals and alloys for automotive OEMs.			◊
Digital vehicle inventories for scrap recyclers, dismantlers, and shredders to enable definition of auto components for potential dismantling.		◊	
Better knowledge of scrap source and composition accessible to processors.	◊		
Tracking of material flows from cradle to grave to enable entire value chain to address sustainability issues effectively.	◊		

The separation and sorting of aluminum at EOL continues to be a challenge. Advances and innovations are needed to improve the speed, selectivity, and efficiency of sorting operations. As the requirements and design of automotive components change with the move toward BEVS, new uses for some types of scrap, such as castings, will need to be explored.

Tracking of material flows from cradle to grave would enable the entire value chain to address sustainability issues effectively and efficiently. Big data and data analysis will play a significant role. As companies move toward smart systems and Industry 4.0 manufacturing plants, data collection points will increase along with ability to rapidly analyze data.

ACTION PLANS

Action plans for research have been developed to address some of the most critical challenges to enhance the recyclability and sustainability of aluminum. The action plans describe the path forward, a detailed research approach, desired outcomes, and benefits to the industry. Specific projects include:

- *Develop High-Speed/High-Volume Sorting and Recycling (Figure 27)*—Advances in methods to recover and reuse aluminum, with a focus on high-speed, high-volume processes for shredding, sorting, and processing pre- and post-consumer aluminum components.
- *Enable and Ensure Life Cycle Management Across the Value Chain (Figure 28)*—Development of data and systems to track information about aluminum and components, from mining to the OEM to consumers and vehicle scrap recovery.
- *Recycle Bonded and Riveted Joints (Figure 29)*—Innovative designs for joining to improve the ability to recycle aluminum and reduce material waste.

Design for recycling enables parts to be more readily dismantled, recovered, and reused in similar applications.

Develop High-Speed/High-Volume Sorting and Recycling

Recycling of post-use aluminum automotive components is an important factor in sustainability and increasing the use of aluminum overall. As the demand for lighter vehicles drives up the use of aluminum, and especially wrought aluminum, recyclers will need advanced methods to recover and reuse this infinitely recyclable material. Table 23 lists some of the potential impacts and considerations of proposed research to develop high-speed and high-volume sorting and recycling technologies.

Table 23. Develop High-Speed/High-Volume Sorting and Recycling: R&D Impacts

Rank	Impacts
●●●●●	**Reduced Cost:** Increased value in alloy separations as a result of segregating specific alloys; increased revenue, which should encourage chasing more of those units.
●●●●●	**Sustainability:** Reduces carbon footprint of the input aluminum; reduces vehicle life cycle carbon footprint; increases purity of recycled material.
●●●	**Vehicle Performance:** Increases potential for use of aluminum in lightweighting.
●●	**Weight Reduction Potential:** Indirectly leads to increased availability of parts with lighter, recycled Al content.

Scrap metal processors and recyclers need to invest in equipment that will effectively sort the scrap material and produce consistently high-quality and high-purity aluminum ready for the furnace. Contaminants such as heavy metals, aluminum-plastic compounds, plastics, and other minerals need to be separated, cleaned, and removed—which is challenging to achieve at high volumes and speeds.

Recyclers have been developing new technology to address this challenge. Shredded material (known as Zorba) from scrapping of vehicles can be further processed into a lighter fraction (separating aluminum and magnesium contents from copper, zinc, brass, bronze, and stainless steel) referred to as "twitch." Through R&D, TOMRA Recycling has developed a technique using x-ray technology in an innovative configuration to enable sorting of aluminum-based scrap at different density levels, including low magnesium twitch.[47] TOMRA has achieved consistently high purity rates of 99% recycled aluminum at test centers in Germany and the United States—potentially creating a viable material for direct input to furnaces.

Additional research is needed to enable sorting and recycling of high scrap volumes at higher speeds (up to 15 tons per hour). Approaches to pursue include technologies that minimize mixing of different alloys and materials in the scrap streams and sorting technologies that can separate, analyze, and quickly sort mixed material and scrap back into relevant aluminum alloy families. The objective is technology with high throughput and versatility, providing efficient alloy separation at low cost.

Figure 27 shows the action plan for improvements that will help to achieve higher speed/volume processing of aluminum scrap.

[47] "Addressing the challenges of aluminium recycling." TOMRA Recycling. July 14, 2020. *Recycling Magazine*. Accessed May 17, 2021. www.recycling-magazine.com/2020/07/14/addressing-the-challenges-of-aluminium-recycling/

Figure 27: Develop High-Speed/High-Volume Sorting and Recycling

Barrier/Problem Statement: Current recycling of scrap has drawbacks due to scrap contamination by other materials, and the mixture of wrought and cast alloys when shredded together. As a result, most recovered scrap can only be used for making certain cast products. Some end products require the scrap to be heavily diluted with primary, pure aluminum. Equipment must be flexible and responsive to reduce cost for overall processing and recycling.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Benchmark current EOL recycling technologies and assess the composition of final recovered scrap; include full spectrum of dismantling, shredding, and sorting. • Share industry best practices for separating and avoiding mixing of manufacturing process scrap early on. • Review and evaluate studies of future twitch composition and impacts on recycling. • Research innovations to improve sorting speed and ability to match alloys to sample element spectrum; could include improved sensors or improved recognition algorithms.	• Cost-effective and selective dismantling, shredding, and sorting (down to the alloy family) at a throughput of up to 15 tons per hour.
5-10 years	• Research and develop technologies to further increase sorting speed and ability to match alloys to sample element spectrum, to include advanced sensors and recognition algorithms, as well as other innovations. • Develop technology and conduct tests of high-speed chemical analysis and sorting of solid-state scrap at relevant rates.	• Cost-effective and selective dismantling, shredding, and sorting (down to the alloy family and some specific alloys) at a throughput of up to 20 tons per hour.
>10 years	• Explore developments to improve sorting speed and ability to match alloys to sample element spectrum. • Research potential for molten metal purification technologies as recovery options, exploiting advances in science or technology.	• Cost-effective and selective technologies at a throughput of up to 20 tons per hour or more. • Processes capable of separating elements from molten metal with minimal loss at acceptable cost.

Stakeholders and Potential Roles

Product manufacturers: *Major equipment producers* – Develop and prototype scrap sorting equipment (e.g., Steinert, TOMRA Recycling, other companies).

End-users/OEMs: Adapt material specifications to allow high recycle content materials; adapt product design to facilitate recycle.

Scrap suppliers, automotive shredders/sorters: Serve as scrap and project partners; key contributors who provide data, testing, and develop new machines/technology.

National laboratories: Scale new technology developments; provides expertise and technology developers.

Government: Support seed projects (e.g., ARPA-E); policy and legislation on product recyclability and recycled content.

Academia: Provide expertise; research on molten metal purification technology and understanding.

Enable and Ensure Life Cycle Management Across the Value Chain

Life cycle management of the value chain follows the energy, carbon, environmental, and other aspects of data on a material: from when it is mined, to its manufacture and use as a product, and through the end of its useful life, when it can be dismantled, disassembled, and reused or recycled. To best compare the advantages of infinitely recyclable aluminum, automotive OEMs will need a line-of-sight, auditable understanding of the supply chain and life cycle of aluminum as well as other materials. The impacts and considerations for research in life cycle management are shown in Table 24.

Table 24. Enable and Ensure Life Cycle Management Across the Value Chain: R&D Impacts

Rank	Impacts
●●●●	**Reduced Cost:** Transparency in metrics will showcase the benefits of aluminum, leading to potential increase in the value of scrap and its recovery and ability to grow markets for products.
●●●●●	**Sustainability:** Consumers demand sustainability; data and metrics will help build confidence in the sustainability of the product. Metrics can be used to educate and inform policymakers.
●●●	**Value of Scrap:** Trackable information could make it easier for scrap sellers to match recovered materials to end-users.

Research will focus on developing data and systems to track information from mining operations to the OEM to consumers and until the vehicle is shredded for scrap recovery. The current scrap market is very broad and based on the standards of the Institute of Scrap Recycling Industries (ISRI). If the details on each alloy, source, and contamination level were made available, they would provide greater transparency and help to match scrap suppliers to the users looking for that scrap. This data access can potentially increase the value of scrap, open new markets for recycled automotive aluminum, and help support advances in scrap segregation. Customers will know exactly what is being delivered (data and metrics)—helping to build confidence in aluminum as a sustainable material of choice. Digital inventories for scrap recyclers, dismantlers, and shredders will also impart greater knowledge of scrap sources and composition to processors.

New areas of research in traceability will determine viable metrics and information collection techniques; encryption or other tools will be explored. Once systems are developed, challenges of cost and implementation will need to be addressed. A system that is streamlined and standardized early on will be most cost-effective.

Collaboration is needed between OEMs and product manufacturers to determine the metrics and data needed to best inform the life cycle. A clearer understanding is needed of the data that can actually be provided by the suppliers to the OEMs (i.e., available and non-proprietary) and still provide the transparency desired.

Figure 28 shows the roadmap action plan for life cycle data and analysis to provide an improved understanding of the automotive supply chain. Successful R&D could establish an improved infrastructure for both data collection and exchange, enabling the tracking of materials throughout their life.

Figure 28: Enable and Ensure Life Cycle Management Across the Value Chain

Barrier/Problem Statement: Materials life cycle data is inadequate to provide the needed transparency, information sharing, and better-informed sourcing and decision making. A consistent set of life cycle data would enhance the potential for better product development, effective emission reduction, and improved recycling strategies and design for recycling at EOL. A common set of sustainability metrics is not available or consistent; once established, metrics could cascade up and down the supply chain to improve sustainability approaches.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Develop and standardize framework (vehicle/system to reporting) and metrics; review existing requests from OEMs to develop a framework. • Streamline metrics for the materials supply chain. • Incorporate metrics and framework into management system (from manufacturers to OEMs to their suppliers). • Develop a roadmap for recycling to be applied using established metrics; start to implement and identify problems. • Identify targets (when to achieve what level of recycling, EOL reuse, etc.) • Create digital vehicle inventories for scrap recyclers, dismantlers, and shredders so they can define auto components for dismantling.	• System that can track information from mining to OEM to consumers, and until car is shredded and scrap recovered.
5-10 years	• Check status in meeting targets and reassess as needed; develop process to continuously improve life cycle data inputs. • Establish a model for educating other stakeholders (e.g., universities, government, OEMs, suppliers). Push for targets in something like the Automotive Industry Action Group (AIAG).	• System that collects and reports data and is accessible and flexible.
>10 years	• Automate information exchange across the value chain (streamlined). • Incorporate cascading engineering data beyond energy and emissions (Industry 4.0 opportunities, such as artificial intelligence or machine learning).	• Fully automated system with LC data collected/ reported under business-as-usual scenarios.

Stakeholders and Potential Roles

Product manufacturers: Collect and manage and share supply chain data; develop environmental product declarations (EPDs) on products; engage with upstream suppliers to communicate data needs.

End-users/OEMs: Define and standardize metrics and targets (collaborate with the supply chain/stakeholders); consume and report metrics.

Scrap suppliers, automotive shredders/sorters: Define recycling composition, provide data, and support metrics.

National laboratories: Support data collection and analysis efforts, communicating best practices and how to understand uncertainties.

Government: Use metrics to guide policy decisions; provide forum for hosting data and provide vetted background data; communicate with industry about standards are needed; facilitate access to public data.

Academia: Help develop metrics, evaluate uncertainties, and research how to be more efficient with blockchain.

Aluminum Association: Reach out to associations of other industries such as the ISRI, American Foundry Society, and others to learn best practices.

Recycle Bonded and Riveted Joints

Improving the recyclability of today's bonded and riveted joints will reduce overall scrap contamination and waste and increase reuse of aluminum. For example, material overlap in bonded joints is essentially a waste of material that, if eliminated or minimized, would contribute to lower material requirements. Ultimately, with improved recyclability, vehicle fleets may not need to be scrapped; components could be incorporated into the manufacture of new vehicles. In the future, vehicles will also be more modular in design, enabling easier component integration. Table 25 lists some of the potential impacts and considerations of proposed research.

Research is needed to overcome some of the challenges in making bonded and riveted joints more recyclable. One of the objectives is to move toward improved reuse of components instead of crushing or shredding the materials.

While recyclable joints will contribute to sustainability, there are some drawbacks. Joint stiffness and disassembly often conflict. Joint stiffness contributes to in-use performance but limits the ease of disassembly at EOL. The use of adhesives also increases stiffness.

Table 25. Recycle Bonded and Riveted Joints: R&D Impacts

Rank	Impacts
●●●	**Cost Reduction:** Life cycle costs may be reduced, but process changes for enhanced recyclability may increase overall cost.
●●●	**Weight Reduction Potential:** Improved joining can reduce bonding surface and material overlaps, reducing overall material usage.
●●●●	**Vehicle Performance:** Reduced material usage impacts loads the vehicle must handle; vehicle stiffness can be impacted by joint methods, impacting ride, handling, noise, and vibration.
●●●	**Implementation Barriers**: The scrap and recycling industry has a heavy investment in conventional approaches; product manufacturers must implement changes in design for greater recyclability, which could impact other design aspects (aesthetics) or performance.
●●●●●	**Sustainability:** Innovations and improvements can help to minimize scrap and waste produced during manufacturing and improve EOL recyclability.
●●●	**Vehicle Safety:** To meet safety requirements, recyclable material joints must not separate during product use, or when unintentionally exposed to certain circumstances.

Figure 29 shows the roadmap action plan for bonded and riveted joints that are more readily recyclable. Successful research could lead to new types of joining with less material waste as well as new methods for recycling, including mixed materials.

Figure 29: Recycle Bonded and Riveted Joints

Barrier/Problem Statement: Good methods are currently lacking to separate for recycling alloys and materials that have bonded and riveted joints; no recycling methods exist for cost-effectively sorting and reusing shredded mixed materials that contain rivets and adhesives along with aluminum. Precision spectroscopy can be used, but processing is slow and cannot accommodate the volume of material to be processed. Current separation processes can differentiate between bulk materials, but alloys and adhesives contribute to waste.

	Roadmap Action Plan	Overarching Goals
1-5 years	• Identify novel pathways for material separation; focus is improving recycling of existing vehicles that will reach EOL in the near future. Potential methods include novel chemical bonds, light activated bond separation, and laser, sound, vibration, or other mechanisms. • Assess baselines to identify avenues for improvements in joining; research new techniques to reduce non-recyclable materials and waste or material overlaps.	• Reduced amount of material that cannot be recycled due to adhesive bond in the joint. • Reduced amount of waste produced during scrap/shred processes. • Identification of new potential joining methods with greater recyclability. • Improved recycling pathways for existing vehicles and joined materials.
5-10 years	• Identify innovations in joining that enable simple separation at EOL or before. • Focus on changing processes to improve recyclability in new vehicles being manufactured. • Identify process adjustments needed in scrap facilities to accommodate new separation processes.	• Adjustments made to enable adoption of new separation processes in scrap facilities. • Production process changes made to allow for new joining methods.
>10 years	• Continue to develop innovative processes to enable greater reuse of aluminum and components.	• Scrapping of vehicle fleets eliminated or minimized; all components integrated into new vehicle manufacture.

Stakeholders and Potential Roles

Product manufacturers, product designers, design engineering groups: Design and specify the joints for performance and recyclability. **Production team:** Implement changes.

End-users/OEMs: Specify vehicle performance, cost, and responsibility for recycling.

Scrap suppliers, automotive shredders/sorters: Assist with recycling methods for batteries; prepare for how to handle incoming BEVs (of various designs) and recover/recycle structural components. Major role in development of scrap separation technologies.

National laboratories: Interface with manufacturers, scrap/shred/sort organizations on research projects (limited role).

Government: Determine recyclability legal or regulatory requirements; support advanced manufacturing research.

Academia: Interface with manufacturers, scrap/shred/sort organizations on research projects (limited role).

Institute of Scrap Recycling Industries: Identify appropriate research topics that members will support.

Remade Institute: Collaborate via potential resources for projects or studies.

European Aluminum Association and other international organizations: Share best practices or lessons learned.

A PATH FORWARD

The use of aluminum is growing steadily in the automotive sector, due to its inherent characteristics: lightweight, strong, and infinitely recyclable. While growth is robust, many opportunities remain to be realized for this remarkable material. This Roadmap provides new directions for optimizing the use of aluminum in the automotive sector through a number of pathways, including:

- Design and product innovation
- Next-generation material and process R&D to lower costs and enhance performance
- Targeted efforts to create alloys and components that meet OEM specifications for emerging BEVs and other propulsion systems
- Increased sustainability and recyclability in all aspects of aluminum production, including a focus on closed-loop recycling and lower energy and carbon footprints
- Greater understanding of how to optimize materials and production through state-of-the-art digital technologies and data
- Uniform testing and validation across the industry.

The goals outlined in the Roadmap are ambitious and far-reaching, impacting all segments of the aluminum industry. Greater collaboration with automakers is foundational to achieving these goals. Increasing awareness of the benefits of aluminum for automotive applications is vital, especially among those in the automotive sector responsible for the design and selection of materials for components.

Table 26 lists some of the mutually beneficial activities identified as important for collaboration between OEMs and suppliers. These activities cover the key apsects of product and process innovation, but with a strong focus on lowering costs and improving recyclability and sustainability. Collaborations are critical to gaining in-depth understanding of performance requirements and designing suitable, high-performing materials and components.

Table 26. High-Value Activities for Collaboration with OEMs

Products/Processes	Cost	Recycling/Sustainability
• Develop new products, components, and test materials • Standardize material specifications across OEMs • Conduct training and workshops on product development • Use shared process data and AI/ML to optimize processing • Create databases of industry standards	• Share expertise to improve products, meet performance needs, and lower costs • Study/compare the benefits and costs of aluminum vs. steel parts • Decouple ingot size from thickness changes/cost • Set benchmarks with broad industry input	• Validate recycling in practice via reuse in components • Identify best recycling practices for supplier tiers • Design components for carbon traceability and recyclability • Access data to understand full aluminum life cycle

Profound challenges facing the automotive sector are stimulating novel cross-sector and supplier collaborations. From joint ventures to public-private partnerships, automakers are increasingly turning to collaborative efforts that can increase the competitive edge while enhancing vehicle performance. Early-stage collaboration can be the most productive and beneficial. Collaborations can help align products to specifications; demonstrate performance and value (and the business case); and build strong, lasting OEM relationships.

Successful collaboration will require mechanisms that are acceptable to OEMs and provide the maximum opportunities and benefits for all parties. Figure 30 illustrates some of the potential future collaborative pathways identified for implementing this Roadmap.

Figure 30. Pathways for Collaboration

- Precompetitive joint ventures
- Public-private partnerships targeting key technology areas
- OEM-specific design projects conducted via consortium
- Innovation consortia to support collaboration, networking, and investment
- Data consortium for North America Al
- Industry-sponsored forums on aluminum with interactive OEM-supplier sessions
- Collaborative pre-competitive research projects with suppliers, national laboratories, academia, and other research institutes
- OEM participation or membership in Aluminum Association
- Onsite, shared, or embedded resources (Al industry reps working onsite at OEMs)

While collaboration is foundational to success, challenges remain. Automotive executives are sometimes wary of large-scale collaborations due to IP, the time and funds commitments, and information-sharing challenges. There is a history of exclusion in the auto industry particularly in early-stage development. Building strong relationships through new partnerships, IP agreements, and successful joint activities can go a long way toward addresssing these. Information sharing is key. Table 27 illustrates some of the communication mechanisms and ideas that have been identified to raise awareness about the benefits and value of aluminum for automotive uses—and help establish long-term OEM relationships.

Table 27. Raising Awareness of Aluminum

Information Sharing	Events	Market Supports
• Brochures, manuals, studies, informational webinars, and videos • Case studies on value of aluminum • Myth-busting white papers and articles • Instruction/guides on designing with aluminum • Information packets for suppliers to distribute to customers	• Trade shows/demos • Supplier Industry Day to highlight technical issues and goals • Free Great Designs in Aluminum Conference • Monthly cross-sector information-sharing forums	• Highlights of aluminum benefits produced via current projects • Unified industry voice on key, data-driven metrics • Social media campaign to raise public awareness • Multi-tier supplier approaches

The aluminum industry is poised to take advantage of the wealth of opportunities arising from the coming surge of BEVs on the market and lasting changes in mobility. To reap the benefits, producers and product manufacturers must continue to innovate and explore new materials and components designs that lower costs, increase performance, and enhance sustainability.

Over the coming years, the aluminum industry will continue to monitor and assess progress toward the goals in this Roadmap. This is a dynamic, living document, and the strategies described here will be evaluated as technologies and markets evolve.

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