ALUMINUM INDUSTRY ROADMAP FOR THE AUTOMOTIVE MARKET:

Enabling Technologies and Challenges for Body Structures and Closures

May 1999

The Aluminum Association, Inc.

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The Aluminum Association, Inc.

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EXECUTIVE SUMMARY

Cooperative partnerships between industry and government are encouraging the development and use of innovative technologies that reduce industrial energy use, processing wastes, and production costs. Aluminum producers, the auto makers, and the U.S. Department of Energy have recognized the opportunity for aluminum to serve as the ideal material for tomorrow's "new generation of vehicles." Automakers plan to offer consumers a vehicle with excellent fuel efficiency, reduced emissions, and enhanced performance. This can only be accomplished by significantly lowering the weight of the body and secondary components of the vehicle, for which aluminum is the logical solution. This *Aluminum Industry Roadmap for the Automotive Market: Enabling Technologies and Challenges for Body Structures and Closures* is a blueprint of the techniques and strategies that will be used by the aluminum industry to ensure that aluminum is a cost-effective application for tomorrow's vehicles.

An earlier document has already made contributions toward this effort. In 1997 The Aluminum Association published, on behalf of the aluminum industry, the *Aluminum Industry Technology Roadmap*, identifying technical challenges the industry must address to remain competitive in the coming decades. This generic *Technology Roadmap* established research goals to achieve greater energy efficiency, productivity, quality, and environmental performance in the primary production of aluminum. Achieving these goals and others will help the aluminum industry provide cost-effective aluminum materials to all its customer markets. This present document, the *Aluminum Industry Roadmap for the Automotive Market,* identifies additional research in the fabricated products area specific to the automotive market. This research will aid the auto industry in reaching the goals it has set for producing cost-effective, aluminum-intensive vehicles by 2004. In fact, both of these aluminum industry *Roadmaps* are complimentary to the thrusts of the auto industry related to materials, which appeared in its1996 planning document, *Partnership for the New Generation of Vehicles (PNGV)*.

The PNGV program calls for technical improvements in feedstocks, casting, forming, joining, and recycling to produce its new vehicles. The generic *Aluminum Industry Technology Roadmap* sets research goals in the production of primary aluminum and aluminum sheet and extrusions to improve process efficiency. This *Aluminum Industry Roadmap for the Automotive Market* discusses the research and development necessary to meet the technological challenges of casting, forming, joining, and recycling cost-effective aluminum components for the vehicles.

Good automotive design is also crucial to the successful use of aluminum in future vehicles. The design engineer is being challenged to integrate the properties of lightweight materials, revolutionary forms for automotive components, unique manufacturing processes, and the recyclability of the vehicle. At the same time, the designer can take advantage of the flexibility inherent in these new materials and processes to propose new vehicles that will appeal to the consumer. Aluminum is the key to making these vehicles not only lightweight but also safe, fuel-efficient, environmentally compatible, and cost-effective.

SECTION I. OVERVIEW

This *Aluminum Industry Roadmap for the Automotive Market: Enabling Technologies and Challenges for Body Structures and Closures* is part of an ongoing technology planning initiative undertaken by the U.S. aluminum industry to position itself to compete effectively in future markets. The aluminum industry recognizes that the U.S. automotive industry is committed to creating a “new generation of vehicles” that offers superior fuel efficiency without compromising safety, performance, or comfort. The aluminum industry intends to help the automakers produce lighter-weight cars that provide fuel savings, reduced exhaust emissions, and enhanced performance that people can afford to buy.

Aluminum represents an ideal solution for achieving tomorrow's vehicles because it offers automakers the opportunity to design and manufacture safe, high-performance, energy-efficient, and environmentally friendly vehicles that are much lighter than current vehicles. In addition to taking advantage of the lighter mass of aluminum compared to steel for the body of the vehicle, further weight reduction is possible through secondary weight savings in the engine, transmission, brakes, wheels, tires, fuel tank, and other systems. Developmental work in aluminum will contribute significantly to the long-term cost-effectiveness of using this material in automobiles.

Aluminum’s status as a material of choice for the next generation of vehicles was confirmed in a report on the Partnership for a New Generation of Vehicles (PNGV) program by the National Research Council (NRC), the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering. The PNGV is a cooperative research and development program of the federal government and the United States Council for Automotive Research (USCAR) that is focusing on the development of a new generation of family-sized vehicles with high fuel efficiency. The report identified aluminum as one of the most promising technologies for meeting PNGV’s goal of having production-ready prototype sedans by 2004 that have a fuel economy of up to three times that of 1994 vehicles without compromising safety, size, utility, or cost.

To accomplish this, engineers must reduce the weight of the vehicle by 40 percent by using more lightweight materials such as aluminum to reduce the mass of the body and chassis by half and to trim the weight of the powertrain and interior components. Since “customer affordability” is a key PNGV goal, these weight reductions must be obtained without increasing the cost of the vehicle above that of current mid-size cars. The *PNGV Technical Roadmap* contains a list of technical projects that are key to achieving this new technology.

In cooperation with the aluminum industry, the automotive industry is striving to produce vehicles that will achieve PNGV goals and comply with federal and state regulations on corporate average fuel efficiency (CAFE), pollutant emissions (including potential limits on emissions of carbon dioxide), landfilling, and recycling.

Over the long term, aluminum-intensive vehicles will help automakers meet increased societal demands to preserve personal mobility, reduce the impact of passenger cars and trucks on the environment, and lessen U.S. dependency on foreign oil.

I-A. A Closer Look at Aluminum's Benefits

There are significant benefits in using aluminum to reduce vehicular weight, provide fuel savings, reduce exhaust emissions, and enhance the performance of future automobiles.

I-A-1. Weight Reduction

It is estimated that substituting aluminum for steel in an automotive body structure optimized for aluminum will directly reduce the automobile's body structure weight by 50 percent without compromising its performance, saving typically 300 pounds in a mid-sized sedan. As a general rule, a weight reduction of 10 percent can increase the vehicle's fuel economy by 6 to 8 percent. Thus, fuel savings of 0.9 to 1.4 gallons per 1,000 miles are achievable for each 100 pounds of weight reduction. The lifetime fuel savings of lighter-weight, aluminum-intensive vehicles compared to steel vehicles will continue to range from 500 to 700 gallons of gasoline. Today, the net value of such fuel savings would be about $600 in the United States.

I-A-2. Environmental Protection

Aluminum is also environmentally friendly. Every ton of automotive aluminum that is used to replace twice this weight of iron or steel reduces greenhouse gas emissions (CO_2 equivalent) by as much as 20 tons over a vehicular life of 120,000 miles, compared to conventional vehicles. The recyclability of aluminum is another significant factor in analyzing the life-cycle of the metal to produce vehicles. Aluminum is completely recyclable, and virtually all post-manufacturing automotive aluminum scrap is recycled. In addition, about 85 to 90 percent of post-consumer automotive aluminum scrap (about 1 billion pounds per year) is recycled. The technology for handling and recycling painted sheet and castings has been established for years, and aluminum can be recycled again and again, without a decline in material performance or quality or excessive buildup of impurities.

Approximately 60 to 70 percent of the aluminum used in today's vehicles is from recycled metal. Feedstocks of recycled aluminum eliminate nearly 95 percent of the energy and CO_2 emissions associated with the production of aluminum from virgin ore. Although automotive aluminum today represents less than 10 percent of the weight of today's typical car and could reach over 35% in aluminum-intensive vehicles, it already contributes as much as 35 to 50 percent of the value of the scrap recovered from a disposed automobile.

I-A-3. Other Advantages

While the principal reason for using aluminum for automobile construction is to reduce weight, aluminum offers many other advantages, including improved performance without having to increase engine capacity; better acceleration and braking; and excellent road holding, handling, and noise, vibration, and harshness (NVH) characteristics. The latter are a result of stiff body structures that can be achieved with both spaceframe and weld-bonded stamped sheet construction. With proper design, choice of alloy, and appropriate processing, aluminum components also provide excellent energy absorption. The structural stiffness and crashworthiness of aluminum bodies are equal to or superior to steel. Further, with the excellent corrosion resistance of aluminum, the crashworthiness of aluminum structures will not deteriorate with time.

I-B. Aluminum-in-Vehicle Cost

Cost — particularly the cost of aluminum relative to the cost of steel — is the main constraint on the further use of aluminum by the automotive industry. There is little chance that aluminum prices will approach steel prices on a per-ton basis. However, automotive components are considered on a functional basis, and aluminum has a density advantage over steel of 2.7. The critical issue is the *cost-effectiveness and life-cycle performance* of using aluminum as compared with steel.

Initial material cost is not a complete indicator of the total cost of substituting aluminum for steel or other materials. By evaluating the entire material usage and the manufacturing system as a whole as well as its life-cycle benefits, aluminum's true value become apparent. Since the use of lightweight aluminum body structures also allows automakers to downsize other parts of the car (e.g., the chassis components can be lighter and the engine smaller), there are additional savings in the vehicle's weight and cost, and further reductions in exhaust emissions during its use. This is particularly important since it has been shown that greater than 85 percent of the life-cycle CO_2 emissions occur during the *use* phase of the vehicle. These secondary cost savings often can be substantial.

1-B-1. R&D To Reduce Cost

Under the preexisting *Aluminum Industry Technology Roadmap*, there are a number of initiatives already underway to reduce the cost of producing aluminum. These new projects, sponsored by the U.S. Department of Energy's Office of Industrial Technologies (DOE/OIT) under the aluminum industry's partnership with the government, are focused on process improvements in primary aluminum production (see Section X for a complete list of projects). Projects related to advanced cell technologies, including wettable cathodes, will provide energy savings of 15-18 percent over current methods if they are successful. When coupled to an inert anode technology, they may provide an additional energy savings of 10 percent, for a total savings of 25-28 percent. Other projects focus on cost savings in the handling and treatment of molten metal. For example, one company claims major savings through more efficient oxygen-enhanced combustion processes while another claims benefits through improved molten metal transport.

The purpose of this *Aluminum Industry Roadmap for the Automotive Market*: *Enabling Technologies and Challenges for Body Structures and Closures* is to encourage the R&D efforts by the aluminum industry and its stakeholders which will result in cost reductions for materials supplied to the automotive industry.

The third area of activity that will have a major positive effect on cost reduction will be work related tot he auto industry's PNGV roadmap. In this regard, two other R&D efforts are underway: (1) Advances in the sorting and recycling of automotive scrap (discussed in detail in Section VIII) have the potential to significantly improve the economics and efficiency of these potential feedstocks; and (2) improvements in the continuous casting of automotive sheet would eliminate several process steps in the production of sheet stock, with significant cost savings. The *Aluminum Industry Roadmap for the Automotive Market* does not, however, recommend initiating new work by aluminum companies on continuous casting because of significant R&D investments in the past, progress to date, and the establishment of considerable intellectual-property positions.

The *Roadmap* <u>will</u> encourage other R&D efforts to reduce the aluminum-in-vehicle cost. However, given the diverse range of activities discussed above and listed in Section X, it is difficult and probably inappropriate to speculate on the timing and potential for success of specific cost reductions for aluminum production.

I-C. Scope of the Roadmaps

This *Aluminum Industry Roadmap for the Automotive Market: Enabling Technologies and Challenges for Body Structures and Closures* is the third document to be produced by the aluminum industry to plan its future course in technology-driven markets. In 1996, under the leadership of The Aluminum Association, the industry published *Partnerships for the Future*, which set forth its long-term vision of how to maintain and build the competitive position of the U.S. aluminum industry. In May 1997, the industry published the *Aluminum Industry Technology Roadmap*, which presented the industry's technology strategy for achieving the goals it has set for itself for the year 2020 related to energy efficiency, environmental production, productivity, and competitiveness in the marketplace. Many of the research needs identified in this "generic" roadmap directly or indirectly impact the use of aluminum in the automotive market. These include proposed efforts to

- develop processes and technologies to reduce the cost of ingot;
- improve understanding of the relationship of aluminum alloy composition and processing and its effect on microstructure and properties;
- develop improved casting processes (including continuous casting) to produce low-cost, defect-free sheet;
- establish alloy and testing commonization, i.e., reduce the number of alloy variants and test practices; and
- develop advanced methods for integrating product design and the material and processing selection.

Figure 1-1 summarizes some of the goals from the *Aluminum Industry Technology Roadmap* that

Energy Efficiency

- Increase the current efficiency of the Hall-Heroult cell process to over 97%
- Reduce the overall intensity of aluminum production
- Reduce the energy requirements of the Hall-Heroult cell to 11 kWh/kg by 2020

Environmental Protection

- Recycle and treat all types of aluminum wastes
- Increase recyclability of aluminum scrap
- Achieve 80% wrought recycling of automobiles by 2004

Cost and Productivity

- Reduce the costs associated with metal production by 25%
- Reduce the cost ratio of aluminum to steel to less than 3 to 1 for automotive applications
- Reduce product costs and product lead times through process reengineering

Markets

- Increase the use of aluminum in the automotive market by 40%

Figure 1-1. These goals of the aluminum industry for 2020, which appear in the *Aluminum Industry Technology Roadmap* of May 1997, will help increase the cost-effectiveness of aluminum for automotive applications.

will allow the aluminum industry to offer the automotive industry a cost-effective product. The aluminum industry's goals to reduce the energy intensity of producing primary aluminum, decrease emissions, enhance recycling, and improve metal quality are particularly important to the automobile industry because they could lead to significant reductions in the cost of aluminum for automotive applications.

This present roadmap, *The Aluminum Industry Roadmap for the Automotive Market*, focuses on the specific actions that the aluminum industry needs to take to enhance the cost-effectiveness of using aluminum in automotive applications, and has been structured to support the automotive industry's own efforts. The goal of the research identified here is to increase the efficiency with which aluminum is used and to reduce the cost of the processes to convert it from an ingot/sheet/extrusion product into a serviceable part or an integral component of the vehicle. Essentially every R&D effort proposed contributes directly or indirectly to lowering the cost of using aluminum in automobiles.

The technical topics addressed in the *Aluminum Industry Roadmap for the Automotive Market* reflect the entire automotive manufacturing process, from the production of semi-finished aluminum shapes through the assembly process to the recycling of automotive aluminum scrap. The specific areas that need to be considered when making an aluminum-intensive vehicle include the product forms (sheet, extrusion, and castings); the secondary processes that are used for the product forms; and the methods for putting the various product forms together (joining and assembly). The crashworthiness of aluminum-intensive vehicles is also covered, as is the use of aluminum metal matrix composites. Research that focuses on improving the production of primary aluminum, which is germane to the goal of reducing the cost of aluminum components, has been addressed adequately in Section XI of the *Aluminum Industry Technology Roadmap*.

The PNGV program's *Technical Roadmap* includes a list of key technical projects on the automotive industry's critical path to developing "new generation" vehicles. These projects are organized according to various technical topics such as feedstock, casting, forming, joining, and recycling. All of these topics will also be covered in the *Aluminum Industry Roadmap for the Automotive Market*, or were addressed in the more generic *Aluminum Industry Technology Roadmap.* Figure 1-2 indicates the program needs of the PNGV effort and where related information may be found in the aluminum industry roadmaps. The research that is recommended in the *Aluminum Industry Roadmap for the Automotive Market* is intended to focus on a midterm time frame (of 3 to 6 years) to maximize the opportunity to help the automotive industry reach the goals of the PNGV program set for 2004.

PNGV Need	Addressed in
Feedstock	*Aluminum Industry Technology Roadmap*: – Sheet and Extrusion Sections
	Aluminum Industry Roadmap for the Automotive Market:
Casting	– Casting Section
Forming	– Sheet and Extrusion Sections
Joining	– Joining and Assembly Section
Recycling	– Scrap Sorting and Recycling Section

Figure 1-2. The R&D needs of the PNGV program identified in the 1996 *PNGV Technical Roadmap* are addressed in the aluminum industry roadmaps.

I-D. Summary of the Overview

The use of aluminum in automotive applications has many demonstrated advantages. Through a unique combination of physical and mechanical properties, aluminum alloys and their manufacturing processes are able to contribute to both lower emissions and greater fuel economy by reducing total vehicular weight. Aluminum's light weight, strength, formability, corrosion resistance, and recyclability give it the potential to meet a wide range of design challenges. Just as importantly, the aluminum industry has the installed capacity, infrastructure, and experience to deliver the materials and components that the automotive industry needs to meet its obligations and goals. Even so, the industry is committed to further enhancing its competitive posture with regard to these applications. This *Aluminum Industry Roadmap for the Automotive Market* attempts to identify areas where additional research would be particularly useful to such an endeavor.

SECTION II. SHEET

Many of the world's leading auto manufacturers have already established the technical advantages of aluminum-intensive vehicles. Specifically, aluminum sheet is currently used in two classes of automotive applications: closure panels, and unibody or body-in-white structures. Aluminum alloy sheet is attractive for automobile body and panel applications because of its low density, high strength, good formability, excellent corrosion resistance, and availability in volume from well-established and highly competent suppliers.

II-A. Trends and Drivers

During the last decade, aluminum closure sheet has been used for specific applications on some high-end production vehicles in North America such as hoods of the Oldsmobile Aurora, Buick Riviera, and Lincoln Towncar. Recently, its use was extended to some very high-volume production vehicles, including hoods for the Ford F150 truck and decklids for the Ford Taurus/Mercury Sable vehicles. Worldwide, aluminum sheet has been used on a large number of specialty vehicles in structural applications, such as on the Audi A8 aluminum-intensive vehicle, the GM EV1 electric vehicle, and the Lotus Elise.

Two types of aluminum sheet alloy are being used for automotive body applications: aluminum-magnesium (5xxx) and aluminum-magnesium-silicon (6xxx) alloys. The latter alloys are more common for external closure panels due to their higher strength and further strengthening in response to paint baking. Use of aluminum saves about 24 pounds of weight for the hood of a mid-sized sedan. Some aluminum closure panels are now being specified for vehicles at the conceptual design stage as designers strive to reduce vehicle weight without compromising size and/or function.

The use of the Al-Mg alloy sheet predominates in body structure applications, including the Honda NSX, the GM EV1, and the Ford AIV and P2000 prototype vehicles. Sheet is also used for the internal closure panels in the Audi A8 and is the predominant material in this vehicle, even though it has an aluminum spaceframe structure. Since body structures are the heaviest single component in steel structured vehicles, the replacement of steel by aluminum yields a very significant weight reduction. In developing a new design, the vehicle designer can use this primary weight reduction to specify a smaller engine and lighter secondary components such as the braking and suspension systems, thereby providing additional, or secondary, weight reduction.

Although aluminum sheet is being used satisfactorily in automotive applications, developing alloys with properties superior to those being used today, and improving the manufacture of the sheet and the forming of the final components from the sheet could reduce the manufacturing costs of aluminum components and hence the cost of using aluminum. In particular, development of advanced continuous casting technologies in which the molten metal is continuously solidified as strip close to the required final thickness would eliminate many of the processing steps required today to produce sheet from large ingot. Additionally, new sheet-forming processes should continue to be investigated for their application in the production of aluminum automotive components and panels. The continuous joining of panels in the assembly of stamped aluminum body panels is critical for maximizing body stiffness, while minimizing the weight of aluminum used. Therefore, the development of more efficient and/or lower-cost continuous joining processes for panel joints could reduce the cost of adopting aluminum vehicle structures.

II-B. R&D Challenges

Issues to be studied include improvements in materials, reduction in the variability of materials, improvements in product form, techniques for manufacturing parts, and new and improved forming processes.

II-B-1. Improved Materials

Description. Designers of aluminum-intensive vehicles need a source of low-cost sheet, and data that characterize well the mechanical, physical, and formability properties of various aluminum alloys potentially available for various components of body structures and panels.

Technological Challenges. The material-property data required for each individual design are often generated on an ad-hoc basis.

Research and Development Focus. The mechanical, physical, and formability data for existing and new materials (as these are developed) need to be generated and incorporated into a database with easy and in-depth access by design engineers. As a first step, the properties critical to the application of materials for body structures, including subassemblies, and the strength and endurance limits of joints should be defined. These needs are being met in part by a series of manuals that the industry is developing through The Aluminum Association, but more specific data are necessary.

II-B-2. Materials Variability

An alloy's composition and performance can vary, and forming dies must be able to accommodate different materials. To design these dies, however, descriptors of the materials must be standardized so they are widely recognized and can be readily used by designers and others.

Alloy Composition and Performance

Description. Aluminum alloys are available in various combinations of strength and formability depending on their composition, processing, heat treatment, cold work, and gauge. Formability of aluminum sheet varies considerably depending on the alloy and temper of the metal. The development of aluminum materials for automotive stampings has focused on two families of alloys:

- Al-Mg for high formability, medium strength, corrosion resistance, and thermal stability
- Al-Mg-Si-(Cu) for high formability and high strength following paint baking

The Al-Mg-Si-(Cu) alloy family has a significant strengthening response to paint baking, providing good dent resistance for external closure panels. Even so, subtle variations in composition within the specified alloy family as well as processing differences arising from particular manufacturing equipment can lead to differences in the strength and formability of materials of the same alloy specification from different manufacturers.

Technological Challenges. The challenge is to establish the range of critical strength and formability properties for each material that auto manufacturers might encounter. This will allow manufacturers to design their part shapes and forming dies to accommodate this range. In time, sheet suppliers could target their materials to fall within these defined ranges.

Research and Development Focus. Methods are needed to more closely define the formability performance of automotive aluminum sheet materials. Also needed is a program to develop a formability testing procedure that properly represents the formability performance of materials. This procedure could then be applied to generate better data on the performance of different aluminum sheet materials. More importantly, the development of this procedure would facilitate the development of alloys with improved combinations of strength and formability.

Materials Descriptors for Aluminum Sheet

Description. Many automotive companies are now designing their dies using CAD-CAM and some form of numerical simulation. These methods rely on a definition of the yield surface in either an isotropic or anisotropic form and the material “hardening” in some form of effective stress-strain relationship. Reliable and widely applicable descriptors of the frictional behavior and failure criteria of the materials are also required for these programs.

Technological Challenges. Specific numerical approaches used by different companies vary greatly. It is not always a straightforward exercise to determine the appropriate forms for expressing the yield surface and effective stress-strain relationships.

Research and Development Focus. The various numerical approaches need to be incorporated into the various software packages. A standardized approach for deriving constitutive equations will allow the preparation of consistent information for the automakers on existing materials and any new materials that may be developed.

II-B-3. Improved Product Form

Improved product form depends directly on improvements to two casting processes associated with aluminum sheet: direct-chill casting and continuous casting.

Direct-Chill Casting

Description. Direct-chill (DC) casting is a semi-continuous casting process in which water-cooled molds initiate the first part of solidification, which is completed by water sprays impinging on the shell of solid aluminum enclosing the still-liquid core. DC casting and its variants are practically the only casting methods used for making rolling ingot and extrusion ingot. To produce sheet, a rolling ingot is progressively rolled to thinner gauges through both hot- and then cold-rolling mills.

Technological Challenges. Direct-chill casting is well-established, although optimization of the process and operating practices could improve recovery and material property consistency. Ensuring safe operations when liquid metal and cooling water are in close proximity is also an important consideration.

Research and Development Focus. Most R&D needs are of a secondary nature and relate to improved sensors and controls for process optimization (i.e., laser systems to control the hydraulic head of liquid metal). Improved sensors may increase the overall speed and productivity of DC casting operations. In addition, the application of advanced process modeling would help optimize both start-up and run conditions for difficult-to-cast alloys.

Continuous Casting

Description. Continuous casting involves solidifying liquid metal directly into strip form, thereby eliminating the need for the capital-intensive, hot-rolling equipment and the associated costs in fabricating large DC ingots to sheet. Further production savings may be attained with this process because the as-cast aluminum can be directly fed into in-line rolling mills, thereby reducing the number of rolling-mill passes and resulting in lower investment costs, higher yields, and shorter processing times. Attention has recently turned to the use of continuous casting as a possible method of producing automotive quality aluminum sheet at lower costs than the DC-ingot process.

Technological Challenges. The key issue in continuous casting is that the purer alloys (e.g., the 1xxx and 3xxx alloys) can be continuously cast because they have a reasonably short solidification-temperature range. The stronger, more highly alloyed materials (e.g., 5xxx, 6xxx) needed for automotive applications have a much wider temperature range for solidification, and continuous casting of these alloys is therefore more difficult to control. Accordingly, continuous casting of aluminum has been limited to the simpler, non-automotive alloys because of the resulting quality issues such as surface quality and macro- and microstructural segregation. However, a recent evaluation of 5xxx and 6xxx automotive sheet materials produced by one continuous casting process has shown that property characteristics approaching those of conventional DC ingot materials can be achieved for yield strength, hardness, and formability.

Research and Development Focus. Further work on the optimization of alloys developed specifically for the continuous casting process, and the optimal processing of those alloys, will help this process become a viable alternative to DC-ingot casting for the production of high-quality automotive aluminum sheet. Research should focus on optimizing the processing and the

composition of the alloys to attain the desired material properties and reproducible quality. Considerable research has already been conducted by the industry with the development of significant proprietary "know-how." Accordingly, additional research is not recommended here as this topic appears to have developed well beyond the precompetitive stage.

II-B-4. Part-Manufacturing Issues

Four areas should be addressed to improve the manufacturing of aluminum parts for the automotive industry: modeling, slivers, hemming, and aluminum handling.

II-B-4a. Modeling

Modeling, or forming-process simulation, is important to optimizing the overall design of an aluminum-intensive product and the die design for forming the product. Modeling can be used to evaluate the relative capabilities of different forming processes in manufacturing specific parts, and to predict how the formed product will behave.

Design for Manufacturability

Description. Design for manufacturability (DFM) refers to the ability to examine part design for manufacturability at all stages of the part-design process. DFM begins with an early-stage evaluation of design (styling), using simple guidelines to avoid features that will make a part unmanufacturable or excessively expensive to make. It progresses through a part-engineering phase that typically integrates a CAD system with a knowledge-based DFM system where material property and formability data, including failure limits, are required. Then, when a part is released for production, tools and knowledge are needed to engineer the die design to meet all the part's requirements to avoid costly die try-out and re-engineering. Finally, as a validation of the tooling design, accurate 3-D FEM tools are needed to analyze the part and its manufacturing surfaces for their robustness relative to normal variations in the manufacturing process.

Technological Challenges. There are existing design tools, and knowledge-based systems for parts and dies have been developed for making steel automotive stampings. While there has been some development of tools and a knowledge base for automotive aluminum sheet materials, they are not adequate for the routing application of these materials for producing automotive stampings.

Research and Development Focus. More robust manufacturability models are required that are widely applicable and user-friendly, and they must be coupled with the generation of knowledge-based data. Models must incorporate effective materials descriptors (such as those described in Section II-B-2), along with frictional and springback data.

Springback

Description. Springback refers to the tendency of formed sheet parts to move or "spring back" from the shape of the die after forming. The elastic springback behavior of aluminum is a partial result of its lower elastic modulus compared with that of steel. However, its higher rate of work hardening (compared with low-strength steel) also contributes to the springback, a trait also exhibited by high-strength steels.

Technological Challenges. Empirical springback data developed for steel are not applicable to aluminum. Also, springback does not necessarily occur uniformly. Differences in yield behavior and work-hardening response of materials from different suppliers can lead to different springback responses in a part. Current computer models for predicting springback are presently limited by inadequacies in their descriptions of material behavior and in their treatment of friction and numerical methods.

Research and Development Focus. The development of better methods for predicting springback could lead to more effective solutions for eliminating this problem. The focus of an ongoing PNGV project is development of an efficient, robust, and well-validated finite element code to predict springback associated with sheet metal stamping. Given the unique properties of aluminum, it is unlikely that springback can be eliminated; effort needs to be directed toward understanding how to compensate for springback and reduce it as a concern.

II-B-4b. Slivers

Description. Thin slivers of aluminum may occur at the edge of a sheet during cutting operations.

Technological Challenges. Slivers may interfere with downstream processing of the component. More importantly, slivers can build up on the surfaces of stamping dies, causing surface defects and necessitating frequent die cleaning.

Research and Development Focus. Methods for reducing or eliminating slivers are being investigated. The development of guidelines for good process design and equipment set-up and for operation to minimize sliver generation is, however, an important and needed first step.

II-B-4c. Hemming

Description. Hemming, the bending of sheet by 180 degrees at the edge, is frequently the last metal-forming operation in the assembly of components such as hoods, deck lids, and doors. This bending process can significantly influence the dimensions, quality, and integrity of the final panel. Some of the aluminum automotive materials can be flat-hemmed, while others must be rope-hemmed. Auto designers generally prefer flat-hemmed parts for obtaining narrow "cut lines" and good part-edge definition.

Technological Challenges. The hemming capabilities of aluminum body sheet are such that splitting may occur at the hem. Hemming capability has never been well-characterized, in part because hemming performance is reduced by the prior deformation, which varies by region in any given part.

Research and Development Focus. Methods should be investigated for achieving flat hems while minimizing the amount of metal required for hemming and avoiding splitting at the hem. A thorough study of the hemming process would improve the hem quality and provide a scientific basis for optimizing the process. The hemming capability of materials as a function of prior deformation also needs to be characterized.

II-B-4d. Aluminum Handling

Description and Technological Challenges. Aluminum is prone to surface damage and scuffing because of its light weight and relative softness, and must be handled appropriately. Also, because it is non-magnetic, conventional magnetic lifting/moving techniques are not applicable. When transported by a robot (especially at high speed), aluminum sheets can act as airfoils unless appropriate precautions are taken. De-stacking blanks is a handling problem that aluminum shares with steel; similar solutions apply but must be adapted for the lighter weight of aluminum.

Research and Development Focus. Suction cups are generally used to replace the magnetic devices used with steel. However, various R&D activities in developing alternative aluminum handling methods are underway.

II-B-5. New/Improved Forming Processes

Research activities are planned or underway to develop or improve five types of forming processes: stamping, tailor-welded blanks, hydroforming, electromagnetic forming, and warm forming.

Improved Stamping

Description. The equipment that produces stamped parts employs technology developed in the first half of the century. A typical production cycle for stamped sheet metal includes product design, blank shape development, die processing, die design, die construction, die tryout, and stamped part production. Improvements to the stamping process are the subject of a recent proposal to the PNGV Program and would use an innovative holding method and other techniques to speed up the process while reducing wrinkling, tearing, and other problems.

Technological Challenges. Sheet metal stamping is a very complex process influenced by the die setup, die-blank-press interaction, material properties, lubrication, and other issues, as well as their interrelationships. The process has been developed largely by experienced workers who have become highly skilled, but their experience is limited almost totally to steel. This further complicates the already lengthy and costly trial-and-error process of die development.

More recently, a better understanding has been developed of the interactions between material characteristics and the forming process, and process models that include material characteristics are becoming available for both steel and aluminum. However, not enough is known about the key process parameters to determine their effects on the final part shape and to improve the predictive capabilities of the models. Key issues are

- determining the feasibility of achieving a particular part shape,
- deciding on the process logic in terms of the amount of stretch versus draw, and
- developing the starting blank shape appropriate to the final die configurations so that the stamped part shape conforms to the required part design.

Research and Development Focus. A new process-model-based approach is needed for the sheet metal stamping of aluminum to allow precision stampings to be achieved rapidly and without the costly trial-and-error, die-development process. The dimensional integrity of stamped sheet metal parts should be improved so that millimeter or even sub-millimeter accuracy can be obtained. Strategies should also be developed to make better use of the readily available measurements on stamping, such as grid circle analysis to determine local strain distribution.

A model-based, computer-aided, die-development and -tryout system should be developed that incorporates current knowledge and can be used to improve the whole stamping process. A relevant activity that is underway is the springback predictability project sponsored by the PNGV, which includes the development of a computer model that would eliminate much of the trial and error of conventional die design.

Tailor-Welded Blanks

Description. The production of tailor-welded blanks (TWBs) involves welding two or more separate sheets of metal, generally of different thicknesses, to make a blank for forming. Using this approach enables manufacturing engineers to "tailor" the blank to optimize the location of the material attributes. It is also used to minimize the amount of offal generated by assembling blanks from smaller, appropriately sized pieces welded together. The use of TWBs is becoming commonplace in the construction of steel automobile body structures, and is equally applicable to aluminum. The major benefits of using this technology are reductions in the cost and weight of components, and reduced generation of offal.

Technological Challenges. A lack of widespread knowledge of appropriate techniques for welding aluminum tailor-welded blanks has held back the adoption of this technology for aluminum. Laser, electron beam, arc, and friction stir-welding techniques can be used to fabricate aluminum TWBs. There are outstanding issues relating to the formability of the welds and also in understanding the cost savings of using TWBs in terms of material weight utilization, reduced waste generation, and stamping tooling costs.

Research and Development Focus. There is already a project underway between some members of The Aluminum Association and USAMP to assess the quality and formability of TWBs made by producers representing a wide variety of welding processes. This will be followed by an exhaustive evaluation of the more effective processes. The following research activities are necessary:

- Development of better cost models for TWBs
- The conduct of technical and economic evaluations of TWBs in manufacturing automotive bodies and components
- Generation and dissemination of information on how sound and reproducible welds are obtained

Hydroforming

Description. A significant amount of attention is focused on the hydroforming process and its variations, including hydro-stretch forming, in the production of automotive components. In the context of a sheet-forming operation, the term "hydroforming" refers to the use of fluid pressure to shape the sheet. Water or oil under hydraulic pressure can be used to form the sheet against a die. Hydro-stretch forming is a related process capable of using conventional double-action presses.

Technological Challenges. The tooling and controls associated with the hydroforming process are relatively expensive; most hydroforming processes require the use of equipment that is not widely available in the North American automotive industry. Cycle times for hydroforming are considered too long to be attractive economically, except for low-volume production.

Engineering issues with hydro-stretch forming include seal design, fluid handling, and lack of information on tool design guidelines and necessary press modifications. It may be difficult to form complex panels because of an inability to maintain hydraulic pressure during sheet flow into the die. In addition, current hydro-stretch forming technology does not have the capability for undercutting and integral trimming.

Research and Development Focus. More work is needed to bring down the costs associated with hydroforming and to identify appropriate applications. Research and development activities that have been identified for improving hydro-stretch forming technology include

- increasing efficiency by reducing the overall cycle time,
- improving seal design and fluid handling, and
- developing better tool design guidelines and identifying required press modifications.

Electromagnetic Forming

Description. Electromagnetic forming is a high-velocity forming process that has been used commercially for the last 30 years, primarily for the joining and assembly of concentric parts. The process holds promise for sheet metal forming and may represent a cost-effective solution to some of the problems encountered in forming aluminum sheet.

This method uses electromagnetic forces to shape the workpiece. There are also hybrid forming processes in which most of the forming work is done using traditional methods, with high velocity forming used strategically where required. For many simpler parts, electromagnetic forming is ready to use.

Technological Challenges. In its present state, electromagnetic forming has not been developed enough to be routinely used for forming large sheet parts. Areas where advancements are needed in the technology are related to ensuring dimensional accuracy, understanding and controlling properties of the process and the product, reducing cycle time, and increasing lifetime of the equipment.

Research and Development Focus. Research and engineering studies into the required supporting technologies may allow electromagnetic forming to become a significant technique in the forming of aluminum sheet for automotive components. Experiments are needed to determine the response of materials to electromagnetic forming and the effect of this new process on material characteristics such as formability and springback. Also necessary are the development and demonstration of robust induction coils and the establishment of an industrial-scale prototype system to validate cost models for this process.

Warm Forming

Description. The tensile elongation and formability of aluminum alloys increase at elevated temperatures. At temperatures in the range of 250ºC to 300ºC, these improvements become significant in terms of achieving part shapes that are difficult or impossible to achieve in room-temperature forming. Moreover, work-hardened 5xxx sheet materials will retain most of their original strength following forming at these temperatures, producing parts with enhanced capabilities.

Technological Challenges. The major challenge in warm forming is the development of a viable production system that operates at high volume for material and/or die heating and for material handling. Another requirement is lubricants that are effective in the higher temperature range but that can be readily removed subsequently through normal automotive cleaning processes. Other issues are developing methods to compensate for thermal contraction and to integrate the warm forming first stage with the subsequent trimming, punching, and restricking dies in a typical press-forming line. The present 5xxx automotive sheet alloys are suitable for warm forming in the fully annealed or work-hardened condition, but there is the opportunity to develop alloys and tempers specifically optimized for warm forming.

Research and Development Focus. An integrated development effort is needed to explore and develop the manufacturing equipment associated with warm forming, including equipment for blank and/or die heating, material handling, lubrication, and die design. Another need is a parallel program to better characterize the warm forming parameters of existing automotive aluminum materials, and to develop new materials optimized for warm forming.

Superplastic Forming

Description. A few aluminum alloys can be processed to exhibit superplasticity at forming temperatures of about 500ºC. Under these conditions, these materials can deform uniformly under tension to elongate by more than 500 percent without failure, and at low loads compared to conventional forming. Relatively low strain rates must be used since the load requires increases and the deformation achievable decreases with increasing strain rate. Superplastic forming has been used to produce external automotive closure for very low volume specialty cars, most recently for the Panoz Roadster using a superplastic variant of a 5xxx series alloy material. Major advantages are that only a single die surface with the final part's surface shape is required. The forming is achieved by air pressure, so that a conventional press is not required, and the tooling is simple and inexpensive to make.

Technological Challenges. The major challenge is that complex processing is required to fabricate sheet that will achieve the metallurgical structure for superplasticity, even in the least expensive and most suitable 5xxx-series of alloys. Also, a high level of superplasticity is necessary to obtain short-forming cycle times, even though the amount of metal forming for an automotive part is small compared with the formability available.

Research and Development Focus. A metallurgical research program is needed to develop an alloy/fabrication process that will achieve a significant degree of superplasticity and that is compatible with sheet production in the high-volume environment of a conventional rolling mill.

SECTION III. EXTRUSION

The extrusion process can potentially offer aluminum an enormous competitive advantage as the material of choice for automotive applications. Extrusions are used in automobiles in the construction of frame and body structures, drive shafts, transmission parts, door and window frames, reinforcement beams, and numerous other components. Extrusions are also used extensively in light trucks and sport utility vehicles (SUVs) for aftermarket trims that allow owners to customize their vehicles at a relatively low cost. Items such as running boards, moldings, roof racks, recreational equipment carriers (e.g. bike racks), side rails (for light trucks), and other items constitute a large market for aluminum alloy extrusions. Air conditioners have become virtually "standard" equipment on today's cars and light trucks, and another significant market for extrusions is tubing for both air conditioner heat exchangers as well as radiators.
No other material can offer extrusions with the shape complexity and detail provided by aluminum.

III-A. Trends and Drivers

The extrusion process allows for the engineering of cross sections that incorporate the strength and stiffness desired for structures. An extrusion can replace a multi-part stamping and minimize riveting and welding operations. It can also combine functional requirements through, for instance, screw bosses or clip-on features. Extrusion tooling costs are also significantly lower than expenses for stamping dies. Almost all forming and fabrication techniques can be applied to extrusions including hydroforming, flanging, flattening, swagging, stamping, expanding, cold heading, and 3-dimensional bending.

Several auto manufacturers are using extrusions in production vehicles. Audi's Spaceframe A8, the Chrysler Prowler, and Lotus Elise are all examples of extrusions in spaceframes. Porsche uses extrusions for axle frames in its new 911 and Boxster. The evolution of spaceframe technology, in particular, shows the tremendous potential of aluminum extrusions in automotive structures. New designs incorporate all-aluminum, semi-finished products, from extrusions for rails, crossmembers, and beams, to cast nodes in stress-critical sections and aluminum sheet stampings for body panels. Audi's new AL2 concept, which will go into production, proves that spaceframe technology is no longer limited to niche vehicles and can be applied to manufacturing volumes of over 50,000 vehicles per year on a very cost-efficient basis.

Enhancements in the materials and processes used to make extrusions will improve the cost-effectiveness of these parts in automotive applications. Optimization of the alloys used for specific applications in the automotive market will facilitate component design and improve product performance. The availability of comprehensive property data on these alloys will lead to more efficient use of the materials.

Extrusion dies for use in space frames are much cheaper than the tools required for sheet forming in steel, although the advantage of lower tooling costs has to be compared with higher material costs.

Extrusions are unique in offering a near-net-shape product at a relatively low cost. They allow the designer to place metal where it is needed (i.e., cross sections do not need to be uniform nor symmetric) resulting in both cost and weight savings. Many of the most effective applications for aluminum extrusions have occurred when the overall design (or re-design) of the vehicle was considered rather than when extrusions were merely substituted for another material. Consideration of the complete system (initial weight savings, reduced secondary operations, assembly ease and functions, weight savings in coupled systems, and overall product performance) allows aluminum assemblies to be competitive with steel ones in mid- to high-volume automotive applications despite its higher cost as a raw material.

III-B. R&D Challenges

There are a number of issues that must be considered in order to fully utilize extrusions in automotive applications. They fall under the categories of Improved Materials Characterization, Extrusion Process Characterization, Improved Product Form, Manufacturing Issues, and New/Improved Forming Processes. Each of these challenges will be discussed in turn.

III-B-1. Improved Materials Characterization

Methods are needed to more precisely define the composition and performance as well as the material properties of a given aluminum alloy.

Alloy Composition and Performance

Description. Aluminum alloys are available with various properties and characteristics, depending on their composition and the methods used in their production. The composition of a given aluminum alloy is specified as a range of values, leading to variability among the alloys produced by different companies.

Technological Challenges. More narrow specification of the composition, and thus the performance, of a given alloy is needed to ensure the reproducibility of components with carefully specified performance properties.

Research and Development Focus. A test program should be devised to develop better data on the performance of different aluminum alloys based upon a more narrowly defined range in their composition and in their anticipated performance (e.g., with regard to temperatures, loads, corrosion).

Material Properties

Description. Designers and product engineers of aluminum applications need reliable data on the mechanical and physical properties of the various aluminum extrusion alloys.

Technological Challenges. A comprehensive database of material properties and characteristics is not currently available. With regard to the intensified use of FEA studies, there is in particular a lack of physical and mechanical properties for computer models.

Research and Development Focus. The required data need to be developed and incorporated into a database management structure that ensures easy and in-depth access to the engineering data. This database should be made available on the Internet to facilitate widespread access to the information it contains.

III-B-2. Extrusion Process Characterization

Description. The temper of an aluminum alloy is critical for its processability and subsequent performance. The temper of an extruded component may be established by process heat treatment while the extrusion is being produced or during a subsequent heat-treating operation. The aluminum industry engineer and a counterpart in the automobile industry, need to work together to select and specify the required alloy and temper. The aluminum industry should describe how to produce these tempers reliably and economically.

Technological Challenges. It is difficult to specify production parameters, given the variations in individual extrusion presses and production practices, and the almost infinite variety of cross-sections of extrusion profiles. The characteristics of extrusion processing are not readily available from fabricators.

Research and Development Focus. Research in the field of extrusion processing will establish an improved data base. Both equipment manufacturers and fabricators need to be involved. The inherent advantages of the extrusion process are most obvious during the processing of alloys that can be press-heat treated (primarily the 6xxx, or Al-Mg-Si, alloys). Work should be undertaken to optimize the extrudability and mechanical properties of these alloys. Also, as the recycling of cars containing aluminum increases in the future, it will be necessary to better understand the role of trace elements in the scrap metals. Current limits placed on chemical composition may need to be revised to permit higher concentrations of certain elements and lower concentrations of others, while simultaneously expanding applications for the alloy.

III-B-3. Improved Product Form

Description. The parameter of concern is dimensional accuracy, which refers to the shape of the final product and how well it meets its specified measurements.

Technological Challenges. The dimensional accuracy of extrusions can be less than optimal because of the change of profile through the life of the die and eventual die deflection. Automotive applications require a defined understanding of geometric tolerances and dimensional ranges that can be maintained for critical characteristics. Typical applications (e.g., airbags, bumper) provide an indication of the geometric tolerances required for fabricated features (holes, bending radii, etc.).

Research and Development Focus. Computer models are needed to simulate die deflection based on the selected die design and other tooling (i.e., backer, bolster) configurations. Surface studies are also needed to improve the wear performance of the tool steel. In addition, studies should be made of alternative materials such as ceramic inserts or intermetallics, which are especially needed for the extrusion of hard alloys and aluminum-based metal matrix composites.

III-B-4. Manufacturing Issues

Issues related to manufacturing include designing new dies and working with long extrusions that bend.

Improved Modeling (Die Design)

Description. New dies are usually designed by experienced designers using a trial-and-error approach. Some models exist for simulating metal flow during extrusion.

Technological Challenges. Many experienced die designers have reached retirement age, leaving a void in the knowledge base for die design. Further, the trial-and-error approach they have used results in too many iterations during die testing. The selected die design needs to allow an optimal metal flow to guarantee the maximum exit speed for the extrusion. A challenge in the die modeling process itself is that existing FEM metal flow models are reliable only for simulating simple axisymmetric extrusions.

Research and Development Focus. A better understanding is needed of the fluid dynamics (including metal flow, shear zone location, grain coarsening, dead zone formation, and evolution) of the extrusion process and specific metallurgical responses of the various aluminum alloys in order to incorporate them into numerical models. More "responsive" numerical models are also needed.

The loss of knowledgeable die designers should be addressed by building a computer-based database involving typical die designs for various extrusion shapes. This database could be linked directly to commonly used CAD/CAM programs.

Bending

Description. Long extrusions are used in the manufacture of some automotive components.

Technological Challenges. Long extrusions tend to bend, which can lead to a change in the dimensions of the part being manufactured. The plastic deformation that occurs in bending can permanently change the wall thickness or cross section of an extrusion. Sometimes bending is coupled to the use of hydroforming as a means of maintaining the dimensions of interior walls of parts.

Research and Development Focus. Better methods are needed to maintain the dimensional stability of long extruded products during their subsequent processing into automotive components such as bumper beams. This issue is particularly troublesome where multiple extrusions are joined together into one assembly.

III-B-5. New/Improved Forming Processes

Three new or improved extrusion processes are under study: hydroforming, isothermal extrusion, and quenching.

Hydroforming

Description. Hydroforming is the use of an internal fluid such as water or oil under hydraulic pressure to reshape the cross section of hollow extrusions or tubes. This method is increasingly used in the production of frames, engine cradles, bumper beams, bumpers, seat frames, window frames, and other components. Hydroforming of tubes is now being seriously considered for many automotive frame members, especially those that require substantial changes in cross section along a relatively long length.

In hydroforming, expanding (bulging) of tubular blanks is also used to produce corrugated cylindrical tubes and bellows, differential cases, stepped diameter tubular shafts, and many other components. Expansion of extruded aluminum tubes can be achieved by the use of sectional or expanding dies, rubber (urethane) punches, or hydraulic pressure. Hydroforming also can be used to expand or bulge straight or previously bent extruded tube blanks against a female die.

Technological Challenges. The tooling and controls associated with the hydroforming process are relatively expensive and are not widely available in the North American automotive industry. Cycle times for hydroforming are often too long to result in attractive economics, except for low production volumes.

Research and Development Focus. More work is needed to reduce cycle times and find other ways to lower the costs associated with hydroforming, as well as to identify appropriate applications. The development of a cost model would be helpful in this area. An investigation of weld integrity should be conducted within in the wide range of applications for the hydroforming process.

Isothermal Extrusion

Description. Present extrusion practices often result in non-uniform structures from the front to the back of the length of the extruded section. Commercialization of isothermal extrusion would result in more uniform extruded products.

Technological Challenges. Process-control technologies and equipment are currently not sufficiently advanced to make isothermal extrusion commercially available.

Research and Development Focus. Among the items needed will be improved process control and equipment (e.g., accurate, non-contact temperature measuring devices).

Quenching

Description. Improved manufacturing techniques are needed for quenching the extruded component as it emerges from the press to enable the tight dimensional control demanded by the automotive market to be met.

Technological Challenges. Due to the virtually infinite variety of cross-sectional geometries extruded, most existing manufacturing systems lack the flexibility required by commercial extruders for optimal performance.

Research and Development Focus. Work is required to improve the mechanics of quenching, and also to address fundamental issues relating to an alloy's response to quench rate.

SECTION IV. CASTINGS

Aluminum castings are used for many automotive applications, including wheels, cylinder blocks and heads, pistons, brake cylinders, and suspension arms. The substitution of aluminum cast components for ferrous castings in the automotive sector is predicted to continue to grow as automakers continue to seek opportunities to reduce vehicular weight.

IV-A. Trends and Drivers

The quality of aluminum castings has increased over the past several decades, particularly following the development of new casting techniques. For some time, it has been the cost of high-quality castings, not their quality, that has been the primary barrier to the application of castings in the automotive industry.

Some of the new casting techniques are capable of producing automotive components that can replace complex machined or fabricated parts. Thin-wall casting techniques can be used to produce clean castings of lower weight and with superior mechanical and physical properties compared to those produced by more complex traditional methods, and are ideal for automotive applications.

The automotive industry is demanding new materials that are stronger, lighter, more reliable, more manufacturable, and lower in cost. The most significant remaining opportunities for greater use of aluminum castings in automobiles are in

- chassis and suspension components (requiring high integrity, good strength/ductility, fatigue endurance, crashworthiness, and weldability);
- body components (requiring high integrity, thin walls, high ductility, crashworthiness, and weldability); and
- engine components (requiring high integrity, stiffness, retention of properties at moderate elevated temperatures, and good wear resistance).

With participation from both the aluminum and magnesium industries, a significant U.S. Automotive Materials Partnership (USAMP) project is underway entitled, "Design and Product Optimization for Cast Light Metals." Its objectives are to develop technology for optimizing designs and improving product capabilities for light-weight, high-strength structural cast components of aluminum and magnesium. Specific tasks call for developing a database with information on design properties and design rules and methodologies, developing process monitoring and control systems, and evaluating predictive modeling techniques. If successfully implemented, all of these tasks will help reduce the cost of castings.

IV-B. R&D Challenges

Three areas need to be addressed to improve castings for automotive applications: materials, casting processes, and manufacturing.

IV-B-1. Improved Materials

Although some manufacturers want to consolidate and rationalize the total number of alloys used in automobiles, they also agree that alloys with certain desirable properties need to be developed. Another R&D issue is production of feedstock for semi-solid metal processing.

Alloy Rationalization

Description. Many different casting alloys are currently specified by automakers for the manufacture of similar automotive components. Some automakers have stated that working with a large number of alloys is costly. Rationalizing the number of alloys would reduce inventory and tracking costs.

Technological Challenges. To meet the requirements of their customers, casters are required to work with many different variations of the aluminum alloys. The amount of property data needed by automobile designers to cover all the alloys is extensive, and is not being developed.

Research and Development Focus. Some type of alloy rationalization would reduce the total number of alloys specified by automotive manufacturers. This would make it easier to collect all the property data for each alloy and make it readily available in a database.

New Alloys

Description. Despite the foregoing argument for alloy rationalization, the aluminum and automotive industries agree that some new alloys with characteristics key to automotive applications are needed. These characteristics include higher strength, higher ductility, and certain other improvements.

Technological Challenges. Most aluminum alloy components for automotive applications must be heat-treated, which adds to their cost and manufacturing time. Quenching the components after heat treating (particularly those that are long and complex) may cause their distortion and straightening, adding additional cost.

Research and Development Focus. Alloys should be developed that do not need high-temperature thermal treatments to meet the property requirements of structural parts. This will avoid the capital and processing cost of heat treatment, as well as the distortion of parts (and the need to subsequently straighten them), which are often experienced when quenching large, thin parts such as cross-vehicle structures and body pillars.

Feedstock Production for Semi-Solid Metal Processing

Description. The use of semi-solid metal (SSM) processing (described in Section IV-B-2) is expanding in the automotive manufacturing sector. SSM feedstock (billets) can be generated in several ways. Rheocasting is most commonly used, in which foundry ingot of normal structure is melted and continuously cast into billet while providing a stirring action to fracture dendrites as they form during solidification. Electromagnetic stirring is typically used, although mechanical methods are used in some processes. An appropriate structure can also be generated by means of grain-refining additions.

Technological Challenges. The ability to make the right stock at an affordable price is a major barrier to the semi-solid forming process. SSM feedstock tends to be premium-priced, sometimes offsetting the benefits of the process (productivity, tool life, and improved properties of components).

Research and Development Focus. New concepts for producing feedstock are needed.

IV-B-2. Casting Processes

Research needs have been identified in at least six casting processes.

High-Pressure Die Casting

Description. Die casting is popular because it is one of the least costly processes for high annual casting volumes and can produce castings with very thin walls, great detail, and excellent dimensional control. Die casting accommodates the use of scrap-based secondary alloys because of rapid solidification, minimizing the adverse effects of "impurity" elements. High-pressure die casting involves forcing molten metal into the cavity of a reusable steel mold (die) under high pressure. The metal is allowed to solidify and the dies are opened and the casting removed.

Technological Challenges. Turbulence can lead to the entrapment of air or other cavity gases as bubbles, oxides, and other non-metallic debris. Molten metal in the die is subjected to high pressure during solidification, compacting trapped bubbles to small size. If die cast parts are later welded, heat treated, or otherwise exposed to high temperatures, those compressed bubbles expand to become blisters.

Research and Development Focus. The casting industry has identified the following R&D needs to improve the quality and productivity of die casting:

- Develop new sensors and controls for automation supervision
- Develop better data to support advanced models and automation systems (e.g., relationships between process conditions and material attributes)
- Develop cleaner melting/pouring technologies

Vacuum Die Casting

Description. In vacuum die casting, the dies are evacuated and completely sealed before the gate is opened to the molten metal, which is forced in by atmospheric pressure. Because vacuum die castings are both heat treatable and weldable, high-purity primary alloys have been developed to take advantage of the improved structural performance that heat treatment can afford, while still fulfilling the process's requirements for solder-resistant and fluid alloys.

Technological Challenges. While the use of a vacuum reduces blistering in die castings, it does not reduce shrinkage voids that tend to occur in isolated thick sections of castings. Heat treatment of vacuum die castings improves properties but has a tendency to distort rangy, thin-walled parts, especially during quenching.

Research and Development Focus. The development of alloys that meet high strength and ductility requirements without the need for heat treatment would provide a distinct advantage. However, most alloy systems with good as-cast properties (e.g., Al-Mg) lack fluidity and tend to crack in the highly restrictive dies. Development of one or more alloys that meet both the property and castability requirements is needed.

Squeeze Casting

Description. In squeeze casting, the molten metal is forced into the dies at a low velocity, eliminating turbulent metal flow while filling voids completely. This produces very dense, ductile, high-quality castings. Typically, this method is limited to smaller castings, but the process may be combined with other methods to produce larger castings. Squeeze castings are heat treatable and weldable without blistering. They are used for aluminum suspension arms where heavier and costlier forged arms would have been used previously. Since squeeze cast metal flows into the cavity at relatively slow speeds, high iron content is not needed to prevent soldering of molten alloy to dies.

Technological Challenges. The challenges in squeeze casting are to avoid inclusions and microstructural segregation in cast parts. Large ingates allow whatever contaminants lie on the surface of metal in the shot tube to enter the die cavity. High pressure during solidification forces feed metal into shrinkage-prone regions of the castings. Because only the low-melting-point eutectic remains able to flow during the later stages of solidification, eutectic concentrations occur in those regions.

Research and Development Focus. The following research needs have been identified for squeeze castings:

- Methods to introduce molten metal without turbulence and contamination
- Methods to control component design and the solidification sequence
- Development of lubricants that protect the die and afford release of cast parts without also reacting with the molten metal

Semi-Solid Metal Processing

Description. Semi-solid metal (SSM) processing is used to cast partially solidified (semi-solid) alloys. The SSM process is based on the fact that agitating a metal alloy during solidification will yield a rounded, globular microstructure rather than the conventional dendritic microstructure that forms in the absence of agitation. Semi-solid metal flows in a viscous manner, allowing thin cast sections to be filled rapidly without the jetting and spraying that would normally occur with liquid metal.

SSM can be used to produce thin sections and other high-integrity aluminum automotive structural components whose mechanical properties exceed those of permanent mold castings and approach those of forgings, yet are cost-competitive with other aluminum near-net-shape forming processes. It can also be used with compositions that are normally wrought, with hypereutectic alloys, and with metal matrix composites that can be difficult to cast from 100 percent liquid.

Technological Challenges. The cost of the feedstock for the SSM process is considered high by automotive manufacturers (see Section IV-B-1). Other challenges include a lack of complete understanding about process parameters and characteristics of the SSM product.

Research and Development Focus. More knowledge is needed about the parameters of the SSM process and about the product's characteristics.

Permanent Mold Casting

Description. The permanent mold process has been used for decades to make high-quality cast aluminum products. The static or top-poured gravity permanent mold (or the semi-permanent mold, incorporating sand cores to make hollow sections) has long been a favored method for producing automotive wheels, cylinder heads, pistons, and brake cylinders. The tilt permanent mold and low-pressure casting are variations of permanent mold casting.

Technological Challenges. Permanent mold casting requires special practices and considerations to avoid harmful turbulence during mold filling; this phenomenon is avoided in tilt permanent mold and low-pressure casting. The degree of automation and computer control of the tilt/fill cycle and casting solidification present opportunities for improving consistency and quality from tilt permanent mold and low-pressure casting. More work is needed in low-pressure casting to improve the life of the stalk tubes and keep contamination from the stalk tube out of the die cavity.

Research and Development Focus. Research to improve the quality and consistency of aluminum castings should focus on the development of advanced automation and computer control methods for mold filling and solidification. Work should continue on lower-cost, extended-life stalk tubes for low-pressure casting, and on techniques to avoid inclusion defects originating in the stalk.

Vacuum Riserless Casting

Description. The Vacuum Riserless Casting (VRC)/Pressure Riserless Casting (PRC) process was developed by Alcoa and re-engineered by CMI for mass production of automotive chassis and suspension components. This process is a variation on the low-pressure casting process but has several distinct refinements specific to high-integrity aluminum parts.

The smallest current version of VRC/PRC equipment is routinely used to cast steering knuckles, wheel carriers, and other small- to medium-sized parts. A larger version is used to cast subframes, crossmembers, and engine cradles, some using sand cores. The largest version will be used to cast complex front subframes and cradles, some also requiring sand cores.

Because this is a proprietary process, the details of specific technological challenges and R&D needs rest with the developers.

IV-B-3. Manufacturing Issues

There are issues to consider at both the front end (design) and finishing phases of manufacturing.

Product Design and Optimization

Description. The lead time to produce a casting depends on the availability of computer-based tools for casting design, prototyping, process control, and production. Emerging technologies in computer hardware, CAD/CAM software, computer modeling (including solidification modeling), rapid prototyping, and rapid tooling make design and development of cast metal prototype components easier, faster, and more accurate.

Technological Challenges. Casters have not always been able to respond quickly to changes in the customer's design (and vice versa). Too much trial and error is currently needed to develop and set up tooling equipment. Casting lead time is affected by the limited availability of standardized data on specific properties.

Research and Development Focus. Predictive software used to design parts and molds can eliminate the high cost of trial-and-error runs or expensive tooling modifications if rules for dimensional control are known. Research is needed to improve the speed and accuracy of tool design simulation software and to develop design-for-casting methods and supporting systems. New methods, possibly digital, for describing individual cast components (including shape, functionality, design intent, and materials) represent a potentially long-term development.

Finishing Operations

Description. Manufacturing issues cover the following processes in the production of a cast component:

- Finishing
- Machining
- Heat treating
- Straightening
- Trimming
- Welding (covered in Section VI)

- Non-destructive evaluation
- Environmental clean-up

Technological Challenges. Insufficient real-time knowledge about the casting process and its effect on the properties of material can hurt the quality and consistency of castings. Quality-related problems increase casting losses and lead to additional processing requirements. All of these factors raise the costs associated with producing cast components.

Research and Development Focus. Research needs in the manufacturing area include methods to

- monitor all important variables in real time,
- apply the appropriate algorithms,
- provide immediate feedback, and
- avoid all scrap production.

Some of these needs are addressed by the USAMP's "Cast Light Metals Program" described earlier in this section.

SECTION V. METAL MATRIX COMPOSITES

Aluminum metal matrix composites (MMCs) consist of an aluminum alloy matrix that is reinforced with another material, usually ceramic. MMCs combine the low density of aluminum with such benefits of ceramics as their strength, stiffness, wear resistance, and superior high-temperature properties.

V-A. Trends and Drivers

MMC components can be formed using methods that accept feedstocks in both the solid and liquid state (including forging, extrusion, rolling, casting, semi-solid forming, formation from precursor powders, and spray deposition).

Aluminum MMCs are already in use in several automotive applications:

- Diesel engine pistons (Toyota)
- Cylinder liners (Honda)
- Drive shafts (Corvette and GM S/T trucks)
- Brake components, including disk brake rotors (Plymouth Prowler) and brake drums (GM EV-1)

The need for cost-effective, light-weight materials for automotive applications is providing incentive for the aluminum MMC industry to develop low-cost materials and processes. In particular, the PNGV program is driving the need for lighter-weight automotive structures as well as engines and drive trains. The use of aluminum MMCs in brakes (replacing conventional materials) is motivated by the need for longer wear in addition to the principal concern of reduced weight. Currently, aluminum MMC billets cost about three times more than aluminum ingots or billets, depending on volume and loading factor.

V-B. Technological Challenges

The primary challenge is to develop MMCs to produce automotive parts with the performance attributes sought, at a cost that is lower than for conventional parts. A barrier to meeting this challenge is the disaggregated nature of the industry, in which small producers lack the technological and financial resources of larger aluminum suppliers and have no coherent research and development agenda for MMCs. There is some evidence that industry's decision makers recognize this situation and are forming a consortium to pool talent and resources. This consortium will focus on the manufacturing-technology issues that inhibit the further exploitation of aluminum MMCs.

Some research efforts for MMCs are already underway, including

- a program to develop aluminum-powder, metallurgy-based composites for automotive engine applications using direct powder forging methods;

- a project to further reduce the cost of aluminum MMC materials produced by a liquid metal route; and
- the development of an improved reinforcement approach, in which Ni-coated graphite and either SiC or alumina are added to an aluminum matrix.

Despite the relatively large financial investment made by some companies in the research, development, and commercialization of aluminum MMCs for automotive uses, there are areas where additional work is needed. A major manufacturer of aluminum MMCs has grouped these areas into the following categories:

- Technological
- Financial/Economic
- Regulatory Environment
- Time Horizon
- Corporate Culture

Table 5-1 shows the specific factors driving the need for R&D in each of these areas.

Table 5-1. Factors Influencing Increased Use of Aluminum MMCs in Automotive Applications

Technological	Financial/ Economic	Regulatory Environment	Time Horizon	Corporate Culture
Insufficient material characterization and data Insufficient product quality and performance Lack of standardized test methods Lack of design optimization and systems concept Materials recyclability Lack of understanding of fundamentals of machining final parts	Investment issues, including lack of other large-scale markets High initial piece cost Validation costs	ITAR regulations CAFE regulations Government regulations on international interchange of processing technologies	Time required for product quality and validation Time required for establishing fabrication network	Risk-averse nature of industry OEM/supplier relationships Corporate separation between technology/product development and decision makers

One institutional barrier to the broad commercial development of aluminum MMCs is the lack of large-scale markets for these materials, other than automobiles. The lengthy systems analysis and prove-out periods, and a risk-neutral engineering approach have led to a long delay in the market acceptance of the new materials.

Government regulations, in particular the Export Control International Traffic in Arms Regulations (ITAR), have hampered an international exchange of information on MMCs, especially information related to processing technologies. These regulations are being reevaluated.

V-C. Research and Development Focus

Research is needed in four broad areas:

- Raw materials and primary synthesis methods
- Secondary processing to semi-fabricated parts
- Final component manufacturing
- Recycling

The primary goal in all R&D on aluminum MMCs is to reduce costs in each of these areas.

In the area of raw materials and primary synthesis, continued effort is needed to develop alternative reinforcements such as conventional ceramic particles and unconventional reinforcements, e.g., flyash as well as *in situ* processes that use low-cost feedstocks. The potential use of low-cost base alloy materials, including scrap/secondary aluminum, should also be investigated. Another potential R&D project is the development of new MMCs that have increased ductility.

In secondary processing, additional work is needed to improve casting practices, which will improve recovery and reduce costs. Research topics include modeling the casting process and establishing workable die designs, increasing the casting yield, and considering new processes such as direct pressure forming and semi-solid forming.

The focus of work in manufacturing the final component should be on improved machining and material-removal practices. Metal matrix composites, with their soft matrix and embedded hard particles of silicon carbide, have traditionally been hard to machine. Consequently, carbide and diamond-tipped tools have been used for machining and the perception has been created that MMCs cannot be machined at speeds required for manufacturing automobiles. Demonstrations are now underway to show that with proper practice and application, diamond tooling can be made to work at speeds appropriate for automotive manufacturing. However, the process is highly part-specific, and research is still needed to improve machining operations such as milling, reaming, and tapping, and to predict and explain the part-specific nature of the machining process. Greater fundamental understanding of the machining process for MMCs will help industry optimize its manufacturing practices and reduce costs.

An R&D need for recycling is development of cost-effective recycling methods for composite materials.

A research need that applies to all four areas is the development of databases with quantitative data on the influence of process variability on material properties.

SECTION VI. JOINING AND ASSEMBLY

Aluminum can be joined by most of the processes currently used to join steel:

- Bonding
- Welding
- Brazing
- Soldering
- Mechanical fastening
- Joining using a combination of techniques

These techniques have been extensively tested, refined, and characterized for use with aluminum to ensure that the structure, crash-worthiness, and operating performance of the products joined will be of high quality. The number of joining options continues to grow in response to specific design and assembly challenges, giving automotive designers even more assembly options for the future.

VI-A. Trends and Drivers

The main technology challenge in achieving an economical structure is the ability to attain an optimal system of component design, joint design, assembly sequence and joining process which yields a reliable, consistent and cost effective process and product. There is a fundamental need to reduce weight or gauge of material and the speed of joining while achieving dimensional and structural integrity. Joining technologies have been a key element of research and development for some time. Assembly and dimensional management technologies have received increased attention as the importance of their role in achieving a total systems solution has been understood. The following describes specific technologies for joining and assembly of aluminum structures.

VI-A-1. Resistance Spot Welding

Description. Resistance spot welding (RSW) is used for 70 percent of the joining of automotive body materials today. RSW uses an electric current to join two or more sheets or work pieces at their interface by resistance heating followed by local fusion (welding). Electric current is brought to the piece through copper alloy electrodes, which also apply a tip force to ensure good contact at the weld site.

Technological Challenges. The typical passenger car contains 2,000 to 5,000 spot welds, 30 percent more than are needed to maintain design requirements. Such over-welding occurs whether the metal is steel or aluminum, and is carried out because it is inexpensive compared to the cost of weld inspection and because it enhances occupant safety. The Intelligent Resistance Welding Program (IRW), created to improve the quality and consistency of resistance spot welds, is developing resistance welding technology for optimal performance with aluminum structures. The IRW program should also address the need for accepted standards for the quality of welds in aluminum body structures, and for standards to guide designers in selecting and evaluating various aluminum alloys for their spot weldability.

The process parameters governing the welding process are different for aluminum and steel. Some of the equipment used today to spot weld steel can be used with aluminum, but this requires a thorough understanding of aluminum's welding parameters. Aluminum resistance, spot welding models are available based primarily on work done for steel. However, they are only moderately effective in modeling aluminum because of aluminum's higher thermal conductivity, lower melting point, and other physical differences from steel. A general model of aluminum resistance welding is available but has not yet been applied to the process monitoring concepts developed for aluminum.

A better understanding is needed of the effect of surface finishes on joint quality when RSW is used to join extrusions to sheets or castings. Effective, economical methods must be available to provide surfaces of uniform roughness and oxide thickness for resistance welding. Electrode life is another concern in using aluminum resistance spot welding in an automotive production environment.

Research and Development Focus. The best joining techniques for various aluminum alloys and their applications are still being determined. However, it is clear the automotive industry is experienced and comfortable with RSW and would prefer to use it to join aluminum as much as possible. To accomplish this, research is needed in the following areas:

- Standards
- Controls and models
- Sheet weldability

Most current standards focus on weld nugget diameter, although it is only one of several indicators of weld quality. Before various welding techniques can be compared, testing methods and criteria for judging weld quality will need to be standardized. Multi-variable controls are needed to accurately simulate aluminum spot welding. Advanced physical models that incorporate the statistical interactions of electrode and sheet surfaces with varying topographies will depict the distribution of current at weld interfaces. A database of the electrode/sheet interfacial resistance as a function of oxide thickness, surface roughness, alloy conductivity, and electrode pressure could reduce the cost of RSW by allowing computer simulations to replace the many costly tests currently used to simulate manufacturing conditions.

Other concepts that have been developed relative to RSW should be translated into technologies. For example, it should be possible to develop on-line equipment to monitor processing conditions, and to use these parameters to predict both the appropriate welding conditions and the quality of the subsequent welds. Such monitoring will ultimately lead to a self-regulating process and reduce the cost of spot-welding aluminum.

Other potential R&D projects that should be carried out on RSW include

- developing reproducible techniques to assess various aluminum alloys for their weldability;
- establishing suitable machine specifications and operating parameters for high-volume, car-production lines;
- conducting quality control measurements during production; and
- developing methods to supply sheet with a consistent, sufficiently thin and stable oxide layer that will prolong electrode life.

VI-A-2. Arc Welding

Description. Arc welding is a standard technique in industrial processing, and is relatively low in cost with the potential for some degree of automation. This makes arc welding attractive for many joining processes in the automotive industry. There are two primary arc welding processes used to join aluminum:

- Gas tungsten arc welding (GTAW, also known as TIG welding)
- Gas metal arc welding (GMAW, also known as MIG welding)

GTAW uses a non-consumable tungsten electrode to maintain an electric arc to the workpiece in an atmosphere of an inert shielding gas (usually argon). *GMAW* uses an aluminum wire as a combination electrode/filler metal, with an inert shielding gas completing the process. In sustained, high-volume welding, if GMAW can be used, it is usually preferred over GTAW because of faster welding speeds.

Technological Challenges. The arc welding processes are difficult to sense because of the ultraviolet light, fumes, molten metal spatter, and noise generated by the welding arc. Small feedback sensors are needed that can be attached to the torch without affecting the access of the torch to the weld seam. Additional automation in the welding processes have until now focused on automating the motion of the welding torch, but there has been little success in automatically controlling the process itself.

Another key challenge related to welding processes is to ensure that, following the joining process, the assembly attains the correct final dimensions. This aspect is discussed in more detail in the section entitled Assembly and Dimensional Management.

Research and Development Focus. A better understanding is needed of the physical principles that govern arc welding processes. This understanding will be achieved through the use of advanced instrumentation and data analysis techniques. Theoretical models of GMAW that explain the relationship between input parameters and the resulting process will enhance both process design and control. Until now, the input parameters have been insufficient to predict the weld pool size because of inadequate quantitative data on heat transfer between the arc and the metal. Data are also needed on enhanced heat transfer between the weld pool, which is in motion, and the adjacent metal.

There are a number of R&D needs specifically related to sensing and controlling the arc welding process:

- Simple, non-intrusive, and robust sensors that provide real-time information on the status of wire-fed welding processes and enable real-time feedback control of the welding process
- Process improvements to make the welding process more robust and tolerant of variations in the weld joint geometry
- An understanding of the welding process coupled with the use of arc-light emissions to monitor and control the process in real-time
- Use of empirical models incorporating actual production data to develop sensing algorithms for GMA welding

VI-A-3. Assembly and Dimensional Management

Description. Assembly Dimensional Management is an integral element of the engineering design responsibilities for the assembly of the finished product. This discipline is part of the product development cycle with a role similar to FEM analysis for structural performance. Assembly Dimensional Management is an engineering discipline that uses Geometric Dimensioning & Tolerancing based on 3-2-1 tolerancing and fixturing schemes and monte-carlo simulation techniques to analyze the effects of component tolerances and the assembly process to insure that the final assembly meets customer geometric tolerances and to insure that the assembly process meets its cost targets.

Technological Challenges. Applying dimensional management requires that the component dimensional tolerance capability and the dimensional impact of the joining process are known quantitatively. The latter of these two requirements is typically the most difficult to quantify and requires a commitment to capturing production data which can be analyzed and synthesized to obtain the required information. Achieving tolerances within 2.0 mm on assemblies with aluminum components that are GMAW welded typically requires post-weld machining processes. Prototyping and production experiences with aluminum structures has shown that weld induced distortion is a significant contributor to assembly tolerances and processing costs.

Research and Development Focus. The ability to predict and control joining induced distortion is a critical need. Specifically, a system of tools that can be effectively integrated to select product forms, assembly methods, fixturing and clamping methods, joining processes, predict joining distortion, and perform tolerance simulations to meet customer cost and performance targets is needed. Integration must include a link to 3-dimensional assembly tolerance simulation tools which accounts for geometry effects of the assembly process and estimates assembly tolerances based on this and component tolerances. This set of tools can be realized by initially focusing on and enhancing predictive capability of the assembly and joining processes and understanding the influence of the type and methods of fixturing components for assembly.

VI-A-4. Adhesive Bonding

Description. Adhesive bonding is defined as the chemical joining of two surfaces. It is best applied to lap joints loaded in shear, compression, or tension, although the normal automotive type of T-joint performs successfully in adhesively bonded vehicle structures. One of the primary advantages of adhesive bonding is that it can be combined with other joining processes to enhance overall performance of the joint. The technique is being used extensively in automotive applications in combination with spot welding in a process called weld bonding. Adhesives also are frequently coupled with mechanical fastening (see Section VI-A-6, below, for a description of mechanical fastening), particularly when the workpiece will experience peel and cleavage loading.

Technological Challenges. The surface condition of the metals being joined (especially the presence of contaminants) significantly affects the strength and durability of adhesive joints. Using adhesive bonding to join pieces that were designed to be joined with welding or mechanical fastening techniques sometimes yields incomplete adhesion. Adhesive bonds respond well to many stresses, but care is needed with peel and cleavage joints, especially if these are not backed up with some form of mechanical joining such as spot welds or rivets. Most organic adhesives are adversely affected by moisture, especially when they are in a stressed condition.

Research and Development Focus. Advanced adhesives that can deliver strength, toughness, and durability will be needed if this joining technique is to gain wider acceptance in automotive applications. Another area of importance is that of adhesives designed for joining dissimilar materials, such as metals to non-metals.

The *Aluminum Industry Technology Roadmap* contains some research and development needs for adhesive bonding, including the following:

- Eliminating the pretreatment necessary for adhesive bonding by developing an adhesive system that incorporates the function of the pretreatment
- Developing more information on the strength and durability of the various bonded joint configurations that are likely to be used in automotive body structures

VI-A-5. Laser Welding

Description. Laser energy is being studied as a method for both welding and cutting metals. Laser welding is a one-sided welding process. The laser sources most commonly used for welding are

- the neodymium (yttrium-aluminum-garnet [Nd:YAG]) laser and
- the CO_2 gas laser

The Nd:YAG laser is available in a power range of up to 4 kW, and the CO_2 laser is available up to 25 kW. Both lasers and their respective power ranges are suitable for welding aluminum bodies. Laser welding allows precise control of the joining process and results in a narrower heat-affected zone than more conventional welding methods. This, in turn, improves the formability of welded sheet components. The response of aluminum alloys to laser welding is similar to their response to other fusion welding processes: some alloys require filler metals while others do not. (The 2xxx and 6xxx series of aluminum auto body sheet alloys generally require fillers while high-magnesium alloys like 5182 do not.)

Technological Challenges. Aluminum's high reflectivity inhibits the absorption of laser energy, and its high conductivity disperses heat rapidly. This dual loss of energy means that there are rather high energy requirements for laser welding. Most lasers operate at about 10 to 20 percent efficiency in converting electrical power into the focused laser beam. If laser welding is conducted without adding filler alloy, there must be a good joint fit and low level of mismatch between the materials welded. Capital requirements are high for laser welding equipment but are justified when there is a high volume of welds or critical weldment applications. Because laser welding is an emerging technique, it is difficult for the technology to be cost-competitive with more established joining techniques.

Research and Development Focus. Until now, the commercial application of laser welding aluminum sheet in the automotive industry has been limited. However, laser welding is the subject of intense developmental work and is likely to become an important process for aluminum joining in the future. A key area of study is the application of laser welding to the development of tailor-welded blanks.

VI-A-6. Friction Stir Welding

Description. In friction stir welding, a cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together. Frictional heat is generated between the wear-resistant welding tool and the material, causing the latter to soften without reaching the melting point. The result is a solid-phase bond between the two workpieces. The joint is generally characterized by higher mechanical properties, less residual stress, and improved corrosion performance when compared to arc welding.

Technological Challenges. Areas for potential improvements in friction stir welding include the following:

- The need for using run-on/run-off plates where continuous welds are required from one edge of a plate to the other
- The hole left at the end of each weld where the tool pin is withdrawn
- Prediction of weld size, which is often used as a basis for judging quality

- The need to support the back side of the weld, requiring two-sided access
- Limited range of joint geometries
- The distribution of the aluminum's surface oxide after joining and understanding of the alloy and process variables that affect this distribution
- The effect of the heat-treated zone on the mechanical and corrosion performance of joints
- Welding speeds, which are relatively slow in comparison to arc welding processes
- Limited use in situations where portable equipment is needed to meet the requirements of the workpiece for clamping and access
- Limitations to mainly straight lines in two dimensions

Ultimately, cost may be the main barrier to using friction stir welding. If this relatively new technique is to make inroads into the automotive industry, it must be proven to be cost-competitive in comparison with more established joining options.

Research and Development Focus. Limits in the cost, manufacturing use, and performance of friction stir welding need to be defined more accurately. Welding tools of the correct size and shape will produce sound welds and will be able to tolerate process parameters at the required working temperature. The microstructures of friction stir welds should be characterized to gain a fuller appreciation of the phenomena that occur at the weld site. Specific tool designs must be developed and optimized for geometries other than the conventional butt and lap joints, which receive the most attention today. Current R&D efforts should be accelerated to develop configurations for more diverse weld types**.**

VI-A-7. Mechanical Fastening

Description. Mechanical fastening of aluminum sheet by ordinary hammered rivets, self-piercing rivets, self-drilling screws, or by clinching is a viable alternative to the various welding methods of joining. Mechanical joining is not sensitive to combinations of dissimilar alloys, and can be used to join aluminum to other metals as well as to non-metallic materials in some cases. Mechanical fastening is often combined with adhesive bonding when joining non-weldable alloys to form a joint similar to a weld-bonded joint.

Technological Challenges. When a carbon steel fastener is placed in contact with aluminum, galvanic corrosion will occur unless measures are taken to avoid the corrosion. Such measures increase costs and may limit the broad application of this joining technique.

Research and Development Focus. Improved coatings will allow the use of various mechanical fastening techniques. These coatings will limit galvanic corrosion, widening the range of potential applications of mechanical fastening.

Table VI-1, below, summarizes the critical technologies that are needed for welding and joining aluminum for automotive and other applications.

Table VI-1. Critical Technologies for the Welding and Joining of Aluminum

Technology	Applications	Critical Issues
Arc welding	Structures of 5xxx and 6xxx sheet, extrusions, and 3xxx castings	Tracking and sensing devices, rectification of distortion, fit-up, automation, joint design
Laser welding	Structures of 5xxx and 6xxx sheet in coach and T-peel joint configurations	Tracking and sensing devices, rectification of distortion, fit-up, automation, joint design and performance
Riveting/ clinching/ adhesive bonding	5xxx and 6xxx sheet, and 6xxx extrusion	Joint performance, quality assurance
Brazing	Low-Mg 5xxx and 6xxx sheet in fillet weld joint configuration	Recovery
Adhesive bonding	Bimetallic joints	Anticipated growth in use of dissimilar materials
Friction stir welding		Increased weld speed, Welding tool development
Non-destructive evaluation (NDE)	Evaluation of industrial joints	Process robustness, clear pass/fail criteria at auto production rates (i.e., 60 inspections/ hour)

SECTION VII. MATERIAL AND STRUCTURAL BEHAVIOR FOR CRASHWORTHINESS

Although cost is perceived as the primary barrier to widespread substitution of aluminum for steel in automobiles, there is also some concern that in crash situations, aluminum structures do not perform as well as those made of steel. Section VII will explore this false concern, and present evidence that in many, if not most parameters, aluminum is equal to steel as the material of choice for automobiles.

VII-A. Overview

In a crash, aluminum acts much like steel in that the principal energy-absorbing components of an aluminum structure fold or collapse in a highly predictable manner, absorbing kinetic energy through the resulting work of deformation. Because aluminum has a lower stiffness modulus than steel, it is typically used in automotive structural applications at a thickness that is 1.5 times greater that the thickness used for steel. Nonetheless, structures that are equivalent in performance can be achieved at half the weight, since aluminum has about one-third the density of steel. The increased thickness results in more material being involved in the deformation process, and hence in the energy-absorbing work in impact collapse situations. This compensates for the lower initial yield strength of the aluminum and results in a similar net energy absorption.

Comparative tests show that a weld-bonded aluminum box beam will absorb as much energy as a structurally equivalent steel beam at 55 percent of the steel beam’s weight. Similar relationships exist for bending collapse. As with steel, the design and dimensions of the aluminum energy-absorbing members of vehicle structures have to ensure that folding collapse develops and that premature buckling does not occur.

It has been shown that aluminum structures can perform as well as, if not better than, steel counterparts when the structure is designed using various engineering parameters appropriate for aluminum. Numerous tests have proven the crashworthiness of aluminum vehicular structures. Test data from a 35-mph frontal crash conducted on the Ford Aluminum Intensive Vehicle (AIV) show similar, and in some instances, superior performance of the AIV compared to the regular steel-production (DN5) Taurus model on which the design of the AIV was based. Moreover, in recent 35-mph frontal barrier crash tests conducted by the National Highway Transportation Safety Administration (NHTSA), the aluminum-structured Audi A8 achieved NHTSA's highest (five-star) rating for the potential safety of both front-seat occupants. The GM EV1 achieved a three-star rating for both front occupants, a rating shared with other recently designed vehicles, including the relatively large Chrysler minivan.

Evidence that aluminum can be part of the design of crashworthy vehicular structures can be found in the aluminum-intensive vehicles in production today in North America, Japan, and Europe. A large number of automobile manufacturers are also using aluminum extensively in their cars and light trucks or have developed concept cars that rely heavily on aluminum. The recent move by

German automobile insurance agencies to lower their insurance rates for the Audi A8, based on their experience regarding its excellent performance on the roads, is further testament to the crashworthiness of aluminum vehicle structures.

Aluminum can also help in terms of improved vehicle compatibility, that is, reduced aggressivity when automobiles impact. Concern about the impact of heavy, high-riding vehicles on smaller vehicles has grown over the past decade as the number of light trucks (which includes pickup trucks, SUVs, and minivans) has increased. As a result, crashes between light trucks and smaller, lighter-weight cars are becoming more frequent, and the discrepancies in the bumper height and weight between these two classes of automobile are especially detrimental to the safety of the smaller vehicle. This problem can be alleviated by reducing the weight of light trucks through increased use of aluminum, and by considering vehicle compatibility during the design phase. It is likely that many of the aluminum-intensive vehicles under development will be designed for compatibility, thereby enhancing safety for everyone on the road.

Recent crash tests to test vehicle compatibility have demonstrated the benefits of using aluminum. When crashed into smaller vehicles, the lighter-weight, aluminum Audi A8 resulted in less impact energy being imparted during a crash than did a similar-sized but heavier Mercedes S300 traveling at the same test speed. The study showed that appropriately designed aluminum vehicle structures are crashworthy and can ease the aggressivity of crashes between larger and smaller automobiles. It also demonstrated that aluminum can be used to create structures that exceed the performance of steel-structured vehicles, and exceed all government safety standards.

Aluminum has other benefits in crash situations. For example, the superior corrosion resistance of aluminum forestalls material deterioration, allowing an aluminum structure to maintain integrity over the full useful lifetime of the vehicle. Also, appropriately designed aluminum structures can have a lower center of gravity, thereby reducing the risk of rollover. In addition, the use of aluminum makes it possible to provide large front and rear crush zones for protection of the passenger compartment without incurring corresponding weight penalties.

With the crashworthiness of aluminum-intensive automobiles already established, the challenge is to develop optimized designs for aluminum structures that both save weight and ensure crash compatibility with other vehicles on the road.

VII-B. Technology Challenges

With the development of aluminum vehicles that have demonstrated significant weight savings as well as crashworthiness in well-conducted and documented frontal crash tests, the outstanding technology challenge is to develop structural designs that are economical to build and that provide enhanced energy absorption for the different types of vehicular construction—from the traditional body-on-frame structure to unibody structures and space frames. For the most part, this is an automotive design issue, although improved models that better represent aluminum automotive structural materials as they undergo the transition from elastic to plastic deformation behavior would be helpful. Such models would enhance the ability of analysts to predict energy absorption in a crash, and hence to optimize their designs.

VII-C. Research and Development Focus

Research is needed to develop improved and innovative design concepts for energy-absorbing structural members. This work should be coupled with that of automotive designers to ensure that component manufacturability is kept in mind. It would require the building and impact-testing of various beam configurations, and should also be coupled with the development of models that incorporate an improved representation of elastic-to-plastic deformation behavior for the various structural materials, as described in the previous section.

SECTION VIII. SCRAP SORTING AND RECYCLING

Aluminum's recyclability contributes significantly to its cost-effectiveness in automotive applications. The recovery and recycling of aluminum from obsolete automobiles will continue to gain importance as the aluminum content of vehicles continues to grow.

VIII-A. Overview

According to leading producers, over 70 percent of the general secondary (scrap-based) aluminum foundry ingot is used in automotive casting applications. Since 100 percent of this aluminum is typically derived from scrap, its processing requires only about 5 percent of the energy necessary to produce primary aluminum in smelters, and correspondingly creates only about 5 percent of the environmental waste generated in primary production.

Aluminum used in the average automobile makes up 5 to 10 percent of the total vehicular weight, but represents 35 to 50 percent of the vehicle's total scrap value. Because of the high value of aluminum scrap, recycling has expanded under free market conditions to the point that at least 85 percent of the aluminum present in automobiles today is recovered and recycled. In the future, it is anticipated that the economic value of recycled aluminum will be further enhanced. This will occur by sorting and recovering the aluminum by alloy family.

The present infrastructure for recycling the aluminum from end-of-life automobiles is depicted in Figure 8-1. In this process, cars from the consumer proceed to the auto dismantler, where the automobile is dismantled as far as is economically viable for useable parts and certain easily sorted aluminum scrap such as wheels and radiators. The remaining "hulk" is sent to the shredder, where it is shredded into fist-sized pieces of varying composition and content. Ferrous and non-metallic scrap is separated magnetically from non-ferrous scrap, and the non-ferrous scrap is sent to separators to remove the non-aluminum scrap such as copper and zinc. The resulting mixed-aluminum scrap, which consists of a mix of cast and wrought alloys, is sold to the secondary aluminum industry for recycling into foundry alloys. Today, this process does not require separation of aluminum scrap by alloy because both the product and more than 80 percent of the scrap is in the form of secondary casting alloys.

There is a two-fold advantage to having the highest degree of separation possible at the dismantler: (1) Scrap that is removed by dismantlers avoids costly downstream processing associated with the shredder and separator; and (2) because dismantlers remove easily accessible parts (i.e., radiators, doors, hoods) and segregate them, they are by nature also separating the scrap into well-characterized categories, possibly by alloy. Segregated alloy scrap can be used to make high-quality secondary aluminum products, often the same as the original parts from which the scrap came.

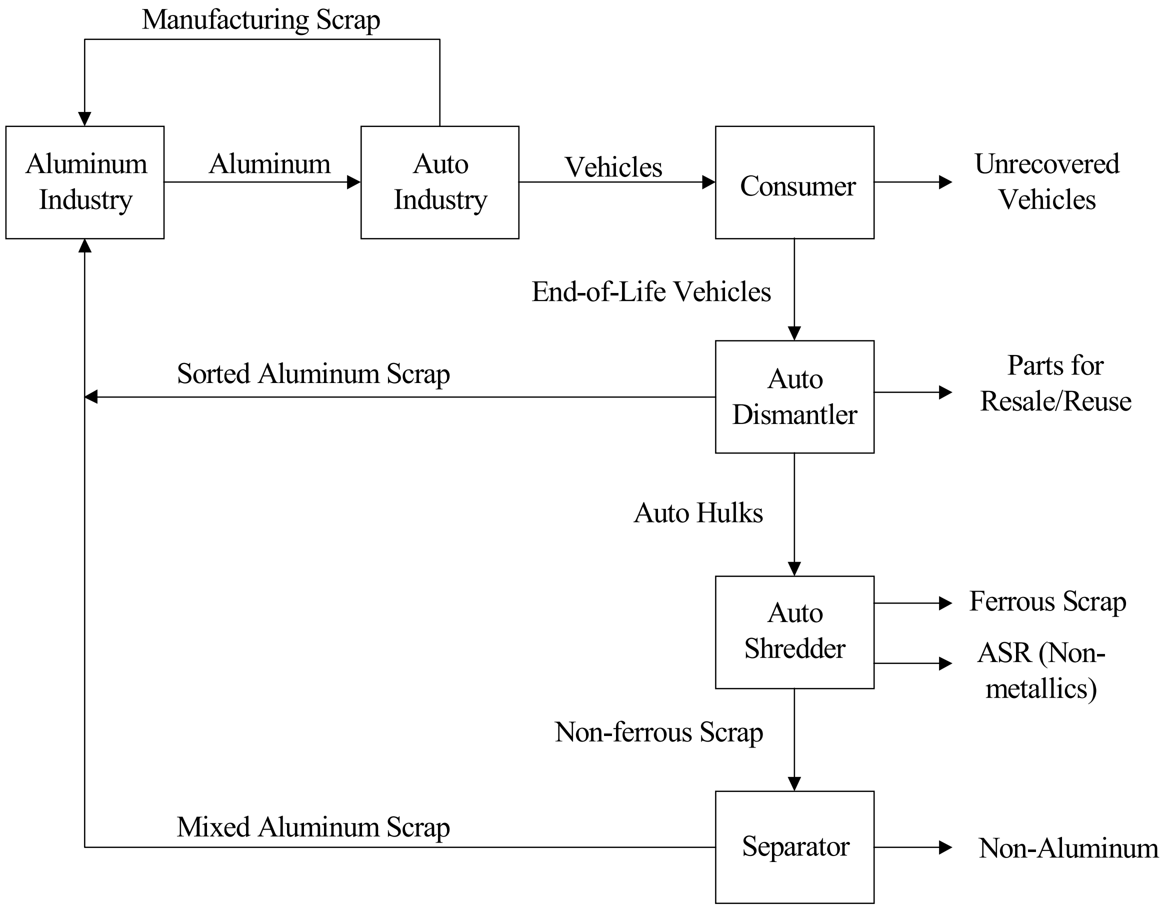

Figure 8-1. Current Automotive Aluminum Recycling Process

VIII-B. Trends and Drivers

In 1976, the average North American passenger car contained 87 pounds of aluminum. The growth of aluminum use in passenger cars and light trucks since 1991 is shown in Figure 8-2. The current level of about 250 pounds per car is expected to increase; in the next ten years, the average amount of aluminum in an automobile could grow to over 400 pounds, with aluminum-intensive vehicles (AIVs) containing up to 900 pounds each. This accelerated growth will drive the recycling industry to expand its capacity and optimize recovery of the increased volume of aluminum scrap that will accompany such growth.

Castings currently represent nearly 80 percent of the aluminum used in automobiles. Projections for both the aluminum used in automobiles and the demand for secondary metal for automotive castings indicate that castings can continue to absorb the aluminum automotive scrap generated in

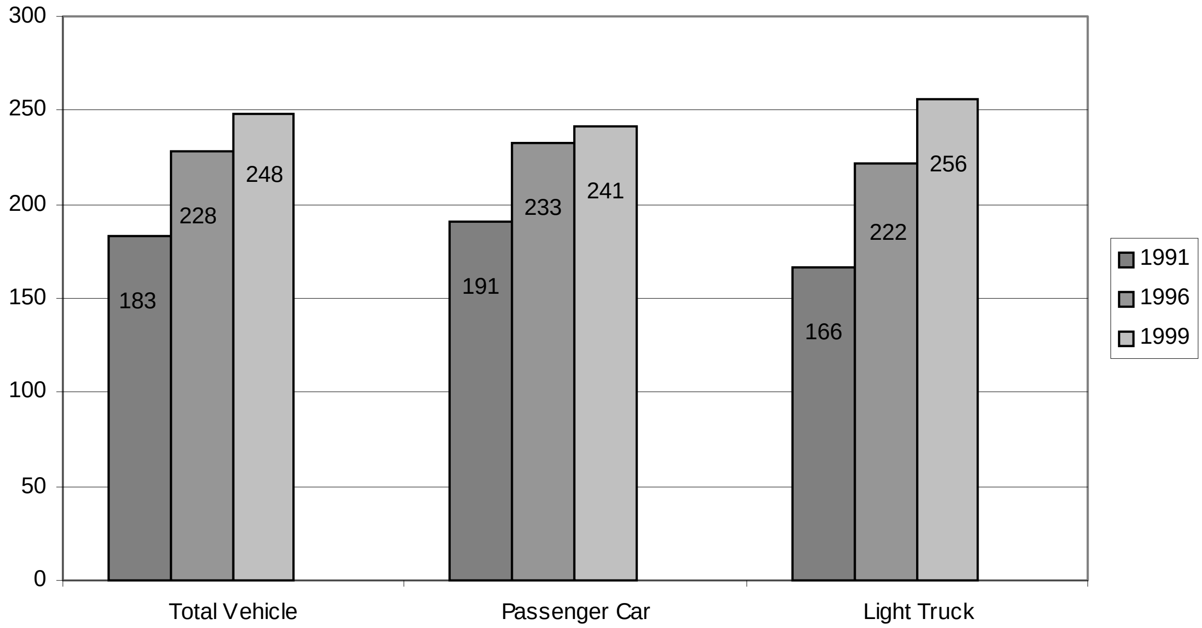

Figure 8-2. The average amount of aluminum (in total pounds) per North American vehicle has been rising through the 1990s. (The values for 1996 are estimated, and those for 1999 are forecasted.) Source: *Passenger Car and Light Truck Aluminum Content Report*, Ducker Research Company, 1999.

the near term. However, as the market develops for closure sheet and aluminum body structures, it will be more economical and increasingly desirable (from the viewpoint of alloy composition) to have these alloys segregated and recycled back into sheet products. The optimal situation would be to recycle them into the same sheet applications from which they came.

A combination of higher percentages of wrought alloys contained in the aluminum fraction of auto shred and tighter metallurgical specifications for castings will put greater demands on the quality of the metal recycled to metal casters. In the long term, as the castings market matures, the supply of recycled metal from auto shred may exceed the demand for secondary metal for automotive castings. All of these factors will drive the need to separate wrought scrap from cast scrap, and will provide the basis for the development of methods to ensure that future recycling of automotive aluminum follows a closed-loop system.

The recycling process of the future, which is an extension of the existing infrastructure, is depicted in Figure 8-3. The point of distinction with Figure 8-1 is the addition of alloy sorting and decoating. To ensure a closed loop, the wrought alloys must be substantially returned to wrought alloy applications, and the cast alloys to fresh castings. This will maximize the value of all the recycled metal and make full use of the alloying ingredients in each of the scrap alloys.

Auto dismantlers should continue to easily remove whole components (e.g., bumpers, hoods) from end-of-life automobiles, thus producing scrap that is sorted by alloy family. Such scrap is valuable to the industry in that it forgoes the shredding, separating, and sorting that must be used to produce sorted scrap from auto hulks. The result will be a premium-quality, recycled source of metal for making the same products once again. Increased efficiency of the dismantler results in lower scrap processing costs and higher quality scrap, and therefore higher product quality. However, in the absence of a technique for complete dismantling of the vehicle, the partially dismantled hulk will need to be shredded to facilitate further separation.

In the future, the separation of the auto shred into different fractions will need new processes that separate the mixed aluminum stream by alloy. Alloy sorting will include a cast-from-wrought separation, decoating, and a further separation of the wrought alloys into respective alloy families or individual alloys.

A recycling trend that is being adopted, particularly in Europe, is “closed-loop” recycling in which a metal supplier enters into a partnership with its customers to receive back their metal scrap. Accordingly, a truck delivering billets to a manufacturing plant will return with cuttings, trimmings, and billet scrap for remelting and subsequent reuse. In this instance, alloy sorting is precluded.

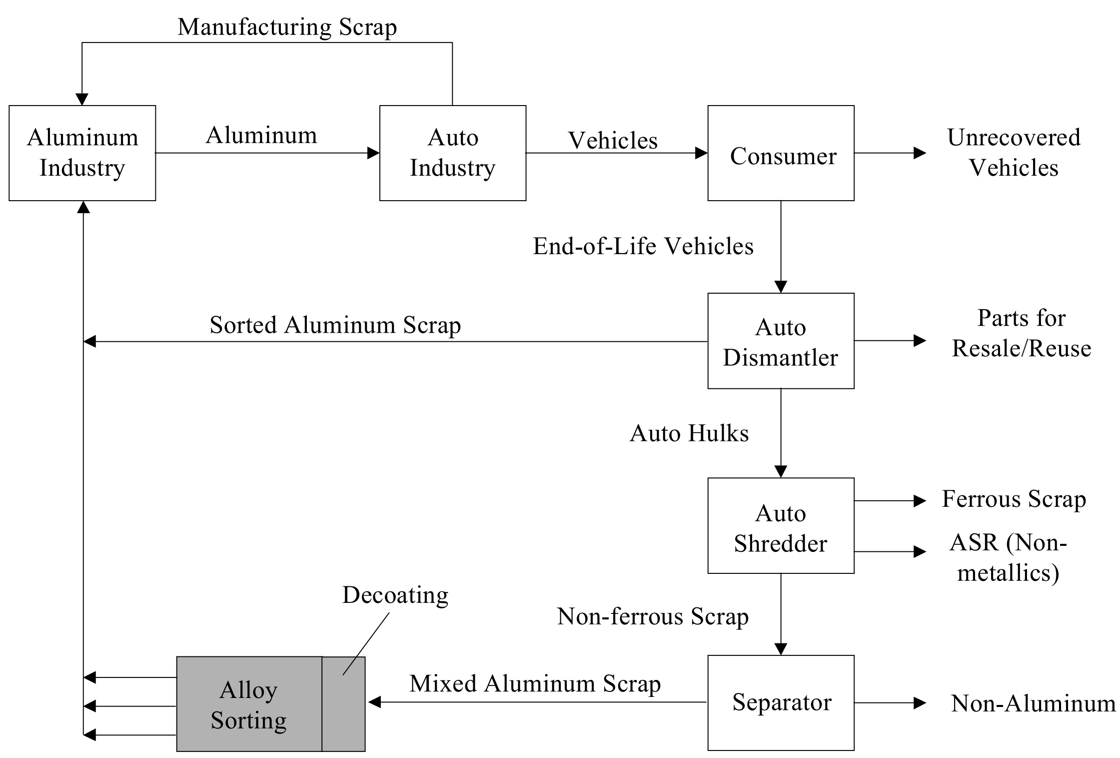

Figure 8-3. Future Automotive Aluminum Recycling Process

Closed-loop recycling is being encouraged by life-cycle considerations, by government regulation, and most importantly, by economics.

VIII-C. Technological Challenges

A significant long-term technical challenge facing the industry is the economical separation of shredded mixed scrap by alloy. A complicating factor is the rapid rate that is necessary for identifying and sorting alloys for automotive scrap processing (probably over 50 pieces per second).

Automotive designers are not yet sufficiently adept at designing cars for efficient recycling. There are basic precepts the designer must follow and this is not always done (e.g., specifying recycling-tolerant alloys; designing for easy part removal by the dismantler; avoiding joining dissimilar materials; and avoiding joining aluminum with problematic materials, such as heavy metals or toxics). The design flexibility of designers is limited by the need to meet stringent performance specifications such as metallurgical property standards. It is a technological challenge for designers to balance this tradeoff.

VIII-D. Research and Development Focus

Further work to develop economical alloy-sorting technologies will enhance the value of recycled metal and reduce demands for additional costly primary aluminum.

VIII-D-1. Alloy Sorting Technology Development

Opportunities are being investigated for recovery of aluminum scrap at the two points at which it will be generated in the future, at dismantling and after shredding. For the post-shredder scrap stream, there are several technologies, both new and established, with the potential to separate mixed scrap efficiently and economically. Two technologies have emerged as the most promising in identifying and sorting alloys:

- Laser-induced optical emission spectroscopy (OES)
- Color recognition following a chemical etch

Laser-Induced Optical Emission Spectroscopy (OES)

Description. Laser-induced OES is an adaptation of the OES system used today in casting centers and foundries in conjunction with a DC arc. Replacing this arc with a laser pulse that vaporizes a portion of each piece of scrap can allow much higher scrap processing rates. The resulting emission is analyzed via OES. This method allows composition analysis on a piece-by-piece basis, which can be used to sort mixed aluminum scrap by alloy.

Technological Challenges. The technology is still in the feasibility demonstration phase.

Research and Development Focus. Continue development and demonstration of laser-induced OES technology for use in segregating alloys from mixed scrap; evaluate its technical and economic feasibility.

Color Recognition Following Chemical Etch

Description. The color recognition technique can also be used to sort mixed scrap by alloy. Aluminum alloys can be chemically etched, resulting in different surface colors based on alloy type. This variety in color can then be used as the basis of scrap sorting.

Technological Challenges. The technology is still in the feasibility demonstration phase.

Research and Development Focus. Continue development and demonstration of color recognition alloy sorting technology; evaluate its technical and economic feasibility.

General Sorting/Recycling Issues

Research and Development Focus. In addition to the specific alloy sorting technologies listed above, other research activities could help the recycling industry optimize scrap sorting and recycling, including

- development of a computer model of the automotive aluminum recycling process and assessment of the capability of new-part production in a given year to absorb the returning scrap that year;
- evaluation of the robustness of the potential sorting technologies;
- determination of whether current scrap decoating technology will be sufficient for future scrap; and
- facilitation of a process that properly addresses all issues during the alloy selection and design process, including formability, machinability, bonding, and cost in addition to recycling.

Because the dismantler has the first and most critical role in the automotive recycling infrastructure, there are numerous R&D needs that relate to increasing dismantler capacity and efficiency, including

- development of an understanding of the dismantlers' capability to disassemble selected parts, sort by alloy or alloy family, and decoat scrap;
- establishment of a database that identifies the location and weight of aluminum used in vehicles, listing alloys used and a target dismantling time that reflects the value of the recovered metal;
- development of advanced dismantler technologies (i.e., component identification by alloy)

to enhance the dismantlers' role in overall automotive aluminum recycling;
- education of dismantlers about aspects of aluminum recycling, including alloy segregation, contamination, packaging considerations for aluminum scrap, and markets for scrap; and
- development of a dismantling-materials flow model that includes costs, inventory, transportation, and trade-offs.

VIII-E. Summary of Scrap Sorting and Recycling

The sorting and recycling of aluminum scrap offer great potential to reduce costs in both the aluminum and automotive industries. In order to capitalize on this opportunity, the top tasks, in order of priority, are considered to be the

- development of alloy identification/sorting technology,
- demonstration of bulk method for separation of cast from wrought alloys,
- demonstration of the dismantlers' capability to remove aluminum from scrapped vehicles with positive economics,
- assessment of the future capability of established separation techniques such as density and eddy current separation technology for the separation/purification of automotive aluminum scrap, and
- development of a database identifying the location and weight of aluminum used in vehicles.

SECTION IX. A FINAL THOUGHT— DESIGN IS A KEY COMPONENT OF SUCCESS

Automotive design engineers are being challenged as never before to explore new technologies that make more efficient use of materials and fuel. An integrated design approach that considers the properties of the materials, the product forms, and the manufacturing processes can help ensure an optimally performing vehicle at minimal cost. To make optimal use of any material, the overall design concept must address the material's key characteristics, including its strength, stiffness, durability, and crashworthiness. Aluminum products can take many forms, allowing the designer to reduce tooling and assembly costs through parts consolidation. The specification of certain joining technologies for manufacturing aluminum automobiles can also reduce costs.

There can be dramatic flexibility in the design of aluminum automobiles when properties of materials, product forms, and joining systems all match the design features sought. As the use of aluminum grows, particularly of wrought alloys, methods will be found to recover and reuse aluminum from these vehicles, enhancing the value of end-of-life vehicles.

Design-for-recycling concepts can be used to improve the value of scrap. These concepts include maximum compatibility of attached or joined alloys, ease of parts removal, recyclable fasteners and components, and (all other factors being equal) selection of recycling-tolerant alloys.

Aluminum companies and automobile manufacturers have already demonstrated that aluminum's unique properties can be exploited in structural designs that use fewer parts and rely heavily on innovative concepts. With an integrated design approach, these properties can be used to their best advantage in the development of safer, more cost-effective, and more fuel-efficient automobiles.

SECTION X. RECENT AND ONGOING R&D ACTIVITIES

This section discusses projects sponsored by the U.S. Department of Energy's Offices of Industrial Technologies (OIT) and Advanced Automotive Technologies (OAAT), and other activities underway by the aluminum industry and the U.S. Automotive Materials Partnership (USAMP). All of these research and development efforts contribute to the goal of increasing the use of aluminum in future automobiles.

X-A. Office of Industrial Technologies Projects

Table X-1, below, lists R&D projects underway in the aluminum industry, which are sponsored by OIT. Many of these projects are focused on reducing the cost of primary aluminum. All of the R&D projects are cost-shared by industry, with industry's share amounting to 30 percent to 60 percent of the funds from the Department of Energy. Annual solicitations are anticipated in the future; several additional projects will begin in the fall of 1999.

Table X-1. OIT-Sponsored R&D Projects of the Aluminum Industry

Project	Partners	Dates	Approx. DOE/OIT Funding (Total $M)
Al Pilot Cell - I	Alcoa	95 - 98	2.5
Spray Forming of Aluminum	Alcoa, Air Products, MIT	95 - 98	5.0
In-Line Sensors for Aluminum Cells	ORNL, RMC, Alumax , Kaiser Aluminum	95 - 98	0.6
Aluminum Bridge Deck	Oak Ridge National Lab, Reynolds Metals CO.	96 - 98	0.9
Aluminum Salt Cake	Argonne National Lab, Alumitech, Inland Steel	95 - 00	6.1
Molten Aluminum Explosion Prevention	The Aluminum Association, Inc., Alcoa, Lockheed Martin Energy Systems	97 - 99	0.5
Vertical Floatation Melter	Energy Research Company, Gillespe & Powers, IMCO Secondary Smelters, Stein Atkinson, Stordy	95 - 00	2.7
Semi-Solid Forming Project	Cast Metals Coalition, MIT, ORNL, Worcester Polytechnic Institute (WPI), WPI Semi-Solid Consortium	97 - 00	1.0
Automotive Aluminum Scrap Sorting	U.S. Automotive Materials Partnership, Aluminum Association, DOE (OIT, OTT), NR Canada	99 - 02	1.0
Removal of Molten Salts from Molten Aluminum	Selee Corporation and Alcoa, Inc.	97 - 99	0.4
Converting Spent Pot Liner to Useful Glass Fiber Products	Vortec Corp, Alumax, Hoogovens, Alfred University	97 - 98	1.0
Wettable Ceramic Based Cathodes	Reynolds, Kaiser, Advanced Refractory Technologies	97 - 00	3.8
Al Melting Using O_2 Enhanced Combustion	Air Products & Chemicals, Inc., Argonne National Laboratory, Roth Brothers, Brigham Young Univ.	97 - 98	0.7
Inert Metal Anode	Northwest Aluminum Technologies (NAT), Brooks Rand, Ltd. (BRL), Electrochemical Technology Corp. (ETC), Oregon State University	98 - 00	1.6

Project	Partners	Dates	Approx. DOE/OIT Funding (Total $M)
Recycling and Reuse of Aluminum Waste	Michigan Technological University, Alcan, IMCO Recycling, Marport Smelting L.L.C., TST, Inc.	98 - 01	1.4
Advanced Production Cells - II	Alcoa, Eltron Research Inc.	98 - 00	1.9
Improved Grain Refiner Process	JDC, Inc., GKS Engineering Services, GRAS (Grain Refining and Alloying Services) Inc., Touchstone Laboratory, Alcoa, Littlestown Hardware and Foundry	98 - 99	0.3
Potlining Additives	EMEC, Century Aluminum , Southwire, SGL Carbon	98 - 01	1.2
Reducing Chloride Emissions from Aluminum Waste	Reynolds, Virginia Dept. of Environmental Quality, NICE[3]	98 - 99	0.4
Onsite Process for Recovering Aluminum Waste	AAP St. Mary's, NICE[3]	92 - 93	0.2
Microsmooth™ Process on Aluminum Wheels	Metal Arts, NYSERDA, NICE[3]	98 - 99	0.4
Recycling of Aluminum Dross/Saltcake	Alumitech, NICE[3]	96 - 97	0.4
Indirect-fired, Controlled Atmosphere Decoating of Aluminum Scrap	Energy Research Company, NYSERDA, NICE[3]	96 - 97	0.4
In-line Rapid Heat Treatment of Cast Aluminum	Technomics, NICE[3]	98 - 99	0.4
Low-Dross Plasma Melter	Edison Technical Solutions, NICE[3]	97 - 98	0.4

X-B. Office of Advanced Automotive Technologies Projects

OAAT also sponsors a series of projects focused on issues related to the manufacture and assembly of aluminum automotive components. Again, the projects are aimed at facilitating the use of aluminum. Some of these projects are monitored through the Northwest Alliance for Transportation Technologies (NATT). A representative list of these projects is given in Table X-2.

X-C. Other Activities

Additional projects are in various stages of planning and formulation by the aluminum industry and the U.S. Automotive Materials Partnership (USAMP). Some of these projects are proposed under an evolving alliance with The Aluminum Association while others are being pursued by teams of individual companies. These projects fall within the following categories:

- Tailor Welded Blanks
- Scrap Sorting
- Electromagnetic Forming
- Aluminum Sheet Characterization

Table X-2. OAAT Projects Related to Manufacturing and Assembling Aluminum Automotive Components

Project	Partners
Long-Term Durability of Aluminum Adhesively Bonded Joints	University of Texas
NDE Techniques for On-Line Inspection of Automotive Structures with Adhesive Joints	
Fly Ash-Enhanced Aluminum Composites for Automotive Parts	EPRI, University of Wisconsin - Milwaukee
Die Casting Die Life Extension	NATT
Characteristics of Aluminum Tailored Blanks for Automotive Panels and Structures	NATT
Optimization of Extrusion Shaping and Forming Technology for Lightweight Automotive Structures	NATT, Alcoa
Advanced High-Volume Manufacturing Technology Validation for Lightweight Automotive Structures	NATT
Hot Crush Technology for Separation of Wrought from Cast Aluminum	NATT

SECTION XI. FOR ADDITIONAL INFORMATION

Those who prepared this report drew upon a large number of published documents, many of which came from within the aluminum industry or are available through The Aluminum Association. Others were very kindly supplied by the U.S. Automotive Materials Partnership.

Readers who wish to do additional reading on various topics will find the most useful resources among the following:

- Altenpohl, Dietrich. *Aluminum: Technology, Applications and Environment. A Profile of a Modern Metal,* 6th Edition. Published by The Aluminum Association and The Minerals, Metals, & Materials Society. 1998.
- Ducker Research Company. *Passenger Car and Light Truck Aluminum Content Report*. 1999.
- The Aluminum Association. *Aluminum Automotive Extrusion Manual*. Publication AT6. December 1998.
- The Aluminum Association. *Aluminum for Automotive Body Sheet Panels*. Publication AT3. December 1998.
- The Aluminum Association. *Automotive Aluminum Crash Energy Management Manual*. Publication AT5. December 1998.
- The Aluminum Association. *Life Cycle Inventory for the North American Aluminum Industry*. Publication AT2. November 1998.
- The Aluminum Association. *Aluminum Industry Technology Roadmap*. May 1997.
- The Aluminum Association. *Partnership for the Future*. March 1996.
- The Aluminum Association website, www.aluminum.org. (For additional related reports and data.)

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Alcan Aluminum Corporation	Alcoa, Inc.
Aluminum Precision Products	ARCO Aluminum, Inc.
Commonwealth Aluminum Corporation	Hydro Raufoss Automotive
Kaiser Aluminum & Chemical Corporation	Nichols Aluminum
Reynolds Metals	Southwire Company
V.A.W. of America, Inc.	Wabash Alloys

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