Aluminum: The Corrosion Resistant Automotive Material

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Automotive aluminum use has been growing for years (from an average of 87 pounds per car in 1976 to 248 pounds in 1999), mainly to reduce weight and improve fuel economy. Each pound of aluminum used can reduce vehicle weight as much as 1.5 pounds. Automotive frames and bodies can make even further use of aluminum’s unique combination of strength, light weight, crash-energy absorption, corrosion resistance, and thermal and electrical conductivity.

As new car prices increase (they roughly quadrupled between 1978 and 1999), durability and corrosion resistance take on new importance. Buyers want vehicles that will retain their appearance and keep a high resale value. That is something that aluminum can provide, as automakers offer longer warranties against component failure and body rust-out.

Aluminum — even unpainted and uncoated — resists corrosion by water and road salt and, in non-cosmetically critical parts, its use can avoid the substantial extra costs of galvanizing, coating and painting required for steel. Aluminum does not rust like steel if the paint is scratched or chipped. Nor is it weakened or embrittled, as some plastics may be, by desert heat, northern cold, or the ultraviolet radiation in sunlight. For its new delivery vans, the U.S. Postal Service specified aluminum bodies designed to last 24 years!

Finally, when a car must be scrapped aluminum is readily recycled with a high residual scrap value, providing both economic and environmental benefits.

Aluminum, with its wide choice of alloys and tempers, offers a wealth of advantages to automotive engineers developing new car designs of the future.
Aluminum in Automobiles
A Brief History

During the past 25 years, the use of aluminum in automobiles has increased steadily, both in absolute quantity per car and as a percentage of vehicle weight. However, aluminum is hardly a newcomer to the automobile; in fact, it has a long and successful history in automotive applications. Aluminum crankcases were used on the 1897 Clark (a three-wheeler) and the 1898 De Dion Bouton. (Figure 1) Substantial use of aluminum in automobiles was reported in 1900 in both France and the United States, twin cradles of the modern aluminum industry. (Figure 2)

FIGURE 1 -- Three-wheeler with aluminum crankcase.

FIGURE 2 -- Aluminum twin cradle.
A number of aluminum parts turned up on cars exhibited in the second New York automobile show, in 1901. Aluminum body panels were replacing wood, the traditional coach-body material, in automobiles around the same time. By 1903, the Gordon Bennett Napier had an aluminum cylinder block; the 1904 Lanchester’s rear axle housing was made of aluminum. And, automotive uses of aluminum multiplied during the early 1900s, showing up in gear housings, fan cowls, oil pans, water pumps, steering boxes, steering wheels, radiators, dashboards and other parts.

Before World War I, the auto industry was aluminum’s biggest single market, absorbing up to half of the aluminum produced.

The popular Ford Model T used aluminum in its transmission and hood. (Figure 3) In 1913, W.O. Bentley pioneered the use of aluminum pistons in racing cars.

What may have been the first “AIV” (aluminum-intensive vehicle) was designed and built in 1923 by L.H. Pomeroy, a famous British engineer. The Pomeroy car weighed only about two-thirds as much as a standard automobile, and proved to be extremely durable.

In mass-production cars steel became predominant, largely for economic reasons. However, the advantages of aluminum continued to give it a prominent role in transportation — particularly in aircraft, railroad cars, trucks and buses where aluminum’s combination of light weight, strength, and corrosion-resistant durability were highly valued.

Those qualities were also highly valued in racing and luxury cars, such as the aluminum-bodied Rolls Royce “Silver Ghost” and the classic 1930 Duesenberg. (Figure 4) Their value for...
standard production cars would be rediscovered after World War II, and particularly after the sudden rise in gasoline prices that began in 1973.

The U.S. aluminum industry expanded rapidly during World War II to meet the nation’s need for military aircraft; after the war, this expanded production capacity made aluminum available for new and renewed markets, including automobiles.

The first U.S. fluid drive transmission, in 1948, had an aluminum housing. Aluminum pistons have been standard on U.S.-made automobiles since 1955. Aluminum trim, virtually unknown in the early 1950s, was in widespread use by the end of that decade; by the mid-60s, most U.S. cars had aluminum grilles.

Since then, automotive applications have multiplied: aluminum bumpers since the early 1970s, aluminum intake manifolds since 1977; aluminum engine heads, engine blocks, wheels, radiators, driveshafts, and in recent years, a significant number of auto body closure panels. More than a hundred types of auto parts are made of aluminum and the list keeps growing.

In 1960, the average U.S. car contained about 54 pounds of aluminum — 1.4 percent of its total weight. Twenty-seven years later, average aluminum content had climbed to nearly 250 pounds, or about eight percent of total weight. And further opportunities lie open, as auto designers choose aluminum to satisfy drivers who want it all: performance, comfort, fuel economy, safety, and durability.

In recent years, the Audi A8 and the Ford AIV have highlighted the performance and benefits achievable by using all aluminum body structures. The field experience that is being gained with these vehicles continues to confirm the excellent corrosion performance and durability of aluminum in automotive applications.
Versatile, Tough, Durable...
Aluminum Parts in the Cars of Today

Since the mid-1970s, the percentage of aluminum use in automobiles has increased almost three-fold. Today, more than a hundred different auto parts are made of engineered alloy aluminum and the list is still growing. While lighter weight and efficient function were the primary reasons for selecting aluminum, extended life through better corrosion resistance provided an added benefit that is highly important in achieving the desired useful life of the vehicle.

A sampling of those wide-ranging applications is depicted on these pages.

Air Conditioners — Aluminum is an excellent conductor of heat and is widely used in automotive air conditioner condensers, evaporators, liquid lines, and compressor housings.

Body Panels — Aluminum has been successfully used in hoods, deck lids and other exterior parts in large production volume models of passenger cars, pickup trucks, vans and sport utility vehicles.

Brackets — Aluminum’s combination of strength, resilience, and durability makes it an excellent material for engine mounting and accessory brackets. It is widely used for power steering brackets, pump-mounting brackets, air conditioner mounting brackets, steering column brackets and similar applications.

Brake Cylinders and Pistons — Light weight, corrosion resistance, economy, and reliability explain the choice of aluminum in this important application.

Brake Drums — Strength and durability under exposure to water, road salt and dirt are among the advantages of aluminum in this application. In addition, the heat-transfer capability of aluminum helps to keep brake linings from overheating and so reduces brake “fading” in severe use, an important safety factor.

Bumper Reinforcements — These safety-related parts have high strength, light weight, good forming characteristics, and resistance to corrosive environments.

Charge Air Coolers — In addition to its good heat exchange and corrosion resistance characteristics, aluminum can be readily formed, cast or extruded into complex hollow shapes, as required for this application.

Complete Bodies — Aluminum has been used successfully for complete auto bodies, demonstrating strength, light weight, durability, and excellent crashworthiness. It is the preferred body material for large trucks, buses and other utility vehicles and was selected for the current U.S. Postal Service van, with a projected body life of 24 years.

Driveshafts — This relatively new application of aluminum was prompted by the metal’s combination of high strength, light weight, and corrosion resistance in a severely exposed location. Aluminum’s light weight not only improves general vehicle performance and
economy, but also reduces driveline vibration and noise.

Engine Heads and Blocks — The engine is one of the heaviest single units in an automobile and offers one of the greatest opportunities for weight saving through the use of aluminum. Many car engines have aluminum heads and some have aluminum engine blocks as well.

Fuel Injection Systems —
Aluminum offers weight savings, corrosion resistance, machinability and extrudability, as manufacturers continue to make fuel injection systems smaller and lighter. Aluminum is used for pump housings, tubing and cylinder parts.

Heater Cores — Aluminum is an appropriate material for heater core applications, since it is an excellent conductor of heat and is formable, and can be brazed, soldered or welded.

Intake Manifolds — Aluminum allows the production of intake manifolds in more advanced shapes and with thinner walls than are practical in iron. In addition, aluminum engine parts of all kinds present an attractive “high-tech” appearance under the hood which effectively conveys a sense of the vehicle’s quality to potential purchasers. As a result of all these factors, aluminum has become the material of choice for these parts.

Load Floors — This application demonstrates the versatility of aluminum. Its combination of light weight, strength, and corrosion resistance provides a part that can take contact with various materials, weights and impacts, without special protection or maintenance.

Luggage Racks and Air Deflectors — In these parts, aluminum combines esthetic appearance and styling with function and durability in environmental exposure without painting or coatings.

Oil Coolers — Auxiliary engine oil coolers and transmission oil coolers make use of aluminum for efficient heat exchange, durability, and light weight.

Pistons — These moving parts must last for the life of the vehicle in a demanding environment of high heat, stress, and potentially corrosive compounds. Aluminum meets these demands, with the added advantage that its light weight makes engines more responsive and efficient in converting fuel energy into vehicle performance. Aluminum has been the standard material for automobile pistons since the 1950s.

Radiators — Throughout automobile history, aluminum has been used in the radiators of selected cars. Now, with new production techniques, automakers are equipping most models with aluminum radiators to take advantage of their light weight, heat-transfer capacity, and corrosion resistance. Aluminum is formable, machinable, and can be brazed, soldered or welded.

Seat Tracks, Shells and Headrests — The mechanical properties of lightweight aluminum alloys and their ease of fabrication make them an advantageous choice for these safety-sensitive parts.

Spare Tire Carrier Parts — These parts are both functional and styled for appearance. Aluminum provides both the necessary functional strength and durability plus the desired styling.

Splash and Heat Shields — Aluminum’s resistance to water, road salt, hydrocarbons and dirt, and its ability to reflect and conduct away heat provides for durable shields to protect auto parts made of more vulnerable materials.

Suspension Parts — Aluminum has proven its value for suspension parts, where strength, light weight, and corrosion resistance are vital, in a popular “high-performance” car. It has been used in such parts as the upper and lower control arms, front and rear
steering knuckles, trailing arms, wheel spindle control rods, tie rod sockets, drive line support, wheel shafts and axle cover beams.

Transmission Housings — In a part requiring strength, corrosion resistance, ease of fabrication and economy, aluminum meets all of the requirements, while substantially reducing vehicle weight. Transmission housings were one of the earliest applications of aluminum in automobiles, for those very same reasons.

Trim Moldings — Aluminum trim moldings have solved corrosion problems and provided an attractive and durable appearance for several generations of automobile designers and owners. Anodized aluminum exterior trim has been used for more than thirty years, with excellent outdoor durability, corrosion performance and a bright finish.

Wheels — Aluminum wheels greatly reduce a car’s unsprung weight, improving ride and handling. They are not susceptible to rusting. Aluminum wheels were introduced as optional equipment for styling reasons. Produced as castings, forgings, fabricated sheet and hybrid cast and wrought configurations, aluminum wheels now have become standard equipment on many makes and models.

Wheel Covers — These visually attractive parts must be lightweight and formable, and must retain their good appearance over the expected life of the vehicle. Aluminum is an excellent material for this application. Its natural corrosion resistance ensures that the esthetic styling given to the part will last.
Aluminum in Today’s Automobile
Key Characteristics of Aluminum

Aluminum offers a wide range of properties that can be engineered precisely to the demands of specific automotive applications through the choice of alloy, temper and fabrication process. To name a few of its advantages, aluminum offers:

**Strength** — Some aluminum alloys and tempers approach or surpass the strength of commonly used automotive steels. To cite a few examples, automotive aluminum alloys achieve tensile strengths of 310 MPa (45 ksi) for alloy 6061-T6; 290 (42 ksi) for 6111-T4; and 430 MPa (62 ksi) for alloy 7029-T6. Some aluminum alloys are heat treated to strengths approaching 700 MPa (100 ksi), although these are primarily used in the aircraft industry.

**Light weight** — Aluminum weighs about 35 percent as much as steel by volume: 170 pounds per cubic foot of aluminum, versus 490 pounds per cubic foot of steel. Aluminum auto parts save weight directly as well as indirectly through redesign of other parts.

**High strength-to-weight ratio** — Aluminum’s strength-to-weight ratio is much greater than that of steel: often double, or more. This property of aluminum has been a key factor in development of the aerospace industry, and it offers the same advantages to auto designers seeking improved performance and higher fuel efficiency.

**Resilience** — Aluminum alloys will deflect under load and spring back, providing flexible strength and shape retention. Aluminum alloys can also be used to meet the stiffness and crash energy absorption requirements for automotive vehicle structures, while providing up to 50 percent weight savings compared with other materials.

**Corrosion resistance** — Aluminum does not “rust away” on exposure to the environment like steel; its natural oxide coating blocks further oxidation. The risk of galvanic corrosion can be minimized by the appropriate choice of alloy, component design, and protective measures.

**Forming and fabricating** — Aluminum can be formed and fabricated by all common metalworking methods including casting, stamping, forging, bending, extruding, cutting, drilling, punching, machining and finishing.

**Joining** — Aluminum can be joined by all common methods including: welding, soldering, brazing, bolting, riveting, adhesive-bonding, weld bonding, clinching, and slide-on, snap-together or interlocking joints.

**Crashworthiness** — Aluminum absorbs more crash energy per unit mass than steel or plastic. Also, it is non-combustible and it does not strike sparks.

**Cold-resistance** — At low temperatures, aluminum does not embrittle; it has higher strength AND ductility at subzero temperatures, and is often used for cryogenic applications down to absolute zero (-273°C, -459°F).

**Recyclability** — Aluminum has substantial scrap value and a well-established market for recycling, providing both economic and environmental benefits.

**Thermal conductivity** —
Aluminum conducts heat about 1.8 times better than copper, pound for pound and more than three times better than steel. This makes aluminum an excellent material for heat exchangers. Aluminum heat exchangers are widely used in automotive radiators, air conditioning systems and similar types of equipment.

Reflectivity — Smooth aluminum is highly reflective of the electro-magnetic spectrum, from radio waves through visible light and on into the infrared and thermal range. Aluminum bounces away about 80 percent of the visible light and 90 percent of the radiant heat striking its surface. Its high reflectivity gives aluminum a decorative appearance; it also makes aluminum a very effective barrier against thermal radiation, suitable for use in automotive heat shields.
5. Designing for Durability

5.1 - Uncoated Aluminum

Nature has provided aluminum with a highly protective “skin” in the form of a clear barrier oxide on its surface that forms quickly and is tough enough to hinder the deeper intrusion of oxygen and other gases and liquids to the subsurface aluminum atoms. This oxide is tightly chemically bound to the underlying surface, and if damaged, reforms immediately in most environments. On a freshly abraded surface, the barrier oxide film is only 1 nm (10 angstroms) thick, but is highly effective in protecting the aluminum from corrosion.

The oxide film develops slowly in normal atmospheres to greater thicknesses, and when corrosive environments are present, the oxide may both thicken and darken. However, it generally retains its protective character.

Thus, in normal environmental exposure, aluminum does not corrode (rust) away as does steel. Aluminum surfaces do oxidize when exposed to air, but this differs from the oxidation of steel in two important ways:

- Aluminum oxide is effectively transparent and invisible to the unaided eye.
- Aluminum oxide clings tightly to the surface of aluminum and forms a protective film that blocks progressive deterioration. It does not flake off, thereby exposing fresh surfaces to further oxidation. When damaged, it quickly reforms again, providing continuing protection.

With this natural corrosion resistance, the aluminum bodies of many commercial motor vehicles, rail cars and aircraft are unpainted; aluminum has proven durability in such applications.

5.2 - Coatings

Although aluminum components generally perform well without coatings, aluminum is an excellent substrate for paints and other coatings, often applied for esthetic reasons as well as for additional corrosion protection.

Adhesion can be maximized with the appropriate pretreatments or undercoats which are compatible with other components of the coating system.

A complete coating system includes the following:
- Cleaner;
- Conversion coating (pretreatment);
- Electrocoat primer;
- Primer/surfacer; and
- Top coat.

5.2.1 - Anodic Coatings

Anodic coatings are among the most useful for many applications because they:
- Increase corrosion resistance;
- Increase paint adhesion;
- Increase adhesive bond durability;
- Improve decorative appearance; and
- Increase abrasion resistance.

The basic approach in anodizing is to increase the thickness of the natural oxide coating on aluminum by converting more of the underlying aluminum surface to...
aluminum oxide while the part being anodized is the anode in an electrolytic cell.

The basic process steps to accomplish anodizing are:

1) Chemical cleaning of the surface to remove soils and contaminants;
2) Etching to remove the existing oxide;
3) Electrolytically treating the part in chromic acid, sulfuric acid or another appropriate solution to build a thick new oxide coating; and
4) Sealing the resultant coating in hot water, a hot dichromate solution, or some other suitable agent.

Such anodic treatments provide both corrosion resistant surfaces and surfaces amenable to additional protective finishes if they are needed.

5.2.2 - Chemical Conversion Coatings

Chemical conversion coatings are excellent for:

- Improved adhesion of organic coatings;
- Mild wear resistance;
- Enhanced drawing or forming operations;
- Decorative purposes when colored or dyed;
- Improved corrosion resistance under supplementary organic finishes or films of oil or wax; and
- Adhesive bonding.

The sequence of operations for applying satisfactory conversion coatings includes:

1) Removal of organic contaminants and oxide or corrosion products;
2) Conditioning the surface with acid or alkaline solutions;
3) Conversion coating with oxide-type, phosphate or chromate processes; and
4) Rinsing followed by supplemental coating if required. The final step can be omitted if no-rinse conversion coatings are applied.

5.2.3 - Painting

The only difference between painting aluminum and steel is the surface preparation. Aluminum is an excellent substrate for organic coating if the surface has been properly cleaned and prepared.

For many applications, such as interior decorative parts, the coating may be applied directly to a clean surface. However, a suitable wash primer or zinc chromate primer usually improves the performance of the finish coat. (Note that chrome-free primers are now recommended and are replacing the chromate primers).

For applications involving exterior exposure, surface treatments such as anodizing or chemical conversion coating are required prior to the application of a primer or finish coat. As noted earlier, sulfuric acid or chromic acid anodic coatings provide excellent surfaces for organic coatings. Usually only thin anodic coatings are required as a pre-paint treatment.

Conversion coatings are less expensive pretreatments than anodic coatings, provide a good base for paint, and improve the life of the paint by retarding corrosion of the substrate. Adequate coating of the entire surface is very important for paint bonding. The conventional automotive finishing system consisting of a) cleaning with a dilute alkali, b) followed by zinc phosphate as the pretreatment, and c) the cathodic electrocoat which provides excellent corrosion resistance.

It is useful to note that many vehicles now have aluminum closure panels made from alloys.
6016 and 6111 which have exhibited excellent corrosion resistance and paint adhesion performance in service.

5.3 - Anti-corrosion Enhancement

In automotive applications, appropriate designs and precautions can protect aluminum against the most likely forms of corrosive attack: galvanic, crevice, filiform, poultice and intergranular stress corrosion.

**Galvanic corrosion** — When dissimilar metals are held in contact in the presence of moisture, galvanic corrosion is possible. Aluminum is anodic (i.e., has a more negative solution potential) to steel and many other common metals, except zinc and magnesium, and so is vulnerable to galvanic corrosion because the more anodic material corrodes preferentially to the other. Protection is afforded by: a) keeping bimetallic junctions dry and, b) separating dissimilar metals with coatings or other insulators. Anodizing also helps combat galvanic corrosion by thickening the protective aluminum oxide film.

**Crevice corrosion** — Unprotected crevices at mating surfaces can collect and retain moisture that may form a pathway for corrosive electric currents. Measures that eliminate or seal crevices, and designs that shield them from splash greatly reduce the risk of corrosion.

**Filiform corrosion** — Filiform corrosion can occur on painted surfaces where a defect or scratch in the coating occurs allows access. This type of corrosion manifests itself as thin filaments that grow under the coating from scratch lines. The filaments are fine tunnels of corrosion product trailing the active cell. Using an appropriate conversion coating and ensuring the consistency and quality of coatings best prevents filiform corrosion. Filiform corrosion is really only of concern for painted exterior panels, and the alloys now used for these applications have been developed to minimize their susceptibility to this type of corrosion.

**Poultice corrosion** — Surface accumulations (“poultices”) that retain moisture promote corrosion in much the same way as crevices. The design of metal components and their surfaces should be such as to shed dirt and liquids; permanent contact between metal surfaces and absorptive materials should be avoided. If these measures are insufficient or impossible, the metal may be given a protective coating.

**Intergranular and stress corrosion cracking** — Stress corrosion cracking (scc) is unlikely with the combinations of alloys and products in most automotive applications. Most 5xxx and 6xxx alloys are resistant to stress corrosion cracking. However, aluminum alloys containing more than three percent of magnesium (Mg) may become sensitized (susceptible) to stress corrosion cracking if exposed for long periods at temperatures above about 75°C (150°F). Therefore their use in exposed structural applications, where there is continuous or intermittent exposure to engine heat or other high temperatures, should be avoided. If the advantages of the 5xxx (Al-Mg) alloys are needed in such situations, the selection of alloys such as 5454 and 5754 with lower Mg levels is recommended. It should be noted that paint-bake cycle aging has no deleterious effect upon the corrosion resistance of 5xxx alloys. Heat treatable 2xxx and 6xxx alloys may show some minor susceptibility to intergranular corrosion when partially aged (as in the paint-bake condition) but this is of no concern after the paint coating is applied.
Anti-corrosion Design Tips

6.1 - Preferred Design Features for Joints and Faying Surfaces

To minimize corrosion attack in butt welded and lap joints, the weld material (or rivet or bolt) should be less active than the larger area metals being joined.

In lap joints, use of fillet welds, insulating material, or a seam sealer is recommended.

Metallic fasteners which join aluminum to a dissimilar metal should be made of an alloy cathodic to aluminum. For example, use steel bolts in an aluminum-steel joint, not aluminum bolts; aluminized steel bolts are even better. Sacrificial protective coatings, typically formed by epoxy resins containing zinc, applied to steel fasteners are very effective.

Entrapment sites in offset lap welds and standing seams should be eliminated with a sealer or a bead weld.

Coatings should be applied to both the anode and the cathode or to the cathode only (e.g., to the steel in an aluminum-to-steel joint), but never to the anode only (e.g., to the aluminum only in such a joint). Damage to the coating on the anode would result in serious corrosion due to small anode-large cathode combination. Coating the faying surfaces of the dissimilar metals as well can increase protection. Sealants should be applied to crevices for best results.

Flanges should protect joints exposed to direct splash. These may have to be angled to protect without creating entrapment sites.

6.2 - Avoiding Entrapment Areas

Orientation of floor panel and side panel lap joints is important in avoiding entrapment areas.

Design, and use of sealer, minimizes entrapment areas.

Flange orientation and design prevents entrapment of moisture and debris.
6.3 - Controlling Entrapment Areas

The proper location of the opening in lower doors can minimize chances of plugging and can enhance drainage. The design above right tends to plug with debris more easily than the design at left. Sealants in tight joints further improve corrosion resistance.

6.4 - Other Design Features

The horizontal catchment areas, as in fender at left, should be avoided. The hood section, at right, requires protective coating and drainage.

6.5 - Design and Orientation of Structural Members and Reinforcements

Hat section and H- or I-beam reinforcements are good designs but the hat section should be open at the bottom for easy drainage.

If not inverted, channels require drain holes to avoid entrapment areas; angle sections should have rounded corners, smooth tapers, and drain holes as indicated.

When joining dissimilar metals design for a large anode/cathode ratio, and insulate the entire contact area with a protective coating as shown in previous column. If possible, the steel plate should be galvanized or painted and sealants should be applied to joints. Steel rivets are better than aluminum in such a joint; coated steel or stainless steel rivets are preferred.

Drain openings should be properly located to enhance drainage and to prevent entry of road contaminants. Sealant in joint crevices enhances corrosion resistance.

When box sections must be used, provide sufficient openings for the application and the drainage of protective coatings. Drain flutes and louvered holes should point down and to the rear of the vehicle. Crevices should be painted or sealed.

Use open construction where possible. In a severe corrosion environment, box sections and enclosed areas should be avoided or treated with a protective coating.
References

Automotive Design


Corrosion Resistance


Aluminum, Properties and Characteristics


Appendix A

Properties of Commonly Used Aluminum Automotive Alloys

The Aluminum Association has published several comprehensive manuals describing the compositions, properties and applications for both the aluminum sheet and extrusion alloys that have been developed or optimized for automotive applications. Respectively, these are entitled “Aluminum for Automotive Body Sheet Panels” - AT3, and “Automotive Aluminum Extrusion Manual” - AT5. The reader is therefore strongly advised to obtain copies of these two documents as well as “Aluminum Standards and Data” for detailed information. However, to aid the reader, the following basic information is provided to give guidance on the composition and typical properties of the materials most commonly used in vehicle structures.

A1 - Aluminum Sheet Alloys

Various non-heat treatable and heat treatable aluminum alloys have been successfully utilized in fabricating prototype unibody structures in sheet metal stampings. The compositions, typical mechanical properties, typical physical properties, and comparative characteristics of the most commonly used sheet alloys are presented in Tables 1 through 4.

The 5xxx (Al-Mg) alloys are non-heat treatable. Their formability generally increases with increasing magnesium content. However, 5xxx alloys with nominal magnesium contents greater than about three weight percent are subject to “sensitization”, whereby, with a combination of cold work (as in stamping) and long-term elevated temperature exposure (as would arise in proximity to the engine compartment), precipitation occurs at grain boundaries. Consequently the material may become susceptible to intergranular forms of corrosion, including stress corrosion cracking. Although the high magnesium alloy 5182-O has been successfully used in a production application (with an appropriate pretreatment and a protective paint coating, e.g., chromating followed by a baked electro-coating), the lower magnesium alloys such as 5454-O and 5754-O are considered the leading choices for structural stampings. Alloy 5754-O is the material that has been almost exclusively used for adhesively bonded unibody sheet structures.

Heat treatable alloys 6009, 6111, and 6022 have been developed primarily for closure panels. They are characterized by high ductility in the T4 temper in which they are formed, and high strength in the finished application because they strengthen during the paint-bake cycle. There are also certain applications where they may be used advantageously in vehicle structures. However, it is inadvisable to use them where they will be continuously exposed to elevated temperatures during vehicle service since this will continue the age hardening process and potentially lead to loss of ductility which may compromise the energy absorption capability.
## TABLE 1. CHEMICAL COMPOSITION LIMITS OF ALUMINUM BODY SHEET ALLOYS \(^{(1,2)}\)

<table>
<thead>
<tr>
<th>AA Alloy Designation</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
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<td>6022</td>
<td>0.8-1.5</td>
<td>0.05-0.20</td>
<td>0.01-0.11</td>
<td>0.02-0.10</td>
<td>0.45-0.7</td>
<td>0.10</td>
<td>0.25</td>
<td>0.15</td>
<td>0.05</td>
<td>0.15</td>
<td>--</td>
</tr>
<tr>
<td>6111</td>
<td>0.6-1.1</td>
<td>0.40</td>
<td>0.5-0.9</td>
<td>0.10-0.45</td>
<td>0.50-1.0</td>
<td>0.10</td>
<td>0.15</td>
<td>0.10</td>
<td>0.05</td>
<td>0.15</td>
<td>--</td>
</tr>
</tbody>
</table>

**Notes:**
- (1) Maximum limit unless a range is shown
- (2) Shown as a percent by weight
- (3) Mn + Cr = 0.10-0.6

## TABLE 2. TENTATIVE MECHANICAL PROPERTIES OF ALUMINUM BODY SHEET ALLOYS \(^{(1)}\)

<table>
<thead>
<tr>
<th>Alloy &amp; Temper</th>
<th>Ultimate Tensile Strength</th>
<th>Tensile Yield Strength (0.2%) offset</th>
<th>Elongation in 50 mm or 2 in.</th>
<th>Ultimate Shear Strength</th>
<th>Modulus of Elasticity, Average for Tension and Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa (ksi)</td>
<td>MPa (ksi)</td>
<td>%</td>
<td>MPa (ksi)</td>
<td>GPa (ksi) (10^3)</td>
</tr>
<tr>
<td>5182-0</td>
<td>275</td>
<td>40</td>
<td>130</td>
<td>19</td>
<td>24</td>
</tr>
<tr>
<td>5454-0 (^{(2)})</td>
<td>250</td>
<td>36</td>
<td>115</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td>5754-0</td>
<td>220</td>
<td>32</td>
<td>100</td>
<td>14</td>
<td>26</td>
</tr>
<tr>
<td>6009-T4</td>
<td>220</td>
<td>32</td>
<td>125</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>6009-T62(^{(3)})</td>
<td>300</td>
<td>43</td>
<td>260</td>
<td>38</td>
<td>11</td>
</tr>
<tr>
<td>6111-T4</td>
<td>280</td>
<td>42</td>
<td>150</td>
<td>22</td>
<td>26</td>
</tr>
<tr>
<td>6111-T62(^{(3)})</td>
<td>360</td>
<td>52</td>
<td>320</td>
<td>46</td>
<td>11</td>
</tr>
<tr>
<td>6022-T4</td>
<td>255</td>
<td>37</td>
<td>150</td>
<td>22</td>
<td>26</td>
</tr>
<tr>
<td>6022-T62(^{(3)})</td>
<td>325</td>
<td>47</td>
<td>290</td>
<td>42</td>
<td>12</td>
</tr>
</tbody>
</table>

**Notes:**
- (1) Not for design; represents typical for all products of these alloys
- (2) Typical per Aluminum Standards & Data, 1997
- (3) Artificially aged 1 hr. at 200-210°C (392-410°F) from the T4 temper
- (4) Artificially aged 1/2 hr. at 200-210°C (392-410°F) from the T4 temper
### TABLE 3 TENTATIVE TYPICAL PHYSICAL PROPERTIES OF ALUMINUM BODY SHEET ALLOYS

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Average Coefficient of Thermal Expansion x10⁻⁶</th>
<th>Melting Range Approx. (°C)</th>
<th>Thermal Conductivity at 25°C. W/M•k (BTU in/ft²•hr) °F</th>
<th>Electrical Conductivity at 20°C (68°F), MS/ m (%) (Percent of Int’l Annealed Copper Standard)</th>
<th>Density 10¹ kg/m³ (lb/in³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5182-O</td>
<td>24.1 (13.4)</td>
<td>575-640 (1070-1185)</td>
<td>132 (840)</td>
<td>18 (31)</td>
<td>2.65 (0.096)</td>
</tr>
<tr>
<td>5454-O</td>
<td>23.6 (13.1)</td>
<td>600-645 (1115-1195)</td>
<td>134 (930)</td>
<td>20 (34)</td>
<td>2.69 (0.097)</td>
</tr>
<tr>
<td>5754-O</td>
<td>23.8 (13.2)</td>
<td>590-645 (1095-1195)</td>
<td>132 (916)</td>
<td>19 (33)</td>
<td>2.67 (0.097)</td>
</tr>
<tr>
<td>6009-T4</td>
<td>23.4 (13.0)</td>
<td>605-650 (1120-1205)</td>
<td>167 (1160)</td>
<td>26 (44)</td>
<td>2.71 (0.098)</td>
</tr>
<tr>
<td>6111-T4</td>
<td>23.4 (13.0)</td>
<td>585-650 (1090-1200)</td>
<td>--</td>
<td>23 (40)</td>
<td>2.71 (0.098)</td>
</tr>
<tr>
<td>6022-T4</td>
<td>23.4 (13.0)</td>
<td>580-650 (1075-1205)</td>
<td>--</td>
<td>--</td>
<td>2.69 (0.097)</td>
</tr>
</tbody>
</table>

**Notes:**

(1) Eutectic melting may be eliminated by homogenization
(2) Typical per Aluminum Standards & Data, 1997

### TABLE 4 COMPARATIVE CHARACTERISTICS OF ALUMINUM BODY SHEET ALLOYS

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Resistance to General Corrosion</th>
<th>Formability</th>
<th>Fusion Weldability</th>
<th>Spot Weldability</th>
</tr>
</thead>
<tbody>
<tr>
<td>5182-O</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>5454-O</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>5754-O</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>6009-T4</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>6111-T4</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>6022-T4</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>A</td>
</tr>
</tbody>
</table>

A=Best    B=Better    C=Good

**Notes:**

(1) Ratings are for original bare aluminum alloy sheet; ratings may vary dependent upon combination of forming and paint bake cycle.
A2 - Aluminum Extrusion
Alloys

Aluminum extrusions in both the 6xxx and 7xxx alloy series are routinely used today in a wide range of automotive applications. The compositions, typical mechanical properties, typical physical properties, and comparative characteristics of the most commonly used sheet alloys are presented in Tables 5 through 8.

For automotive space frame structures, however, the 6xxx (Al-Mg-Si) alloys are the preferred ones due to ease of extrusion, good formability, excellent corrosion resistance and good weldability. These alloys provide

**TABLE 5 CHEMICAL COMPOSITION LIMITS OF ALUMINUM EXTRUSION ALLOYS**

<table>
<thead>
<tr>
<th>AA Alloy Designation</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Others Each</th>
<th>Others Total</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>6005</td>
<td>0.60-0.9</td>
<td>0.35</td>
<td>0.10</td>
<td>0.10</td>
<td>0.40-0.6</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.05</td>
<td>0.15</td>
<td>--</td>
</tr>
<tr>
<td>6005A</td>
<td>0.50-0.9</td>
<td>0.35</td>
<td>0.10</td>
<td>0.10</td>
<td>0.40-0.7</td>
<td>0.30</td>
<td>0.20</td>
<td>0.10</td>
<td>0.05</td>
<td>0.15</td>
<td>(4)</td>
</tr>
<tr>
<td>6061</td>
<td>0.40-0.8</td>
<td>0.7</td>
<td>0.15</td>
<td>0.15</td>
<td>0.8-1.2</td>
<td>0.04-0.35</td>
<td>0.25</td>
<td>0.15</td>
<td>0.05</td>
<td>0.15</td>
<td>--</td>
</tr>
<tr>
<td>6063</td>
<td>0.20-0.6</td>
<td>0.35</td>
<td>0.10</td>
<td>0.10</td>
<td>0.45-0.9</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.05</td>
<td>0.15</td>
<td>--</td>
</tr>
<tr>
<td>7004</td>
<td>0.25</td>
<td>0.35</td>
<td>0.05</td>
<td>0.20-0.7</td>
<td>1.0-2.0</td>
<td>0.05</td>
<td>3.8-4.6</td>
<td>0.05</td>
<td>0.05</td>
<td>0.15</td>
<td>(5)</td>
</tr>
<tr>
<td>7005</td>
<td>0.35</td>
<td>0.40</td>
<td>0.10</td>
<td>0.20-0.7</td>
<td>1.0-1.8</td>
<td>0.06-0.20</td>
<td>4.0-5.0</td>
<td>0.01-0.06</td>
<td>0.05</td>
<td>0.15</td>
<td>(6)</td>
</tr>
<tr>
<td>7029</td>
<td>0.10</td>
<td>0.12</td>
<td>0.50-0.9</td>
<td>0.03</td>
<td>1.3-2.0</td>
<td>0.05</td>
<td>4.2-5.2</td>
<td>0.05</td>
<td>0.05</td>
<td>0.15</td>
<td>(7)</td>
</tr>
<tr>
<td>7116</td>
<td>0.15</td>
<td>0.30</td>
<td>0.50-1.1</td>
<td>0.05</td>
<td>0.8-1.4</td>
<td>0.05</td>
<td>4.2-5.2</td>
<td>0.05</td>
<td>0.05</td>
<td>0.15</td>
<td>(7,8)</td>
</tr>
<tr>
<td>7129</td>
<td>0.15</td>
<td>0.30</td>
<td>0.50-0.9</td>
<td>0.10</td>
<td>1.3-2.0</td>
<td>0.10</td>
<td>4.2-5.2</td>
<td>0.05</td>
<td>0.05</td>
<td>0.15</td>
<td>(7,8)</td>
</tr>
</tbody>
</table>

**Notes:**
(1) Maximum limit unless a range is shown.
(2) Shown as a percent; remainder is aluminum.
(3) The sum of those “others” metallic elements: expressed to the second decimal place before determining sum.
(4) Mn + Cr = 0.12-0.50
(5) Zr = 0.10-0.20
(6) Zr = 0.08-0.20
(7) V = 0.05 max.
(8) Ga = 0.03 max.
good strength at low cost, are readily formed in the T4 temper and yet can be aged to the T5 or T6 temper to give quite high strengths. Of the commonly produced alloys, 6063 has the lowest strength, followed by 6005, 6005A and 6061.

The most commonly used alloys in space frames for crash energy management are 6063, 6005A and 6061. As with the 6xxx sheet materials, consideration must be given to the thermal stability of the 6xxx extrusions alloys when used for the crash energy management structural members in locations where these will be subjected to elevated temperature during vehicle service. This can lead to changes in strength and, in some instances, to a tendency to develop cracking upon impact collapse. However, this problem can be overcome by overaging the materials to the T7 temper (e.g. 8 hr. at 210°C). This reduces the strength level from the fully age hardened condition (T6) but improves the ductility, toughness and minimizes any tendency to crack on impact crushing while providing stable properties, even with long exposure to above ambient temperatures.

It should be noted that the chemical composition limits for these alloys are relatively wide and individual suppliers have versions of these alloys and tempers optimized for automotive structural applications.

### TABLE 6 TYPICAL MECHANICAL PROPERTIES

<table>
<thead>
<tr>
<th>ALUMINUM EXTRUSION ALLOYS(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alloy &amp; Temper</strong></td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>6005-T5(2)</td>
</tr>
<tr>
<td>6005A-T5(2)</td>
</tr>
<tr>
<td>6061-T6</td>
</tr>
<tr>
<td>6063-T5</td>
</tr>
<tr>
<td>6063-T6</td>
</tr>
<tr>
<td>7004-T5(2)</td>
</tr>
<tr>
<td>7005-T53(2)</td>
</tr>
<tr>
<td>7116-T5(2)</td>
</tr>
<tr>
<td>7029-T5(2)</td>
</tr>
<tr>
<td>7129-T5(2)</td>
</tr>
</tbody>
</table>

Notes:
(1) Not for design; represents typical for all products of these alloys
(2) Tentative
<table>
<thead>
<tr>
<th>Alloy Temper</th>
<th>Average Coefficient of Thermal Expansion $x10^{-6}$</th>
<th>Melting Range Approx.(1)</th>
<th>Thermal Conductivity at 25°C</th>
<th>Equal Volume</th>
<th>Equal Weight</th>
<th>Density ($10^3$ kg/m$^3$ (lb/in$^3$))</th>
</tr>
</thead>
<tbody>
<tr>
<td>6005-T5(2)</td>
<td>23.4 (13.0)</td>
<td>605-655 (3) (1125-1205)</td>
<td>188 (1310)</td>
<td>28 (49)</td>
<td>93 (161)</td>
<td>2.70 (0.097)</td>
</tr>
<tr>
<td>6005A-T5(2)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2.70 (0.098)</td>
</tr>
<tr>
<td>6061-T6</td>
<td>23.6 (13.1)</td>
<td>580-650 (3) (1080-1205)</td>
<td>167 (1160)</td>
<td>25 (43)</td>
<td>82 (142)</td>
<td>2.70 (0.098)</td>
</tr>
<tr>
<td>6063-T5</td>
<td>23.4 (13.0)</td>
<td>615-655 (1140-1210)</td>
<td>209 (1450)</td>
<td>33 (55)</td>
<td>105 (181)</td>
<td>2.70 (0.097)</td>
</tr>
<tr>
<td>6063-T6</td>
<td>23.4 (13.0)</td>
<td>615-655 (1140-1210)</td>
<td>201 (1390)</td>
<td>32 (53)</td>
<td>102 (175)</td>
<td>2.70 (0.097)</td>
</tr>
<tr>
<td>7004-T5(2)</td>
<td>23.8 (13.2)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2.77 (0.100)</td>
</tr>
<tr>
<td>7005-T53(2)</td>
<td>23.8 (13.2)</td>
<td>605-645 (1125-1195)</td>
<td>—</td>
<td>22 (38)</td>
<td>72 (135)</td>
<td>2.77 (0.100)</td>
</tr>
<tr>
<td>7029-T5(2)</td>
<td>22.8 (12.6)</td>
<td>—</td>
<td>163 (1130)</td>
<td>25 (42)</td>
<td>77 (133)</td>
<td>2.77 (0.100)</td>
</tr>
<tr>
<td>7116-T5(2)</td>
<td>23.4 (13.0)</td>
<td>—</td>
<td>27 (46)</td>
<td>86 (148)</td>
<td>2.78 (0.101)</td>
<td></td>
</tr>
<tr>
<td>7129-T5(2)</td>
<td>22.8 (12.6)</td>
<td>—</td>
<td>163 (1130)</td>
<td>25 (42)</td>
<td>77 (133)</td>
<td>2.78 (0.100)</td>
</tr>
</tbody>
</table>

**Notes:**
(1) Eutectic melting may be eliminated by homogenization
(2) Tentative
<table>
<thead>
<tr>
<th>Alloy</th>
<th>Resistance to General Corrosion&lt;sup&gt;(1)&lt;/sup&gt;</th>
<th>Formability&lt;sup&gt;(2)&lt;/sup&gt;</th>
<th>Fusion Weldability&lt;sup&gt;(3)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>6005-T5&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td>A</td>
<td>B-C</td>
<td>A</td>
</tr>
<tr>
<td>6005A-T5&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td>B</td>
<td>B-C</td>
<td>A</td>
</tr>
<tr>
<td>6061-T6</td>
<td>B</td>
<td>B-C</td>
<td>A</td>
</tr>
<tr>
<td>6063-T5</td>
<td>A</td>
<td>A-A</td>
<td>A</td>
</tr>
<tr>
<td>6063-T6</td>
<td>A</td>
<td>B-B</td>
<td>A</td>
</tr>
<tr>
<td>7005-T53&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td>C</td>
<td>A-B</td>
<td>A</td>
</tr>
<tr>
<td>7029-T5&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td>C</td>
<td>A-B</td>
<td>(5)</td>
</tr>
<tr>
<td>7116-T5&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td>C</td>
<td>A-B</td>
<td>(5)</td>
</tr>
<tr>
<td>7129-T5&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td>C</td>
<td>A-B</td>
<td>(5)</td>
</tr>
</tbody>
</table>

A=Best  B=Better  C=Good

Notes:
(1) Ratings are for original bare extrusions; ratings may vary dependent upon combinations of alloy, temper and filler alloy for welded structures. Alloys with A and B ratings can be used in industrial and seacoast environments without protection. Alloys with C ratings should be protected.
(2) Ratings are consensus of formability experts from experience in forming extruded shapes, in decreasing order of merit from A to C. First letter compares alloys in their as-extruded temper (F) or immediately after heat treatment (W). The second compares alloys in their standards hardened temper (T5, T53 or T6). These alloys naturally age harden at room temperature after extrusion or solution heat treatment, so delay in subsequent forming may be critical.
(3) Ratings are consensus of Aluminum Association Welding & Joining Advisory Panel. Ratings assume use of recommended filler alloys and use of GMAW or GTAW procedures. A = Generally weldable by all commercial procedures and methods. B = Weldable with special technique only.
(4) Preliminary
(5) Welding of 7029, 7116, and 7129 is not recommended. Use mechanical fasteners and/or adhesives.