AUTOMOTIVE ALUMINUM–PART II THE GREAT AMERICAN AWAKENING: THE OIL CRISIS

When the Big Three automakers started thinking about replacing steel sheet with aluminum, they found an industry vastly different from the Alcoa-dominated world of the pre-war era.

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If the period before World War II was the automobile industry's childhood, then the 20 years that followed the war were its adolescence: self-confident, self-centered, exuberant, and a little mad. Cars grew fins and sported fancy two-tone paint jobs overflowing with chrome. They got bigger, more powerful, and added all kinds of new features to entice customers such as automatic transmissions, air conditioning, power steering, power brakes, power windows, folding and disappearing roofs, and more. It worked. Car sales grew almost threefold between 1947 and 1965.

President Dwight D. Eisenhower started the interstate highway system during his first term and a whole new way of life developed around automobiles. People used their cars to commute from new homes in the suburbs. But the industry was changing: The Big Three automakers used their large production numbers to amortize fast model changeovers. Smaller companies struggled to keep up, consolidated, and eventually disappeared. The coach builders of the pre-war era survived for a time, but they too were fading. Dark

Nobu McCarthy poses with a Datsun from Japan at the 1958 Imported Car Show in Los Angeles. Courtesy of USC Libraries, Los Angeles Examiner Photographs Collection, 1920-1961.

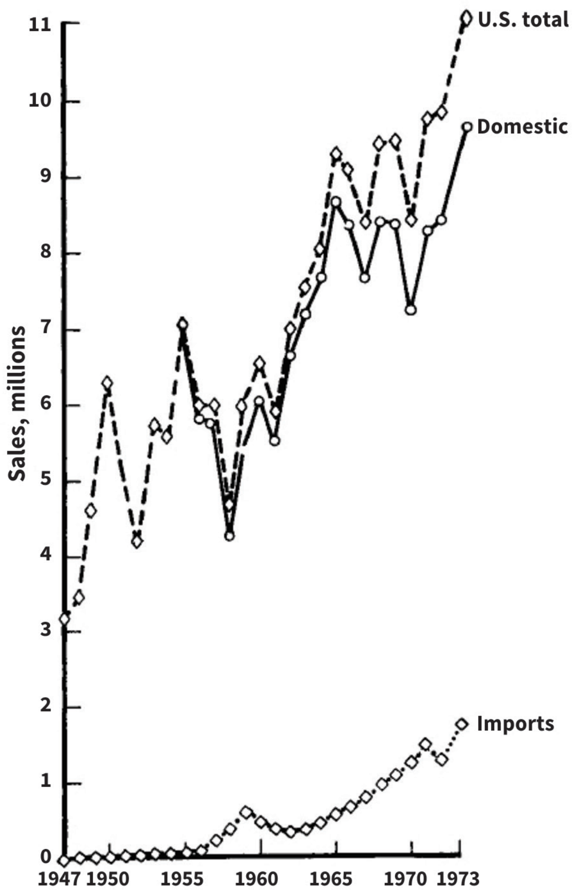

Fig. 1 — U.S. total passenger car sales, 1947-1973.

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clouds were appearing on the horizon and the industry would face a serious crisis that suddenly opened the door for a return to aluminum sheet in the automotive world.

The first pressure point came from the growing number of imports. Not every American liked big cars and an increasing number of buyers were opting for smaller and more efficient imports, first from Europe but increasingly from Japan. From a modest start in 1949, Volkswagen was selling enough Beetles by 1955 to officially set up a U.S. sales operation. In January 1958, Californians got their first look at a Toyota and a Datsun at the Imported Car Show in Los Angeles. Yearly imports passed the half-million mark by 1960 and the million mark by 1968 (Fig. 1).

Second, the increasing number of cars that grew heavier and thirstier only added to the accumulated pollution created by America's powerful industrial base. In congested areas, air pollution had become a serious problem and the government began to legislate solutions. The modest 1955 Air Pollution Control Act came first, followed by the Clean Air Act of 1963, and finally the 1965 Motor Vehicle Air Pollution Control Act. By the 1968 model year, cars would need to start meeting increasingly stringent emission standards. Mandatory safety standards were now appearing as well. All of this meant that heavier cars would get even heavier at the same time as engines were being strangled by the early emission control systems. Indeed, the curb weight of a standard class car would grow by almost 1000 lb between 1958 and 1973, despite the adoption of an increasing number of weight saving strategies (Fig. 2).

Third, as the car population soared, oil consumption grew proportionally. Domestic oil production could not keep up. By the 1960s, the U.S. began a dependence on imported oil that grew dramatically after production started to decline past 1970 (Fig. 3), although U.S. crude oil production has recently rebounded due to shale oil. In October 1973, Arab nations who were members of the Organization of the Petroleum Exporting Countries (OPEC) agreed to use oil to influence U.S. support for Israel during the Yom Kippur War. They enacted an oil embargo that caused severe shortages at the pump for U.S. motorists. The Big Three were in a vulnerable position with little to offer to an American public that suddenly demanded fuel efficiency. When President Gerald Ford signed the Energy Policy and Conservation Act in December 1975, Corporate Average Fuel Economy (CAFE) was a household name and fuel efficiency was now regulated.

ALUMINUM INDUSTRY EVOLVES

When the Big Three started thinking about replacing steel sheet with aluminum, they found an industry vastly different from the Alcoa-dominated world of the pre-war era. WWII had required an all-out industrial commitment to war production. To that end, Congress had established the Defense Plant Corporation (DPC) in August 1940 and tasked it with expanding production capabilities. When aluminum production peaked at 835,000 tons in 1943, DPC controlled 52% of the production. After the war, the aluminum industry was essentially reshaped through the sale of DPC assets, allowing new competitors to enter the sheet business. Newly formed Kaiser Aluminum bought DPC's Trentwood plant in Spokane, Washington, and Reynolds Metals Company bought DPC's Chicago-McCook plant in Illinois. Both were capable producers of aluminum sheet, as they were facilities built by Alcoa for DPC. Alcan got a similar deal for another key wartime sheet production facility when it bought the Kingston Works in Ontario, which came with a first-class research laboratory. In 1949, after having been forced to divest itself of much of its wartime capacity, Alcoa invested in new facilities in Davenport, Iowa.

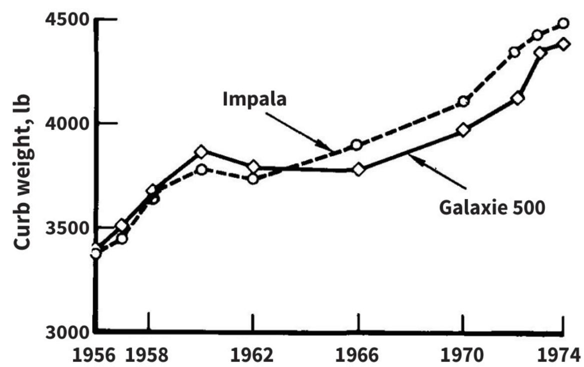

Fig. 2 — Passenger car curb weight trends by nameplate (standard class). Courtesy of EPA Report #460/3-73-006a, Passenger Car Weight Trend Analysis, Vol. 1, Executive Summary, January 1974.

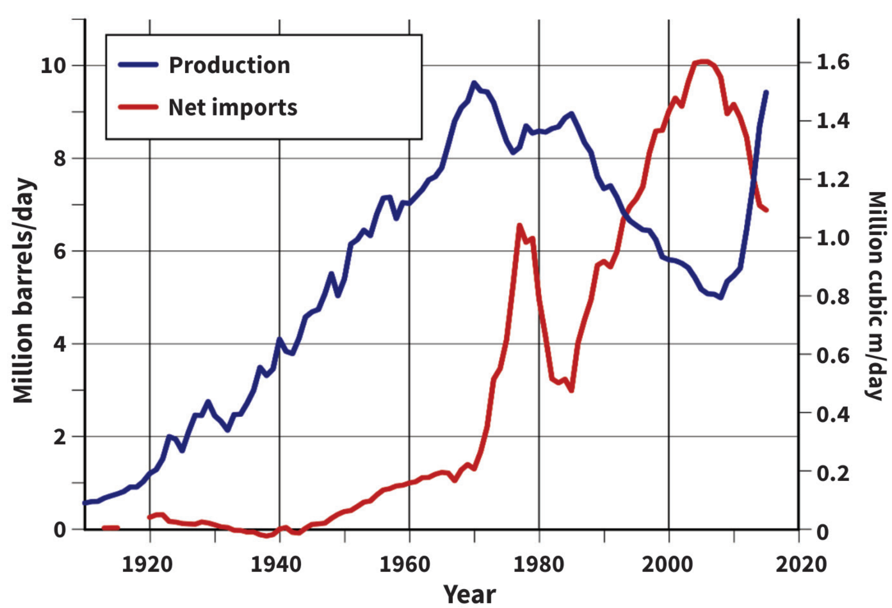

Fig. 3 — U.S. crude oil production and imports. Courtesy of U.S. Energy Information Administration.

The post-WWII North American aluminum industry quickly focused on products to replace war production. In the U.S., sheet and extruded products for buildings became high priorities for the industry. Alcoa-Tennessee produced roofing sheet from the remains of scrapped warplanes. Alloy 6063, registered in 1944, soon became a staple for extruded doors and windows. Key alloys for the marine and ground transportation industry were introduced between 1950 and 1958 including 5083, 5454, 5086, and 5456. These alloys, containing ~3-5% Mg, made high strength welded structures possible for truck tankers and shipbuilding. The first incremental steps in the development of aluminum cans were also taken during this period. Alcoa, in particular, continued to invest in 2xxx and 7xxx alloy aerospace research.

By 1951, ingot dimensions had increased so that a 6000-lb ingot was possible at Alcoa's Davenport Works. This was only the beginning, as the U.S. government undertook a major "large press" program that led to the development of much larger DC ingots. While much of the effort focused on difficulties with casting 7xxx alloys, the improved casting processes enabled larger ingots of all major rolling alloys.

By the 1960s, Alcoa, Reynolds, and Kaiser focused on new alloys and larger products for airplanes and ground transportation. All three were engaged in the emergence of the modern beverage can industry. Modernization of the aluminum rolling industry brought about by rigid container (can) sheet would prove instrumental for automotive sheet years later.

Both Reynolds and Alcoa had been quietly working on sheet alloys that could replace steel in auto body parts. But they were facing a significant challenge. By the 1960s, stamped body parts were produced cheaply and efficiently in modern stamping plants. Hoods, doors, and trunk lids were now assemblies made of an outer skin hemmed over a supporting inner panel, with special spot welding techniques to join the inner and outer components without damaging the outer surface. All of the manufacturing infrastructure and the tooling industry supporting it was optimized for steel; any aluminum sheet solution would have to fit in because any significant changes would simply be too expensive.

The most immediate challenge was that, at room temperature, aluminum alloys with enough strength to replace steel could not match the forming abilities of good quality sheet steel. 5xxx series alloys with higher magnesium content such as 5182 seemed to offer the best combination of strength and formability. Their excellent work hardening characteristics brought them to an acceptable strength level after forming, but at the cost of surface appearance. Finished parts often exhibited unacceptable surface micro-ridging known as Lüders bands (Fig. 4). French and British carmakers had been using lower Mg 5xxx series alloys in series production for years, but they were making do with lots of metal finishing. In response, France's Pechiney had introduced AU2G series alloy for the hood of Citroën's revolutionary 1955 DS model. In T4 temper, this 2.5% Cu 0.6% Mg alloy had acceptable strength with a formability similar to the AG3 alloy it replaced, but without the Lüders bands. Citroën would produce close to 1,500,000 hoods with that alloy during the 20-year run of the DS model.

Fig. 4 — Lüders bands, micro-ridges on aluminum sheet (collection of the author).

E-COAT PROCESS DEBUTS

In the U.S., another automotive development held hidden promise for aluminum. In late 1960, G.E. Brewer and his Ford Motor Company boss, G.L. Burnside, had filed a patent for an electrophoretic coating process now known as E-coat. The intent was to greatly improve the corrosion protection of sheet metal. The process involves dipping the entire body-in-white into an electrolytic bath to deposit a coating even in the most hidden cavities of the body, then baking it before conventional primer and top coats are applied. Ford licensed the rights of the invention to PPG, and despite the large costs associated with the infrastructure additions caused by the process, carmakers the world over rapidly adopted it. By 1978, 70% of the world's car production was E-coated. The addition of this high temperature baking process was a double-edged sword for aluminum: The baking cycle was hot enough and long enough to initiate softening of 5xxx series alloys, but

Citroën DS, produced from 1955-1975. Courtesy of Wikimedia Commons/Klugschnacker.

it might serve as an abbreviated artificial aging cycle for the right alloy. In time, the aluminum companies would take notice.

By this time, Reynolds was the second largest U.S. aluminum company and it had a sizable research laboratory. Headquartered in Richmond, Virginia, it had become a trusted supplier to the automotive industry. From 1957 onward, it supplied GM with the specialty aluminum alloy used in the Corvair aluminum block and several other parts, many of which went to the Corvette. Their automotive sheet alloy development bypassed 5xxx and instead followed a path opened more than 20 years earlier by Pechiney and their AU2G alloy. In 1970, they registered the first successful U.S. alloy developed specifically for automotive sheet, 2036. It was the first alloy to combine formability, surface quality, and strength, taking advantage of the recently introduced E-coat baking process. Due to the artificial aging capability, its strength could actually increase slightly during the baking cycle and this allowed a 20% reduction in gauge for the outer skins compared to existing 5xxx alloys. It also did not suffer from the Lüders bands during forming as the Al-Mg alloys did, eliminating costly metal finishing requirements. Suddenly, aluminum skins seemed plausible.

ALLOY DEVELOPMENT

In 1972, GM had just completed a steel version of an experimental Corvette, the XP-895. The car was gorgeous, but it had a problem: The all-steel body weighed 100 lb more than the production Corvette. John DeLorean, Chevrolet's general manager, asked Reynolds to reengineer the body as an all-aluminum solution using Reynolds' new 2036 sheet alloy (Fig. 5). They were given access to the existing prototype tools and jigs used for the steel body and completed the task in three months. Side by side and painted silver, the aluminum and steel versions were twins, but the aluminum version was 450 lb lighter. The car made its public debut at the 1973 New York Auto Show. The effort was not for the faint of heart and the methods used were not production-ready because the design could not be modified for the aluminum solution. Even 2036's improved formability could not match that of steel.

That same year, Alcoa announced several new alloys for aluminum sheet use (Table 1). In the introduction, the company pointed to aluminum's success in other ground transportation applications. They offered 2036 (already in the market from Reynolds) and 6151 alloys as possible solutions to reduce outer panel weight. Alloy X5020 (2.8%Mg-1.6%Cu-0.3%Mn) was a truly unique, heat treatable composition offering a better combination of after-bake strength and formability compared to 2036. This alloy was apparently aimed at an improved recycling compatibility with 2036 outers.

Alloy X5085 (6.2%Mg-0.2%Mn) was touted for inner panels due to its high n-value and uniform elongation, as shown in Table 1. The engineering data published in the company's 1972 "Body Sheet Alloys" document and 1974 SAE "Development of Aluminum Alloys for Body Sheet" paper included typical r- and n-values as well as forming limit curves similar to those used today. The need for alloys to strengthen during automotive paint baking—and the concurrent impact of pre-strain on baked strength—were clearly known and discussed in this publication.

However, these alloys were extremely short-lived. The X5020 alloy seems to have had little or no implementation by major automakers. One reason was probably its high incoming yield strength, which would have exacerbated the already considerable springback problems seen in other alloys. The X5085 alloy was successfully used by General Motors but quickly withdrawn by Alcoa after a few years and replaced by 5182. Production problems during rolling of the high-Mg X5085 alloy included high loads during

Fig. 5 — All-aluminum 1972 XP-895 Corvette produced by General Motors and Reynolds Metals Corporation.

TABLE 1 – PROPERTIES OF ALLOYS OFFERED BY ALCOA FOR ALUMINUM AUTOMOTIVE SHEET, 1972

Alloy	Temper	Yield Strength		Ultimate Tensile Strength		Elongation	n-value
		KSI	MPa	KSI	MPa	2-in. gage length	
X2036	T4	26	179	43	296	22	0.21
X5020	T4	30	207	50	345	24	0.25
X5085	H111	23	159	45	310	27	0.30
6151	T4	24	165	38	262	23	0.19

hot rolling and poor productivity (extra passes and edge cracking) during cold rolling. Both alloys were delisted in 1977 by The Aluminum Association at Alcoa's request.

The favorite alloy for difficult inner panels quickly became 5182 because its deep drawability was superior to 2036 and other 6xxx alloys. In addition, with 4.5% Mg and 0.3% Mn, it was much more amenable to existing rolling equipment than X5085. However, like other 5xxx alloys, 5182 was prone to Lüders bands during forming, which made it unacceptable for outer skins. At the time, Reynolds proposed that this issue could be solved by special processing techniques. The 5182 SSF (stretcher-strain free) material exhibited better surfaces after stretch-forming, but still could not meet the automakers' surface quality requirements. Finally, 5182's high Mg content made it susceptible to stress corrosion cracking (SCC) under certain environmental conditions. One of the Big Three learned that the hard way when air filter boxes made out of 5182 started cracking for no apparent reason. The root cause of the failure turned out to be SCC, prompted by the high temperature and sometimes highly humid underhood environment and the stresses experienced while being attached to a vibrating engine.

Kaiser Aluminum did not possess the resources of its two bigger competitors and was left behind in these efforts, although the company was far from inactive despite not being able to offer any new alloy of its own. There were talks about licensing the French alloys, but nothing seems to have come of it. They did supply some 2036 for trial purposes, but did not enter into production with any automaker.

Several aluminum sheet papers were presented at the 1973 SAE Congress in Detroit, including one from a visiting delegation from Pechiney, who even brought some stamped parts made with its own AU2G and AG3 alloys. Papers presented by the automakers noted the growing weight of cars: From an average of 3850 lb in 1973, weight was expected to jump to 4200 lb by 1974 and 4500 lb by 1977. All stressed the need to save weight with a target to shed 700 lb by 1977, using aluminum extrusions for the bumpers, plus high strength steels and aluminum sheet whenever possible. Smelling success, the aluminum industry was quietly making preparations for selling between 15,000 to 18,000 tons for the 1975 model year, mostly for GM. Ford was playing catch-up, having only recently decided to consider aluminum sheet for body parts.

What the aluminum industry insiders did not realize was that having a potential alloy solution and making prototype parts was one thing; having a complete solution capable of surviving in mass production was still four long years away. There were many challenges to be overcome for aluminum sheet to challenge steel. For one, neither industry understood the other. The aluminum mills, coming from aerospace production, were used to strict specifications, custom solutions, and careful and measured production methods. If something did not turn out as expected, the project stopped until the issue was solved.

MOVING TOWARD MASS PRODUCTION

Automotive mass production is quite different. Product development follows a strict schedule and delays are normally unthinkable, especially in the new environment of government mandated changes. In the early 1970s, the system worked because everyone involved in the launch of the product had an implicit knowledge of what to do. These included the designers who styled it, engineers who designed it, manufacturing engineers who prepared the production processes, and the tool shop workers who designed, built, and launched the stamping tools.

This was especially true for the legions of tool and die makers who were critical to crafting the stamping tools to actually produce acceptable parts. Designing and getting a draw die to work was the world of a few highly prized specialists who used their years of experience, intuition, and guts to move things forward. It took years to gain the knowledge to become a draw die specialist, but all of their accumulated knowledge and expertise was based on mild steel. When aluminum arrived, they were suddenly at sea with a material that did not behave as expected. Aluminum sheet was very different than mild steel. While it stretched reasonably well, it had a much lower ability to be drawn into corners, with wrinkles that none of the old tricks could conquer. The only remedy was to change the part design by simplifying and softening shapes. Design guidelines to help product engineers get closer to a workable design on the first try were urgently needed, but it would take time.

The second and more intractable problem was springback. When a die opens, the formed part is suddenly released of its external constraints. Internal residual stresses spring the part away from the tool, springing it back to an unloaded state, hence the term. Springback is directly related to the ratio of yield strength to elastic modulus, and unfortunately for aluminum, its elastic modulus is one-third that of steel. At near equal yield strength, this represents a threefold increase in springback potential. Springback is not linear—it is a complex 3D deformation. The toolmaker had to guess what distortion to apply to the tool shape so that the part, once released, assumed the design shape. The problem was exacerbated by the fact that few engineers truly understood the potential artificial aging enabled by the new E-coat ovens, and still specified alloys with high incoming yield strengths. In 1970, without analytical or computer modeling, correcting springback was a daunting task that could take eight to 10 iterations, each lasting four to six weeks. It added a great deal of uncertainty to both cost and timing, a situation despised by program planners.

ALUMINUM SHEET CHALLENGES

All car bodies and closure parts were spot welded together. Steel spot welding was a well understood process, with capable equipment suppliers. One of the advantages of spot welding was that it took place on "as is" surfaces, directly from stamping and without any intermediary cleaning. Although aluminum spot welding was invented during WWII, it was based on the assumption of a cleaned surface. Introducing a cleaning requirement was a nonstarter in the automotive world, so automakers had to look to alternatives until a more robust and tolerant spot welding process became available. Mechanical clinches were available, but that meant the outer and the inner could not be hemmed together, so they needed to be joined on downstanding flanges or on pinch flanges hidden under moldings. Both solutions imposed styling limitations, causing aluminum sheet to lose friends in all levels of the car development process. From accountants and design studios to product engineers and stampers, all bemoaned the use of aluminum and clamored for something more accommodating, more like steel.

However, cars needed to lose weight and the hood was a good place to start: The part was large and aluminum resulted in 50% weight savings, more than 25 lb on a car of that period. So development continued. By 1974, Alcoa had registered a pair of new, scrap compatible alloys: 6010 for outer skins and 6009 for inners. Both were designed to offer enhanced properties compared to 2036 with a slightly better age hardening response in the E-coat baking cycle, allowing them to overcome a slightly lower incoming strength. That lower incoming strength was actually an asset in the fight against springback, and GM would adopt the pair for their first mass produced parts. Ford did not see significant advantages and stuck with 2036.

By the time of the oil crisis, the U.S. aluminum industry was only partially ready for the production of high quality automotive sheet. The first problem was coil width, as most standard finished coil (after trim) widths at that time were 48 or 60 in. Automakers targeted hoods as the first part to switch to aluminum, and the hoods on the large cars of that time required widths of up to 1800 mm (72 in.). The problem did not lie with ingot sizes or rolling capabilities; these had been upgraded due to aerospace and can stock requirements. The issues with production of automotive sheet were mainly related to the continuous heat treatment process. The thin sheet (~1 mm) and wide width dictated a continuous coil process. Heat treatment of individual sheets, as performed during WWII, would have been a production nightmare for sheet handling and surface quality. Continuous annealing, which did not necessarily require a rapid quench, was available in locations such as Alcoa-Tennessee and Alcan-Kingston by the early 1960s. Most of the production was for non-heat-treated alloys, although Alcoa-Tennessee did produce some 6xxx canoe sheet with an air quench around this time.

Alcoa-Davenport commissioned an 86-in.-wide continuous heat treatment line in 1969 for aerospace sheet. Several important differences made for difficulties in auto sheet production. The 2xxx or 7xxx aircraft sheet was thicker and needed a strong water quench. Similar quenches for softer, thinner (~1 mm) 6xxx sheet caused problems with distortion and surface quality. Separate leveling to meet stringent flatness requirements was sometimes required. All of this added to low productivity (T/hour), low volume, and much lower margins compared to the aerospace sheet produced on the same equipment. This made early auto sheet production unpopular at times with plant management. Nevertheless, the 86-in. line at Davenport would produce the bulk of Alcoa's heat-treated auto sheet for more than 15 years.

1980 Lincoln Versailles. Courtesy of Wikimedia Commons/55allegro.

For the 1978 model year, both GM and Ford launched the first modern American vehicles with aluminum sheet: GM was ahead of Ford and launched aluminum hoods on four models, with two adding an aluminum trunk lid. Ford was content to launch one hood on their new Lincoln Versailles.

Both the automotive and aluminum industries had learned a lot in the preceding eight years, with the early enthusiasm for automotive aluminum sheet tempered by the harsh realities of production. For now, aluminum sheet was viewed simultaneously as a low margin, low productivity product by the mills, and as a constraining, expensive, and low productivity material by the automakers. It was more of a shotgun wedding than a love affair. **~AM&P**

Note: Look for the third part of this article series in the September issue of *AM&P*.

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