Aluminum Applications in the Rail Industry

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Introduction

The connection between the aluminum industry and railroads goes back a long way, in fact almost to the inception of the aluminum industry itself in 1888. The first reported use of aluminum in this market was by the New York, New Haven, and Hartford Railroad in 1894 when it built a special lightweight car with aluminum seat frames. This was followed in 1931 by the development of the all-aluminum hopper cars for freight.[1] At the World's Fair in Chicago in 1933 the first two main-line, all-aluminum, passenger railroad cars were exhibited.[2] The development of further applications of aluminum in the railroad area continued especially following World War II when excess material capacity was available. Developments have continued apace, driven by aluminum's light weight, corrosion resistance, and overall durability. This paper provides an update to this interesting and dynamic market, explores some recent advances in the technology, and discusses the potential impact of newer aluminum alloys and fabrication technologies, such as Friction Stir Welding (FSW).

A Proven Material in Rail: Experience with aluminum over the past several decades has resulted in numerous applications for the metal not only in freight cars, but also in light rail and inner city commuter trains, metros, and underground trains as well as in the express, intercity passenger trains. There is also considerable use of aluminum in the advanced high speed trains such as the Acela, the TGV, Transrapid, Shinkansen, and Pendolino-type trains, and the futuristic magnetic levitation (Maglev) trains.

Aluminum Applications and Advantages

Freight Applications: One of the most significant applications of aluminum in rail has been in the development of freight cars for the transportation of a range of commodity materials, especially coal. Typically, rail cars are designed for a 30-year life, and materials developments have tended to evolve gradually.[3] However, much of the existing rail stock is now approaching the end of its original design life. This, together with the recent high demand for the transport of low-sulfur coal from the western mines to the eastern markets, has caused a boom in the construction of coal cars. An article in *American Metal Market (AMM)*[4] forecast that deliveries of railcars will approach some 60,000 units per year by 2009 and projected a 50% growth in coal car deliveries over the five years starting in 2005. In a more recent article, *AMM*[5] estimated that some 27% of these cars will be aluminum. The lighter aluminum railcar bodies, about two-thirds the weight of the comparable steel body, enable a greater payload. The higher payload capacity repays the higher initial cost of aluminum in less than two years, and the resistance of aluminum to corrosion by the high-sulfur coal ensures long durability for these coal cars. In addition to the operational advantages, the U.S. DOE has reported that the conversion of coal cars to aluminum has facilitated a significant decrease in the total CO_2 emissions produced by the transportation sector.[6] To further emphasize this application, FreightCar America, a builder of rail cars, recently celebrated the delivery of the 100,000th aluminum car in a ceremony with its customer in December, 2006.[7] Figure 1 shows a line of open-top, hopper cars for hauling coal made using aluminum plate and extrusions.

Figure 1. Aluminum intensive open-top hopper cars. (Photos courtesy of Freight Car of America)

The use of aluminum in coal freight cars is only one of many freight applications. Aluminum cars are used to transport a variety of metal ores and minerals from mine to market. In all these applications the high specific strength (strength to weight ratio) of aluminum enables increased payload and fuel savings. Johnstown America's website[8] offers an excellent overview of the large number of designs available in aluminum freight cars. Recently, FreightCar America has been able to redesign its Bethgon line of cars to further increase capacity through use of alloy 6061 extrusions. In other products, aluminum sheet side walls offer improved aerodynamics and lower wind resistance and eliminate the need for paint, thereby lowering operating costs.

Another recent and popular product has been the automotive vehicle carrier. Here the car, enclosed with aluminum sheet, protects new vehicles in transit from the factory to the dealer. Extensive use of aluminum extrusions has enabled lightweight designs, with high carrying capacity for larger vans and SUVs, and especially large doors to facilitate rapid loading and unloading operations. In Johnson America's August 3, 2004 press release on the delivery of their first production aluminum vehicle carrier (AVC™) as shown in Figure 2a, Jack Thomas, president, First Union Rail was quoted as saying, "We are pleased to be innovators in the vehicle transportation field by being the first to lease the new AVC cars to Canadian National (CN). With their projected long service life and corrosion-free aluminum superstructure, we are confident the AVC cars will serve CN and its customers well." In addition, Bill Wiles, vice president, automotive for Johnstown America stated, "Rugged, yet light, the AVC is designed for minimum out-of-service time, further reducing the cost of operation. A

Figure 2a. Aluminum Vehicle Carrier (AVC). (Photo courtesy of Johnson America Corp.)

longer-term benefit is that through an AAR exemption, the aluminum superstructure never needs recertification over its extended life span."

One of the most significant advantages of aluminum is the application of internally-stiffened large hollow extrusions to fabricate moveable side walls for freight cars. As compared to conventional steel walls, this type of design enables the wall to be fabricated with many fewer parts, reducing the extent of welding required, and is significantly lighter, which has the further advantage that the wall can be manipulated by a single worker, thereby saving labor. The 6xxx series alloys (aluminum-magnesium-silicon) normally used for this application offer excellent extrudability, as well as moderate strength and high corrosion resistance, and as a result the wall can be used unpainted and the cut ends of extrusions need not be sealed. The overall aluminum side wall is virtually maintenance free (Figure 2b).[9]

Figure 2b. High capacity railcar with sliding aluminum sidewall. (Photo © Alstom Transport)

Lastly, another advantage of aluminum freight cars is that they retain a high salvage value when recycled at the end of their life cycle. In a recent example, several hundred 100-ton hopper cars initially built around 1967 were recently sold for almost 90% of the original manufactured cost!

Commuter and Passenger Trains: The commuter and passenger rail category has an enormous variety of train designs and structures. These range from the light rail, commuter and metro trains, and trams to the more substantial inter-city and express trains. Alstom, a leading transnational corporation and producer of the European TGV and of Pendolino-type trains, has a comprehensive description of some of these trains available on their website.[10]

In these trains the structural loads imposed by the passengers and their seating dictate the designs. Here the advantage of long aluminum extrusions has become dominant. These rail cars are made of longitudinal extrusions that run the total length of the car, and the individual extrusions are then welded together longitudinally. In the case of the Washington, DC metro system, these extrusions are 75 feet long. The overall structure is then stiffened by horizontal members that are attached around doors and windows. The floor structure is strengthened by the use of the hollow, integrally stiffened extrusions and the area near the wheel bogie is strengthened by several transverse members. This design also minimizes the number of parts required, as compared to steel fabrication, and simplifies and reduces the amount of welding.[9] The overall result is a stiff structure that is able to handle complex loads and aerodynamic forces that result from going through tunnels, and which is about two-thirds of the weight of a comparable structure fabricated from steel.

This weight reduction is especially significant for commuter trains with frequent stops as it enables energy savings in service and reasonable acceleration between stops (Figure 3). The other advantages of aluminum in durability and corrosion resistance also provide low maintenance costs and long system life.

Figure 3. DC Metro train. (Photo courtesy of http://en.wikipedia.org/wiki/Washington%2C_D.C.)

The weight reduction enabled by the use of aluminum is also critical in the newer inter-city tilting, or Pendolino-type, trains. Pendolino, which means pendulum in Italian, was the company that pioneered this tilting development and was taken over by Alstom in 2002. Just as a cyclist leans into the curve as he rounds a bend, the tilting train leans into curves and can negotiate bends at ~35% higher speed than compared to conventional trains. This development is especially important in improving the speed of inter-city service without making significant and costly track modifications or building new rail lines exclusively for high speed service. The Acela train, which operates in the northeast corridor of the U.S., (Figure 4) is one example of the tilting train, though in this case some design considerations compromised the extent of the benefit that could be derived by the tilting mechanism.

Many tilting, Pendolino-type trains are operating throughout Europe (the French TGV), and one recently achieved the Czech Republic rail speed record of 237 km/hr. Another recent development in some of these trains is the regeneration of electricity when braking. Operational experience indicates an energy savings of

Figure 4. Acela Express train. (Photo courtesy of Amtrak)

~17% through the use of regenerative braking. In all these systems, the use of aluminum technology enables extremely low axle weight and good exploitation of passenger space, all without compromising structural integrity and safety.[11]

Advanced High Speed Trains: For the purposes of this article, these are advanced trains that require extensively modified high speed tracks for their operation or totally new redesigned track, as is the case for the magnetic levitation (Maglev) technology. These high speed trains are under development in Germany (Transrapid) and Japan (MLX01 as a successor to the existing Shinkansen). The existing Shinkansen (Figure 5) has developed a double decked version and increased its speed from 220 to 270 km/hr. This was feasible without overloading the wheel bogie assembly through lightweight aluminum construction technology.

Figure 5. Shinkansen 300 (left) and 700 Series at Tokyo Station. (Photo courtesy of http://en.wikipedia.org/wiki/Shinkansen)

The Transrapid, which uses aluminum alloys 6061 and 6063, is designed for speeds in the range of 400-500 km/hr while the Japanese MLX01 version is planned to operate at speeds of 550 km/hr. On a test track the Japanese Railway Maglev train is reported to have achieved a speed of 581 km/hr. As would be anticipated, at these design speeds, there is a premium on light weight structures. Aircraft and aerospace construction technology is increasingly being adopted. In addition to the use of longitudinal extrusions, there is considerable use of sheet material for foamed core panels for side wall and panel construction. The Maglev system closest to full scale operation and with most operational experience is in Shanghai, China (Figure 6). Here the system operates

Figure 6. Shanghai Maglev. (Photos courtesy of http://en.wikipedia.org/wiki/Shanghai_Maglev_Train)

between the Pudong suburb and the airport and has pleased its investors with excellent high speed, low noise operation, and relatively low operating costs.[12]

While it is not clear at present what the upper limits of this advanced rail technology will be, it is obvious that both sheet and extruded aluminum and their fabrication technologies are vital to achieve these advances in transportation and infrastructure development. Table I summarizes the key attributes of aluminum and their impact on the various rail applications from freight to high speed passenger systems. Clearly the multiple properties of the metal enable safe, economic, and durable performance of a host of rail systems.

Containerization

It is difficult to discuss rail transport of freight and commercial goods without at least a reference to the ubiquitous container. In the past, railroads have specified aluminum for some four out of every five containers.[13] Goods can be placed into large containers and shipped to their destinations interchangeably by rail, road, sea, or air. The adaptability of the container for each mode of transport has simplified the transport of goods. Containers speed the loading and unloading processes, protect the goods from the elements and from pilferage, and serve as mobile warehouses. With a backbone of aluminum extrusions and with considerable use of aluminum sheet, the growth of containerization has greatly facilitated the rail transportation industry.

Aluminum Alloys and Processing Technology

Aluminum Alloys: Alloys chosen for railcars are selected based on ease of fabrication, mechanical strength, weldability, and corrosion resistance. As a result, the workhorse materials normally used are the aluminum-magnesium (5xxx) and aluminum-magnesium-silicon (6xxx) alloy series. The 5xxx alloys are not heat-treatable but can be strengthened by cold work and offer moderate strength and excellent corrosion resistance and weldability. The 6xxx alloys are heat treatable and can offer higher strength, good corrosion performance, and good weldability.

The Aluminum Association (AA) manual on the repair of aluminum railcars indicates that the commonly used sheet or plate materials are alloys 5052, 5083, 5086, 5454, and 6061. The commonly used extrusion materials are 5083, 6061, and to a lesser degree, 7005. Newer alloys, such as 5059, 5383, and 6082, have also been used for railcar applications. Welding is not an issue for most of the alloys just mentioned. A 5xxx filler alloy, such as 5356 or 5556, is generally recommended for the conventional fusion welding processes. The AA offers publications that provide much information on fabrication methods and weld repair procedures for all these materials.[14, 15] As the repair manual states, "working with aluminum is, in some cases, different from working with steel—but no more difficult." In the past the highest strength 7xxx and 2xxx alloys were not widely used because of poorer weldability

Freight Applications	
Attribute	*Impacts*
Light weight	– increased payload, fuel savings – higher initial cost repaid within two years
Durability	– lower maintenance, high salvage value
Corrosion resistance	– reduces or eliminates painting
Fabricability (including extrudability, formability, weldabilityc etc.)	– novel designs – integrally stiffened sections with decreased weight – improved side wall design, reduces labor – reduces number of components – reduces need for welding/machining
Recyclability	– retains high value at EOL – supports a sustainable industry
Passenger Applications	
Attribute	*Impacts*
Light weight	– energy savings in service (commuter trains) – higher acceleration from propulsion systems
Stiff structures	– high passenger safety – more controlled tilting for Pendolino designs
Corrosion resistance	– low maintenance – unpainted structures or reduced need to paint – long service llife
Recyclability	– retains high value at EOL – supports a sustainable industry
Advanced High Speed Trains	
Attribute	*Impacts*
Light weight	– enables double decked designs on similar bogies – aluminum sheet sandwich panels employed
Aircraft construction techniques	– stiff, robust structures

Table I. Aluminum attributes in rail applications.

and corrosion performance,[14, 16] but the development of friction stir welding, which is discussed hereafter, may change that situation.

It is interesting to note that the advanced trains are still using these similar materials. For example, the Japanese Shinkansen uses 5083 alloy, and also some 7075 material, which is more frequently used as an aerospace material, while the German Transrapid uses 5005 sheet for panels and 6061, 6063, and 6005 for extrusions.

Recent Alloy Developments: Some recent research for improved rail materials has been evaluating newer aluminum alloys containing scandium additions.[16] Scandium provides the highest amount of strengthening per atom percent of any alloying element when added to aluminum. Small additions (0.1-0.2 wt%) have been shown to improve mechanical properties, refine the microstructures of wrought aluminum alloys, and improve weldability by reducing hot cracking in the weld region. Since all of these factors are relevant to rail applications of aluminum, a study was conducted to establish whether scandium-containing 5xxx, 6xxx, and 7xxx alloys could be used in conjunction with advanced welding technology such as friction stir welding, to improve the performance of aluminum alloys for rail applications.[14]

While previous studies showed that scandium additions improved weldability of 6061 alloy, this study demonstrated that scandium additions reduced the strength of 6061 and did not refine the grain size. In the case of the 5456 alloy, the addition of scandium did refine the grain structure and improve mechanical properties; however, the intergranular corrosion performance was adversely impacted.

In the case of the 7xxx alloy, however, scandium additions did significantly improve mechanical properties, weldability, and corrosion resistance. Because of higher mechanical properties, however, the extrusion rate of this alloy is somewhat slower, and hence production costs can be expected to be higher. So the trade-off is whether the improvements in mechanical properties, weldability, and corrosion resistance from the scandium addition to the 7xxx alloy are sufficient to overcome some increase in material cost. To date, scandium has only been used in relatively small quantities in high performance sporting goods such as baseball bats and archery arrows, and it remains to be established how widespread the use of these alloys will become. As the construction techniques of the advanced trains become more akin to aerospace technology, it could well be that the scandium modified 7xxx alloy could provide some significant system advantage. For example, a higher strength extrusion (due to the addition of a scandium-containing alloy) when used to build a total assembly might enable certain design improvements such as the need for less material resulting in a lighter, more fuel efficient system.

Friction Stir Welding: As pointed out in the "Aluminum Industry Technology Roadmap,"[17] the technology of aluminum joining has advanced rapidly in recent years. Developments in FSW especially have been most significant and have provided aluminum with a significant competitive advantage in some markets (Figure 7). Since its inception in the early 1990s, FSW has advanced most rapidly with aluminum due to its combination of low melting point, high thermal conductivity, and ductility and is now being used on the external tank of the Space Shuttle and the Eclipse business jet. FSW has enabled the joining of previously difficult to weld alloys, often with improved mechanical properties and corrosion resistance. Experience with FSW in the fabrication of fast ferries and bridge decks indicates that the process has increased automation, improved dimensional tolerances, reduced residual stresses, and lowered manpower needs. The process is especially advantageous in the fabrication of long butt welds, but welding along curves and around cylinders is now also possible.

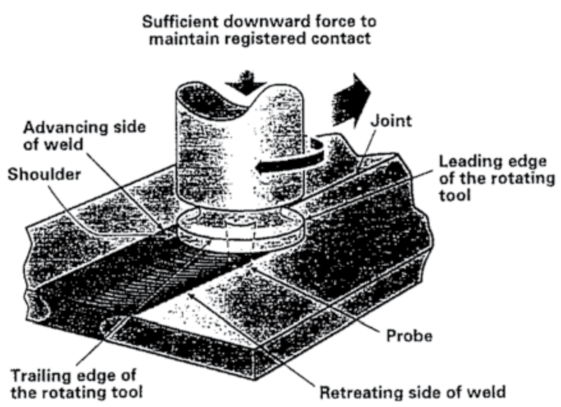

Figure 7. Schematic of Friction Stir Welding.

While FSW is being developed for other metals as well, its application for aluminum has been most dominant. One reason for this is that tooling costs are relatively low for aluminum. The relatively low melting temperature of aluminum (~660°C) as compared to steel (~1,500°C) for example, ensures that the wear of the spinning tool and the forces required for the welding process are much reduced.

For the fabrication of rail and passenger cars, FSW is an ideal process for the butt welding of the lengthy longitudinal extruded sections that comprise the roof and floor sections of the cars. The fact that the technology enables the joining of some alloys that traditionally have been difficult to weld, e.g. most 2xxx and 7xxx alloys, provides a further competitive advantage. As the fabrication techniques for the advanced trains become like those of the aerospace industry and if history there is any guide, the application of FSW to the rail industry will improve the welding of rail cars, automate the process, and lower overall costs. A recent study at the South Dakota School of Mines & Technology indicated that cost savings of greater than 20% could be obtained with FSW as compared to the baseline bolted design when fabricating aluminum hopper cars.[18]

The Future—Striving for Sustainable Mobility

In the U.S. the development of passenger rail services has lagged behind the rapid growth of air traffic and air terminals and the continuing development of the interstate road system. The status of the rail industry was highlighted in a recent news article.[19] The article pointed out that high speed rail got attention in the 1990s when the U.S. government designated high speed rail corridors around the nation. Now while there are 11 designated rail corridors through 28 states, the article notes that "actual development of high speed rail service has slowed to a crawl or become completely dormant." All this is because of a lack of both federal and state funding for major infrastructure projects. The article goes on to question whether there is a real market for rail ridership in this country. Further, it is noted that virtually all the railroad tracks in the U.S. are privately owned by freight companies that are running slower, heavier trains, and these companies are not interested in mixing advanced, high-speed passenger trains with the slower moving freight trains.

The U.S. situation is in marked contrast to that in many other countries in Europe and Asia. In Germany, France, and Japan, for example, the rail industry is driven by significant government investments. The national high speed train systems are viewed with a certain amount of national pride and prestige and as an aid to tourism, and there is a continual interest in upgrading performance and establishing speed records between cities.

As in several other areas of commerce, much of the future of rail transportation will probably be impacted by the growth of rail infrastructure in China. China is already investing heavily in a large array of infrastructure projects. In advanced rail technology, the Chinese have surprised many by jumping ahead to operate a high speed Maglev system (established by the German makers of the Transrapid system) and also are importing large numbers of different advanced trainsets from Europe to establish a national infrastructure. Of course, it remains to be seen how all these different national approaches will work out in the development of effective national transportation systems.

One major challenge for all countries in this new century surely will be the development of transportation systems that ensure sustainable mobility. With growing evidence of climate change and global warming, it will be increasingly difficult for the nations of the world to ignore these issues. Almost certainly, national transportation systems will strive to become as energy efficient and environmentally acceptable as possible. People around the world will also seek to travel more both for business and recreation and so the concept of enabling this increased mobility in a sustainable manner will become more important.

While it is not clear how the various rail systems discussed will evolve and which technology will become predominant, it is clear that the many attributes of aluminum for the transportation industry, and especially for rail cars and passenger trains, will undoubtedly ensure aluminum's critical role in the development of sustainable mobility. Aluminum is already considered one of the most sustainable metals due to its excellent recyclability and the fact that recycling saves ~95% of both the energy and emissions, as compared to making the metal from the ore.

The results from recent modeling of comprehensive life cycle studies indicate that aluminum will become "climate neutral" by the year 2020.[20] To date, no other metal has been able to make such a claim. In other words, the fuel savings achieved through the lightweighting of transportation vehicles by increased aluminum usage, and the resulting reduction of CO_2 emissions, will more than compensate for the additional CO_2 emissions generated by the production of the additional metal. In rail transportation, the data has not been as well documented but in the case of automobiles, a 10% reduction of vehicle mass translates directly to a fuel saving of 6-8%, with an equivalent reduction in the CO_2 emissions derived from the fuel. Accordingly, the various attributes of aluminum and especially its light weight, durability, and corrosion resistance will ensure that aluminum sheet and extrusions will have a strong future in the development of rail transportation systems around the world, and in striving to attain a situation of sustainable mobility for future generations.

Editor's Note: For more information on how to obtain Aluminum Association publications, go to: www.aluminum.org/bookstore.

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