Chapter

Applications of Aluminum Alloys in Rail Transportation

Xiaoguang Sun, Xiaohui Han, Chaofang Dong and Xiaogang Li

Abstract

This chapter focus on the latest applications of aluminum alloys in rail transportation field. The typical high-strength aluminum alloys used on high speed train is introduced. The unique properties of aluminum alloys are analyzed. The detailed application is illustrated including car-body, gear box and axle box tie rod. The main challenges encountered in the application are also mentioned. The key manufacturing techniques, such as casting, forming, welding, are analyzed. Finally, the future improvement directions for better application is summarized. It is expected to set up a bridge for materials providers, equipment manufacturers and end-users, thereby promoting the advance of manufacturing technology and application of aluminum alloys in wider fields.

Keywords: aluminum alloy, application, rail transportation

1. Introduction

With the rapid development of human civilization, the consequent air pollution and greenhouse gas (GHG) emissions have threaten human being for years. Energy conservation and emission reduction is an increasing priority in the development of transportation industry.

A number of approaches can be used to improve energy efficiency and reduce CO_2 emission, such as reducing aerodynamic resistance, transmission loss, tire rolling resistance, and weight [1]. Among these options, lightweight structure is currently considered as one of the most efficient solutions. In recent years, lightweighting has become a major research theme in the transport industry around the world.

Material substitution appears a promising option for lightweighting. Traditionally, steel, such as low-carbon steel and stainless steel, is used as main material to build major structure of transportation equipment. Titanium, aluminum and magnesium are promising lightweight metallic materials as alternatives to steel and cast iron. Among these materials, aluminum shows a balanced performance, such as light weight, good corrosion resistance, good formability, high specific strength and relatively low cost. Density of aluminum alloy is only one third of steel. Considering structural optimization due to material replacement, the overall weight of rail car-body is decreased by 50% when aluminum is used. This degree of reduction deserves an effort in engineering application.

Although aluminum accounts for ~8 wt% (by mass) of the earth's crust, the high affinity of aluminum for oxygen, as well as the stability of aluminum oxides and silicates hindered its separation for a long time. For this reason, aluminum became economic for engineering applications only at the end of the nineteenth century [2].

Aluminum alloys was originally used in aviation industry which is an important part of the transportation industry. It was firstly used on Junker F13 fuselage with the invention of 2017-T4 alloy in 1920. It began to be used in the manufacture of train with increase of the train speed until 1980s. So far, it has been widely used in passenger cars with speeds above 200km/h, such as German ICE series high-speed EMU car-body, French ALSTOM double-decker TGV high-speed EMU car-body, Italy Pendolino(ETR) series pendulum high-speed EMU car-body, Japanese Shinkansen, and Chinese CRH high-speed EMU car-body and so on. Especially with the huge expansion of high-speed rail lines in China in the last 20 years, the development and application of aluminum alloy prospered.

A series of new manufacturing processes, such as friction stir welding and laser welding, were developed and applied. These technical progress promoted application of aluminum alloy not only in high speed trains but also urban rail vehicles, which continuously contributes to energy conservation and climate change. This chapter will introduce the application status and key technologies of aluminum alloy for manufacturing high speed train. It is expected that the technical analysis and summary will inspire and encourage material scientist and engineers to vigorously push technological innovation for comfortable travel experience in an environmental-friendly mode.

2. Characteristics of aluminum alloy

The special operating environment of trains and unique properties of aluminum alloy promotes the their combination, which favored the popularization of high speed train and in-depth application of aluminum alloy in transportation industry. For engineering application on rail transit vehicles, aluminum has the following advantages:

(1) The net weight of the vehicle can be greatly reduced. The use of aluminum alloy can greatly reduce the net weight of rail passenger car while it meets the safety requirements in the aspect of strength and rigidity. Generally speaking, car-body made of aluminum alloy is 30%~50% lighter than that of steel. For high-speed and double-deck trains, the most effective way to make vehicles light is to increase the proportion of aluminum used in vehicles as much as possible.

(2) Aluminum alloy has excellent fire resistance. Although the melting point of aluminum (660 °C) is much lower than that of steel (1530 °C), the fire-resistant of the car body is not only related to the melting point of the material, but also to the thermal conductivity of the material. Compared with steel, aluminum alloy has excellent thermal conductivity and better heat dissipation.

(3) Aluminum alloy has good corrosion resistance. The surface of aluminum alloy is easy to form a layer of dense oxide film, which has a good anti-oxidation ability in the atmosphere. Therefore, car-body made of aluminum alloy has better corrosion resistance than that of steel, especially in the components that are not easy to be coated, such as the box structure and some of its internal beams and columns, aluminum counterpart show obvious advantages. At the same time, aluminum alloy surface can be colored, painted, sprayed, through chemical methods to greatly improve the corrosion resistance of the components, together with improved decorative effect.

(4) Aluminum alloy is easy to process, manufacture and maintain. With the development and application of large hollow and complex section aluminum

profiles, aluminum welding technology is constantly improving, and vehicle manufacturing technology is becoming more and more mature. Aluminum alloy parts is easy to be replaced, and suitable for all kinds of surface treatment. The workload need for manufacturing rail car-body is also greatly reduced than the steel one.

(5) The price of aluminum alloy is moderate. The high price of aluminum material increases the manufacturing cost of vehicles, but aluminum alloy also makes vehicles light, which leads to the increase of transport capacity, reduction of energy consumption and reduction of maintenance costs. Taking the comparison of maintenance hours of vehicles leaving the factory at 10 A as an example, steel car is 100%, aluminum car is 52%.The recovery value of scrapped vehicles is 100% for steel vehicles and 480% for aluminum vehicles. From the perspective of comprehensive economic benefits, the use of aluminum vehicles is economical and reasonable. Therefore, the final cost of using aluminum alloy is moderate.

3. Typical aluminum alloys and their properties

Aluminum alloys commonly used in high-speed trains include 5000 series, 6000 series and 7000 series. 5000 series alloys show maximum strength and high corrosion resistance among the typical non-heat treatable alloy, which adapt to welded structure. 6000 series alloys show moderate strength and good corrosion resistance, together with perfect extrusion formability making complex and thin-wall hollow section possible. 7000 series alloys show excellent strength among age-hardening aluminum alloy, which provide wide space for weight reduction. Typical aluminum alloys for high speed train car-body are shown in **Table 1**.

Series	Designation	State	Mechanical properties			Application area	Note
			Tensile strength/MPa	Yield strength/MPa	Elongation/%		
5000	5083	O	≥275 ~ 350	125 ~ 200	≥16	Front skin	Plate
6000	6005A	T6	≥270	≥225	≥8	Underframe, sidewall, roof, end wall, beam	Plate, 3 ~ 5 mm
	6005A	T6	≥255	≥215	≥6	Underframe, sidewall, roof, end wall, beam	Section, 3 ~ 5 mm
	6082	T6	≥310	≥260	≥10	Underframe, end beam	Plate, 3 ~ 6 mm
	6106		≥250	≥200	≥8	End wall	Section
7000	7B05	T4	≥315	≥195	≥11	Underframe, end beam	P, 2.9 ~ 6.5
	7B05	T5	≥325	≥245	≥10	Underframe, end beam, traction beam	Section

Table 1.
Typical aluminum alloys for high speed train car-body [3, 4].

4. Detailed application

In railway vehicles, aluminum alloy is primarily used in manufacturing car-body and its ancillary structure. The car-body is a prolonged hexahedral structure. Aluminum is used to manufacture all parts of the structure, including roof, underframe, end wall and side wall. However, different aluminum designations are selected for different parts of the car-body based on their properties shown in section 3. Both extruded section and plate are used. Extruded profiles account for about 70% of the total weight of the aluminum alloy car-body, while the plates account for about 27%, and the castings and forgings account for about 3%. On the other hand, there is an emerging trend that aluminum alloy come into application to other structures such as gear-box and axle box than car-body. The detailed introduction is as follows.

4.1 Car-body

The development of aluminum alloy materials and large extruded profiles paves the way for the modernization and lightening of railway vehicles, In recent years, with the popularity of lightweight design concept for railway vehicles, as well as the requirement of simplified construction and maintenance, large integral thin plate and hollow complex thin wall profiles has been developed successfully. In Japan, 6N01(6005 alloy) alloy with better extrusion, welding and corrosion properties has been developed to produce porous complex thin-wall hollow profiles, widely replacing 7N01 and 7003 profiles as the floor, side plate and roof structure of the car-body. In Western Europe, aluminum alloy body is mainly made of 6005A extruded profiles, the main reason of which is that the extrusion performance of 6005A is better, the production process is more simplified, and the stress corrosion problem of 7000 series alloy can be avoided. The application of typical aluminum alloys on 300 series Shinkansen high speed train is shown in **Figure 1**. A complete car-body is shown in **Figure 2**. As is shown, the car-body is mainly composed of extruded section.

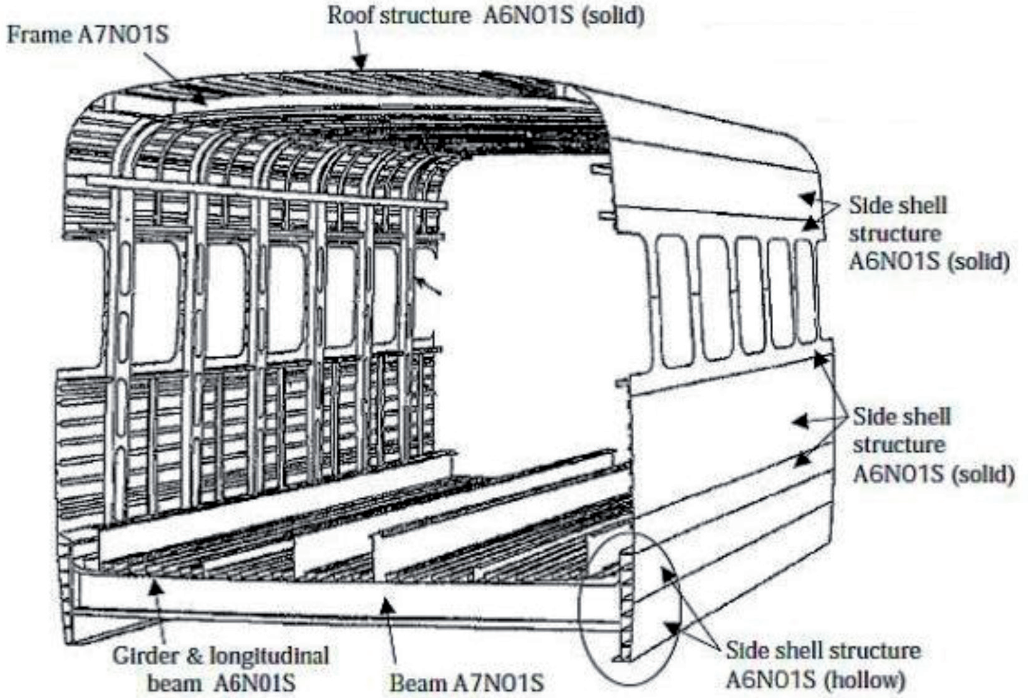

Figure 1.
Application of aluminum alloys on car-body of Shinkansen 300 series high speed train.

Figure 2.
Typical car-body of high speed train made of aluminum alloy.

Figure 3.
Typical sidewall of high speed train composed of extruded sections.

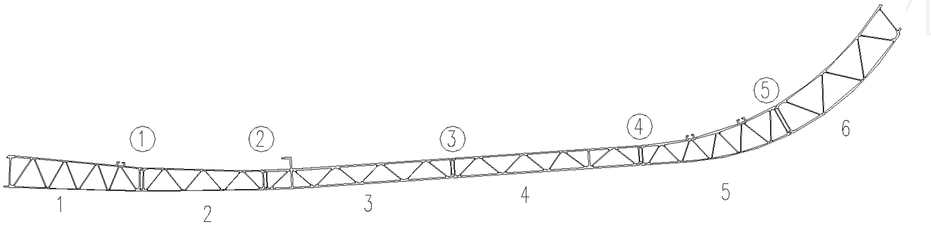

Figure 4.
Part of a section structure of high speed train car-body.

The car-body can be easily welded automatically with through - length welds, as shown in **Figure 3**. The aluminum section profiles can be designed according to the section structure of the car-body, as shown in **Figure 4**. Typical extruded section profiles for high speed train are shown in **Figure 5**.

However, when it comes to the head car, the structure is quite different. In order to achieve optimal aerodynamic performance running at high speed, a streamlined

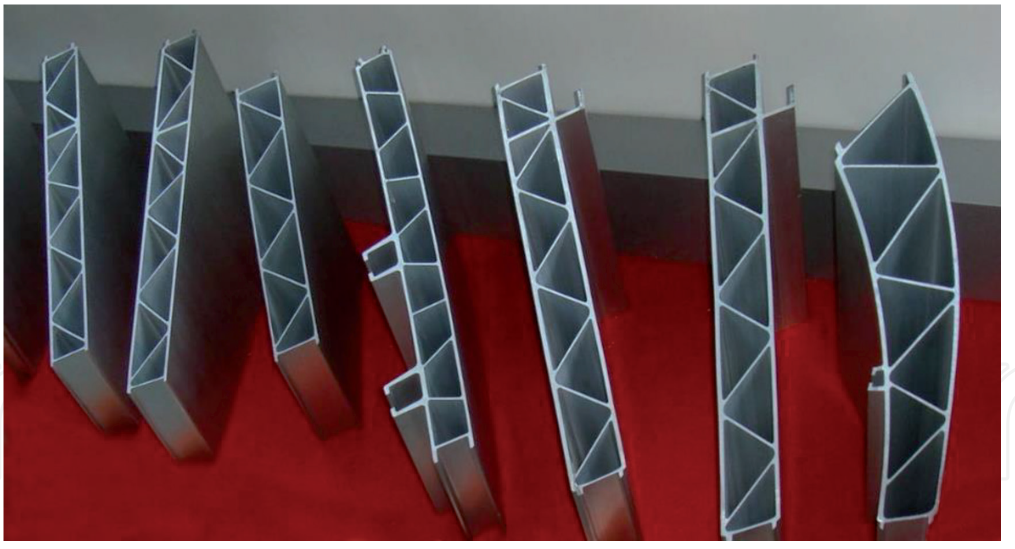

Figure 5.
Typical extruded section profiles for high speed train.

Figure 6.
Streamlined head car of CRH 380A high speed train.

design was given to the head car, as shown in **Figure 6**. This unique shape make the it impossible to manufacture with relatively regular and straight sections. Therefore, beam and slab structure became the optimum option for head car. As shown in **Figure 7**, a framework is designed based on the requirement for stiffness and strength to support the front skin against plastic deformation. It is welded with hundreds of beam made of aluminum plates prior to skin fixation. Afterwards, the skin is divided into small pieces based on the principle of good workability. Each piece is deformed to specific shape based on the design profile. Then the piece is fixed on the framework one after another, shown in **Figure 8**.

4.2 Gear box

For further reduction of the weight of the train, it is obviously not enough by reducing the weight of the car-body because the car-body accounts for only about 20% of the total mass of the train. Key components of bogie including traction motor, wheel-sets, frame and braking system attracted attention of proponents of lightweighting.

Figure 7.
Internal structure of the head car of high speed train.

Figure 8.
Head car of high speed train.

The lightweighting of gear box can help to reduce unsprung mass and wear or damage to rail. In this part, the application of aluminum alloy on gear box is introduced.

Gear box of high speed train is manufactured by casting aluminum rather than wrought alloy due to complex and unequal thickness. Low pressure casting is widely used in non-ferrous alloy casting because of its high feeding pressure and temperature gradient and stable filling, which can effectively improve the density of castings and product yield.

AlSi7MgA and AlCu4Ti are commonly used as casting materials for gear box due to good flowability, low thermal expansivity and shrinking percentage. Typical aluminum gear boxes on CRH series high speed train are shown in **Figure 9**.

4.3 Axle box

Axle box is one of the important bearing parts of trian bogie and transfer joint of motion. The left axle box part is installed on the axle journal through a rolling bearing, and the right swivel arm is connected with the positioning swivel seat on the

Figure 9.
Typical aluminum gear boxes on CRH series high speed train.

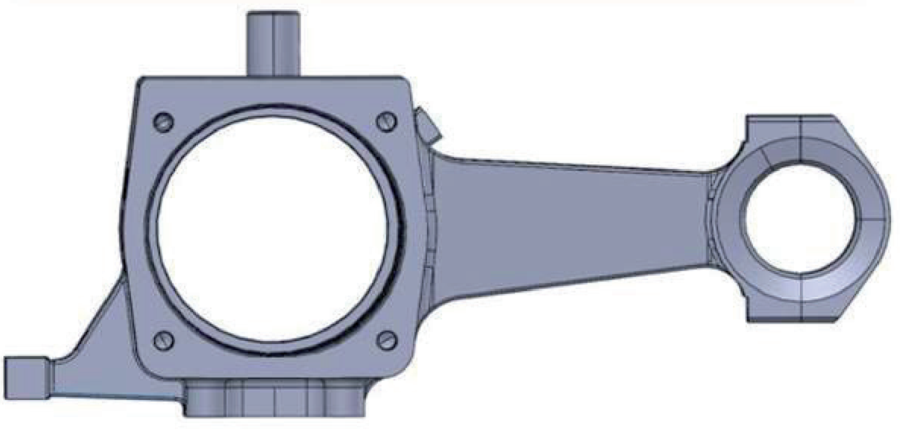

Figure 10.
3D model of an aluminum alloy axle box.

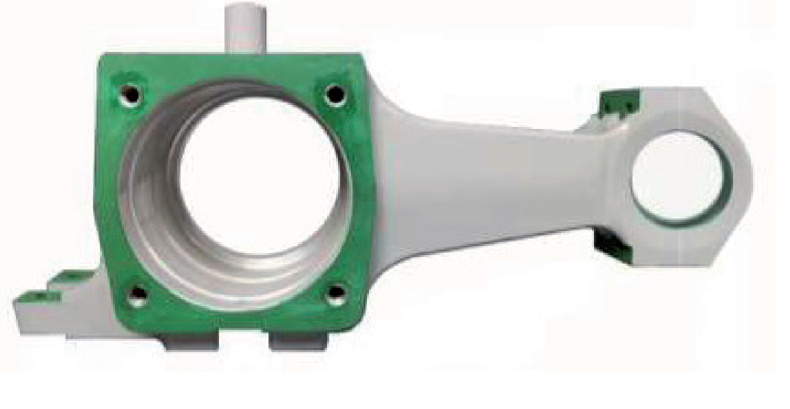

Figure 11.
Finished aluminum alloy axle box of high-speed train.

frame through an elastic node. When the train is running, axle box bears the action of vertical force, longitudinal force and transverse force.Therefore, the bearing condition of the axle box body is complex, and its structure and performance stability are very important for the safe operation of the train. 7050 aluminum alloy forgings shows high strength and toughness, which can significantly reduce unsprung weight. The weight of forged aluminum product decrease 62.5% as compared to the traditional carbon steel one. Therefore, forging aluminum alloy axle box is widely used on high-speed train. 3D model of an aluminum alloy axle box is shown in **Figure 10**. A typical finished aluminum alloy axle box of highspeed train is shown in **Figure 11**.

5. Key manufacturing techniques

The engineering application of aluminum alloy in the field of rail transportation encounter a series of challenges, which promote the development of a series of key manufacturing techniques including casting, forming welding and anti-corrosion processes.

5.1 Casting

Casting is an important process for the manufacture of complex structures such as gear box. The main challenges of gearbox casting process are as follows:

(1) Ensure there is no cold partition, porosity and other defects in the thin-walled area, so as to meet the requirements of casting appearance quality.

(2) Ensure there is no excessive shrinkage porosity, shrinkage cavity and other defects on the box surface, flange, hanging and other key parts, so as to meet the internal quality requirements of castings radiographic inspection.

(3) Ensure a high requirements for machining surface pinhole and non-machining surface, especially for aluminum alloy castings that are easy to produce pinhole defects.

In the production of aluminum alloy gearbox for high-speed EMU, the common casting defects include porosity, pinhole and shrinkage cavity.

In order to eliminate those pores, two measures need to be taken on the premise of controlling the air production content of molding sand. Firstly, the venting near the inner runner and riser should be improved by opening more air hole and hollowing out the loam core of the outer molding. Secondly, thickness of the coating should be guaranteed to decrease surface void on the sand (core) by using coating with high thermal conductivity such as zircon powder. The filling pressure and holding pressure are increased appropriately, so as to increase the resistance of gas entering the metal liquid.

The key of eliminating pinhole mainly relies on the control of hydrogen content in liquid aluminum. The refining process can reduce the oxidation inclusion and hydrogen content in liquid aluminum, and thus effectively reduce pinhole forming tendency.

Regarding to shrinkage cavity at the top of gear box, it is proved effective by simulating the solidification process with MAGMAsoft. Chilling block and riser locating can be optimized to ensure the feeding channel of the top riser unblocked under reasonable temperature distribution.

5.2 Forming process

There are four different technologies available to manufacture the front skin panels of the head car. The most commonly used one is the hammer press where a hammer machine is used conveniently to produce the target shapes. However, the dimensional tolerance of the produced product heavily depends on the worker's experience. After installing the panels on the structural frame, any further modifications of the geometrical features can only be completed by using the hand tools such as hammer. Such a manual process renders the high repeatability of manufactured components almost impossible. The second technique is the expanding-stretching process. It is applicable for the panels with curved profile but only to a certain extent. Additionally, the rotating press machine, which mainly aims for manufacturing a panel with small and uniform curvature, is used, while a process called mould press that uses mould to produce the target shape is employed for the panel with complicated and small curvature.

As shown in **Figure 12**, the front skin of a typical CRH 380A high speed train is divided into around 70 small pieces which are joined together through a total of 170 meters long welding line. As the length of each panel is limited to only 1 meter, the manufacturing process becomes time consuming and low efficient for producing a considerable amount of small components. The product quality of the front panel is also compromised due to the increased residual stress resulted from the uneconomical and complicated assembling process.

In order to ensure the assembly precision of each piece, a commercial finite element analysis simulating the skin drawing and springback process based on flexible multi-point die is necessary. In order to improve the computational efficiency and obtain satisfactory

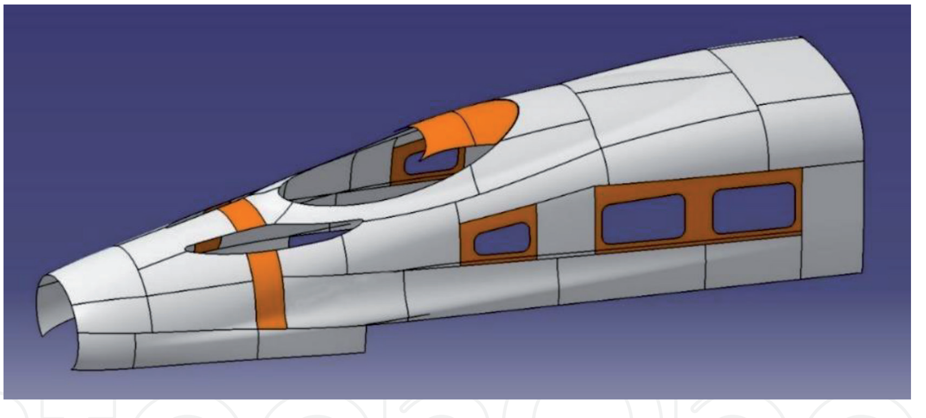

Figure 12.
Front panel of CRH 380A high speed train.

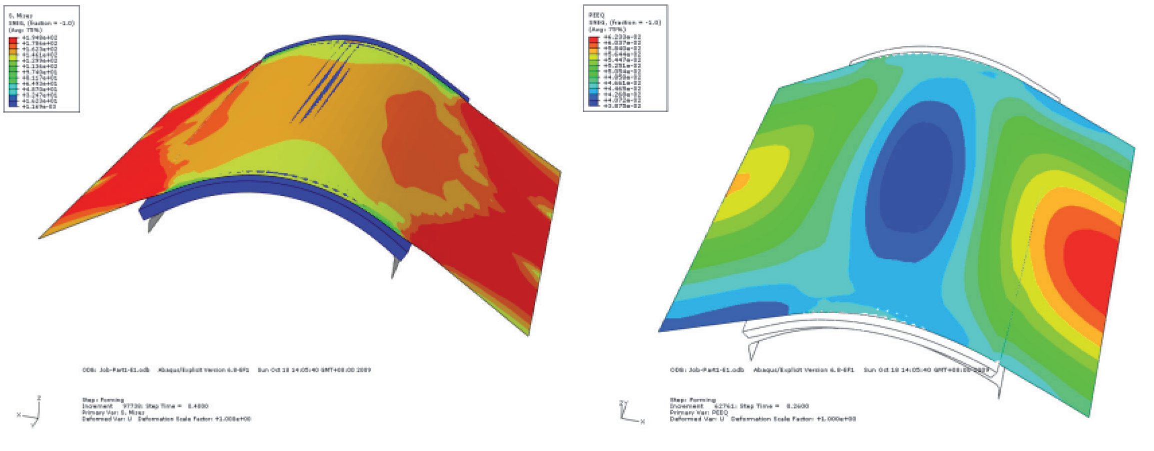

Figure 13.
Distribution of MISES stress and equivalent plastic strain for forming of a single piece.

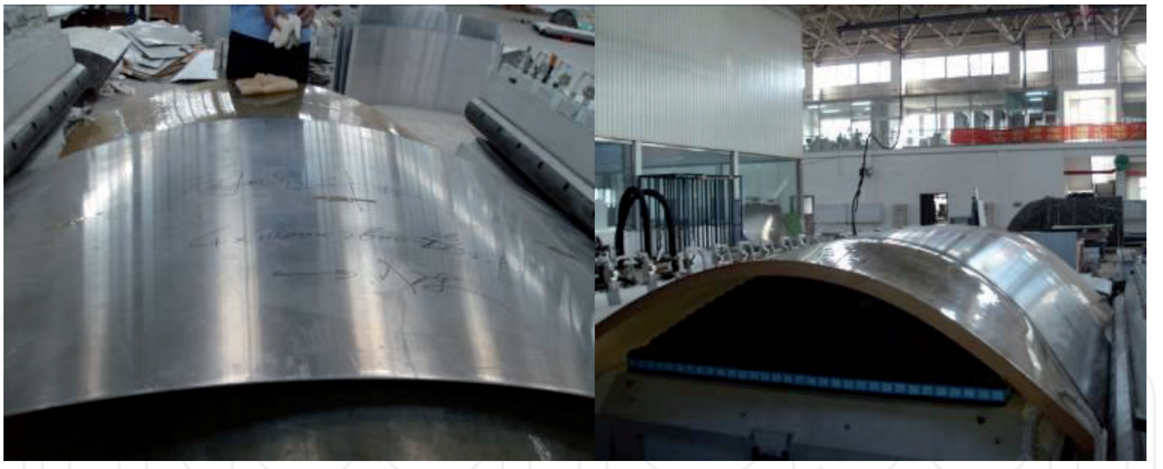

Figure 14.
Skin drawing based on flexible multi-point die.

computational accuracy, the dynamic explicit algorithm is used to simulate the drawing process, and the static implicit algorithm is used to calculate the springback. **Figure 13** shows the Distribution of MISES stress and equivalent plastic strain for forming of a single piece. The forming process is developed based on the simulation results which can save experimental time and improve adaptability to different products, shown in **Figure 14**.

5.3 Welding

Due to special thermal physical properties and welding characteristics of aluminum alloy, such as low melting point, thermal conductivity, high electrical conductivity and the expansion and shrinkage, high content of alloy elements as compared to carbon steel and stainless steel [5, 6], it is much more easily to produce pores, crack, lack of penetration, incomplete fusion, large welding deformation, bite edge and slag when aluminum alloys are welded. The assembly precision, quality and performance can be severely affected by welding process. Therefore, the welding process is quite crucial in the manufacture of high speed train.

The following aspects should be considered as the basis of selecting welding method:

(1) Aluminum alloy is coated with a dense oxide film which can easily adsorb moisture and bring hydrogen to molten pool. The aluminum can also become oxidate slag existing in the weld which affecting the performance. Therefore, it is very important to remove the oxide on the base metal and groove surface of aluminum alloy before welding.

(2) The thermal conductivity of aluminum alloy is five times that of low carbon steel. High power or energy concentrated welding heat source should be a preferential option. And preheating is necessary for thick plate welding.

(3) The thermal expansion coefficient and cooling shrinkage rate of aluminum alloy are two times that of steel. Therefore, aluminum alloy melting welding deformation is serious. Deformation control measures such as reverse deformation and reinforcement constraint should be considered.

(4) Aluminum alloy material has different kinds of alloying elements, and the loss of alloying elements during fusion welding is easy to lead to the decrease of joint strength and corrosion resistance, and the weld metal and heat affected zone are easy to produce intergranular cracks. Cracking susceptibility should be considered.

In this section, three typical welding processes which are widely used in manufacturing process of high speed train are introduced.

5.3.1 Arc welding MIG

Pulse MIG welding is the most widely used and developed method of aluminum alloy welding which is characterized by large thermal power, high linear energy, good energy concentration and good protection effect. The above features are suitable for welding aluminum alloy based on its unique thermal physical properties. Pulsed MIG welding can be used to control wire melting and droplet transition, improve arc stability and achieve droplet jet transition with small average current, thus suitable for all-position welding.

Considering the cathodic atomization effect of MIG welding on removing aluminum oxide film, DCEP (Direct Current Electrode Positive) is commonly used for pulse MIG welding. Semi-automatic pulse MIG welding are fit for irregular short welds while regular long straight welds are usually automatically MIG welded with laser tracking, shown in **Figure 15**.

Typical defect includes poor formability, burning through, excessive penetration, cracking, pore and slag, as shown in **Figure 16**.

5.3.2 FSW welding

In addition to the traditional MIG welding, friction stir welding(FSW) has been widely used. This process and MIG welding process are not compatible on the design groove. Groove designed according to MIG welding process cannot be used for friction stir welding, so the promotion of this technology is subject to certain restrictions. However, FSW shows unique advantages as follows:

(1) Low manufacture cost. No consumable welding materials, such as electrode, wire, flux and protective gas, are required during the welding process. Welding stirring head is the only consumption. It is not necessary to remove the oxide film before welding, which reduce cleaning time and improve production efficiency.

(2) Good welding quality. The temperature of friction stir welding is relatively low, so the microstructure change of the heat affected zone is negligible, and the residual stress is low leading to a low deformation. The joint efficiency is high as compared to MIG weld.

(3) Environment-friendly. The welding process is safe. There is no pollution, no smoke, no radiation, etc.

(4) Less energy consumption. Because friction stir welding solely depends on the welding head rotation and movement, it saves more energy than fusion welding or even conventional friction welding.

(5) High welding efficiency. It can complete the welding of long weld, large section and different position at one time.

The above advantages promote its application in rail transportation field, shown in **Figure 17**. It can be seen that FSW showed flat weld than MIG which requires little post-processing (**Figure 18**).

Figure 15.
Automatically MIG welding process.

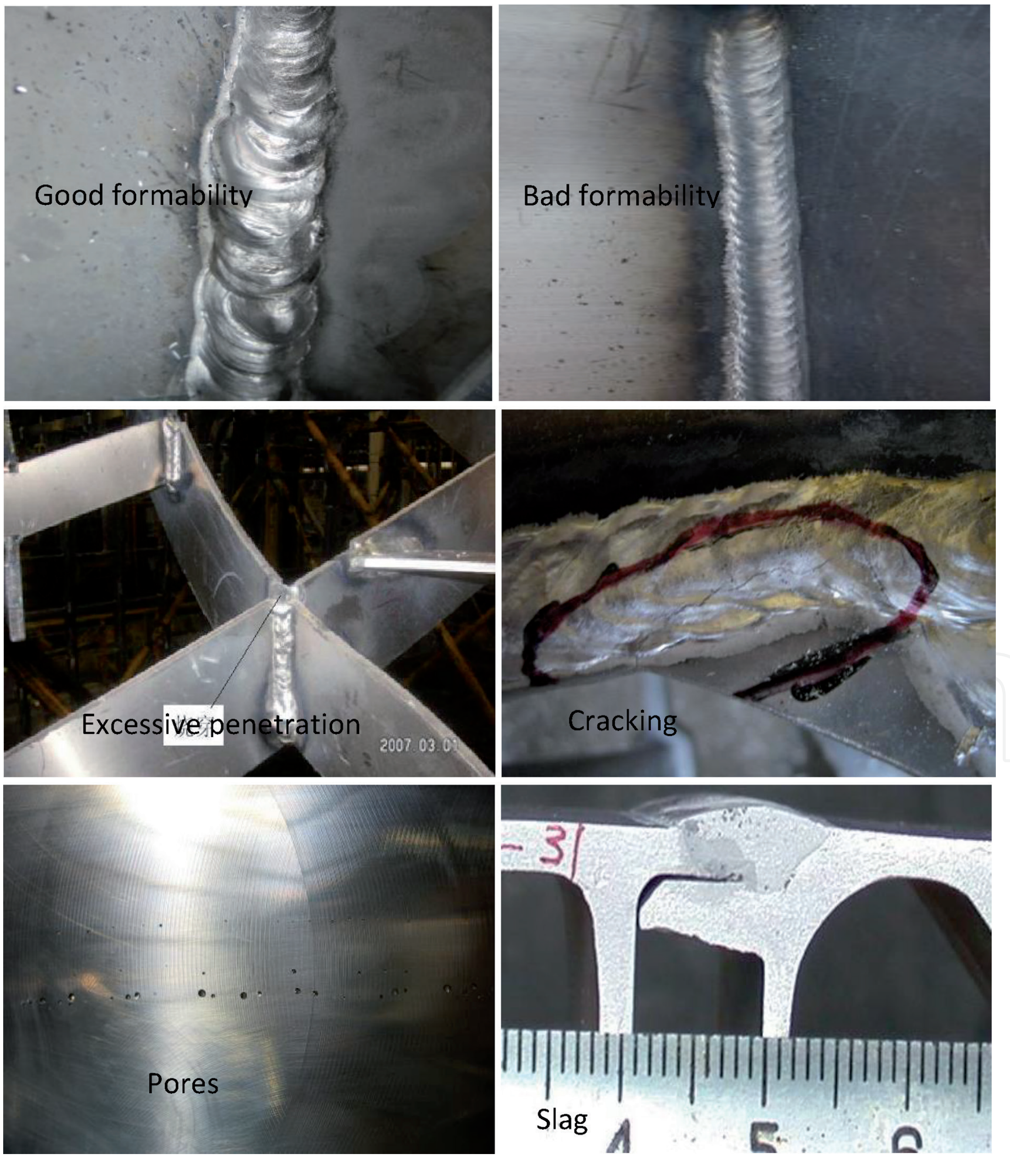

Figure 16.
Typical defect in aluminum alloy weld.

Figure 17.
FSW process of a sleeper beam.

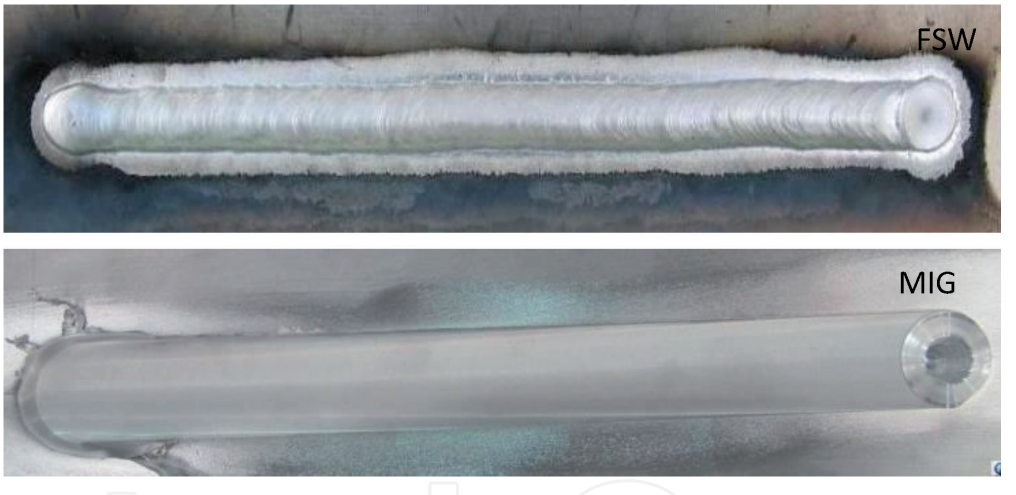

Figure 18.
A comparison between MIG and FSW welds.

The defects in friction stir welding joints mainly include holes, unwelded joints, flaps and grooves. Defects are mainly caused by the fact that in the welding process, different parts of the weld metal have undergone different thermomechanical processes, and thus bring overheating or insufficient flow of plastic materials. The top of the weld is subjected to the strong friction and stirring effect of the stirring needle and the shaft shoulder at the same time, even if the welding speed is very high or the stirring head speed is not high enough, it can still ensure a certain heat input and form a defect free connection; In the middle of the weld, the heat input is less than the top, but the heat output is also less than the top and bottom, so the total heat absorption is greater than the top and bottom, and the material softening degree is the highest. The heat input at the bottom of the welding seam is the least and the output is the largest. so the welding defects will appear at the bottom of the welding seam when the process parameters are not properly selected or the size of the welding tool is not appropriate.

5.3.3 Laser-MIG welding

Laser-MIG welding is a new welding technology, which has a wide development prospect. The laser -MIG hybrid welding technology combines the laser welding technology and MIG welding technology organically, which overcomes each other's shortcomings, and thus favor to obtain high quality welding joint.

Laser -MIG welding uses both laser beam and arc, which has the characteristics of high welding speed, stable welding process, high thermal efficiency and allowing greater welding assembly clearance. The laser -MIG welding pool is smaller than that of MIG welding. As compared to MIG welding, laser-MIG welding shows lower heat input, smaller heat affected zone and smaller work deformation.

Based on the characteristics of concentrated heat source, strong penetration and arc wire filling welding, a new design of joint and groove of laser-MIG hybrid welding was carried out through experimental optimization and verification. Compared with the traditional MIG welding, the upper groove angle is smaller, the depth is smaller for laser-MIG hybrid welding.

The wide application range and high efficiency of laser-MIG welding enhance its competitiveness in terms of investment cost, reduced production time, reduced production cost and improved productivity. Currently It is in the stage of small-scale application in the manufacture of high speed train and relevant component, shown in **Figure 19**.

Figure 20 shows a comparison between MIG and laser-MIG hybrid welds. The laser-MIG hybrid welds is flat which reflect a good formability.

Figure 19.
Lase-MIG weld machine for roof of aluminum car-body of high speed train.

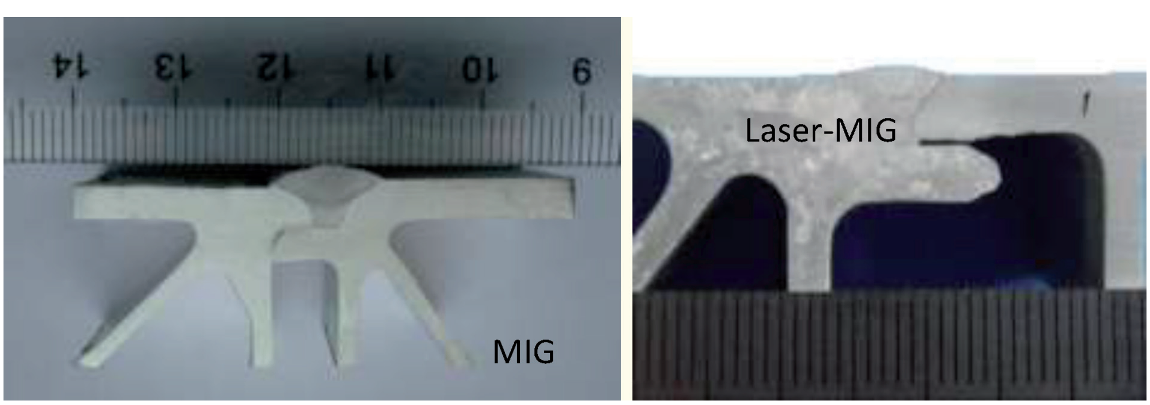

Figure 20.
A comparison between MIG and laser-MIG hybrid welds.

5.4 Anti-corrosion process

The increasing operation speed of train make it experience the baptism of different environments within hours. The environmental change is quite complex when the train goes from inland to coastal cities, from high to low latitudes, from low to high altitude. The weather may change dramatically from sunny to rainy. The temperature may change from subzero to 40°C, The humidity may change from very dry to very damp (~100%). The air may change from fresh and clean to polluted. It may contain dust, oxysulfide, oxynitride, or chloridion. These ingredients would lead to corrosion to aluminum alloy which is detrimental to the safety and long-term reliability of the train, especially when it's running at speed higher than 200 km/h.

As is known, aluminum shows good corrosion performance since it can form passive film in atmosphere. However, the corrosion resistance is also threatened by alloying elements and aggressive environmental factors. Pitting, galvanic and stress corrosion are common types of corrosion for engineering structure made of aluminum used in atmospheric environment.

For rail vehicle, an organic coating system is used to protect aluminum against corrosion. In order to deal with different environments, the coating system for outer surface is different from internal surface. The outer coating system is used to fight against harsh natural environment while the internal coating tackle the condensing water and leaking water from washing room. Therefore, it has higher requirement for the outer coating system. It needs to be evaluated by a series of accelerated corrosion test including salt spray test, damp heat test and high-low temperature test. The outer coating system consists of sand blasting pretreatment, epoxy primer, polyurethane putty, polyurethane interlayer, polyurethane finishing coat and varnish. The internal coating system consists of cleaning, etch coating, rust inhibiting primer and polyurethane top-coat. In case aluminum component joints with other alloys, a surface pre-treatment accompanied by rust inhibiting primer is necessary to ensure physical isolation from each other and against galvanic corrosion (**Figure 21**).

Figure 21.
Coated outer surface and internal surface of aluminum car-body.

6. Conclusion

In this chapter, the latest applications of aluminum alloys in rail transportation field is introduced. The typical high-strength aluminum alloys used on high speed train was illustrated combined with the unique characteristics of aluminum alloys. The detailed application on key part of rail vehicle including car-body, gear box and axle box tie rod, were introduced. The main challenges and engineering experience were also mentioned. The key manufacturing techniques, such as casting, forming, welding, and anti-corrosion were analyzed. Hopefully, the chapter can promote the development and application of advanced materials, especially aluminum alloy, and continuously contribute to sustainable development of human civilization through technological innovation.

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Conflict of interest

There is no conflict of interest regarding to the content of this chapter.

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References

[1] Kawajiri, K.; Kobayashi, M.; Sakamoto, K., Lightweight materials equal lightweight greenhouse gas emissions?: A historical analysis of greenhouse gases of vehicle material substitution. Journal of Cleaner Production. 2020;253:119805. DOI: 10.1016/j.jclepro.2019.119805

[2] Ashkenazi, D., How aluminum changed the world: A metallurgical revolution through technological and cultural perspectives. Technological Forecasting and Social Change, 2019; 143: 101-113. DOI: https://doi.org/10.1016/j.techfore.2019.03.011

[3] GB/T 32182-2015 Aluminium and aluminium alloy plates and sheets for railway application.

[4] GB/T 26494-2011 Aluminium alloys extruded profiles used for structural material of railway vehicle carbodies.

[5] Mallick, P. K., Designing lightweight vehicle body. In Materials, Design and Manufacturing for Lightweight Vehicles, 2021; pp 405-432

[6] Mallick, P. K., Joining for lightweight vehicles. In Materials, Design and Manufacturing for Lightweight Vehicles, 2021; pp 321-371