АКАДЕМИЈА НАУКА И УМЈЕТНОСТИ РЕПУБЛИКЕ СРПСКЕ

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Књига LVII

ОДЈЕЉЕЊЕ ПРИРОДНО-МАТЕМАТИЧКИХ
И ТЕХНИЧКИХ НАУКА
Књига 46

САВРЕМЕНИ МАТЕРИЈАЛИ

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REVIEW WORK

REVIEW OF ALUMINIUM ALLOYS AND QUALITY CONTROL STANDARDS IN THE RAILWAY INDUSTRY

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Abstract: In this paper, brief review of aluminum alloys and their properties is presented. Aluminum alloys are among the most commonly used materials in railway and other industries in general. Aluminum alloys are suitable for production of lightweight and good carrying capacity constructions. These alloys are corrosion resistant which makes them suitable for application in various environments. Classification of aluminum alloys is presented, with main groups of cast and wrought alloys, whereas aluminium alloys of 5xxx and 6xxx series are the most important in the railway industry. Properties of 5xxx and 6xxx aluminium alloys are reviewed, especially focusing on the most commonly used aluminum alloys in railway industry: 5052, 5083, 5754, 6005A, 6061, 6063, 6082, and 6106 alloys. Comparison between their tensile and yield strength is given. Aluminum alloy 6082 is currently considered to be the material of choice for testing in friction stir welding of railway vehicle elements. Possibility of fusion and friction stir welding (FSW) is discussed. Some of the relevant quality control standards are listed.

Key words: *aluminum alloys, 5xxx series, 6xxx series, friction stir welding - FSW, quality control standards*

1. INTRODUCTION

Aluminum is the third most common element in the Earth's crust. Even so, it took until 19th century for aluminum to be extracted from bauxite ore, because of its highly reactive nature. According to some historical records, aluminum is thought to have been used in the Roman Empire, albeit to a limited extent, however no serious commercial use of aluminum happened before the late 19th century. The first aluminum processing factory, Alcoa, was opened in the US and it still successfuly operates today.

Even though it's a relatively new metal, aluminum quickly became the second most commonly produced metal material after steel, as well as the most commonly produced non-ferrous metal. This is due to its favorable properties such as low density, high thermal conductivity and electrical conductivity, stability, elastic properties, toughness, corrosion resistance and excellent recyclability [1]. Aluminum alloys are suitable for casting and sheet forming. They can be joined by arc welding (MIG, TIG) and friction stir welding (FSW). Friction stir welding is particularly common for welding aluminum alloys in the railway industry [2]. Aluminum has found a significant application in the railway industry, because it reduces the weight of vehicles, and thus increases transport capacity and speed. Some of the famous rail vehicles such as Shinkansen and Maglev (Japan), ICE (Germany), TGV (France) and CHR3 (China) incorporate aluminum-based alloys in their construction [1].

Histories of aluminum industry and railway industry go hand in hand. Aluminum constructions were included in railroad vehicle production as early as in 1894, in the form of lightweight seat frames and the first fully aluminum railroad carriage was exhibited in 1933, at the World's Fair in Chicago. Research in this area continued and application of aluminum increased in passenger and cargo trains. Aluminum vehicles are used for the transportation of various metal ores, minerals, coal, etc. Aluminum vehicles are very economical due to their favorable strength to weight ratio that leads to the fuel savings. Good corrosion resistance, aerodynamics and lower wind resistance also lower the cost by eliminating the necessity for coatings. Aluminum alloys are used for the production of automobile carriers, that are tasked with protecting the newly made vehicle during transportation and, due to aluminum's great carrying capacity, they can transport large vehicles such as vans and SUVs. As for passenger vehicles, decrease in weight is very important because it contributes to energy savings during frequent stopping and enables reasonably good acceleration afterwards [2; 3].

2. CLASSIFICATION OF AL-BASED ALLOYS

Aluminum alloys are grouped into cast alloys and wrought alloys, which are both further classified into grades or series. These grades differ from one another by their chemical composition – most importantly dominant alloying elements.

Table 1 lists cast alloys and their dominant alloying element. Table 2 shows that list for the wrought alloys.

Table 1 *Cast alloy grades and their dominant alloying elements [1]*

GRADE LABEL	DOMINANT ALLOYING ELEMENTS
1XX.X	Al (≥99 wt.%); No alloying elements
2XX.X	Cu (3.5 – 11%)
3XX.X	Si (4 – 23%), Mg (0.2 – 1.1%), Cu (0.5 – 8%)
4XX.X	Si (4.5 – 13%)
5XX.X	Mg (2.5 – 12%)
6XX.X	Mg + Si
7XX.X	Zn (5 – 8%), Mg (1.5 – 2.5%), Cu (0.4 – 1.5%)
8XX.X	Sn

Table 2 *Wrought alloy grades and their dominant alloying elements [1]*

GRADE LABEL	DOMINANT ALLOYING ELEMENTS
1XXX	Al-Fe; pure Al (99.0 – 99.75%)
2XXX	Cu
3XXX	Mn
4XXX	Si
5XXX	Mg; Mg + Cu (Zr, Sc)
6XXX	Mg + Si
7XXX	Zn
8XXX	Li, Fe, Ni, etc.

Aluminum wrought alloys are also classified into non-heat treatable (1xxx, 3xxx, 4xxx, 5xxx Mg) and heat-treatable (2xxx, 5xxx Mg + Cu (Zr, Sc), 6xxx, 7xxx) [1].

In this paper we will mostly focus on grades 6xxx and 5xxx, as they are currently the most important for the railway industry.

2.1 Aluminium alloys of 5xxx series

This series of aluminum cannot be age hardened but can be strain hardened, through hot forming and cold forming with annealing. Thermal annealing is necessary for improving ductility in materials subjugated to strain hardening, which improves mechanical properties and hardness but makes them less deformable. This is especially true for the 5xxx grade of aluminum because of its high magnesium content and presence of the intermetallic compound β-Al_3Mg_2. Soft annealing also stabilizes its microstructure and increases its intergranular corrosion resistance. Heat treatment can be carried out even during working of the material and H3X temper is common for this aluminum grade. This grade is also susceptible to filiform corrosion during hot rolling due to the effect of the disturbed surface layer. Another way to improve ductility and increase resistance to cracking is the addition of scandium to alloying elements [4]. Scandium provides significant strengthening per atom added, possibly more than any other aluminum alloying element [2; 5]. Li et al. investigated the effects of trace elements, such as Er, Zr, Cu, Si and Zn on the properties of the 5xxx aluminum alloy series. Addition of these elements causes the formation of new intermetallic compounds or second phases, which improve tensile and yield strength of these alloys and results in the refinement of the fiber-like elongated crystal structure after cold rolling. The authors also state that erbium can be an effective and less expensive substitute for scandium [5]. The aforementioned β-Al_3Mg_2 compound is prone to precipitation at grain boundaries, especially when the magnesium content is greater than 3.5 wt.%, which can then cause intergranular corrosion. This is where addition of zinc can be beneficial [4].

Material characteristics, such as corrosion resistance, can be changed by the processing, such as friction stir welding (FSW). Nugget area of the FSW is very different than a weld area of TIG or MIG welding. The temperature reached during FSW is lower and the material is not heated for long enough to be sensitized. The temperature, however, is high enough to dissolve the intermetallic compound β-Al_3Mg_2, which results in FSW welds showing better corrosion resistance than TIG and MIG [4].

Compared to the other non-heat treatable aluminum alloys (1xxx and 3xxx), 5xxx grade is the strongest and offer more strength per unit cost [6].

2.1.1 Aluminum alloy 5052

AA5052 is a weldable, formable, fatigue resistant and corrosion resistant magnesium-containing (2.5 wt.%) aluminum alloy, whose use began in 1930s. It found various applications because it offers a compromise between ductility and good mechanical strength [4].

Abbasi et al. examined friction stir processing (FSP) on AA5052 TIG welded joints. In their work used a modified version of FSP called friction stir vibration processing or FSVP was used in order to improve the weld quality via grain refinement. FSP induces an intense plastic deformation locally, thus changing the microstructure. This is done by the rotating tool motion which heats the material and moves it laterally. In FSVP the material is also vibrated in a direction orthogonal to the direction of processing. Authors found that this type of processing results in grain transformation – from large columnar grains (characteristic for TIG welding) to small non-elongated grains. They also compared friction stir processed samples and friction stir vibration processed samples and found that FSVP is better at improving ductility [7].

Mogami et al. experimented with high-frequency linear friction welding of dissimilar joint (AA5052 and AA6063) and found that this method produced good quality welds with joint coefficient > 80%. They state that this type of friction welding shows a lot of promise for joining alloys that exhibit precipitation hardening [8].

2.1.2 Aluminum alloy 5083

Aluminum alloy 5083 contains 3.5 to 5 wt.% of magnesium and is known for its formability, machinability and excellent corrosion resistance [4]. Due to its Mg content, it is possible for this alloy to exhibit intergranular corrosion, although that shouldn't happen with proper fabrication and exploitation at room temperature. Susceptibility to sensitization increases with prolonged exposure to temperatures above 27°C, higher Mg content and higher amount of cold work it was submitted to [6]. Semi-finished rolled products made from AA5083 offer high mechanical characteristics even in very low temperatures. AA5083-H16 has a melting range of 574 - 638°C, density of 2,660 kg/m^3, tensile stress R_m of 305 MPa, elongation A of 10%, Brinell hardness of 90 HB and modulus of elasticity of 71,000 MPa [4]. With the right grain size and particulate size distribution, this alloy can exhibit superplastic ductility. Small variations in alloying elements can also greatly affect the superplastic response [9]. Aluminum alloy 5083 is used in production of Japanese Shinkansen train [2].

AA5083 is suitable for welding with AA5356, AA5556 or AA5183 as the filler material. Such welded parts usually have good corrosion resistance but cracking due to stress corrosion can occur when AA5083 is preheated prior to welding [6]. AA5083 is also suitable for friction stir welding (FSW), for the production of similar or dissimilar joints with good mechanical properties [10, 11, 12, 13]. Kalemba-Rec et al. concluded that the tool rotational speed and the workpiece placement (in dissimilar welds) affects weld formation greatly. They note that mechanical properties decrease with an increasing tool speed [12]. Paik found that FSW produced welds with superior tensile strength compered to fusion welding (MIG) [13].

Park et al. investigated the influence of small amounts of Sc on AA5083 and found that it reduces the grain size by approx. 50% and significantly improves the mechanical properties. On a nano scale, Sc induces a fine precipitation, which can lead to accumulated dislocations, the density of which increases after hot rolling, favorably affecting the tensile properties. The best results were achieved with the addition of Sc 0.15 wt.% and hot rolling and, importantly, elongation and mechanical strength were both improved at the same time [14].

2.1.3 Aluminum alloy 5754

Aluminum alloy 5754 contains 2.5 to 4 wt.% of magnesium. It's characterized by good formability, corrosion resistance and weldability. This alloy has a lot of application in mechanical industries, construction and transportation industry [4]. Other alloying elements possibly present are manganese and chromium. Manganese in Al-Mg alloys serves to refine the grain size and strengthen the solid solution [5].

AA5754 can be joined by FSW and its variant friction stir spot welding (FSSW), which can also be employed to produce dissimilar joints [15]. FSSW can be a good alternative to resistance spot welding or riveting. Pin tool profile was found to be one of the crucial parameters.

2.2 Aluminium alloys of 6xxx series

This grade of aluminum is often used for decreasing weight of high-speed vehicles. Replacing a component made of steel with an aluminum alloy component results in weight savings and decreased inertia. This series is characterized by good atmospheric corrosion resistance in many different environments, from industrial to marine. It can be joined by welding. Unlike 5xxx, 6xxx can be hardened by age hardening. Alloys of this series can be quenched immediately after hot working and either naturally or artificially aged – tempers T1 (quenched and naturally aged) and T5 (quenched and artificially aged). Intermetallic compound Mg_2Si is a hardening phase present in this series, whose precipitation occurs during aging. 6xxx alloys are used for forming, usually followed by soft annealing to restore ductility. Like 5xxx, this grade is also susceptible to filiform corrosion due to formation of disturbed layers, that can happen during grinding, polishing and machining in general. Machining can also result in sensitizing of the material surface. Sensitization to filiform corrosion is possible during paint baking, as well. Mechanical properties of this grade of aluminum are known to be good and can be further improved by alloying with silicon or copper [4, 6]. The 6xxx series with its excellent extrudability can be used for production of moveable side walls for cargo trains. These walls are hollow and internally stiffened, making them lighter than conventional steel walls.

2.2.1 Aluminum alloy 6005A

Aluminum alloy 6005A is often found in railway industry, due to its excellent fracture toughness, mechanical strength of around 290 MPa (T5 Temper) and good extrusion properties. It can be hardened by press quenching. It has good machinability, formability and corrosion resistance and is suitable for welding. It is often used for production of extruded semi-finished products [4]. German Transrapid train incorporates extrusions made from 6005 alloy, among others [2].

2.2.2 Aluminum alloy 6061

AA6061 is used for sheet metal fabrications, extrusion of semi-finished products and other mechanical applications. It was introduced in the US in 1935. It has a medium strength of 310 MPa (T6 temper) and good corrosion resistance, which can be further improved by adding protective films. ZnAl-LDHs and ZnLaAl-LDHs show potential to replace chromate passivation films, that have been banned in Europe since 2007. These protective films are necessary because, even though AA6061 is generally thought to have good corrosion resistance, this is not the case in some environments, such as solution containing Cl- ions. AA6061 is used for the production of railway carriages, transportation in general, gas storage and many other applications [16, 4]. Wang et al. did research on hybrid laser-TIG welding of this alloy and achieved tensile strength and elongation values of 286 MPa and 20.5%, respectively, after an ageing treatment [17].

2.2.3 Aluminum alloy 6063

AA6063 is an excellent extrusion alloy that can be used for the production of complex shapes [4]. It possesses a good corrosion resistance in general, as most aluminum alloys do. Pitting corrosion resistance, in particular, can be improved through the right combination of cold work (rolling) and heat treatment, which induces Mg_2Si precipitation and grain refinement [18]. Ding et al. investigated the effect yttrium and Al-Ti-B master alloy on AA6063 and found that these additions helped decrease the grain size, as well as improve the tensile strength by 5% and elongation by 75% [19].

2.2.4 Aluminum alloy 6082

AA6082 is also characterized by formability, machinability, good corrosion resistance and weldability, and overall good mechanical properties, e.g., strength 320 – 340 MPa (T6 temper). 6082 is often found in form of extruded profiles and rolled semi-finished products. This alloy is frequently utilized in the railway industry and has wide range of mechanical applications. Its use contributes to weight savings, especially significant with large vehicles, such as railway carriages. Another advantage of this alloy are its good cryogenic properties [4]. On the other hand, to improve its properties at elevated temperatures, Qian et al. found that the inclusion of Mn and other Mn-containing materials can strengthen the material [20].

Like most aluminum alloys, AA6082 is suitable for friction stir welding, although the heat generated in the process does have a negative effect on mechanical properties of heat-treatable alloys, such as this one. Water cooling can mitigate this problem. Wahid et al. report increased tensile strength after underwater friction stir welding, compared to the convention FSW. The maximum achieved tensile strength was 241 MPa, which was 10.7% higher than conventional, with optimal parameters (rotational speed of 900 r/min and welding speed of 80 mm/min) [21]. Figure 1 shows 6082-T6 aluminum plates welded by using the FSW process under different FSW parameters.

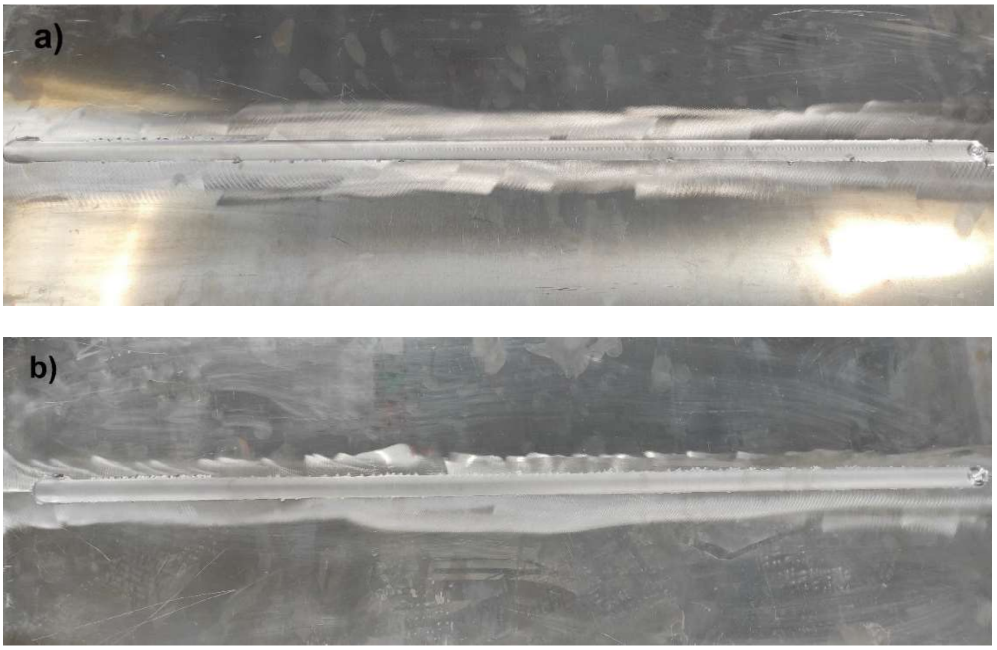

Figure 1 *Thick aluminum 6082-T6 plates, 5 mm thick plates; welded by FSW at: a) rotational speed: 1200 rpm, traverse (welding) speed 900 mm/min, axial force: 14,5 kN; b) rotational speed: 1200 rpm, traverse (welding) speed 700 mm/min, axial force: 11 kN*

During the FSW, significant stirring of the material occurs. One such example is given in Figure 2 showing material stirring exhibited at weld face of 6082-T6 alloy.

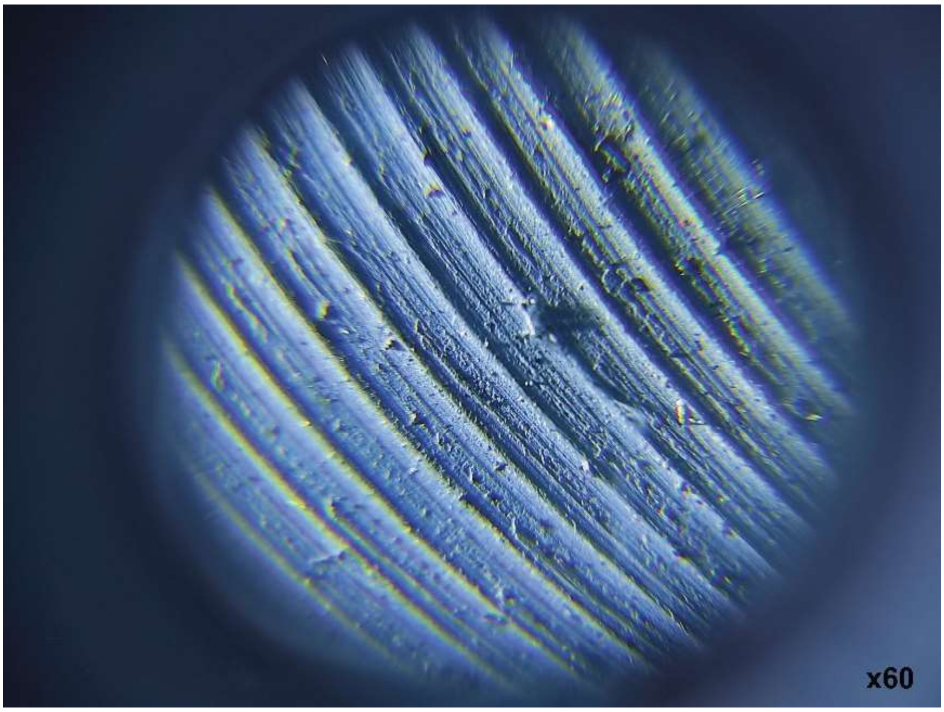

Figure 2. *Material stirring at weld face of FSW welded 6082-T6 alloy*

2.2.5 Aluminum alloy 6106

AA6106 is suitable for joining by welding and metal forming operations. It is commonly subjected to quenching and natural/artificial ageing [4]. This alloy found an application in railway industry to an extent.

3. Comparison of the 5xxx and 6xxx alloys strength

Figures 3 and 4 give a comparison between tensile strength and yield strength values in the temperature range of 0 – 30°C for the aforementioned alloys of the 5xxx and 6xxx series, according to the international standards [22–26].

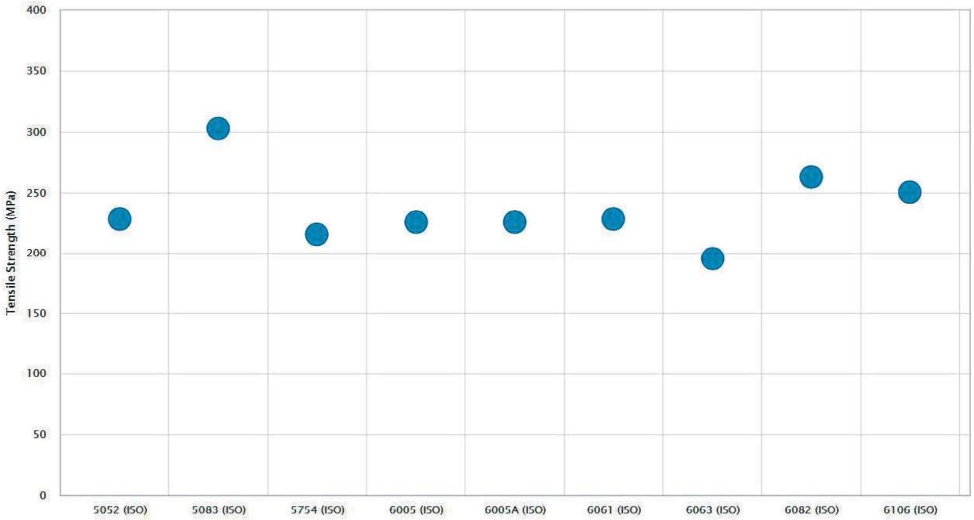

Figure 3 *Tensile strength comparison of different alloys*

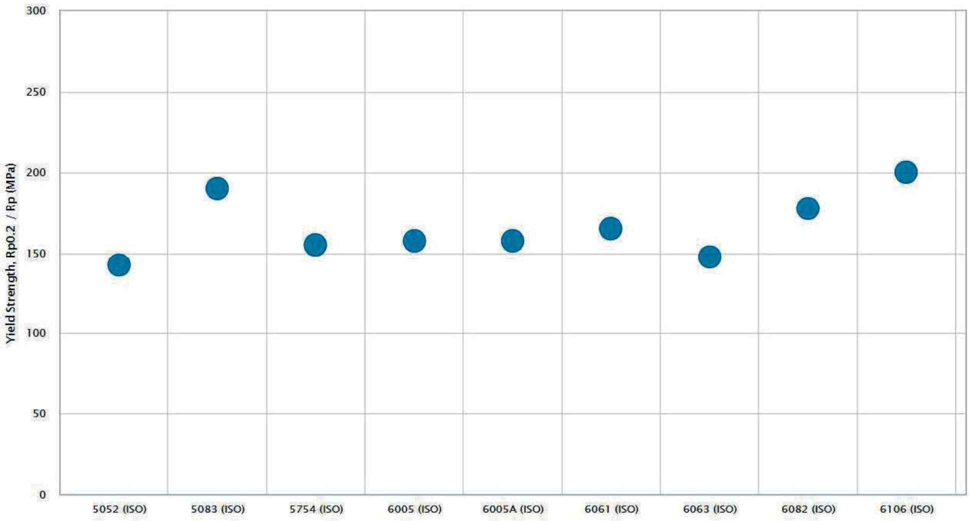

Figure 4 *Yield strength comparison of different alloys*

4. QUALITY CONTROL STANDARDS FOR AL-BASED ALLOYS IN RAILWAY INDUSTRY

Testing methods commonly performed for certifying the quality of aluminum and aluminum weld samples such as tensile testing, hardness testing etc. are described by the following standards [22–33]:

- EN ISO 6892-1 *Metallic materials – Tensile testing – Part 1: Method of test at room temperature*;
- EN ISO 6506-1 *Metallic materials – Brinell hardness test – Part 1: Test method*;
- EN ISO 6507-1 *Metallic materials – Vickers hardness test – Part 1: Test method*;
- EN 485-1 *Aluminium and aluminium alloys – Sheet, strip and plate – Part 1: Technical conditions for inspection and delivery*;
- EN ISO 25239 *Friction stir welding — Aluminium*;
- EN 573 *Aluminium and aluminium alloys – Chemical composition and form of wrought products*;
- EN ISO 18273 *Welding consumables – Wire electrodes, wires and rods for welding of aluminium and aluminium alloys – Classification*;
- ISO 6361-2 *Wrought aluminium and aluminium alloys – Sheets, strips and plates – Part 2: Mechanical properties*
- ISO 6362-2 *Wrought aluminium and aluminium alloy extruded rods/bars, tubes and profiles – Part 2: Mechanical properties*
- ISO 6363-2 *Wrought aluminium and aluminium alloys – Cold-drawn rods/bars and tubes and wires – Part 2: Mechanical properties*
- ISO/TR 2136 *Wrought aluminium and aluminium alloys – Rolled products – Mechanical properties*
- ISO/TR 2778 *Wrought aluminium and aluminium alloys – Drawn tubes – Mechanical properties*

For quality control in the railway industry, different standard and custom based procedures are used, but previously listed standards represent the main framework. They comprise basic recommendations for testing of the specific material properties, as well as validation of the processing parameters from aspects of the final component. FSW process has recently evolved as the promising techniques and it can be expected that related standards will be further complemented, especially regarding the dissimilar material welding quality.

5. CONCLUSIONS

Since its early days back in 19^{th} century, aluminum gained a lot of importance in the railway industry due to its excellent properties that gave aluminum the advantage over steel and other materials, which were more conventionally applied before. Some of these properties are, as previously mentioned, lower density, good corrosion resistance, ductility, ease of machining, possibility of joining by welding etc. One of the big breakthroughs in aluminum welding is friction stir welding (FSW) and its variations, as well as similar procedures such as friction stir processing (FSP). Developments in welding technologies and material science, together, made aluminum the material of choice for many industries today. With the increase in application of a material comes the need for developing and standardizing testing methods to prove reliability of aluminum alloy product or joint.

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[23] ISO 6362-2 *Wrought aluminium and aluminium alloy extruded rods/bars, tubes and profiles – Part 2: Mechanical properties*

[24] ISO 6363-2 *Wrought aluminium and aluminium alloys – Cold-drawn rods/bars and tubes and wires – Part 2: Mechanical properties*

[25] ISO/TR 2136 *Wrought aluminium and aluminium alloys – Rolled products – Mechanical properties*

[26] ISO/TR 2778 *Wrought aluminium and aluminium alloys – Drawn tubes – Mechanical properties*

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