Using resistance spot welding for joining aluminium elements in automotive industry

A. AMBROZIAK, M. KORZENIOWSKI
Wrocław University of Technology, Łukasiewicza 5, 50-371 Wrocław, Poland.

The aluminium alloys are more frequently used in automotive industry especially as an alternative material for car-bodies.

In this article the comprehensive summary concerning technology of resistance spot welding of aluminium alloys was presented. The welding schedules, electric parameters of welding, electrodes materials and electrodes life time by resistance spot welding aluminium were described.

Few examples directly from automotive industry were presented and advantages of aluminium as a material for some vehicle parts were also discussed.

Keywords: resistance spot welding of aluminium alloys, automotive industry

1. Introduction

Aluminium as a pure metal is known since the beginning of the 18th century. It was extracted and isolated by Christian Oersted in 1825. Although the massive production method of extraction aluminium from its ore bauxite was discovered in the second half of 18th the century, the process in its basis is has been using until today. It consists of 2 stages: the first one – extraction of Al₂O₃ (aluminium oxide) from the ore, the second one – the electrolytic reduction of Al₂O₃ in high temperature bath of Na₃AlF₆ [1].

The mechanical strength of pure aluminium is relatively weak; this is the reason that for constructional purposes is used rarely. To increase the mechanical strength of pure aluminium some alloy elements are added, mainly silicon, magnesium, copper and zinc.

Currently, aluminium alloys are common used in aircraft, military industry and automotive industry. It is possible to join aluminium most of the known welding methods by using conventional equipment.

Today, the automotive industry struggles with weight problem, which should be taken into account by the engineers [2]. The demands of customers regarding safety and luxury cause the thicker sheets and components for more responsible parts of body like frame, chairs, reinforcement must be applied. This is the reason some parts of body are replaced by light materials (like aluminium and magnesium alloys [3]), which mechanical properties are similar or even better than steel.
The newest predictions estimate that increasing use of light non-iron alloys like aluminium alloys decrease the total weight of vehicle. What is more, otherwise than in case of steel aluminium, and aluminium alloys are corrosion-resistance.

2. Properties of aluminium

Aluminium and its alloys are a silvery white which have density from 2.6 g/cm$^3$ up to 3.0 g/cm$^3$.

Although pure aluminium is light metal, the mechanical strength of some its alloys exceeds the strength of mild steel. It has high thermal and electrical conductivity, high reflectivity to both heat radiation and the light. It is non-magnetic material. The characteristic feature of aluminium is that there is no colour change during heating.

The melting temperature of pure aluminium is 660 ºC (1220 ºF). Aluminium alloys have approximately melting range from 480 ºC (900 ºF) up to 660 ºC (1200 ºF), it depends of the composition of alloying components.

Both high thermal conductivity and high electrical conductivity cause, the resistance spot welding requires welding higher current and shorter welding time (as compared to steel). What is more, the welding parameters must be controlled more precisely.

One of the disadvantages during welding aluminium is its oxide film – Al$_2$O$_3$ (known sometimes as alumina), which appears rapidly on the surface of aluminium. Its melting temperature exceeds 2000 ºC, so it should be removed chemically or mechanically before welding. The second disadvantage is high electrical conductivity. From the other hand aluminium oxide protects the surface of aluminium before the corrosion. This is the reason any coatings need to be used.

Physical properties of aluminium alloys and mild steel are presented in Table 1.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>1560</td>
<td>5–10</td>
<td>0.32–0.66</td>
<td>11.4</td>
<td>7.8</td>
</tr>
<tr>
<td>Aluminium alloys</td>
<td>480–660</td>
<td>14.3–37.7</td>
<td>1.2–2.37</td>
<td>22–23</td>
<td>1.7–3.0</td>
</tr>
</tbody>
</table>

It was mentioned the pure aluminium is not used as a material for mechanical constructions. To make it stronger alloying ingredients as copper, zinc, manganese, magnesium, silicon are applied.

The designation of aluminium alloys indicates directly the form and composition of alloys and main alloying elements. The first digit identify the main alloying elements, the last three the composition of alloy. There are two forms of aluminium alloys: wrought and casting alloys. For automotive body sheet the wrought alloys mainly
5xxx and 6xxx series are used, so it will be taken into account. Designation of wrought alloys, the main alloying elements, production forms and application are presented in Table 2 [1], [4].

Table 2. Designation, product form, and application of aluminium alloys

<table>
<thead>
<tr>
<th>Aluminium wrought alloy designation</th>
<th>Product form</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure aluminium 1XXX*</td>
<td>Foil, rolled plate, extrusions</td>
<td>Packaging and foil, roofing, cladding, low-strength corrosion resistant vessels and tanks</td>
</tr>
<tr>
<td>2XXX (Al-Cu)</td>
<td>Rolled plate and sheet, extrusions, forgings</td>
<td>Highly stressed parts, aerospace, structural items, heavy duty forgings, heavy goods vehicle wheels, cylinder heads, pistons</td>
</tr>
<tr>
<td>3XXX (Al-Mn)</td>
<td>Rolled plate and sheet extrusions, forgings</td>
<td>Packaging, roofing and cladding, chemical drums and tanks, process and food handling equipment, vehicles</td>
</tr>
<tr>
<td>4000 series (Al-Si)</td>
<td>Wire, castings</td>
<td>Filler metals, cylinder heads, engine blocks, valve bodies, architectural purposes</td>
</tr>
<tr>
<td>5000 series (Al-Mg)</td>
<td>Rolled plate and sheet, extrusions, forgings, tubing, piping</td>
<td>Cladding, vessel hulls and superstructures, structural members, vessels and tanks, vehicles, automotive body sheet</td>
</tr>
<tr>
<td>6000 series (Al-Si-Mg)</td>
<td>Rolled plate and sheet, extrusions, forgings, tubing, piping</td>
<td>High-strength structural members, vehicles, rolling stock, marine applications, architectural applications, automotive body sheet</td>
</tr>
<tr>
<td>7000 series (Al-Zn)</td>
<td>Rolled plate and sheet, extrusions, forgings</td>
<td>High-strength structural members, heavy section aircraft forgings, military bridging, heavy goods vehicle</td>
</tr>
</tbody>
</table>

* In case of pure aluminium the last two digits indicate the minimum purity of aluminium (e.g., 1060 is 99.60% Al minimum).

3. Applying aluminium alloys in automotive industry

Aluminium is the ideal material for future development of designing car bodies. The main purpose for applying aluminium is decreasing total weight of vehicle by assuming, that safety, and strength of constriction will be at least the same. What is more, applying aluminium as an alternative material involves the aspect of engine-load reduction and decreasing the consumption of gasoline and the reduction of exhaust emission.

Furthermore, the costs of exploitation of vehicle concerning breaks, tries, bearings and many others will decrease as well.

It was proved that the reduction the total mass of vehicle of 10% involves saving 6–8% of gasoline. Decreasing the total weight of each 100 pound causes savings 3.4–5.3 per 1000 miles [5].

Aluminium is fully recyclable. Its scarp can be easy recovered. Moreover, it can be recycled again and again without changing quality. Its properties will be the same as aluminium obtained from its ore. Even now, approximately 60–70% aluminium used
in vehicles (engine, body, wheels, etc.) comes from recycling. The cost of recycling of aluminium is considerably lower than steel due to lower than in case of steel the energy consumption.

There is one disadvantages connected with recycling of aluminium alloys. The different alloys must be selected and they cannot be mixed. It is especially important and crucial by production of sheets.

4. Resistance spot welding

The resistance spot welding is the most popular method of joining metal sheets. The connection arises by flowing the current and action of welding force. Heating of joining parts during resistance welding is an effect of heat generation on electrical resistance of welding circuit according to Joule–Lenz law:

\[ Q(t) = \int_0^\tau I(t) \cdot R \cdot dt \]  

where:
- \( Q \) – generated heat,
- \( I \) – welding current,
- \( R \) – electrical resistance of welding circuit,
- \( t \) – welding time.

Scheme of resistance spot welding was shown on Figure 1.

![Resistance Spot Welding Diagram](image)

Fig. 1. Schematic view of the spot welding process [6]

Connecting 2 or 3 parts of sheets is possible by the resistance spot welding. During this process one or more welding joints can be obtained. It depends of applied welding machines.

Resistance spot welding (RSW) is the most popular method of joining parts in automotive industry, which prefers this joining method because it is low-cost, rapid, simply and easy for automation. Over 90% of spot welds of all over the world are performed by automotive industry [7]. It was estimated, that each body car and its com-
ponents contains over 50 hundred spot welds. For many years the material the car-bodies consisted of was mild steel, with or without galvanized layers. Now, the engi-neers try to find alternative light-materials: aluminium and magnesium alloys.

Unconformities which can appear in spot welds cause the spot welds can have less strength and can lead into total destruction of manufacturing parts of cars bodies. The typical unconformities of spot welds are [8]:

- cold weld,
- small-diameter nugget,
- bad shape of welding nugget,
- cracks inside/around welding nugget,
- deep indentation of welding electrodes in sheets.

Fig. 2 Typical flaws in spot welding joints [9]

5. Resistance spot welding of aluminium

The weldability of aluminium alloys used by joining car bodies is very good but some conditions and rules must be applied. Resistance Spot Welding of aluminium and its alloys involves applying high power welding guns because welding current must be 2–3 times higher than in case of steel but the welding time is 1/3 weld time of
steel. The main of that is 3 times higher than in case of steel its thermal and electrical conductivity. It means the electric parameters (current and voltage) must be controlled more precisely in narrower window of time [10].

Sometimes the welding guns using for welding steel has not enough power to ensure required welding current, thus the sources of power are often designed for resistance spot welding of aluminium.

The comparison the typical RSW parameters for 1.0+1.0 mm mild steel and aluminium sheets are included in Table 3.

Table 3. RSW parameters for 1.0+1.0 mild steel and aluminium sheets

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>11</td>
<td>8</td>
<td>2.7</td>
</tr>
<tr>
<td>Aluminium alloy 5xxx, 6xxx series</td>
<td>25</td>
<td>4</td>
<td>2.5</td>
</tr>
</tbody>
</table>

6. Electrodes for resistance welding aluminium

An ideal electrode’s material for RSW of aluminium should have high thermal and electrical conductivity and high hardness as well. Moreover it shouldn’t tend to make alloys thus it is very difficult to find a compromise. The pure electrolytic copper has a conductivity 100% IACS (58 MS·m), however its hardness is relativity low (considerably below 100HV) and its tendency to alloying with aluminium is very high.

The main problem connected with electrodes by Resistance Spot welding of aluminium and its alloys is relatively short time of life of electrodes [11]. It can be a crucial problem especially by massive production. The rapid deterioration of tips surface is the result of high pressure, high temperature and alloying process during welding [11], which directly involves pickup effect, electrode alloying with aluminium, pitting effect and cavitations. Thus the quality of spot-welds rapidly decreases. The comprehensive numerical and experimental study, concerning pitting effect and its influence on spot-welds quality of aluminium-alloys joints were described in [12–14].

The alloying effect causes increasing resistance of contact tip-sheet. This is the reason the heat is generated in tip-sheet layer, instead sheet-sheet. To ensure the better contact between electrode and worksheet the lubricants are applied. It was investigated, that some metalworking lubricants extended the electrodes life-time and directly led to reduction alloying effect and concurrently pitting and pickup effect [15].

To avoid high costs of electrode’s materials replaceable caps are used and also cleaning after at least 20 spot-welds is required as well.

It was proved, that increasing hardness of electrodes reduces mushrooming of electrodes. To achieve higher hardness pure copper is alloyed by zirconium, cadmium, chromium and also dispersion hardened with aluminium oxide is used. It was investigated that using some special copper alloys especially alloyed by gold [16–17]. This way 5 times longer time of life can be achieved.
Recommended by resistance welders manufacturing association electrodes for spot welding aluminium are group A class 1 alloys.

Group A class 1 alloys have the highest electrical conductivity thus are the best for welding pure aluminium worksheets. For Al-Mg and Al-Mg-Si alloys higher hardness is required so, electrodes A class 2 can be used. [4]. Electrodes materials properties were presented in Table 5.

<table>
<thead>
<tr>
<th>Copper alloy class</th>
<th>Properties</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>high conductivity 95–100% IACS (ca. 58 MS·m)</td>
<td>resistance welding of aluminium and aluminium alloys</td>
</tr>
<tr>
<td>A2/1</td>
<td>Hardness: 130–170 HV, electric conductivity: 80% IACS (43 MS/m), softening temperature: 450–500ºC</td>
<td>resistance welding of mild steel, brass, aluminium alloys</td>
</tr>
<tr>
<td>A2/2</td>
<td>Hardness: 160–240 HV, electric conductivity: 50% IACS (23 MS/m), softening temperature: over 500ºC</td>
<td>resistance welding of stainless and austenitic stainless steel</td>
</tr>
</tbody>
</table>

The properties of copper alloys using for electrodes in automotive industry are presented in Table 5. In the columns shaded on grey, properties of copper alloys for resistance spot welding of aluminium are mentioned.

<table>
<thead>
<tr>
<th>Designation of alloy</th>
<th>CRM16X</th>
<th>BICOP</th>
<th>CB4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>Cr: &gt;0.4%</td>
<td>Al: 0.6%</td>
<td>Co: 2.2%</td>
</tr>
<tr>
<td>Zr: 0.3–0.15 Al: 0.6% Co: 2.2% Be: 0.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardness [HB]</td>
<td>160</td>
<td>150</td>
<td>240–260</td>
</tr>
<tr>
<td>Conductivity [% IACS]</td>
<td>76–46</td>
<td>85</td>
<td>&gt;43</td>
</tr>
<tr>
<td>Tensile strength MPa</td>
<td>480</td>
<td>430</td>
<td>700</td>
</tr>
</tbody>
</table>

Table 6. Electrodes diameter and recommended nugget size related to sheet thickness for mild steel and aluminium alloys series 1xxx, 3xxx, 5xxx and 6xxx [1]
To maintain correctly tips condition electrodes efficient cooling must be ensured. The coolant flow rate should be of 5–10 litres per minute (more than in case of steel). Its temperature should be ca. 20 °C in inlet area and outlet area 30 °C. Inlet channel should be carried as close to the tips as possible by the distance 12–20 mm from outlet channel.

In Table 6 technological parameters of electrodes for welding aluminium alloys and mild steel are presented. Please notice that diameter of tips and dome radius is bigger for aluminium alloys.

6. Conclusions

According to the newest studies, automotive industry tends to use light alloys like aluminium and magnesium alloys. Companies more often use aluminium as an alternative material for vehicle body. The most popular method of joining body sheets is resistance spot welding. Aluminium and its alloys series 5xxx and 6xxx can be connected by this technique. It requires high power welding gun and precocious steering of current and time. The aspects of rapid deterioration of tips must be taken into account.

References


[18] Electral, Le bronze Industrial datasheets.

Zastosowanie zgrzewania oporowego do zgrzewania konstrukcji w przemyśle motoryzacyjnym

Stopy aluminium są coraz częściej stosowane jako materiał alternatywny do budowy elementów karoserii samochodowych.

W artykule opisano technologiczne problemy podczas zgrzewania oporowego punktowego materiałów ze stopów aluminium (głównie z grupy 5xxx i 6xxx), skupiając się na parametrach elektrycznych zgrzewania, materiałach na elektrody oraz czasie ich życia.

Przedstawiono zalety zastosowania materiałów ze stopów aluminium, jako materiału, z którego mogą być wykonywane niektóre części w pojazdach samochodowych.