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Examination of the Weld Brazed Joints of Steel and Aluminium Thin Plates

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Abstract

In our research, overlapped thin sheets of hot-dip galvanized steel and aluminum alloy were bonded by braze welding, for which we used the CMT (Cold Metal Trasnfer) sub-versions of the welding manufacturer Fronius. The settings of the welding parameters were based on the smallest possible heat input and the thickness of the zinc layer. Cohesive bonds on the aluminum side and adhesive bonds on the coated steel side were subjected to metallographic test and the composition and distribution of the resulting intermetallic compounds were determined with the help of literature sources. Based on visual inspection, aesthetic and well reproduciable joints were formed, but large amounts and sizes of porosites were formed on the cross-sectional grinds due to the burning of the zinc layer. We also deduced the strength characteristics of the joints from the shear-tensile tests and the fracture surfaces. The fracture of the test specimens occurred at the junction of the weld metal and the alumnium base material.

Keywords: *braze welding, CMT, mixed joint, intermetallic compound.*

1. Intorduction

The appearance of aluminum and steel mixed joints was advocated by the vehicle industry after the turn of the millennium. Weight reduction and the ever-increasing resistance of structural elements to stress require solutions in which it becomes necessary to bond different metals. In the vehicle industry gluing or welding is the most often preferred. Ideally, during welding, the surface of the steel does not melt and an adhesive bond is formed with the filler material, while the aluminum forms a weld metal with the filler material due to its low melting point. Even in the solid state, steel can dissolve aluminum to a small extent, which results in the precipitation of intermetallic compounds [1]. The majority of the 6 stable ($FeAl_2$, Fe_2Al_5, $FeAl_3$, FeAl, Fe_3Al) and 3 metastable (Fe_2Al_9, Fe_2Al_7, $FeAl_6$) compounds are brittle and reduce corrosion resistance. Iron has a higher diffusion factor in aluminum [2], therefore aluminum-predominant compound phases, which are brittle, are more likely to form. From a welding technical point of view, the chemical composition of the filler material and the use of pulse process variants can also affect the appearance of brittle phases [1, 2].

Since it is not possible to prevent the formation of brittle compound phases on raw plates, a hot-dip galvanized steel plate with a pure zinc coating is most often used, which improves the corrosion properties of the seam and prevents the formation of iron-aluminum compounds by forming a bond with the aluminum, which results in a more favorable seam with low heat input. On the other hand, due to its low boiling point, it can form porosity and brittle iron-zinc compounds in the seam when burned [1, 3]. In this research, we investigated the definition, location, and shape of the intermetallic compounds appearing in the seams. The connection of thin plates is usually done by overlapping, so it is relevant to subject them to a shear-tear test and to examine the fracture surfaces. As part of the research, we looked for a correlation between the solidity characteristics and the settings of the power source.

2. Materials and experimental methods

2.1. Used materials

We welded 23 experimental joints of AlSi1MgMn and S355J2 hot-dip galvanized 0.8 mm, 1 mm and 2 mm thick plates, 100 mm long, with $AlSi_5$ filler material in the assembly according to **Figure 1.** The steel plates were made with zinc coating of three different thicknesses – 24 μm (0.8 mm), 17 μm (1 mm), 123 μm (2 mm) – the effect of which on the joints is also being investigated.

For the mixed joints of aluminum and steel, non-iron-based bonding materials, such as $CuSi_3$, $AlSi_5$, $AlSi_{12}$ wire, are often used. The melting point of the listed welding materials must be below the melting point of the steel material and must have good wetting ability.

2.2. Welding characteristics settings

To carry out the research, we used the CMT Universal and CMT Cycle Step (CMT CS) process subversions, which were developed for the weldability of mixed joints, thin coated plates and good thermally conductive materials. These processes are characterized by low heat input, stable electric arc and thus controlled droplet separation. In a welding cycle, an electric arc is ignited by advancing the wire electrode, then a short circuit occurs and the wire is pulled back by a Push-Pull system, installed at the front of the welding torch. The sudden movement of the wire in the opposite direction separates the melted droplet and the melted electrode end falls into the seam and solidifies, and then the process is repeated. When a short circuit occurs, the system gives the instruction to retract the wire, so the Push-Pull control operates the forward and backward push with a time-varying frequency **[4]**.

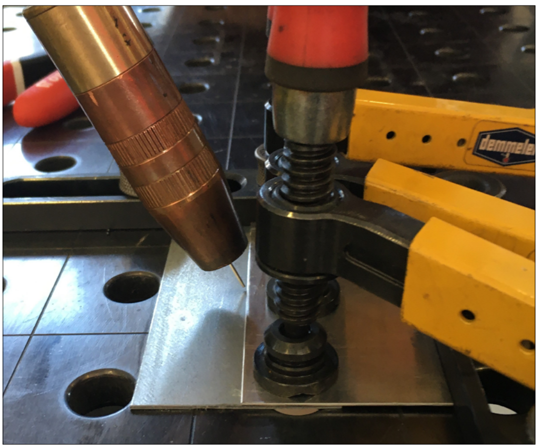

Fig. 1. *Steel-aluminum overlapped plates while determining the position of the welding torch.*

In contrast to the drop separation of short-circuit procedures this version of the procedure detects the short-circuit and prevents the high current, thereby ensuring splash-free material transfer and the formation of a large volume weld pool. CMT CS is an extension of Universal, which can create a „fish scaled" seam face at a constant speed by alternating the number of welding cycles and the pause cycles between them. It performs the number of cycles specified by the user, presented in CMT Universal, and then restarts the process after taking a pause for a given time, so the heat input is even smaller compared to CMT Universal **[4, 5]**.

2.3. Metallographia and test specimens

2.3.1. Microscopy

The metallographic evaluation was performed with an Olympus PMG-3 optical microscope and a Zeiss EVO MA 10 scanning electron microscope (SEM) **[6]**. In addition, energy dispersive spectroscopy (EDS) was used to determine the chemical composition of the weld **[7]**.

2.3.2. Tensile test specimens

The strength of the overlapped joints was determined by testing non standard shear-tensile specimens **[8]** on a MTS 810 tensile machine. The force was introduced on non joint gaped plates, which caused eccentric tensile, shear and bend stresses in the plates. Depending on the location of the fracture, the failure may occur I.) in the heat-affected zone, II.) in the weld metal, III.) in the base material, or IV.) the seam may separate at the junction of the weld metal and the stell plate, as shown in **Figure 2**. In the research, the tearing experiment served as a comparative study.

3. Results and their evaluation

We evaluated 18 out of 23 joints in the research. By changing the travel speed of the welding torch and the welding power, we found the speed range between 30 cm/min and 60 cm/min, at which the zinc layer burn doesen't cause an excessively porous, splattering seam. The favorable setting of the arc length correction value helped to minimize arc bending, which was cause by the better conductivity of the aluminum.

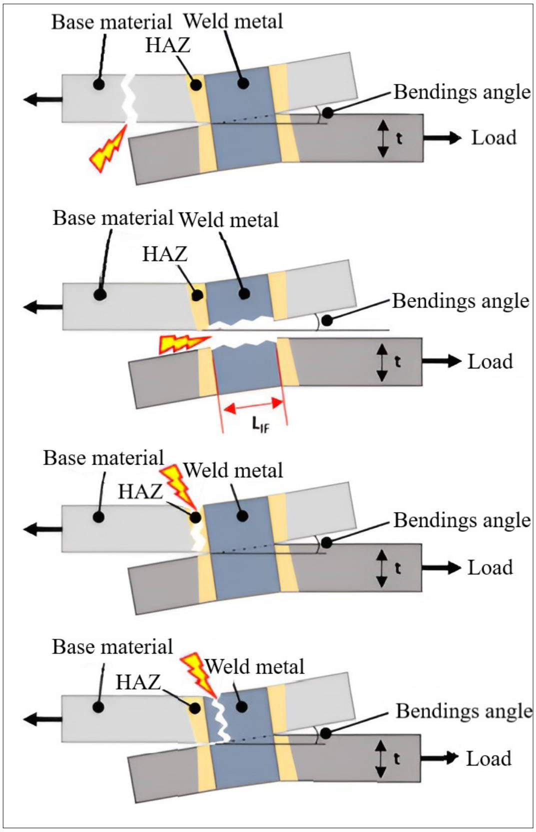

Fig. 2. *Failure modes of tensile-shear test specimens in the case of lapped joints.*

3.1. General weld seam characteristics

For a more in-depth review, we prepared metallographic grindings. In most of the roots, incomplete fusion occurred along the entire length of the weld (**Figure 3**).

This could have resulted from the zinc gases trying to escape towards the tightly compressed plates **[9]**. Due to the large number and size of porosity, none of the welds would meet the quality level D of the aluminum standard **[10]** because the diameter of the individual gas porosities is in many cases greater than 600 µm, and the uniformly distributed porosity percentage is greater than 2.5 % in the cross-section area.

3.2. Intermetallic compounds

In general, it can be said that the zinc layer in the weld cross-section is completely burnt or partially incorporated into the weld metal **[11]**. As expected, intermetallic compounds were formed when the steel and the filler material came into contact. In all cases, the compound phases arranged in layers and they are located in the center line of the seams. Their maximum width is 1.5 mm. Along the length of the seam, the compound phases appear in different spots, which may have been caused by temperature differences in the contact line of the base materials.

To identify the compound phases formed in the seams, literature research was used as a basis **[2, 12]**. As expected, intermetallic compounds were formed when the steel and the filler material came into contact. In all cases, the compound phases arranged in layers and they are located in the center line of the seams. Their maximum width is 1.5 mm. Along the length of the seam, the compound phases appear in different spots, which may have been caused by temperature differences in the contact line of the base materials. To identify the compound phases formed in the seams, literature research was used as a basis (**Figure 4**). The compound phase $FeAl_3$ also

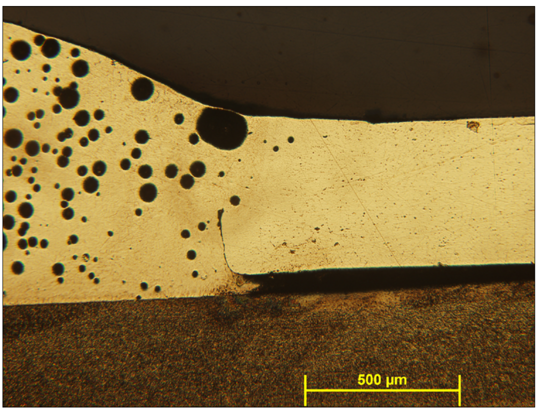

Fig. 3. *Gas porosities and incomplete fusion in the weld seam cross-section.*

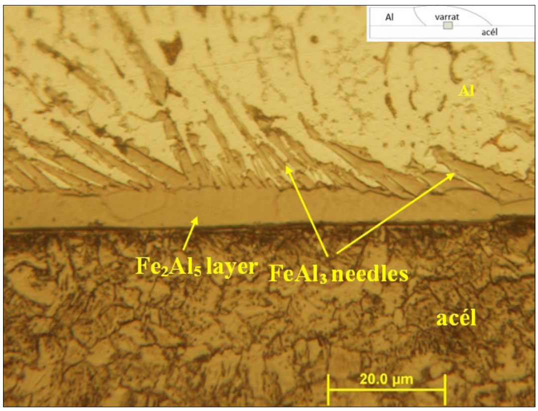

Fig. 4. *Determination of intermetallic compound phases at the junction of steel and weld metal.*

appears above the Fe_2Al_5 layer in the form of needles.

In the case of joints made with the CMT Uinversal subversion, a limit of heat input can be observed – between 0.72–0.80 kJ/cm – where the intermetallic layer thickness becomes measurable. Below this heat input, a weak oxide layer or a few µm thick phase appear at most. Continuous layers with a thickness greater than 2 µm can be found in the middle of the seams, where the heat input is the greatest. Based on research in the literature [13] intermetallic compounds have a significant effect on the strength of the bond when the thickness is over 10 µm.

3.3. Line scan chemical composition test

Line scan EDS analyses were made from the intermetallic transition zones. In the case of all welds, we examined the compounds between the filler material and steel bond in the center line of the weld, where the presence of zinc in the weld metal can be clearly detected.

The eutectic contains an average of 8 % zinc in the weld for more than 100 µm long (Figure 5), so a part of the zinc forms a new eutectic alloy in the weld metal instead of turning into a gaseous state during welding (Figure 6) [14, 15, 16].

3.4. Tensile test

The tensile tests were performed on 80×15 mm specimens. In 90 % of the joints, the fracture occurred at the cohesive connection between the aluminum base material and the weld metal. It can be traced back to the release of the gases described earlier and the inadequate melting of the base material. Comparing the force-displacement curves of the test specimens (Figure 7), the bearing and deformation capacity of the welded plates coated with a thick layer of zinc stand out by far compared to those measured for other joints.

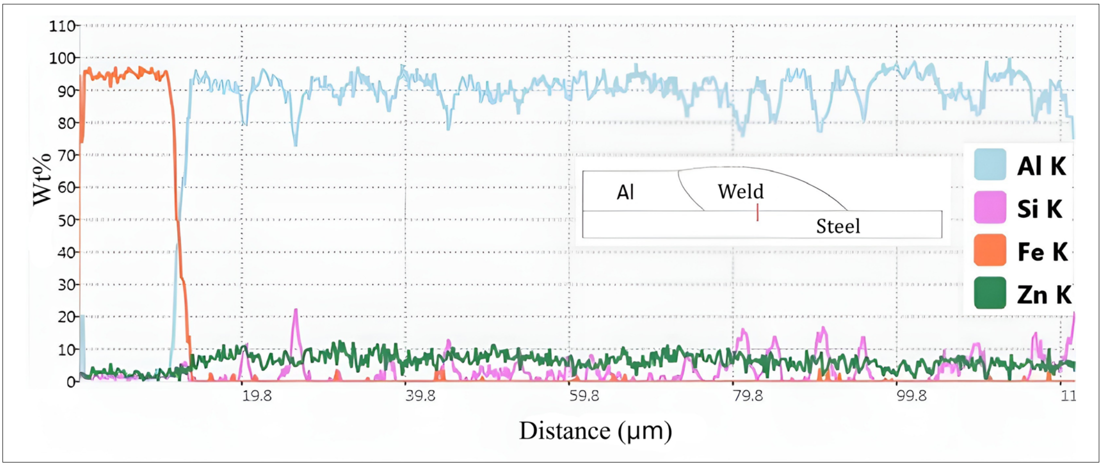

Fig. 5. *EDS line scan chemical composition analyses in the line of the steel and the weld metal.*

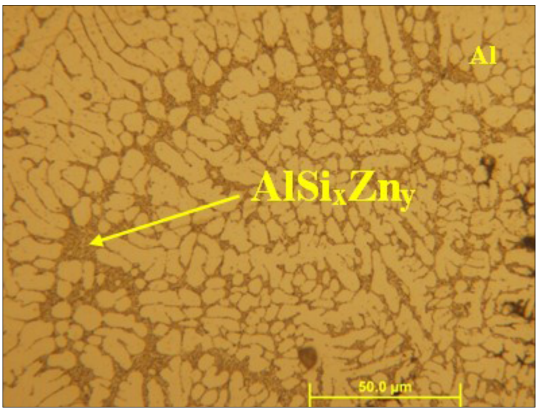

Fig. 6. *Eutectic alloy in the weld metal.* [16]

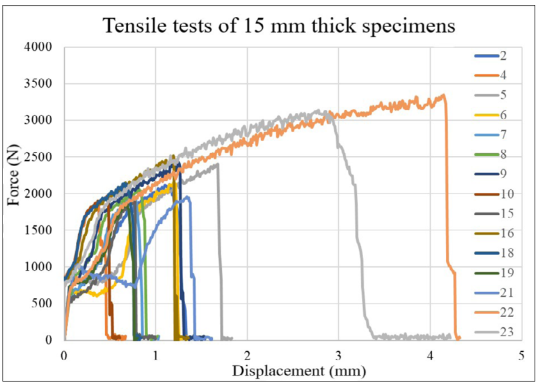

Fig. 7. *Force-displacement curves recorded by tensile tests.*

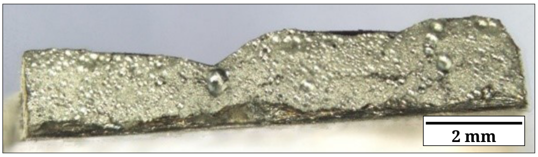

Fig. 8. *Large porosities are visible on the fracture surface, which promoted the propagation of the crack.*

The countless porosity visible on the fracture surfaces (**Figure 8**) played a major role in the rapid propagation of the cracks. In several test specimens, the joint cracked only up to a certain width, the complete separation occurred later in time. This was caused by the growth of porosities starting from the surface through crack propagation. The process took place with brittle fracture everywhere, before the stage of plastic deformation, the failure had already occurred.

4. Conclusions

In summary, it can be concluded that the applied welding parameters can be well reproduced with brazewelding, and appropriate seam shape and aesthetics can be formed on steel-aluminum thin plates. The large amount and size of porosities visible on the images clearly show the unfavorable effect of the zinc layer, which was not significantly reduced at any seam. The formed intermetallic compound phases could be easily identified based on the literature, and their existence was confirmed by the EDS line scan tests. Despite the fact that, in some cases, thick compound layers were also formed in the weld seams, the fracture of the joints during the tensile tests almost always occurred at the junction of the weld metal and the aluminum base material. The effect of the zinc layer thickness on the mechanical properties of mixed joint is shown by the outstanding tensile strength of the steel plate joint coated with the thickest zinc layer.

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