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MIG arc brazing processes for hot-dip galvanized medium-thickness sheets and their quality verification

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Abstract

Steel construction relies on welded structures to provide strength and stability, but when exposed to outdoor conditions, these structures can suffer from corrosion and unsightly defects. To combat these issues, assemblies are typically welded in the black state and hot-dip galvanized afterward to meet harsh corrosion requirements. However, arc brazing is an often overlooked alternative to welding that offers unique advantages, such as joining individual parts in the galvanized state without reducing strength. In this article, the applicability of MIG brazing for hot-dip galvanized structures with a thickness of 3 mm is explored through the validation procedure of three different types of arc: short arc, pulse arc, and hybrid short-circuit based pulse arc. It demonstrates the methodology according to the brazing procedure specification (BPS) for each arc type, providing valuable insights into the potential of arc brazing for steel construction.

Keywords: MIG brazing, CuSi3Mn, hot-dip galvanized sheet metal, medium-thickness sheet metal, Brazing procedure specification - BPS

1. Introduction

Brazing is a commonly employed method to form a joint between multiple components using a filler metal that has a liquidus temperature exceeding 450 °C [1, 2]. A diverse range of brazing processes can be utilized to achieve this objective. Of particular interest in this study is MIG arc brazing, which is a complex process characterized by a vast array of process parameters and a nonlinear dependency among them. The interdependent nature of the setting parameters poses a significant challenge, as their mathematical description remains incomplete. Consequently, numerical simulations employing multiple empirical parameters are necessary to determine the appropriate process for each brazing application and are limited to this purpose.

For a high-quality joint with the base material, several critical factors must be considered. These include the design, manufacturing conditions, material properties, sheet metal thickness and arc type.

While research efforts have investigated laser brazing processes for electrogalvanized thin sheets utilized in the automotive industry [3-6], limited studies have focused on the Cold Metal Transfer (CMT) arc brazing of thin sheet metals, including dissimilar joining of steel and aluminum. Previous studies with the CMT arc have primarily examined the metallurgical characteristics and corrosion behavior [7-10] or joint strength of such brazed joints [11-15]. Though some works have examined the arc brazing of hot-dip galvanized steel components, these studies have typically employed conventional arcs such as the short-circuit arc [16] or pulsed arc [17-19].
To date, research reports in the thin sheet metal domain have not adequately addressed fundamental questions regarding the intermediate sheet metal of 3 mm thickness, such as the optical characteristics of the seam, zinc layer thickness, microstructure change, corrosion protection, and yield strength concerning various arcs. Thus, this work aims to validate the MIG arc brazing process on hot-dip galvanized medium-thickness sheets of 3 mm, employing three different arc types: short arc, pulsed arc, and the hybrid short-circuit based pulse arc.

2. Experimental approach

Several studies have investigated the Cold Metal Transfer (CMT) brazing process for car body construction applications, and it has already been implemented in series production. However, the use of arc brazing is infrequent in typical steel construction with higher plate thicknesses and hot-dip galvanized surface coatings. According to the standard, hot-dip galvanized surfaces on steel structures (with a thickness of 3 mm) should have a coating thickness of at least 45 µm, and on average, at least 55 µm [20]. This may result in segregation at the edges of the molten metal during brazing. Furthermore, the mixing and conduction of the increased sheet thickness can lead to corrosion and strength issues at the joint. The higher sheet thickness also causes greater conduction in the heat-affected zone, allowing potential β-phases to form. The objective of this study is to evaluate whether the brazed joint with different arc types can be considered as a load-bearing joint according to the BPS (Brazing Procedure Specification) and whether the zinc layer's corrosion protection is preserved on both sides of the joint.

2.1. Generating parameter set

In this study, the wire feed rate, brazing speed, and gap size were varied to investigate their effects on the brazing process. To ensure a more uniform distribution of experimental points than a purely random distribution, the Latin Hypercube Sampling (LHS) method was employed. The entire range of values for each input variable was divided into intervals, and one value is randomly selected from each parameter range to create a parameter set with no correlation between individual input variables. The resulting parameter sets exhibit a normal distribution over all input variables, enabling the identification of optima more efficiently than classical design of experiments [21-23]. Moreover, each sample is assigned a unique ID that accompanies the component throughout the entire process.

2.2. Brazing process

The experimental procedure involves brazing two 3 mm hot-dip galvanized S235JR sheet metals with an average coating thickness of 60 to 65 µm. The brazing was performed on a typical fillet joint with a target measurement of 2 mm to 3 mm.

Experiments were conducted using a Reis RV20 welding robot equipped with a Fronius TPS500i power source. The brazing speed was limited to a maximum of 48 cm/min to ensure sufficient time for degassing of the burning zinc layer. In addition, an optimal torch position is determined for all processes, slightly in a forehand position, and maintained consistently across all the different brazing processes [24]. This position has been found to be equally effective for all processes. The filler metal was directed into the throat and the robot guided the torch along the 40 mm throat using the point-to-point method.

Figure 1 illustrates the experimental setup for the brazing. Both sheets were fitted with stops on the sides and end faces, with specimens laser-cut to tolerances <0.1 mm.

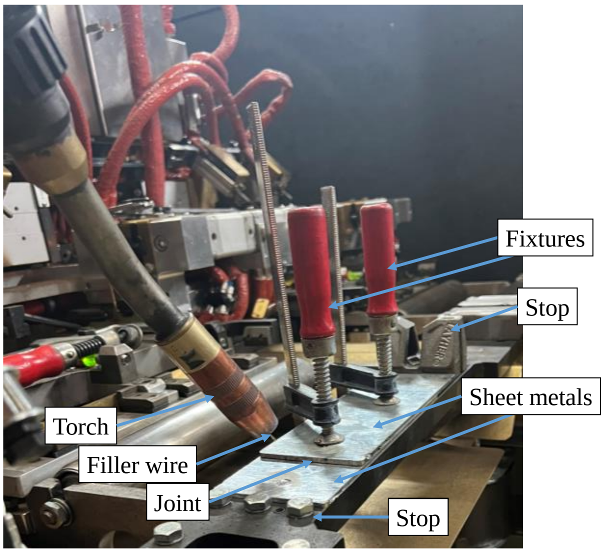

Figure 1. Experimental setup at the Reis robot cell

The filler metal used was CuSi3Mn1, material number 2.1461, with a Ø1.2 mm diameter from the Esab brand, model OK Autrod 19.30. This is a versatile wire electrode suitable for joining galvanized and bright steel sheets, with technological properties listed in Table 1.

Table 1. Mechanical technological properties of the wire and base material

Material	Yield Strength $R_{p0,2}$, MPa	Tensile strength R_m, MPa	Elongation A_5, %
Wire	130	350	40
Base	235	360	26

2.3. Arc types

The short arc is the most widely used and oldest arc type for welding and brazing. The short arc works by transferring droplets exclusively when the filler metal and base material are in contact, so in a short circuit. As a result, the arc must be reignited after each droplet transition, reducing the heat input and making the process ideal for thin sheets. The control parameters of the short arc are limited to voltage and maximum current at constant wire feed speed. These parameters affect both the droplet size and the frequency of droplet transition, not just their maximum values but also their time response.

The pulsed arc process is useful for brazing thin to medium sheets, as it allows for control of the heat input through adjusting process variables such as basic current, pulse current, pulse duration, and pulse frequency. The pulsed arc is composed of base current phases with low amperage followed by pulse current phases with high amperage, and the material transition is short-circuit-free.

To further improve the pulsed arc process, Fronius developed the short-circuit based pulse arc, also known as the Pulse-Multi-Control (PMC) arc. This process adds controlled short-circuits before current reduction for droplet detachment, increasing the process reliability, brazing speed, and heat input. By combining the benefits of the short arc and pulsed arc processes, the PMC brazing process enables an increase in deposition rate and overall process efficiency.

3. Evaluation of the quality characteristics

The following test criteria are based on empirical values gathered from practical experience, and therefore go beyond the standard. According to the standard, only 100% visual inspection, two macrosections, and either a sheer or peel test are required for lap joints using different arc types [25-27].

3.1. Measurement of current and voltage

The HKS WeldScanner S3 is a suitable measuring instrument for recording current and voltage in brazing experiments due to its high accuracy and ability to measure and record current, voltage, gas volume flow, and wire feed over time. For detecting BPS, a frequency of 25 Hz is sufficient to identify process anomalies such as wire feeding problems or robot positioning issues.

3.2. Visual inspection and appearance

The visual inspection conditions for a braze seam require an illumination of 500 lx, at a maximum distance of 600 mm and a viewing angle of less than 30° [28]. The test characteristics include the following example criteria [29]:

- External irregularities (collapsed brazed seam, cracks, open porosity, insufficient fillet, local melting of the base material, rough braze surface, spatter, flux residues, erosion in the surface of the base material)
- Internal irregularities (cracks, filling defects, solid inclusions, gas inclusion, flux inclusion, bonding defects, excessive dissolution of solder and GW-sometimes referred to as erosion).

Based on the provided samples, it appears that the seam appearance at the short arc is irregular and suggests a lack of connection to the lower sample. The seam exhibits fine and appealing scaling in the middle of the seam, but the irregularity of the scaling increases at the end of the seam visible zinc burn-off at the upper specimen edge can be seen, that is not enclosed by the filler material.
In the case of pulse arc, the seam is surrounded by traces of burnt zinc, but the reverse side shows no damage or burning, indicating that the corrosion protection effect on the reverse side is intact. The seam shows no obvious bonding defects. However, there is still no clear demarcation from the base material, and the seam appears irregular at the edge zones with partially not uniformly pronounced flow behavior of the filler material.
The brazing seam created by the short-circuit based pulse arc appears to be similar to that of the pulsed arc, with spatter marks surrounding the entire brazing area. The zinc coating in the HAZ is minimally damaged but shows no damage on the reverse side that would indicate impaired corrosion protection.

3.3. Measurement of hardness
Hardness is a measure of a material's resistance to indentation or scratching and is an important property to consider in many engineering applications. The hardness test was used to determine structural changes caused by thermal influences during brazing. The measurement makes sure that there is no hardening above critical values of the base or filler material, that reduces the ductility.
Figure 2 shows the results of the hardness profile measurements at eleven different points. The profile is based on measurements taken from the root center and is presented sequentially for both upper and lower specimen base materials.

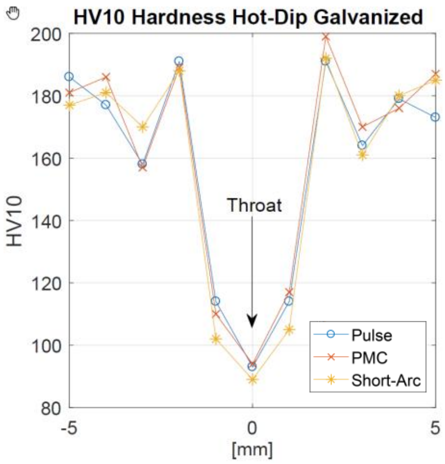

Figure 2. HV10 Hardness of the samples with the throat in the middle of the samples

The base material shows uncritical values of 173 to 187 HV10 for all three curves. The hardness of the filler material remains constant at 84 HV10 (equals unbrazed condition).
A correlation was observed between the applied arc energy of the different brazing processes and the increase in filler material hardness.

3.4. Quasi-static tensile test
During a tensile test, specimens are subjected to a quasi-static load to test their strength. A correctly designed joint geometry can prevent cracks from occurring in the base material of the specimens [30]. The seam length is shortened to exclude fracture in the base material to 40 mm. If the seam is executed correctly, fracture should occur in the seam during the tensile test. However, Figure 3 shows such incorrect samples with fractures in the diffusion zone, where the samples appear visually indistinguishable from those with higher heat exposure. This poses a risk of undetected defects in manual brazing.

Figure 3. Tensile test of the hot-dip galvanized specimens with crack in the diffusion zone. Pulse (left), PMC (middle) & Short-Arc (right)

The specimens brazed with the short arc exhibit the lowest failure values, even with the best parameter set. Due to the low heat exposure, the joint fails not in the seam as required, but in the diffusion zone. In contrast, samples brazed with the pulse and short-circuit based pulse arc exhibited fractures in the brazed seam. The greater heat input at identical torch positions resulted in a sufficient diffusion layer formation.

3.5. Macroscopic evaluation
For macroscopic measurements the relevant dimensions are shown in Figure 4.
Due to the overlapping of the seam, a relatively steep wetting angle of 89.5° is produced. This wetting angle is unfavorable for the introduction of force since it generates a notch effect that is reflected in dynamic loading [31]. This borderline value of 89.5° cannot be significantly improved in tests by increasing the brazing voltage. The accompanying change in stickout causes control problems for the current source, leading to an irregular seam. This effect cannot be detected in the specimens, and thus the results are acceptable, which is confirmed by the values obtained in the tensile test.

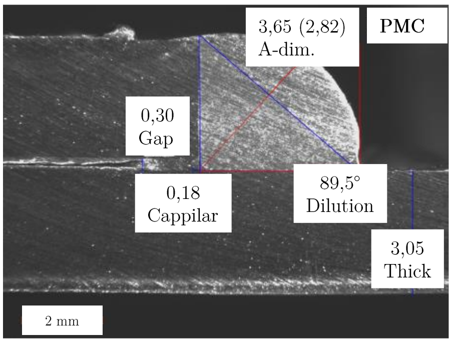

Figure 4. Macroscopic evaluation of the PMC brazing with the A-dimension of 3.65 mm and the effective A-dimension of 2.82 mm

4. Conclusions

The present investigations aim to explore the practical and theoretical feasibility of arc brazing on galvanized steel assemblies that are 3 mm thick. To achieve this objective, three different arc types, namely short arc, pulse arc, and short-circuit based pulse arc, were examined. The study focused on evaluating the quality of the brazed seams and the damage caused to the zinc coating on both front and back sides of the specimens.

In addition, the hardness history measurement was carried out on the specimens to investigate the hardening behavior of the brazed seams. Anomalous hardening was observed in the galvanized components due to the heat effect. To evaluate the applicability of arc brazing on load-bearing structures, a quasi-static tensile test was conducted as well. The results showed that the pulse and short-circuit based pulse arc exhibited higher heat input and are effective. The study concluded that the low arc energy of the short arc was insufficient for this thickness due to the comparatively large mass of the components and the good thermal conductivity of steel. There is no save connection assured.

To summarize, the pulse arc and the short-circuit based pulse arc fulfill the requirements of a BPS and can be applied in a series production for load-bearing joints.

Overall, these findings have important implications for the practical use of arc brazing on galvanized steel assemblies and may guide future research and development efforts in this field.

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