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RESIDUAL STRESSES IN THIN-SHEET GALVANIZED STEEL JOINTS AFTER ARC WELDING AND PLASMA BRAZING

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In the manufacture of thin-walled structures by welding, residual stresses appear in them, which negatively affect the geometric parameters and quality of the obtained products. The paper presents the results of evaluation of residual stresses on simulators-samples made of galvanized steel 08ps (semi-killed) after MAG welding, plasma brazing using constant and modulated current. Reduction of residual stresses and avoidance of brazing filler metal spattering are promoted by reduction of heat input, when making permanent joints. One of the ways contributing to it is application of plasma brazing, which provides the ability setting the current, independently of filler material feed rate. Determination of the magnitude of residual stresses in the joints was performed by magnetoelastic method. It is shown that in plasma brazing with constant current the dimensions of the plastic strain zone are much smaller than in MAG welding, which is associated with a decrease in the amount of thermal energy applied to the metal. Plasma brazing with constant current allows lowering residual stresses from 149, which is obtained in welding to 119 MPa. Further reduction of residual stresses (up to 85 MPa) during plasma brazing of joints of galvanized steel 08ps is possible due to the use of modulated current. 18 Ref., 6 Figures.

Keywords: MAG welding, plasma brazing, modulated current, residual stresses, shrinkage force, plastic deformation, elastic deformation, heat input, galvanized steel, magnetoelastic method

In fabrication of thin-walled structures, for instance, car bodies, with application of welding, residual stresses arise in them, which have a negative effect on the geometric parameters and quality of the manufactured products. Residual stresses always develop, their magnitude in the weld area reaching values, equal to the yield limit. Violation of the geometric parameters leads to distortion of the shape of individual parts and requires application of labour-consuming operations of fitting-up in the connection points. Moreover, distortion of the shape of structure elements may lead to inadmissible violations in operation and can cause overstress in individual intersections of structural elements. Therefore, when designing such structures, it is necessary to take measures to prevent formation or reduction of the magnitude of residual stresses that can be achieved by the appropriate welding method or by application of alternative joining methods [1–3].

Effective methods of lowering the negative impact of residual welding stresses and strains in permanent joints is heat removal with application of heat-concentrated pastes; and reduction of heat input into the structure being welded. Used for this purpose are highly-dissipating heat sources (electron beam, plasma, pulsed-arc), as well as modes of welding with a low heat input and high speed of heat source movement (bare electrode over a layer of flux, etc.). By energy density the plasma heat source is in an intermediate position between the electric arc and beam (electron beam and laser) heat sources. It allows achieving a higher density of the heat flow in the treated product, compared to arc sources, despite being inferior to the beam sources by energy concentration, but it is much less expensive and more accessible by its engineering implementation [4, 5].

Galvanized steel is widely used in manufacture of car bodies. In a number of cases producing permanent joints from this material runs into considerable difficulties. Zinc starts melting at the temperature of 419.58 °C, and at 907 °C it evaporates. In MAG welding, when the temperature of base material edges exceeds that of zinc boiling, zinc coating burns from both sides. In order to ensure the corrosion resistance, the destroyed zinc layer has to be restored, that leads to additional expenses. Zinc penetration into the weld pool liquid metal leads to formation of porosity, cracks, spatter, incomplete penetration and unstable arcing (Figure 1) [6–8].

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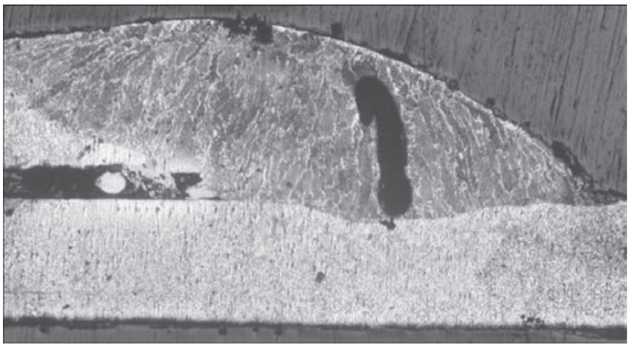

Figure 1. Macrostructure of overlap joint of galvanized steel produced by MAG welding

Plasma brazing is a promising method of joining galvanized steel. An advantage of plasma brazing is the ability to set the current, irrespective of the filler material feed rate, that allows reducing residual stresses by lowering the current and producing sound joints with preservation of zinc coating integrity. Different methods are used to determine the residual stresses [5, 9].

The objective of the work is determination of the magnitude of residual stresses which appear in permanent joints of galvanized steel 08ps in MAG welding, plasma brazing by constant and modulated current and their dependence on the heat input.

Input energy q_p is an important factor that affects the residual stresses and allows for the heat impact per a unit of length [10]. Input energy is the ratio of arc power q to welding or brazing speed:

$$q_{\mathrm{p}} = \frac{q}{V} = \frac{IU_{\mathrm{a}}\eta_{\mathrm{e}}}{V}, \qquad (1)$$

where q is the arc power, J/s; V is the brazing and welding speed, cm/s; I is the brazing and welding current, A; U_a is the arc voltage, V; η_e is the effective arc efficiency.

It was determined empirically that in MAG welding of galvanized steel the input energy is equal to 380 J/cm. Application of plasma brazing by constant direct current allowed reducing the heat input to 324 J/cm. Further lowering of the heat input to 273 J/cm is achieved due to application of plasma brazing by modulated current.

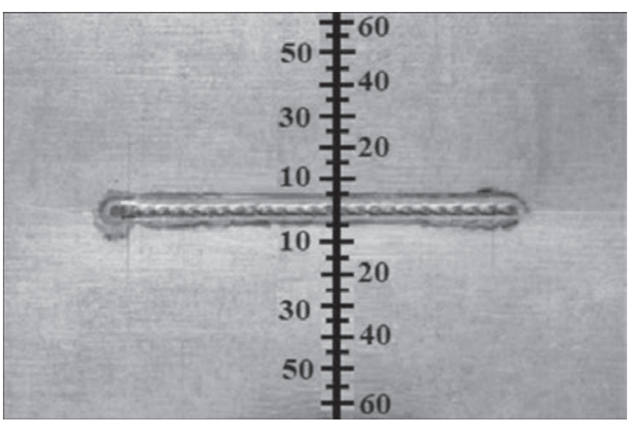

Figure 2. Sample from galvanized steel with brazed seam

Measurement of residual stresses was conducted by magnetoelastic method using MESTR-411 instrument on witness samples of 300×200×0.7 mm size.

Instrument graduation was performed at uniaxial tension. A flat sample made from galvanized steel 08ps was used for instrument graduation. Sample dimensions were equal to 500×50×0.7 mm. Rolling direction was along the longer side. The sample was fastened in the clamps of tensile-testing machine R-10. An electromagnetic transducer oriented along the direction of applied loading, was placed on the sample. The sample was loaded up to appearance of stresses on the level of 80 % of the yield limit, as further loading of the sample can cause plastic strains in it. Acting stresses were determined as the ratio of loading force to the sample cross-sectional area. During loading, instrument readings were recorded at each increase of stresses by 0.1 of the yield limit.

Graduation results were used to determine graduation coefficient T as the average stress increment per a unit of instrument readings by the following relationship

$$T = \frac{1}{N}\sum_{i=1}^{N}\frac{\Delta\sigma_i}{\Delta A_i}, \qquad (2)$$

where ΔA_i is the increment of instrument readings, corresponding to increase of stresses readings $\Delta\sigma_i$, N is the number of measurements at loading.

When any physical methods of measurement of mechanical stresses are used, obtained results are affected by deformation of metal grains in the direction of plate rolling, i.e. by the texture. In order to move away from the effect of the texture, it is necessary to determine the initial readings of the instrument for this type of structures from the given steel grade.

At determination of the initial readings of the instrument, the electromagnetic transducer was installed on the surface of galvanized steel plates, and it was oriented along the rolling direction. Rotating the transducer around its longitudinal axis clockwise and counterclockwise in a sector of approximately 30°, the largest reading of the instrument, A_0, was determined. Measurements were repeated in 10–15 points and the average value was determined. This value is the initial reading of the instrument for this type of structures from this steel grade [11, 12].

In order to measure residual stresses on welded and brazed samples, the electromagnetic transducer was installed on the sample surface along the weld and brazed seam. Measurements were conducted in the mid-section of the weld and brazed seam with 5 mm step on both sides from the weld on witness-samples of 300×200×0.7 mm size in the cross-section on the face and reverse sides with further averaging of the obtained values (Figure 2).

Acting mechanical stresses were determined by the following relationship

$$\sigma = T(A - A_0), \qquad (3)$$

where T is the graduation coefficient; A_0 is the initial reading of the instrument.

Results of measurement of the residual stresses on samples produced by consumable electrode welding (MAG welding) and plasma brazing, are shown in Figure 3.

As one can see from the Figure, the nature of residual stress distribution in the welded and brazed samples is identical and corresponds to the classical one [13, 14]. So, in the welded sample tensile stresses occur in the weld zone, their maximum value reaching 149 MPa on the weld axis (Figure 3).

Magnitude of residual stresses on the weld axis is a little smaller than the base metal yield limit (175 MPa). The residual stress magnitude decreases smoothly with greater distance from the weld axis. At the distance of 10–12 mm from the joint axis tensile stresses become equal to zero, then they change their sign and transform into compressive stresses. Compressive stresses first increase, then decrease and are equalized.

Residual stresses in brazed samples are distributed similarly (Figure 3). In this case, the magnitude of maximum tensile stresses on the joint axis decreases to 119 MPa.

Presence of residual stresses in the joints can be regarded as the action of the shrinkage force [13, 15, 16] that causes distortion of the shape (deformation) of the welded and brazed samples.

Magnitude of such a shrinkage force is defined by expression (4) [13, 15]

$$P_{sh} = (|\sigma_t| + |\sigma_{com}|) b_{pl} \delta, \qquad (4)$$

where σ_t is the magnitude of active residual tensile stresses, MPa; σ_{com} is the magnitude of reactive residual compressive stresses, MPa; b_{pl} is the width of plastic deformation zone, mm; δ is the thickness of welded and brazed samples, mm.

Indeed, for sheet structures with low rigidity, presence of such a shrinkage force, and, hence, of residual stresses, is an important factor, both from the viewpoint of structure performance, and from the viewpoint of its appearance.

In view of the above-said, let us analyze the quantitative characteristics of residual stresses in welded and brazed samples.

As one can see from the experimental results, maximum value of residual active tensile stresses of welded

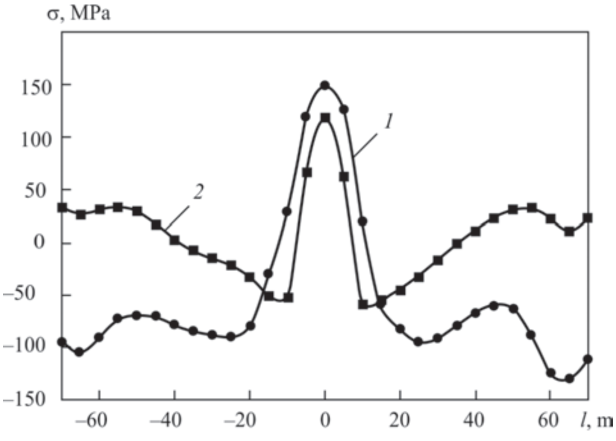

Figure 3. Distribution of residual longitudinal stresses in mid-section of brazed sample, compared to welded sample: *1* — MAG welding; *2* — plasma brazing by constant current

and brazed samples is on the level of 149 and 119 MPa, respectively. Such an experimental result can be explained in terms of the mechanism of residual stress formation at nonuniform heating of the middle band of the model of welded and brazed samples — a plate with slots for the general case, when the dimensions of the heated zone are smaller than those of the plate proper, i.e. $F_{mid} < F_{edge}$ (Figure 4) [15].

At heating of the middle band it develops temperature deformations $e_t = \alpha T$.

Impossibility of realization of the arising temperature deformations by the middle band, because of the bonds between the middle band and the unheated

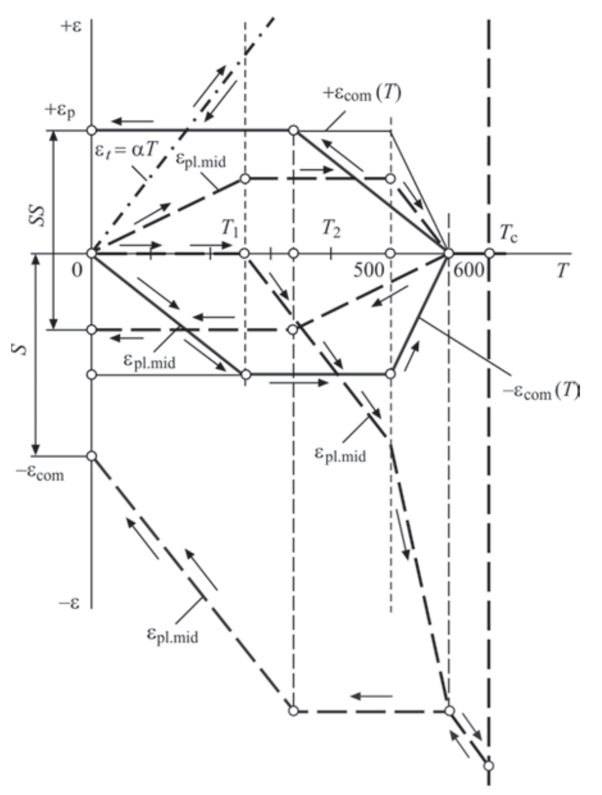

Figure 4. Scheme of strain development in a slotted steel plate at $F_{mid} > F_{cr}$ [15]

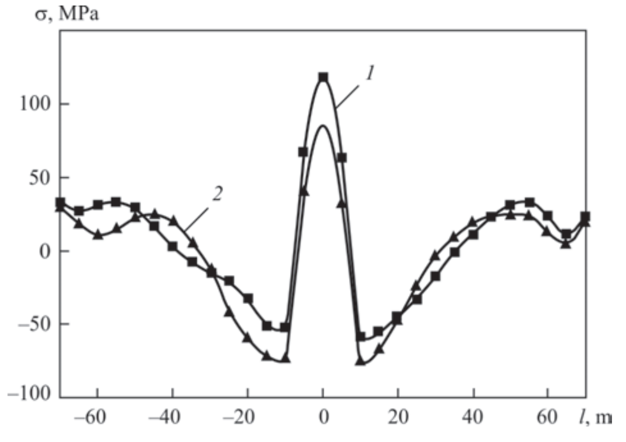

Figure 5. Distribution of longitudinal stresses in brazed samples produced using plasma heating with application of direct constant and modulated current: *1* — plasma brazing by constant current; *2* — plasma brazing by modulated current

edge zones, causes elastic shrinkage strains (compressive stresses) in the middle zone.

By the condition of equilibrium, tensile elastic strains (stresses) develop in the extreme bands. At T_1 temperature elastic shrinkage strains of the middle band reach its maximum value, which is followed by development of plastic shrinkage strains $-\varepsilon_{pl.\ mid}$ in the middle band (Figure 4).

At further heating, elastic strains of the middle band remain on the level of $-\varepsilon_{pl.\ mid}$, and starting from temperature T_1 plastic shrinkage strains develop in the middle band.

In the temperature range from 500 to 600 °C, elastic strains of the middle zone decrease to zero. At the same time, plastic strains of the middle band dramatically increase their growth rate.

At the cooling stage, thermal deformation processes proceed with opposite signs. At the same time, as follows from Figure 4, complete compensation of plastic strains accumulated at heating does not take place. As a result, a nonuniform distribution of residual plastic strains in the plate cross-section is found in the slotted plate (they are present in the middle band, but absent in the extreme ones) that is exactly what causes development of residual stresses in the welded and brazed joints.

In this case, if the metal was heated to temperature above 600 °C, the magnitude of residual tensile stresses forms on the level of the yield limit. Depending on the ratio of areas, where residual active tensile stresses and reactive compressive stresses arise, residual compressive stresses $-\sigma_{com} = \varepsilon_{el}E$ form in the reactive zone, according to the equilibrium condition. Considering that the technology of making the brazed joints envisages compulsory melting of the filler metal, i.e. heating above 600 °C, the magnitude of maximum tensile stresses on the weld axis for the welded and brazed joints should be close that is confirmed by experimental results (Figure 3). In the zone of reactive compressive stresses, depending on their formation mechanism, reactive compressive stresses form (in the extreme zone of the plate). Their magnitude is determined by the condition of equilibrium of forces in the zones of residual active tensile stresses and reactive compressive stresses of the welded and brazed joints [14]:

$$\sigma_t b_n \delta = -\sigma_{com}(h - \delta_n)\,\delta, \tag{5}$$

$$\sigma_{com} = -\frac{\sigma_t b_n \delta}{(h - b_n)\delta}, \tag{6}$$

where h is the considered joint width.

As one can see from Figure 3, the magnitude of residual compressive stresses is smaller in brazed joints than in welded joints. Reduction of the value of residual reactive compressive stresses, in keeping with expression (6), is attributable to reduction of the width of plastic strain zone.

It is obvious that such a reduction of the magnitude of reactive and active stresses will lead to a considerable reduction of shrinkage force, and, therefore, also to reduction of residual strains of the structure.

Studying the precise dimensions of the width of plastic strain zone requires performance of special studies with involvement of specific investigation procedures. Therefore, in this work we limited ourselves to qualitative assessment of comparison of the values of the width of plastic strain zone in welded and brazed samples. Various approaches to determination of the width of plastic strain zone are described in publications [13, 17].

Analyzing the dimensions of plastic strain zone (Figure 3) with application of the procedure of [17], we can see that this zone does not exceed 30–35 mm in brazed joints, while the width of plastic strain zone in welded joints reaches 50–60 mm. Such a considerable reduction of plastic strain zone in brazed joints is explained by, firstly, a smaller amount of thermal energy introduced into the metal. Moreover, at plasma brazing the heat is introduced into the metal by a highly concentrated source that also promotes a reduction of the width of the heated zones and leads to narrowing of plastic strain zone.

An essential factor of reducing the heat input into the joint in plasma brazing also is heat introduction using modulated current [18]. This can be confirmed by the results of measurement of residual stresses in brazed samples that were made with application of constant and modulated current (Figure 5).

As one can see from Figure 5, the magnitude of maximum tensile stresses on the weld axis at modulated current application, decreases to 85 MPa, compared to the seam brazed at direct constant current. Such a reduction of tensile stresses in the sample is explained by that the sample was brazed in the mode with modulated current at maximum value of the process duty cycle, i.e. minimum value of pulse time (τ_i = = 0.05 s), which causes a significant reduction of the heat input into the base metal. This provides confirmation of the statement that heat introduction into the product using modulated current ensures lowering of residual stresses.

Conclusions

1. Studies performed by magnetoelastic method revealed that residual stresses arise in MAG welding of galvanized steel, the magnitude of which is equal to 149 MPa at the heat input of 380 J/cm.

Application of plasma brazing by constant current allows reducing the heat input to 324 J/cm and residual stresses to 119 MPa.

Further reduction of the heat input to 273 J/cm, and, the resulting reduction of residual stresses to 85 MPa, is ensured by application of modulated current in plasma brazing of galvanized steel 08ps.

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