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Utilization of plasma arc at the metallurgical joining of zinc coated plates to aluminium

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Abstract

Current trend of maximum utilization of properties of metal materials forces the fabricators to use different materials for different construction parts. Thus the fabricators of welded constructions, such as automobile constructions, today combine cold rolled steel plates with high strength low alloy steel as well as with aluminium or its alloys. Especially metallurgical joining of steel to aluminium represents certain issues resulting from different physical properties (e.g. different melting point temperature). Following paper is focused on the analysis of utilization possibilities of plasma arc at the performance of zinc coated steel to aluminium heterogenic joints and on the comparison with the MIG process using the AlSi5 filler material.

Key words: joining of dissimilar materials, plasma arc welding, MIG welding, aluminium, coated plates

1. Introduction

Structural parts and components are often designed of dissimilar materials in order to take the advantages of their properties. Application of welding process in the production is subject to possibility of utilization of conventional welding process for the joining of dissimilar materials, realized by the proper selection of filler material.

For joining of dissimilar materials, mainly mechanical methods (e.g. screw connections, riveting) or solid state welding technologies, such as explosion, friction or diffusion welding are applied [1]. In the frame of fusion welding technologies, mainly technologies using the concentrated source of energy (e.g. laser, electron beam) or partially arc technologies as TIG or MIG welding have been employed into production practice. Employing of laser beam is suitable for joints of difficult geometrical shapes and to achieve the absence of the spatter. However, this method is very sensitive on the proper base material positioning (gap width between base materials) and can be employed only in an automatic mode since it requires special safety equipment [2].

Issues connected with metallurgical joining of dissimilar materials using fusion welding technologies are primarily related to different physical properties of materials – melting temperature, thermal and electrical conductivity and thermal expansion as well as to chemical composition of weld metal. In the case of dissimilar materials welding such as aluminium to steel or zinc coated steel, melting temperature difference is almost 900 ℃ (melting point of T(Fe) = 1535 ℃, T(Al) = 660 ℃). Joining of steel to aluminium (using non-pressure technology) is then characterized by the heterogenic joint; welded joint from the side of aluminium, brazed joint from the side of steel [3, 4]. Therefore this fact on the one hand requires proper filler material choice which will ensure the proper wetting of zinc coated steel plate and on the other hand formation of weld metal with an absence of volumetric defect and with required structure in the aluminium part of a joint. For the welding of the dissimilar joints Al-steel using the MIG/Ar method, previous results approved use of AlSi5 and AlSi12 type filler materials [3–5]. Within the frame of arc technologies excepting the TIG and MIG welding, for the joining of zinc coated plates to aluminium, also the plasma arc process (PAW) is suitable, which is being often applied to the joining of zinc coated plates [6]. In the term

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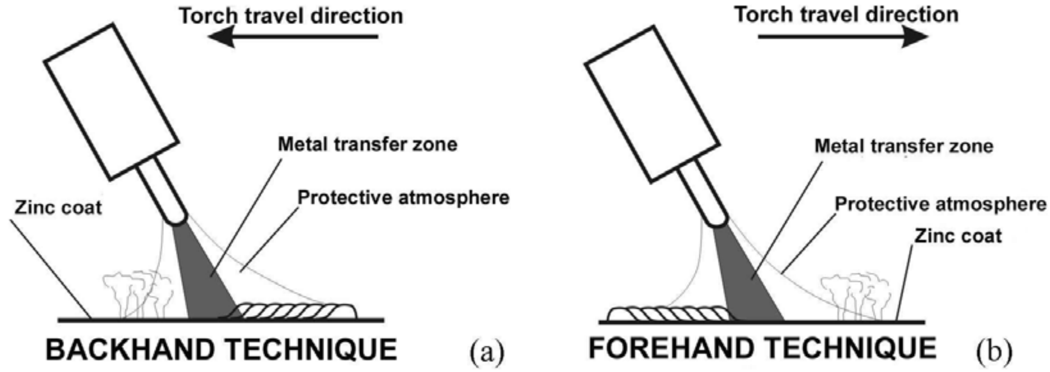


Fig. 1. Schematic illustration of zinc coated plate welding in different torch travel directions: a) backhand technique, b) forehand technique.

of energy concentration level, plasma arc can be categorized right after the laser and electron beam [7, 8]. Plasma arc welding/brazing is a compromise between the MIG technology and the laser. High energy concentration provides high thermal efficiency of the process, which results in high deposition performance at the low heat affection of the base material as well as low evaporation level of Zn from zinc coated sheet [9].

1.1. Weldability of aluminium and its alloys

When welding the aluminium and its alloys, there are several changes, whose extension and quality depend on the welding technology used, welding heat input and a type of an aluminium alloy.

The main issues in welding of aluminium are following [10]:

– Weld porosity.

– Presence of hot cracks in welded joints.

– Presence of oxide layer on the surface of welded materials and its rapid formation at higher welding temperatures.

The weld porosity presence is caused by the effect of hydrogen induced by dissolvability difference of hydrogen in the aluminium during the state form change. In order to eliminate the weld porosity, following recommendations are stated:

1. Elimination of hydrogen source prior to welding, during preheating and during the welding.

2. Decreasing the time of direct melting and eliminating the possibility of overheating of the weld pool.

3. Using the appropriate protection atmosphere of the weld pool.

To comply with the mentioned recommendations, there are certain requirements on the quality of filler materials, welding technology selection and welding mode. Related to the mechanized MIG welding, it is recommended to substitute the spray transfer mode by the pulse transfer mode, providing required arc stability even at lower current load on the wire. Ideal solution is pulse transfer mode which provides one drop per one pulse peak [11].

The surface of aluminium material is covered by Al_2O_3 film, presence of which causes significant issues during the welding. Al_2O_3 oxide is characteristic by high thermal stability (melting temperature 2040 ℃); it deteriorates the conditions for local melting, does not dissolve in the molten weld pool and has a negative influence on the forming of the weld bead shape. Aluminium oxide is an electric insulator, so in the case of higher layer thickness, it may result in the poor electric contact and cause arc ignition problem [10]. Due to the mentioned reasons, it is necessary to remove aluminium oxide film shortly before the welding as well as prevent its formation on the surface during the welding. In the phase of base material preparation for the welding, oxide layer can be removed by mechanical or chemical way or during the welding using the fluxes or by the direct effect of an electric arc.

1.2. Weldability of zinc coated steel plates

Welding conditions of zinc coated plates are affected by the existence of metallic coating. Compared to steel, zinc has a significantly lower melting temperature (420 ℃). Also the temperature of zinc evaporation (906 ℃) is about 600 ℃ lower than melting temperature of low-carbon steel. Fusion welding processes are therefore connected with intensive zinc coat evaporation from the surface of coated steel. Zinc evaporation in the process of welding generally causes:

– Instability of the process, i.e. instability of an electric arc during the arc welding, improper shielding gas flow or disruption of metal transfer from wire to molten weld pool. Those effects mainly cause the higher level of spatter around the weld. In order to eliminate the negative effect of zinc evaporation, it is recommended to use forehand welding technique, when the evaporation of zinc coating occurs at the greater distance from the zone of the metal transfer into the molten weld pool, Fig. 1 [12].

– Except the welding process itself, Zn evaporation

T a b l e 1. Selected physical and mechanical properties of Al and Fe [14]

Material	Tensile strength Rm (MPa)	Melting temperature (℃)	Density (kg m^{-3})	Specific thermal conductivity at 25 ℃ (kJ m^{-1} s^{-1} K^{-1})
Fe	340 ÷ 470	1535	7850	0.46
Al99.5	100	660	2700	2.09

T a b l e 2. Intermetallic compounds in Fe-Al system [19]

Phases	Stability range (at.% Al)	Crystal structure	Vickers hardness (9.8 N)
FeAl	23 ÷ 55	bcc (order)	470 ÷ 667
Fe_3Al	23 ÷ 34	bcc (order)	330 ÷ 368
Fe_2Al_3	58 ÷ 65	cubic (complex)	not investigated
$FeAl_2$	66 ÷ 67	triclinic	1058 ÷ 1070*
Fe_2Al_5	70.0 ÷ 73.2	orthorhombic	1000 ÷ 1158*
$FeAl_3$	74.5 ÷ 76.5	monoclinic	772 ÷ 1017

bcc – body-centered cubic system

negatively affects also the structure of the weld. Often due to insufficient degassing, the pores occur in the volume of the weld metal, which has a negative influence on the mechanical properties of the weld joint. These negative effects are intensified by the increasing of the zinc coating thickness, therefore the decisive criteria of weldability is the thickness of zinc coating. It should not exceed the value of 20 μm [13].

1.3. Problems of the metallurgical joining of steel to aluminium

At the metallurgical joining of dissimilar materials such as steel to aluminium, it is necessary to take into account the physical properties such as the melting temperature, coefficient of thermal expansion and thermal conductivity, and mechanical properties, especially the tensile strength.

Selected properties of Al and Fe are included in Table 1.

In regard to different physical and mechanical properties of Al and Fe (especially the melting temperature difference) joints have a combined – welded/brazed character. Dual character of this joint is displayed in Fig. 2.

In the frame of evaluation of the joint quality, the decisive parameter is the interface layer between the weld metal and steel – brazed joint (Fig. 2), which consists of intermetallic phases of type Al_xFe_y. The nature of intermetallic phases (IM phases), their composition and thickness have an influence on the performed joint quality [15, 16]. The reason of IM formation consists in minimum dissolvability of Fe in Al in the solid state (Fig. 3). These phases are having extremely high hardness values at ambient temperatures, up to 1200 HV (Table 2) and very low toughness

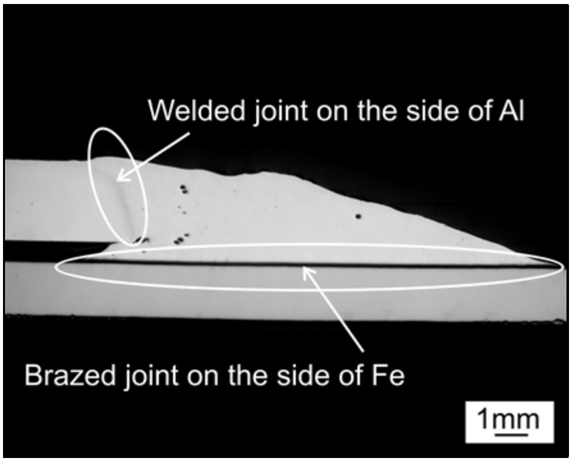


Fig. 2. Al-Fe joints have a dual character; welded joint on the side of Al, brazed joints on the side of Fe.

[16, 17]. Formation of IM in fusion welding primarily depends on the heat input level. The higher the heat input is, the higher thickness of IM will occur, what has a negative influence on final mechanical properties of the joint. Due to this reason, all thermal joining processes are directed at the way of decreasing of thermal heat input in order to avoid or completely eliminate the formation of IM [18, 19]. Ryabov [17] states, that the highest strength of a joint can be achieved, providing that IM thickness does not exceed the value of 10 μm.

2. Experimental

In order to clarify the possibilities of plasma arc utilization for the welding/brazing of aluminium to zinc coated plates, an experiment has been carried out in two stages:

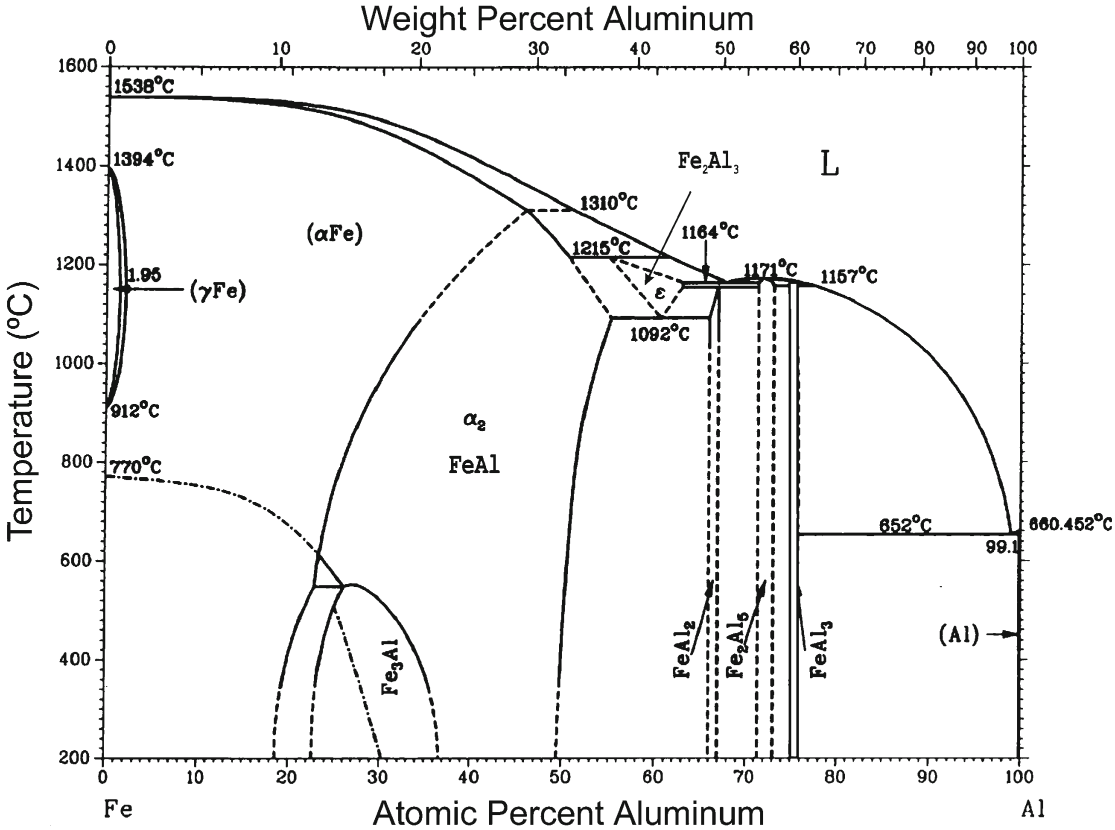


Fig. 3. Fe-Al equilibrium phase diagram [20].

T a b l e 3. Selected properties of aluminium plate Al 99.5

Material	Tensile strength Rm (MPa)	Melting temperature (℃)	Plate thickness (mm)	Thermal conductivity at 25 ℃ (kJ m^{-1} s^{-1} K^{-1})
Al 99.5	100	660	2	2.09

1. In the first stage, parameters of the production of overlapped joint samples have been optimized using the pulse MIG and plasma arc process. Parameters of processes have been optimized on the basis of the results of visual examination; evaluation has been supplemented by macroscopic analysis in the cross sections. Joints performed using the plasma arc process have been compared to the referential samples performed by MIG process.

2. In the second stage, samples performed with optimized parameters by MIG and plasma arc, have been analysed using the microscopic analysis. Microscopic analysis has been used in order to evaluate the thickness and phase composition of interface layer on the side of the brazed joint.

For the production of experimental samples, following materials were used:

– Cold rolled plate, zinc coated on both sides, type DX53+Z 100MB (designation according to STN EN 10142), thickness of zinc layer 6 ÷ 12 μm [22].

– Al99.95 aluminium plate.

– Filler material, AlSi5 wire (ESAB OK AUTROD 4043), designation according to EN ISO 18273: S Al 4043 (AlSi5); diameter 1.0 and 1.2 mm [23].

Selected properties and chemical composition of used materials are given in Tables 3–7.

T a b l e 4. Chemical composition of plate DX53+Z 100MB [20]

Material	C (%)	Mn (%)	P (%)	S (%)
DX53+Z 100MB	0.06	0.35	0.025	0.025

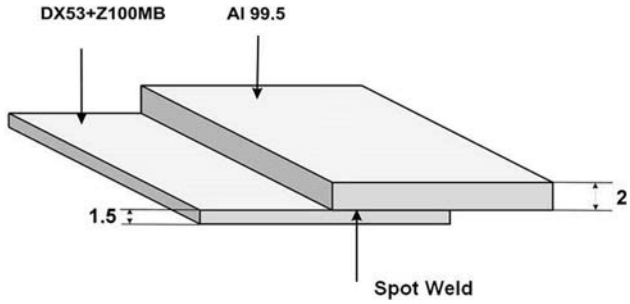


Fig. 4. Positioning of plates for the welding/brazing.

Procedure of sample joints production has been as follows:

1. Samples of dimensions 150 × 50 mm^2 were cut from the blank plate material.
2. Aluminium plates were mechanically brushed and cleaned prior to welding using the stainless steel brush and an acetone.
3. Plates were positioned to constant overlapped joint position and fixed by spot welds. Joint positioning scheme is displayed in Fig. 4.
4. Torch travel direction, distance between the torch nozzle axis and the axis of overlapping (axis of Al plate edge) and torch angle in the perpendicular and parallel to the axis of joint are displayed in Fig. 5.

The heat input per the length unit produced by MIG pulse transfer mode and plasma arc welding/brazing process has been calculated according to the following formula [24]:

$$Q = k\frac{UI}{v_s}10^{-3} \quad (\text{kJ mm}^{-1}), \qquad (1)$$

where k is coefficient of thermal efficiency of welding method, k (MIG) = 0.8; k (PAW) = 0.6 [24], U is voltage (V), I is amperage (A), v_s is welding speed (mm s^{-1}).

Sample joints have been performed in the scope of the following process parameters:

A. Using the MIG process; the inverter power source with synergic control system of welding, HOBART ARC-MASTER 501, which enables welding in pulse transfer mode and provides the software program for the welding of aluminium using the wire of 1.2 mm diameter.

B. Using the plasma arc process; the power source THERMAL ARC ULTIMA-150 with 4-roll drive wire feeder; plasma gas Ar, shielding gas Ar and He.

Optimization of MIG and plasma arc welding/brazing process of zinc coated plates to aluminium has been carried out using the parameters given in Tables 8 and 9.

3. Results

In the optimization process of MIG and plasma arc welding/brazing parameters, such process parameters have been obtained, which provided the formation of joints showing the surface with absence of defect, interface layers between the weld metal and base material and absence of zinc coating affection on the bottom (opposite) side of joint (Table 10).

The joint samples obtained in the process of optimization have been afterwards subjected to macroscopic analysis of the joints cross sections, which has been focused on the evaluation of weld bead geometry documented using the optical microscopy, focusing on

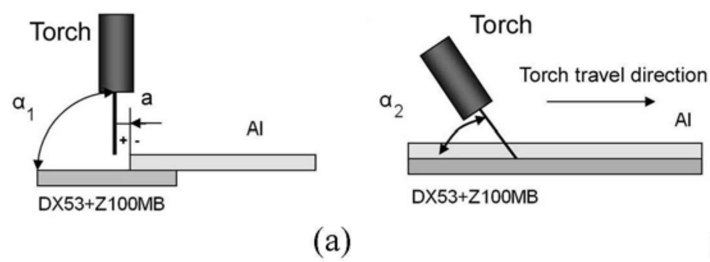


Fig. 5. Torch positioning and movement scheme; α_1 is angle of torch in the perpendicular direction to the axis of joint, α_2 is angle of torch in the parallel direction to the axis of joint, a is distance between the torch nozzle axis and the axis of Al plate edge.

Table 5. Selected properties of plate DX53+Z 100MB [20]

Material	Tensile strength Rm (MPa)	Yield strength Re (MPa)	Plate thickness (mm)	Thermal conductivity at 25 °C (kJ m^{-1} s^{-1} K^{-1})
DX53+Z 100MB	270 ÷ 380	140 ÷ 260	1.5	0.46

Table 6. Typical chemical composition of wire S Al 4043(AlSi5) [21]

Material	Al (%)	Mn (%)	Si (%)	Fe (%)	Zn (%)
S Al 4043(AlSi5)	95.0	< 0.05	5.0	< 0.60	< 0.10

the following parameters:

– width of the contact area from the side of zinc coated plate,

– wetting angle from the side of the zinc coated plate,

– porosity of the weld metal.

Width of the contact area, height of the weld bead and wetting angle have been measured on the cross sections of the selected joint samples prepared using the standard metallographic procedure. Porosity has been evaluated by an area image analysis using the software Impor 5.0 Professional, which on the basis of the colour differences of particular areas enables to determine its percentage amount.

Macroscopic analysis showed the following findings:

A. Amount of heat input affects the geometry of the joint.

B. Porosity of weld metal of the joint samples performed by MIG process is significantly higher in comparison with the weld metal of joint samples performed by plasma arc.

A. Measurements of the contact area (weld) width w_W and wetting angle α_{BM} on the selected sample joints have shown that increasing of the heat input results in the increase of the contact area. The highest width values ($w_W = 11.5 \div 13.7$ mm) have been measured at the heat input $Q = 162.2 \times 10^{-3}$ kJ mm^{-1} on the sample performed by plasma arc process in He. The values of wetting angle on the samples performed by MIG process were measured in the range of $\alpha_{BM} = 12 \div 54°$ and on samples performed by plasma arc in the range of $\alpha_{BM} = 14 \div 41°$. According to these measured values, the wettability can be classified as

Table 7. Typical weld metal mechanical properties of wire S Al 4043(AlSi5) [21]

Material	Tensile strength Rm (MPa)	Yield strength $R_{p0.2}$ (MPa)	Elongation A_5 (%)
S Al 4043(AlSi5)	165	55	18

Table 8. MIG arc welding/brazing process parameters

Process parameter	Value
Effective value of welding current I_{EF} (A)	$71 \div 80$
Effective value of the voltage on arc U_{EF} (V)	$15 \div 18$
Welding speed v_s (mm s^{-1})	$7.5 \div 9.2$
Torch movement geometry (Fig. 5)	$\alpha_1 = 80 \div 90°$, $\alpha_2 = 70, 75°$, $a = -1.5 \div 0.5$ mm
Wire diameter d (mm)	1.2
Heat input Q (kJ mm^{-1})	$115.6 \div 147.8 \times 10^{-3}$
Shielding gas: Ar 4.6, flow rate (l min^{-1})	10

Table 9. Plasma arc welding/brazing process parameters

Process parameter	Value
Plasma current I_P (A)	$40 \div 80$
Voltage on arc U_P (V)	$15 \div 18$
Welding speed v_s (mm s^{-1})	$3.3 \div 5.0$
Wire feed speed v_F (m min^{-1})	$2.16 \div 3.04$
Torch movement geometry (Fig. 5)	$\alpha_1 = 75 \div 90°$, $\alpha_2 = 75°$, $a = 0 \div 4.5$ mm
Wire diameter d (mm)	1.0
Heat input Q (kJ mm^{-1})	$108.1 \div 172.9 \times 10^{-3}$
Plasma gas: Ar 4.6, flow rate (l min^{-1})	1
Shielding gas: Ar 4.6, He 4.6, flow rate (l min^{-1})	10 and 15

Table 10. Joints sample performed by MIG and plasma arc technology with optimized parameters

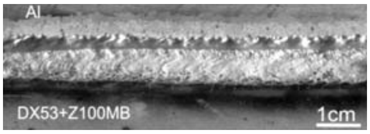
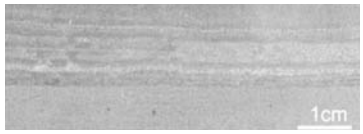
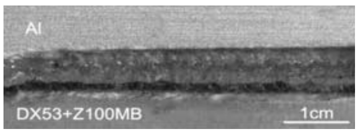
Sample	Joint surface	Bottom side of the joint	Notes
MIG pulse transfer mode			$Q = 123.2 \times 10^{-3}$ kJ mm^{-1} Uniform melting of Al plate edge; uniform wetting of zinc coated plate, with the absence of zinc coating affection on the bottom side of the joint.
Plasma arc in the protection of Ar			$Q = 144.12 \times 10^{-3}$ kJ mm^{-1} Smooth and uniform melting of Al plate and wetting of zinc coated plate; bottom side with the absence of zinc coating affection.
Plasma arc in the protection of He			$Q = 162.2 \times 10^{-3}$ kJ mm^{-1} Uniform melting of Al plate edge; uniform wetting of zinc coated plate, with the absence of zinc coat affection on the bottom side of the joint.

Table 11. Cross sections of selected joints performed by MIG and plasma arc process with optimized parameters

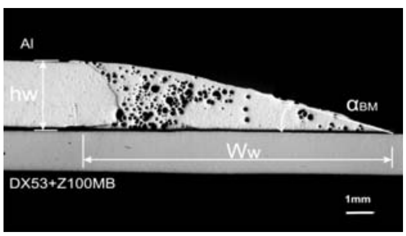
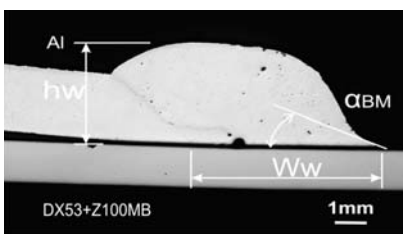
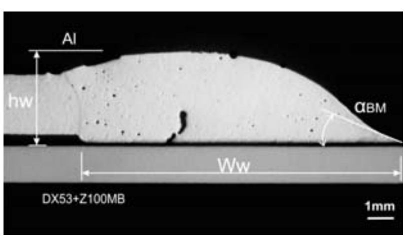
Sample	Cross sections	$Q \times 10^{-3}$ (kJ mm^{-1})	w_W (mm)	h_W (mm)	α_{BM} (°)	Porosity (%)
MIG pulse transfer mode		129.4	9.2	2.5	16	12.1
Plasma arc in the protection of Ar		144.1	7.5	3.8	18	0.6
Plasma arc in the protection of He		162.2	12.4	3.6	19	0.78

Table 12. Cross section of the joints – details

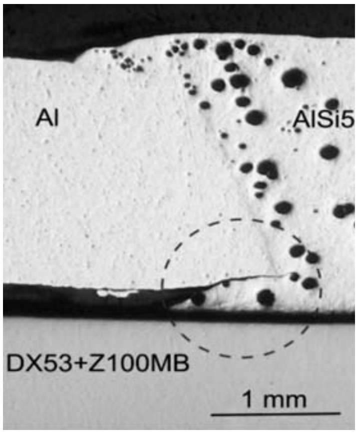
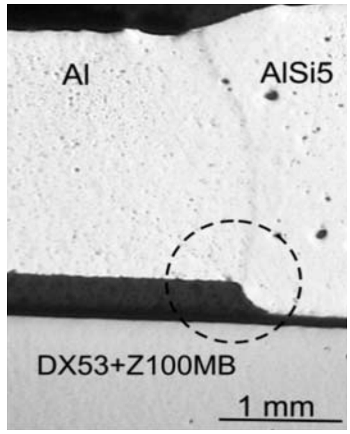
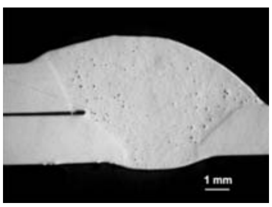
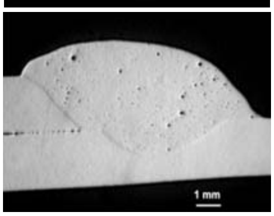
	MIG Pulse transfer mode	Plasma arc in the protection of He
Cross section detail		
Notes	Non-uniform melting of Al plate in the cross section direction. Undercut and notch on the bottom side of Al plate.	Uniform melting of Al plate in the cross section direction. Smooth transition from the Al plate surface to the weld in the bottom part of joint.

Table 13. Cross sections of Al99.5 to Al99.5 weld

Sample	Cross sections	$Q \times 10^{-3}$ (kJ mm^{-1})	Porosity (%)
Al 1		148.4	0.198
Al 2		134.1	0.559

"very good" up to "excellent". Cross sections of selected joint samples performed using the MIG and plasma arc process are documented in Table 11.

In the term of the notch effect, the transition zone between the weld metal and aluminium plate and wetting of zinc coated plate is preferable on the joints performed by the plasma arc process. Cross section details of joints performed by MIG and plasma arc process aimed at the melting of aluminium plate are documented in Table 12.

B. High porosity using MIG process was not possible to eliminate by the change of heat input rate either. Porosity was measured in the range from 5 to 21 %. Pores were uniformly distributed in the volume of the weld metal. Significantly lower porosity level was noticed on the joint samples performed by plasma arc process. Porosity ranged from 0.6 to 4.1 %.

In general, porosity at the welding of aluminium and its alloys is caused by the hydrogen which is released from the surface of welded material. In order to identify closer the source of porosity in the weld metal, overlapped joint samples have been performed of aluminium plate Al99.5, by the MIG process with the same plates positioning, welding/brazing procedure and parameters as were used for the performance of dissimilar joint samples. By the elimination of zinc coated plates from the experiment, zinc was eliminated as a potential source of porosity. Cross sections of aluminium joint samples and evaluation of the weld porosity are documented in Table 13.

Cross sections of Al-Al weld joints show much lower level of porosity and the size of pores comparing to Al plate – zinc coated plate joints. It can be assumed that the primary cause of porosity in welded/brazed Al to zinc coated plate joints is connected with incomplete evaporation of zinc from the weld metal. As the quantity of evaporated Zn directly depends on the Zn layer thickness, one of the solutions to decrease the porosity will be application of zinc coated plates with minimum zinc coating thickness.

Joint samples, performed with optimized parameters, were further subjected to:

– Microscopic analysis, where the thickness interface layer was measured from the side of brazed joint.

– EDX analysis, in order to identify the compos-

Table 14. Average values of the transition zone thickness of joints performed by MIG and plasma arc process

Process	Average value of the interface layer thickness (μm)
MIG pulse transfer mode	4.5
Plasma Ar	1.9
Plasma He	5.5

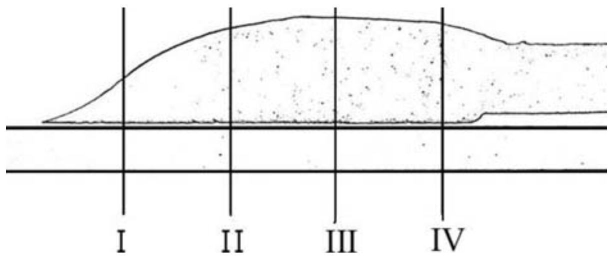


Fig. 6. Scheme of interface layer thickness measuring.

ition of elements presented in the interface layer and to determine the phase composition.

Based on the existing literature sources [17, 25], for the evaluation of the properties of mentioned type of a joint it is important to evaluate the structure and transition zone thickness between the zinc coated plate and weld metal formed of AlSi5 wire. The structure of transition zone is multi-phased with the dominant presence of Al-Fe and Al-Fe-Si types of intermetallic phases. Given the above, an attention has been focused on the structure and the thickness analysis of the mentioned zone using an optical microscopy and EDX analysis.

Thickness of the transition zone has been measured on the cross sections of the joint samples performed by MIG and plasma arc process in four locations (I, II, III, IV) of reaction zone according to the scheme in Fig. 6. In each location, three measurements have been performed. Figures 7–9 document the measuring of the transition zone thickness (measuring location II, Fig. 6); average measured values of transition zone thickness are included in Table 14.

Measurement results of interface layer thickness (Table 14) and interface layer shape (Figs. 7–9) show that interface layer thickness has different values and varies depending on the joining process and the location of measurement. Comparing the joint samples performed by plasma arc process in the protection of Ar to the same process in the protection of He, it is possible to identify the differences in the thickness and the shape interface layer. Argon and helium are both inert gases, but have different physical properties. Helium has a higher thermal conductivity and ionization energy in contrast to argon, what has an influence on the properties of electric arc. Arc voltage in the protection of He is higher compared to arc voltage in Ar [10]. Thermal output of arc in the He is higher. Therefore it causes higher welding heat input into the joint, what is an assumed cause of interface layer thickness increase.

Literature sources state [11], that the highest strength of the joint can be achieved providing that the thickness of intermetallic phases (which are the part of the structure in the transition zone) does not exceed the value of 10 μm. The results of IM thickness

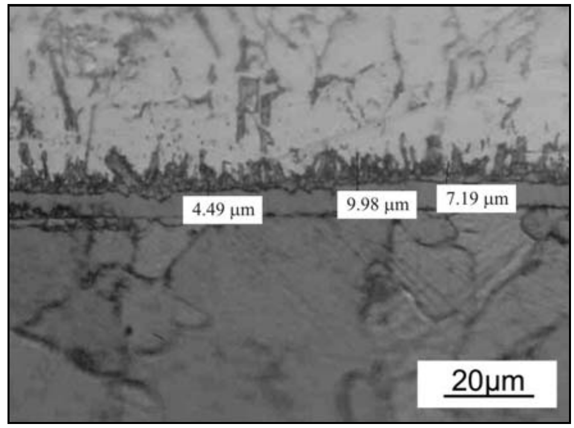


Fig. 7. Interface layer of the joint performed by MIG pulse transfer mode.

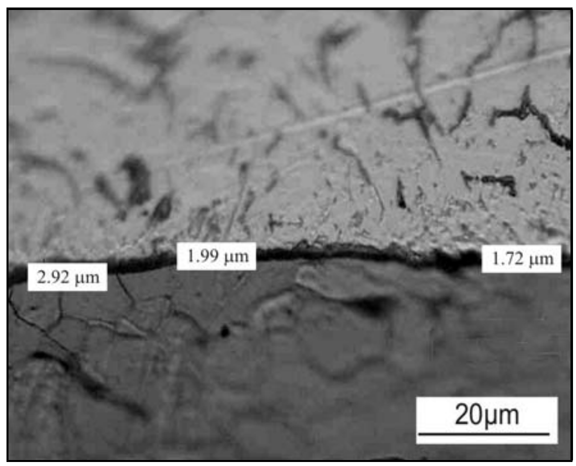


Fig. 8. Interface layer of the joint performed by plasma arc process in Ar.

measurement show that the value of 10 μm was not exceeded in either case. An analysis of the interface layer thickness shows, that in the frame of used joining methods (MIG pulse transfer mode process and plasma arc process), the most suitable will be the application of plasma arc process in Ar as a shielding gas. On the samples performed by this technology, there was identified the most uniformly and sharply

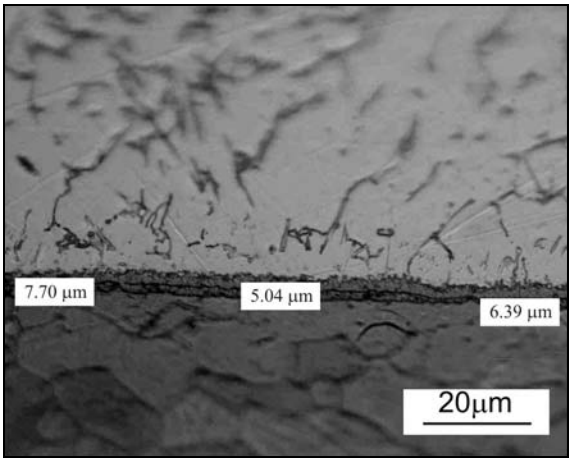


Fig. 9. Interface layer of the joint performed by plasma arc process in He.

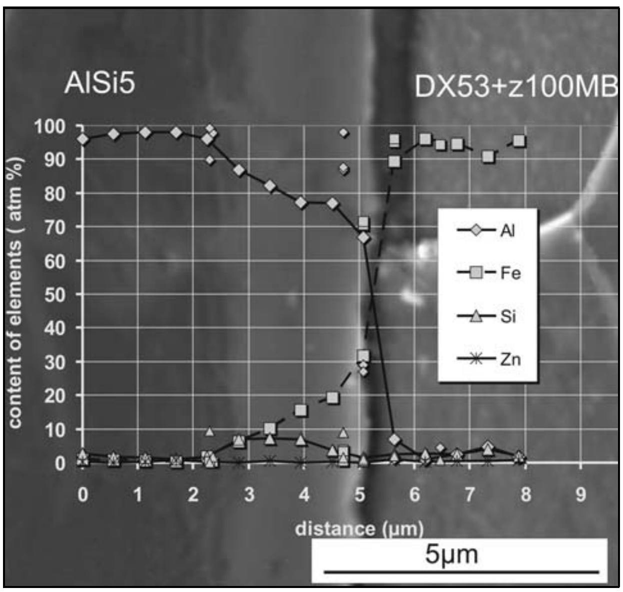


Fig. 10. Concentration profiles of the AlSi5-DX53+Z 100MB interface layer; sample performed by MIG pulse transfer process.

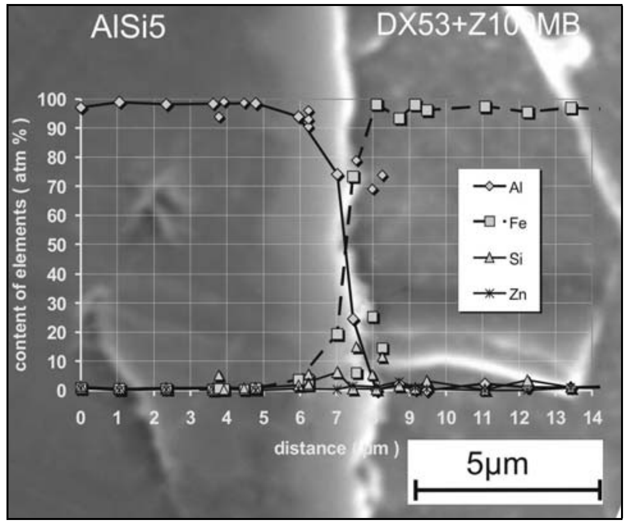


Fig. 11. Concentration profiles of the AlSi5-DX53+Z 100MB interface layer; sample performed by plasma arc process in the protection of Ar.

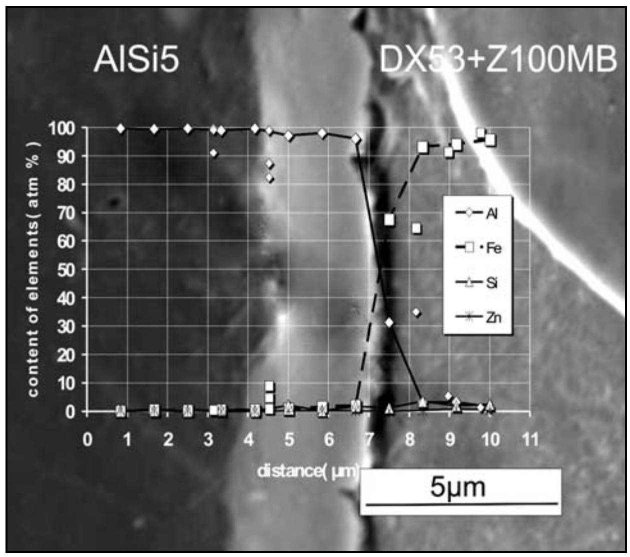


Fig. 12. Concentration profiles of the AlSi5-DX53+Z 100MB interface layer; sample performed by plasma arc process in the protection of He.

defined interface layer with the lowest thickness values ranging from 1.46 to 2.21 µm.

For the more detailed analysis of transition zone, the EDX analysis has been used. Atomic and mass determination of the elements in the interface layer (Al, Fe, Si and Zn) between the zinc coated steel plate and AlSi5 weld metal was evaluated using the electron microscope JEOL JSM 5310, which was equipped by the energy-dispersive X-ray spectrometer KEVEX delta IV. Atomic and mass determination of elements was evaluated using the EDX analysis perpendicular to the interface of zinc coated steel plate – AlSi5 weld metal (Figs. 10–12).

Measured values were processed to the diagrams showing the progression of atomic and mass concentration of Al, Fe, Si and Zn in dependence on the distance from the interface layer. The structure was specified on the base of EDX analysis results, Al-Fe and Al-Si phase diagrams, Al-Fe-Si ternary system and literature sources [20, 26, 27].

Based on the analysis results, it can be concluded, that almost 100 % evaporation of Zn has occurred from the surface of zinc coated steel plate in the measured zone between the AlSi5 weld metal and zinc coated steel plate. In the interface layer between the AlSi5 weld metal and zinc coated plate, there was

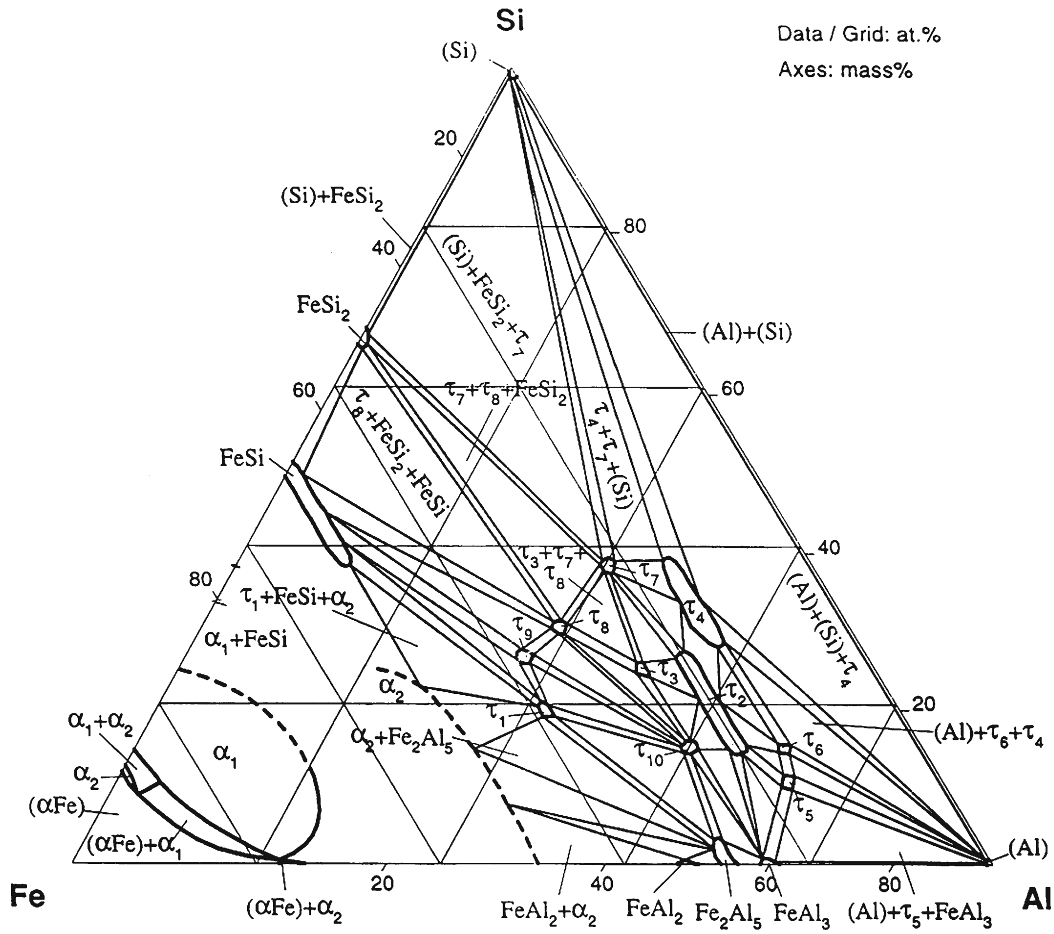


Fig. 13. Isothermal section of the Al-Fe-Si system at 600 °C [28].

found a higher content of Fe, while its increase in the interface layer corresponded to the decrease of Al content. EDX analysis results showed intensive diffusion of Si to the interface layer, while its maximum content reached the value of 9.32 atm.% (sample performed by MIG process), 14.90 atm.% (sample performed by plasma arc process in the protection of Ar) and 8.58 atm.% (sample performed by plasma arc in the protection of He). The structure of diffusion zone was formed of Al-Fe-Si phases. On the base of EDX analysis results and identification of phase composition using the ternary system Al-Fe-Si, the following phase composition in the interface layer AlSi5 – zinc coated steel can be concluded: solid solution of αFe, intermetallic phases $FeAl_2$, $FeAl_3$ (Fig. 3) and ternary phases of type τ_5 ($Al_{15}Fe_6Si_5$); τ_6 ($Al_{4,5}FeSi$), Fig. 13.

4. Conclusions

The aim of the presented paper was to analyse the possibilities of utilization of plasma arc process at the welding/brazing of dissimilar joints – zinc coated steel plate to aluminium using the AlSi5 wire. For the purpose of comparison, overlapped sample joints were performed with optimized parameters by plasma arc process and by referential MIG process. Parameters were optimized on the base of the visual examination; evaluation was supplemented by macroscopic analysis of joints in cross sections. In the next part, joint samples performed with optimized parameters were subjected to microscopic analysis, which was focused on the examination of transition (diffusion) zone thickness and phase composition from the side of brazed joint.

On the base of the results, following can be concluded:

1. Regarding to results of macroscopic analysis of cross sections (evaluation of contact area width between the zinc coated steel plate and AlSi5 weld metal – w_W and wetting angle – α_{BM}), it can be concluded, that with the increase of heat input, the width of the contact area increases. The highest value of the width w_W has been measured at the heat input $Q = 162.2 \times 10^{-3}$ kJ mm^{-1} on the welds performed by plasma arc process in He as a shielding gas. Joint samples performed by plasma arc process in Ar have shown lower values of width w_W comparing to joints performed by reference MIG pulse transfer process (Table 11).

The cause of width differences can be found in the different physical properties of used gases. Compared to argon, helium has higher ionization energy, thermal conductivity and thermal capacity, what significantly affects the heat distribution and maximum temperature of an electric arc, and therefore also the conditions of heat distribution into the base material [11]. Using He, the temperature of molten weld pool increases, while the heat is distributing more in the direction of width than to the depth, what has a positive influence on the heating conditions (heating to the brazing temperature) and enables to reach the brazing temperature in the greater distance from the axis of the joint, what has also affected the wetting conditions of zinc coated plate surface (Table 11).

2. After the examination of macroscopic cross section images and comparison between joint samples performed by MIG pulse transfer process and joints performed by plasma arc process, the difference in the porosity level is evidently visible (Table 11).

The analysis has been focused on the determination of:

A. Porosity source.

B. Causes of differences in porosity between the joints performed by MIG and by plasma arc process.

A. Major cause of gas entrapment in the weld metal can be closely related to:

1. Insufficient removal of oxides from the surface of an aluminium plate.

2. Evaporation of Zn resulting from the heating of the zinc coated plate above the temperature of its evaporation point (906 ℃).

The analysis of overlapped joints performed by MIG process on aluminium plates prepared by the same procedure as applied on dissimilar joints has shown, that the dominant influence on the porosity of dissimilar joints Al-Zn-coated plate probably consists in the evaporation of Zn. As the quantity of vaporized Zn is directly related to the thickness of zinc coating, in the term of reducing the porosity level, it can be recommended to use zinc coated plates with lower thickness of zinc coating. Porosity of AlSi5 weld metal performed by plasma arc process in Ar and He was considerably lower than the porosity of weld metal performed by MIG pulse transfer process. It can be assumed, that the porosity level closely depends on the temperature of molten weld pool and the type of metal transfer mode:

– Concentrated heat source – plasma arc – is causing the higher level of heating of the weld metal, what provides better conditions for its degassing during the solidification.

– It can be concluded, that lower porosity level in the joints welded/brazed by plasma arc process compared to MIG pulse transfer process is related to the different mechanisms of the gassing of molten weld pool. In the case of the plasma arc, the filler material is being continuously added into the plasma arc while it starts to melt when the wire tip directly contacts the molten weld pool. During the globular metal transfer in MIG process, gassing of molten filler material may occur during the movement of drops across the arc gap and also in the molten weld pool [13].

3. During the microscopic analysis of joint samples, attention had been focused on the evaluation of thickness and structure analysis of interface layer between zinc coated plate and AlSi5 weld metal, which were decisive in the term of the mechanical properties of joint (presence of intermetallic phases). The evaluation of thickness and character of interface layer showed, that the mentioned criteria depended on the type of the joining process (MIG, plasma) as well as on the parameters of the process. Structure and thickness of transition zone were significantly affected by the process thermal cycle, which had an influence on the processes of diffusion, what was also reflected in the thickness of interface layer measured in different locations of the joint (Table 14). The minimum average thicknesses were measured on joint samples prepared by plasma arc process in the protection of Ar, average and maximum thickness was observed using the plasma arc in the protection of He. For the evaluation of the impact of interface layer thickness on the mechanical properties of the joint, the criteria published in the literature have been adopted [16, 17], which state, that the highest strength of a joint can be reached on the condition that the transition zone does not exceed the thickness of 10 μm. The results of the thickness measurements performed in the transition zone of joints indicate that the thickness was not greater than 10 μm, which is the precondition for achieving appropriate mechanical properties.

4. The results of EDX analysis showed the intense diffusion of Si to the transition zone where the highest measured value was 14.9 at.% Si. As expected, the diffusion of Fe to the transition zone was observed from the side of AlSi5 weld metal and diffusion of Al to the transition zone from the side of a zinc coated plate. On the base of EDX analysis results it can be concluded, that the structure of interface layer contains intermetallic phases $FeAl_2$, $FeAl_3$ and ternary phases τ_5 ($Al_{15}Fe_6Si_5$); τ_6 ($Al_{4,5}FeSi$).

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